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Potential for the integration of decarbonised gases in industry

PUBLIC SUMMARY

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Study carried out for ALLICE by Blunomy, CETIAT, CETIM and CTMNC.

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Le CTMNC *Centre Technique de Matériaux Naturels de Construction* (French Technical Centre for Natural Construction Materials) is the national industrial technical centre (CTI) for the terracotta and natural stone sectors. Created in 1957 under the name CTTB, as it was initially dedicated to roof tiles and bricks, the organisation was renamed CTMNC in 2007 with the integration of an Ornamental and Building Stone department. As a CTI, its mission is to support manufacturers in developing these sectors by offering, among other things: collective and private R&D studies on topics ranging from the characterisation of raw materials and processes to the characterisation of products either on their own or in other applications; assistance with the development of quality processes; participation in standardisation work; active technological monitoring; and training.

Executive summary

Accounting for 18% of national CO_{2eq} emissions, industry is one of the main GHG emitting sectors and faces major decarbonisation challenges [1]. According to France's National Low Carbon Strategy (*Stratégie Nationale Bas Carbone* – SNBC), this sector must reduce its emissions by 35% by 2030 compared with 2015, and by 81% by 2050 [2]. To achieve these targets, it is essential to green the industrial energy mix, and in particular its thermal processes. In France, thermal uses in industry currently account for 258 TWh of annual consumption, including 240 TWh of non-electric consumption, and are mainly divided between furnaces (61%) and drying processes (27%). According to the PEP study (*Potentiel d'électrification des procédés thermiques industriels* – Potential for Electrification of Industrial Thermal Processes) [3], "taking into account only technical and operational constraints, the theoretical maximum potential for electrification by 2035 is 29%". Other decarbonisation solutions are therefore needed.

Decarbonised gases are gaseous energy carriers that are alternatives to fossil gases. They emit less CO_2 equivalent than the latter based on life cycle analysis. In addition to reducing the carbon footprint of thermal MWh produced, there are four main criteria that will influence manufacturers' use of these alternative gases:

- the availability on the market of the volumes of gas required;
- the stability of the composition and the volumes of gas delivered;
- the economic competitiveness of these gases (purchase price and additional sources of income);
- ease of technical integration into industrial processes.

The availability of decarbonised gases on the market is currently average for biogas, biomethane and hydrogen, and low for other gases. However, advances in production methods combined with public support should accelerate their development. The "Transition(s) 2050" study [4] recently published by ADEME, predicts that, depending on the scenario, in 2050:

- 94 to 128 TWh of biomethane (compared with the 6 TWh forecast for the end of 2021);
- 96 TWh of hydrogen produced by electrolysis
- 67 TWh of synthetic methane from pyrogasification.

Biomethane is the gas for which the prospective scenarios forecast the largest volumes in 2030 and 2050, with the least uncertainty. For hydrogen from electrolysis and synthetic methane, the volumes are more uncertain, with significant differences between the minimum and maximum values of the scenarios in the prospective studies.

Stability, both in terms of composition and the volumes delivered, is a key issue for unpurified gases: biogas and syngas. After purification, biomethane and synthetic methane can be stored and transported via existing gas networks. Under a supply contract, for example via guarantees of origin, industrial consumers will be able to continue using gas from the network with a controlled composition. The required quantity and quality of hydrogen, produced through electrolysis or reforming with CCUS,

can also be delivered under a supply contract between a producer and an industrial consumer. Biogas and syngas, on the other hand, are difficult to transport and store. Their availability and quality are directly dependent on that of their feedstocks.

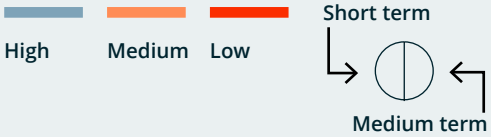
In terms of economic competitiveness, at present, the only option that is sometimes cheaper for industrial consumers than natural gas is biomethane. In the medium term, biogas (produced and consumed on site) could also become competitive, particularly if the price of natural gas rises and if the forecast cost reductions in the biogas production chain are achieved. Renewable hydrogen, when not produced on site, has a much higher purchase cost than natural gas (around ten times higher). Even when produced on site, its production cost is around twice the average price of natural gas. However, this cost is set to fall as a result of progress in the industry and the scale-up of production. The price of synthetic methane is still uncertain at present, but according to the available projections, costs will remain higher than for gas.

Finally, it is important that the decarbonised gas purchased by an industrial company is easy to use and can be integrated into its processes. The use of biomethane or synthetic methane in industrial processes does not pose any specific technical challenges because both gases have a composition very close to that of natural gas (and compliant with network specifications). Any adaptations that would need to be made to accommodate higher proportions are related to the network and are handled by gas network operators.

CRITERIA LIKELY TO INFLUENCE MANUFACTURERS WHEN CHOOSING DECARBONISED GASES (DETAILED TABLE AVAILABLE IN THE FULL STUDY REPORT)

TABLE 1

	BIOGAS	BIOMETHANE	RENEWABLE HYDROGEN	METHANE (VIA POWER-TO-GAS)	SYNGAS (VIA GASIFICATION)	SUBSTITUTE NATURAL GAS (SNG) (VIA GASIFICATION)
Reduction in carbon footprint						
Availability of required volumes of gas						
Stability in terms of composition and supply volume						
Economic competitiveness						
Ease of integration						



Notes
1 - There are more integration constraints when producing hydrogen on site compared to using hydrogen from the grid.
2 - The decarbonisation potential of syngas and SNG depend on the percentage of biomass in the feedstocks.

The technical analysis carried out in this study shows that there is already initial feedback[1] on the use of biogas, syngas and hydrogen in boiler burners and furnaces. Technologies are currently being developed[2], but a number of technical questions remain, particularly concerning the impact of these gases on products, the composition of flue gases, etc. From a technical point of view, hydrogen and syngas are the most problematic, especially when used pure or blended with natural gas in high concentrations. The use of biogas to produce heat has been trialled more extensively in the food processing, woodworking, pulp and paper, chemicals and pharmaceuticals, ceramics and terracotta and textile industries.

The adoption of decarbonised gases by industrial companies therefore depends on a number of criteria, and will not be the same for all sectors and processes. For boilers, it will be easier to use raw gases such as biogas or syngas. For furnaces, on the other hand, the use of decarbonised gases is more complex, but use for cooking is of greater interest, because the required temperature range (between 850 and 1150°C) and the thermal power required (around 20 MW) are higher, making electrification of the process more complex and costly. This is one of the reasons why certain decarbonised gases are already being used or tested.

Finally, the development of certain specific applications, such as the use of hydrogen in the iron and steel industry or the recycling of blast furnace gases, will depend on the results of the demonstrators currently underway, while others, such as the recovery of VOCs, will depend on regulatory changes.

Forecast scenarios, such as those developed by ADEME, point to a sharp increase in the volumes produced for all decarbonised gases. These technologies are expected to be deployed mainly through the injection of biomethane and synthetic methane into gas networks, as well as through the potential development of hydrogen networks. Projects for the production and industrial consumption of biogas and syngas will also continue to develop, but on a more local scale and probably initially in cases where there are interesting synergies, such as the presence of feedstocks close to or within the industrial site.

The support mechanisms and public aid envelopes dedicated to the development of these sectors, such as France's €7.2 billion National Hydrogen Strategy, will play an important role in the deployment of production sectors. However, this will not happen if the extra costs involved are too high. The current trend seems to indicate an increase in the price of natural gas and the carbon tax in the EU (which rose above €65/tCO_2 in October 2021) along with a fall in production costs for all decarbonised gases.

1 - See the feedback sheets in the full study report.

2 - See the technology sheets in the full study report.

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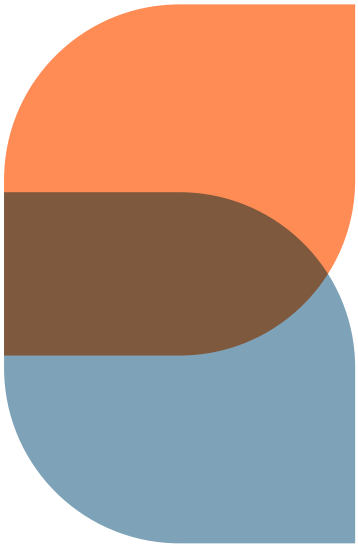
Introduction

Accounting for 18% of national CO_{2eq} emissions, industry is one of the main GHG emitting sectors and faces major decarbonisation challenges [1]. According to France's National Low Carbon Strategy (*Stratégie Nationale Bas Carbone* – SNBC), this sector must reduce its emissions by 35% by 2030 compared with 2015, and by 81% by 2050 [2]. To achieve these ambitions, it is essential to green the industrial energy mix, and in particular its thermal processes. The use of decarbonised gases is one alternative to the use of fossil fuels.

As part of its activity to support innovation and energy efficiency for industry, ALLICE wanted to inform its members about the potential for integrating decarbonised and recovered gases into industrial thermal processes. This report follows on from a previous study on the electrification of processes, which is a complementary solution for the decarbonisation of industrial thermal uses. From a methodological point of view, this study weighs up the technical feasibility of using decarbonised gases for certain industrial processes with the accessibility and availability of these alternatives to industrial companies. It does not include quantitative modelling to forecast the volumes of decarbonised gases that will be used in industry, but it does make reference to the results of certain prospective studies.

This summary of the study begins by outlining the main decarbonisation challenges facing industry. It then describes the different types of decarbonised gases, the technical feasibility of their use in industry, and their availability on the market. The final section qualitatively assesses the potential for deploying decarbonised gases in industry by comparing their respective strengths and examining the development scenarios set out in benchmark studies on the subject.
Full details of the analysis are given in the full report of the study (only available to ALLICE members).

Part 1



The challenge of decarbonising industrial thermal processes

In 2019, the estimated final energy consumption of the industrial sector in France was 373 TWh, i.e. 23% of the final energy consumed in France[3] [5]. Approximately 65% of this demand corresponds to thermal requirements, 93% of which are met predominantly by fossil fuels, as shown in **Figure 1** [3]. Decarbonising industrial heat production is therefore key to reducing France's GHG emissions.

Four main categories of industrial thermal processes can be identified: (i) furnaces, (ii) heating of liquids and gases (boilers), (iii) drying and (iv) distillation [6]. This study focuses on the first two applications, which have a low electrification potential according to the results of the PEP study on the electrification potential of industrial thermal processes [4]. The maximum penetration of electrical solutions in 2035 for heating fluids at temperatures above 150°C and for furnaces at 400-1000°C has been estimated at 20% and 10% respectively, i.e. 2 and 4 times lower than for drying and distillation [3]. These low values can be explained by the operational constraints associated with certain processes (ramp-up time, need for a uniform temperature, etc.), which are more difficult to meet with electric solutions. The role of decarbonised gases in these two processes could therefore be of interest, and is thus explored in greater depth in this study.

FINAL ENERGY CONSUMPTION OF INDUSTRIAL THERMAL PROCESSES IN FRANCE COMPARED WITH TOTAL NATIONAL AND INDUSTRIAL CONSUMPTION (TWH/YEAR) [3] [18]

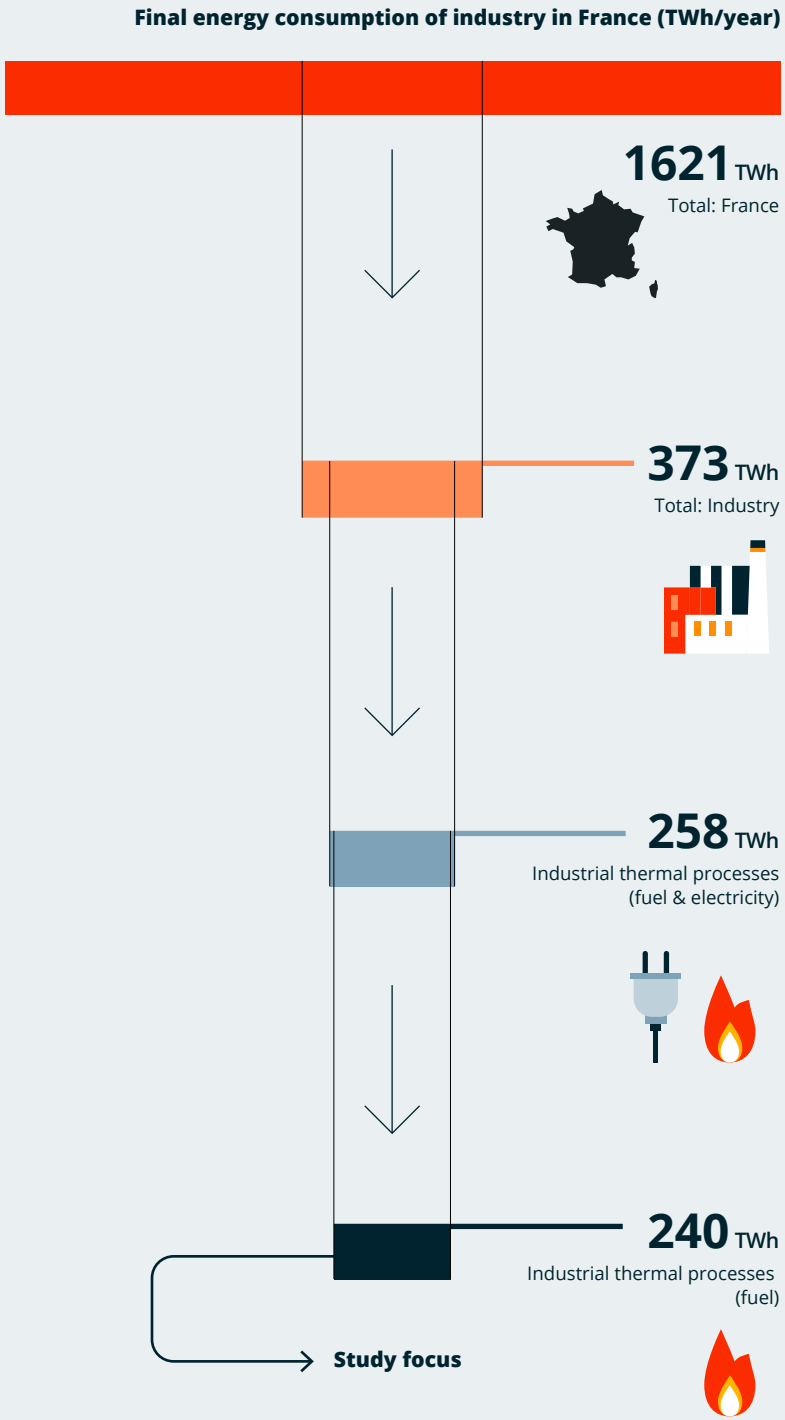


FIGURE 1

3 - Including the smelting and refining sector

These two thermal applications are used in many industrial sectors. This initial study focuses on two sectors with significant thermal requirements: **the production of terracotta materials and the iron and steel industry.**

In both of these sectors, energy management is a priority. For each, from an economic point of view, energy represents a cost item that must be controlled, representing between 15% and 33% of production costs [7]. From an environmental point of view, energy accounts for a large proportion of the GHG emissions of these players, who face significant decarbonisation challenges. In France, around 160 kg of CO_2 are emitted for every tonne of clay products produced [8]. For steel, when averaged worldwide, the carbon intensity is 10 times higher than this. The World Steel Association estimates that between 7 and 9% of direct emissions linked to global fossil fuel consumption are attributable to the steel industry [9]. In France, the contribution of the terracotta and steel sectors to total emissions is also significant.

With around 19 million tonnes of CO_2 emitted each year, steel accounts for 24% of national industrial emissions, while the clay sector accounts for 0.8% of industrial emissions, with just over 650,000 tonnes of CO_2 emitted in 2018 [10] [11].

These emissions are concentrated at a small number of sites, with around 130 clay materials manufacturing centres and 3 steelworks with blast furnaces. Decarbonising the activity of one of these sites would therefore have a greater impact than for sectors with a similar volume of emissions, but scattered over many smaller sites.

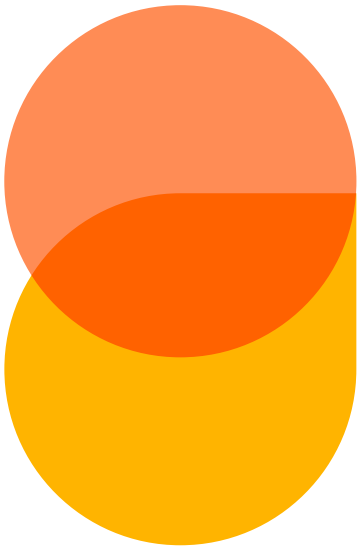
Today, there are two main ways of producing steel: blast furnaces and direct reduction. In blast furnaces, iron ore is smelted into cast iron using coke produced from mineral coal. This process emits CO_2 because coke is used as a fuel and raw material in the same way as ore. It should be noted that certain fuels, such as plastic waste or natural gas, can partially replace coke.

The Direct Reduced Iron (DRI) process produces iron from ore using a reducing gas: syngas (H_2+CO), derived from reformed natural gas. The metal produced is then often compressed to form briquettes, which are used mainly in electric arc furnaces (this is known as the Direct Reduced Iron – Electric Arc Furnace process, or DRI-EAF for short). The traditional DRI process, using natural gas, still emits greenhouse gases, but in smaller quantities than blast furnaces.

The use of hydrogen instead of natural gas is beginning to be developed to reduce the carbon footprint of steel production, and will be detailed later in this report.

The manufacture of clay building products requires a drying stage for the wet-formed clay-based products, followed by a high-temperature firing stage (between 850 and 1100°C) to obtain the desired use and durability properties. Most of the energy for the firing process comes from the combustion of natural gas.

Part 2



Gas solutions to decarbonise industrial thermal processes

2.1

P.12 Characteristics of decarbonated and recovered gases

2.2

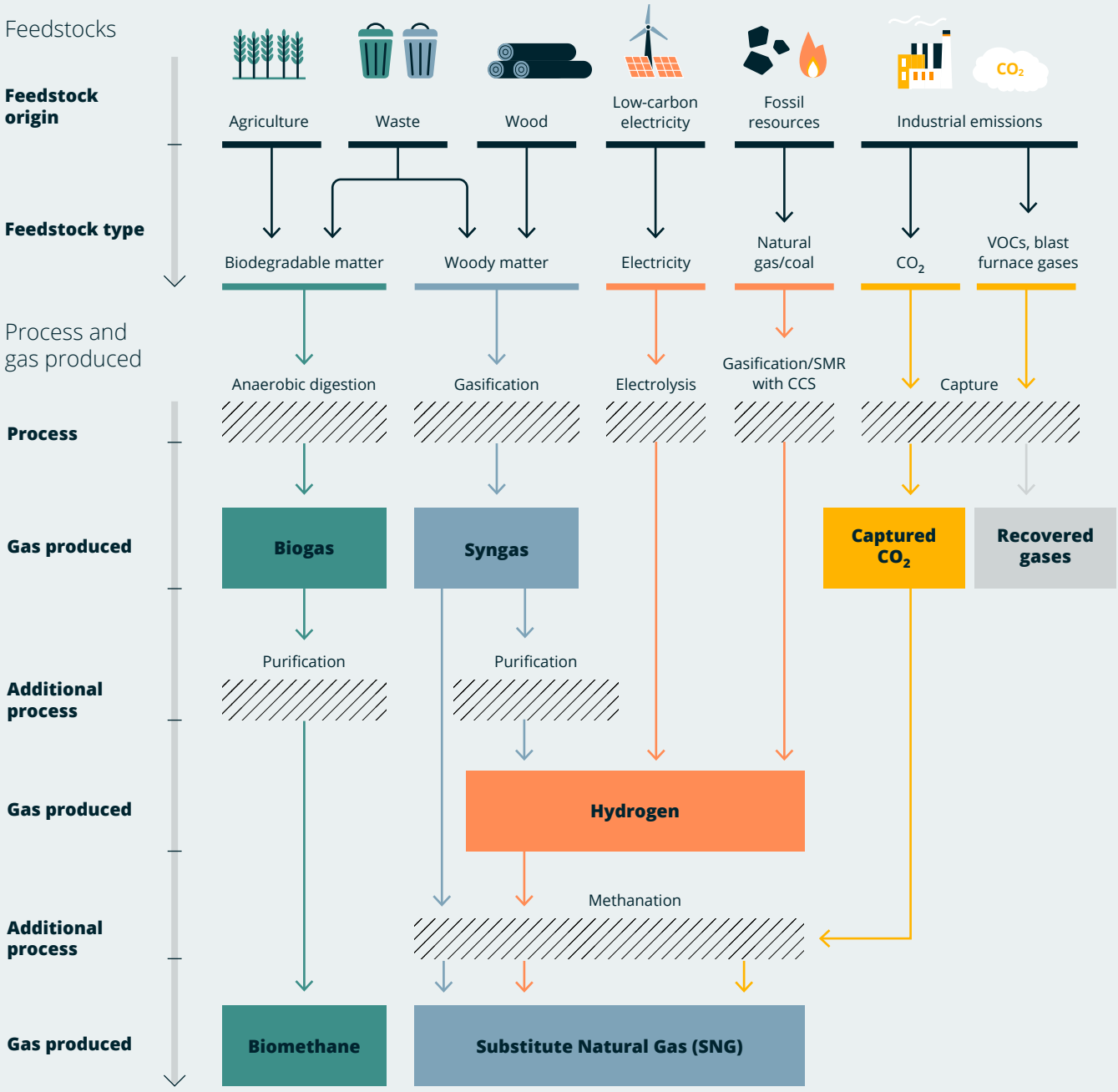
P.15 Technical solutions for using decarbonised gases in industry

2.3

P.21 Availability of decarbonised gases for manufacturers

2.1 Characteristics of decarbonated and recovered gases

DIAGRAM OF DECARBONATED GAS PRODUCTION ROUTES [12]



Decarbonised gases

FIGURE 2

Decarbonised gases are gaseous energy carriers that are alternatives to fossil gases. They emit less CO_2 equivalent than the latter based on life cycle analysis. They can be divided into several broad families according to their production methods, as shown in **Figure 2**. The level of maturity of each method is detailed in **2.3**.

Biogas

Biogas is produced by the degradation of organic waste (usually very wet waste), through a biological process of anaerobic digestion known as methanisation. This reaction produces a gas composed mainly of CH_4 and CO_2. The residual fraction of CO_2 can then be eliminated by a purification process to obtain **biomethane** (97% methane) that can be injected into networks [13]. To be considered renewable, gas production facilities must have the potential to reduce greenhouse gas emissions by at least 70% compared to the greenhouse gas emissions resulting from the use of fossil fuels[4]. According to the emission factor of biomethane, this criterion is fulfilled (see **Table 2**).

Synthetic gas - Syngas

Synthetic gas, or syngas, is produced by the thermochemical degradation of organic biomass or waste. Syngas is obtained either by pyrogasification of dry materials or by hydrothermal gasification of very wet materials, and contains a significant proportion of CO_2, CO and H_2.

Synthetic methane

Synthetic methane is produced by a methanation process that involves reacting CO_2 or CO molecules with H_2 under specific operating conditions. These reactants may already be in contact upstream of the reaction, as is the case in syngas. They may also come from two separate streams when the methanation unit is coupled with an electrolyser; this is known as power-to-methane. Synthetic methane has a composition close to that of natural gas after purification and upgrading to network specifications. As with biomethane, the renewable nature of synthetic methane production facilities is determined by their potential to reduce carbon emissions, which depends on the energy resources used as feedstocks.

Hydrogen

There are several categories of "decarbonised" hydrogen, each produced using a different method[5]. Hydrogen produced either by electrolysis using electricity from renewable energy sources (...), or by any other technology exclusively using one or more of these same renewable energy sources and not conflicting with other, direct, uses of this energy, is classified as **renewable**. Hydrogen is classified as **low-carbon** if its life-cycle analysis of its manufacturing process generates emissions that are less than or equal to the threshold of 3 $kgCO_{2eq}/kgH_2$ produced: electrolysis using electricity from the French grid, or steam methane reforming with captured CO_2 emissions for example. Electrolysis involves breaking down water molecules by applying a low-carbon electric current. In the case of steam reforming, the H_2 is obtained by cracking methane molecules. This process releases large quantities of CO_2, which must be captured. In the rest of this document, if the type of hydrogen is not specified, the text refers to the molecule in general, irrespective of its origin. For the purposes of this study, it has been decided to focus only on the most mature production methods: electrolysis and reforming.

Recovered gases

Finally, recovered gases are gases co-produced by industrial processes. They are captured and then reused. Their reuse avoids the need to use fossil gases, and is therefore a solution for decarbonisation and the circular economy. This study focuses in particular on **blast furnace gases** and **gases containing volatile organic compounds**.

4 - According to the draft order transposing Articles 29 to 31 of Directive (EU) 2018/2001 of 11 December 2018 into French law. The 70% threshold concerns installations commissioned between 01/01/2021 and 31/12/2025.

5 - As defined in French Ordinance no. 2021-167 of 17 February 2021 on hydrogen.

Blast furnace gases are collected at the blast furnace outlet used in steelmaking. They are made up of carbon monoxide and hydrogen. The practice of recovering these gases is already widespread, and their use encompasses a variety of applications such as electricity generation or reuse in industrial processes. This report focuses on their use in thermal processes.

Volatile Organic Compounds (VOCs) are organic substances with a vapour pressure of 0.01 KPa at a temperature of 293.15 K. They are therefore characterised by high volatility in gaseous form [14]. In industry, they are most often found in organic solvents used in paints. **Table 2** below summarises the main characteristics of these gases.

MAIN CHARACTERISTICS OF DECARBONISED AND RECOVERED GASES [15], [16], [17], [18] [19]

TABLE 2

	COMPOSITION	NCV kWh/Nm³	PODUCTION METHOD	EMISSION FACTORS gCO_2/kWh (NCV)
Biogas	CH_4: 50%–60%	5–7	Methanisation of organic waste	Production from agricultural/ municipal waste[(1)]: 35
	CO_2: 40%–45%			WWTP production route[(1)]*: 0
Biomethane	CH_4: >97%	10	Purification of biogas	Average mix of feedstocks[(2)]: 44
				WWTP production route[(2)]: 16
				Production from agricultural /municipal waste[(1)]: 52
Syngas	CH_4: 3–12%	1–5	Gasification of biomass, wood waste or SRF	Variable
	CO: 5–50%			
	H_2: 10–40%			
	CO_2: 10–30%			
Substitute Natural Gas (SNG)	CH_4: >97%	10	Methanation of syngas or a CO_2/H_2 mixture (Power-to-Gas)	Methanation of syngas produced via gasification of wood[(3)]: 64
Hydrogen	H_2: 99.5–99.99%	3	Water electrolysis Steam reforming of (bio)methane	Renewable mix[(2)]: 48
				French grid mix[(2)]: 84
				Steam reforming of biomethane[(2)]: 65
Blast furnace gases	CO_2: 22%	1	Recovery from blast furnaces + cleaning	968 (*recovered gases, so not counted*)[(2)]
	CO: 22%			
	H_2: 5%			
	N_2: 51%			
Gas containing VOCs	VOC concentration in fumes** < 110 mg/Nm³	< 8.10^{-4}	Recovery at end of process	Variable
Natural gas	CH_4: 81–97%	10–11	Extraction	Average mix: 227
Grey hydrogen	H_2: 95–99.9%	3	Steam reforming of natural gas	336

(1) Data from a study carried out in 2020 by Enea Consulting and Quantis on behalf of GRDF, for the ADEME Carbon Database ("*Base Carbone*®")
(2) Data from the ADEME Carbon Database
(3) Data based on the results of the Gaya project. It is not specified whether the unit is NCV or GCV.
* For the WWTP production route, emissions from the digester are considered to be zero because the biogas produced is considered a waste product. The agricultural production route corresponds to a mix of feedstocks comprising organic waste from industry (agrifood sector), crop residues, slurry/manure and intermediate energy crops.
** Concentrations may be higher if there is a post-treatment step.

2.2 Technical solutions for using decarbonised gases in industry

PRODUCTION AND SELF-CONSUMPTION OF BIOGAS

There are several types of methanisation site: agricultural, municipal waste and industrial. As of 1 January 2021, ADEME counted 114 industrial methanisation units, which is just over 10% of all sites. Most of these facilities are located on industrial sites with methanisable waste, such as paper mills or agri-food complexes. Self-consumption is the preferred reuse model, and 80% of industrial anaerobic digesters are designed to produce heat for self-consumption [20]. The remaining 20% are used to produce electricity through cogeneration, or to inject biomethane into the gas network. However, while industrial companies are theoretically able to produce biogas and some examples of this already exist, its use in equipment raises a number of technical issues, which are detailed below.

USE OF UNTREATED BIOGAS IN INDUSTRIAL BOILERS

Biogas can be transformed into electricity or heat in a turbine or gas engine, or into heat in a boiler or furnace.

The industrial sectors in which biogas is already being used for heating purposes are the food industry, woodworking, the pulp and paper industry, the chemicals and pharmaceuticals industry, the ceramics and terracotta industry and the textile industry. The facilities may be relatively old. The biogas sector dates back to the 1980s, with strong development in recent years for agricultural, cogeneration and industrial applications.

The availability of the resource, and therefore of the biogas, is dependent on the industrial company's production output. Industrial resources include production waste (sludge, grease, etc.) or effluent (washing water, etc.). In the agri-food industry, for example, the usable sources (those that are technically and economically accessible and socially acceptable) would represent more than 700 GWh, or 20% of the net potential sources available in this sector [21]. Operational, maintenance and on-site integration constraints range from moderate to complex, depending on the facilities using the biogas and the resource available. If an industrial company has a potential methanisation resource but does not wish to produce biogas on its site, it can choose to send this waste to local methanisation facilities.

Methanisation plants that recover heat from biogas are eligible for funding from ADEME (via the *Fonds Chaleur Renouvelable* – Renewable Heat Fund, and the Fonds *Economie Circulaire* – Circular Economy Fund), provided that at least 1.16 GWh/year (100 toe/year) is recovered [22].

Exemple :
An example of an industrial application is the investment in a biogas-fired steam boiler at a paper mill (company: PALM) in 2004. This investment produces part of the site's steam requirements using a 5 t/h boiler, fuelled 50% by biogas and 50% by natural gas, to produce 16 bar steam (capacity 4.6 MWth). The process effluents are treated in the site's wastewater treatment plant, and methanisation enables biogas to be produced to supply the boiler (in the past, biogas was burnt in flares).

This example can be reproduced on industrial sites that have the resource (feedstock) needed to produce biogas.

USE OF BIOGAS IN TERRACOTTA KILNS

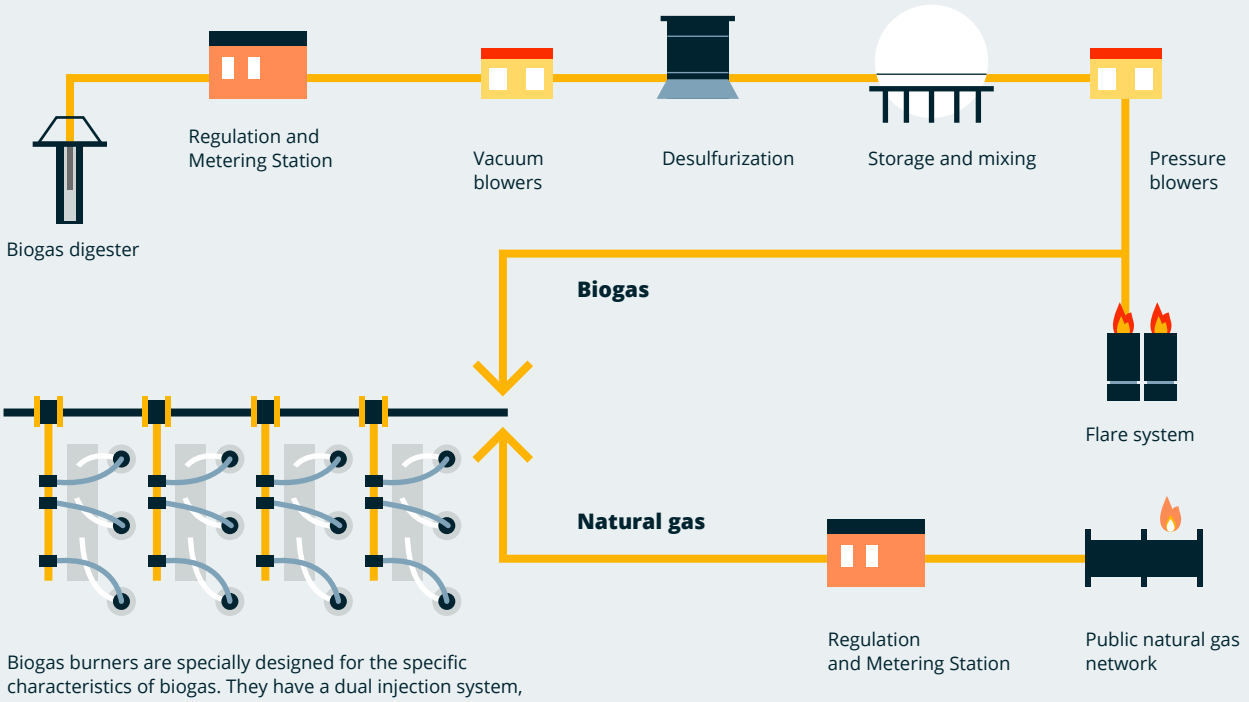
Some manufacturers of clay structural bricks have been using biogas for a long time (several decades), sourced from nearby landfill sites (some of which are located in former clay quarries).

This biogas, which comes from the anaerobic treatment of municipal waste, is captured and transported to the site using pumps and compressors. It is pre-treated with activated carbon filters to remove siloxanes (to prevent rapid clogging of the burners) and sulphur. Its methane content is generally around 55%, which gives it a lower calorific value: the NCV of biogas is around 5-7 kWh/Nm³ compared with around 11 kWh/Nm³ for natural gas. This difference reduces burner output (by around 40%). Using biogas requires the use of an independent supply network with a larger cross-section (lower pressure and larger gas volumes), the installation of diaphragm flowmeters to avoid pressure drops, and the installation of a flare to burn off excess gas during burner stoppages, particularly as the gas moves through the system (see diagram below). The reduction in the power supplied by the burners also means more burners are necessary.

Biogas is generally not used on its own, but as a complement to other fuels: natural gas and biomass (where biogas generally represents between 10 and 50% of the thermal input). There are therefore dual-gas burners that can use biogas or natural gas both in alternation and simultaneously.

FIGURE 3

DIAGRAM OF A PLANT USING BIOGAS [23]



Biogas burners are specially designed for the specific characteristics of biogas. They have a dual injection system, for biogas and natural gas. The latter is necessary to compensate for occasional fluctuations in biogas supply.

USE OF SYNGAS IN TERRACOTTA KILNS AND INDUSTRIAL BOILERS

On the scale of industrial energy production, two low-power syngas turbine projects (maximum 200 kW_e) were set up in France in the 1980s, but then stopped. More recently, a report published in 2017 by the RECORD association highlighted the success of industrial units around the world, such as a cogeneration plant in Finland that converts 250,000 t/year of RDF into electricity and heat. In addition, experiments are underway in France combining pyrogasification and methanation (to inject methane into the grid). Notable examples are Gaya in Saint Fons, Titan V in Nantes and PlainEnergie in Ain department. The recurring problem with pyrogasification plants remains the treatment of tars, which have a high fouling potential that complicates operation and maintenance. There are a number of technologies for removing tars, including water or oil washing systems.

Pyrogasification is also of interest to sites that are isolated from the natural gas network, or that wish to replace natural gas with a more environmentally-friendly alternative. To this end, smaller units (300 kW, for example) are available on the market, with modules that can be adapted to the needs of industrial companies.

These installations accept class A wood waste (wood that has not been treated or painted) or class B wood waste (wood that has been lightly treated, painted or varnished, but is still non-hazardous), and allow syngas to be used directly in industrial burners (an example in France, at Bouyer Leroux, is described in the next paragraph), or in cogeneration or hot water production modules. The sector is developing rapidly, with European and French manufacturers and a number of pilot operations underway. The challenges for this type of local use are to adapt the equipment (particularly the burners) to the characteristics of the syngas used, the compositional stability of the syngas (which depends in particular on the feedstocks), and the fact that the required flame temperatures are sometimes incompatible with the use of syngas. The economics, which depend very much on the feedstock used, may prove attractive with wood as an input, with a price of €25 to €50/MWh_{NCV} depending on the feedstock, and wood to syngas conversion efficiencies of over 80%. This use in industrial burners is fairly recent and potentially requires development depending on the characteristics of the syngas. Use in hot water production boilers, for example, is more mature than use in boilers that supply industrial processes directly. Finally, regulatory issues also remain an obstacle to integration at sites that must be declared to or authorised by the French DREAL (Direction régionale de l'Environnement, de l'Aménagement et du Logement - Regional Directorate for the Environment, Planning and Housing) (updates are sometimes necessary due to the presence of a flare and the storage of flammable materials).

The use of syngas in terracotta kilns is currently only at the pilot stage.

Exemple

Bouyer Leroux is the first industrial company to start using syngas from biomass pyrogasification to fire its structural bricks. The ADEME-subsidised project is now in the pilot commissioning phase. The pilot plant, located at the Saint Martin des Fontaines site in the west of France , is equipped with 4 NAODEN co-current fixed-bed gasifiers delivering 1.2 MW of power. The syngas produced is cooled (from 600-700°C to 350-450°C) to feed specific burners (manufactured by Spanish company Beralmar) used in the pre-fire zone (below 650°C). These burners burn a high-temperature gas to avoid the issues of tar condensates and very low calorific value (8 to 10 times less calorific than natural gas). Integrating this syngas into the energy mix (natural gas/ biomass/syngas) required the creation of a specific gas network, the installation of a flare and the setting up of an ATEX zone and equipment. Pyrogasification produces char, which requires additional waste management: reprocessing or recovery. According to the manufacturer, the associated management costs are around €50/tonne of char.

USE OF HYDROGEN IN INDUSTRIAL BOILERS

First of all, it is important to distinguish between thecombustion of pure H_2 and that of a natural gas/H_2 mixture.

The main technical challenges for the development of burners running on 100% hydrogen have been identified and are listed below.

These impacts and issues will be lower for a natural gas/H_2 mix, depending on the percentage of hydrogen present.

For hydrogen contents of up to 20-30%, discussions with burner manufacturers have not revealed any particular difficulties, but there are a number of points that require careful consideration. In this case, the burner technology has to be adapted to a natural gas/H_2 mixture and to different gas characteristics.

Optimisations include, but are not limited to, the design of the gas injectors, progressive supply of H_2, recirculation of the flue gases and adjustment of the excess air to adapt it to variations in the NCV and combustive power of the gas.

It should be noted that burners supplied with 100% hydrogen, or hydrogen percentages of over 60%, have been used for several decades in the iron and steel industry, using coke oven or blast furnace gases.

TECHNICAL ISSUES TO BE STUDIED FOR THE DEVELOPMENT OF 100% HYDROGEN BURNERS

POINTS TO CONSIDER	REASON	EQUIPMENT AFFECTED
Flame stability	High flame speed, risk of flashback	All
Ignition	Wide flammability range, detonation risk	All
Flame detection	High combustion temperature, shorter flame without carbon-containing ions	All
Heat transfer by radiation	Low flame and combustion gas emissivity	High-temperature furnaces
Temperature of combustion products	Less efficient heat transfer, but higher temperature for combustion products	High-temperature furnaces
Composition of combustion products	High concentration of water vapour in combustion products	High-temperature furnaces
Nitrogen oxide emissions	High combustion temperature	All
Choice of materials for the burner	High combustion temperature	All

TABLE 3

In the petrochemical and chemical industries, the use of hydrogen mixtures in industrial boilers has been successfully tested.

These results can be reproduced providing that hydrogen is available on the industrial site. In addition, the use of heat production is largely reproducible in different industrial sectors. The temperature level in this case is between 80°C and 200°C, depending on the fluid carrying the heat (hot water or steam).

USE OF HYDROGEN IN FURNACES AND DRYERS

Beyond the issues linked to the specific features of burners, the use of hydrogen in furnaces and dryers raises the question of the impact on manufactured products and the need to adapt processes. A number of issues are currently being raised by manufacturers, including:

- Possible risks to the performance of refractories at high temperatures;
- The possible impact on the drying kinetics of a product due to the higher proportion of water vapour in the combustion products;
- Specific constraints on process settings (zone heating and burner settings, float glass melting bath);
- The impact on the quality of the product manufactured, due to the direct contact with the combustion products.

At this stage, these are issues that need to be verified. To do this, studies are starting up in France, with analyses in several industrial sectors. The glass and bricks and tiles sectors, for example, are investigating this issue, as has the iron and steel industry, where there is already some feedback.

USE OF HYDROGEN IN STEELMAKING

Steelmakers are studying several technical solutions to decarbonise steel production. Among them, the use of hydrogen in blast furnaces as a reducing agent and/or source of energy might be a solution for reducing iron ore. A number of projects and initiatives have already been launched in this area, including H_2 Green Steel in Sweden, H_2Future financed by the European Union, and ArcelorMittal's future project in Spain. To date, these technologies have only been tested on a small scale in pilot plants in Europe, but industrial-scale projects such as the one at ArcelorMittal have now been launched.

Hydrogen in blast furnaces

Hydrogen can be injected directly into blast furnace tuyeres to replace coal. In Sweden, the first plant to produce non-fossil steel was inaugurated in August 2020 by steelmaker SSAB, using a process called HYBRIT, which implements this principle [24]. This technology is also being tested by ArcelorMittal in Germany [25]. An alternative is to develop a hybrid DRI/blast furnace process which combines the injection of DRI gas into the blast furnace vessel with the injection of gas into the blast furnace tuyeres.

Hydrogen in the DRI process

Direct reduction of iron ore currently uses syngas derived from natural gas. In this case, the iron ore is reduced using a gaseous mixture of hydrogen and carbon monoxide. It is theoretically possible to increase the proportion of hydrogen in the reducing gas, or even to use 100% hydrogen. Projects have been launched to prove the technical feasibility of this solution on an industrial scale.

Hydrogen in downstream processes

Hydrogen can also be used in combustion in other processes involved in the manufacture of steel parts. In 2020, the steel group Ovako experimented with replacing natural gas with hydrogen to heat steel in order to shape it into coils and plates on rolling mills [26].

BLAST FURNACE GAS RECOVERY

Blast furnace gas has a net calorific value (NCV) ten times lower than natural gas, but since it is a recovered gas that is produced in large quantities and on a consistent basis, its use is attractive. Many sites have already set up systems to capture this gas and feed it into boilers or turbines for cogeneration. But significant volumes (which vary according to production parameters) remain unused, and the prospects for using them in industrial processes are not yet set in stone. Indeed, electricity production, which is a major outlet for steelmaking gases, is now competing with other applications, such as use in downstream processes or direct recycling in heating networks.

Exemple
The Saint-Gobain Pont-à-Mousson site in France uses its blast furnace gas to fuel its heat treatment furnaces. These furnaces can switch between natural gas and blast furnace gas depending on the amount of excess blast furnace gas available. The burners, pipes and injectors in the furnaces had to be modified. This experience highlights the following issues:

- the low NCV of the gases recovered;
- the presence of large quantities of dust, the composition of which may vary depending on the production of cast iron.

The first issue affects the heating time and performance of the furnaces, which means process adjustments are necessary. As far as dust is concerned, the gas is cleaned before it is used for combustion, but no additional flue gas treatment has been necessary. Fixed and mobile detectors have nevertheless been installed, as blast furnace gas is odourless, colourless and highly toxic due to its high CO concentration.

Recovering blast furnace gas to fuel thermal processes is therefore technically feasible, subject to a few adaptations, and offers cost savings as well as a reduction in CO_2 emissions.

These steelmaking gases could also be reused directly in blast furnaces thanks to their reduction properties. In this case, major modifications to the equipment are required, particularly to the nozzle and torch systems. To overcome these technical hurdles, a consortium of players including ArcelorMittal, Europlasma and the Toulouse Institute of Fluid Mechanics (IMFT) have launched a project called IGAR. The aim of this initiative is to validate the blast furnace gas recycling process and achieve a 17% reduction in emissions at the Dunkirk site over the next 5 years [27].

VOC RECOVERY

For environmental, health and financial reasons, sectors that emit VOCs are seeking to reduce emissions of these toxic and polluting compounds. To do this, manufacturers can start by trying to reduce the emissions, by identifying the products that emit them and choosing alternatives with lower, or no, emissions. For example, the use of solvent-based paints and degreasers has fallen sharply in industry.

For other applications, VOC emissions are more difficult to reduce, so it may be worthwhile treating them. The first option is to recycle them by absorption, adsorption or condensation.

Alternatively, they can be incinerated in oxidisers to produce heat, which has the advantage of eliminating their direct release into the atmosphere, but the disadvantage of releasing CO_2 and NOx.

The maximum residual concentration authorised in direct discharge for some of these gases is 110 mg/Nm³. To be used for thermal recovery, they must generally be highly concentrated.

In heat recovery, VOCs are often burnt in a mixture with natural gas because of their low concentration. A heat exchange system is used to recover the heat produced. To increase energy efficiency, a catalyst can be added to the combustion chamber. There are a number of technical issues: the presence of dust and heavy metals, the presence of chlorine and silicone-based compounds, and the life of the catalyst [28].

USE OF BIOMETHANE AND SYNTHETIC METHANE FOR ALL APPLICATIONS

The use of biomethane or synthetic methane in industrial processes does not present any specific technical challenges because their composition is very similar to that of natural gas. The adaptations that need to be made relate to the gas network and are handled by network operators.

2.3 Availability of decarbonised gases for manufacturers

The availability of decarbonised gases for industrial use depends first and foremost on the technological and commercial maturity of their production methods. **Figure 4** shows how levels of development differ for the different gases.

The production of syngas by pyrogasification of mineral coal or biomass is well established, with numerous industrial projects around the world. However, pyrogasification of waste wood or solid recovered fuels (SRF) is more recent, with fewer and smaller projects. It nevertheless benefits from advanced technological maturity and a dynamic ecosystem of players, mainly from the waste sector.

The methanation of syngas into synthetic methane is just getting off the ground in Europe, with the first commercial-scale demonstrator units. Feedback from these will help to optimise the operation of these systems.

The production of hydrogen by electrolysis is more advanced and is generating a lot of interest, with around a hundred projects already running or being set up, according to French hydrogen observatory Vig'Hy [29].

Efforts in this production sector are now mainly focused on scaling up to hundreds of megawatts of electrolyser capacity in the short term, and then to gigawatt-scale in the long term.

Finally, biomethane and biogas have the highest number of commercial installations, with more than 1,000 methane plants in operation in France in 2021, including more than 200 dedicated to the injection of biomethane.

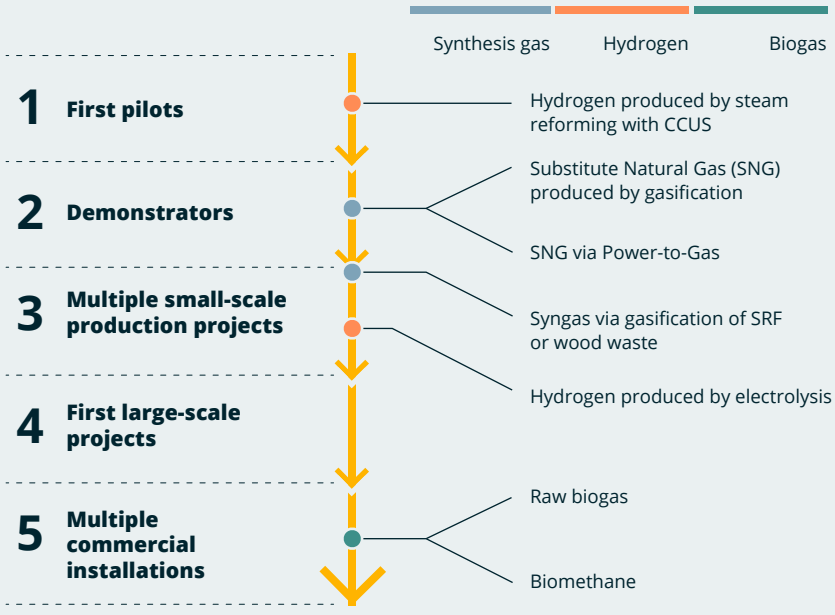
Although volumes of decarbonated gas represent less than 3% of the gas consumed in France, the development prospects for these sectors are significant [30] [31] [32].

This is due primarily to their potential to contribute to decarbonisation, and also to the positive externalities perceived by producers. Biogas, biomethane and synthetic methane, for example, offer waste producers[6] a virtuous recovery pathway and stimulate local economies through job creation. The number of direct jobs in the biogas value chain was estimated at just over 4,000 in 2018 [33]. Hydrogen stands out for its ability to store and transport electricity produced by decentralised and intermittent energy sources.

6 - Wood waste or SRF for syngas and organic waste for methanisation

FIGURE 4

STATE OF DEVELOPMENT OF LOW-CARBON GAS PRODUCTION IN FRANCE



MAIN DRIVERS AND CHALLENGES FOR PRODUCTION SECTORS (NON-EXHAUSTIVE)

	DRIVERS	CHALLENGES
Biogas	Valorisation of **residual organic matter**	Availability of **feedstocks compatible with methanisation**
	Reduced use of **mineral fertilisers** thanks to the valorisation of digestate	Difficult to **store** and **transport**
	Creation of **local jobs**	
Biomethane	Valorisation of **residual organic matter**	Availability of **feedstocks compatible with methanisation**
	Reduced use of **mineral fertilisers** thanks to the valorisation of digestate	
	Creation of **local jobs**	
	Easy to **store** and **transport** because it can be injected	
	Multiple uses (transport, heat, raw material, etc.) because the technical specifications are the same as for natural gas	
Syngas	Difficult to convert into other forms of energy	**Low priority** in the waste hierarchy
	Creation of **local jobs**	Competition with **other forms of energy recovery** (boilers compatible with Grade B wood waste, etc.)
Substitute Natural Gas (SNG)	All production methods: Easy to **store** and **transport**	The **methanation process** is complex and costly
	Via Power-to-Gas: Valorisation of CO_2 and **storage of electricity**	Via Power-to-Gas: Low **energy efficiency**
	Via gasification: Recovery of **energy from waste**	Via gasification: Competition with **other forms of waste-to-energy recovery**
Hydrogen (produced via electrolysis powered by renewable energy)	Links gas and electricity grids	**Injection into gas grids** is limited (e.g. 20% by volume in the EU), and equipment/grid adaptation costs are uncertain
	Emits **no pollutants** when used in fuel cells, but emits NOx when burned	Lack of infrastructure for **transport*** , **distribution and storage**
	Vector for **storing intermittent renewable energy**	**Safety challenges**
	Industrial sector that creates jobs	Not yet at industrial scale

TABLE 4

* Lack of transport infrastructure is not a significant constraint if the hydrogen is produced on site.

While storing pure hydrogen is more complicated because of regulatory constraints and the associated costs (suitable materials), it can easily be stored if mixed with natural gas. This makes it a very attractive energy carrier given the increasing proportion of renewable energy in electricity grids. However, the thermodynamic properties of hydrogen make it slightly more complicated to manage operationally than natural gas, due to its wider flammability and explosivity range and the increased risk of leaks. **Table 4** sets out the main advantages and challenges inherent in the production ofdecarbonised gases.

The growth of these sectors benefits from various support mechanisms, such as CAPEX subsidies for hydrogen, the introduction of feed-in tariffs for biogas and the current introduction of an extra-budgetary mechanism for biomethane, as detailed in **3.1.1**. Under France's National Hydrogen Strategy, €7.2 billion will be invested between now and 2030 to support the industrial scale-up of the sector. By speeding up the development of these sectors, public support reassures manufacturers, who anticipate an increase in volumes available for consumption. Financial aid also encourages manufacturers to use decarbonised gases without significantly increasing their energy bills. **Table 5** compares current and future decarbonised gas prices. The projections are only estimates and should be treated with caution. There is currently a consensus that the price of natural gas is likely to rise in the coming years, particularly as a result of tax increases, including the carbon tax. On the other hand, the production costs of decarbonised gases are expected to fall over the next few years thanks to technological advances and the standardisation of equipment. This drop in production costs should in turn lead to lower purchase prices for manufacturers.

TABLE 5

DECARBONATED GAS COSTS AND PRICES (SEE THE FULL REPORT FOR A DETAILED ANALYSIS)

GAS	PRODUCTION METHOD	TOTAL PRODUCTION COSTS (€/MWh GCV)			PURCHASE PRICE FOR INDUSTRY (€/MWh GCV)		
		2019	2025	2030	2019	2025	2030
Gaz naturel		15	30	45	19–37	28–54	35–69
Biogas	All excl. WWTPs	63–93	50–81	42–73	65	50	45
Biomethane	All excl. WWTPs	82–121	65–105	55–95	22–52 GO at 3–15 €/MWh	31–69 GO at 3–15 €/MWh	38–84 GO at 3–15 €/MWh
Hydrogen	Electrolysis powered by renewable energy	101–178	73–145	58–127	203–305	178–254	152–228
Syngas	SRF	N/A (~50 en 2050)			60–86	N/A	N/A
	Grade B wood waste	N/A (82–115 en 2050)			N/A	N/A	N/A
Substitute Natural Gas (SNG)	Gasification	N/A (~50–140 en 2050)			N/A	N/A	N/A
	Power-to-Gas	N/A (estimation ~ 250)			N/A	N/A	N/A

Main hypotheses

1 - Natural gas: Average PEG (virtual trading point) price in 2019 for 2019 production costs; IEA scenario with carbon tax at €100/t for the 2030 costs; 2025 cost extrapolated from 2019 and 2030 figures; 2019 prices based on SDES data for consumption bands I3 to I6, inclusive of TICGN, exclusive of VAT; estimations based on Enerdata's "Ener-Blue" scenario for the 2025 and 2030 prices.

2 - Biogas: Purchase price corresponds to the cost of production for one industrial facility, based on self-consumption; Cost data based on calculated LCOE of biomethane acc. to the ENEA report on the French biomethane sector ("*Renforcer la compétitivité de la filière biométhane française*"), excluding the WWTP route, updated with the latest GRDF data.

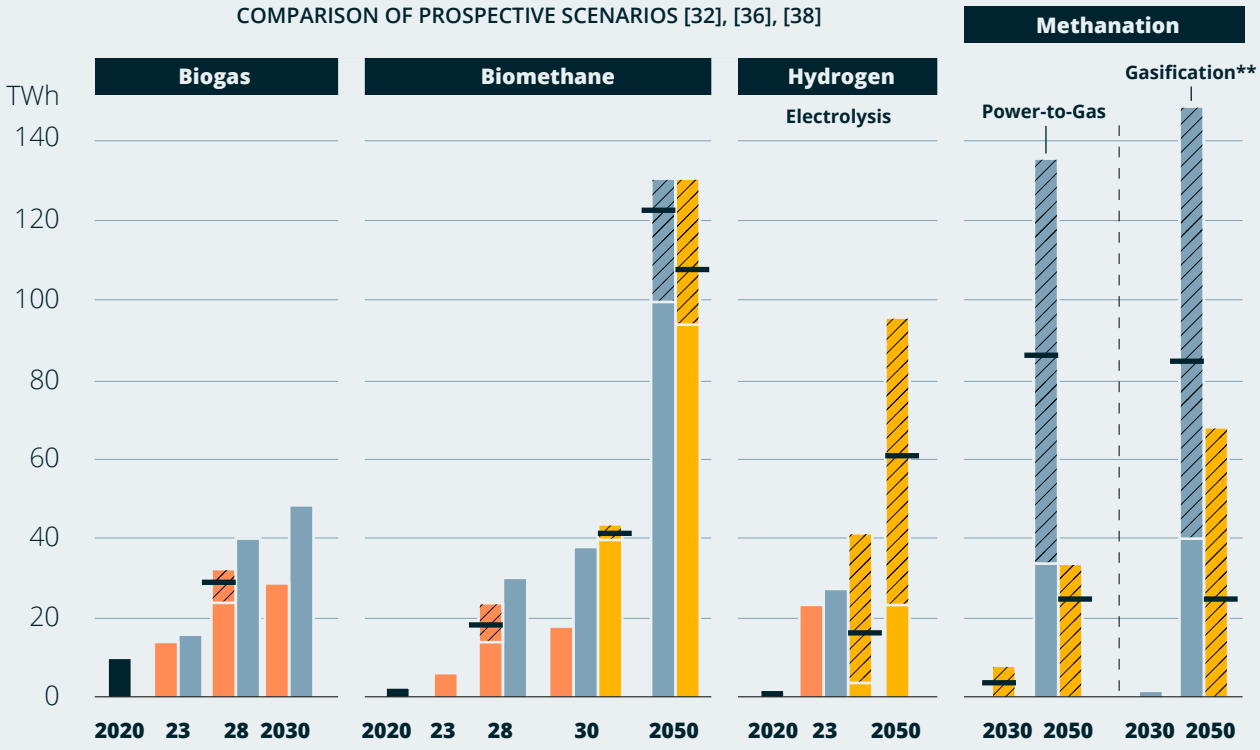
3 - Biomethane: Cost data based on calculated LCOE of biomethane acc. to the ENEA report on the French biomethane sector ("*Renforcer la compétitivité de la filière biométhane française*"), excluding the WWTP route, updated with the latest GRDF data; Prices calculated based on the price of natural gas, plus the price of the Guarantee of Origin (GO). The price increase for biomethane is thus explained by the price increase of natural gas.

4 - Hydrogen: 2019 costs and price acc. to ENEA study of most recently launched projects; Average of ETC and IRENA forecasts for 2025 and 2030 costs and prices; Production costs are for production (via electrolysis) only: if the H_2 is not produced on site, the manufacturer must also cover storage and transport costs.

5 - Syngas and SNG: ADEME report, "*A 100% renewable gas mix in 2050?*" and ENEA study.

FIGURE 5

COMPARISON OF PROSPECTIVE SCENARIOS [32], [36], [38]



* The values of the national targets for 2030 are the values projected by the "Transitions" organisation in their report on the French biogas sector ("*Etude d'impact de la filière biogaz sur l'emploi en France de 2018 à 2030*");
** Gasification of fossil fuels is not included.

The attractiveness of decarbonised gases is therefore set to increase, especially as the price of CO_2 is currently on a rising trajectory, with the price on the European market exceeding €65/tCO_2 [34] [35]. A detailed analysis of these costs is available in the full study report.

To assess the future development of these sectors, various studies have drawn up scenarios for the development of decarbonised gases. These include the "A 100% renewable gas mix in 2050?" (*Un mix de gaz 100 % renouvelable en 2050*) study carried out ADEME along with GRDF and GRTgaz (2018) [12], the PPE (2020) [32]; ADEME's 2050 energy scenarios, "*Transition(s) 2050*" (2021) [4]; and the work of industry players. In the medium term, the various scenarios presented all point to significant production levels for biogas, biomethane and hydrogen between now and 2030 (between 12 and 40 TWh depending on the studies and the gases). However, synthetic methane production is likely to remain very low over the next 10 to 15 years. Over the long term, the values estimated by the various studies are more dispersed, except for biomethane, for which the studies all point to a potential of around 120 TWh of biomethane production in 2050. For injected gases, they show that biomethane is likely remain the predominant gas. Hydrogen, synthetic methane from pyrogasification and methane from power-to-gas plants will complete the gas mix in varying proportions.

All in all, large potential volumes of renewable gases can be expected in 2030 and 2050. Their adoption in industry will depend in particular on their accessibility and the operational constraints they pose. These issues vary greatly depending on the gases considered. They are detailed in the following section and are supplemented by other selection criteria relevant to industrial companies.

Part 3

Prospects for integrating decarbonised gases in industry

3.1

P.27 Comparative analysis of gases from the point of view of manufacturers

3.2

P.32 Decarbonised gas consumption forecasts for industry

3.3

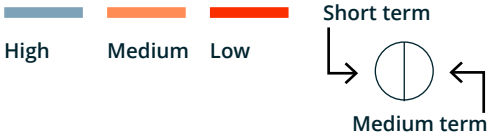
P.33 Conclusions

3.1 Comparative analysis of gases from the point of view of manufacturers

CRITERIA LIKELY TO INFLUENCE MANUFACTURERS' CHOICE OF DIFFERENT DECARBONISED GASES (DETAILED TABLE AVAILABLE IN THE FULL STUDY REPORT)

TABLE 6

	BIOGAS	BIOMETHANE	RENEWABLE HYDROGEN	METHANE (VIA POWER-TO-GAS)	SYNGAS (VIA GASIFICATION)	SUBSTITUTE NATURAL GAS (SNG) (VIA GASIFICATION)
Reduction in carbon footprint						
Availability of required volumes of gas						
Stability in terms of composition and supply volume						
Economic competitiveness						
Ease of integration						



Notes
1 - There are more integration constraints when producing hydrogen on site compared to using hydrogen from the grid.
2 - The decarbonisation potential of syngas and SNG depend on the percentage of biomass in the feedstocks.

COMPARISON OF THE SPECIFIC CHARACTERISTICS OF DECARBONISED GASES FOR INDUSTRIAL THERMAL PROCESSES

The decision to switch from natural gas to a low-carbon gas is primarily motivated by the objective of reducing an industrial site's Scope 1 carbon footprint.

In this respect, all the gases studied here have a carbon footprint at least five times smaller than that of natural gas (10 to 45 gCO_2/kWh compared to 230 gCO_2/kWh) [36].

Another key criterion for manufacturers is the availability of the volumes required to meet their needs. In the short term, only biogas and biomethane are readily available in sufficient quantities.

Biogas, however, requires a local source, which is not always available. At present, the volumes of decarbonated hydrogen, syngas and synthetic methane being produced are still limited. In the longer term, pressure on methane resources and increased demand could generate competition for access to biogas and biomethane. Thanks to the development of hydrogen, pyrogasification and methanation,

it should become easier for industry to source other decarbonised gases, particularly through a model of guarantees of origin for network gases.

Once manufacturers have confirmed the possibility of a contract to secure volumes, they will look at the quality of the gas supply, particularly if it is to be used for process applications. In this respect, gases injected into the network and purchased via mechanisms such as guarantees of origin pose no problem, since the industrial operator physically continues to consume gas from the network, the composition of which will be guaranteed by the network operators. Hydrogen from electrolysis will be produced at a stable level of purity and in quantities that can be controlled thanks to storage. Industrial consumers should therefore not experience any variability in its quality. For biogas and syngas there are more questions, as their composition is highly dependent on feedstocks.

Another key criterion for manufacturers will be the price they have to pay to make their energy consumption greener. In this context, the competitiveness of decarbonised gases should be compared in terms of cost to manufacturers, rather than in terms of production costs. However, production costs can be used to estimate future price trends for manufacturers, based on their expected evolution over the coming years.

Visibility over the evolution of support mechanisms is an important parameter for project developers. France's National Hydrogen Strategy sets out a vision for 2030 and provides for an investment of €7.2 billion between now and then [37]. The regulatory context for biomethane and biogas is more fluid. Energy policies seem to be focusing on support for biomethane rather than biogas. The French government recently consulted stakeholders on the introduction of an extra-budgetary system involving biogas production certificates to replace the current feed-in tariff. Article 95 of the French Climate Resilience Act enacted on 22 August 2021 introduces this mechanism, which will enter into force in 2023 and will require energy suppliers to contribute to the financing of biomethane production in proportion to their shares of the gas markets [38]. Finally, the level of government support for syngas and synthetic methane is difficult to predict. In 2021, the CRE drew up an agreement to test the injection of synthetic methane for 7 projects in order to assess their performance and potentially draw up the basis for a suitable support mechanism [39]. For the time being, synthetic methane injection benefits from the same guarantee of origin system as biomethane under Decree 2021-1273 of 30 September 2021.

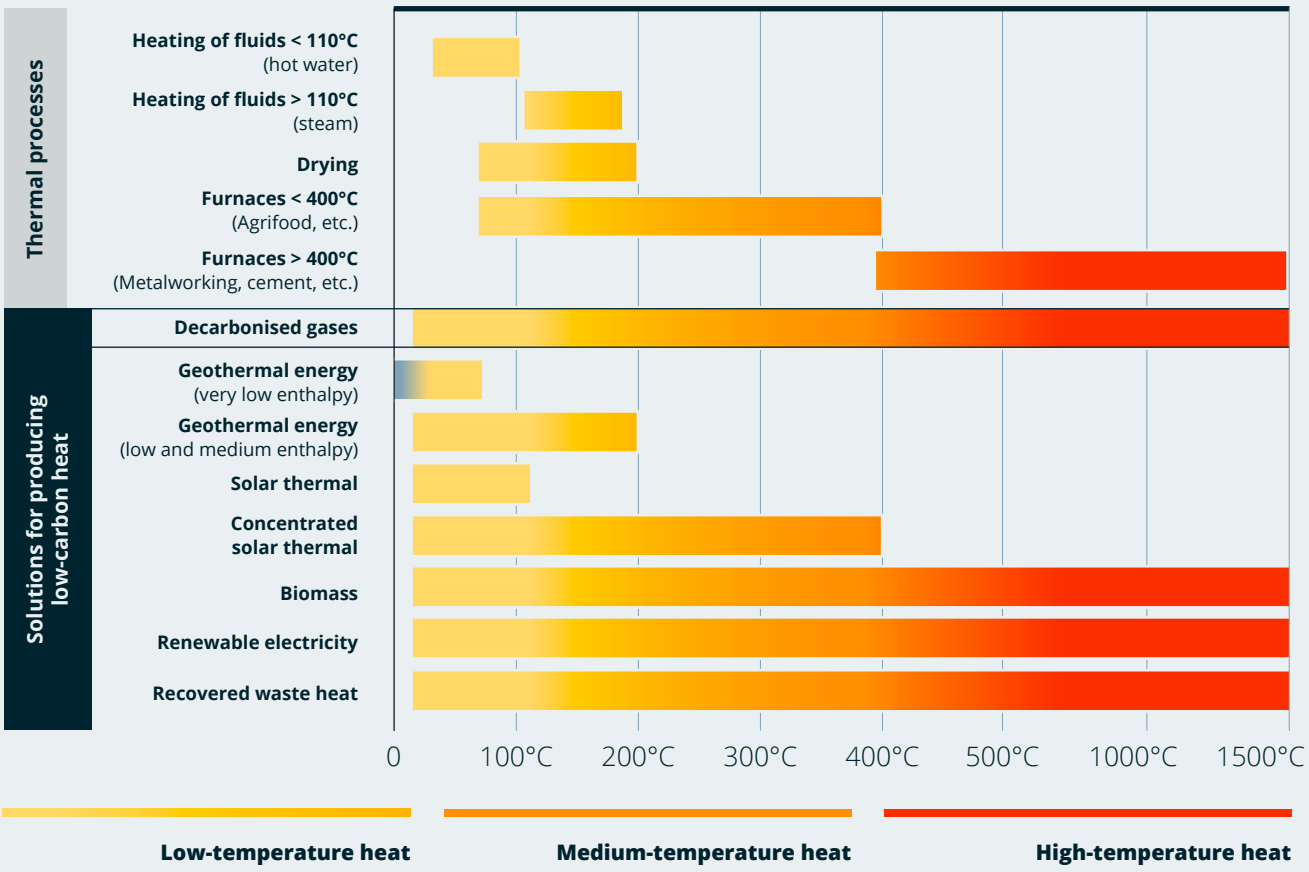
The competitiveness of decarbonisation solutions for a manufacturer should also take into account the external elements that can be recovered. This includes, for example, the recovery of waste or physical CO_2 emissions from industrial fumes.

Finally, operability issues relate exclusively to biogas, hydrogen and syngas because their composition differs from that of natural gas. Biogas and syngas have a lower NCV, which means that burner capacity must be increased and equipment start-up has to be controlled differently. In addition, they require a dedicated on-site distribution network and can affect product quality because of the impurities they contain. In the case of hydrogen, the impact depends on the concentrations considered, and may involve problems of product colouring, cooking homogeneity and increased water vapour and NOx levels in the fumes.

POTENTIAL APPLICATIONS IN BOILERS AND FURNACES

CAs explained in **2.1**, the use of decarbonised gases in boilers and furnaces has been covered in a specific analysis. For each of these applications, the deployment potential of decarbonised gases depends on the relevance of other low-carbon alternatives. **Figure 6** shows the distribution of temperature ranges for the four main thermal processes and low-carbon heat production solutions.

BREAKDOWN OF THERMAL PROCESS TEMPERATURE RANGES
AND CARBON-FREE HEAT PRODUCTION SOLUTIONS [22]



Notes

1 - Some dryers have an operating temperature of more than 200°C

2 - The feasibility of electrifying very-high-temperature thermal processes (> 1000°C) depends on the sector (e.g. possible for glass furnaces with a capacity of less than 300 tons/day, but complex for cement works). Power requirements must also be considered.

FIGURE 6

Boilers

Boilers are one of the most widely used pieces of equipment in industry, for both hot water production and steam production, for tertiary or process use. These boilers generally run on natural gas. To decarbonise them, a number of solutions exist. As well as decarbonised gases, there are other sources of low-temperature heat such as geothermal, solar thermal and biomass.

The potential for using decarbonised gases in boilers depends on the operating temperatures of the systems. **Figure 6** shows that although many alternatives exist for hot water boilers, they are not suitable for steam production. According to the PEP study [3], the potential for electrifying steam boilers is only 20% [3]. For the decarbonisation of steam boilers, decarbonised gases will therefore have less competition.

From a technical point of view, boilers used to heat a fluid (water or steam), which is the intermediary between combustion and the industrial product, can more easily accept the use of raw gases such as biogas or syngas. Although there are technical issues (sizing of burners to adapt to the low NCV), the impact on product quality will be low to nil.

Furnaces

Once energy efficiency measures have been implemented, there are two main families of solutions for decarbonising furnaces. The first covers measures to green the energy mix, with 3 main options: electrification, use of biomass, and use of decarbonised gases. The second covers actions to reduce the carbon content upstream and downstream of the process. Upstream, this involves modifying the composition of raw materials to reduce CO_2 emissions during processing. The terracotta industry, for example, is seeking to reduce the proportion of limestone in the clays used to limit the decarbonation reaction, which emits GHGs. Downstream, the measures concern the capture and use of CO_2 in flue gases.

The suitability of low-carbon gas solutions depends on the furnace systems under consideration, and in particular on the following parameters:

- If the gas comes into direct contact with the products and contains impurities, it can deteriorate their quality.
- If the oven does not operate continuously, the power required at each stop and start phase is significant and requires burner capacity to be increased if low NCV gas is used.
- If the furnace has a limited production volume, the volumes of CO_2 emissions are lower, so decarbonising is less crucial. In the short term, the manufacturer has less incentive to implement decarbonisation solutions.

Assessing the benefits of using decarbonised gases in kilns in general is complex and requires a specific approach for each system. The following section looks in more detail at the case of terracotta kilns.

POTENTIAL APPLICATIONS IN THE TERRACOTTA AND STEEL SECTORS

The terracotta sector

The use of decarbonised gases is of interest in the terracotta industry. This interest is modulated by the thermal requirements, the use of the products, the availability of these gases nearby and the maturity of the combustion technologies.

The use of decarbonised gases for drying applications in the terracotta industry appears to offer several benefits compared with alternatives for the production of decarbonated heat. For example, using biomethane in an air stream burner is more energy efficient than using a biomass boiler, which requires a heat exchanger. It is also more mature than a high-temperature heat pump and is easier to control than a solar thermal installation. However, most dryers today are already equipped with kiln heat recovery systems and therefore do not need to be supplied by other energy sources. The potential for integrating decarbonised gases is therefore low.

However, there is greater interest in using decarbonised gases for cooking, because the temperature range targeted (between 850 and 1150°C) and the thermal power required (around 20 MW) are higher, making electrification of the process more complex and costly. This is one of the reasons why certain decarbonised gases are already being used or are in the testing phase.

Nevertheless, the current firing method, using a direct flame in the kiln, can have an impact on product quality, particularly in the case of products intended to be visible, such as roof tiles, to which surface coatings can be applied before firing (engobing or enamelling). The appearance of these materials is very sensitive to the cleanliness and composition of the combustion products.

Unpurified decarbonised gases (such as biogas or syngas) have great potential for deployment in brick kilns, where the bricks will be coated and aesthetic appearance is therefore less important. The obstacle to this use is the lack of availability of these gases close to the industrial site.

Clean, decarbonised gases (biomethane or synthetic methane) are more appropriate for tile works (one tile works in France has been using biomethane mixed with natural gas for several years to fire its tiles). Unlike bricks, roof tiles are visually important materials. Purified gases are therefore preferable, as their combustion does not release impurities that alter the appearance of the products.

Hydrogen is also of interest to the terracotta industry, but with a longer-term vision due to the lack of demonstrators (impact on products, impact on kilns, burner technologies) and economic balance (availability and costs).

The iron and steel industry

In the iron and steel industry, manufacturers are fine-tuning their roadmaps for producing carbon-neutral steel. ArcelorMittal Europe has already announced that it will reduce its emissions by 30% by 2030 and that it aims to be carbon neutral by 2050, in particular through the use of hydrogen in its direct reduction process (DRI-EAF) and/or in its blast furnace [41].

Hydrogen could be used to decarbonise the smelting process in blast furnaces thanks to its reducing properties. It can also be used to decarbonise downstream uses, for example as a fuel for heating materials to be shaped. It is the subject of several pilot projects in Europe, and is included in the decarbonisation roadmaps of the industry's manufacturers. The development of hydrogen in this sector is a credible option and is being explored. The main determinant of this growth will be the price of supplying the molecule. ArcelorMittal, for example, has warned that its project for a "large-scale, zero-carbon steel plant" in Sestao, Spain, would be abandoned if hydrogen purchase prices were not competitive.

Blast furnace gases could also be used to reduce the carbon footprint of blast furnaces and downstream heat treatment furnaces. The appeal lies in the wide availability of these gases. On the one hand, they are produced in large quantities, with an estimated volume in 2019 of 15 TWh [5]. Secondly, this potential is accessible, as recovery processes have been used since the beginning of the 20th century and are well established. Their use in thermal furnaces is already a reality, as shown by the example of Saint-Gobain, which has significant potential for replication. On the other hand, they are more complex to use in blast furnaces. Several consortia are in the process of setting up initiatives to assess the feasibility of this technique. Large-scale implementation of this solution is therefore likely, but will depend on the results of the studies currently under way.

VOC recovery is an application that only concerns the secondary steel processing sector, and in particular foundries. This is one of the last sectors to use VOCs, which are very strictly regulated. The extent of recycling and heat recovery of VOCs on these sites will depend primarily on the development of regulations in this area and the accepted threshold limits.

3.2 Decarbonised gas consumption forecasts for industry

In its recent study on the outlook to 2050, ADEME modelled a number of scenarios presenting different trajectories for the use of decarbonised gases in industry [4]. First of all, all the scenarios forecast a fall in industrial production in 2050 compared with 2014: on average for the sub-sectors considered (although the trends vary from one sector to another), between 2 and 14% for the business-as-usual scenarios and those characterised by major technological developments, and 26%-38% for the scenarios in which greater efforts are made to reduce energy consumption. In all the scenarios, industry continues to consume gas, whose share falls from 30% (in 2014 and in the business-as-usual scenario) to 16-25%. The energy demand for industrial thermal processes in 2050 can be estimated by projecting current values from the above trajectories. As a first approach, 135 TWh of non-electrified thermal energy would be consumed in the business-as-usual scenario. This value falls to 122 TWh in the case of massive deployment of renewable energy technologies (Scenario S3 – "Green technology") and 72 TWh in a model where energy efficiency is prioritised [3].

By 2050, network gas is considered to be highly decarbonised on average and made up of biomethane and synthetic methane from Power-to-Gas and pyrogasification. As far as hydrogen is concerned, for this exercise, ADEME excluded the injection of hydrogen into the network, and the combustion of hydrogen in boilers or industrial furnaces. In 3 out of the 4 scenarios, direct hydrogen consumption varies from 3 to 10% of industrial consumption (use of biomass in 2 scenarios, and electricity and fossil fuels with CCUS in the last). In Scenario S3 ("Green Technologies"), hydrogen accounts for 18% of industrial consumption in 2050, and is used as a raw material in industry (steel production, methanol, HVO, refining, ammonia).

These projections can be compared with the potential volumes of decarbonised gases over this timeframe. The ADEME 100% renewable gas study [12] provides an estimate of these potential volumes, based on the assumption that available resources will be used primarily for the production of decarbonised gases rather than for other energy uses.

For the valorisation of wood waste, for example, pyrogasification is preferred over burning the waste in boilers. The study models several scenarios for greening between 75% and 100% of the natural gas network, with a gas demand level of around 300 TWh. It shows that to achieve this objective, on average[7], it would be necessary to produce 121 TWh of biomethane, 84 TWh of synthetic methane from pyrogasification and 86 TWh of synthetic methane from power-to-gas, i.e. a total of 291 TWh [12]. Assuming that industry continued to consume 38% of network gas, it would consume 111 TWh of renewable gas from the network [42]. This is not sufficient for all the industrial thermal uses in the new ADEME Transition(s) S3 "Green Technologies" and business-as-usual scenarios. It therefore shows the need to direct the use of low-carbon network gases towards industry or to supplement these solutions with other alternatives. Hydrogen and locally produced gases such as syngas and biogas are two such options, as are the use of geothermal energy, solar thermal energy and bio-based fuels.

7 - These values vary slightly depending on the scenarios modelled.

3.3 Conclusions

There has already been some feedback on the use of decarbonised gases in industrial processes. This study has highlighted a number of questions, which vary according to the gases considered and the intended applications. These technical questions relate to the use of gases with a composition that is very different from that of natural gas (biogas, syngas and hydrogen) and concern, among other things: the technical modifications required (sizing of burners, for example), the impact of these gases in terms of pollutants, their impact on product quality, their integration into processes and their operability.

The use of these alternative gases in boilers for fluid heating is much simpler and generates fewer risks than in the case of process heating applications, particularly those where the product is in direct contact with the gas or combustion fumes.

Decarbonised gases injected into the natural gas network, to which industrial companies will have access via a tracing mechanism (such as guarantees of origin), pose no technical issues, since the industrial company continues to be physically supplied by the same network gas. **The use of unpurified biogas or syngas in industrial processes is possible,** as a number of case studies have shown, but raises more technical questions. **Hydrogen also raises many questions,** depending on whether it is used pure or mixed with natural gas.

Over and above the technical considerations, one of the key parameters for the penetration of all these gases in industry will be the availability of the required volumes at a cost that is competitive for manufacturers compared with natural gas. **For gas injected into the grid, this availability will depend on supply and demand at national level,** as well as on the players in the production chain and the public authorities regulating injection. **In the case of gases that are not injected (biogas, syngas, hydrogen), manufacturers will have to find local supplies.** Hydrogen could also be delivered from remote production sites if a dedicated pipeline network is developed, such as the European backbone proposed by network operators.

The volumes available for industry will largely depend on the other uses that these alternative gases to natural gas can decarbonise. Priority will probably be given to uses for which gas is difficult to substitute or for which few alternatives exist: for example, long-distance transport, high-temperature industrial uses and industrial uses of gas as a raw material. **For example, the terracotta and steel sectors on which this study focuses should be given priority access to decarbonised gases (for furnaces and blast furnaces in particular).**

Manufacturers' access to a supply of decarbonised gases will also depend on the commercial scale-up of production processes. It should also be noted that manufacturers are traditionally more inclined to invest in widely deployed solutions that have already been used successfully on sites similar to their own.

Forecast scenarios, such as those developed by ADEME, point to a sharp increase in the volumes produced for all of the decarbonised gases. These technologies are expected to be deployed mainly through the injection of biomethane and synthetic methane into gas networks, as well as through the potential development of hydrogen networks. Projects for the production and industrial consumption of biogas and syngas will also continue to develop, but on a more local scale and probably initially in cases where there are interesting synergies, such as the presence of feedstocks close to or within the industrial site.

The support mechanisms and public aid envelopes dedicated to the development of these sectors, such as France's €7.2 billion National Hydrogen Strategy, will play an important role in the deployment of production sectors.

However, this will not happen if the extra costs involved are too high. The current trend seems to indicate an increase in the price of natural gas and the carbon tax in the EU (which rose above €65/tCO_2 in October 2021) along with a fall in production costs for all decarbonised gases.

It is clear that gas, in its decarbonised forms, will remain a vector for the energy transition of industry. **The role of each of these gases and their level of penetration in different industrial applications will depend on the development of the production sectors, the level of support for these sectors (which will have an impact on their competitiveness), and the technological choices made for each of the other French energy uses.**

Energy management at existing facilities (improving the performance of existing installations, recovery of waste heat) and the capture and use or storage of CO_2 are also important complementary solutions for decarbonising industry and could be the subject of further studies.

Glossary

CET
Technical landfill centre

CO_{2eq}
CO_2 equivalent

DRI
Direct Reduced Iron

EAF
Electric Arc Furnace

GHG
Greenhouse gases

HVO
Hydrotreated vegetable oils

NOx
Nitrogen oxide

P2G
Power to Gas

PAC
Heat pump

PPE
Programmation Pluriannuelle de l'Énergie - Pluriannual Energy Programming

VOC
Volatile Organic Compounds

WWTP
Waste water treatment plant

Bibliography

[1] Ministère de la Transition Ecologique, « Les émissions de gaz à effet de serre du secteur de l'industrie manufacturière, » 2021. [En ligne].

[2] Ministère de la Transition Ecologique et Solidaire, « Stratégie Nationale Bas Carbone, » 2020.

[3] Allice, « Potentiel d'électrification des procédés thermiques industriels, » 2021.

[4] Ademe, « Étude Transition(s) 2050, » 2021.

[5] Ministère de la transition écologique, « Bilan énergétique de la France pour 2019, » 2021.

[6] Ademe, «Climat Air et Energie: Chiffres-Clés,» 2018.

[7] ATEE, « État des lieux des solutions de financement et de garantie de la performance énergétique dans l'industrie, » 2019.

[8] FFTB, «Rapport Développement Durable 2020,» 2020.

[9] World Steel Association, «Our indicators (environmental performance),» 2019. [En ligne].

[10] Fédération Française Tuiles & Briques, «Rapport de développement durable 2018,» 2019.

[11] Senat, « Rapport sur les enjeux de la filière sidérurgique dans la France du XXIe siècle : opportunité de croissance et de développement - Troisième partie, » 2019.

[12] Ademe, « Un mix de gaz 100 % renouvelable en 2050 ?, » 2018.

[13] Cegibat, « Le biométhane, définitions, principe et chiffres clés, » 2021. [En ligne].

[14] Ademe, « Les composés organiques volatils (COV), » 2018.

[15] Ademe, « Base Carbone, » 2020.

[16] ATEE, Club Pyro, « Fiches techniques sur la pyrogazéification, » 2020.

[17] Ademe, « Méthanisation - Fiche technique, » 2015.

[18] Afhypac, « Les données de base physico-chimiques sur l'hydrogène, » 2013.

[19] ATEE, « Position Paper de la filière « Injection de biométhane de synthèse » (issu de pyrogazéification), » 2018.

[20] Ademe, « Chiffres clés du parc d'unités de méthanisation en France au 1er janvier 2021, » 2021.

[21] SOLAGRO & ADEME, « Étude des gisements potentiels de substrats utilisables en méthanisation, » 2013.

[22] Ademe, « Intégration des énergies renouvelables et de récupération dans l'industrie, » 2018.

[23] BERALMAR, Écrivain, Appareils de combustion à gaz - *Brûleurs pour fours et séchoirs céramiques.* [Performance].

[24] SSAB, « HYBRIT – Production d'acier sans énergie fossile, » [En ligne].

[25] ArcelorMittal, « ArcelorMittal Europe produira de l'acier vert à partir de 2020, » 2020. [En ligne].

[26] Interesting Engineering, « For the First Time Ever, Hydrogen Is Used to Power Commercial Steel Production, » 2020. [En ligne].

[27] Eco121, « ArcelorMittal se met au vert, » 2020. [En ligne]. Available: https://www.eco121.fr/arcelormittal-se-met-au-vert/.

[28] Ademe, « Traitement par oxydation thermique et oxydation catalytique, » 2014. [En ligne].

[29] VIG'HY, « L'observatoire de l'hydrogène, » 2021. [En ligne]. Available: https://vighy.france-hydrogene.org/cartographie-des-projets-et-stations/.

[30] GRDF, GRTgaz, Spegnn, SER, Teréga, « Panorama du gaz renouvelable en 2020, » 2020.

[31] France Hydrogène, « L'hydrogène en France édition 2020, » 2020.

[32] Gouvernement, « Programmation Plurinannuelle de l'énergie, » 2019.

[33] GRDF, « L'emploi dans la filière biogaz en France, » 2021.

[34] Smarter Climate policy Sandbag, « Tracking the EU ETS carbon market pirce day by day, » 2021. [En ligne]. Available: https://sandbag.be/index.php/carbon-price-viewer/. [Accès le 2021].

[35] Les Echos, « CO_2 : la tonne de carbone bat de nouveaux records, à plus de 65 euros ».

[36] Ademe, « Un mix de gaz 100 % renouvelable en 2050 ?, » 2018.

[37] Ademe, « Base Carbone, » [En ligne].

[38] Ministère de l'économie des finances et de la relance, « Présentation de la stratégie nationale pour le développement de l'hydrogène décarboné en France, » 2020. [En ligne].

[39] Legifrance, « LOI n° 2021-1104 du 22 août 2021 portant lutte contre le dérèglement climatique et renforcement de la résilience face à ses effets,» 2021. [En ligne]. Available: https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000043956924.

[40] CRE, « Délibération Numéro 2021-59, » 2021.

[41] ArcelorMittal, « ArcelorMittal Europe Produira de l'acier vert à partir de 2020, » 2020. [En ligne].

[42] Ministère de la transition écologique, « Chiffres clés de l'énergie édition 2020, » 2020.

[43] Gaz d'aujourd'hui, « Biométhane : le gouvernement ouvre une large concertation avec la filière, » 2020. [En ligne].

[44] Transitions, « Étude d'impact de la filière biogaz sur l'emploi en France de 2018 à 2030, » 2019.

[45] GRTgaz, S3D, « Fiche brique avale - pyrogazéification, » 2019.

[46] CEREN, ADEME, « Première analyse du potentiel technique d'électrification des procédés industriels thermiques par des technologies matures, » 2020.

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