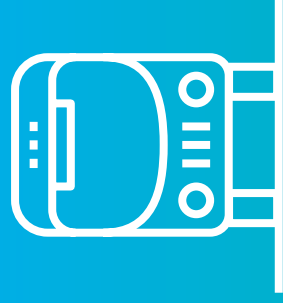
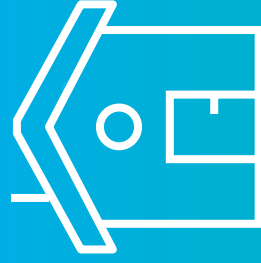
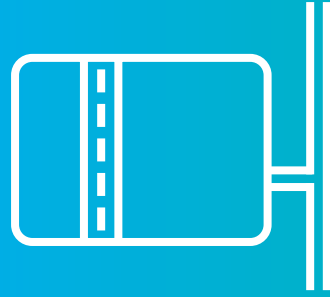
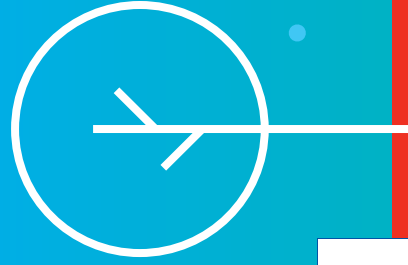


GAS INDEPENDENCE IN FRANCE IN 2050

A 100% renewable gas mix in 2050?

STUDY SUMMARY





This document is published by ADEME

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BP 90406 | 49004 Angers Cedex 01 FRANCE
Contract number: 16MAR000891

The study was initiated by ADEME and GRDF; it was jointly managed by ADEME, GRDF and GRTgaz, and coordinated by ADEME: Guillaïn Chapelon (GRDF), Emmanuel Combet (ADEME), David Marchal (ADEME), Laurent Meunier (ADEME), Ony Rabetsimamanga (GRDF), Alban Thomas (GRTgaz), Anne Varet (ADEME), Isabelle Vincent (ADEME)

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Graphic creation: Créapix

Printing: Printed in France
on FSC Mixte paper, European Ecolabel certified 
Frazier printing - ISO 14001 certified

This work is available on-line at www.ademe.fr/mediatheque

Brochure ref. 010521

ISBN: 979-10-297-1054-4 - January 2018 - 2 000 copies

Legal registration: ©ADEME Éditions, January 2018

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A 100% RENEWABLE GAS MIX IN 2050?

STUDY SUMMARY

EDITORIAL

The fight against climate change, according to the ambitions adopted by the Paris agreement, relies on the success of the energy transition. France has made commitments to reduce its greenhouse gas emissions on world-wide, European and national levels. France Climate Plan, initiated in July 2017 by Nicolas Hulot, France's Minister of the Ecological and Inclusive Transition, re-affirmed the proactive strategy for the energy transition with ambitious objectives, such as achieving carbon neutrality by 2050.



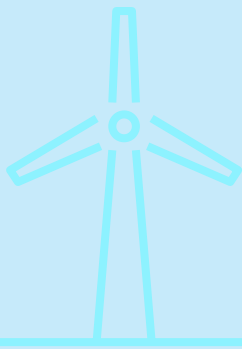
ADEME has been contributing since 2013 through regular publications of energy-climate scenarios. To update these scenarios and broaden the scope of discussions, more exploratory prospective studies are carried out to assess options with more open hypotheses on certain specific vectors or industries. The purpose is to identify possibilities, not to propose a public policy scenario. This then enables all those involved to reconsider these options and to redefine their perception of the future to build shared visions of tomorrow.

This study about a 100% renewable gas mix by 2050 follows several publications released in 2016 and 2017 with regards to the evolution of the energy mix, and is focussed on the second most consumed grid energy in France, which is gas. ADEME, in an effective collaboration with GRDF and GRTgaz, has explored the technical and economic feasibility of 100% renewable gas in 2050, based on ADEME's 2035-2050 energy-climate scenario. This document does not provide a roadmap to achieve 100% renewable gas by 2050; it explores the conditions of feasibility and obstacles of such an ambition. The results are therefore based on sensitivity analyses and various hypotheses regarding the renewable gas production mix.

Aside from observing that there is a theoretical potential source of renewable gas that could exceed the level of demand proposed for 2050 by ADEME's 2035-2050 energy-climate scenario, a number of conditions to achieve 100% renewable gas by 2050 have also been identified. Although these ambitious results encourage immediate, accelerated deployment of agricultural anaerobic digestion projects, they also highlight the importance of optimising the use of biomass sources by improving the balance between the different energy vectors (heat, electricity or gas). This confirms that to improve the sustainability of our energy system, we must strengthen the interactions between the energy vectors and optimise their synergies, at various territorial scales. These findings will help to update the ADEME energy-climate scenario in 2019.

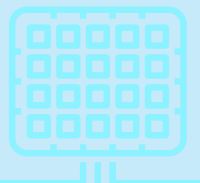
Bruno LECHEVIN





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1. CONTEXT AND OBJECTIVES

After an initial study carried out by ADEME on the role of renewable electricity in the energy mix – which revealed notably that a very high level of renewable electricity could be envisaged in technical and economic terms – this study focussed on the second most consumed grid energy: the gas vector.

In this period of great importance to the energy transition, this work carried out in collaboration by ADEME, GRDF and GRTgaz contributes to the discussions centred on France's proactive strategy to reduce its CO₂ emissions while controlling its energy consumption and developing renewable energies.

This is a prospective technical study and not a political scenario.

The energy efficiency improvements and reduction in energy demand used in this study are those indicated in the *ADEME 2035-2050 energy-climate scenario update* ⁽¹⁾. The total demand in 2050 for mains gas is therefore around 300 TWh, compared with today's figure, 460 TWh.

The main goal of this study is to analyse the conditions of technical and economic feasibility of a gas system based entirely (100%) on renewable gas by 2050. It aims to answer the following questions:

- **How much renewable or recoverable gas could be available in 2050 in mainland France? Would this be enough to satisfy the demand for gas every day and throughout the network?**
- **What changes would have to be made to the networks or production industries?**
- **What are the constraints and what technical flexibility is available?**
- **What would be the impact on the average cost of gas delivered?**

Study scope:

- The study is centred on mainland France: the resources are national and the possibilities of importing renewable gas are not included;
- The study concentrates on mains gas: it does not look into all the potentials for usage increase outside the renewable gas network (e.g.: biogas co-generation) or via third party infrastructures (e.g.: decentralised hydrogen production/consumption or dedicated network) ⁽²⁾;
- This study does not identify the roadmap from now until 2050;
- This study does not aim to optimise the overall energy system (all vectors, all usages).

(1) <http://www.ademe.fr/actualisation-scenario-energie-climat-ademe-2035-2050>. Hereinafter, this document will be referred to as "ADEME's 2035-2050 energy-climate scenario".

(2) However, it does not exclude the possibility of a certain proportion of direct injection of hydrogen into the gas networks.





2. STUDY PROCESS

The study was implemented as follows (see figure 1 and details in paragraph 6 - *Methods and hypotheses*)

1- The theoretical potentials of available renewable resources corresponding to three production sectors were assessed:

ANAEROBIC DIGESTION	Production of methane using micro-organisms that break down organic matter
PYRO-GASIFICATION	Production of methane from organic matter, mainly wood, via a thermo-chemical process
POWER-TO-GAS	Production of methane by electrolysing water using renewable electricity and then methanation of the hydrogen produced in the presence of carbon dioxide

These production sectors are described in paragraph 6.2.1.

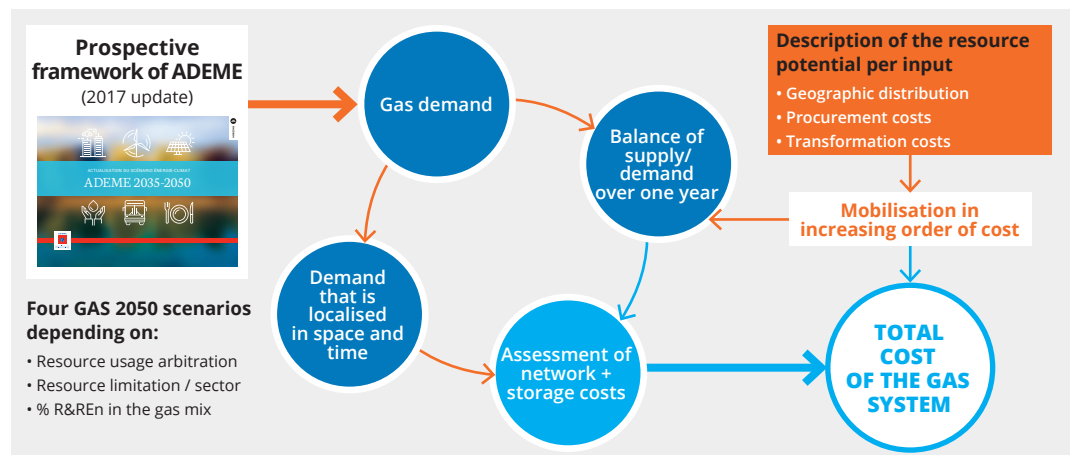
This assessment of the potential of available resources takes into account durability criteria⁽³⁾.

2- Starting from the slightly adjusted demand of ADEME's 2035-2050 scenario, the production mix was estimated, mobilising the production sectors in increasing order of cost, while including the necessary adaptation of the gas network.

3- Four scenarios were defined to assess different hypotheses, particularly with respect to the resources:

- **"100% R&REn" (Renewable and Recovered Energies):** biomass and resource usages are similar to ADEME's 2035-2050 scenario, substituting some of the wood and heat co-generation usages with gas;
- **"100% R&REn with high pyrogasification":** the same as 100% R&REn, but gas usage is enhanced, by increasing the production of renewable gas by pyrogasification using wood resources made available by the lesser development of wood-fired co-generation and wood for heat networks. This scenario corresponds to a higher demand for gas;
- **"100% R&REn with limited biomass for gas usages":** the same as 100% R&REn but with biomass resources limited to 80% of their potential. The objective is to assess the impact of resource mobilisation difficulties (e.g. under-estimated environmental impacts or social acceptability, etc.) and/or development difficulties of the less mature sectors;
- **"75% R&REn":** biomass and resource usages are similar to ADEME's 2035-2050 scenario, natural gas represents 25% of final energy consumption.

FIGURE 1: STUDY METHODOLOGY



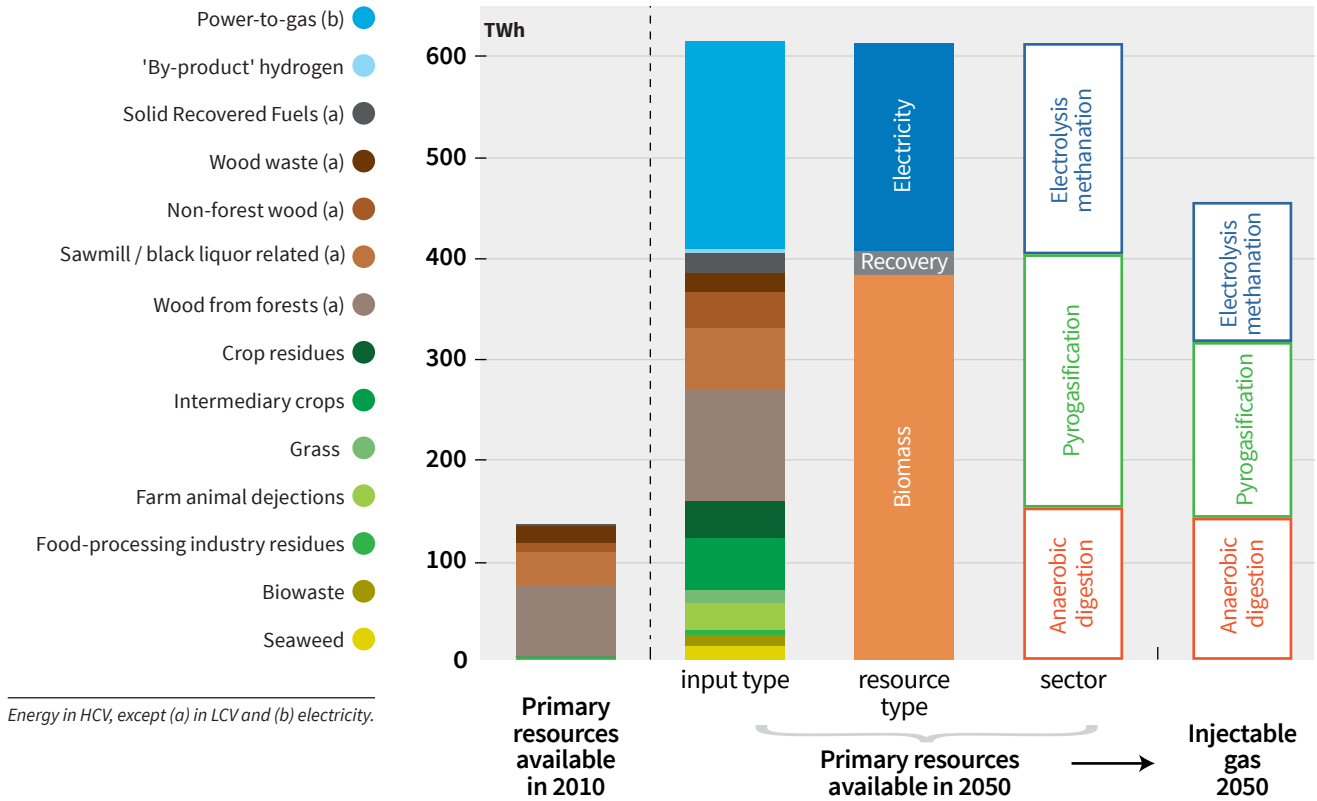
(3) In particular, specific energy crops are excluded and the resources used are not in competition with "raw material" usages (agriculture, forest, wood industry and biomaterials).



3. RESULTS

3.1. A theoretical potential of 460 TWh of renewable gas

FIGURE 2: RESOURCE AVAILABILITY AND POTENTIAL PRODUCTION



The total potential of renewable primary resources liable to produce gas is approximately 620 TWh. It is not in competition with "raw material" (agriculture, forest, wood industry and biomaterials) and food usages, which remain priority.

This is available potential before any allocation to competing energy usages (e.g. energy wood can be used in a boiler), and it incorporates durability criteria (specific energy crops are therefore excluded) ⁽⁴⁾. Compared with the resources currently (2010) mobilised for energy production and potentially convertible into gas, the 2050 estimated potential is much higher, which

implies new practices and organisations for agriculture and forests. Biomass resources represent almost 390 TWh, 230 TWh of which come from wood and its derivatives, 130 TWh from agriculture, 15 TWh from biowaste and food-processing industries and 14 TWh from seaweed. Electricity contributes 205 TWh. Recovered energies represent a little under 25 TWh.

Taking into account conversion efficiency, the theoretical potential of primary resources identified could produce up to 460 TWh_{HCV} of injectable renewable gas:

- 30% could be supplied by the mature anaerobic digestion industrial sector,

(4) Although currently permitted to a level of 15% in tonnage.



enabling the conversion of agricultural inputs, biowaste and seaweed residues to produce up to 140 TWh_{HCV} of gas⁽⁵⁾⁽⁶⁾;

- 40% could be supplied by the pyrogasification sector from wood and its derivatives, Refuse-Derived Fuel (RDF) and a low proportion of agricultural residues, to produce up to 180 TWh_{HCV} of gas⁽⁷⁾;

- 30% could be provided by power-to-gas in the context of a 100% renewable electric mix to maximise the production of synthetic gas, i.e. 140 TWh_{HCV} of gas⁽⁸⁾.

3.2. Gas demand from 276 to 361 TWh in 2050 could be met by renewable gas in the four scenarios studied...

Bearing in mind other usages of biomass, the potential of 460 TWh_{HCV} of injectable renewable gas is enough to meet the demand for gas in 2050 for a scenario similar to ADEME's energy-climate scenario ("100% R&REn" with a demand of 293 TWh) but also a scenario in which the demand for gas is higher ("100% R&REn" with high pyrogasification" with a demand of 361 TWh).

The adjusted demand (see figure 4) for each scenario takes into account different effects, such as arbitrations on usages of anaerobic digestion and wood. The available resource

for the injection sectors depends upon the level of mobilisation of the other usages (direct usage or co-generation). The production mix was defined after adjustment of demand for each scenario and the available resources (see figure 4); the resources were mobilised in increasing order of cost (see figure 11): the anaerobic digestion and pyrogasification sectors were thus mobilised to their maximum limit; power-to-gas, which is the most expensive, is the adjustment variable to balance supply and demand (described in the *Results* section, paragraph 6.4).

FIGURE 3: RENEWABLE GAS MIX IN THE FOUR SCENARIOS



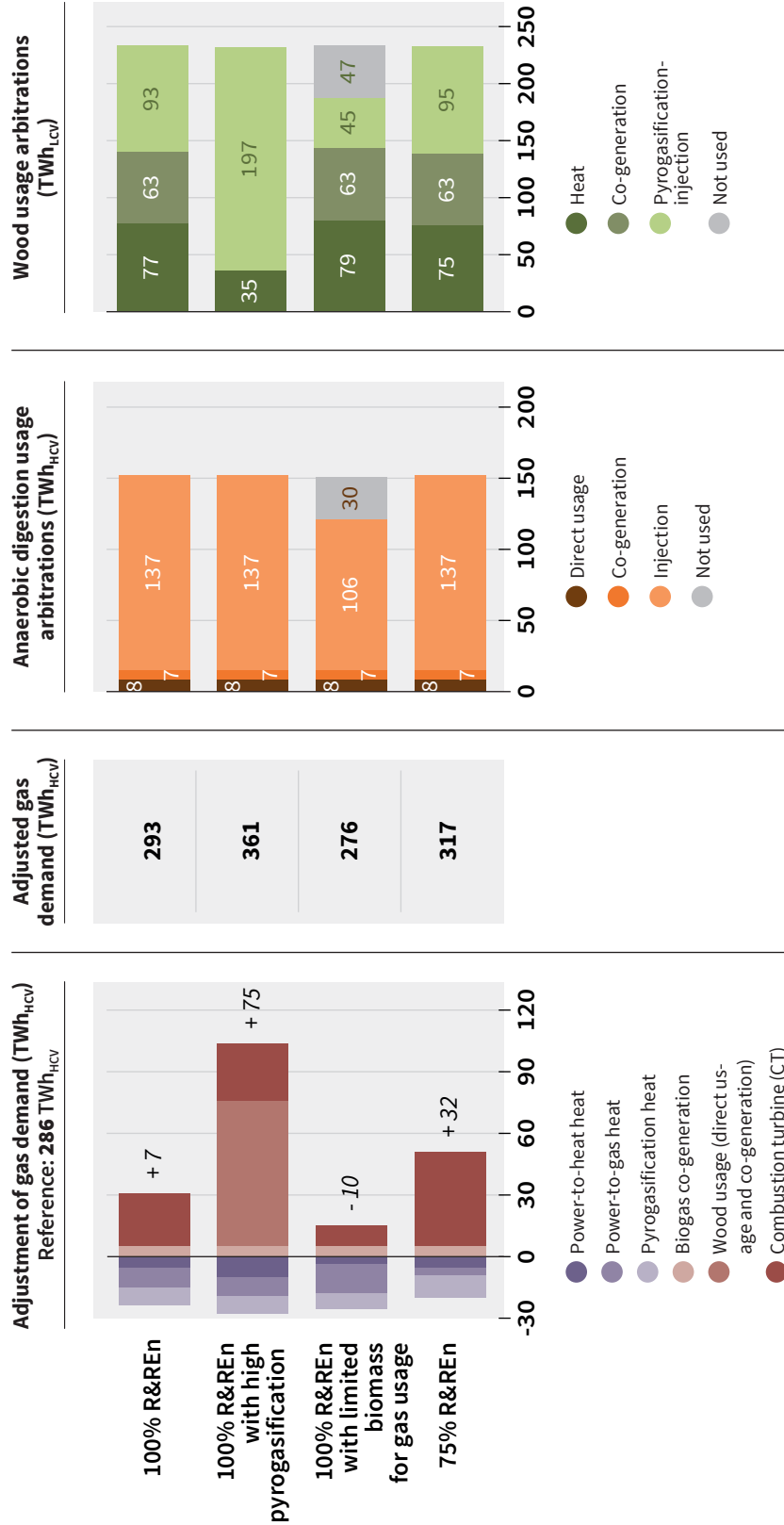
(5) For crop residues and particularly straw, anaerobic digestion was preferred over pyrogasification because it enables stable carbon and nutrients (including nitrogen) to be returned to the soil.

(6) 94% efficiency determined by injectable methane (HCV) / biogas produced (HCV).

(7) 70% efficiency determined by injectable methane (HCV) / input (LCV).

(8) 66% efficiency determined by injectable methane (HCV) / electricity consumed.

FIGURE 4: ADJUSTMENT OF DEMAND AND BIOMASS RESOURCE USAGE SCENARIOS



NB: For each of the scenarios, figure 4 shows the gas demand adjustments, considering the various arbitrations on the use of biomass resources (see scenario description, 2.3), and the effect on demand of greater or lesser use of pyrogasification and power-to-gas (see demand adjustment method, 6.1.). This figure also shows the breakdown of biomass resources according to energy usage.



3.3. ... for an overall cost of 100% renewable gas between €116 and €153/MWh

The total cost of gas consumed per MWh, i.e. the sum of production costs ⁽⁹⁾ and network and storage costs, varies from €105 (for the "75% R&REn" scenario) to €153 per MWh (for the "100%R&REn with limited biomass for gas usages" scenario) – see figure 5. These costs are similar to the €120-130/MWh calculated for electricity in the study "A 100% renewable electricity mix? Analyses and optimisations"(2015) ⁽¹⁰⁾.

Network and storage costs only represent a small proportion: 15-20% of total cost (€20-23/MWh). **In particular, the sole cost of connection, including limited distribution network reinforcement needs and reverse flow stations, represent approximately €3/MWh.**

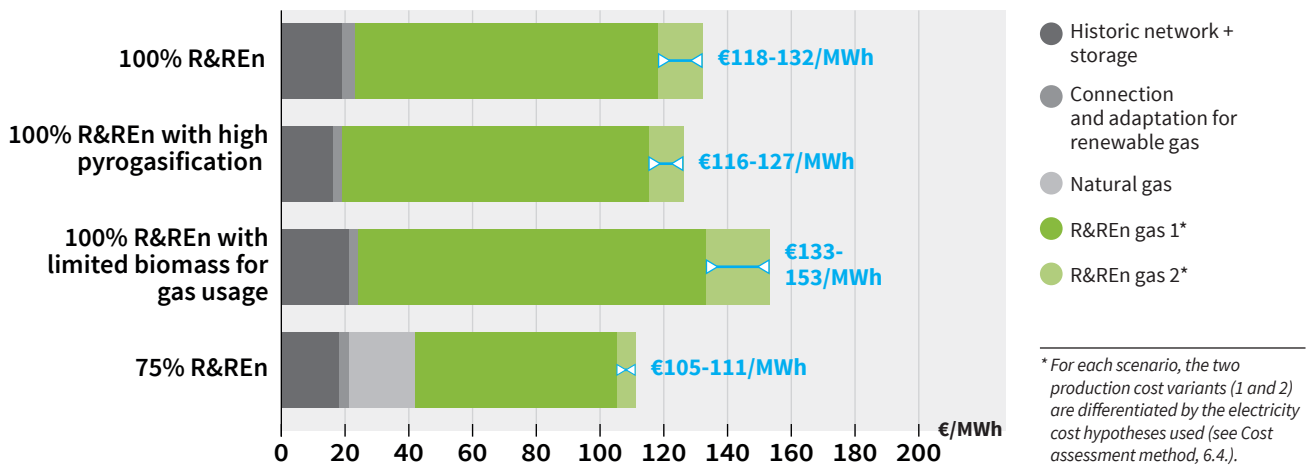
Although demand for gas is 23% higher than in the "100% R&REn" scenario, greater mobilisation of the biomass resources for

gas usages in the "100% R&REn with high pyrogasification" scenario does not result in significant cost differences. This is due to the greater use of the pyrogasification sector, in which production costs are lower than for power-to-gas.

The "100% R&REn with limited biomass for gas usages" scenario also enables 100% renewable gas, but at a higher cost, approximately 15% more than the "100% R&REn" scenario. This extra cost is due to increased use of power-to-gas to compensate for the lesser use of biomass sectors for anaerobic digestion and pyrogasification usages (limited to 80% of potential).

Finally, the "75% R&REn" scenario, which keeps 25% natural gas in its mix, costs 10-20% less, while applying a carbon tax of €200/tCO₂ in 2050 ⁽¹¹⁾.

FIGURE 5: TOTAL COST PER MWh OF GAS CONSUMED



3.4. ... enabling the avoidance of direct emissions of approximately 63 MtCO₂/year

These 100% renewable scenarios would enable direct emissions of approximately 63 MtCO₂/year ⁽¹²⁾ to be avoided, representing €12.6 billion for a shadow value of carbon of €200/tonne of CO₂

in 2050. The avoided emissions would represent around 45 MtCO₂/year for the 75% R&REn scenario.

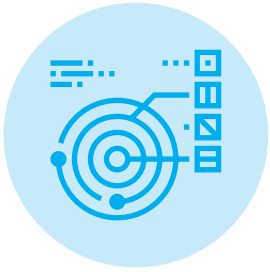
This estimation does not include possible modifications of the carbon sink.

(9) Renewable gas production costs are described in detail in part 6.4.

(10) <http://www.ademe.fr/mix-electrique-100-renouvelable-analyses-optimisations>.

(11) The price of natural gas in 2050 is taken to be €42/MWh_{HCV}, a hypothesis identical to that of the study on ADEME, ARTELYS, ARMINES-PERSEE et ENERGIES DEMAIN, "Un mix électrique 100% renouvelable? Analyses et optimization" (A 100% renewable electricity mix? Analyses and optimization), 2015. This price estimation is provided by World Energy Outlook. The carbon tax of €200/tCO₂ increases this price by €44/MWh_{HCV} i.e. a price of €86/MWh_{HCV}.

(12) Emissions for a scenario in which the reference demand (286 TWh) is 100% fulfilled by natural gas. The figure of 63 MtCO₂ takes into account a zero emission factor for biomethane. With a factor of approximately 23.4g/kWh, the estimated fall in emissions would be 56 MtCO₂.



4. FINDINGS

4.1. A gas system compatible with 100% renewable gas, with necessary evolutions

Huge production of renewable gas will require more decentralised management of the network than at present:

- the study reveals that it is possible to collect most of the resources disseminated in rural areas without massive use of road-transported gas or other innovative and non-mature solutions: the cost of the collection networks to be built represents a low proportion of the overall cost (2-3%),
- a number of technological solutions already exist to make the gas network bidirectional (reverse flow, meshing), the anticipation and optimisation of their deployment will enable costs to be controlled,
- transport and storage infrastructures continue to represent key elements to ensure the balance between supply and demand, notably during cold spells.

Regarding the evolution of the resources to be mobilised to achieve 100% renewable gas, changes will also be required beyond the gas system itself:

- in the agriculture sector, notably via the generalisation of intermediate crops, and anaerobic digestion as an energy and agronomic tool,
- in the forestry sector and wood industry, via the development of sustainable, dynamic forestry (positive carbon footprint, preservation of biodiversity) respectful of the hierarchy of usages (material wood, then energy wood).

4.2. The complementarity of the gas network with the electric grid represents a key success factor for a highly renewable energy mix

This study supports the fact that at a high level of renewable energy production, the gas and electric systems will interact strongly and evolve together:

- Power-to-gas will enable inter-seasonal storage of electricity and geographic optimisation of the electric system via the transport and storage infrastructures

of the gas network. It will also provide an additional source of renewable gas for the gas vector (34-135 TWh_{HCV}).

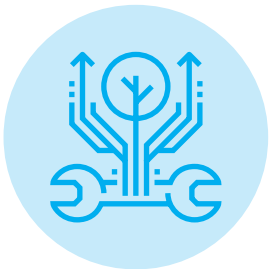
- Renewable gas will help to balance the highly renewable electric system with peaking thermal power plants supplied by renewable gas (10-46 TWh_{HCV} depending on the scenarios).





5. LIMITS AND PERSPECTIVES

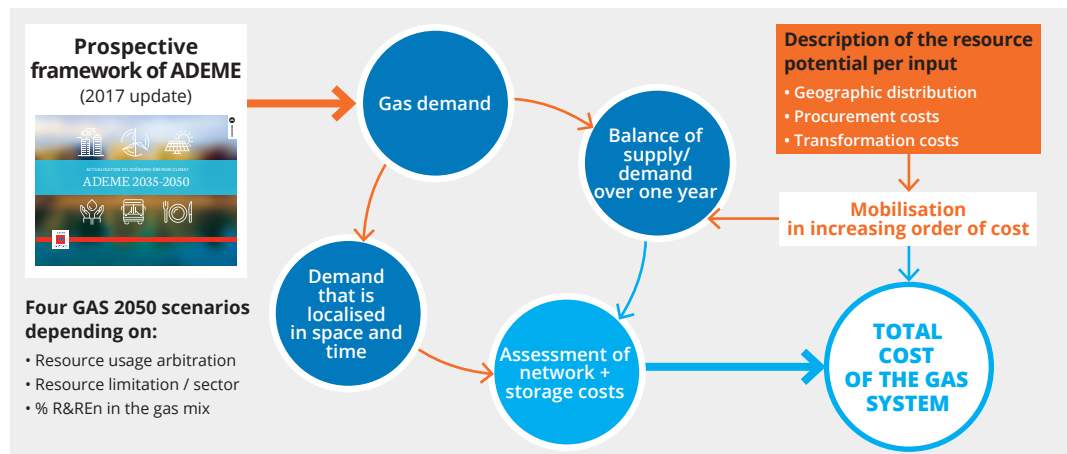
- This study is not an overall optimisation of the energy system; it does not indicate the optimal proportion of renewable gas in technical and economic terms based on defined climatic or environmental objectives. Final consumption figures in usages and annual volumes are input data for the study, taken from ADEME's 2035-2050 energy-climate scenario. The macro-economic balance will be carried out subsequently by ADEME in 2019.
- The study does not model the time line of the transition between the current situation and the scenarios presented.
- The hypotheses considered to define the potentials of the various resources, particularly those of biomass, include uncertainties (changes to agriculture and forest systems, social acceptability of projects, environmental review of the industrial sectors, etc.) the assessment of which must be continued.
- The study does not assess a certain number of external elements. For example, in all the scenarios, the mass development of renewable gas helps to strengthen France's energy independence and has a positive effect on the French economy as a whole, in terms of trade balance (at present, almost all gas is imported, represented a total of approximately €10 billion per year ⁽¹³⁾), economic activity, CO₂ emissions avoided. It could foster job creations with the deployment of around 10,000 production units. These externalities were not quantified in the study.
- Other scenarios could be envisaged, with different arbitrations on the biomass or gas usages in 2050. For example, these scenarios could explore the optimal vector breakdown to meet final demand or explore other usages with higher added value to reduce CO₂ emissions in other sectors (industry, transport, etc.).



6. METHOD AND HYPOTHESES

The study considers a single scenario for the final demand for gas in 2050 and explores a number of gas supply scenarios.

FIGURE 6: STUDY METHODOLOGY



(13) "Bilan énergétique de la France pour 2015" (Energy review for France for 2015), November 2016, SOeS.

The study is based on four major phases, as indicated in figure 6:

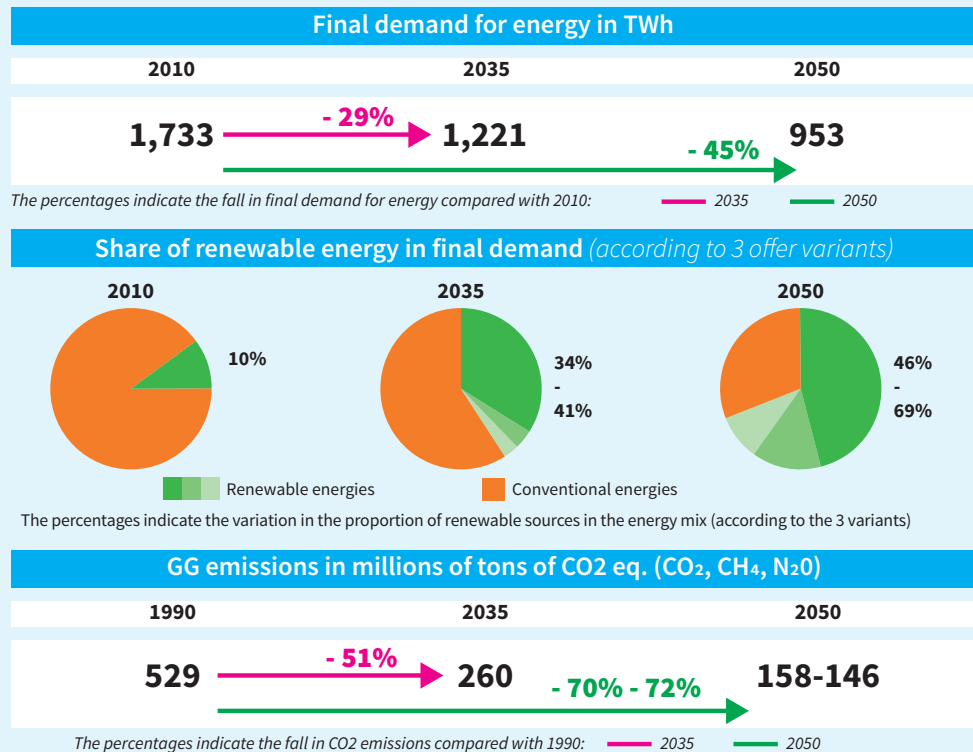
- **Adjustment of demand in 2050:** annual demand defined on the basis of ADEME's 2035-2050 scenario (2017) is adjusted for the four scenarios. It is broken down to the level of the town and with daily load graphs.
- **Characterisation of the renewable gas offer in 2050:** the offer is based on already existing scenarios regarding the different potentials. It is then broken down to the level of the department, even canton. The evolution of production costs in the various production sectors, according to the mobilised resource, is evaluated.

- **Balancing of supply/demand and network adaptations required:** this is carried out at department scale using the data described above and a vision of the current network installation (see description of paragraph 6.3.). Connection and network adaptation costs are evaluated, as are storage requirements.
- **Study of 4 scenarios defining 4 offer variants.** They enable the evaluation of different effects: greater or lesser allocation of the biomass resource to the production of gas (competition between energy vectors, underestimated constraints, etc.), preservation of a proportion of natural gas in the gas mix.

6.1. The gas demand scenario in 2050

The prospective framework 2050 is based on ADEME's 2035-2050 energy-climate scenario, updated in 2017, which describes the final annual demand for energy for each sector, usage and energy vector.

SUMMARY OF ADEME'S 2035-2050 ENERGY-CLIMATE SCENARIO



READING: The 2017 energy-climate scenario covers all energy consumption in mainland France (excluding consumption by international air traffic). It describes the development of renewable energy sources and technologies. The proportion of renewable energy evolves according to three variants of the electric mix. The same therefore applies to greenhouse gas emissions (CO₂, CH₄ and N₂O).



The prospective framework is based on a proactive scenario aimed at energy efficiency and optimisation, with an overall volumes reduction in 2050 of almost 35% compared with 2015.

The 2035-2050 energy-climate scenario thus served as a basis to determine the level and composition of the final demand for gas in 2050 (see table 1), and the use of energy resources excluding gas usages (e.g.: wood for boilers).

TABLE 1: EVOLUTION OF FINAL MAINS GAS CONSUMPTION

<i>TWh</i>	2015	2050	Evolution
Residential	150.8	49.2	-67%
Offices	85.3	13.2	-84%
Industry	152.5	99.3	-35%
Transport	0	106.1	-
Agriculture	2.9	2	-30%
Other ⁽¹⁴⁾	45.2	16.4	-64%
Total excluding power generation	436.5	286.3	-34%

The reference demand taken from ADEME's 2035-2050 energy-climate scenario is adjusted for each of the scenarios. It takes into account different effects:

1. Demand increase related to:

- the substitution of usages initially provided by other vectors (heat, directly or via co-generation),
- peak electricity production (combustion turbines); the quantity required depends

on the electric system linked to the "gas" scenario. In this exercise, the electric system is determined by the level of power-to-gas used. The combustion turbine (CT) requirement is lower in the scenarios in which power-to-gas is developed⁽¹⁵⁾.

2. Demand decrease due to:

- pyrogasification and power-to-gas conversion technologies co-produce heat, which can partially replace "gas" heat⁽¹⁶⁾,
- power-to-heat⁽¹⁷⁾ generates heat which can partially replace "gas" heat. The contribution of power-to-heat depends on the electric system linked to the scenario, and therefore on the level of power-to-gas involved.

The adjusted demand values are indicated in figure 4 - *Adjustment of demand and biomass resource usage scenarios*.

A model is used to describe the demand at town level, per day and according to several sets of weather data to take into account particularly warm or particularly cold years⁽¹⁸⁾, and daily cold spells. The daily load graphs for 2015 and 2050 were modelled. The demand for gas for electricity production, notably in winter, presents larger power demands than today⁽¹⁹⁾. In 2050, there is a significant drop in consumption in winter due to the reduced gas requirements for heating in residential and office buildings. In summer, energy savings are compensated by the increase in transport usage⁽²⁰⁾.

(14) Losses, water and waste sector, internal branch consumption, co-generation, refinery sector.

(15) Additional capacity from wind farms and solar farms set up to enable higher power-to-gas production also ensure better cover of the demand for electricity and thus reduce, to a certain extent, the use of peak production means, such as gas combustion turbines (CT), in terms of both capacity and energy.

(16) The heat efficiency figures used are 15% for pyrogasification and 23% for power-to-gas. Only 30% of this heat is considered to be recycled and replaces heat produced from gas.

(17) Power-to-heat is a process that consists in using electric boilers (resistance or heat pump) in addition to fuel-powered boilers or thermal processes. These electric systems are triggered for surplus electricity production to shed load from thermal facilities.

(18) All the sectors take into account a heat-sensitive effect, except the electricity production sector, which is exogenous to the model. Global warming was taken into account, based on the sets of data from Météo France's Aladin model (scenario RCP 4.5), see <http://www.drias-climat.fr/accompagnement/sections/175>

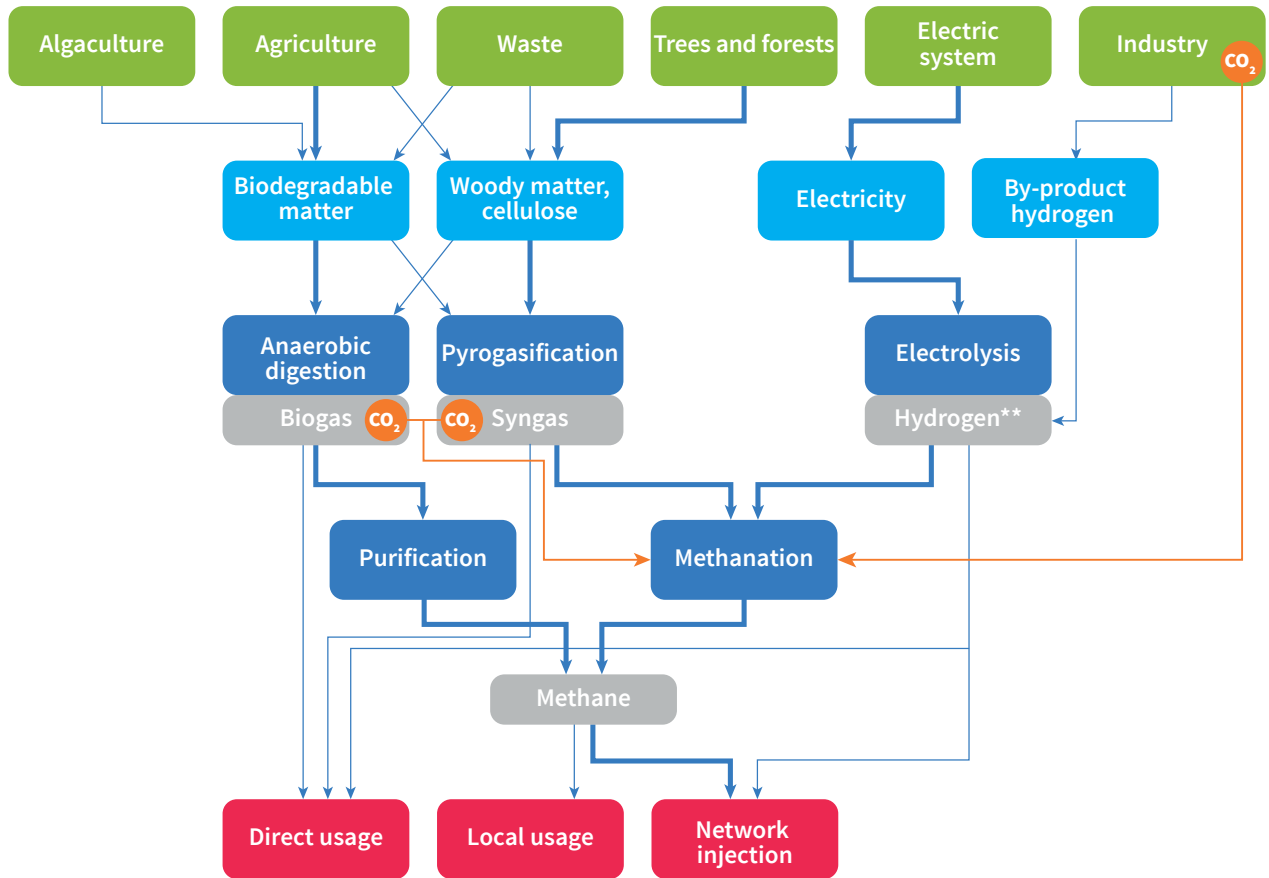
(19) The demand for gas for electricity production depends on the scenario and the power-to-gas contribution, which determines the electric system associated.

(20) In ADEME's 2035-2050 energy-climate scenario, gas fuel represents 48% of final energy in the transport sector.

6.2. Assessment of potential renewable gas production

6.2.1. RENEWABLE GAS PRODUCTION CHANNELS

FIGURE 7: THE DIFFERENT PRODUCTION CHANNELS OF RENEWABLE GAS



* "Pyrogasification" includes hydrothermal pyrogasification of seaweed.

** Hydrogen can also be used directly for various usages; this is not included in this study.

Renewable gas comes from three main sectors:

- **Anaerobic digestion:** biological method using micro-organisms to break down organic matter and produce a mixture called biogas, mainly composed of methane and carbon dioxide. After purification, biomethane has thermodynamic properties equivalent to those of natural gas. The organic matter comes from agriculture (farm animal dejections, crop residues, intermediary crops, grass), industry (by-products and waste from food-processing), sludge from urban sewage processing plants, and household and food waste.

- **Pyrogasification:** thermo-chemical method, in the broad sense, enabling production of a synthetic gas, called syngas, (mainly composed of methane, hydrogen, carbon monoxide and carbon dioxide) from organic matter. The process can be completed by methanation or separation to produce a gas whose thermodynamic properties are equivalent to those of natural gas. Pyrogasification mainly concerns dry woody matter or cellulose: wood and its derivatives, straw and various woody by-products from agriculture. It may also involve waste, typically RDF⁽²¹⁾.

(21) Refuse-Derived Fuel



- **Power-to-gas (PtG):** process to convert renewable electricity into synthetic gas. The first step involves electrolysis to produce hydrogen (power-to-H₂). A second step can be added to convert the hydrogen to methane via a methanation reaction (power-to-CH₄). This reaction requires a source of CO₂.

It should be noted that the levels of maturity and the production processes of these three main sectors are different. Pyrogasification and power-to-gas technologies are therefore considered mature in 2050 with efficiency increase hypotheses. However, this study does not take into account possible technological breakthroughs or significant economies of scale. We also consider that the first two sectors ensure basic production, while power-to-gas operates during periods of surplus electricity production, making the use of power-to-gas discontinuous.

6.2.2. MAIN HYPOTHESES TO ASSESS FEEDSTOCK POTENTIALS

Feedstock availability is notably dependent on the evolution of agricultural and forestry systems as well as energy systems (electricity and heat).

Biomass potentials respect several of the study's fundamental standpoints: non-competition of bioenergies with food or with raw material usage, and increased biological life in soil. The framework data in terms of agriculture and forestry are based on integrated prospective scenarios which take into account the diversity of the objectives for agriculture and forests.

These scenarios are "Factor 4" compatible, i.e. they represent the agricultural and forestry component of scenarios aimed at dividing by four our greenhouse gas emissions, in all sectors, by 2050 (the greenhouse gas reduction factor for the agriculture sector is 2)⁽²²⁾:

- concerning agricultural feedstock in 2050, the potential used is mainly based on SOLAGRO'S works, presented in the Afterres 2050⁽²³⁾ prospective study;
- concerning wood resources, forest extractions are estimated on the basis of works by ADEME, IGN, FCBA⁽²⁴⁾ and INRA⁽²⁵⁾. The time line of these works was 2035, so the figures were extrapolated to 2050, based on the "dynamic forestry" scenario drawn up by Ecofor⁽²⁶⁾;
- biowaste potential estimates are mainly from the study entitled "*Estimation des gisements potentiels de substrats utilisables en méthanisation*" (Estimation of the potential sources of substrates for use in anaerobic digestion)⁽²⁷⁾. Finally, the potential of by-products from the food-processing industries comes from the study entitled "*Étude du potentiel de production de biométhane à partir des effluents des industries agroalimentaires*" (Study of the biomethane production potential from food industry waste)⁽²⁸⁾;
- seaweed is considered to be converted to liquid fuel. Only the residues are considered for the gas sector, according to the 2014 study by ADEME/ENEA/INRIA⁽²⁹⁾.

The potential for renewable electricity to supply power-to-gas plants comes from the data of the 2017 ADEME/ARTELYS study⁽³⁰⁾ evaluating various optimised

(22) However, it is estimated that it would be possible to produce at least as much resource with a 'baseline' agricultural scenario, but the negative impacts involved would be more significant.

(23) SOLAGRO, "Afterres 2050", 2016.

(24) ADEME, IGN, FCBA, "Disponibilités forestières pour l'énergie et les matériaux à l'horizon 2035" (Forest availabilities for energy and materials in 2035), 2016.

(25) INRA and IGN, "Quel rôle pour les forêts et la filière forêt-bois française dans l'atténuation du changement climatique ?" (How can forests and the French forestry-wood industry help to attenuate global warming?) June 2017.

(26) Caulet, "Climat, Forêt, Société - Livre Vert" (Climate, forest, society - Green paper), 2015.

(27) ADEME, SOLAGRO and INDDIGO, "Estimation des gisements potentiels de substrats utilisables en méthanisation" (Estimation of potential sources of substrates usable for methanation), 2013.

(28) GRDF et SOLAGRO, "Étude du potentiel de production de biométhane à partir des effluents des Industries Agro-Alimentaires" (Study of the production potential of biomethane from food-processing industry waste), 2017.

(29) ENEA, INRIA and ADEME, "Évaluation du gisement potentiel de ressources algales pour l'énergie et la chimie en France à horizon 2030" (Evaluation of potential seaweed resources for energy and chemistry in France in 2030), July 2014. Total conversion of seaweed into gas enables a production potential of up to 60 TWh, with efficiency approximately half that of the diesel + gas conversion.

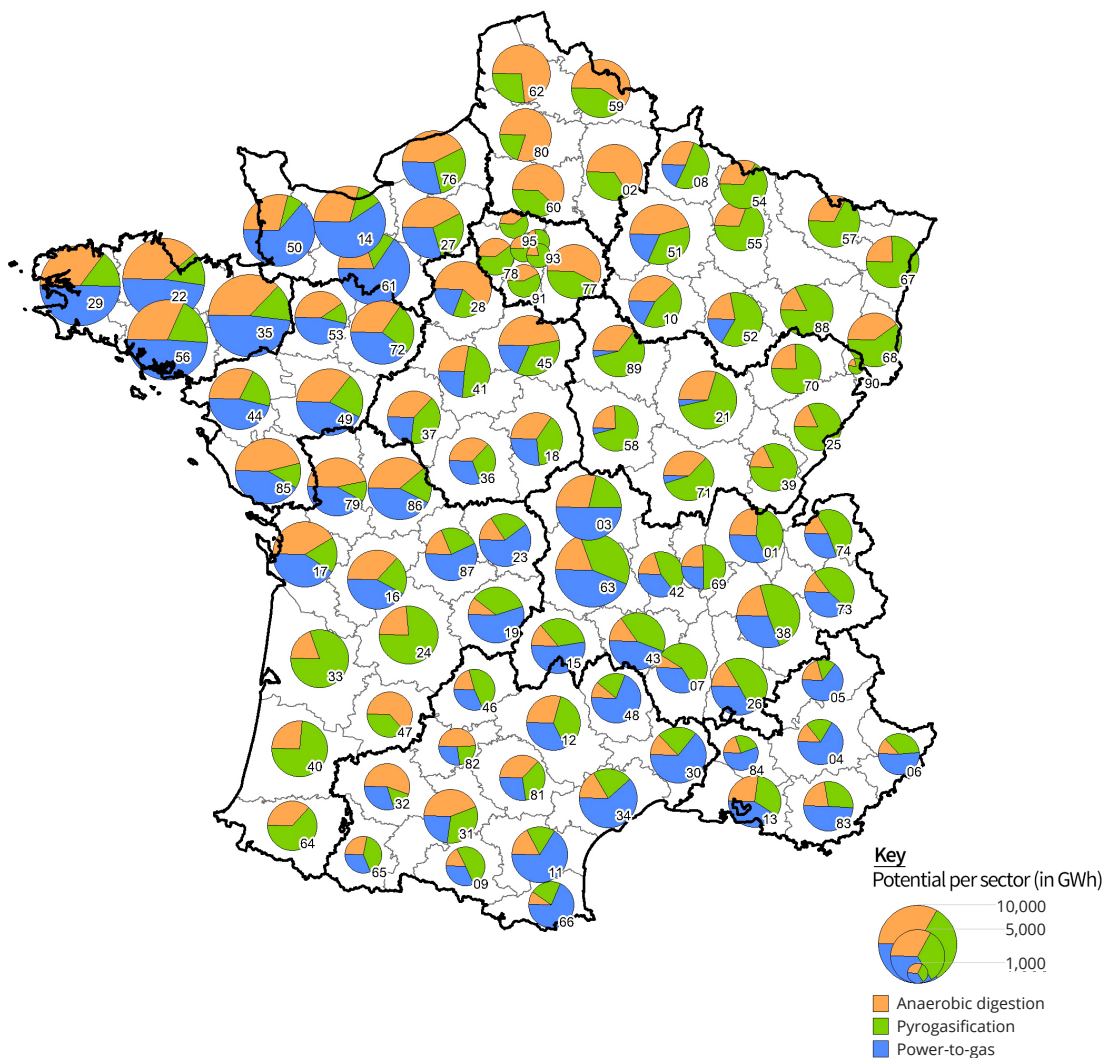
(30) ADEME and ARTELYS, "Un mix électrique 100 % ENR en 2050, quelles opportunités pour décarboner le système gaz et chaleur ?" (A 100% R&REn electric mix in 2050, how to reduce the carbon footprint of the gas and heat system), 2017.

configurations of the electric system with power-to-gas developed to a greater or lesser extent: installed capacity per region, operating time profile, electricity costs.

In terms of recovered gas, RDF (Refuse-Derived Fuel) ⁽³¹⁾ and by-product hydrogen ⁽³²⁾ potentials were also estimated, representing figures significantly lower than the renewable potentials *in the strictest sense*.

The map below shows the injectable gas potential per department and per sector. These potentials correspond to the entire available resource for an energy usage, before arbitration between the energy usages in competition.

FIGURE 8: BREAKDOWN OF THE THEORETICAL POTENTIAL OF INJECTABLE GAS BY DEPARTMENT AND SECTOR IN 2050



(31) GRDF, GRTgaz and S3D, "Étude sur les gisements valorisables par la filière pyrogazéification phase 1 : état des lieux bibliographique et 'fiches intrants'" (Study of the sources recyclable by the phase 1 pyrogasification sector: bibliographic review and 'input datasheets'), 2017.

(32) GRDF, ADEME and SOLAGRO, "Évaluation du potentiel de méthanation à partir de gaz industriels fatals (hydrogène et dioxyde de carbone)" (Evaluation of the methanation potential from by-product industrial gases (hydrogen and carbon dioxide)), 2017.



6.3. Assessment of network adaptation

The method used enables the demand for gas to be covered by the most competitive renewable sectors first; it also enables consideration of the costs of adapting the gas network (distribution and transport to a lesser degree) to convey this renewable gas to consumers.

The positioning of the production units and the necessary changes to the network (connection pipelines, storage capacities, reverse flow stations) were evaluated in detail for four typical departments with different profiles in terms of consumption and production density.

An optimisation algorithm then enabled identification of a new configuration for the gas network to enable the connection of production units involving a range of connection solutions: connection to the distribution network, connection to the transport network or connection via road-

transported gas. If applicable, solutions to eliminate the constraints on the gas network were implemented (meshing, reverse flow). These solutions are presented in figure 9. These profiles and solutions were then extrapolated to the whole of mainland France.

The national supply-demand balance was examined for all the scenarios, using different sets of climate data to test the resilience of the gas system to exceptionally hot or cold years, and daily cold spells.

The resilience of the gas system was studied using different sets of climate data for each scenario.

The storage requirements thus evaluated were compared with existing storage capacity, or storage capacity whose development has already been confirmed, both in terms of volume and output.

FIGURE 9: ILLUSTRATION OF THE RANGE OF SOLUTIONS TO CONNECT AN ANAEROBIC DIGESTION PLANT

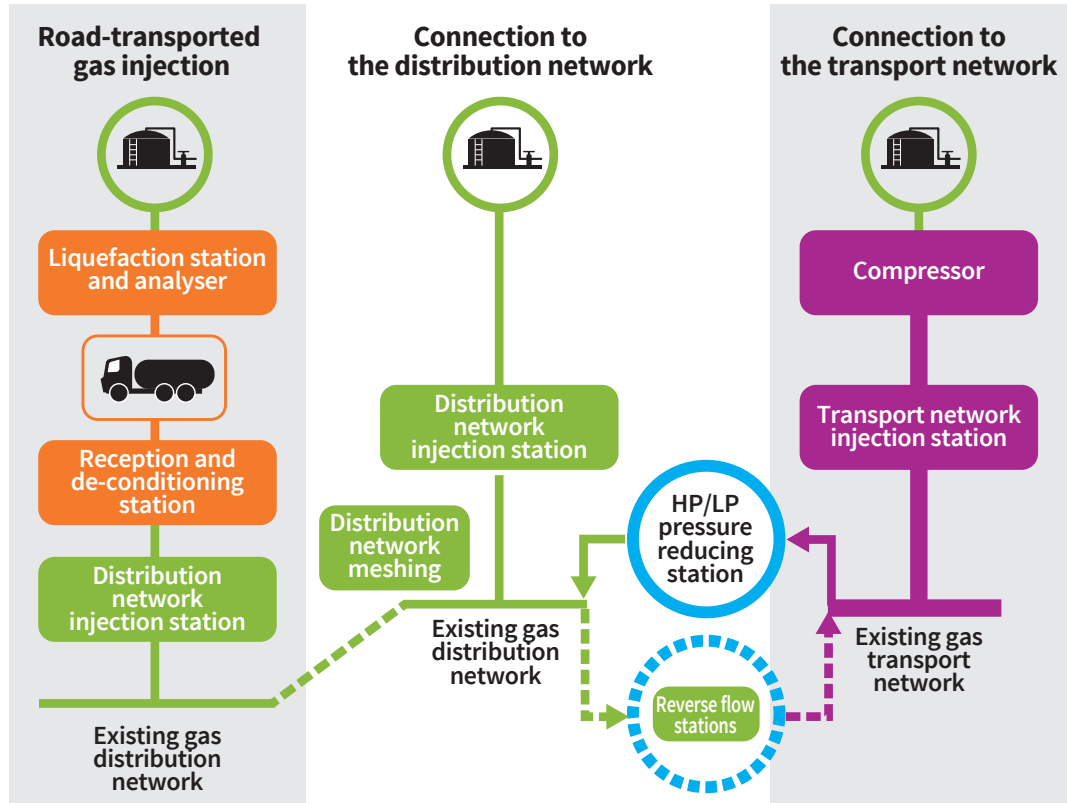
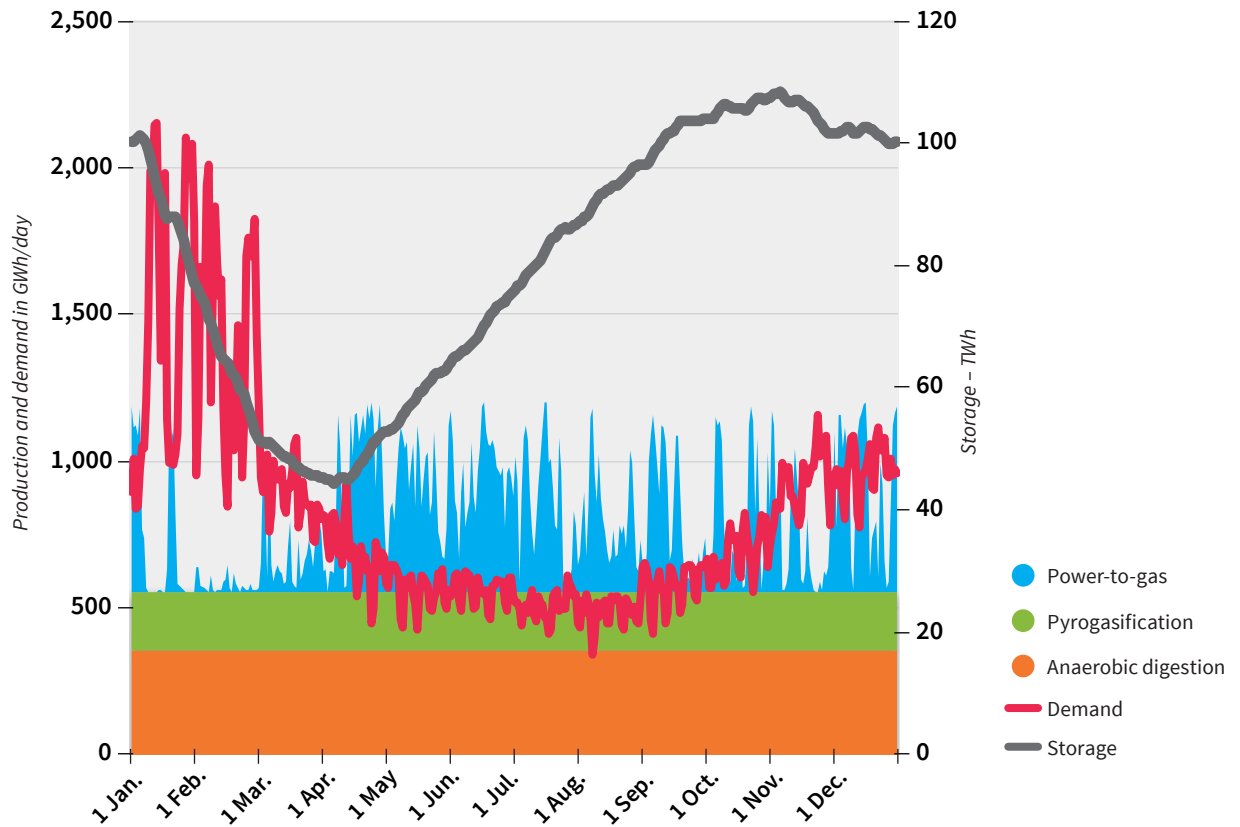


FIGURE 10: SUPPLY-DEMAND BALANCING AND STORAGE EVOLUTION (NORMAL YEAR)



6.4. Full cost assessment

The cost assessment includes:

- production costs;
- distribution and transport costs;
- storage costs.

Production costs are evaluated for each sector, including resource procurement costs and transformation costs. These costs increase with the level of resource mobilisation due to increasing mobilisation costs: for example, the last TWh of wood would have to be extracted from forest areas that are more difficult to operate (access difficulties, rough terrain, degree of plot division, etc.).

In increasing order of cost, this gives:

1. Recovered energies at €30-40/MWh_{HCV}
2. RDF pyrogasification at €40/MWh_{HCV}
3. Anaerobic digestion, with costs below €80/MWh_{HCV}
4. Biomass/wood pyrogasification with costs of €80-120/MWh_{HCV}

5. Power-to-gas with costs of €65-185/MWh_{HCV}, depending on the sector. The Power-to-CH₄ sector falls within the range of €105-185/MWh_{HCV}. It is important to note that this cost also includes an average CO₂ procurement cost of €10/MWh_{HCV}⁽³³⁾. Power-to-H₂ costs less than Power-to-CH₄ within the range of €65-125/MWh. The ranges presented depend on the hypotheses used for the purchase price of electricity. The development of power-to-gas induces extra costs (development of electricity production means) and benefits (drop in flexibility requirements for the electric grid), which, depending on their economic allocation, are reflected in two variants. The "preferential price of electricity for flexible consumer" variant corresponds to a price of electricity below its production cost price, reflecting the economic benefit of power-to-gas for the electric system.

⁽³³⁾ This cost varies from one scenario to another (€7-17/MWh_{HCV}, i.e. €41-77/tCO₂), depending on access to CO₂ sources. Anaerobic digestion and pyrogasification provide sources of relatively pure CO₂ that are considered free: they are therefore used first. More costly solutions are then considered to meet the needs of each scenario: capture from combustion plants, transport, storage.



The "price of electricity at spot market price" variant corresponds to a higher cost of procurement⁽³⁴⁾.

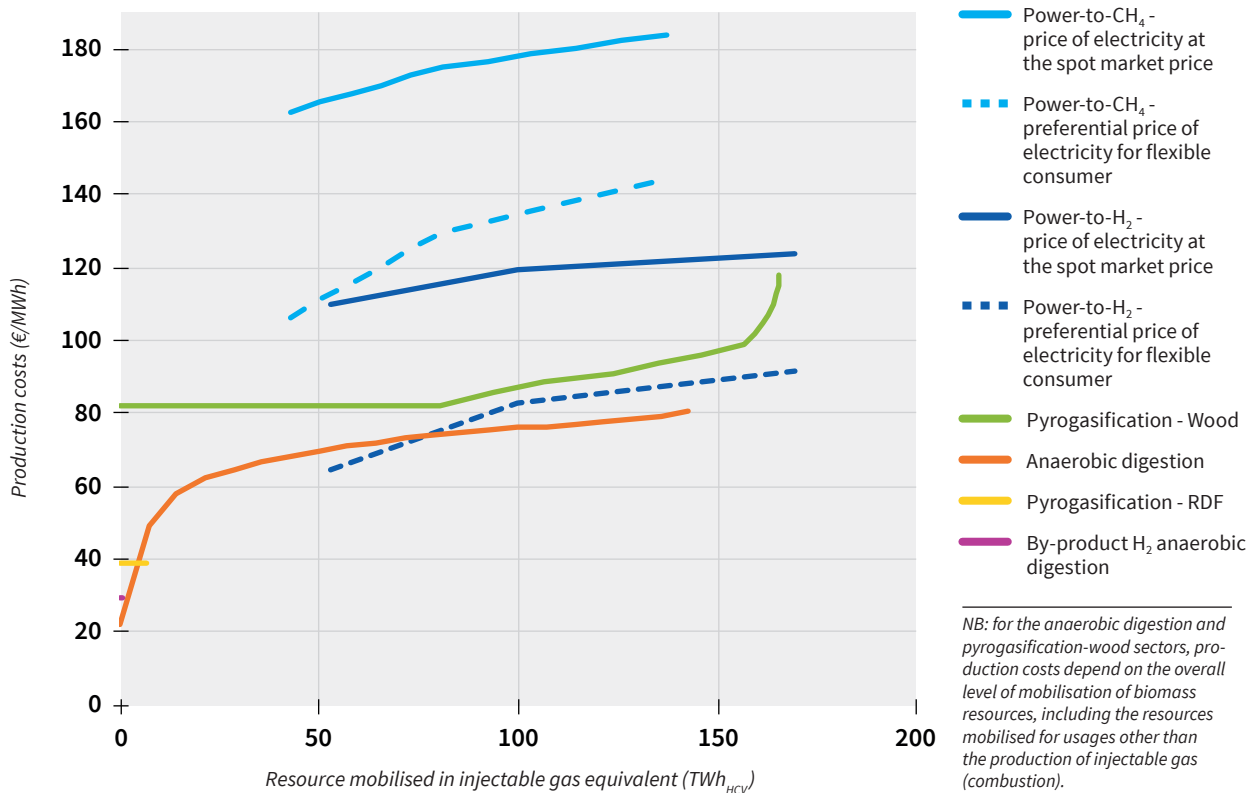
The costs of connection and network adaptation were then assessed. These adaptations include the creation of reverse flow compression stations between the distribution and transport networks. The exercise was carried out for four typical departments. The results were extrapolated nationally, taking into account the differences in access to biomass resources (distance).

The costs of transport network modification were deemed insignificant. An initial analysis indicates that the size of the current transport network is compatible with the 2050 scenarios studied.

For the other existing network costs, it is assumed that network operation and renewal costs will remain similar to current costs. The estimation was based on the transport (ATRT5) and distribution (ATRD5) tariff evaluation.

Storage costs were estimated on the basis of current costs, modulated according to the annual storage volume used in each of the modelled scenarios.

FIGURE 11: PRODUCTION COSTS OF THE DIFFERENT SECTORS IN 2050, ACCORDING TO THE OVERALL RESOURCE MOBILISED



(34) Depending on the level of power-to-gas production in the scenarios, the average cost of electricity procurement varies from €67 to €82/MWh in the "price of electricity at the spot market price" variant and between €30 and €56/MWh in the "preferential price of electricity for flexible consumer" variant.

ADEME IN BRIEF

ADEME (the French environment and energy management agency) contributes to the implementation of public policies in the fields of environment, energy and sustainable development. It provides expertise and advice to companies, local authorities, public authorities and private individuals to enable progress in environmental initiatives. The agency also helps with project funding, from research to implementation in the following areas: waste management, ground preservation, energy efficiency and renewable energies, raw material savings, air quality, reducing noise pollution, transition to a circular economy and reducing food waste.

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A 100% RENEWABLE GAS MIX IN 2050?

ADEME contributes to the discussions on France's proactive strategy, notably by examining possible trajectories for the French energies of the future and has been publishing energy-climate scenarios on a regular basis since 2013. This study, "A 100% renewable gas mix in 2050?", conducted by ADEME in collaboration with GRDF and GRTgaz, follows on from the works published in 2016 - 2017, and concerns the second most consumed energy in France, gas. Herein, ADEME explores the conditions of the technical and economic feasibility of a gas system in 2050 based on 100% renewable gas.

The work is based on ADEME's 2035-2050 energy scenario, with a level of final demand for gas in 2050 of around 300 TWh, compared with today's figure of 460 TWh. The results, based on sensitivity analyses and various renewable gas production mix scenarios, reveal that there is a theoretical potential source of renewable gas that could fulfil this lower demand for energy in 2050 at an overall cost of gas between €116 and €153/MWh. It would involve making some modifications to the gas system and notably development of the complementarity between the gas network and the electric grid. This confirms that to improve the sustainability of our energy system, we must strengthen the interactions between the energy vectors and optimise their synergies, at various territorial scales.



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ISBN 979-10-297-1054-4
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