March 2022

Potential for electrification of industrial thermal processes

PUBLIC SUMMARY



ALLICE
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Study conducted by:

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Preamble

This summary was published in March 2022 on the basis of a study carried out in 2021. It therefore does not take into account the changes in energy prices that have occurred since summer 2021. The realisation of this study was supported by ADEME (French Agency for Ecological Transition) and CETIAT.

Study carried out for ALLICE by the Enea Consulting team: Jérémie Benhamou, Angélique Maillot, Jacques Arbeille.

Enea Consulting is an independent strategy consultancy specialising in energy and environmental transition. Since 2007, we have advised and supported more than 200 private companies and public authorities around the world, from the largest energy and industrial companies to start-ups, financial players and investors.

This document is a summary of the study "Electrification potential of industrial thermal processes – Phase 2" carried out by Enea Consulting on behalf of ALLICE. The detailed report on the study, which describes the hypotheses, results and methodological issues in greater depth, is available to ALLICE members.

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We would like to thank the following companies and technical centres, whose input informed the technical and economic analyses and feedback presented in this study: EDF, CTMNC, EFD Induction, SAIREM, GRDF, GRTgaz, TotalEnergies, CETIM and CETIAT. d'expérience présentés dans cette étude.

In line with its activity of supporting innovation and energy efficiency in industry, **ALLICE wanted to inform its members about the electrification potential of different industrial thermal processes and the competitiveness of the electrical solutions** that exist in the various sectors.

The *Centre Technique des Industries Aérauliques et Thermiques* (CETIAT) and the *Centre Technique des Industries Mécaniques* (CETIM) carried out an initial study on the electrification potential of thermal processes on behalf of ALLICE (hereinafter referred to as the "PEP 1 study") [1]. **This study analysed the technical, economic and operational feasibility of switching to electric power at the scale of an industrial site, and identified areas for innovation in electrification.**

In addition to the PEP 1 study, ALLICE commissioned Enea Consulting to carry out a second study (hereafter referred to as the "PEP 2 study"). This report summarises the PEP 2 study. A more complete report detailing the hypotheses, results and methodological issues of the study is available to ALLICE members. **The objective of the PEP 2 study was to extend the scope of the PEP 1 study to national level in order to provide an overview of the potential for electrification in various industrial sectors between now and 2035** and present a critical analysis of the underlying trends in electrification, in particular in relation to the long-term dynamics of energy markets. The study has three parts:

1 Calculation of the maximum techno-economic potential for the electrification of industrial processes in France by 2035;

2 Assessment of the impact of long-term changes in the market prices of energy and CO_2 on electrification potential, for 3 price scenarios;

3 Analysis of the feasibility of industrial electrification from the point of view of the electricity grid in mainland France and the positive externalities for the country (job creation and reduction of CO_2 emissions).

The study analyses underlying trends in electrification, but in its current form cannot be used to carry out a techno-economic feasibility study for an industrial site. The technical feasibility of electrification is specific to each industrial process, as well as to the operational constraints on site. The results of this study make it possible to identify general trends in industrial electrification and assess the possibilities available to industry over the long term in several energy price scenarios, and serve as a basis for dialogue on industrial decarbonisation between public authorities and industrial players. However, the study does not allow any conclusions to be drawn about possible electrification solutions for specific industrial sites.

The estimated electrification potential figures are the result of a theoretical approach and not intended to replace audits of industrial sites.

Furthermore, the study is a forward-looking reflection on the electrification of industrial thermal processes and not an attempt to forecast the energy mix of the various industrial sectors in 2035.

Note

The aim of this study is to analyse the relevance of electrification in relation to fossil fuels (natural gas, coal). **An ALLICE study dealing specifically with the use of green gases in industry was carried out and published at the same time as this summary.**

In particular, it is important to bear in mind the following points:

- The competitiveness analysis in this study only assesses electric solutions and does not include other low-carbon solutions (green gases, CCUS, hydrogen, etc.).
- It is assumed that pipeline gas contains no biomethane.
- The positive externalities of other decarbonisation solutions are not taken into account in this study.

Alliance ALLICE

Our raison d'être

Encourage **the emergence of new solutions** and support innovation in a cross-functional approach

by bringing together supply and demand and demand, prescribers and and centres of excellence.

Our organisation

- a **membership-based** model
- an **independent** animation structure
- governance that meets **members' needs** and ensures a **strategic vision** of the challenges facing the industry
- over than 120 members and partners

Our activities



Collective studies

- ✓ Roadmaps
- ✓ Collective studies
- ✓ State of the art overviews
- ✓ Monitoring

Collaboration and project facilitation

- ✓ Early technical structuring
- ✓ Identification of partners

Community facilitation

- ✓ Workshops for members
- ✓ Participatory workshops open for all
- ✓ Actions for public authorities

Representation of the sector

- ✓ Biennal Congress & Waste heat Convention
- ✓ Technical meetings
- ✓ Collective representation towards institutions

Founders and shareholders

CETIAT · cetim · ctcpa · enea CONSULTING · CTMNC

Partners

pexe · atee · eit InnoEnergy Knowledge Innovation Community · tenerrdis · axeLERa

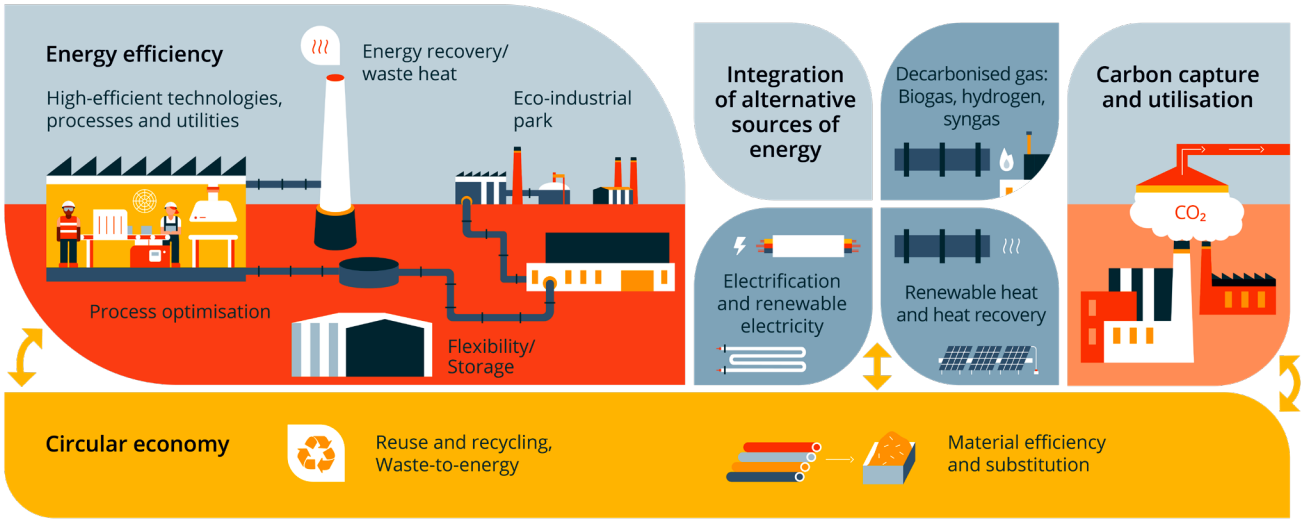
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Our areas of expertise





Executive summary

INDUSTRIAL THERMAL PROCESSES ACCOUNT FOR A SIGNIFICANT PROPORTION OF FINAL ENERGY CONSUMPTION IN FRANCE, BUT HAVE NOT YET BEEN ELECTRIFIED TO ANY GREAT EXTENT.

French industry accounted for 23% of the 1,621 TWh of final energy consumed in France in 2019 [2]. In particular, a major part of the energy consumed by industry is used for thermal processes, 93% of which rely on fossil fuels [3]. As a result, industry is one of the main greenhouse gas (GHG) emitting sectors, accounting for **18% of the 440 Mt $CO_{2,eq}$ emitted in France in 2019 [4]**.

While many decarbonisation efforts have already been undertaken by industrial players over the last few decades, **the French public authorities are committed to continuing and supporting the reduction of CO_2 emissions from the industrial sector**. The National Low Carbon Strategy (*Stratégie Nationale Bas Carbone* – SNBC) aims to reduce industrial emissions by 35% by 2030 and 81% by 2050, compared with 2015 levels.

The transition to a near-zero-carbon industry requires, first and foremost, greater energy efficiency and operational optimisations – in particular the recovery of waste heat – complemented by **changes in fuels and associated thermal processes**, and the development of CO_2 capture technologies. **Several low-carbon energy sources can contribute to reducing emissions from thermal processes**, including biogas, biomass, hydrogen (H_2), solid recovered fuels (SRF) **and electricity, which is the subject of this study**.

France's electricity mix is one of the most carbon-free in Europe [5], so **the electrification of thermal processes is a potential lever for decarbonisation for industrial players**. Indeed, the SNBC is based on "extensive electrification of the industrial sector", with a long-term target of 70% industrial electrification (the share of electricity in total final consumption) by 2050, compared with 39%[1] in 2019.

Most of the electricity currently consumed by industry is used for motor applications (71% of the electricity consumed), which are now fully electrified. Thermal uses, on the other hand, mainly rely on the consumption of fossil fuels.

Thermal processes therefore represent the majority of industrial uses that need to be electrified in order to achieve the national long-term objective of the SNBC. At European level, there are no explicit electrification targets, although electrification is **being studied as one of the major decarbonisation paths in the long-term carbon neutrality scenarios**, along with other low-carbon fuels [6].

However, the electrification of thermal uses faces a number of constraints. On the one hand, there are a number of operational challenges to be taken into account, such as the increased electrical power required on site for electrification, or the essential role of fuel combustion (gas, coal) in the quality of the finished product in certain sectors. **The lack of long-term visibility regarding energy market prices and their volatility can also act as a brake on the electrification of industry.**

1 - Data from the French Ministry for Ecological Transition. The scope of the SNBC excludes steelmaking via blast furnaces and refining, and includes the construction sector, unlike the scope of the PEP 2 study. The CEREN study, whose scope is close to that of the PEP 2 study, estimates this share at 33% for 2016.

THE MAXIMUM TECHNO-ECONOMIC POTENTIAL FOR THE ELECTRIFICATION OF FOSSIL-FIRED GENERATION BY 2035 IS 29%

Non-electric thermal uses in the industrial sectors studied[2] represented 240 TWh of annual final consumption in 2014 [3], which is 64% of industrial energy consumption. These thermal uses can be categorised into four major processes: furnaces, fluid heating, drying and distillation.

Of the 240 TWh of energy consumed annually by non-electric industrial thermal processes, **from a techno-economic point of view, a maximum of 69 TWh could be electrified by 2035 (in terms of annual consumption), i.e. the electrification potential is 29% of the 240 TWh.**

This electrification potential takes into account technical feasibility, the existence and maturity of electrical technologies, operational constraints and competition with other existing decarbonisation methods. It is therefore not a technical potential, but a potential that takes into account constraints regarding the penetration of electrical technologies, including both mature technologies and those under development, that can be expected by 2035.

The electrification of 69 TWh of fuel would increase annual industrial electricity consumption by 46 TWh due to the greater efficiency of thermal-electric technologies in terms of final energy. The share of electricity in energy consumption of thermal processes would therefore rise from 18 TWh (7%) to 64 TWh (27%).

By applying these figures to the same sectors as the SNBC[3], the share of electrification could reach 51% of final industrial consumption by 2035, compared with the SNBC's target of 41% by 2030. This scenario is therefore more ambitious than those put forward by the public authorities.

Electrification is therefore a significant avenue for industrial decarbonisation, particularly for low-temperature thermal applications or for specific processes for which highly efficient technologies exist.

2 - The sectors studied here are: iron and steel, basic chemicals, non-metallic minerals, food and drink, paper and printing, metallurgy, capital goods, fine chemicals, refining and textiles.

3 - I.e. excluding steelmaking via blast furnaces and refining, and including the construction sector.

BREAKDOWN OF THE 240 TWH OF ANNUAL ENERGY CONSUMPTION FOR NON-ELECTRIC THERMAL USES BY PROCESS AND BY SECTOR (2014) [3]

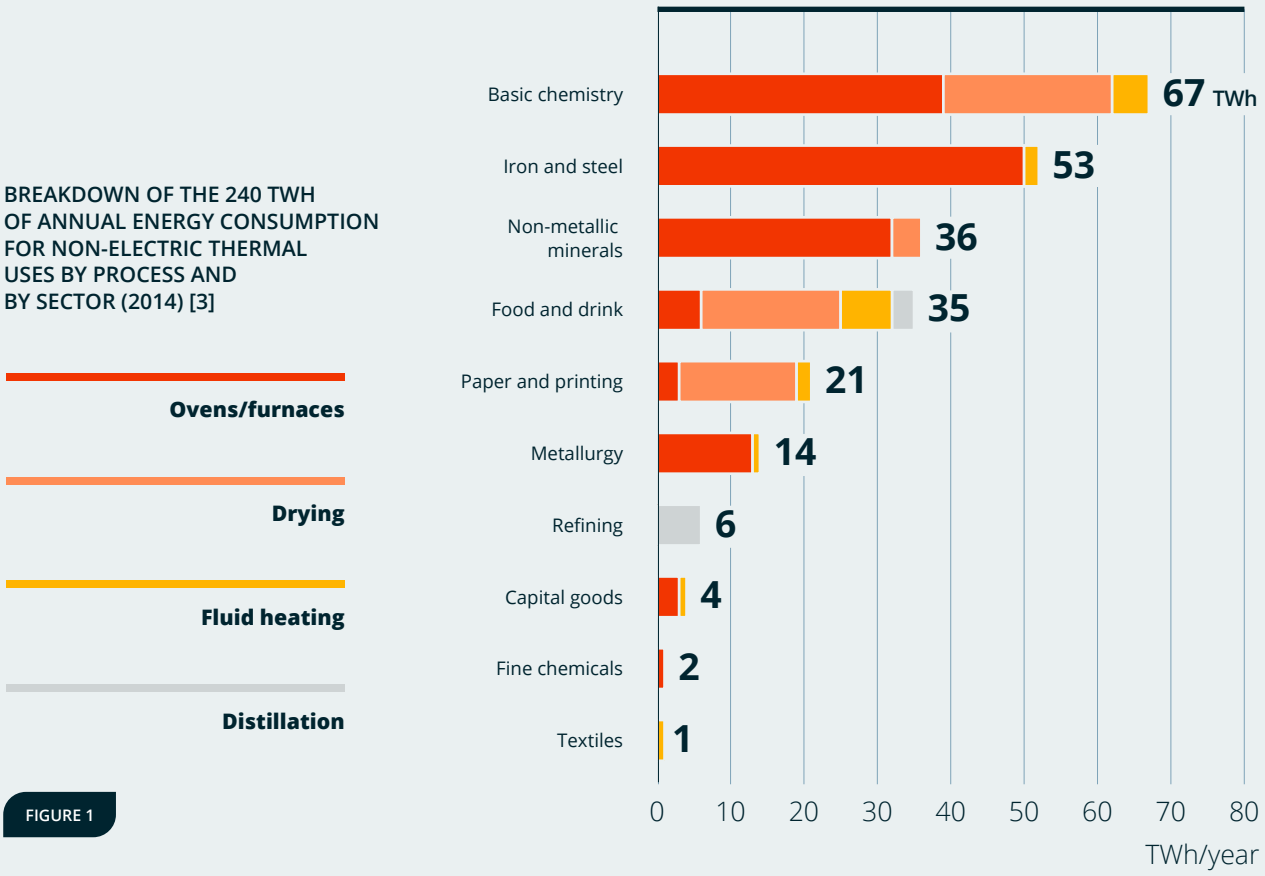


FIGURE 1

The potential for electrification by 2035 is particularly high in sectors such as food and drink, paper, and fine chemicals. Much of the energy demand in these sectors is for drying or fluid heating processes, which have good prospects for electrification. **There is also significant potential for electrification in the iron and steel sector.**

However, mass electrification of the iron and steel sector would require a profound transformation rather than a simple energy substitution. This is because the electrical route is based on the production of steel from recycled scrap metal, which entails both a change in the supply chain of a site and a change in the composition of the finished products.

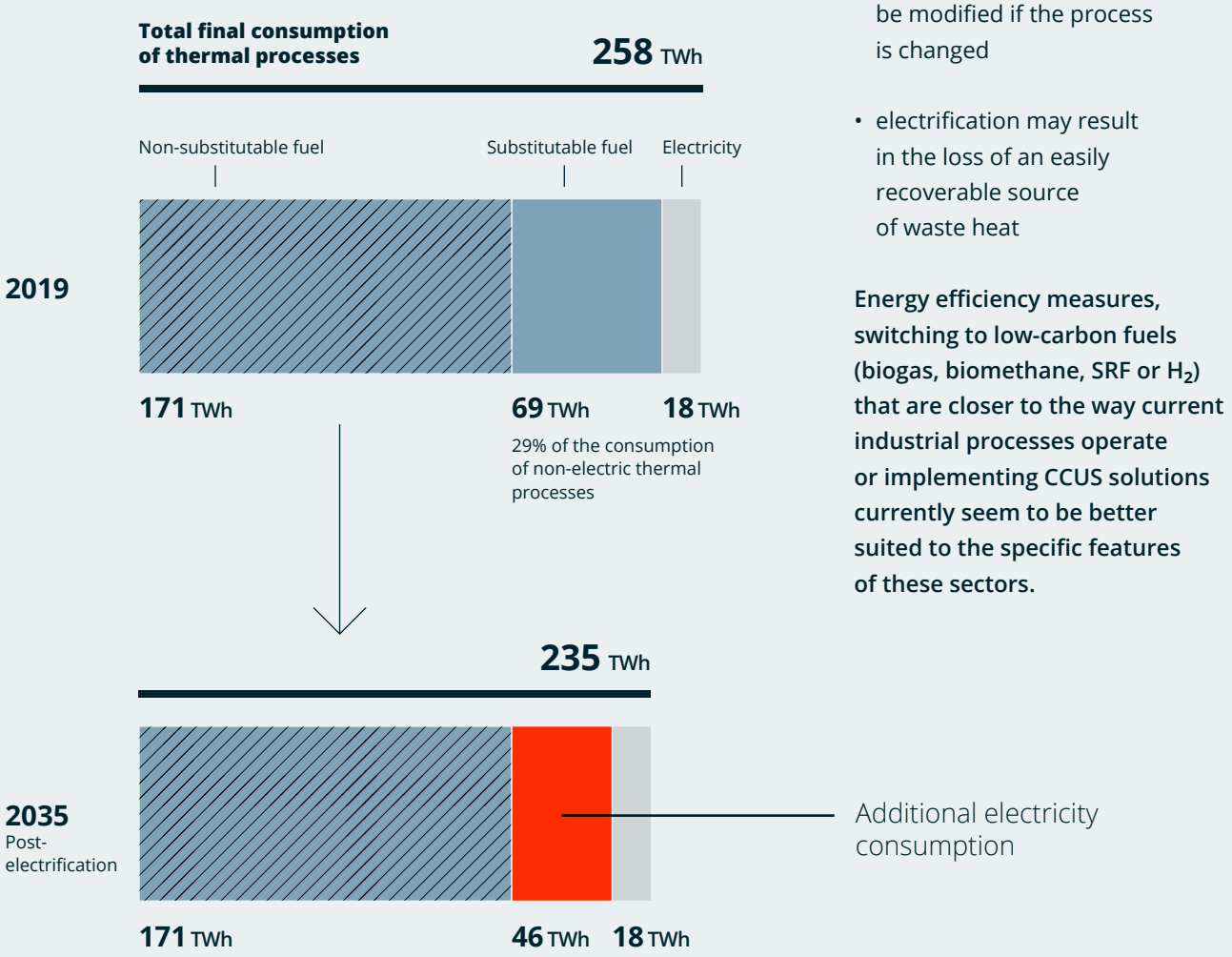
On the other hand, in some sectors, such as metallurgy and non-metallic minerals (in particular glass and cement manufacture), electrification currently seems less feasible for various reasons, and alternative decarbonisation solutions will be required in the medium term. In these sectors, electrification is limited by operational constraints:

- thermal processes generally require very high temperatures and the electrical technologies that could meet this need are either immature or non-existent
- production quality may be modified if the process is changed
- electrification may result in the loss of an easily recoverable source of waste heat

Energy efficiency measures, switching to low-carbon fuels (biogas, biomethane, SRF or H_2) that are closer to the way current industrial processes operate or implementing CCUS solutions currently seem to be better suited to the specific features of these sectors.

FIGURE 2

SHARE OF CURRENT FUEL CONSUMPTION THAT COULD BE ELECTRIFIED BY 2035



A different perspective

The study "*Première analyse du potentiel technique d'électrification des procédés industriels thermiques par des technologies matures*" (Initial analysis of the technical potential for electrifying thermal industrial processes using mature technologies) carried out by CEREN and published in 2020 (hereinafter "CEREN study") estimated the technical potential for electrification to be 42 TWh of annual consumption, compared with 69 TWh in the PEP 2 study [3].

The differences in the methodological approaches used explain the disparity in the calculated potentials:

The CEREN study identifies the technological feasibility of implementing existing, mature solutions in industrial processes on the basis of existing projects, relying in particular on current industrial energy consumption data. **The PEP 2 study is based on a qualitative analysis of the potential for electrification of several industrial thermal uses in the medium term (2035)**, based largely on the results of a prior technical study (PEP 1 study).

- Thus, the major calculation assumption used in the CEREN study is to consider that substitution by an electrical technology is possible if it already represents more than 1% of the total consumption of a thermal use.

- The methodology of the PEP 2 study involved constructing hypotheses for electrification potential in a qualitative manner, taking into account the existence and maturity of electric technologies, their technical feasibility, operational constraints and competition with other decarbonisation paths. The main source of data for the hypotheses of the PEP 2 study is the PEP 1 study carried out by CETIAT and CETIM, supplemented where necessary by a review of the literature and interviews with experts.

As a result of its methodological approach, **the CEREN study only considers mature electrical solutions in its analysis**. The PEP 2 study, on the other hand, also considers solutions currently at the R&D stage, in particular high-temperature heat pumps.

Consequently, the respective objectives of each study are distinct:

- The CEREN study estimates a technical electrification potential based on mature electrical solutions.

- The PEP 2 study estimates a techno-economic electrification potential based on mature solutions or those under development and expected to be mature by 2035.

The categorisation of industrial thermal uses varies in the two studies. The CEREN study divides thermal uses into 10 energy operations. The PEP 2 study defines 4 thermal uses, subdivided into different temperature levels.

The PEP 2 study includes analysis of the energy consumption of thermal processes in refining (~6 TWh/year), unlike the CEREN study, meaning there is a minor difference in the industrial energy consumption input data.

THE INCLUSION OF ECONOMIC CONSIDERATIONS IN THE ANALYSIS LEADS TO THE CONCLUSION THAT WITHOUT PUBLIC SUPPORT, THE FULL TECHNO-ECONOMIC POTENTIAL WILL NOT BE ACHIEVED

In the reference scenario for the prices of energy (gas, electricity, coal) and CO_2, the proportion of fossil-fired consumption that can actually be electrified without a specific support mechanism is 15%. Specific support mechanisms will therefore have to be put in place if a larger proportion of the maximum potential – which amounts to 29% of fossil fuel consumption – is to be achieved.

Three long-term price scenarios were used to compare the competitiveness of fossil fuel and electric technologies. These prices were simulated using three possible scenarios developed by Enerdata:

Blue
Reference scenario

Green
The most favourable scenario for electrification. This is a particularly optimistic scenario in which gas prices rise very sharply compared with electricity prices.

Brown
The scenario the least favourable to electrification. In this scenario, gas prices rise less quickly compared to electricity prices than in the other scenarios.

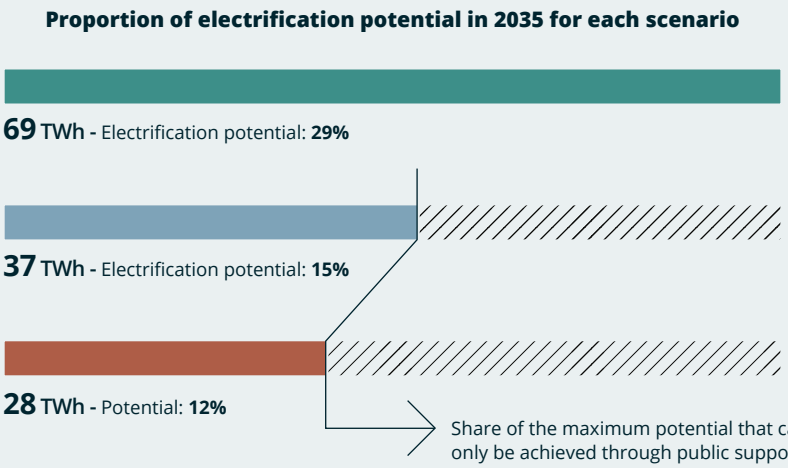
The proportion of the maximum techno-economic potential that could be achieved without public support was estimated by comparing the competitiveness of electricity and fossil fuel technologies on the basis of a calculation of the full cost of the technologies. The electrification potential was calculated for each of the three energy price scenarios (**Figure 3**).

To identify the role that the price of CO_2 can play in electrification, the sensitivity of the results to different market price scenarios for the European Union's CO_2 trading scheme (EU ETS) was analysed. The aim of the EU ETS is to limit CO_2 emissions by requiring emitting companies to purchase CO_2 quotas. The application of the EU ETS thus increases the cost of carbon-intensive fossil fuel processes, favouring lower-emission technological alternatives[4].

The sensitivity analysis for the sectors concerned showed that although high CO_2 costs contribute significantly to the competitiveness of electrical technologies, **the ETS alone does not provide a sufficient incentive for technological substitution in all sectors in the medium term**. Indeed, in the reference scenario, the additional ETS costs associated with the use of gas technologies (~€50/tCO_2 in 2035 and €200/tCO_2 in 2050) only represent a maximum of 20-25% of the total costs of thermal processes, calculated over the lifetime of the fossil technologies concerned. This is a significant contribution to the competitiveness of electricity solutions, but not sufficient in sectors where the costs of fossil fuels are the lowest.

The maximum techno-economic electrification potential can therefore only be achieved with public support, particularly in the Blue and Brown scenarios.

4 - However, sectors where there is a risk of carbon leakage (e.g. glass, iron and steel) benefit from free allocations on the EU ETS market and are not, at present, fully impacted by the price of CO_2, which limits the scope of the mechanism. The risk of "carbon leakage" is the risk that a company will relocate its production operations to avoid the costs associated with climate policies. This risk is higher in energy-intensive industrial sectors. The list of sectors at risk of carbon leakage is drawn up by the European Commission.



69 TWh
Maximum techno-economic electrification potential (**29%**)

PROPORTION OF ELECTRIFICATION POTENTIAL REQUIRING SPECIFIC PUBLIC SUPPORT (HATCHED), FOR THE GREEN, BLUE AND BROWN ECONOMIC SCENARIOS

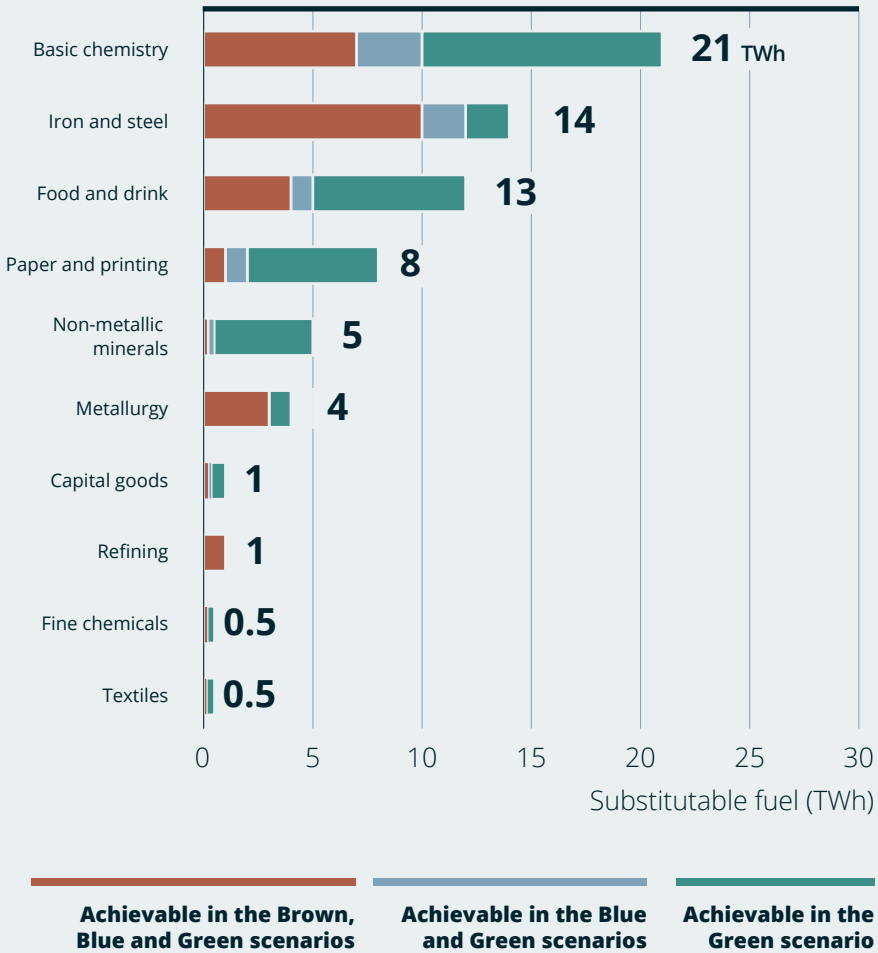
FIGURE 3

This support could take several forms, depending on the sector and the type of technology:

- Investment aid to offset CAPEX costs, which are sometimes higher for electrical equipment than for gas-fired equipment.
- Operating aid to address the challenges of unpredictable fluctuations in gas and electricity market prices (coverage of OPEX linked to energy expenditure for these technologies)
- This aid could be concentrated in sectors where the need for subsidies to achieve a high proportion of the maximum potential is greatest.
  Thus, **Figure 4** shows that in the reference scenario (Blue), for the non-metallic minerals, food and drink and paper sectors, more than two-thirds of the maximum potential cannot be electrified without public support. In the chemicals sector, half of the maximum potential cannot be achieved without subsidies.

FIGURE 4

AMOUNT OF FUEL THAT CAN BE SUBSTITUTED IN EACH SECTOR IN THE DIFFERENT ENERGY PRICE SCENARIOS



INDUSTRIAL ELECTRIFICATION CAN BE ACCOMMODATED BY 2035 WITHOUT OPERATIONAL DIFFICULTIES FOR THE FRENCH ELECTRICITY NETWORK, PROVIDED THAT INVESTMENT IS MADE IN THE NETWORK

By 2035, the French electricity network should be able to accommodate industrial electrification thanks to surplus generation (~150 TWh surplus in the reference scenarios) and the preservation of a majority share of controllable capacity. A more detailed study at hourly intervals has yet to be carried out by RTE[5].

This conclusion is confirmed by a comparison with two new uses with a similar order of magnitude of consumption, whose integration by 2035 has been studied in detail by RTE: electric vehicles and hydrogen production. On the basis of these two case studies, **we can estimate that industrial electrification of an order of magnitude of 25-50 TWh could be accommodated without operational difficulties for the electricity network**, both from the point of view of power demand and security of supply. The flexibility of certain industrial processes, as well as the stable and predictable nature of industrial electricity consumption, are factors that favour integration into the electricity grid.

5 - The analysis work for this report was carried out before RTE published its "Futurs énergétiques 2050" (Energy Futures 2050) report.

However, certain risk factors could limit the feasibility of electrification from the point of view of the electricity network: a very sharp increase in electricity consumption linked to new uses, combined with more limited development of demand-side flexibility than that forecast in the public objectives (4.5 GW in 2023 and 6.5 GW in 2028) and an unsuitable level of investment in the network could limit the possibilities of industrial electrification.

ELECTRIFICATION LEADS TO POSITIVE EXTERNALITIES IN TERMS OF CO_2 EMISSIONS AND JOB CREATION IN THE ELECTRICITY SECTOR

In 2019, the industrial sectors studied here[6] emitted a combined total of 80 Mt of $CO_{2\ eq}$, or 18% of the 440 Mt of $CO_{2\ eq}$ emitted in France. Industrial GHG emissions are on a downward trend, with a 46% reduction in 2019 compared with their 1990 level[7]. This drop in GHG emissions is due, among other things, to the fall in industrial production, energy efficiency efforts and the lower carbon content of the energy fuels used [4].

In the study's reference scenario (the Blue scenario), electrifying 15% of thermal processes by 2035 **generates a reduction in annual emissions of 10.5 Mt CO_2 compared with the 80 Mt CO_2 emitted in total by industry in 2019, i.e. a 13% reduction** (including emissions linked to the additional production of electricity). 70% of the emission reductions are concentrated in three sectors: chemicals, iron and steel and food and drink. Electrification could thus contribute to the SNBC's objective of reducing industrial emissions by 35% by 2030. However, other decarbonisation solutions will have to be implemented to achieve the SNBC targets and cover the remaining emissions that electrification alone will not be able to eliminate.

In addition, industrial electrification could help to create jobs in the French electricity sector, particularly through the extra demand it would generate for the electricity system and the increased demand for equipment manufacturers and installers of electrical solutions. The French Electricity Union (*Union Française de l'Electricité* – UFE) has estimated that the objectives of the SNBC and the Multi-Annual Energy Plan (*Programme Pluriannuelle de l'Energie* – PPE) **could create 13,000 jobs in the industry (manufacturing, distribution and maintenance of electrical equipment) by 2030**. As the electrification scenarios for 2035 presented in this study of electrification potential are more ambitious than those of the public authorities, the number of jobs created in the electrical sector as a result of electrification could be greater than that estimated by the UFE.

However, these new jobs must be considered in the context of job losses in other sectors, particularly gas. Some of the jobs linked to gas consumption in France, particularly in the operation of gas infrastructure, would be threatened by a fall in demand due to industrial electrification. In addition, the jobs of gas equipment manufacturers, installers and maintainers could also be jeopardised by a drop in demand for gas-related services. To provide figures for this analysis, an ad hoc study could be carried out to estimate the net job creation resulting from the electrification of industry.

6 - The sectors studied here are: iron and steel, basic chemicals, non-metallic minerals, food and drink, paper and printing, metallurgy, capital goods, fine chemicals, refining and textiles.

7 - This is a reduction in CO_2 eq and therefore takes all GHGs into account. Most of the fall in GHG emissions since 1990 can be attributed to the regulation of N_2O emissions from the late 1990s to 2007, as well as a fall in production volumes.

Prospects for the electrification of industry

1

Electrification is a credible route to decarbonisation, and could make it possible to reduce French direct industrial CO_2 emissions by 14% by 2035 in the reference scenario (Blue scenario) and by up to 21% if the estimated maximum potential is achieved. Electrification is therefore an essential solution for industrial decarbonisation, but is not sufficient on its own if France is to achieve the SNBC target of a 35% reduction in industrial CO_2 emissions by 2030. To identify the most appropriate low-carbon solution for a specific industrial site, a techno-economic analysis must be carried out at process level. At an overall level, the decarbonisation of industry can only be achieved through a varied mix of low-carbon energy solutions. Indeed, the long-term reduction objectives for industrial emissions can only be achieved if electrification is implemented in conjunction with energy efficiency efforts and the use of other low-carbon fuels.

2

There is considerable potential for electrification in a number of industrial sectors. Electrification is particularly promising in low-temperature sectors with high fluid heating (steam) or drying requirements, such as paper, food and drink, and chemicals. There is also significant potential in the iron and steel industry, despite the profound change of model that would need to be implemented in order to electrify this sector. Together, these four sectors represent 80% of the total maximum electrification potential. If maximum electrification is achieved, the share of electricity in the energy consumption of industrial thermal processes, which currently stands at 7%, could be multiplied by up to 4x by 2035, to reach 27%.
This degree of electrification requires investments of up to €6 billion in resistance heating and heat pump installations by 2035.

3

Decarbonisation through electrification is made possible here by the long-term price conditions anticipated in the study scenarios, which reduce the competitive gap between electricity and gas in favour of electricity. These conditions make it economically feasible to achieve between 41% and 100% of the maximum techno-economic potential of 69 TWh in annual consumption by 2035, depending on the scenario studied. The lack of visibility on long-term prices and market

fluctuations mean that the full electrification potential cannot be achieved in two of the three scenarios.[8] To achieve the long-term objectives set out in the SNBC (70% electrification by 2050), **support from public authorities is needed to kick-start industrial transformation**. If the conditions forecast in the study are met, and particularly if CO_2 prices are high, electricity should become more competitive with fossil fuels, thereby facilitating electrification and reducing the need for targeted public support. More generally, a high CO_2 price would support all decarbonisation solutions.

4

In light of the electrification potential identified, the target set out in the government's roadmap – which envisages an industrial electrification rate of 41% by 2030 – could be revised upwards to 45% or 50%. Indeed, in its reference scenario, the SNBC envisages a rate of industrial electrification in final energy consumption of 41% in 2030 and 70% in 2050, compared with 39% in 2019[9].

If the results of PEP 2 are applied to the same scope as the SNBC, the share of electrification could reach between 43% (Brown scenario) and 51% (Green scenario) of final industrial consumption by 2035 in the scenarios presented in the study. **This result illustrates the possibility of faster electrification than that envisaged in the public authorities' low-carbon roadmap.**

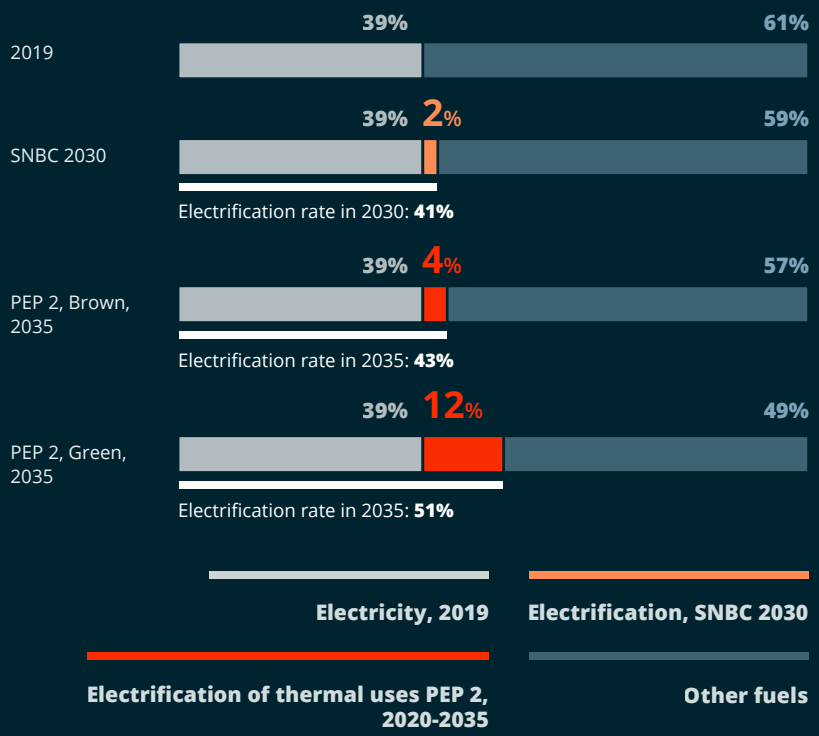
5

More than 50% of the potential for electrifying industrial thermal processes lies in the large-scale deployment of technologies based on electrical resistors

for high-temperature processes, for example in the chemicals and non-metallic minerals sectors. The investment cost of resistive technologies is low, but their operating cost is high due to the lower energy efficiency of these technologies compared with other electrical solutions. **Despite its low efficiency, resistive heating is, and will remain, the main mature technology that can be deployed on a large scale, and is essential for electrifying industrial thermal uses at low and high temperatures (<1000°C).**

FIGURE 5

COMPARISON OF THE SNBC 2030 REFERENCE SCENARIO WITH THE PEP 2 2035 SCENARIOS – % OF FINAL ENERGY CONSUMED BY INDUSTRY [7]



8 - Movements on the wholesale energy markets in the second half of 2021 show that electricity and gas prices are highly volatile and have a major impact on manufacturers.

9 - The scope of the SNBC and the PEP 2 study are not identical: the SNBC excludes the foundry and refining industries. In the national statistics, these two sectors are conventionally included in the energy transformation sector and are therefore not included in the SNBC reference scenario for industry.

6

The remaining 50% of the electrification potential will have to be realised through more specific technologies that are less easily deployed on a large scale, but which are highly efficient. These technologies include medium-temperature and high-temperature heat pumps (particularly in the food and drink and chemicals sectors) as well as microwave and high-frequency technologies (for drying in the chemicals and paper sectors). The development of these technologies could generate significant final energy savings: up to 75% for high-temperature heat pumps such as those analysed in the PEP 1 study. **If electrification is implemented in conjunction with these efficient technologies, it is possible both to decarbonise industrial thermal uses and to achieve significant energy savings.** Such energy savings are less easily achieved by switching to other low-carbon fuels (hydrogen, biomethane, biomass).

7

Support mechanisms for electrification must be developed in line with the specific characteristics of thermal electric technologies. These mechanisms will have to take several forms depending on the sectors and technologies targeted:

- Aid to finance installation or upstream technical studies on decarbonisation (CAPEX). This type of installation aid could be introduced for specific technologies with particularly high CAPEX costs (for example, to finance heat pumps replacing immersed tube burners).

- OPEX assistance in the form of operational support or energy tax exemptions aimed at reducing energy costs. This aid could be directed towards technologies that are less expensive to install but have higher operating costs (for example, to finance resistors to replace immersed tube burners).

More specifically, these support mechanisms could be targeted at sectors that most need public aid to achieve their maximum electrification potential, such as the iron and steel, non-metallic minerals, food and drink and paper sectors.

8

Electrification is not suited to the constraints of certain very high-temperature processes (>1000°C). Electrification will not be the main route to decarbonisation in several heat-intensive sectors (cement, brick and tiles) where electrical solutions face numerous operational constraints: changes in production quality, loss of a source of recoverable waste heat, etc. Decarbonisation paths that are closer to current operating methods could therefore be better suited to industrial decarbonisation in these sectors.

Methodology

1.

Calculation of the maximum techno-economic potential for 2035

The aim of phase 1 is to estimate the maximum techno-economic potential for electrifying industrial thermal processes by 2035. The potential here corresponds to the proportion of non-electric fuel consumption (gas and coal) in 2019 that could be electrified by 2035. The calculation takes into account the existence and level of maturity of electric technologies, technical feasibility, operational constraints and competition with other decarbonisation options.

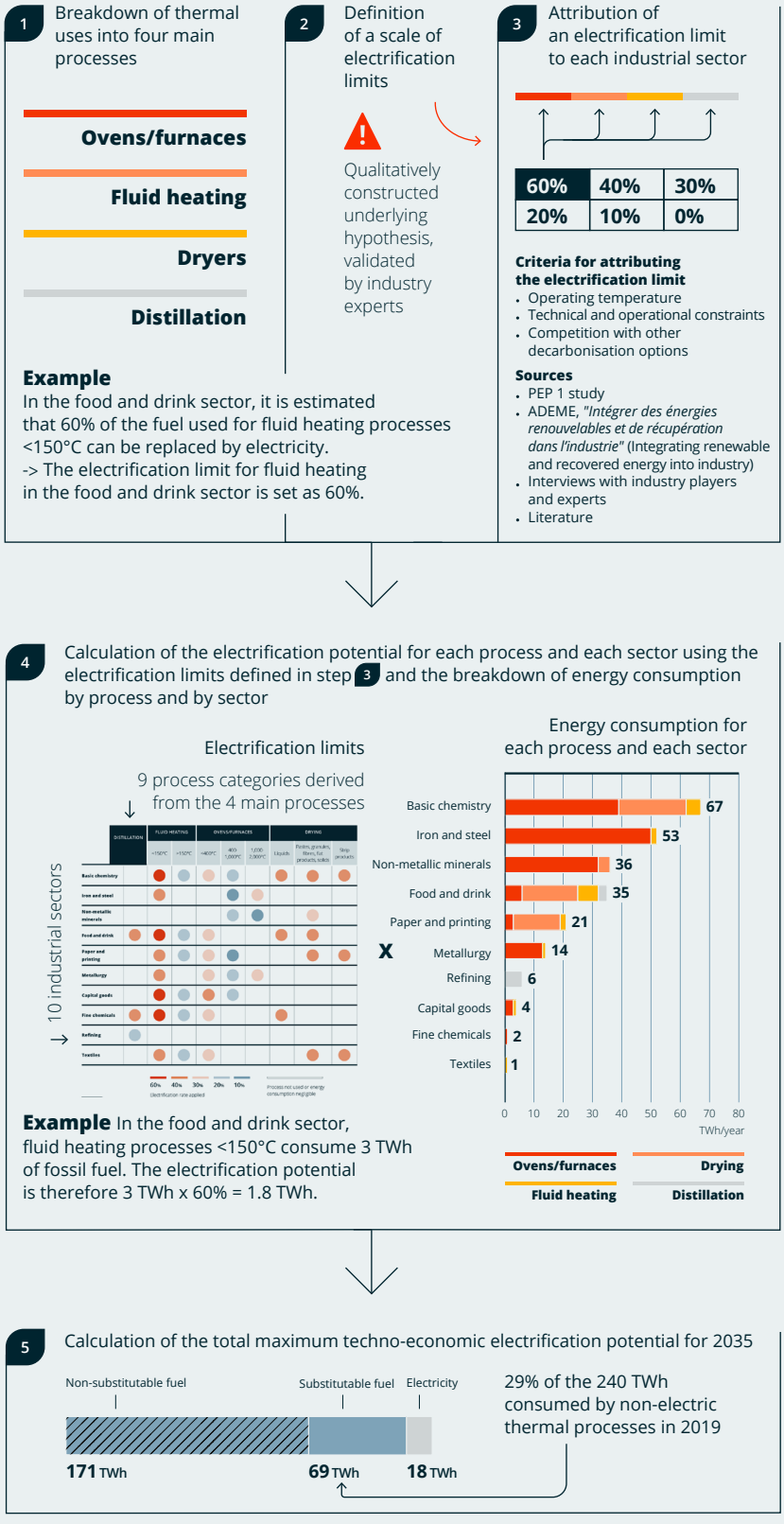


FIGURE 6

METHODOLOGY FOR CALCULATING THE MAXIMUM TECHNO-ECONOMIC POTENTIAL OF PART 1

2.

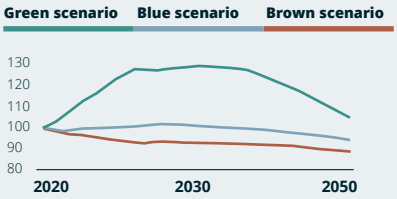
Assessing the impact of market prices on electrification potential, in 3 scenarios

The second part of the study explores the competitiveness of the electrification of industrial thermal uses compared with the main fossil fuel technologies used today, in particular natural gas. The share of the techno-economic potential that is accessible in terms of competitiveness is estimated for three long-term energy price scenarios.

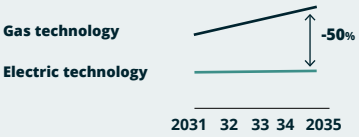
FIGURE 7

METHODOLOGY FOR CALCULATING THE ELECTRIFICATION POTENTIAL IN EACH SCENARIO IN PART 2

6 Use of three long-term energy price scenarios (electricity, coal, gas) based on data from Enerdata (2040), extrapolated by Enea (2050)



7 Calculation of the gap in competitiveness between gas and electric technologies in 2035 for each scenario



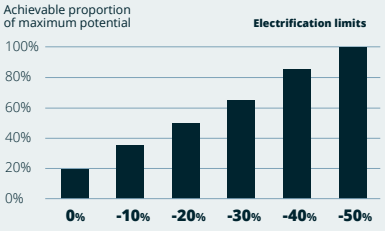
The PEP 1 study was the main source for the technical and economic data

Example
For low-temperature furnaces, in the Blue scenario, the cost of an electric furnace in 2035 is €550/MWh and the cost of a gas furnace is €1056/MWh. The gap in competitiveness is 47.9%.

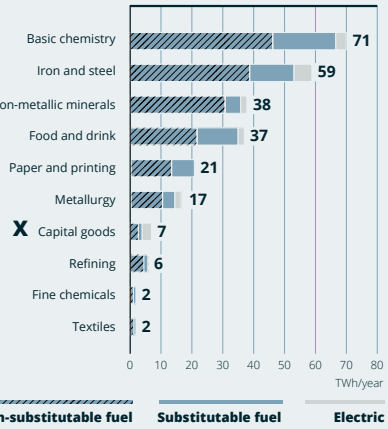
8 Use of the competitiveness gap to determine the achievable proportion of the maximum techno-economic electrification potential calculated in step 5

Scale for determining the achievable portion of the maximum potential, based on the gap in competitiveness

Empirically constructed underlying hypothesis, validated by industry experts

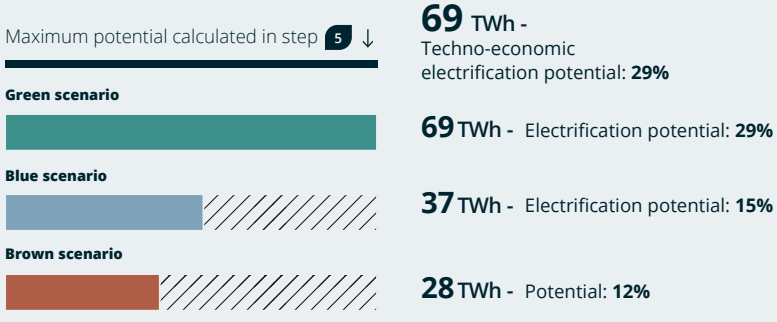


Maximum techno-economic potential for each of the 10 industrial sectors studied



Example
For low-temperature furnaces, the gap in competitiveness is 47.9%, which corresponds to an electrification limit of 85%. Thus, across all sectors, in the Blue scenario, the electrification potential for low-temperature furnaces is 85% of the maximum electrification potential calculated for low-temperature furnaces in each sector in step 4

9 Calculation of the total electrification potential for each energy price scenario



Limitations of the study
The conclusions of this study are based on broad hypotheses and simplifications that make it possible to carry out an analysis at national level. However, it is important to identify and highlight the limitations of the study and the additional research that needs to be carried out to expand on these initial results.

- The maximum techno-economic potential for overall electrification was obtained on the basis of electrification hypotheses for each industrial sector. However, there may be many disparities within the same sector, between different sectors or sub-sectors, and between industrial sites. **A more in-depth analysis could therefore take a sectoral approach and study the maximum electrification potential of a given sector**, in order to take account of all the specific features of the sector and deliver more precise results.

- The analysis of the competitiveness of thermal solutions (both fossil-fired and electric) is based on energy cost projections derived from the Enerdata scenarios used for modelling. These scenarios range from an ambitious projection for the increase in gas prices (Green scenario) to a slight change in prices (Brown scenario). The study assumes an EU ETS carbon allowance price of €200/t in 2050 [15]. **These scenarios lead to results that are generally favourable to electrification. The outlook for changes in energy and CO_2 prices could be the subject of a separate economic study.**

- The full costs of heat production were determined on the basis of technical operating data and economic data on installation and maintenance costs, taken from the PEP 1 study. For each technology, an average value was used for installation and operating costs. However, for technologies that are less widespread in industry today (heat pumps, microwaves), these costs can vary greatly depending on the capacity installed, the temperature range reached, etc. **It might therefore be worthwhile calculating the full costs in more detail, using price ranges for all these technologies, to obtain a framework for calculating the potential in each scenario.**

- Part 2.3 of the study determines the proportion of the maximum potential that can be achieved for each energy cost scenario. This achievable share is estimated for each thermal process and then extrapolated to all industrial sectors, for the same thermal process. This means that the calculations of potential for each scenario are based on the same energy cost in every industrial sector. However, energy costs can vary greatly from one sector to another and from one industry to another, depending on the energy consumption profile. **A more detailed analysis could take into account this variation in energy prices depending on profile.**

- Electrification could have an impact on the local electricity network, particularly in certain industrialised regions where the network is not very robust. **An analysis of the geographical distribution of industrial players should be carried out to identify the geographical areas most exposed to grid constraints, which could potentially limit the electrification capacity of certain industrial zones.**

- This study analyses the competitiveness of electricity compared with fossil fuels, but does not include other decarbonisation solutions (biomass, biogas, hydrogen, geothermal energy, etc.) in the comparison. **A more detailed analysis could include these other options in order to identify more precisely the share of electricity in the energy mix of industrial thermal processes in 2035.**

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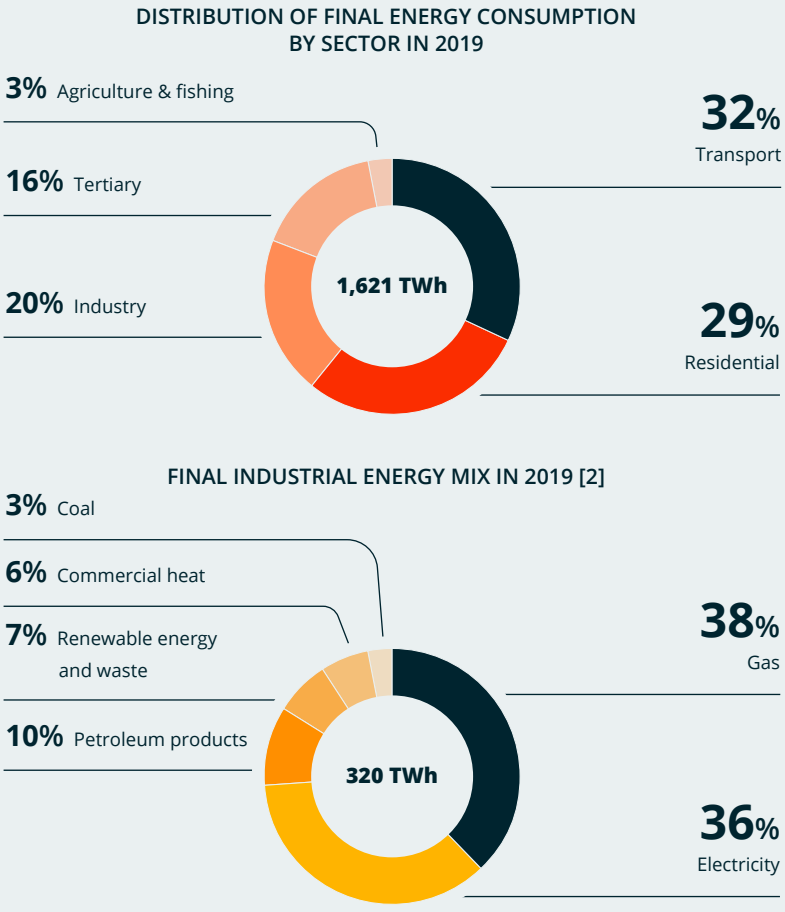
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Introduction and background

Thermal uses, which are still only slightly decarbonised, account for a major share of energy consumption in industry

FIGURE 8



Industry is a major consumer of energy in France, with a final consumption in 2019 of 320 TWh, i.e. 20% of the final energy consumed in France in 2019[10]. If the smelting[11] and refining industries are included, these figures increase to **373 TWh and 23%** respectively [2].

Industrial energy consumption has fluctuated in recent times: it peaked in 2001 at 391 TWh (511 TWh including the smelting and refining industries), before falling sharply following the 2008-2009 crisis, and then declining slightly from 2011 to the present day [2].

The final industrial energy mix in 2019 was dominated by electricity (36%) and natural gas (38%), supplemented by petroleum products (10%), renewable energies such as biomass and waste (7%), commercial heat (6%) and coal (3%)[12].

10 - Raw materials excluded – industrial energy consumption figures may vary depending on the source and some include raw materials (e.g. ADEME "*Climat air et énergie*" 2018, CEREN 2016).

11 - In France, most of the energy consumed in the smelting industry is attributable to steelmaking using blast furnaces. Hereafter, the term "smelting industry" refers to smelting processes across all metal sectors. In this study, "iron and steel" includes the steelmaking part of the smelting industry, and "metallurgy" includes the other sectors of the smelting industry.

12 - Unless otherwise stated, the figures presented in this introduction do not include the consumption of the smelting industry (essentially relies on coal) or the refining industry, which are conventionally included in the energy conversion sector in national statistics. However, in the rest of the study, this sector is taken into account in the calculation of electrification potential.

Coal's share rises to 15% if the smelting and refining industries are included. Consumption of coal and petroleum products in industry has fallen sharply since 1990 (-68% and -63%), leading gas and electricity to play an increasing role in the mix [2].

As a result of the large volumes of fossil energy consumed, **industry is one of the main GHG emitting sectors**, responsible in 2019 for the emission of 80 Mt $CO_{2\ eq}$ (including the smelting industry), i.e. **18% of the 440 Mt $CO_{2\ eq}$** emitted in France [4].

The French public authorities are committed to reducing industrial emissions through European and national targets. In particular, **the National Low Carbon Strategy (SNBC) introduced in 2015 and revised in 2020 aims to reduce emissions from the sector by 35% by 2030 compared with 2015** and by 81% by 2050, defining the trajectory needed to achieve France's long-term objective of carbon neutrality by 2050 [7].

A major part of industrial energy consumption (258 TWh or 69% in 2014[13]) is due to thermal processes, i.e. industrial processes that require the production of heat. Thermal processes are present in almost all industrial sectors and in many forms: chemicals (steam production, distillation), food and drink (pasteurisation, vacuum evaporation), metallurgy (heat treatment), glass (firing), brick and tiles (drying), etc. The vast majority are powered by fossil fuels, in particular natural gas and coal.

The transition to a near-zero-carbon industry by 2050 will require energy efficiency efforts and the development of CO_2 capture technologies **as well as decarbonisation actions through changes in energy sources for thermal processes**.

Electrification is one of the ways of decarbonising industrial thermal uses in France

Several "low-carbon" fuels can play a role in reducing emissions from thermal processes, such as biogas, biomass, hydrogen (H_2), solid recovered fuels (SRF) **and electricity, which is the subject of this study**. A fuel is described here as "low-carbon" if it emits **significantly less CO_2 over its entire life cycle than traditional fossil fuels such as gas and coal[14]**.

France's electricity mix is one of the most carbon-free in Europe, with 52 gCO_2/kWh compared with an average of 275 gCO_2/kWh for the European Union (EU) in 2018[15] [5]. **The electrification of thermal processes therefore appears to be a particularly relevant way of decarbonising industry.** The SNBC has identified this opportunity, and its decarbonisation strategy is based on "significant electrification of the industrial sector", presenting a reference scenario with an industrial electrification rate[16] of 41% in 2030 and 70% in 2050, compared with 39% in 2019[17]. **Thermal processes account for the majority of the remaining processes that need to be electrified to achieve this objective.**

Despite the objectives set out in the government's roadmap, **until 2020 there was no specific support mechanism for the electrification of industrial processes in France**. In autumn 2020, as part of the **"France Relance" recovery plan**, ADEME launched a Call for Expressions of Interest to identify mature projects aimed at decarbonising industry (including via electrification), followed in 2021-2022 by several Calls for Projects, including one open to process electrification projects, with €1.2 billion financed by the public authorities.

13 - CEREN data. For the sectors included in the study, including steelmaking via blast furnaces and refining, but excluding construction. See Part 1.1.

14 - For example, H_2 and electricity can be described as "low-carbon" if they are produced using low-emission methods (renewable or nuclear for electricity; green electrolysis or reforming with CO_2 capture for H_2, etc.). In addition, biogas, biomethane and biomass are considered low-carbon because of their low CO_2 footprint over their entire life cycle.

15 - Data from the European Environment Agency. According to data from the ADEME carbon database for 2018: 57 g CO_2/kWh for the average mix, 39 g CO_2/kWh on average for "basic industry" uses.

16 - The electrification rate is the proportion of final energy consumption that is electric.

17 - The targets set out in the SNBC do not include steelmaking via blast furnaces and refining, but do include the construction sector.

The aim of this study is to estimate the potential for electrification of industrial thermal processes in France, to identify the impact of changes in energy prices, and to assess the feasibility and external impacts of electrification

In line with its activity of supporting innovation and energy efficiency in industry, **ALLICE wanted to inform its members about the electrification potential of different industrial thermal processes and the competitiveness of the electrical solutions that exist in the various sectors**.

The *Centre Technique des Industries Aérauliques et Thermiques* (CETIAT) and the *Centre Technique des Industries Mécaniques* (CETIM) carried out an initial study on the electrification potential of thermal processes on behalf of ALLICE (hereinafter referred to as the "PEP 1 study") [1].
This study analysed the technical, economic and operational feasibility of switching to electric power at the scale of an industrial site, and identified areas for innovation in electrification.

In addition to the PEP 1 study, ALLICE commissioned Enea Consulting to carry out a second study (hereafter referred to as the "PEP 2 study").

This report summarises the PEP 2 study. A more complete report detailing the hypotheses, results and methodological challenges of the study is available to ALLICE members. **The objective of the PEP 2 study was to extend the scope of the PEP 1 study to national level in order to provide an overview of the potential for electrification in various industrial sectors between now and 2035** and present a critical analysis of the underlying trends in electrification, in particular in relation to the long-term dynamics of energy markets.

The study has three parts:

1

Calculation of the maximum techno-economic potential for the electrification of industrial processes in France by 2035;

2

Assessment of the impact of long-term changes in the market prices of energy and CO_2 on electrification potential, for 3 price scenarios;

3

Analysis of the feasibility of industrial electrification from the point of view of the electricity grid in mainland France and the positive externalities for the country (job creation and reduction of CO_2 emissions);

The methodology is based in particular on the use of the technical and economic results of the PEP 1 study to estimate the national electrification potential, and on analyses of the competitiveness of several electric and fossil-fired thermal solutions based on **the long-term energy price scenarios of the economic research firm Enerdata**.

The study also aims to open a discussion on the limits of electrification and on low-carbon alternative fuels (biogas, biomass, SRF), which will play an essential role in decarbonising non-electrifiable processes. However, no competitive analysis comparing thermal electric solutions with low-carbon alternatives was carried out as part of this study.
To complete the work presented here, the possibilities offered by the use of green gases in industry are examined in an ALLICE study published in 2022.

Part 1

Calculation of the maximum techno-economic potential for electrification by 2035

1.1

P.23 Thermal uses account for a significant proportion of energy consumption in France and can be broken down into four main processes

1.2

P.26 The electrification hypotheses reflect the constraints of thermal processes: low-temperature applications are easier to electrify

1.3

P.30 Conclusions after analysing the maximum techno-economic potential for electrification: 29% of the consumption of fossil thermal processes in 2019 can be electrified

1.1

Thermal uses account for a significant proportion of energy consumption in France and can be broken down into four main processes

ENERGY CONSUMPTION FOR THERMAL USES ACCOUNTS FOR A MAJOR PROPORTION OF INDUSTRIAL ENERGY USE

In industry, **thermal uses are all transformations requiring an input of energy in the form of heat**. These include cooking, water evaporation, metalworking and heat treatment of materials.

The main energy sources for industrial heat production are natural gas, coal, petroleum products (fuel oil), biomass and electricity, which is the focus of this study. Non-electrified thermal processes account for the majority of final industrial thermal energy consumption (93%). More generally, they account for a significant proportion of France's total energy consumption: **15% of final energy consumption in France [3].**

18 -The national and sectoral (industry) data is taken from the "Bilan Energétique de la France 2019" (Energy Balance in France in 2019) published by the French Ministry for Ecological Transition. Data on the energy consumption of thermal process comes from CEREN (2020) statistics for 2014.

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

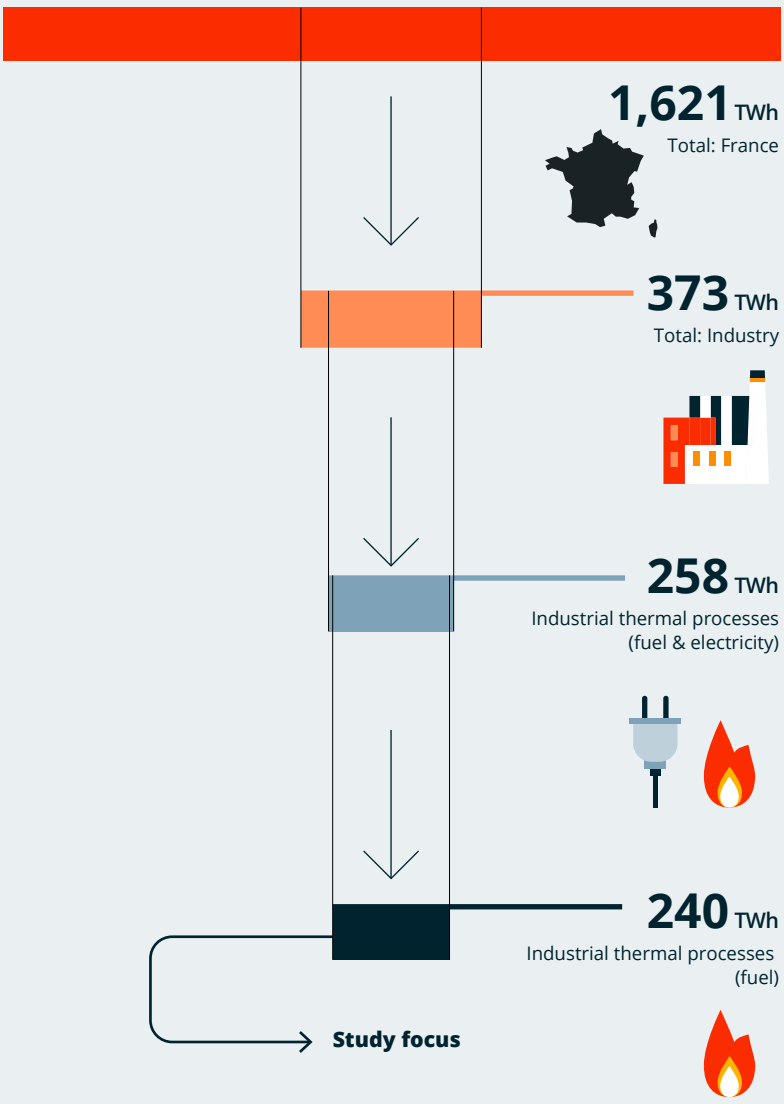


FIGURE 9

Four sectors account for 80% of the energy consumed by thermal processes: basic chemicals, iron and steel, non-metallic minerals and the food and drink industry[19].

The share of electricity in industrial heat production is low, representing less than 10% of the final energy consumption of thermal processes. Most industrial heat is produced from natural gas, which accounts for 67% of the fossil fuels used [8].[20]

INDUSTRIAL THERMAL USES INVOLVE FOUR MAIN PROCESSES

Industrial sectors use a wide variety of thermal processes. In its annual "Climate, Air and Energy" report [9], **ADEME distinguishes between four categories of fuel consumption in industry for heat production: furnaces, drying, heating of liquids and gases, and distillation.**

Ovens and furnaces

This category covers all processes that increase the temperature of a product in a closed enclosure. At lower temperatures, this may involve cooking food in the food industry, or at higher temperatures, heating metal parts in the capital goods sector. Above 1,000°C, the furnace category includes metalworking processes, the firing of bricks and tiles, and the primary transformation of glass.

CONSUMPTION OF THERMAL PROCESSES BY INDUSTRIAL SECTOR [3]

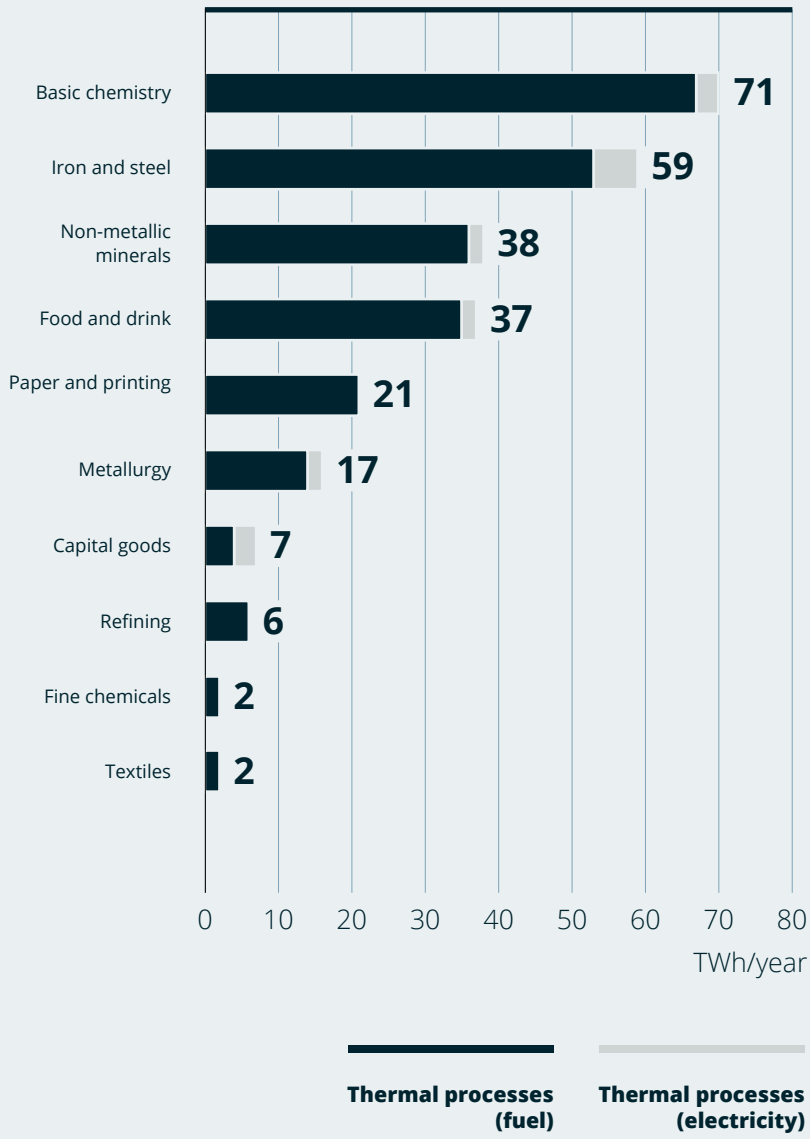


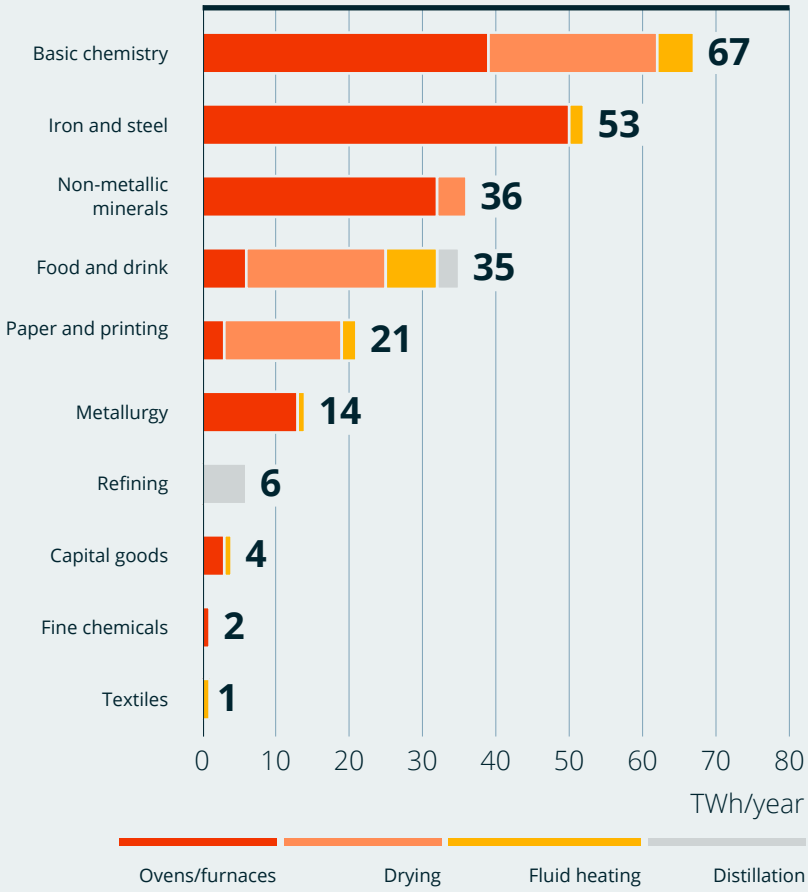
FIGURE 10

19 -See **Appendix 2** for details of the sectors studied.

20 -As electric heat production technologies generally have better energy efficiency factors than fossil fuel technologies, the share of electricity shown in **Figure 1** is not necessarily representative of the breakdown of production methods. By way of comparison, in the residential sector, 37% of households were heated using electric energy in France in 2018, while electric energy consumption accounted for only 12% of residential heating.

FIGURE 11

BREAKDOWN OF ANNUAL ENERGY CONSUMPTION OF NON-ELECTRIFIED THERMAL USES BY TYPE OF PROCESS AND BY INDUSTRIAL SECTOR (CEREN DATA FOR 2014)[22] [3]



Fluid heating

This category covers the heating of a fluid (e.g. water, oil) for use as a heat carrier. A distinction can be made between heating to temperatures <150°C for hot water and low-temperature steam applications and heating to temperatures >150°C for high-temperature steam applications[21]. These include, for example, hot water pasteurisation processes used in the food industry.

Drying

These are water evaporation operations designed to reduce the mass of water in a solid or liquid. These processes generally require temperatures below 200°C. Drying processes can be categorised by product type: liquids, pastes, fibres, webs, solids, granular and flat products. Drying processes are mainly used in the food and drink, chemicals and paper sectors.

Distillation

These are operations involving the separation of the components of a liquid mixture by evaporation, and generally take place between 100 and 500°C. This type of process is mainly used in three sectors: food and drink (e.g. alcohol production), fine chemicals (e.g. essential oils) and oil refining.

Furnaces account for the largest share of energy consumption (61%), concentrated in the iron and steel, non-metallic minerals and chemicals industries.

The electrification potential of furnaces will therefore have a major influence on the overall electrification potential of thermal processes.

Operating conditions and temperatures vary significantly between processes. As mentioned above, fluid heating processes can be carried out at temperatures below 100°C, while industrial furnace temperatures can sometimes exceed 1,000°C. For drying, it is the type of product to be dried that will determine the operating conditions, and therefore the technology to be used.

21 - This temperature breakdown was chosen for technological reasons, which are described in the PEP 1 study.

22 - This data comes mainly from the CEREN report "*Première analyse du potentiel technique d'électrification des procédés industriels thermiques par des technologies matures*" (2020) (Initial analysis of the technical potential for electrifying thermal industrial processes using mature technologies), combined with several other sources.

1.2 The electrification hypotheses reflect the constraints of thermal processes: low-temperature applications are easier to electrify

CALCULATION OBJECTIVE AND METHODOLOGY: estimation of maximum techno-economic potential based on hypotheses about the potential for electrification of thermal processes

This study assesses the techno-economic electrification potential of thermal uses in French industry by 2035. This assessment is based on hypotheses that take into account the technical feasibility of electrification, the existence and maturity of electrical technologies, operational constraints and competition with other existing decarbonisation methods.[23] Taking this competition into account indirectly brings economic considerations into the calculation of the potential.

23 - More details on the methodology are available in the full study report.

24 - Given the very wide diversity of industrial processes, there are still major differences within the categories themselves. To simplify matters for the purposes of this study, each category has been treated in the same way for the purposes of calculating the electrification potential.

CONSTRUCTION OF HYPOTHESES: the electrification hypotheses take into account operating temperatures, specific operational features and the existence of other decarbonisation options

Whether or not it is possible to electrify a thermal use depends on a number of technical parameters, such as the operating temperature required, the rate of temperature rise needed, and the amount of energy consumed. As stated above, for this study, thermal uses are segmented into four main processes. Each of the four categories groups together uses with similar operating and temperature characteristics[24]. In order to take account of the specific features of each operating mode, it is therefore appropriate to estimate electrification potential for each type of industrial process, for each industrial sector. The electrification potential is estimated for each sector for the following process sub-categories in **Figure 12**.

SUB-CATEGORIES OF THERMAL PROCESSES CONSIDERED IN THE STUDY

Ovens/furnaces

<400°C (low-temperature)

400°C-1000°C (high-temperature)

>1000°C

Fluid heating

<150°C

>150°C

Drying

Liquids

Pastes, granules, fibres, flat products, solids

Strip products

Distillation

100-500°C

FIGURE 12

In this study, the term "electrification potential" means the share of the consumption of non-electrified industrial thermal processes in 2020 that can be electrified. The aim is to assess this electrification potential for each process, in each sector. Maximum (60%) and minimum (0%) hypotheses were defined qualitatively, and the intermediate levels were applied by comparing the electrification potential of the processes in relation to each other.

Processes < 1,000°C

Particular attention is paid to the operating temperature of thermal processes, with the observation that low-temperature processes are generally easier to electrify for both technical and operational reasons. In addition to temperature, competition from other decarbonisation options (biomass and biogas in particular) and the operational specificities of certain processes were taken into account[25] [10] [11]. The following underlying hypotheses were constructed qualitatively on the basis of the results of the PEP 1 study, available literature and interviews.

Although validated by industry experts, these hypotheses about electrification potential are not intended to reflect the very wide diversity of situations on industrial sites or replace technical audits of specific industrial processes.

25 - For some of the processes studied in PEP 1, the electrification hypotheses were based on the conclusions of the PEP 1 study. For the other processes, the hypotheses were taken from available literature and from interviews with experts.

Following the technological analyses carried out during the PEP 1 study, a decision was made to distinguish between two categories of low-temperature fluid heating operation: below 150 degrees and above 150 degrees. The technological arguments justifying this categorisation are detailed in the PEP 1 study.

Note
For methodological simplicity, to calculate the electrification potential, it was assumed that **industrial energy consumption will remains constant between now and 2035.**

SCHEMATIC REPRESENTATION OF THE ELECTRIFICATION POTENTIAL CONSIDERED FOR THIS STUDY

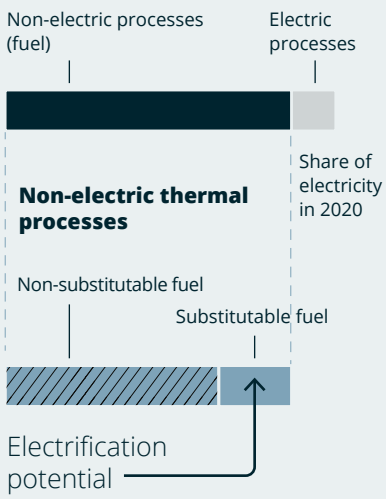


FIGURE 13

TABLE 1 ASSUMED ELECTRIFICATION POTENTIAL BY 2035 FOR DIFFERENT THERMAL PROCESSES [26]

FLUID HEATING	<150°C	Easy to electrify with heat pumps or resistors. In many cases, no particular technical or operational constraints.	**40%**
	>150°C	Gas and biomass are the main fuels used. Electricity could be used for back-up.	**20%**
FURNACES	<400°C	Easily electrified, but less so than fluid heating, because these are often very specific processes where switching to electric would involve more technical constraints.	**30%**
	400°C-1,000°C	Some can be electrified, but manufacturers prefer gas because it sometimes contributes to the quality of the product (convection) and allows a rapid rise in temperature.	**10%**
	>1,000°C	See next section	**N/A**
DRYING	<200°C	Easily electrified using MVR, infrared, microwave, hot air or heat pump technologies for pre-drying.	**40%**
DISTILLATION	100°C - 500°C	Often electrifiable due to low temperatures and low energy levels.	**40%**
Assumed potential			

TABLE 2

ASSUMED ELECTRIFICATION POTENTIAL FOR HIGH-TEMPERATURE PROCESSES AND THE REFINING SECTOR

HIGH-TEMPERATURE PROCESSES		
NON-METALLIC MINERALS FURNACES >1,000°C	**Glass manufacture** Electric furnaces exist, but only on a small scale (<300 tonnes per day); large-scale furnaces are being developed [12]. However, for the production of flat glass, the quality traditionally obtained in a conventional gas furnace is difficult to achieve with an electric furnace.	**10%**
	Cement manufacture No electrical substitution possible to date, but studies are underway (plasma torch).	
	Brick and tile manufacture Electrification is rarely considered because of operational constraints, in particular the reuse of waste heat from the kilns to power the dryers.	
IRON AND STEEL INDUSTRY FURNACES >1,000°C	Two routes for steel production [13]: **Use of blast furnaces** Iron ore is converted into steel by reducing iron oxides in a blast furnace using coal. ____ Stagnation by 2050 (World Steel Association). **Use of electric arc furnaces** Recycling of scrap metal in electric arc furnaces ____ Growth between now and 2050 (World Steel Association). ____ Changes to the supply chain are leading to far-reaching industrial transformation. In addition, other ways of decarbonising blast furnaces are being studied in France (biomass, CO_2 capture, hydrogen).	**30%**
METALLURGY FURNACES >1,000°C	**Electric induction furnaces or resistance furnaces** can be used to reach metal melting temperatures (~700-1500°C).	**30%**
	Significant operational constraints on metallurgical sites, which are also often limited in their investments.	
Assumed potential		

Processes > 1,000°C

As shown in Figure 11, furnaces account for a significant proportion of total energy consumption. Furnaces that operate >1,000°C are particularly energy-intensive, although they are only used in three sectors: iron and steel, metallurgy and non-metallic minerals. The technical specificities of these sectors, as well as those of refining, were analysed separately.

26 - The analysis of each thermal process is based on interviews with industry experts.

REFINING SECTOR		
REFINING DISTILLATION	Operating temperatures low enough to be electrified (400-500°C) [14].	**20%**
	Very few thermal processes in refineries in France are currently electrified.	
	A refinery's main source of energy is flue gas (known as "refinery gas"), which comes from the lighter layers of crude oil. ____ This gives refineries a very low-cost source of energy, meaning a switch to electric power is of little competitive interest.	

MAXIMUM TECHNO-ECONOMIC ELECTRIFICATION POTENTIAL IN 2035 FOR THERMAL USES NOT ELECTRIFIED TODAY, BY PROCESS AND BY INDUSTRIAL SECTOR

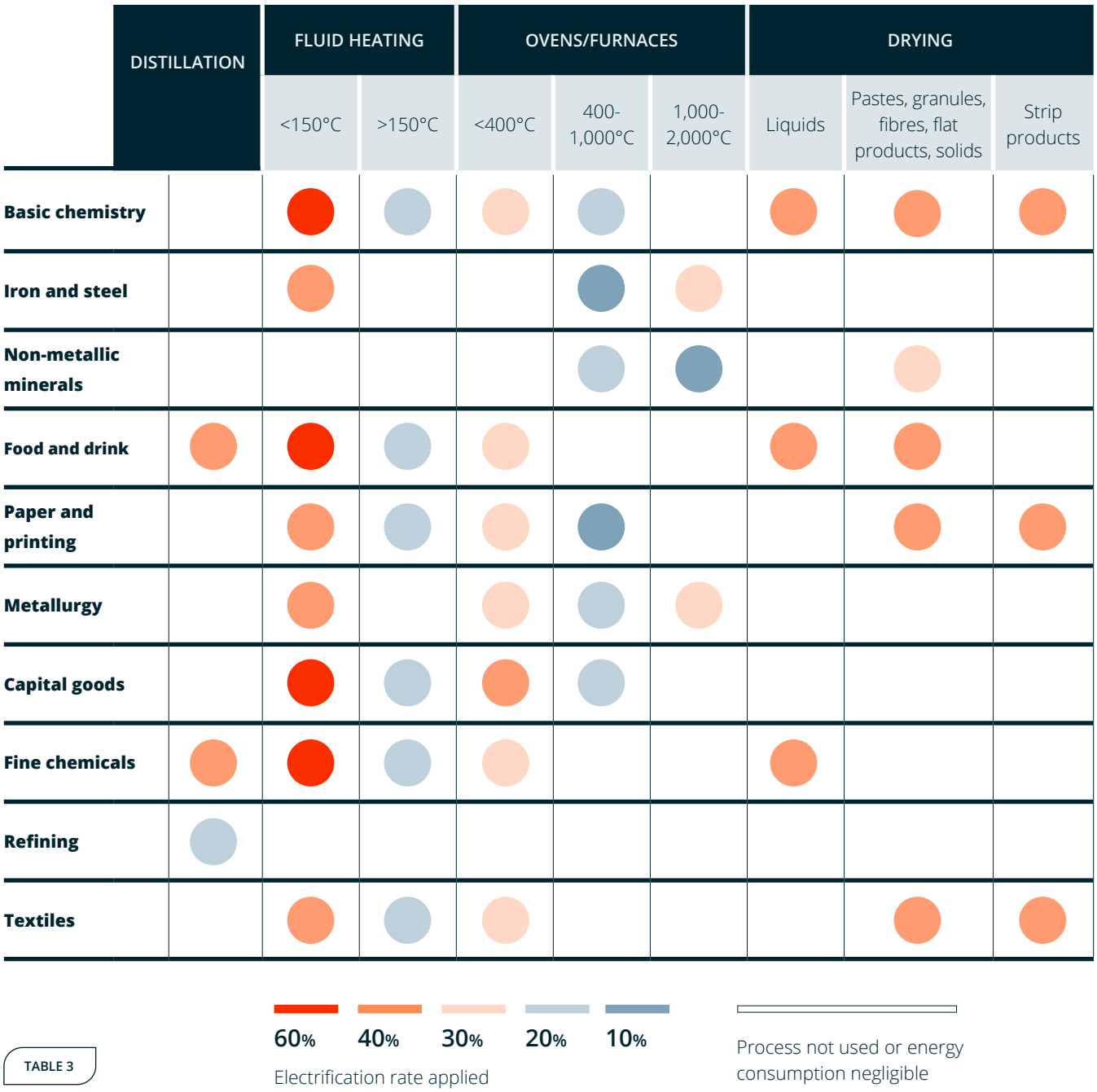


TABLE 3

Based on the above reasoning, a maximum techno-economic electrification potential was obtained for each process in each sector (Table 3).
Drying, heating of fluids and low-temperature furnaces are the easiest processes to electrify.

Based on the evaluation criteria selected, low-temperature processes have a higher overall potential for electrification: drying, fluid heating and low-temperature furnaces[27]. Based on this potential for substitution by electricity, and on energy consumption data (**Figure 11**), the volume of fuel that could be electrified by 2035 was calculated.

27 - Les enjeux d'électrification liés à la distillation étant modérés en quantité d'énergie et en potentiel, aucune analyse technico-économique spécifique des procédés associés ne sera présentée dans la suite de la synthèse.

1.3

Conclusions after analysing the maximum techno-economic potential for electrification: 29% of the consumption of fossil thermal processes in 2019 can be electrified

OF THE 240 TWH OF NON-ELECTRIC THERMAL CONSUMPTION, 69 TWH (29%) COULD BE ELECTRIFIED BY 2035.

The electrification of 69 TWh of fuel leads to additional electricity consumption of 46 TWh. Substituting electricity for fuel reduces the total final consumption of thermal processes by 9%, from 258 TWh to 235 TWh.

The 69 TWh of substitutable fuels are divided between the various sectors, with electrification potential ranging from 15% to 38% per sector. The three sectors with the highest potential for electrification are food and drink (38%), paper and printing (37%) and fine chemicals (35%).

More than 75% of the electrification potential is spread across just four sectors: basic chemicals, iron and steel, food and drink, and paper and printing. The basic chemicals sector accounts for the largest volume of electrifiable energy, with almost a third of the total (21 TWh).

SHARE OF CURRENT FUEL CONSUMPTION THAT COULD BE ELECTRIFIED BY 2035 [28]

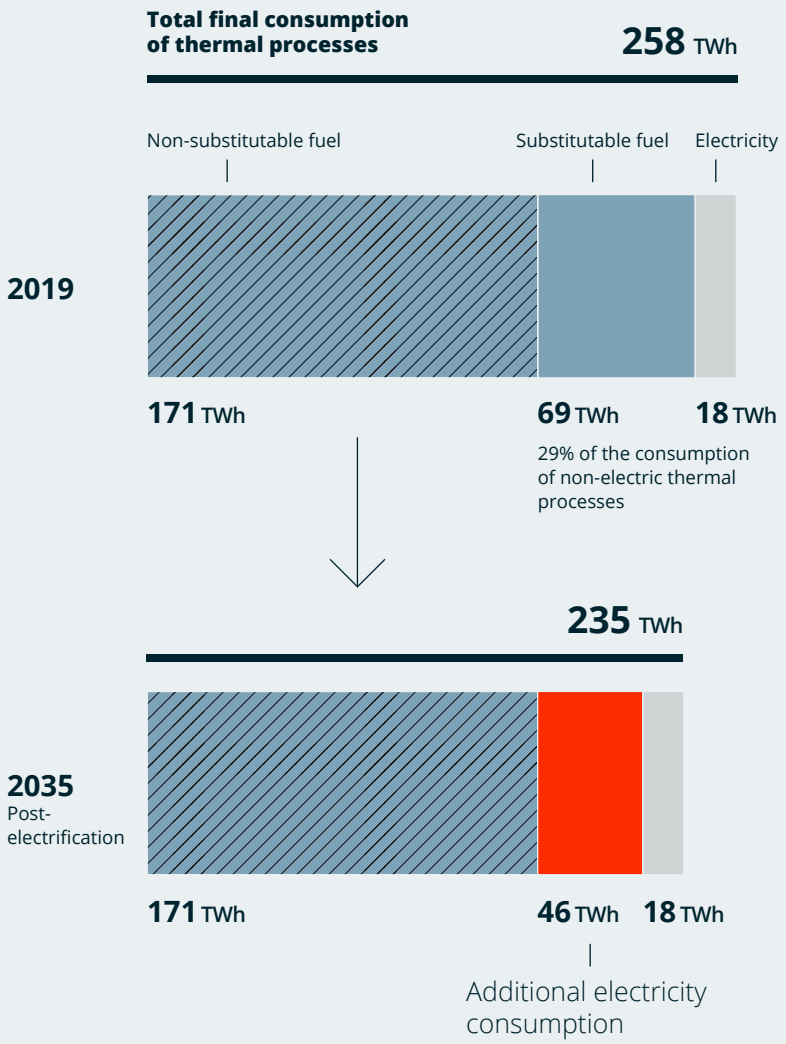


FIGURE 14

28 -The consumption data for 2019 is taken from CEREN (2020) statistics for 2014. For the sake of simplicity, it was assumed that the level of energy consumption of each thermal process was unchanged between 2014 and 2019.

Methodological reminder
The 29% potential is an estimate based on qualitatively constructed hypotheses about the electrification potential of each thermal process. Although reviewed and validated by industry experts during the course of the study, these hypotheses do not constitute predictions for the level of industrial electrification in 2035, and a degree of uncertainty as to the electrification potential remains.

The potential for electrification by 2035 is particularly high in sectors such as food and drink, paper and fine chemicals. Much of the energy demand in these sectors is for drying or fluid heating processes, which have good prospects for electrification. Other low-carbon alternatives such as biomethane, biogas and biomass can be used to produce steam for these processes. **The iron and steel sector also has significant potential for electrification.** However, mass electrification of the iron and steel sector would require a profound transformation of the sector, rather than a simple energy substitution. This is because the electrical route is based on the production of steel from recycled scrap metal, which entails both a change in the supply chain of a site and a change in the composition of the finished products.

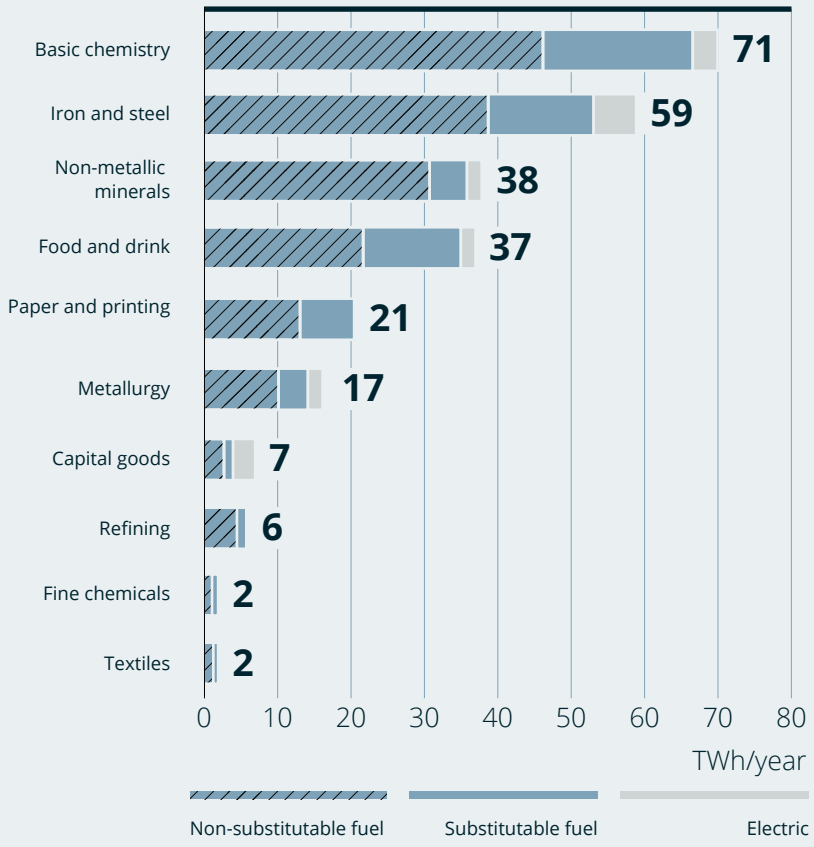
On the other hand, in some sectors, such as metallurgy and non-metallic minerals (in particular glass and cement manufacture), electrification currently seems less feasible for various reasons, and alternative decarbonisation solutions will be required in the medium term. In these sectors, **electrification is limited by the operational constraints involved in switching to an electrical technology**, in particular a change in production quality[29], or the loss of an easily recoverable source of waste heat.

Furthermore, electrical technologies are either immature or non-existent, and the thermal processes generally require high temperatures. **Energy efficiency measures, switching to other low-carbon fuels that are closer to the way current industrial processes operate, and implementing CCUS solutions currently seem to be better suited to the specific features of these sectors.**

29 - For example, some processes require the presence of an open flame, which cannot be obtained if the energy source is electricity (e.g. coffee roasting).

FIGURE 15

BREAKDOWN OF ANNUAL FINAL ENERGY CONSUMPTION OF INDUSTRIAL THERMAL PROCESSES BY SECTOR, SHOWING THE SPLIT BETWEEN SUBSTITUTABLE AND NON-SUBSTITUTABLE FUELS



Part 2

Assessment of the impact of market prices on the potential for electrification by 2035

The aim of this second part is to evaluate the respective operating costs of fossil and electric technologies in order to compare their competitiveness for several processes in 3 main market price scenarios.

2.1

P.34

The competitiveness calculations are based on three scenarios for energy and EU ETS CO_2 quota prices, which favour electricity in the long term

2.2

P.35

Calculating competitiveness: gas technologies are more competitive today than electric technologies, but the trend could be reversed in the long term as market prices evolve

2.3

P.44

Calculation of the competitiveness of the technologies: between 41% and 100% of the maximum techno-economic electrification potential of 69 TWh of substitutable fuel could be achieved in the scenarios used

2.1

The competitiveness calculations are based on three scenarios for energy and EU ETS CO_2 quota prices, which favour electricity in the long term

In order to compare changes in the competitiveness of fossil fuel and electricity technologies, **the impact of several long-term scenarios for energy prices and EU ETS CO_2 quotas were analysed**. The price scenarios extend to 2050.

ENERGY PRICES WERE SIMULATED ACCORDING TO THREE PROSPECTIVE SCENARIOS developed by Enerdata for 2050 and extended to 2060 by Enea

The three scenarios used reflect a range of potential market variations over the long term, depending on changes in regulation, energy consumption and energy supply. They result in very different price levels. The general shapes of the price curves are available in **Appendix 3**.

Blue scenario

The Blue scenario is the median scenario, based on assumptions that are less favourable to electrification than those of the Green scenario, and more favourable than those of the Brown scenario.
In this scenario, electricity prices fall while gas prices rise.
The Blue scenario is considered as **the reference scenario in the rest of the study**;

Green scenario

The Green scenario is the most favourable scenario for electrification, with a sharp increase in fossil fuel prices due to restrictive energy policies, combined with a limited increase in electricity prices. In this scenario, electricity prices stagnate while gas prices rise sharply.
It is important to bear in mind that this scenario presents a particularly ambitious trend for gas prices;

Brown scenario

The Brown scenario is the least favourable to electrification.
In this scenario, electricity prices stagnate but gas prices rise.

In all the scenarios, even the Brown scenario, **the increase in fossil fuel prices is greater than the increase in electricity prices**.

In particular, the characterisation of a scenario as favourable or unfavourable to electrification is made by analysing the evolution of the price differential between electricity and gas, and not the gross value of the price of these energies.

These single energy prices were applied to all industrial sectors, without any specific variations.

CHANGES IN THE PRICE OF EU ETS ALLOWANCES VARY SIGNIFICANTLY IN THE DIFFERENT PROJECTIONS: in the main scenario adopted, the increase in prices does not exceed +20% over the period 2020-2030

The EU ETS is the CO_2 emissions trading scheme in force in 31 European countries (the 27 EU Member States, the UK, Iceland, Norway and Liechtenstein) and applies to the majority of energy-intensive industrial installations in the economies concerned.

The study used EU-ETS CO_2 price projections from three different institutes that propose price trajectories for the period 2020-2030: Energy Aspects, BNEF and ICIS [15]. Enea Consulting extrapolated the price trends over the long term (2050) by extending the trends observed over the period 2025-2030 to forecast CO_2 price values for 2050, thus creating three distinct scenarios. **The following graph shows the reference scenario used in the competitiveness calculations.**

REFERENCE SCENARIO FOR EU-ETS CO_2 PRICES [15]

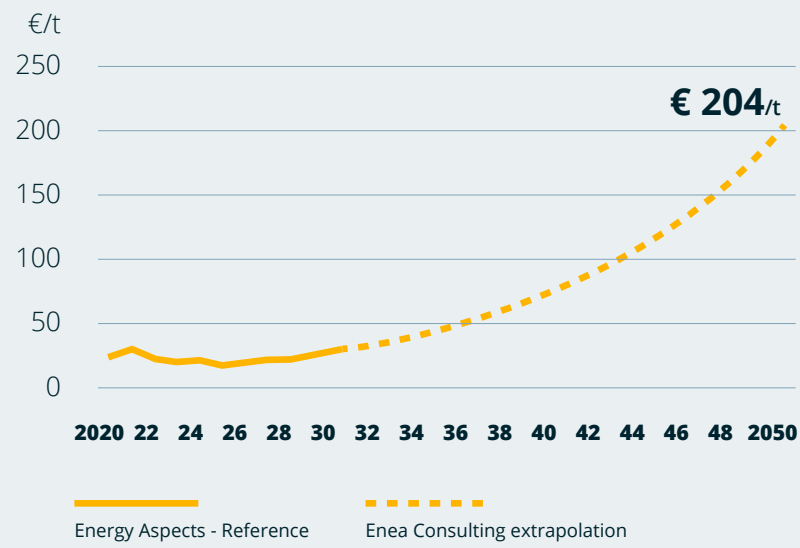


FIGURE 16

2.2

Calculating competitiveness: gas technologies are more competitive today than electric technologies, but the trend could be reversed in the long term as market prices evolve

METHODOLOGY
A competitiveness analysis was carried out for 7 electrical technologies and 5 fossil technologies used in different industrial processes

The full costs of the most common fossil-fired and electric thermal technologies for each process were compared.

The following table shows the electrical and fossil fuel technologies that were compared for each thermal process in this study. This list is not exhaustive and technologies other than those mentioned below may be used to electrify these processes, such as resistors for the primary transformation of glass or induction for high temperature (HT) furnaces in certain sectors. A description of the various electrical technologies studied is given in **Appendix 1**.

SUMMARY OF ELECTRIC AND FOSSIL FUEL TECHNOLOGIES STUDIED FOR EACH THERMAL PROCESS

THERMAL PROCESS	TEMPERATURE OR TYPE OF PRODUCT	INDUSTRIAL SECTOR	ELECTRIC TECHNOLOGIES	FOSSIL TECHNOLOGIES
FLUID HEATING	<150°C	All sectors	Heat pumps	Immersion tube burners [3] (gas) Burners (gas)
			Resistors	
	>150°C	All sectors	Resistors	Steam boilers (gas)
OVENS/FURNACES	<400°C (low-temperature)	All sectors	Resistors	Burners (gas)
	400-1,000°C (high-temperature)	All sectors		
	>1,000°C	Iron and steel	Electric arc furnaces	Blast furnaces (coal)
	>1,000°C	Glass	Conduction	Furnaces (gas)
DRYERS	Liquids	All sectors	MVR [1]	TVR [2] (gas & steam)
	Other solid products	All sectors	Resistors	Burners (gas)
			Microwave heating	
			High-frequency heating	

[1] Mechanical Vapour Recompression [2] Thermal Vapour Recompression [3] Immersion tube burners

TABLE 4

Note

The technical and economic data used for the competitiveness analyses was taken from the PEP 1 study. It was collected through real, specific application cases for given sectors, and is therefore correlated to the specificities of the sectors considered in the PEP 1 study. The PEP 1 study analyses the electrification potential of several specific thermal uses at industrial sites and establishes a "ranking" of the different decarbonisation solutions (energy optimisation, electricity, biomass) according to cost, energy consumption and CO_2 emissions. **A public summary** of the study's conclusions is available.

The methodology of the PEP 2 study transposed these specific cases to national scale. The results presented here do not therefore constitute a detailed analysis of the economic stakes of industrial sites; they are an extrapolation of the analyses in the PEP 1 study.

The aim of the competitiveness calculation was to identify the cheapest technology for a thermal process, in the context of technological replacement for example, taking into account energy and CO_2 price projections over the long term (2060) and without considering public subsidies.

To assess changes in the competitiveness of the technologies, the main indicator used was **the relative difference in full costs compared to thermal technologies**. For a given year n, this is the difference between the full cost of the electric technology and the full cost of the fossil fuel technology, over the entire lifetime of the installation, assuming both technologies were installed in year n.

This full cost calculation was carried out for all the thermal processes listed in Table 4. By way of example, the section below presents the detailed calculations and results for the fluid heating process. This calculation was replicated for all the other processes. The detailed hypotheses and results can be found in the full study report[30].

"CLOSE-UP" LOOK AT FLUID HEATING : immersed tube burners remain the least expensive technology in 2035, except in a scenario where particularly high gas prices are anticipated, making HT heat pumps competitive as early as 2020.

Fluid heating processes are of particular interest in terms of their electrification potential: firstly because such uses are found in all the industrial sectors studied, and also because, as they are generally isolated from the rest of the production chain (unlike furnaces), their conversion to electrical technologies is often simpler from a technical point of view. As a result, fluid heating processes show significant potential for electrification (see **Table 3**).

Analysis in the three energy price scenarios

For fluid heating processes, two electrical technologies – HT heat pumps[31] and resistors – and two fossil technologies – immersed tube burners and steam boilers – were compared. HT heat pumps can only be used for temperatures between 100 and 150°C.

The technologies compared are not all equal in terms of commercial maturity: resistors, immersed tube burners and steam boilers are widely deployed in industry. HT heat pumps, on the other hand, are an emerging technology and are still relatively uncommon in industry and their cost is expected to decrease.

30 - The full report of the study is available to ALLICE members.

31 - Most of this study focuses on HT heat pumps. However, for thermal uses below 70°C, standard heat pumps – using air as a heat sink, as in residential heat pumps – can also be considered.

DATA AND ASSUMPTIONS FOR FLUID HEATING TECHNOLOGIES [32] [33] [1]

ENERGY		ELECTRIC		GAS	
Technology		Heat pumps	Resistors	Immersion tube burners	Steam boilers
Service life		20 years	25 years	20 years	25 years
CAPEX (€/kW$_{th}$)	**Technology**	430	80	90	250
	Other related equipment	270	200	4	50
Maintenance costs (€/kW$_{th}$/year)		2% of installation cost	2% of installation cost	2% of installation cost	2% of installation cost
Installed power (kW$_{th}$)		450	660	500	550
Useful energy required for the fluid (MWh/year) (1)		412	412	412	412
Free carbon allowances		N/A (no CO_2 emissions on site)	N/A (no CO_2 emissions on site)	2020-2026: 30% 2026-2030: 30%→0% After 2030: 0%	2020-2026: 30% 2026-2030: 30%→0% After 2030: 0%

(1) Calculated using data from the PEP 1 study, taking into account all losses for a standard installation.
Note: The data used here does not consider potential economies of scale for higher capacities.

TABLE 5

32 - The data and hypotheses used for the other processes are detailed in the full study report, available to ALLICE members.

33 - The technical data comes from the PEP 1 study and is therefore based on specific applications (these applications are described in the PEP 1 report available to ALLICE members).

In particular, technology and installation costs (here in €/thermal kW) can vary significantly depending on the use case and the temperature level required. Here, for example, the HT heat pump is presented and analysed; a standard heat pump operating at a lower temperature (<70°C) is more mature and less costly to install and could be used for medium-temperature applications.

FIGURE 17

The results for each energy price scenario are presented below.

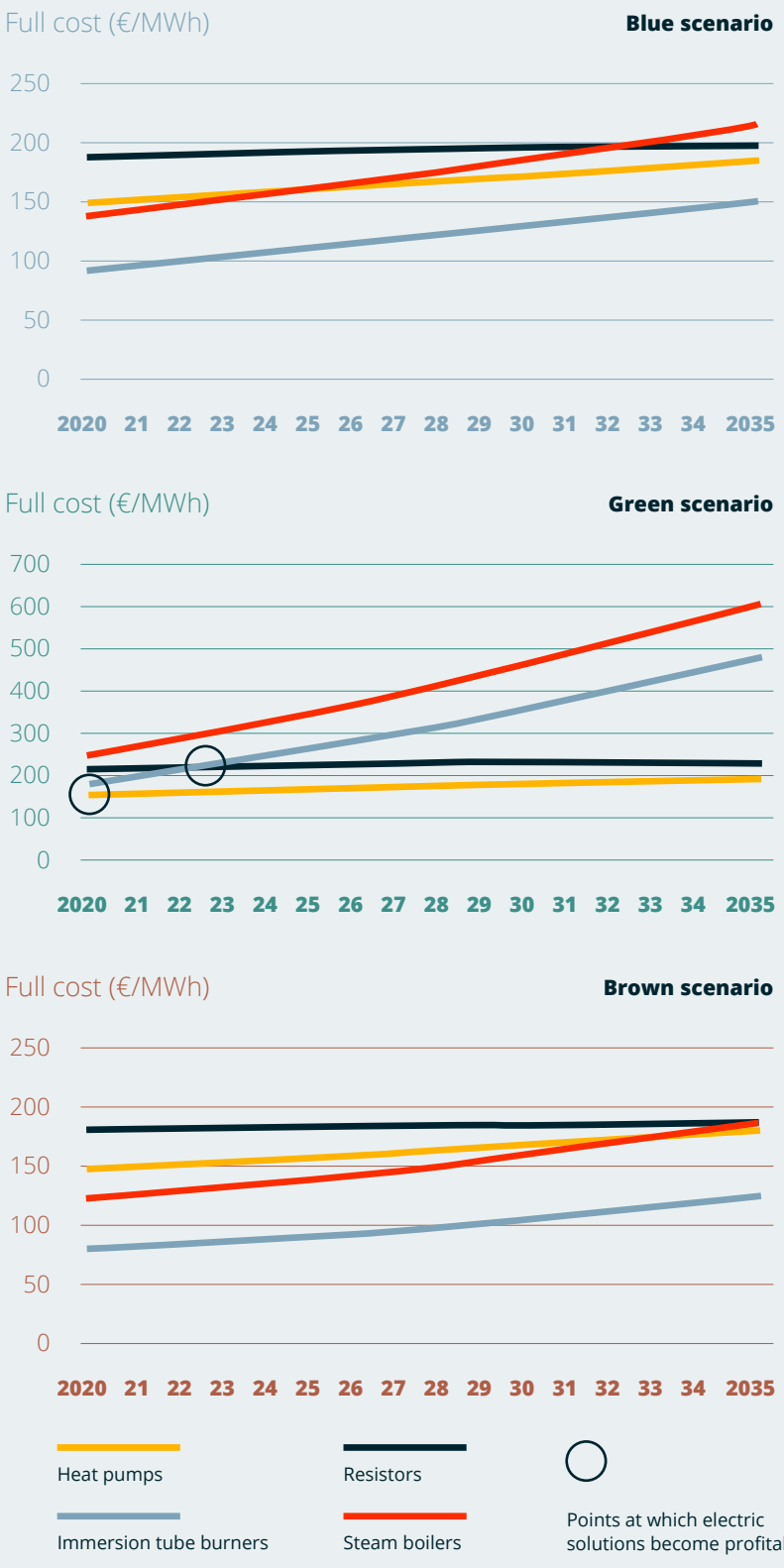
How to read the graphs

In this full cost calculation, the useful energy to be supplied is the same for all the technologies, and the aim is to compare the cost of producing this useful energy using each technology, with similar operating times. The useful energy indicated here does not include energy losses associated with the efficiency of the technologies or heat losses (walls, flue gases, etc.). The useful energy is therefore lower than the amount of electrical or gas energy consumed.

Each point on the graphs represents the full cost of producing 1 MWh of useful thermal energy using a given technology over its lifetime, for an investment made in the year shown on the x-axis. For a given year, this calculation takes into account changes in energy prices over the period of operation (20 to 25 years). As a reminder, the general trends in energy prices are described in **Appendix 3** and are explained in greater detail in the full report, available to ALLICE members.

For example: in the Blue scenario, the full cost of the ITCs is €123/MWh if installed in 2028, with a lifespan of 20 years, making it the most competitive solution available to an industrial site.

FULL COSTS OF FLUID HEATING TECHNOLOGIES IN THE THREE ENERGY PRICE SCENARIOS



These graphs show in which year installing an electric technology becomes more competitive than installing the cheapest fossil fuel technology (in this case immersed tube burners), taking into account only market prices, without public support [34]. There are several points to note here:

- **Immersed tube burners remain the most competitive technology in the Blue scenario (reference case) and the Brown scenario until 2035.** However, the differences in competitiveness between the electric solutions and immersed tube burners are narrowing.
- HT heat pumps are the most competitive electrical technology in all the scenarios, and become less expensive than immersed tube burners in the Green scenario.
- In all scenarios, the steam boiler is the least competitive technology in 2035.

The full costs of each technology in 2020 (left) and 2035 (right) in the Blue scenario are broken down in **Figure 18** below to illustrate the factors driving the competitiveness, or lack of competitiveness, of electric technologies.

The installation costs of HT heat pumps are high and account for a significant proportion of total costs, making it difficult for HT heat pumps to compete if the possibility of a significant reduction in installation costs is excluded[35].

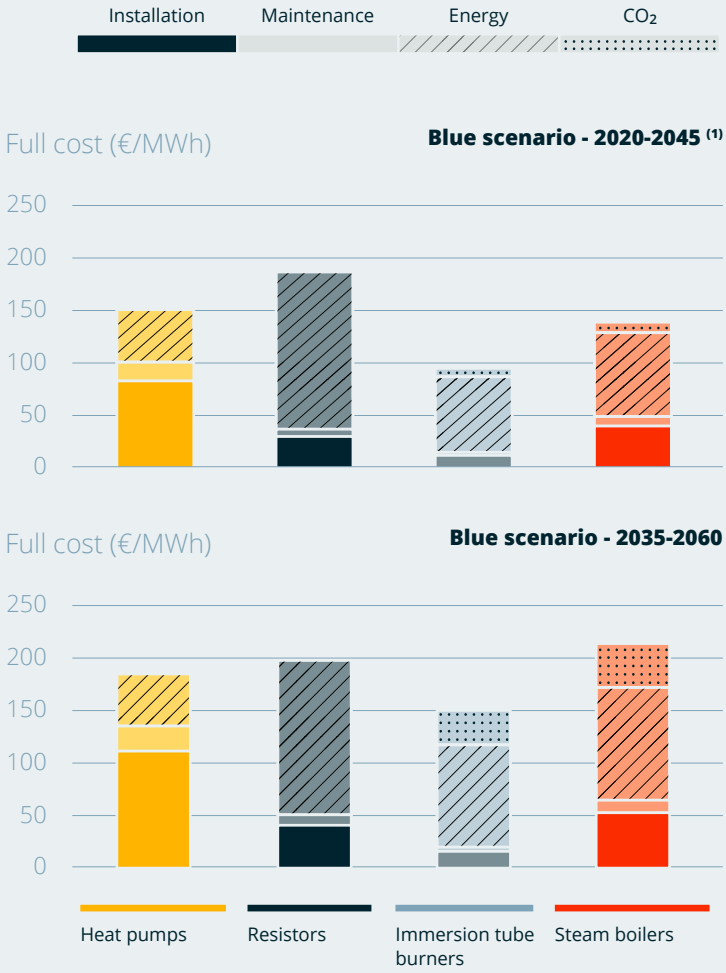
For resistors, immersed tube burners and steam boilers, energy is the largest item of expenditure. Resistors are more efficient, and gas costs rise faster than electricity costs in the Blue scenario, but this is not enough to make resistors more competitive than immersed tube burners. Finally, the CO_2 costs applicable to gas technologies also help increase the competitiveness of resistors over the long term.

34 - Aid for electrification currently exists as part of the French "*Plan de Relance*" (Recovery Plan).

35 - The significant increase in installation costs for all the technologies between the two periods (2020-2045 and 2035-2060) is due to inflation, calculated at 2% per year.

FIGURE 18

BREAKDOWN OF FULL COSTS BY EXPENDITURE ITEM IN 2020 AND 2035



(1) For an investment made in 2020 and a service life running from 2020-2045 (2040 for heat pumps and immersion tube burners)

Sensitivity to reduced installation costs: a 15% reduction in installation costs significantly improves the competitiveness of HT heat pumps.

A 15% reduction in installation costs by 2035 was applied for heat pumps and resistors [16].

As installation accounts for a large proportion (60%) of the cost of a heat pump, the assumption of a 15% reduction in costs significantly improves the competitiveness of HT heat pumps. The full cost differential with immersed tube burners is reduced from +23% to +12%. For resistors, competitiveness is also improved, but to a lesser extent, as installation represents a smaller item of expenditure.

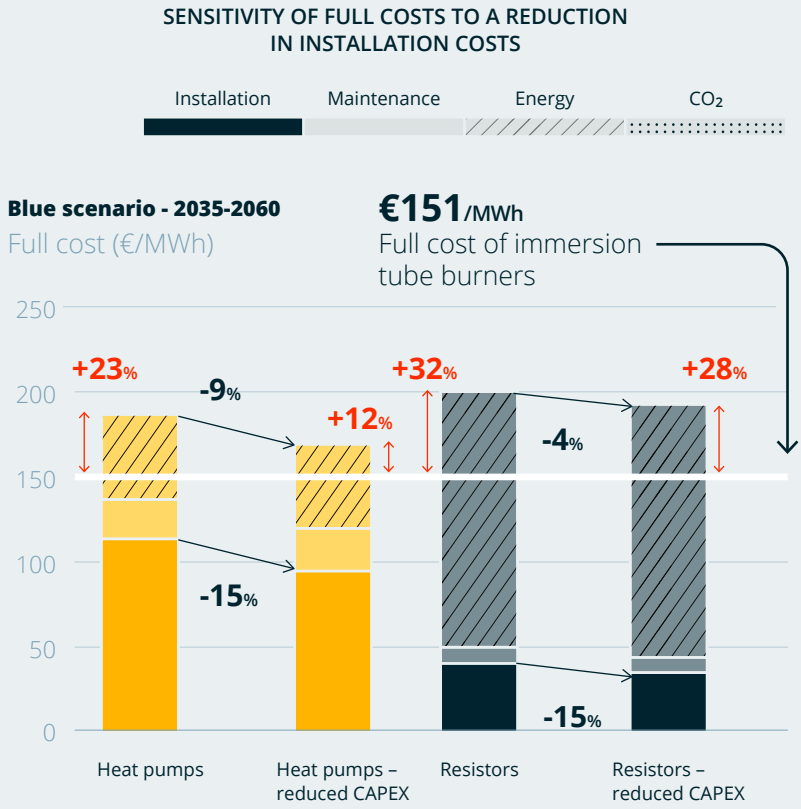


FIGURE 19

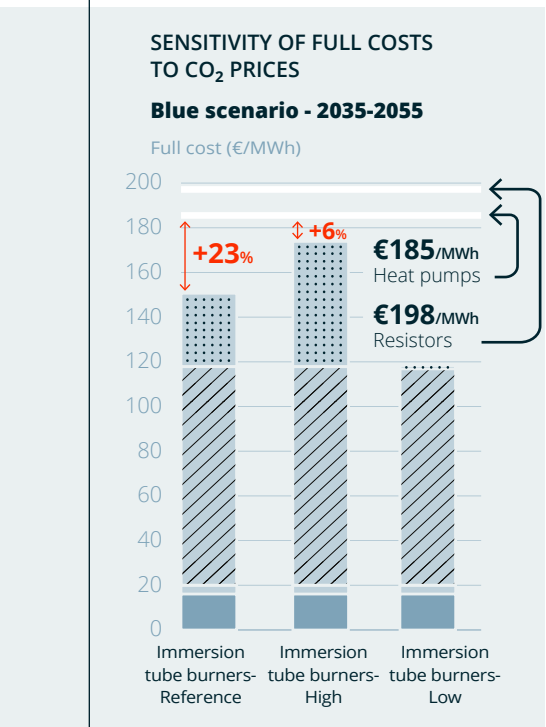


FIGURE 20

Sensitivity to CO_2 prices: representing ~30% of costs in the High scenario, high CO_2 prices can improve the competitiveness of electricity

For the High and Low CO_2 scenarios, the target values for the price per tonne of CO_2 in 2035 were set at €350/t and €10/t respectively. The two sensitivities studied are immersed tube burners - high (high CO_2 price over the long term) and immersed tube burners - low (low CO_2 price over the long term). Variations in the price of CO_2 have a significant impact on the competitiveness of electricity compared with immersed tube burners:

- In the High CO_2 scenario, high EU ETS market prices favour the competitiveness of electric technologies. In 2035, the full cost differential between HT heat pumps and immersed tube burners is reduced to +6% (compared with +23% in the reference scenario). For resistors, the gap is reduced from +32% to +14%.

- **In all the High CO_2 scenarios, immersed tube burners remain more competitive than resistors and HT heat pumps over the entire period.** So, although the EU ETS makes a major contribution to reducing the cost differential between the solutions, this mechanism alone is not enough to ensure the long-term competitiveness of electrical technologies.

Key results

In 2020 and in all scenarios, immersed tube burners are the most competitive solution to install. In 2035, in the Green scenario only, HT heat pumps become the most competitive technology to install. In the Blue and Brown scenarios, immersed tube burners remain the most competitive solution to install until 2035. However, the assumptions of a sharp increase in gas and CO_2 prices reduce the competitive gap between electricity and gas in 2035.

Because of their high CAPEX, the competitiveness of HT heat pumps is significantly improved by assumptions of lower technology and installation costs. The analysis of sensitivity to CO_2 costs showed that even in the High scenario with very high price projections (€357/t in 2050), CO_2-related expenses represent only 30% of the full costs of immersed tube burners.

In practice, HT heat pumps face technical constraints:

- **Need to balance the energy requirements of the process with the supply of a recoverable source of waste heat.**
- **HT heat pumps currently operate at a maximum of between 120 and 140°C, but are not suitable for heating fluids >150°C.**

Current research into heat pumps is looking at applications at higher temperatures. It should be noted that converting fluid heating processes to electrical technologies is technically simpler than changing furnaces, as these processes are generally isolated from the rest of the production chain (unlike furnaces).

ELECTRIC TECHNOLOGIES ARE BECOMING COMPETITIVE mainly thanks to the rise in gas prices and their greater energy efficiency compared with fossil fuel technologies (in final energy terms)

The full report of the study contains a detailed analysis of all the processes. A summary is presented below [36]. **The greater energy efficiency of electric technologies compared with fossil technologies (in final energy terms), and the increase in gas prices in the Enerdata scenarios used in the modelling, are the two main factors contributing to the competitiveness of electrical technologies**, despite the fact that installation costs are often higher. However, in many cases, in the scenarios least favourable to electrification (Blue and Brown), permanently high electricity prices do not succeed in making electric technologies competitive before 2035.

Sensitivity to CO_2 prices varies according to process and technology. The influence of CO_2 prices on competitiveness can be significant, particularly for drying processes and furnaces.

Microwaves, high frequency technologies and heat pumps are particularly sensitive to reductions in installation costs, as they are more CAPEX-intensive than their alternatives. Their competitiveness depends heavily on future cost reductions.

36 - The full report is available to ALLICE members

Summaries for all thermal processes

Heat pumps struggle to become competitive, because **their installation costs are much higher** than those of resistors and immersed tube burners. **Sustained high electricity prices** are not sufficient to make electric solutions more competitive, although the **full cost differentials are reduced by 2035**.

Summary of analyses of low- and high-temperature furnaces

Low-temperature resistors easily become competitive, **because they have a high energy efficiency compared with burners**. On the other hand, the competitiveness of high-temperature resistors is more difficult to achieve, and is only possible in the longer term, when electricity prices are significantly more competitive with gas (i.e. in the Green scenario in particular), because of the higher installation costs.

Note

The electrification of the iron and steel industry goes further than a simple "technological substitution", since it requires a complete change of model. Steel is no longer "primary", made from iron ore and coal, but recycled, from iron scrap. It should be noted that the quality of "electrical" steel is correlated to the quality of the molten scrap. As high-quality primary steel is essential for certain applications, it does not currently seem logical or desirable to fully electrify the French iron and steel sector.

Summary of analyses of furnaces >1,000°C (glass)

Despite the shorter lifespan of conduction furnaces compared with gas furnaces, **installation costs are lower, and the furnaces are much more efficient. As a result, the energy costs widen the competitive gap and this, combined with the rise in gas prices**, makes this technology more competitive in the Green scenario. However, in the Brown and Blue scenarios, gas furnaces remain more competitive thanks to lower energy costs. Electrification also faces constraints, particularly when gas combustion plays a direct role in the quality of the final product, as is the case for certain paper production processes or for flat glass production. Furthermore, there are few large-capacity electric furnaces (>300 t/day) to date.

Summary of analyses of furnaces >1,000°C (steel)

Raw material costs are higher for arc furnaces than for blast furnaces. However, **arc furnaces are very efficient, while the cost of coal (for blast furnaces) increases significantly in the long-term price scenarios used**. This growth makes arc furnaces more competitive from 2020, in all scenarios.

Summary of analyses of drying processes

Microwaves and high-frequency technologies have high energy efficiencies, but installation costs are high compared with alternative technologies. These radiant energy solutions are competitive in all scenarios, whereas resistors have a higher overall cost than gas burners because of their low energy efficiency. **Some industrial players are also showing a strong interest in microwave and high-frequency technologies, which enable high production rates to be achieved thanks to rapid heating**, providing major operational advantages. It should be noted that mature infrared technologies offering real opportunities for electrifying drying processes were not studied here.

Summary of analyses of liquid concentration processes

Mechanical Vapour Recompression (MVR) is competitive from 2020 in all scenarios, mainly because it is more energy efficient than its fossil fuel alternative, Thermal Vapour Recompression (TVR), which reduces energy costs. In practice, however, TVR may be appropriate, for example, when a potential source of waste heat makes it possible to produce steam at low cost, which reduces the full cost of TVR.

2.3

Calculation of the competitiveness of the technologies: between 41% and 100% of the maximum techno-economic electrification potential of 69 TWh of substitutable fuel could be achieved in the scenarios used

IN THE THREE ENERGY PRICE SCENARIOS, NOT ALL THE ELECTRICITY TECHNOLOGIES STUDIED BECOME COMPETITIVE WITH GAS BEFORE 2035

The evolution of energy prices in the three scenarios used leads to a greater competitiveness of electrical technologies, which would allow a significant part of the maximum techno-economic electrification potential to be achieved. The reduction in the price differential between electricity and gas over the long term contributes to these results, but does not always make electric solutions cheaper than gas solutions. Thus, in the scenarios studied, part of the maximum potential cannot be electrified without public support.

The EU-ETS contributes to the competitiveness of electricity, but will not be sufficient in a low-price scenario. Given the reference hypothesis for CO_2 prices (> €50/t in 2035 and €200/tCO_2 in 2050), the EU-ETS market represents between 20 and 25% of the full costs of the gas technologies installed in 2035, and thus favours the competitiveness of electricity. However, even in the High CO_2 scenario, with very high long-term prices (€357/t in 2050), **CO_2 costs represent only 30 to 35% of the full costs of gas technologies[37].**

In addition to financial considerations, electrifying an industrial site **may involve technical and operational complexities or additional costs** that were not considered here (e.g. the need for ventilation to maintain cooking homogeneity, loss of sources of waste heat, significant changes to the production chain, etc.).

The development of CO_2 capture technologies and the emergence of other low-carbon heating solutions offer new prospects for industrial decarbonisation that may compete with electrification. For example, very high EU-ETS prices combined with continually low gas prices **could encourage manufacturers to invest massively in capture technologies** rather than converting to electricity, particularly in sectors that emit fumes with a high concentration of CO_2 (iron and steel, cement, certain chemical sectors, etc.).

37 -As a reminder, the possibility of incorporating biomethane was not studied. At high CO_2 prices, substituting fossil natural gas with biomethane could become competitive.

METHODOLOGY
The full cost calculations can be used to refine estimates of the potential for electrification between now and 2035

The first part of this study established the maximum techno-economic electrification potential for each process, in each sector. The results of the second part of the study incorporate economic considerations to estimate how much of this maximum potential could actually be achieved.

The relative difference in full costs between electricity and fossil fuel technologies in 2035 was used to refine the electrification potential. The cost differentials were associated with electrification limits, corresponding to the proportion of the maximum techno-economic potential that could actually be electrified. Under the assumptions used, the greater the cost differential between electric and fossil fuel technologies, the greater the proportion of the maximum techno-economic potential that could be electrified.

The level of electrification is therefore correlated with the energy price scenarios. This scale of electrification limits was constructed on the basis of the relative differences in full costs observed in the results of the competitiveness analyses. This is a qualitatively constructed hypothesis that has been validated by industry experts, but a degree of uncertainty regarding the electrification potential remains.

By way of example, the following paragraph details the calculation for low-temperature furnaces in the Blue price scenario. These calculations were carried out for all the processes and energy price scenarios.

Illustration
Pour un procédé électrique thermique dont l'écart de coût avec le procédé thermique fossile concurrent est de 40% à l'installation en 2035, on considérera que 85% de potentiel maximum est accessible.

"Close-up" look at low-temperature furnaces

The results obtained from the full cost calculations carried out in **section 2.2** are as follows:

Figure 21 shows that since the difference in total costs between electric furnaces and gas furnaces in 2035 is -47.9%, 85% of the maximum potential can be electrified. The electrification potential of each sector in the Blue scenario was determined in this way.

SCALE OF ELECTRIFICATION LIMITS USED IN THE STUDY, BASED ON RELATIVE DIFFERENCES IN FULL COSTS FOR ELECTRIC VS. FOSSIL FUEL SOLUTIONS

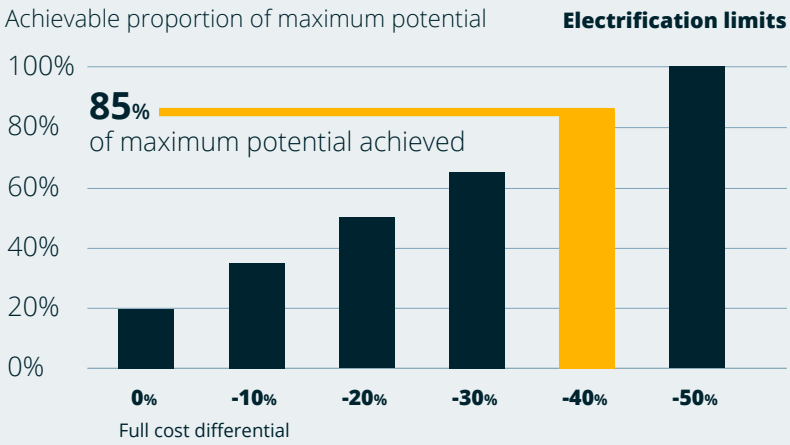


FIGURE 21

TABLE 6

RESULTS FOR ELECTRIC AND GAS FURNACES (LOW-TEMPERATURE FURNACES - BLUE SCENARIO)

	2020	2025	2030	2035
Full costs for electric furnaces (€/MWh)	516	529	542	550
Full costs for gas furnaces (€/MWh)	652	783	920	1,056
Cost differential between electric and gas furnaces	-20.9%	-32.4%	-41.1%	**- 47.9%**
Proportion of maximum potential that is electrified	50%	65%	85%	**85%**

The sum of Blue scenario potentials for each sector gives the total electrification potential for fluid heating processes in the Blue scenario. By replicating these calculations for the other thermal processes, the total electrification potential in 2035 in the Blue scenario is obtained.

SECTOR	THEORETICAL MAXIMUM POTENTIAL	POTENTIAL IN THE BLUE SCENARIO
Food and drink	1.82 TWh	1.55 TWh
Basic chemistry	5.89 TWh	5.00 TWh
Capital goods	0.67 TWh	0.57 TWh

x 85 %

TABLE 7

ELECTRIFICATION POTENTIAL IN THE BLUE SCENARIO FOR LOW-TEMPERATURE FURNACES IN THREE SECTORS

ELECTRIFICATION POTENTIAL BY SCENARIO

Almost half of the maximum techno-economic potential is attainable in all the scenarios, but public support remains essential to reach the maximum potential

Applying the electrification limits, between 41% and 100% of the 69 TWh maximum techno-economic potential is accessible, depending on the scenario.

ELECTRIFICATION POTENTIAL IN THE GREEN, BLUE AND BROWN SCENARIOS (FROM TOP TO BOTTOM) COMPARED WITH THE MAXIMUM TECHNO-ECONOMIC POTENTIAL (HATCHED)

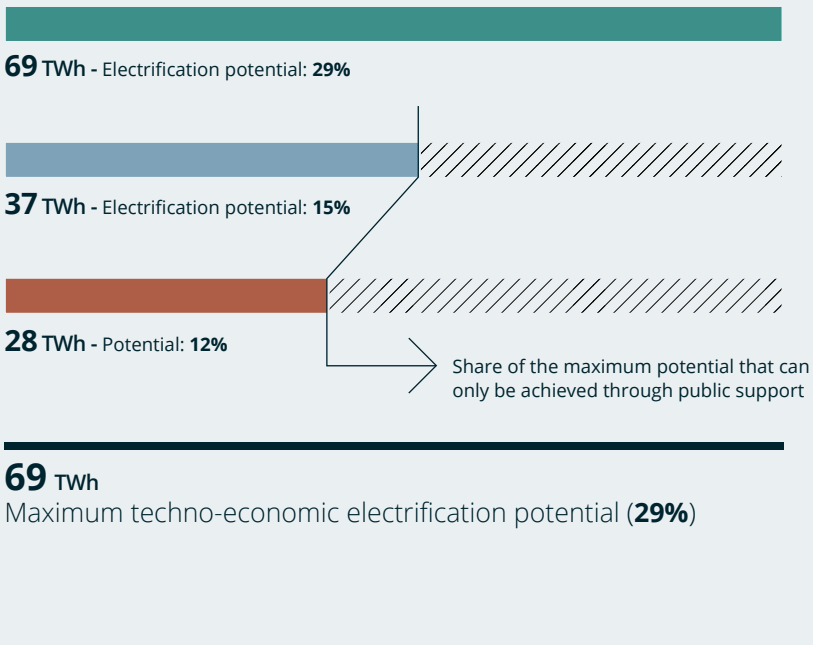


FIGURE 22

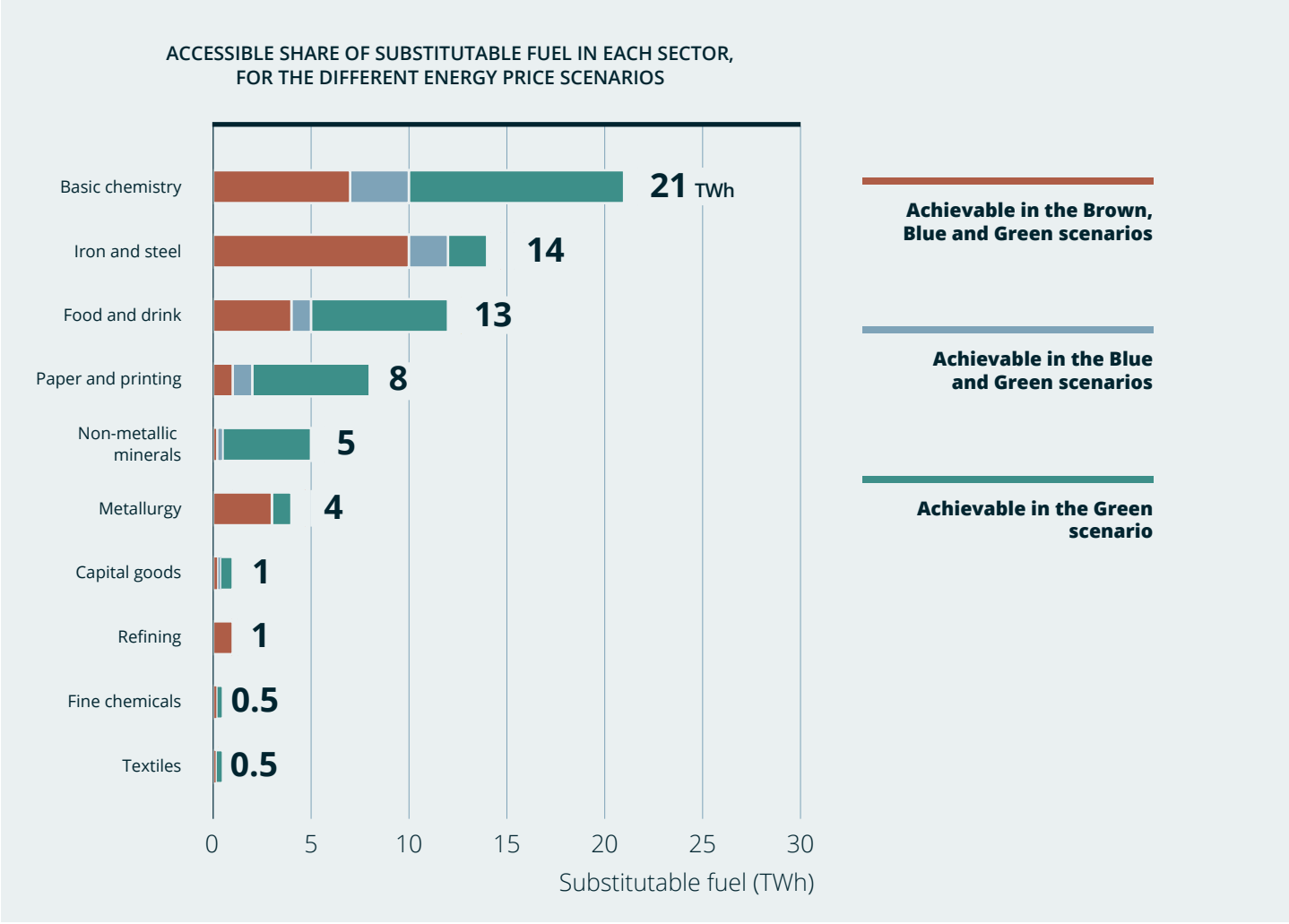


FIGURE 23

The maximum techno-economic electrification potential is only achieved in the Green scenario. Even in the Brown scenario, which is the least economically favourable to electrification, more than 40% of the maximum techno-economic potential can be electrified by 2035. This corresponds to the electrification of 12% of non-electric industrial thermal processes.

The distribution of the electrification potential and the contribution of each sector varies little between scenarios. In all the scenarios, the sectors with the greatest electrification potential are basic chemicals, iron and steel, and the food and drink industry. However, for the iron and steel industry, the accessible share is higher in the Brown scenario than for the other sectors: this is due to the fact that coal prices are particularly high in this scenario compared with gas prices.

In all sectors, the maximum potential is reached in the Green scenario. In the reference scenario, the accessible shares per sector vary greatly, with between 12% and 87% of the maximum potential calculated in part 1 being reached in 2035.

For several sectors, such as non-metallic minerals, food and drink, chemicals, and paper and printing, **a significant proportion of the electrification potential (between 25% and 40%) is only accessible under market conditions that are very favourable to electric power, meaning greater public support would be required.** For these sectors, in the reference scenario, half of the maximum techno-economic potential is not reached.

Part 3

Feasibility of electrification for the electricity grid, and positive externalities in terms of CO_2 savings and job creation

3.1

P.50 On first analysis, the French electricity network is capable of accommodating industrial electrification

3.2

P.54 Electrification generates a reduction in GHG emissions of 11 Mt $CO_{2\ eq}$ per year in the reference scenario

3.3

P.57 Electrification could create jobs in the electricity sector, but lead to job losses in the gas sector

3.1

On first analysis, the French electricity network is capable of accommodating industrial electrification

ENERGY BALANCE: In terms of supply-demand balance, reserve margins in 2035 will be sufficient for industrial electrification

The PPE and SNBC objectives will lead to changes in electricity production and demand by 2035, in particular:

- **Growth in intermittent and decentralised production** (renewable energy, self-consumption, offshore wind, decommissioning of nuclear power).
- **Emergence of new uses:** electric vehicles (EV), hydrogen (H_2)

RTE (*Réseau de Transport d'Electricité*), the operator of the French electricity network, uses supply-demand balance forecasts (*Bilans Prévisionnels*) to set out public objectives for electricity development in a number of scenarios. This study uses five scenarios developed by RTE in 2017 for the period up to 2035: PPE, Ampère, Volt, Watt, Hertz[38].

38 - No scenario includes demand linked to the development of H_2 production by electrolysis. This is detailed in separate RTE reports (see 3.1.3).

The two reference scenarios closest to the public objectives are the PPE scenario and the Ampère scenario. The detailed assumptions used in the scenarios are presented in RTE's 2017 balance forecast [18]. A brief summary of the main assumptions for the two reference scenarios is given below:

Reference scenarios for the study

- **PPE:** achievement of the objectives set out in the PPE.

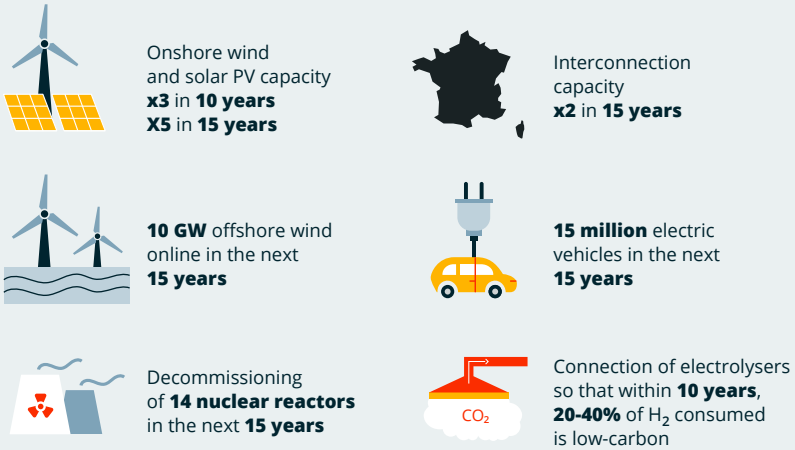
Ampère: diversification of the electricity mix with a reduction in nuclear generation in line with the effective development of renewable energies. By 2030, nuclear production reaches 50% and renewable energy production reaches 40%.

Most of the scenarios anticipate the creation of significant generation surpluses – defined as the difference between national generation and national consumption – by 2035. This is because the development of generation (renewable energy in particular) combined with stagnant or falling consumption[39] means that comfortable reserve margins can be built up for the supply-demand balance: between 155 and 172 TWh in the reference scenarios.

39 - The assumptions of stagnating or falling electricity demand by 2035 are based on the scenarios developed in RTE's 2017 balance forecast. More recent work by RTE (including the 2021 balance forecast, which had not yet been published when the PEP 2 study was underway) assumes moderate growth over the period 2020-2035, albeit still accompanied by growth of reserve margins due to the development of renewable energies.

FIGURE 24

PUBLIC TARGETS FOR TRANSFORMING THE ELECTRICITY MIX, DERIVED FROM THE DRAFT PPE AND SNBC [17] [7]



Based on a preliminary analysis, in the reference scenarios, these margins enable the electricity system to accommodate the surplus demand generated by industrial electrification, which is 32 TWh in the Blue scenario. The supply-demand balance is assured for the French power system in 2035. A more detailed study at hourly intervals has yet to be carried out by RTE[40].

Furthermore, industrial consumption is on the whole predictable and stable, with few seasonal load peaks. In the long term, in an electricity system with a high penetration of renewable energy, possible consumption constraints will not be due to winter consumption peaks, but to periods of low availability of intermittent production assets.

SYSTEM OPERATION: the development of renewable energy is not a constraining factor in increasing electrification by 2035

Although the grid will be supplied by a growing proportion of renewable energy, **RTE does not foresee any major challenges from the point of view of system operation by 2035.**

According to the PPE/SNBC objectives, intermittent energies (solar photovoltaic (PV) and wind) will not produce more than 40% of the grid's electricity in 2035 in the reference scenarios [18]. This is a significant increase compared to the share of intermittent energies in 2019 (8%), but does not pose any operational challenges for RTE. In fact, most of the system should still be controllable in 2035 – via nuclear and hydro assets in particular.

EXAMPLES: EVS AND H_2 GENERATION: RTE does not anticipate any major issues arising from an increase in electricity demand of several tens of TWh by 2035

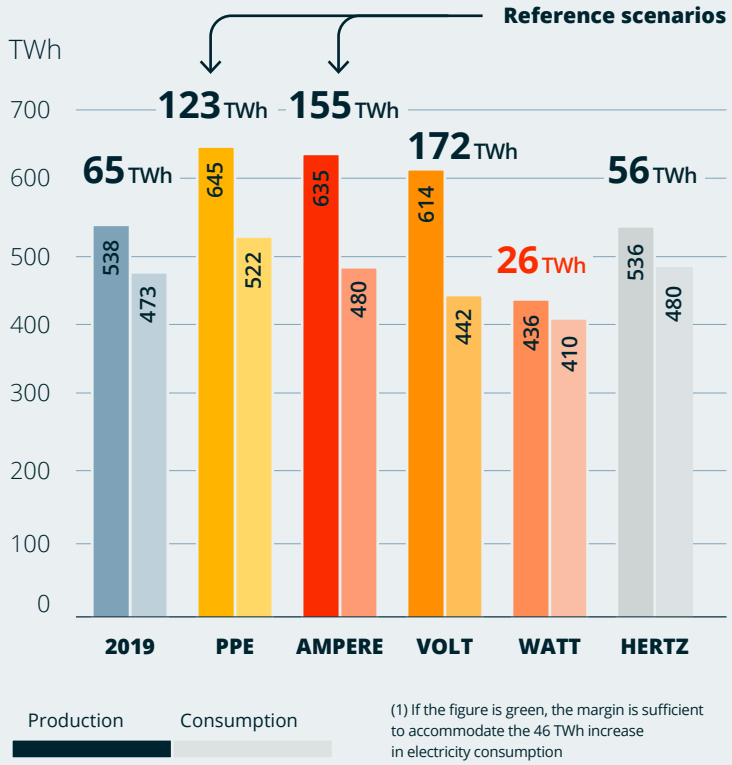
RTE has carried out specific technical analyses of the power system's capacity to accommodate the development of new uses: EVs and the production of hydrogen (H_2) by electrolysis.

Development of individual electric mobility: RTE does not anticipate any major challenges regarding the integration of 40 TWh of EVs by 2035 [18]

The Ampère scenario forecasts additional electricity consumption of 12 TWh/year in 2028 and 35-40 TWh/year in 2035 due to the development of electric mobility.

FIGURE 25

RESERVE MARGINS IN 2035 IN THE DIFFERENT SCENARIOS OF THE 2017 BALANCE FORECAST [18]



(1) If the figure is green, the margin is sufficient to accommodate the 46 TWh increase in electricity consumption

40 - The analysis underlying this report was carried out before RTE published its "*Futurs énergétiques 2050*" (Energy Futures 2050) report.

According to RTE, this additional consumption will not cause any problems in terms of ensuring the supply-demand balance. The reduction in consumption of other electrical uses and the establishment of significant reserve margins will ensure the supply of the electricity network. In addition, the introduction of flexible control tools, in particular Vehicle-to-Grid (V2G), will make it possible to integrate these new power demands.

Development of H_2 production by electrolysis: the H_2 roadmap is not a cause for concern for RTE, either for the supply-demand balance or for the management of power demand [19].

The public authorities have identified low-carbon hydrogen through electrolysis as an essential element in the decarbonisation of gas uses in industry and mobility. The production of H_2 by electrolysis would represent additional electricity consumption of 30 TWh/year in 2035, in line with the SNBC's target of producing 630kt/year of decarbonised H_2. According to RTE, the electricity system projected by the PPE is capable of handling this additional consumption, both in terms of security of supply and power demand.

By extrapolating the reasoning presented in these two examples, we can make an initial estimate **that industrial electrification of an order of magnitude of 25-50 TWh could be accommodated without operational difficulties for the electricity grid**, both from the point of view of power demand and security of supply[41].

LIMITS FOR ELECTRIFICATION: local network constraints may constitute limits for electrification, as may failure to meet the PPE targets or under-investment in the network

Major changes to the electricity system must be accompanied by increased investment in the network and the development of demand-side flexibility.

The development of renewable energy, and more specifically self-consumption, is leading to decentralisation of the electricity network. This decentralisation requires new investment in adaptations and the implementation of a robust digital framework. The investments anticipated by the operator were defined without anticipating a high level of industrial electrification [19]. To accommodate new uses at industrial sites, the network operator and the public authorities should ensure that planned investments are in line with the growth in consumption and the new power requirements generated by electrification.

Another factor favouring electrification is the development of industrial demand-side flexibility[42]. Demand-side flexibility offers possibilities for moderating the demand for power from new uses during periods of peak demand, while at the same time creating a revenue stream for industrial consumers.

41 -It should be noted, however, that "stacking" all the electrification uses studied (electrification of industry, electrolysis, electric vehicles) could potentially lead to higher levels of demand than anticipated by the public authorities and cause difficulties in managing the network, which are not analysed here.

42 -https://www.ademe.fr/effacement-consommation-electrique-france

FIGURE 26

FRENCH DEMAND-SIDE FLEXIBILITY CAPACITY IN RELATION TO THE PPE OBJECTIVES [20]

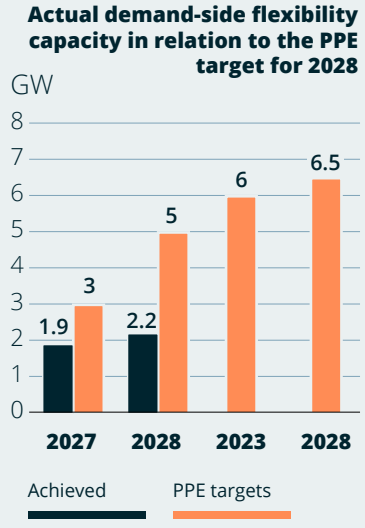
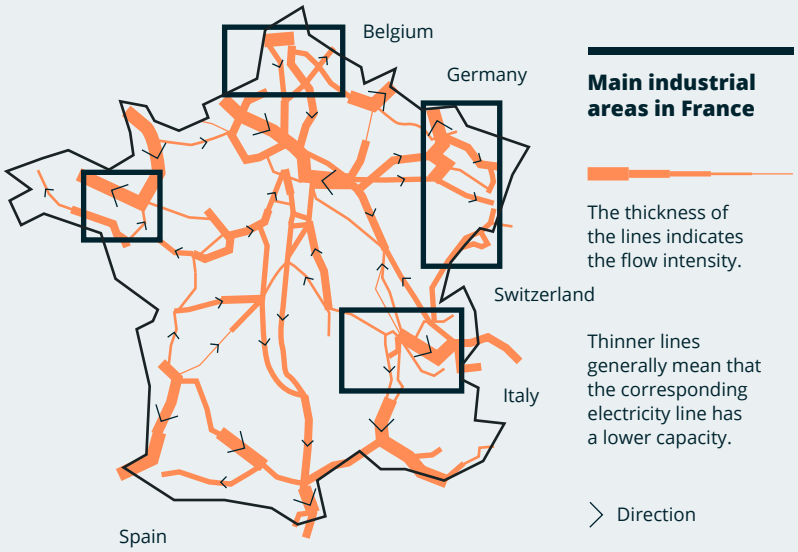


FIGURE 27

ILLUSTRATION OF FLOWS ON THE MAIN DISTRIBUTION NETWORK AND REGIONAL NETWORKS IN RELATION TO MAJOR INDUSTRIAL ZONES IN FRANCE [19]



One major challenge for electrification is that of designing **a demand-side flexibility mechanism that is sufficiently remunerative to attract new participants.** The demand-side flexibility targets set out in the PPE have so far only been partially achieved. One of the major difficulties for the future development of demand-side flexibility is to attract more diffuse uses, as the majority of "large" industrial consumers are already involved in demand-side mechanisms.

Local network issues, or the development of a high electricity demand scenario, may hinder the development of industrial electrification

Changes in the regional distribution of electricity generation, particularly towards greater decentralisation, coupled with the intermittent nature of renewable energy, may create points of weakness in the French electricity grid.

An analysis of the geographical distribution of industrial players must be carried out to identify the geographical areas most exposed to network constraints, as these could potentially limit the electrification capacity of certain industrial zones.

CONCLUSION: on first analysis, the French electricity network is capable of accommodating industrial electrification. However, certain limitations need to be examined in greater detail.

Energy balance

According to RTE's long-term vision, the supply-demand balance is not a constraint on electrification, because there will be sufficient reserve margins in the French electricity system.

System operation

The penetration of renewable energy will therefore not be a limiting factor for increased electrification in the medium term.

H_2 and EVs

Based on these 2 case studies, we can estimate that an industrial electrification level of 25-50 TWh could be accommodated without operational difficulties for the electricity grid.

Limits to electrification

The main obstacles to industrial electrification from the point of view of the electricity network are inadequacy of investment in the electricity system, a low level of demand-side flexibility, local network constraints, and the development of a high-demand scenario.

3.2

Electrification generates a reduction in GHG emissions of 11 Mt $CO_{2\,eq}$ per year in the reference scenario

THE INDUSTRIAL SECTORS STUDIED ACCOUNT FOR AROUND 18% OF FRENCH EMISSIONS

In 2019, the sectors studied in the PEP 2 study emitted 80 Mt $CO_{2\,eq}$[43], or 18% of the 440 Mt $CO_{2\,eq}$ emitted in France.

The sectors with the highest emissions are those with the highest thermal energy consumption: chemicals, iron and steel, non-metallic minerals and food and drink. **Together, these four sectors are responsible for 80% of GHG emissions from industry.** Reducing emissions from industrial sectors is a major lever for achieving French and European climate objectives.

Industrial CO_2 emissions are on a downward trend, with a 46% reduction in 2019 compared with their 1990 level[44]. This reduction can be explained, among other things, by an improvement in the energy efficiency of manufacturing processes and by a reduction in the carbon content of the energy consumed (-22% over the period 1990-2018) thanks to the replacement of coal by gas and electrification [21].

BREAKDOWN OF GHG EMISSIONS IN 2019 BY INDUSTRIAL SECTOR (MT CO_{2eq}) [4] [2]

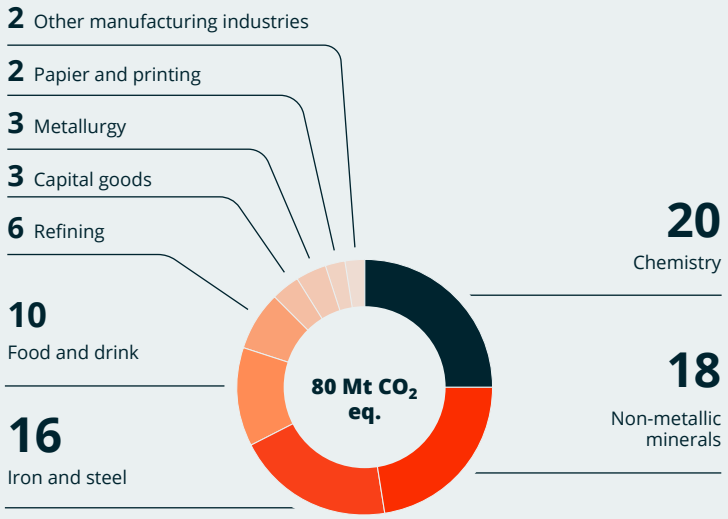


FIGURE 28

Major decarbonisation efforts have therefore already been made in the form of energy efficiency improvements. **Some of the remaining emissions from thermal processes can be decarbonised through fuel substitution, such as switching to electricity or renewable heat.** For emissions coming directly from industrial processes (~11 CO_{2eq} per year) [4] CO_2 capture technologies or conversion to lower-emission processes, in particular by substituting materials, could reduce emissions.

As electricity production in France is low-carbon[45], electrification has been identified in the government's roadmap as a way of decarbonising industry.

43 - Data for the "Manufacturing industry and Construction" sectors from data from the French Ministry for Ecological Transition, with the "Construction" sector removed and emissions from the "Refining" sector added.

44 - This is a reduction in $CO_{2\,eq}$ and therefore takes all GHGs into account. Most of the fall in GHG emissions since 1990 can be attributed to the regulation of N_2O emissions from the late 1990s to 2007, as well as a fall in production volumes.

45 - 52 gCO_2/kWh in France vs. 275 gCO_2/kWh on average for the EU in 2018 [5]

REDUCTION IN CO_2 EMISSIONS POST-ELECTRIFICATION

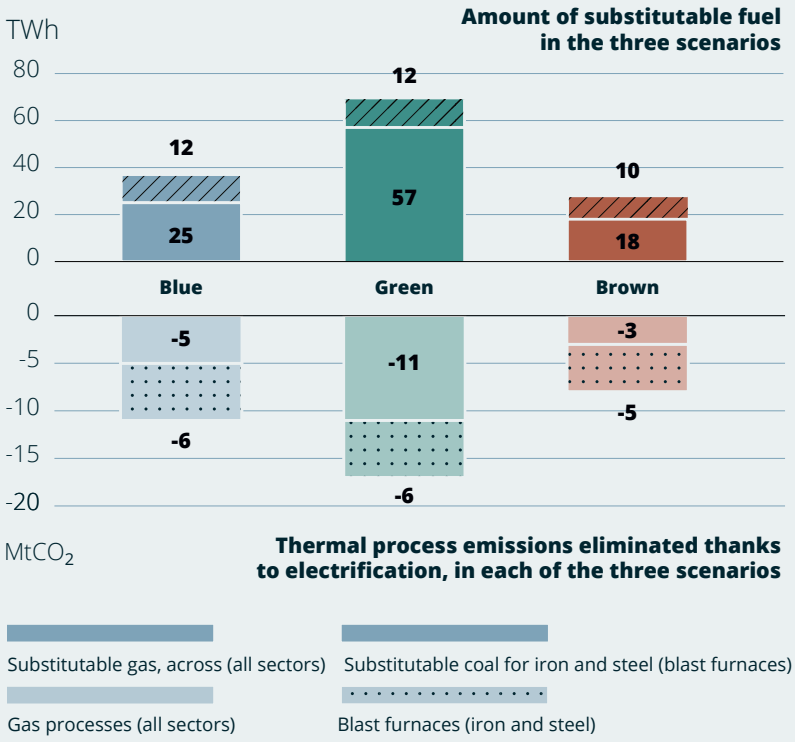


FIGURE 29

ADDITIONAL CO_2 EMISSIONS ASSOCIATED WITH ADDITIONAL ELECTRICITY GENERATION IN THE DIFFERENT SCENARIOS

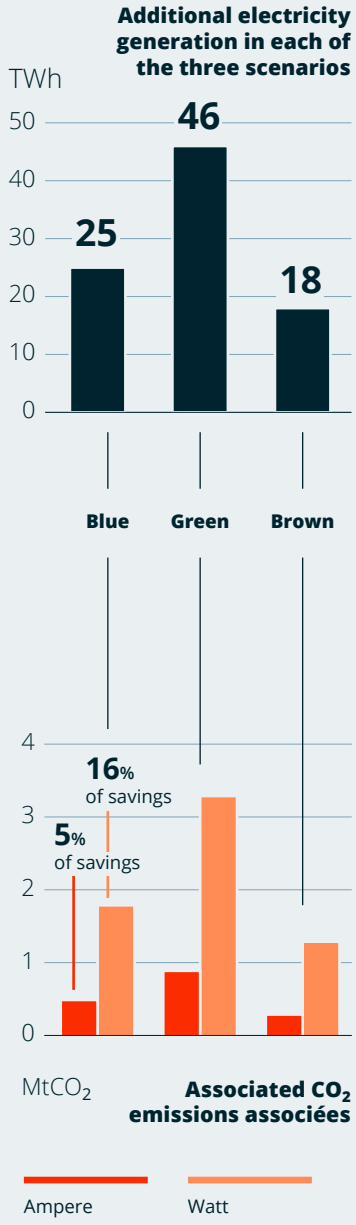


FIGURE 30

THE ELECTRIFICATION OF THERMAL PROCESSES IS A MAJOR DECARBONISATION VECTOR, making it possible to reduce direct emissions from industry as a whole by 14% in the reference scenario

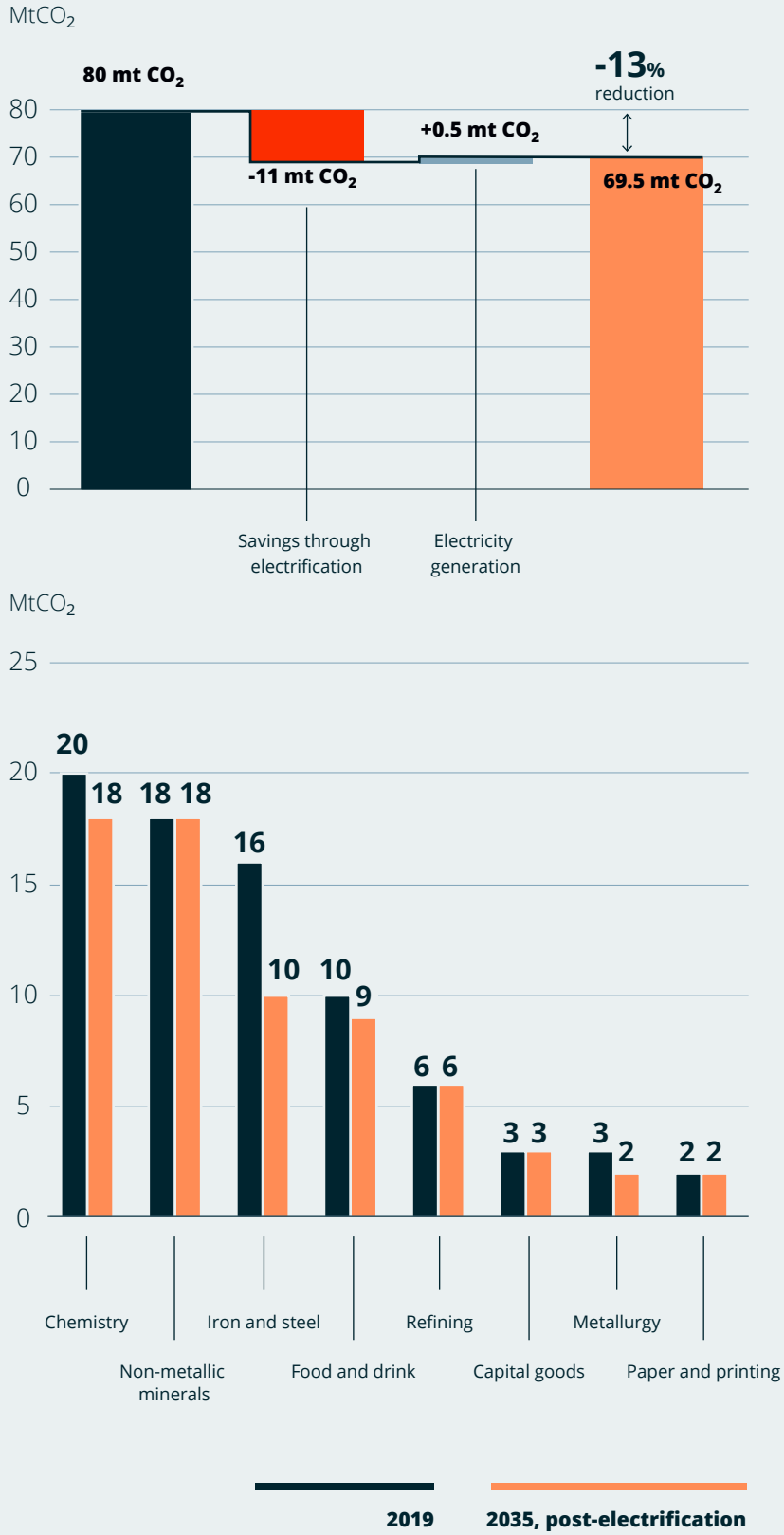
By 2035, electrification of fossil-based thermal processes could eliminate between 8 and 17 Mt of CO_2, representing between 10% and 21% of direct emissions from the industrial sector. In the reference scenario, this reduction corresponds to 2.5% of French CO_2 emissions in 2019.

Electrification leads to additional emissions associated with electricity production. In the reference scenario (19 $kgCO_2$/MWhe in 2035), **the emissions generated by additional electricity production amount to 0.5 Mt of CO_2.** The impact of the additional emissions generated is therefore marginal (5% of the 10 Mt saved on site).

In the Watt scenario presented here for illustrative purposes (72 $kgCO_2$/MWhe in 2035)[46], the impact of emissions linked to electricity production is more significant, with an additional 1.8 Mt of CO_2 generated by additional electricity production, which represents 16% of the emissions saved on site through electrification.

46 - The Watt scenario is presented here for illustrative purposes as an extreme scenario for the carbon intensity of the electricity mix: it is a scenario in which nuclear capacity is significantly decommissioned. The Watt scenario has not been selected as one of the reference scenarios by the French public authorities.

SUMMARY OF DIRECT CO_2 EMISSION SAVINGS GENERATED BY ELECTRIFICATION IN THE BLUE-AMPÈRE SCENARIO BY 2035 [47]



The 11 Mt of CO_2 eliminated by electrification are concentrated in the following sectors: iron and steel (55% of savings), chemicals (20%), and food and drink (11%).

CO_2 issues for the European electricity system

A broader analysis of CO_2 emissions could also take into account the impact on the European market of an increase in French electricity consumption. Indeed, an increase in French demand could indirectly lead to the start-up of thermal units (coal and gas) in other European countries that could have benefited from French exports of low-carbon electricity.

47 - 0.1 Mt CO_2 is also saved in the textile sector, which is not represented here.

FIGURE 31

3.3 Electrification could create jobs in the electricity sector, but lead to job losses in the gas sector

It is important to consider direct and indirect job creation driven by industrial energy consumption throughout the energy systems value chain. In the case of electrification, technological substitution in favour of electricity could create jobs in the electricity sector but destroy jobs in the fossil fuel sectors, particularly in the gas sector.

THE PPE OBJECTIVES FOR THE ELECTRICITY SECTOR COULD CREATE AROUND 40,000 NET JOBS in the electricity system and electrical equipment sectors.

The French Electricity Union (*Union Française de l'Electricité* – UFE) has estimated that, **in 2018, the electricity sector accounted for around 600,000 jobs throughout France**, with 50% in the electricity system, 35% in the building sector (particularly the installation of electrical equipment in residential buildings), 7% in industry and 7% in urban infrastructure and mobility [22].

The UFE study estimates that achieving the objectives set out in the jobs and skills section of the PPE could create around 200,000 net jobs in the electricity sector by 2030. Most of these jobs (~150,000) will be created in the buildings sector (for energy renovation), and in mobility infrastructure (for the development of EVs). Most of the jobs will therefore be created independently of industrial electrification [22].

However, UFE estimates that 36,000 jobs could be created in the electricity system (production, transport, distribution) and 13,000 jobs in the industry sector (manufacture and installation of electrical equipment) by 2030 [22]. By increasing French electricity demand and stimulating the need for electrical equipment, industrial electrification could directly contribute to the development of these ~50,000 jobs.

In particular, the 13,000 jobs created in industry by 2030 will be in industrial processes, energy efficiency and electrical safety equipment and services. **These 13,000 jobs will be directly generated by industrial electrification efforts.**

JOB TRENDS IN THE ELECTRICITY SECTOR BY SEGMENT IN THE PPE 2030 SCENARIOS, ACCORDING TO THE UFE 2020 STUDY [22]

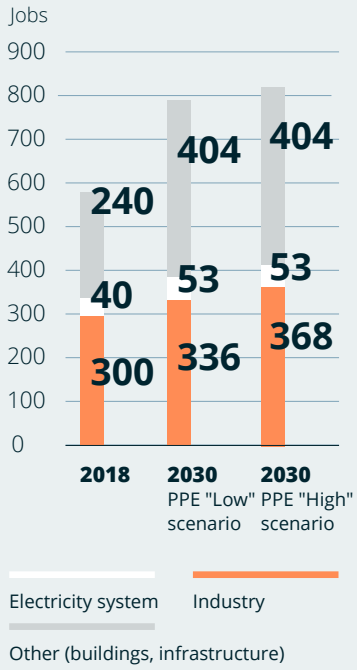


FIGURE 32

These new jobs will benefit industrial sectors that have developed an ecosystem of local players. There are many French companies offering electrical solutions for industrial thermal processes.

CHANGE IN JOBS IN THE ELECTRICITY SYSTEM AND INDUSTRY BY 2030
BASED ON THE SNBC/PPE OBJECTIVES, IN THOUSANDS [22]

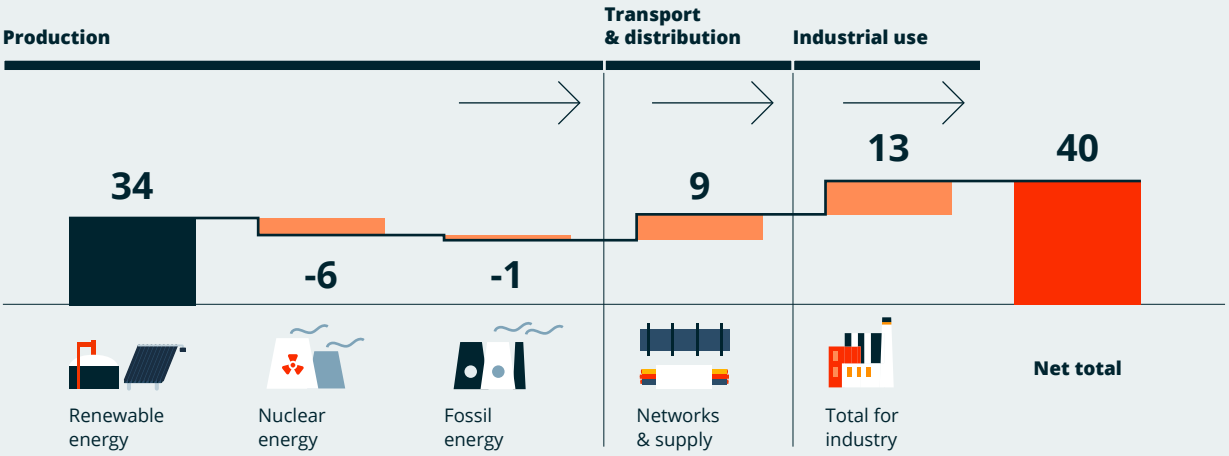


FIGURE 33

The PPE scenario for industrial electrification is more pessimistic than those in the PEP 2 study

The estimates in the UFE study are based in particular on the objectives of the SNBC and the PPE, which are less ambitious in terms of the electrification of industry than the 2035 electrification scenarios in the PEP 2. As a result, the number of electrical jobs created in industry could be higher than estimated by UFE.

HOWEVER, THE ELECTRIFICATION OF PROCESSES COULD LEAD TO JOB LOSSES in the gas technology sector and, more indirectly, in the operation of the gas system

Based on a study by the French Gas Association (*Association française du gaz* – AFG), **the number of jobs in the industry indirectly associated with gas consumption (excluding direct jobs in the residential gas industry) can be estimated at between 50,000 and 60,000 [23].** The maximum techno-economic potential for electrification estimated in this study, which corresponds to a reduction in annual gas consumption of 56 TWh, would represent a 12% reduction in all the gas consumed in France in 2035 compared with 2019. This decline in gas use could affect jobs in the gas system.

Furthermore, the jobs of gas equipment manufacturers, installers and maintainers could be threatened by industrial electrification. Although the majority of gas technologies used in French industry are imported (mainly from Germany and Italy), France still has a network of equipment manufacturers producing gas heating technologies (immersed tube burners, burners, boilers, etc.).

The majority of these companies are SMEs with between 50 and 100 employees, spread throughout France and representing several thousand jobs[48]. However, a significant proportion of the turnover of French manufacturers comes from exports, which helps to limit their dependence on changes in the French energy mix.

This rudimentary analysis of the dynamics of job creation and destruction could be supplemented by a more detailed study of the macroeconomic issues associated with the electrification of energy consumption, particularly in relation to the impact of electrification on the French balance of trade.

48 - Based on discussions with a member of GRDF's "*Industries*" team, supplemented by AFG data.

Appendix 1

Description of the 7 electrical technologies studied

TECHNOLOGY	DESCRIPTION
Resistors	Resistors are components that conduct electricity. When electrical current passes through them, heat is generated through the Joule effect.
Heat pumps	Heat pumps use electric energy to transfer heat from one medium to another, by circulating a heat transfer fluid through cycles of compression and expansion. The most advanced "high-temperature" heat pumps can heat fluids up to 120-150°C.
Direct resistance furnaces	Direct resistance furnaces rely on the Joule effect to heat electrically conductive materials. Current is made to flow between electrodes immersed in the liquid material, and the material itself acts as the resistor.
Induction furnaces	Induction furnaces are electric furnaces that heat metal using induction heating. They are used to melt iron, steel, non-ferrous metals and precious metals.
Mechanical Vapour Recompression (MVR)	MVR is a technology used to dry liquids via vacuum evaporation. Electricity is used to compress water vapour, which in turn heats the liquid.
High-frequency and microwave heating	High-frequency or microwave radiation rapidly reverses the electromagnetic field of the material being heated, making the polar molecules vibrate and rotate. This phenomenon generates heat.
Electric arc furnaces	Electric arc furnaces are used in steel production to melt scrap steel. An electric arc is formed between the charge material and the electrodes, and the heat generated by the arc melts the scrap.

Appendix 2

Industrial sectors included in the study

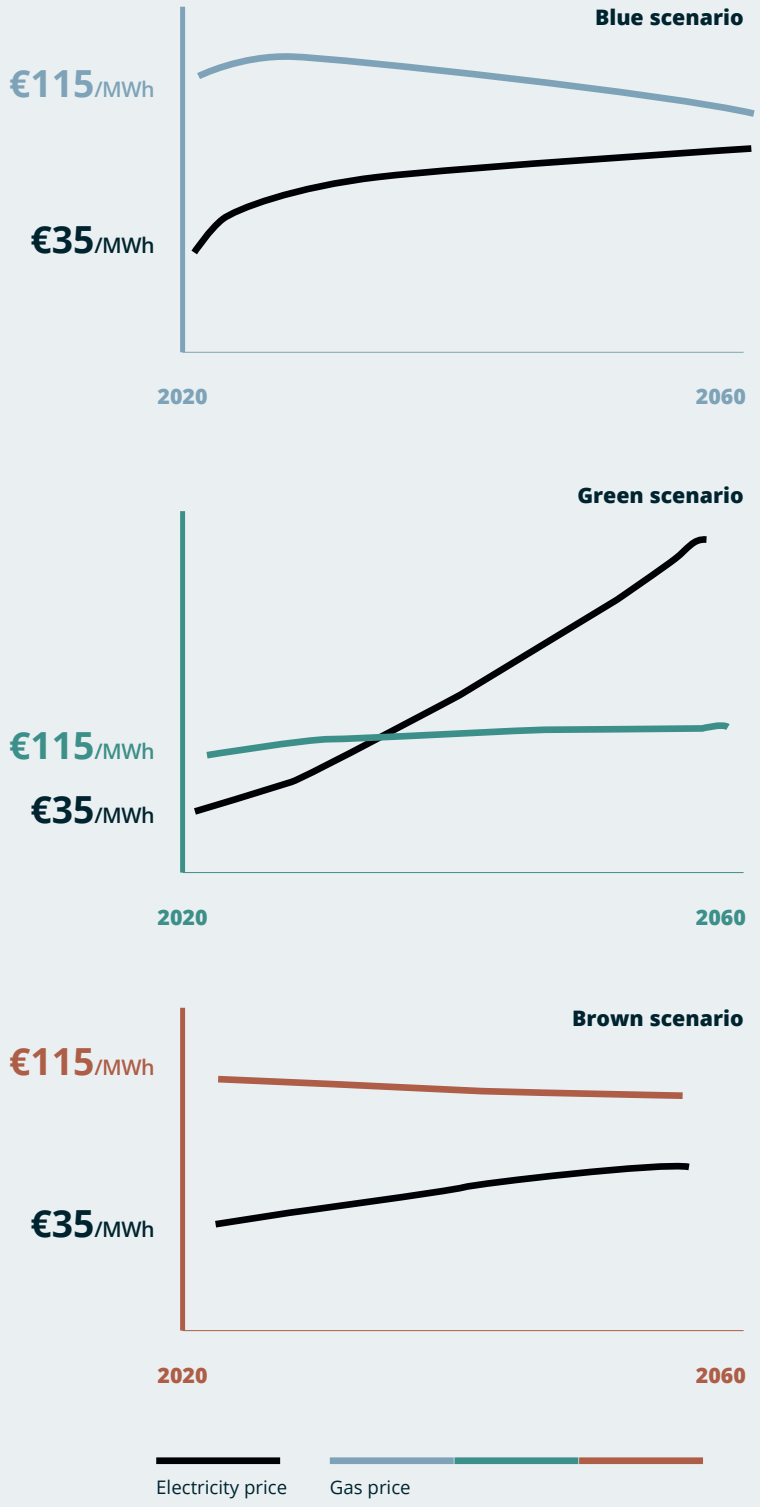
INDUSTRIAL SECTOR CATEGORISATION DERIVED FROM THE PIPAME 2017 REPORT	CORRESPONDENCE WITH THE FRENCH NCE CLASSIFICATION SYSTEM FOR OF ENERGY-CONSUMING ACTIVITIES
Iron and steel	**E16** – Iron and steel
	E29 – Smelting, metalworking and primary steel processing (steel only)
Basic chemistry	**E23** – Fertilisers
	E24 – Inorganic chemicals excluding fertilisers
	E25 – Plastics, synthetic rubber
	E26 – Organic chemistry excluding plastics
	E36 – Rubber industry
	E37 – Plastics processing
Non-metallic minerals	**E19** – Miscellaneous minerals
	E20 – Gypsum, lime, cement
	E21 – Building materials other than gypsum, lime and cement
	E22 – Glass industry
Food and drink	**E12** – Dairy industry
	E13 – Sugar refineries
	E14 – Food and drink, excluding dairy and sugar
Paper and printing	**E35** – Pulp and paper
Metallurgy	**E18** – Non-ferrous metals
	E29 – Smelting, metalworking (except steel)
Capital goods	**E31** – Mechanical engineering
	E32 – Electrical and electronic engineering
	E33 – Shipbuilding and aerospace, armaments
Fine chemicals	**E28** – Speciality chemicals, pharmaceuticals
Refining	**E04** – Oil refining
Textiles	**E34** – Textile, leather and clothing industry

Appendix 3

Trends in energy prices

The following figures show the trends in energy prices between now and 2060 in the three price scenarios: Blue, Green and Brown. A comparison of these three graphs illustrates the different *spread* between electricity and gas prices in the three scenarios. It can be seen that the Green scenario is the most favourable to electrification, since the price spread is the widest, while the Brown scenario is the least favourable, since the price spread is the narrowest.

Detailed graphs and costs are presented in the full study report.



Table

Acronymes

CAPEX
Capital Expenditure

CCUS
Carbon Capture, Utilisation and Storage

ETS
Emissions Trading Scheme

EU
European Union

EVs
Electric Vehicles

GHG
Greenhouse gases

HF
High frequencies

HP
Heat pump

IEA
International Energy Agency

INDC
Intended Nationally Determined Contributions

MVR
Mechanical Vapour Recompression

OECD
Organisation for Economic Co-operation and Development

PEP
Process Electrification Potential

PIPAME
French interministerial centre for forecasting and anticipating economic change (*Pôle interministériel de prospective et d'anticipation des mutations économiques*)

PPE
Multi-annual Energy Plan (*Programmation pluriannuelle de l'énergie*)

RTE
Operator of the French electricity grid (*Réseau de transport d'électricité*)

SNBC
France's National Low Carbon Strategy (*Stratégie Nationale Bas Carbone*)

TVR
Thermal Vapour Recompression

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