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ADEME
AGENCY FOR ECOLOGICAL TRANSITION

SECTORAL TRANSITION PLAN FOR THE FRENCH ALUMINIUM INDUSTRY

EXPERTISES

# ALUMINIUM

## Summary report

MARCH 2023

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Finance ClimAct

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# Joint editorial

### Boris RAVIGNON
### Chairman and CEO
### of ADEME


Aluminium, like other materials, is a metal that plays a relatively discreet role in our lives, but is one that we come across every day. Due to certain advantageous properties (lightness, machinability, etc.), its use has prevailed in many applications, as demonstrated by the continuous increase in its consumption since the end of the Second World War.

Although relatively "young", the aluminium industry has to meet climate imperatives, especially since this metal is often referred to as being essential to the climate transition: vehicle lightweighting, electric cables, renewable energies. The challenges facing the sector therefore call for a clear vision and anticipation of the actions to be taken.

While barely recovering from the Covid-19 pandemic, soaring energy prices in Europe, largely due to the war in Ukraine, are a further reminder of the vulnerability of our production system. In a context of increasing international competition and reliance on the European supply of alumina and aluminium, the climate imperative must now be extended to include the industrial sovereignty strategies to be implemented.

The history of the aluminium industry largely unfolded in France, thanks to former national champion Pechiney. From this industrial past, the French ecosystem has retained know-how and a strong capacity for innovation, which are major assets for seizing the opportunity of decarbonisation and reinventing production methods. This Sectoral Transition Plan, drawn up by ADEME in close interaction with the industry, contains two decarbonisation trajectories for the French sector to shed light on technological and financial issues.

The results of this report, which is the result of more than a year's work, should feed into the major Ecological Planning project launched by the Government to achieve emission reductions in line with our French and European climate commitments (a 55% reduction in our GHG emissions by 2030 following the European Fit for 55 package and carbon neutrality in 2050 in accordance with the Paris Agreement) The project will also ensure the preservation of our industrial sovereignty. We would like to thank all who contributed to this work and in particular Cyrille Mounier, Executive Officer of Aluminium France, for his availability and his valued role as industry facilitator.

### Guillaume DE GOYS
### President
### of Aluminium France

France imports an average of half a million tonnes of aluminium and 700 000 tonnes of semi-finished products each year. The carbon footprint (direct emissions, indirect emissions and inputs/transport) of these imports is 2 to 3 times larger than for our domestic production, and may even be 5 times larger if imported from China.

The future of our society will be based on aluminium, as all the prospective studies point out, but will it be French aluminium?

Our country's goal could be to become a net exporter of low-carbon aluminium and thus send an encouraging signal to a society that must necessarily be decarbonised. With new recycled aluminium production capacity and the potential for additional electrolysis capacity, this challenge is within reach if we work together to provide the means.

2023 is the turning point for this ambitious target. We will see whether the aluminium industry and our country manage to maintain low-carbon production facilities or whether we simply let the trade balance increase in favour of our non-European competitors. The same reasoning can be applied at European level. In 2023, two measures must be put in place: the competitive long-term supply of decarbonised electricity for primary aluminium plants, and the extension of the Carbon Border Adjustment Mechanism to downstream value chains to secure our industrial fabric and prevent carbon leakage.

Without these, France will lose a major competitive advantage, both for the ecological transition and its sovereignty, and will have to rely on other countries, often embroiled in complex and uncertain geopolitical issues, for its strategic supply for our defence, for example, or our health.

Our ability to achieve ambitious decarbonisation targets, sovereignty and re-industrialisation depends on long-term policy decisions to maintain and develop a competitive supply of low-carbon electricity. 2023 must demonstrate this commitment in a visible way.

# 1. Background

## 1.1. From the National Low Carbon Strategy to the Sectoral Transition Plan

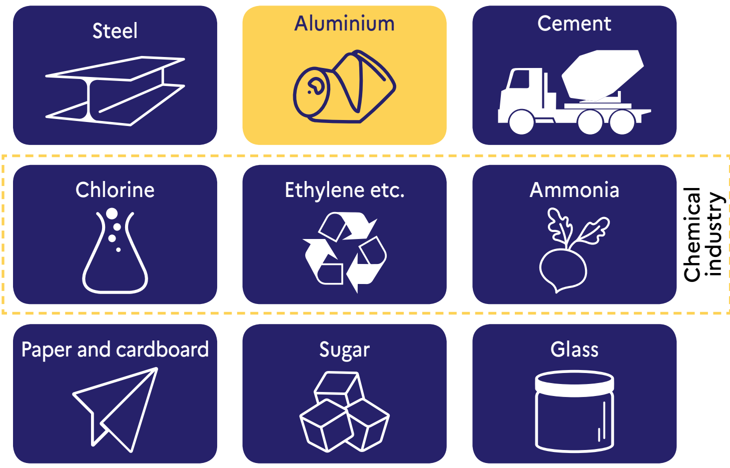
The French National Low Carbon Strategy (Stratégie Nationale Bas Carbone or SNBC) defines the path France intends to take to achieve carbon neutrality by 2050 The commitment was made following the 21st Conference of the Parties (COP 21) to the United Nations Framework Convention on Climate Change (UNFCCC) and was revised SNBC in 2020. for the French industry, the SNBC sets an 81% reduction target in greenhouse gas (GHG) emissions compared to 2015 levels. While the literature provides some guidelines on industrial decarbonisation (e.g. preferring carbon-free energy and more circular economy), their content and their cost at an operational level have not been detailed. Yet industrialists need medium-term visibility to make their investments. Indeed, as industrial facilities have a lifespan of several decades, today's investments will have consequences until 2050. The Sectoral Transition Plans are developed and implemented within this time frame. The aim is also for public authorities to introduce effective supporting policies to encourage investments aligned with the 81% reduction target.

By working hand-in-hand with key players in the sector, **ADEME seeks to offer visibility to both industry and investors, as well as public authorities.** The project is a continuation of the work carried out for the SNBC, dividing heavy industry into nine energy-intensive sectors (shown in Figure 1) to put forward specific decarbonisation solutions for each sector.

The vast majority of the research described in the national, European and international literature focuses primarily on the industrial transition from a technological standpoint. This project adopts a more comprehensive overview that covers considerations related to markets, costs, financing and jobs. As part of a European LIFE[1] programme entitled Finance ClimAct[2], these transition plans are based on cross-analysis of the deployment of decarbonisation technologies and their costs, to anticipate financing needs, the effects on competitiveness and on market developments in terms of demand and competition by 2050. The effects on employment and the possible changes in skills necessary to adapt to the transition are also discussed in the Sectoral Transition Plans, as are the topics of territorial anchorage and the degree of a region's dependence on the industrial sector studied. **Ultimately, this work should lead to the formulation of "public-private" action plans to speed up the transition of these key sectors.**

This document summarises the main results of the Sectoral Transition Plan applied to the aluminium sector.

**Figure 1. The nine industrial sectors to be covered by an STP.**




[1] The LIFE programme is the EU's funding instrument for the environment and climate action created in 1992. The funding period 2014-2020 had a budget of €3.4 billion.

[2] https://presse.ademe.fr/2019/12/finance-climact-mobilisation-pour-un-plan-daction-sur-la-finance-durable.html?hilite=%27FINANCE%27%2C%27CLIMACT%27

Project

Finance ClimAct

With the contribution of the European Union LIFE program

| | | |
|---|---|---|
| **30** | **18** | **5** |
| **people** working full time on the project | **million euro** budget | **years** |


## Projet partners

ACPR, AMF, Banque de France, Finance for Tomorrow, GreenFlex, Institute for Climate Economics, Ministry of Ecological Transition, 2° Investing Initiative

## 1.2. The French aluminium industry in figures

**894 000**

**tonnes**

**French aluminium production in 2019**

of which approximately 53% is from recycling compared with a global average of 34%

**420 000**

**tonnes**

**French aluminium production in 2019**

or approximately 0.7% of world production and 10% of European production

**The aluminium industry accounts for about 6% of electricity consumption of the entire French manufacturing industry.**

**Between 2020 and 2021, European waste exports increased by 32%.**

**Energy consumption** in this sector accounts for **BETWEEN 30% AND 50%** of the production cost.

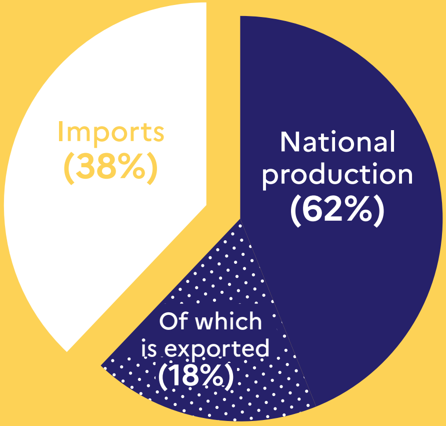
**Process emissions** represent **UP TO 90%** of the direct emissions from a primary aluminium production site (anode baking, electrolysis and fluorinated gases).

**In France, 37% of aluminium consumption is for transport, 26% for construction and 16% for packaging.**

**10 %**

**of aluminium waste** generated in Europe is exported, 80% of it to Asia.

**FRENCH CONSUMPTION OF METAL ALUMINIUM (INGOTS, SLABS, BILLETS) IN 2019 BY ORIGIN**




**70 %**

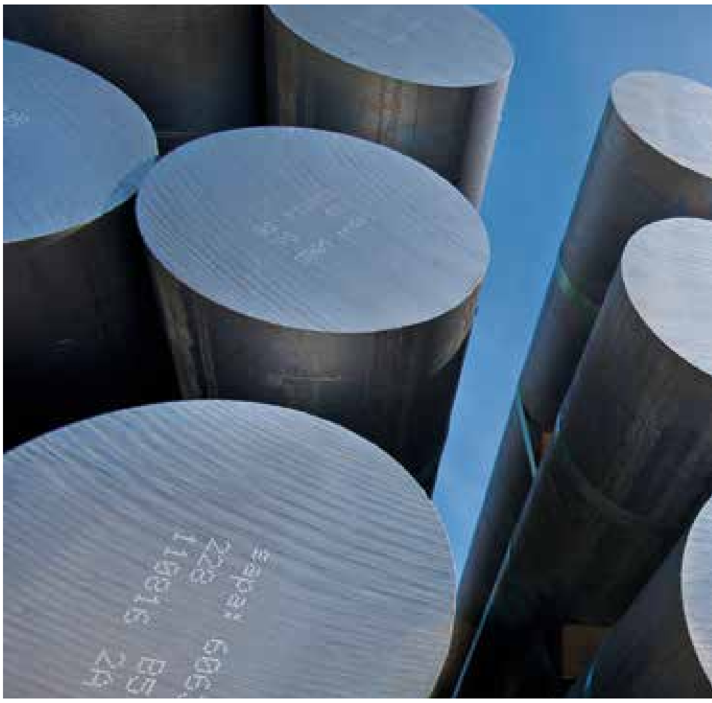
**of aluminium waste collected in France** is exported, mostly to European countries.

Approximately 1.2 million tonnes of $CO_2$eq emitted annually, representing **1.5% OF INDUSTRY GREENHOUSE GAS EMISSIONS**

# 1.3. Specific characteristics of the aluminium sector

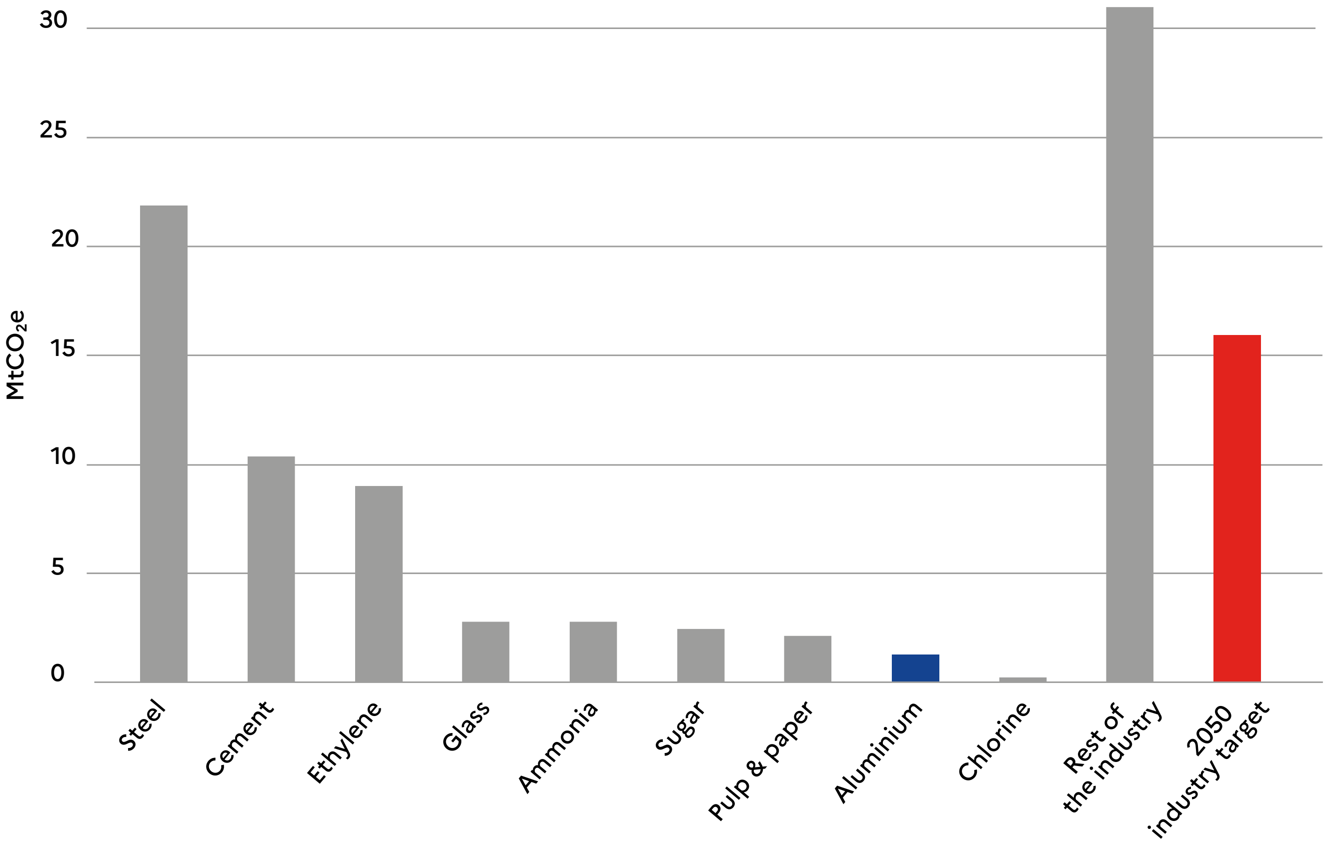
## A more energy-intensive industry than highly emitting

The French aluminium industry accounts for about 1.5% of direct emissions from manufacturing industry and is one of nine sectors covered by a Sectoral Transition Plan (Figure 2), given its high consumption of electricity. The two primary aluminium production sites account for 5% of industrial electricity consumption in France. In addition to indirect greenhouse gas emissions from electricity consumption, nearly two-thirds of emissions are process-related: aluminium is produced by alumina electrolysis, and the anode consumed during production emits $CO_2$. To decarbonise, primary aluminium will have to innovate to change the process, hence the various scenario-building exercises incorporating different innovative technologies.



→ Picture by HYDRO/Anders_Eliassen_PrimaryAluminium3

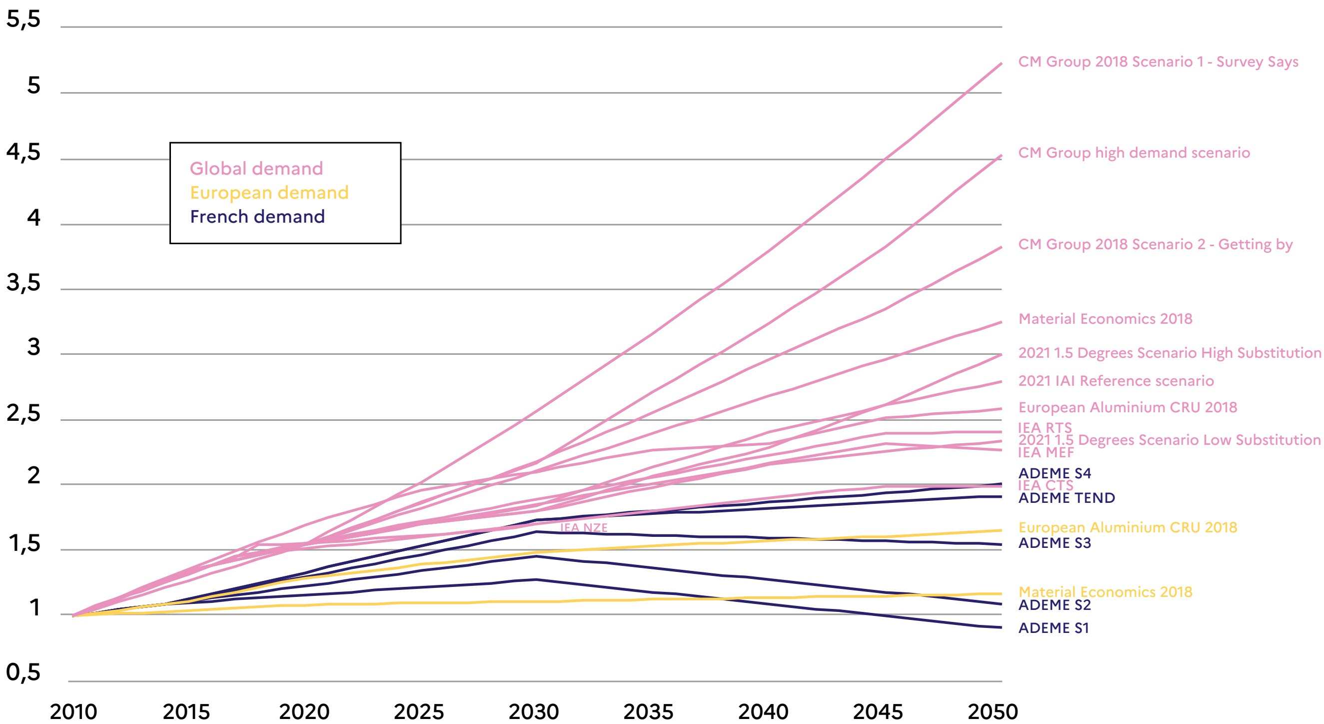
**Figure 2. Direct industrial GHG emissions in 2015 from main sectors.**



## Growth prospects that add burden to the technological transformation

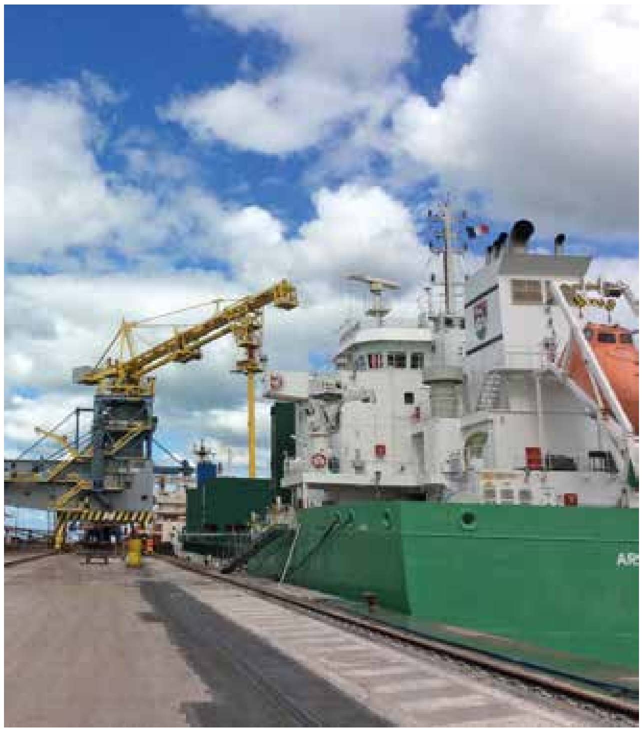
Unlike some other industrial commodities, prospective studies available in the public literature seem to unanimously identify aluminium as a "winning" material of the transition due to its properties and potential applications (Figure 4). The outlook for change in demand for aluminium is therefore strongly looking upwards due to structural transformation (vehicle lightweighting, trend towards electrification, etc.) and the scenarios presented in this Sectoral Transition Plan are no exception. Decarbonisation of the sector must be considered against this background of growing demand. It will not be achieved through a fall in production, thus placing an even greater burden on other drivers for decarbonisation such as improving energy efficiency through technology or electrification of recycling processes. In this respect, recycling is seen here as a way of meeting the increase in demand in parallel with an increase in primary aluminium production that will be necessary to meet the need. Recycling is not treated as a decarbonisation lever as it does not substitute primary aluminium production but is rather an additional means of meeting demand. It will also be necessary to decarbonise both primary and secondary aluminium production routes by combining various more or less mature technologies.

**Figure 3. Change in aluminium demand under different international (IEA, European) and national scenarios (Transition(s) 2050 ADEME) (base 100 in 2010).**



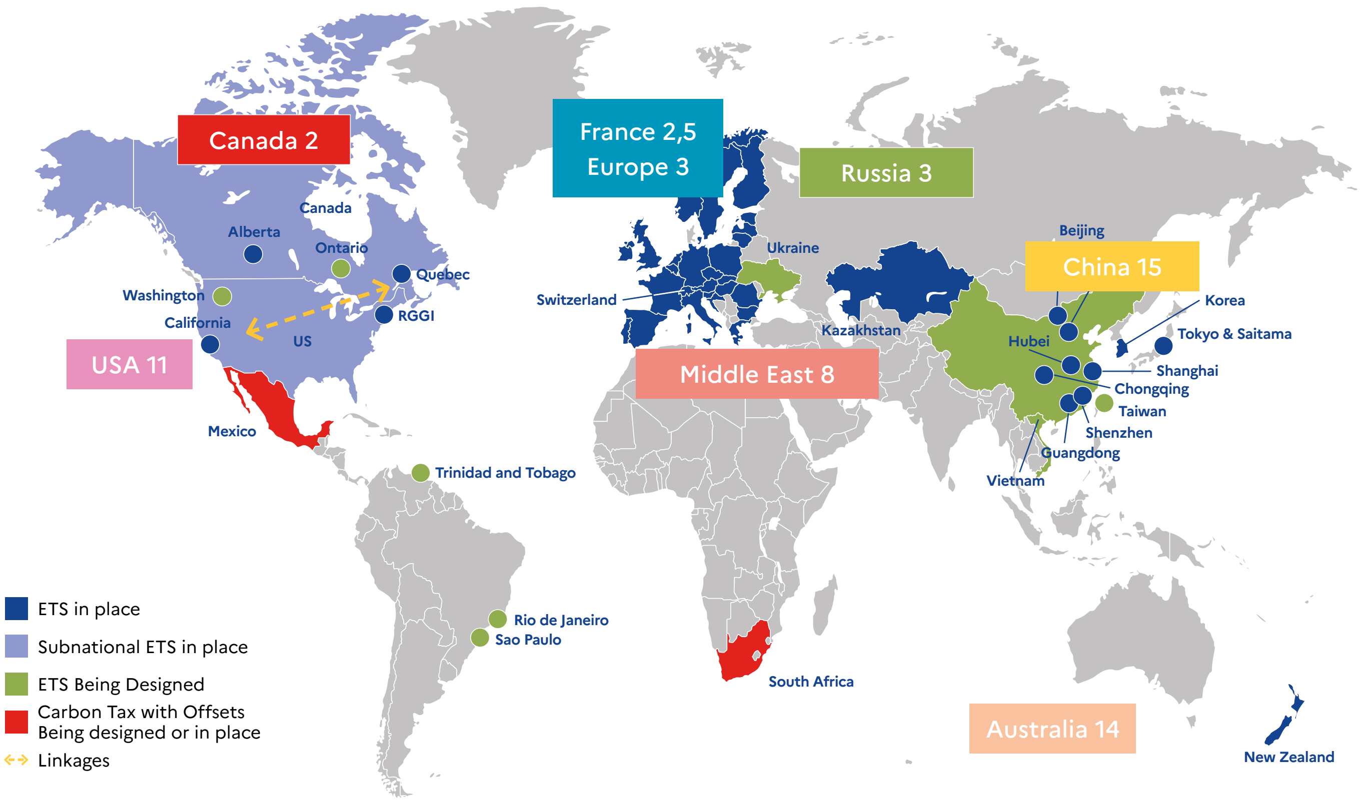
# The magnitude of imported emissions compared with direct emissions makes it worth considering the opening of new production capacity in France

Due to the highly electro-intensive production process of primary aluminium, the carbon content of the electricity consumed represents a major component of the carbon weight of aluminium production. As such, France is well positioned because of the low carbon content of its electricity generation mix. Hence, imports of primary aluminium from countries with a higher-carbon electricity generation mix contribute to an increased carbon footprint compared with primary aluminium production in France. Given that the country is a net importer of aluminium, **the two scenario-building exercises carried out under this STP thus led to modelling the potential opening of new primary aluminium production capacity in France in addition to an increase in direct recycling production capacity,** to meet the French demand for aluminium **while replacing more carbon-intensive imports.** In addition, the resulting two scenarios illustrate two very different worlds in terms of international trade and the deployment of the circular economy.



➜ Picture by Aluminium Dunkerque/Déchargement de matières premières

**Figure 4. GHG emissions (scope 1 + 2 in $tCO_2e/t$) of aluminium produced in different regions of the world (source: Aluminium France).**



# 1.4. Main limitations of the Sectoral Transition Plans scenario-building exercise

All the results presented originate from an ambitious exercise to model decarbonisation trajectories for the aluminium industry by 2050. It builds on an innovative methodology that is not without its limitations, particularly in terms of scope and access to data. The reader should bear this in mind when drawing conclusions from this report, particularly by considering the following elements:

• **A common target for reducing emissions across different industrial sectors:** The SNBC[3] 81% reduction target for the manufacturing industry has been applied to the aluminium industry sub-sector as an input constraint to the scenario-building exercise. This choice has the advantage of defining a common working framework for all sectors covered by a Sectoral Transition Plan. However, this assumption closes the door to a more flexible allocation of emission reduction targets between industrial sectors for which abatement potentials and associated decarbonisation efforts may be different. An analysis of all sectors could eventually lead to more appropriate targets being defined.

• **An expanded vision of the aluminium sector, which is therefore highly dependent on exogenous factors:** While focusing on the capacity of the aluminium sector to reduce its direct GHG emissions (modelling based solely on scope 1 emissions), this exercise is intended to provide the broadest possible view of the key factors for this change. It was thus necessary to make assumptions, directly or indirectly, on parameters external to the sector, such as demographics or the availability of alloying elements such as silicon or magnesium. In addition, a view of scope 2 indirect emissions (related to electricity generation) has been proposed for each scenario (Figure 12 and Figure 15) given the highly electro-intensive nature of aluminium production. However, no modelling or quantification of scope 3 emissions has been performed: though the approach may be relevant for another study, the Sectoral Transition Plans are not intended to offer a carbon footprint analysis of materials. Above all, the STP exercise aims to clarify the scope of action and the area of influence of French players on the decarbonisation of their production facilities.

**<u>What are scenarios for?</u>**

➜ Allow the reader to assimilate the main challenges and conditions of success.

➜ Offer a dialogue tool to engage with the stakeholders of the sector.

➜ Provide reading keys to identify and foster decarbonisation actions.

**<u>What scenarios are not?</u>**

➜ The scenarios do not aim to be a comprensive foresight exercice free of any inconsistancies.

➜ They are not intended to substitute, legitimate nor disprove a vision supported by the industry.

➜ Scenarios are not exclusive and do not pretend to hold all the possibilites of evolution of the industry.

• **And yet, an approach that could be further refined by other key factors driven by other economic stakeholders:** Indeed, as the aluminium industry is a node in a complex economy that interacts with entities upstream and downstream (which are themselves evolving), a comprehensive systemic approach to decarbonising the sector would require a vision that goes far beyond the perimeter of this sector, and therefore numerous assumptions regarding other nodes making up the system. This is notably the aim of ADEME's more comprehensive prospective project entitled Transition(s) 2050 which was published late 2021.

• **In addition, as is the case with any foresight exercise, there is an infinite number of possible assumptions and an infinite number of combinations of these assumptions. And each scenario could be even more "challenged" by the various stakeholders involved:** Thus, without giving them a predictive character, the "international cooperation" and "regional polarisation" scenarios are the result of internal work by ADEME which has been submitted to stakeholders in the sector for comment. For all that, these scenarios reflect two technically plausible, more or less desirable worlds. The aim is to help stakeholders take ownership of the exercise, with the same requirement for transparency regarding the assumptions made and the worlds envisaged, while recognising the limitations of the exercise.

In addition, the full report that goes with this summary also provides information about the contexts of the various scenarios and how the transition could occur, the effect on employment and potential industrial strategies. The aim is to broaden the scope of discussion in relation to the various results in the summary. These analytical components, which could be described as academic, are based on numerous literature searches, public sources of information, and interviews with stakeholders in the sector, and are intended to be as objective as possible given the cross-referencing of these sources by the authors.

[3] The current revision of the SNBC (3rd edition) may potentially lead to the definition of new sectoral targets. For further information: https://www.ecologie.gouv.fr/strategie-francaise-lenergie-et-climat-lancement-consultation-publique

[4] For more information, visit the dedicated website: https://transitions2050.ademe.fr/

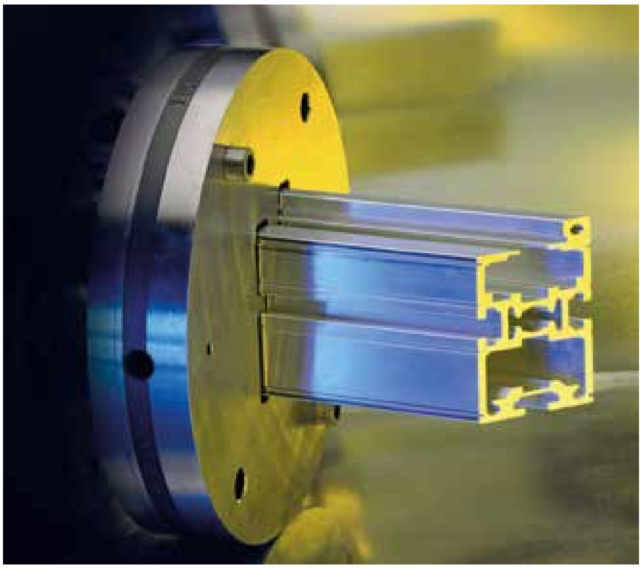
# 2. Summary for decision-makers

## Two scenarios to illustrate the challenges faced by the sector depending on two major conditions: the availability of inert anodes and the evolution of international trade.

Aluminium, like other metals, is subject to intense global trade and, in France, is increasingly at the centre of issues surrounding industrial sovereignty. In this context, it thus seemed obvious to go beyond the sole decarbonisation of industrial sites and to describe the international context for the sector more broadly. It was with this in mind that two deliberately contrasting scenarios, which achieve the SNBC reduction target of 81% by 2005, have been devised.

**Two key drivers that could completely change the face of the decarbonisation trajectory were selected to serve as a basis for comparing the two scenarios:**

- **The availability of inert anode technology,** for which the Technology Readiness Level ("TRL") is now estimated at 4-5 out of 9[5]. It represents a potential technological breakthrough in the primary aluminium manufacturing process, since it would eliminate virtually all direct emissions at a theoretically lower production cost, according to the literature available to date. To reflect the importance of the inert anode for manufacturers but also the uncertainty about its deployment in France, a first scenario was built with a set of favourable conditions for its deployment; conversely, a second scenario without inert anode technology is proposed, which in contrast uses carbon capture and sequestration technology.
- **The second key condition relates to the outlook for international trade in the coming decades.** Beyond developments on the domestic market, which forms only part of the demand for French manufacturers (approximately 40% for rolled aluminium and 50% for primary aluminium in 2014), the major change that should impact international trade in aluminium in the coming years is the entry into force of a European Union Carbon Border Adjustment Mechanism (CBAM). Building the two 2050 scenarios would thus require imagining the consequences of the potential application of the CBAM, for which the outlines were defined in an agreement between the Parliament, the Commission and the Council in December 2022[6].



➜ Picture by HYDRO/ExtrudedProfiles3

[5] Mission Possible Partnership, "Closing the Gap for Aluminium Emissions: Technologies to Accelerate Deep Decarbonization of Direct Emissions", World Economic Forum, 2021.

[6] Press release on the CBAM Agreement: https://www.europarl.europa.eu/news/fr/press-room/20221212IPR64509/climat-accord-sur-un-nouvel-instrument-de-lutte-contre-les-fuites-de-carbone

# Deux incertitudes qui conditionnent la décarbonation de l'industrie de l'aluminium

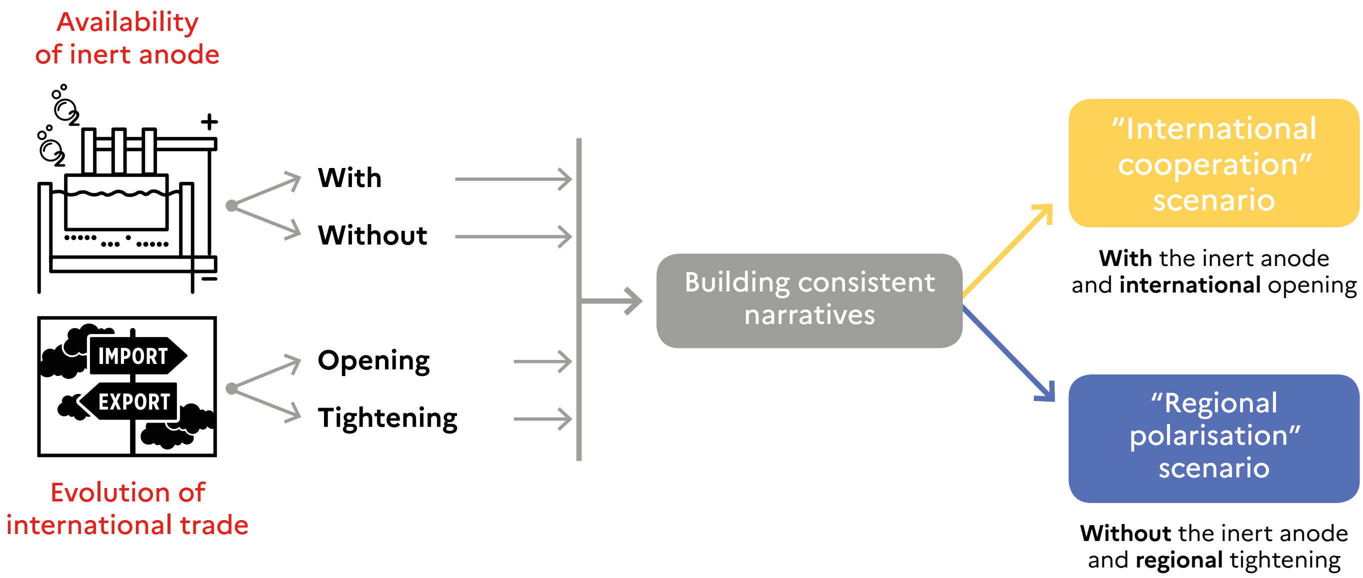



Table 1 presents the main technical and economic results of the aluminium Sectoral Transition Plan. Both scenarios show a **significant increase in primary aluminium production and from recycling due to the combined effect of increasing needs and the onshoring of part of the activities to France.** Table 1 presents the main technical and economic results of the aluminium Sectoral Transition Plan. Both scenarios show a significant increase in primary aluminium production and from recycling due to the combined effect of increasing needs and the onshoring of part of the activities to France. This increase in production, combined with the electrification of some processes, leads to an increase in electricity consumption of several TWh per year by 2050 (i.e. about the annual production of between half and one nuclear plant unit according to the scenario). New sources of decarbonised electricity will have to be deployed to meet this demand.

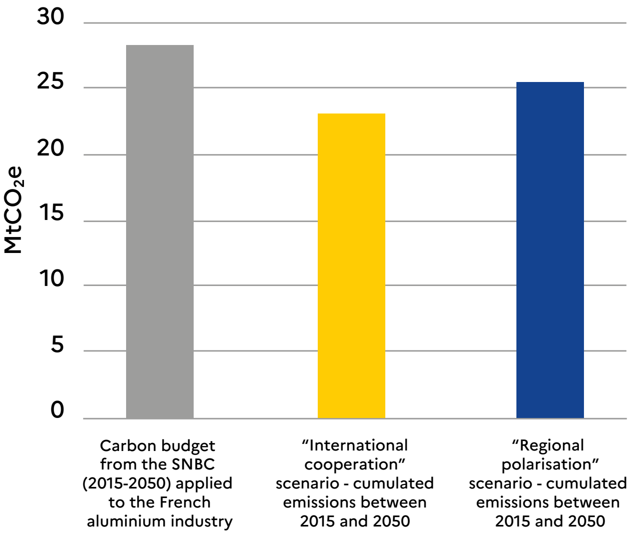
The investment required for each of the two scenarios has been estimated at between €3.3bn and €3.4bn, of which approximately 40% is related to the opening of new capacity (primary and recycled aluminium).

**Tableau 1. Summary of the main technical and economic results of the aluminium Sectoral Transition Plan.**

| | "International cooperation" scenario | "Regional polarisation" scenario |
|---|---|---|
| Level of decarbonisation achieved in 2050 compared to 2015 | -94 % | -81 % |
| Change in national primary aluminium production in 2050 compared with 2015 | + 100 % | + 35 % |
| Maximum waste incorporation rate for direct recycling (35% in 2015) | 50 % | 73 % |
| Net import rate of primary aluminium in 2050 (72% in 2015) | 75 % | 50 % |
| Net export rate of aluminium waste in 2050 (65% in 2015) | 80 % | 10 % |
| Electricity consumption in 2050 | 13.5 TWh (+6.7 TWh) | 9.9 TWh (+3.1 TWh) |
| Estimated CAPEX[7] | €3.3bn | €3.4bn |

[7] The costing of deployment of the inert anode (which is included in the amounts presented) is based on assumptions from literature sources that are considered not very robust and hence these economic results should be taken with great caution. The cost of acquiring inert anode technology today remains a major source of uncertainty for aluminium stakeholders. Furthermore, no confidential information has been provided to ADEME by the industrial groups involved in the development of the inert anode.

Figure 5. Carbon budget and cumulative emissions of the French aluminium industry between 2015 and 2050.




➜ Picture by HYDRO/Alumina1

## Fundamental prerequisites for decarbonising the aluminium industry

Whatever the limitations of this approach, the prospective exercise for decarbonisation of the aluminium industry has brought to light several implementation conditions common to both scenarios. The three findings listed opposite stand out.

To try to meet these prerequisites, several courses of action have been identified through a multi-stakeholder consultation process.

**Regardless of the decarbonisation scenario modelled, in addition to meeting the 81% reduction target, cumulative emissions between 2015 and 2050 are below the SNBC carbon budget applied to the French aluminium industry (see Figure 5).** However, this result is directly linked to the timing of the deployment of the technologies, in particular the inert anode and Carbon Capture and Sequestration (CCS). The choice of very ambitious deployment was made for both scenarios (as early as 2030 for CCS and 2032 for the inert anode). If these technologies are introduced on an industrial scale at a later date (in 2045, for example), the cumulative emissions would far exceed the SNBC carbon budget, hence the need to deploy these technologies as quickly as possible. In the shorter term, it also seems inevitable and a "no regrets" solution to meet the technical and economic conditions that will allow for better mobilisation and recovery of aluminium waste in France. In the absence of bauxite deposits in the country, the increase in recycling and the incorporation of recycled raw materials will be a major lever in the development of the circular economy and will contribute to strengthening the resilience of the industrial fabric, in particular via the potential creation or long-term future of local jobs in recycling (collection, sorting, etc.).

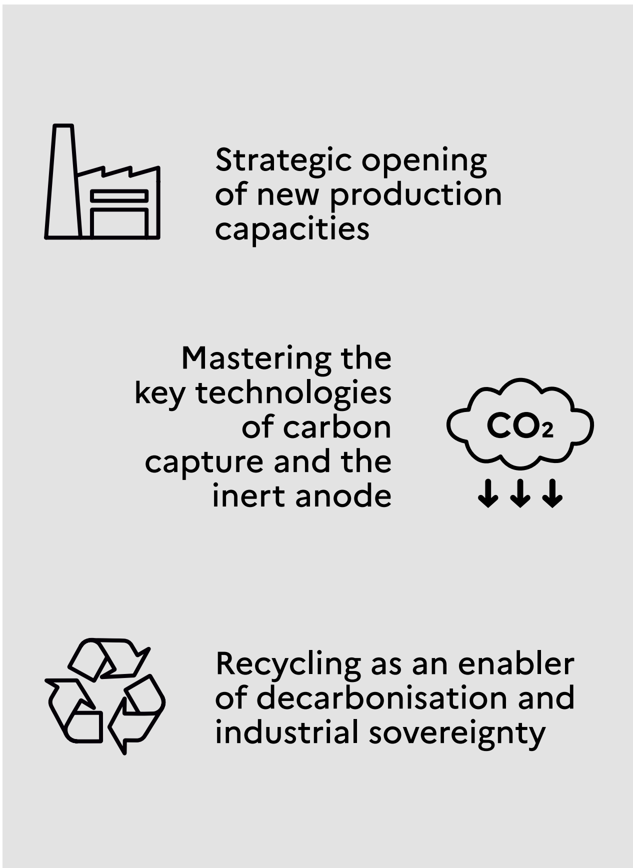



Figure 6. Fundamental prerequisites for decarbonising the aluminium industry.

## Strategic opening of new production capacity to meet increasing demand and reduce reliance on imports

The scenarios highlight the likely increase in future aluminium requirements and thus pave the way for building new production capacity, for environmental reasons but also for strategic independence and to pursue a policy of industrial sovereignty. Opening new capacity is as much about waste recycling as it is about primary aluminium production and even alumina production, a segment of the value chain that is sometimes neglected. Despite a clear desire to promote aluminium recycling and to secure supply in Europe, France and Europe do not yet have sufficient capacity to absorb aluminium waste, which is currently largely exported. It will thus be necessary to create favourable conditions for the opening of new recycling capacity as soon as possible, to ensure that the pool of aluminium is retained within a European circuit in anticipation of future needs. However, the scenarios tend to show that the waste available will not be sufficient to meet demand by 2050 for either the quantity or quality of the alloys to be produced, hence the need to continue injecting new metal into the circuit. In addition, due to its highly decarbonised electricity mix, primary aluminium production in France has a lower carbon impact than the same metal produced and imported from a country with a higher-carbon electricity mix. However, **while the environmental benefit of producing primary aluminium in France is now very real, it may tend to fade by 2050 as other nations will also decarbonise their electricity generation mix in parallel, at least according to climate commitments and national roadmaps. The environmental relevance of the operation is thus conditional on opening this new capacity as soon as possible.** For this reason, the scenarios propose the opening new "smelters[8]" within a relatively short time frame, by around 2030. Finally, as the main input for primary aluminium production, the question of alumina supply is equally crucial. As with other industrial activities, the onshoring of alumina production would provide control of an additional segment of the value chain and better manage all the associated environmental impacts, including GHG emissions.

### A crucial need to secure access to cost-competitive electricity supply

For a smelter, electricity can represent up to 45% of the production cost of primary aluminium. Since aluminium is subject to market prices and operates in a highly competitive international environment (in particular due to overcapacity), access to a favourable electricity tariff is a major factor for competitiveness. This is why, historically, primary aluminium plants have tended to be located in regions where electricity was available at low cost, such as near hydroelectric dams (Quebec, Norway, the Alps) or, more recently, in regions with abundant fossil-fuel resources such as Asia (coal) or the Gulf countries (natural gas). In France, the creation of the Aluminium Dunkerque site in the 1990s was made possible due to a close link between the historic electricity supplier (EDF) and the former French industrial group Péchiney (nationalised in 1982), which concluded an agreement in 1988 for the supply of electricity to the future plant at a favourable tariff. Nevertheless, this project took place in an already unfavourable industrial context for aluminium, as no new site had been built since 1960 and several French smelters in the Alps had been successively shut down due to lack of competitiveness. The current TRIMET Saint-Jean-de-Maurienne plant almost suffered the same fate in 2013-2014 when it was sold by RIO TINTO before an agreement was finally reached between the German TRIMET group and EDF (now a 35% shareholder in the plat) to secure electricity at a preferential tariff. History thus shows that the cost of electricity is a key factor in the creation and long-term future of a primary aluminium production site. Stronger initiatives (public or private) are therefore required to secure the electricity price in the long term (e.g. the Exeltium offer, consideration of a new mechanism for long-term electricity contracts[9], etc.) while at the same time operating in an increasingly integrated European electricity market.

[8] In the industry jargon and in the rest of this document, "smelter" refers to a primary aluminium production plant using the electrolysis process.

## Mastering the key technologies of carbon capture and the inert anode

Globally, scope 2 emissions from electricity consumption account for about 2/3 of the emissions from the aluminium industry (scopes 1 and 2), thus focusing the debate on decarbonisation of the electricity generation mix. Given that the electricity generation mix in France is already low in carbon, decarbonisation of the French aluminium industry focuses mainly on direct emissions from sites (scope 1). This focus on direct emissions has highlighted the contribution of process emissions from primary aluminium production and hence on potential solutions to reduce these emissions. Two innovative technologies still under research and development, the inert anode and carbon capture on electrolysis cells, have emerged as being absolutely decisive for the deep decarbonisation of the French aluminium sector. The inert anode, currently the most promising of the two technologies, has been under development for several years by two major industrial groups: ELYSIS in Quebec, a joint venture between RIO TINTO and ALCOA, and the giant RUSAL at its Krasnoyarsk site in Siberia, which has announced a commercial solution by 2025-2030. **Its development is kept under tight industrial secrecy, to the extent that European players have very little visibility on the exact architecture of the technology, its potential date of release and its cost.** It is not even certain that these groups, which compete globally with European companies, would be willing to make the technology available, given its strategic aspect and its theoretical promise to improve competitiveness.

### Inert anode: a European research consortium to give visibility to stakeholders

**While the ELYSIS consortium is currently working on the development of inert anode technology at its research centre in Saguenay, Quebec, and RUSAL group is doing the same at its Krasnoyarsk site in Siberia, there is no European consortium working on such a project. Yet Europe offers a favourable environment for welcoming and financing the development of new industrial technologies. Several large-scale projects of this type for other sectors can be cited, such as the ULCOS project for the steel sector, the "Furnace of the Future" project for the glass sector, the LEILAC project for the cement and lime sector and the "Cracker of the Future" project for petrochemicals. The SIDERWIN consortium led by ArcelorMittal Group has also received European funding from Horizon 2020. SIDERWIN aims to develop a direct iron electrolysis process with no $CO_2$ emissions, so comparable to the inert anode but for the steel industry. Even without reaching commercial deployment of an inert anode, such a project would, at a minimum, enable study of the possible configurations and thus give visibility to manufacturers on the operation and the materials required for the technology. The creation of such a research consortium has, in any case, emerged as a possible measure during the various discussions and it does not necessarily preclude an attempt to join forces with ELYSIS in order to benefit from the inert anode. The fact that this consortium has not yet been set up is probably due to industrial groups already having taken up the subject a long time ago, making other European stakeholders now reluctant to get involved in view of the entry cost and the technological backlog that has accumulated.**

➜ Picture by BigTunaOnline/Shutterstock.com

[9] To this end, former deputy industry minister Agnès Pannier-Runacher tasked Philippe Darmayan, former director of ArcelorMittal France, with conducting an expert investigation into a new mechanism for establishing long-term electricity contracts, in particular given the forthcoming end to the ARENH system, planned for 2025. The investigation was announced in the press in January 2022 and was initially planned to last six months. It forms part of a broader effort to strengthen the competitiveness of French industry.

# Recycling as an enabler of decarbonisation and industrial sovereignty

➜ Picture by Aluminium France/cycle de vie

The discussions held while developing the Aluminium Sectoral Transition Plan were an opportunity to highlight an already widely known and shared conclusion, namely that recycling is a "no regrets" measure that should be deployed to its maximum, given its climate benefit and also due to the scarcity of resources. Recycling one ton of aluminium generates one-quarter of the emissions of its primary equivalent (in direct emissions, scope 1), so it is quite natural that the paths developed in the scenarios both make significant use of recycling. **However, the available waste is not sufficient to meet all the demand. In a world of increasing demand, and where, despite efforts made on eco-design and developing sorting and collection technologies, the average quality of waste is steadily and irrevocably deteriorating, primary aluminium will still be needed to meet part of the demand.** The scenario-building exercise also revealed a major uncertainty regarding the future of recycling: refining, which accounts for about 40% of secondary aluminium produced in France (the other sector being direct recycling), is currently beset with numerous economic difficulties. Refiners find it difficult to make a profit because the potential margin is caught in a vice between the price of two commodities subject to market volatility: the purchase price of increasingly sought-after waste and the price of foundry alloys, upon which the automotive industry pressures the prices down. The situation gives cause for concern over the long-term sustainability of the sector, even though there is broad consensus on increasing and improving recycling. Finally, recycling also helps guarantee the supply of certain strategic materials to France and Europe at a time of increasing geopolitical tension[10].

## Limiting waste exports

There is significant international trade in metal waste. About 10% of aluminium waste generated in Europe is currently exported, 80% to Asia (mainly China and India). In France, approximately 70% of collected waste is exported, the vast majority to European countries, while imports account for between 55 and 60% of recycled waste. In addition, metal waste is also regularly stolen and illegally exported, although the extent of this problem is not yet clear. Limiting waste exports is in line with a short cycle approach that reduces the impact of transport and helps to secure metal supply. Capturing this waste represents an opportunity for French stakeholders, who will have to develop new recycling capacity to absorb this flow. In addition, waste exported to third countries is often processed under social and environmental conditions that do not comply with European standards. There is a very similar issue surrounding the export of scrap metal in the steel sector. For this reason, within the framework of the European Waste Shipment Regulation, the European Commission proposed a revision on 21 November 2021 to restrict the export of non-hazardous waste (including scrap metal and aluminium waste) to non-OECD countries. Action also appears to be possible at national level. In early 2022, for example, Italy classified scrap metal as a critical raw material. As a result, exports of such waste must now be notified to the relevant national authorities, which may prohibit the operation depending on demand on the domestic market.

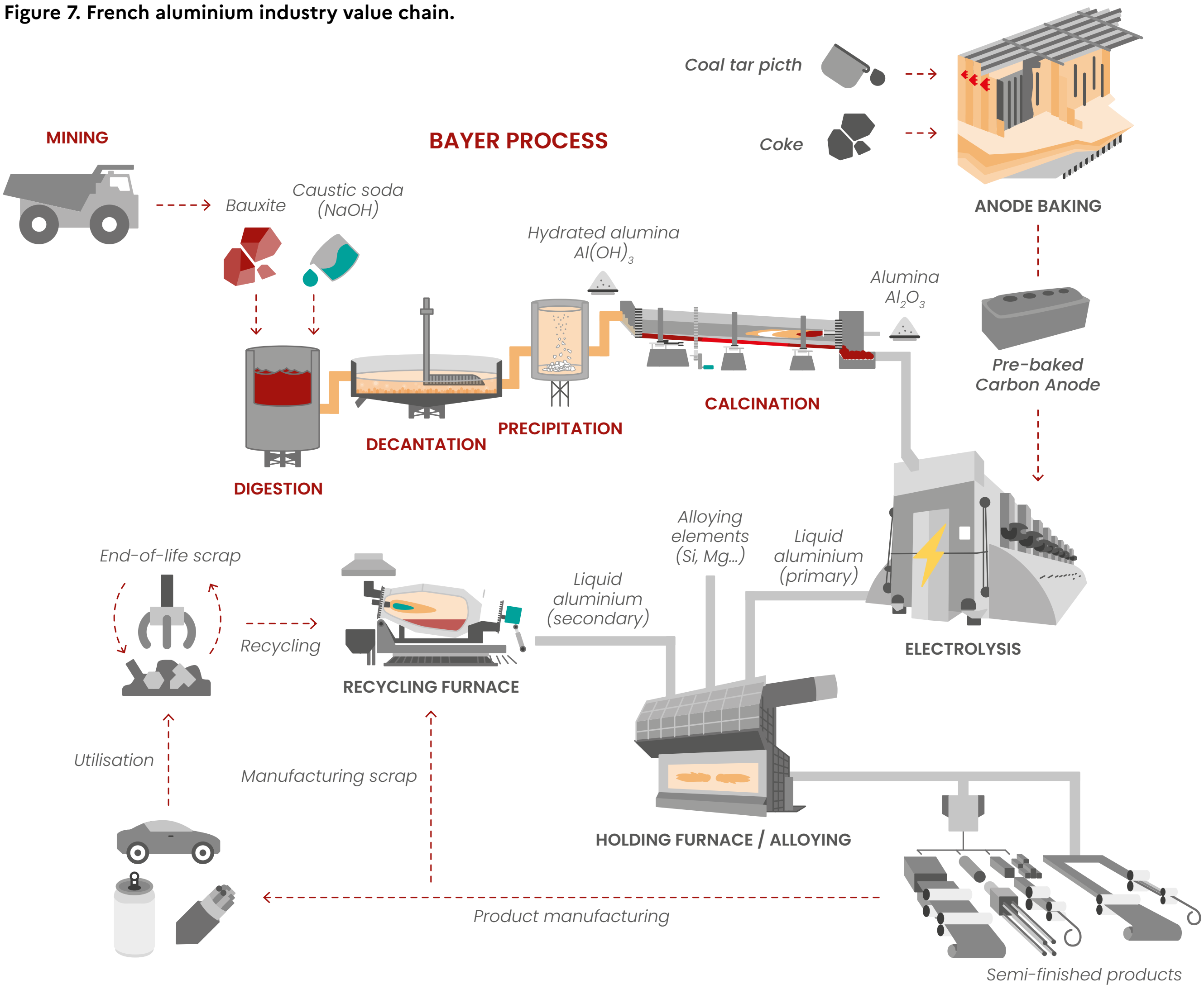
[10] Some regions of the world with few natural resources, such as Japan, have elevated recycling to the rank of a national security issue for metal supply.

# 3. The decarbonisation challenge of the aluminium industry

## 3.1. The aluminium value chain: from production...

Several production steps are required to transform the metal into a finished product. In addition, these steps are generally spread out geographically over several specialist industrial sites. The value chain is shown schematically in Figure 7.

**Figure 7. French aluminium industry value chain.**




Aluminium exists naturally as alumina, an oxide with the formula $Al_2O_3$, which is found in high concentration in bauxite: this is a white, red or grey sedimentary rock, characterised by its high content of alumina and iron oxides. This is the basic raw material for aluminium production. It is chiefly extracted from open-cast mines, with the largest known deposits being in Guinea, Australia, Vietnam, Brazil and Jamaica. It owes its name to Les Baux-de-Provence, the town in the Bouches-du-Rhône in France where it was discovered by the French chemist Pierre Berthier in 1821. France was to remain the world's leading producer of bauxite until 1939. Due to the depleting resource, French production peaked in 1973. In France today, the bauxite used for alumina production is all imported.


➜ Picture by HYDRO/Dag_Jenssen_Recycling2

The extraction of the alumina contained in the bauxite is now carried out by the Bayer process. The rock is heat treated with sodium hydroxide, which dissolves the alumina allowing the insoluble impurities to be separated. The alumina is thus obtained in its hydrated form, which then undergoes a calcination step at over 1,100°C, driving off the water of hydration and forming alumina $Al_2O_3$ in the form of a white powder. Around the world, approximately 90% of alumina is used to produce primary aluminium and the remaining 10%, called "specialty aluminas", have a variety of non-metallurgical uses such as water treatment, manufacture of refractory products, ceramics, abrasives, special glasses, etc. Specialty aluminas account for most of the production at ALTEO Gardanne, the last alumina production plant in France. Alumina production also generates bauxite residues, more commonly known as "red mud". These residues are rich in iron oxides ($Fe_2O_3$ which is responsible for the red colour), alumina ($Al_2O_3$), silica ($SiO_2$) and lime ($CaO$). Bauxite residues are usually first washed to extract as much caustic soda as possible and then stored in dedicated areas. This waste is sometimes put to use, particularly in the construction sector or agriculture.

The alumina thus obtained can be used to produce aluminium by electrolysis. The resulting metal is then called "primary" aluminium. In the Hall-Héroult process, invented in 1886 by the American Charles Hall and the Frenchman Paul Héroult, alumina is dissolved in a liquid bath at approximately 960°C, which is placed between two carbon electrodes. The electric current flowing between the anode (+ pole) and the cathode (- pole) converts alumina $Al_2O_3$ into liquid aluminium and $CO_2$ by combination of oxygen with the carbon that makes up the anode. These so-called process $CO_2$ emissions form an essential part of the direct emissions of the French aluminium industry, in the order of 50%. The liquid metal is then siphoned off and sent to the foundry for processing and shaping.

**Bauxite owes its name to Les Baux-de-Provence, the town in the Bouches-du-Rhône where it was discovered by the French chemist Pierre Berthier in 1821. France was to remain the world's leading producer of bauxite until 1939. The Hall-Héroult electrolysis process, still the most widely used for primary aluminium production, was invented in 1886 by the American Charles Hall and the Frenchman Paul Héroult.**

# 3.2. ... up to consumption on various markets

Figure 8 shows the dispersion of aluminium consumption flows along the value chain. While already complex, this illustration remains simplified as it masks a reality in which many steps in the processing of the metal are used together, depending on the required market applications. For example, rolling provides plates, sheets or foils, mainly for the automotive and packaging markets. The extrusion process provides sections and wire, which are generally used in the construction (window frames) and cable markets. Aluminium products can also be subjected to surface treatments (lacquering, anodising) and heat treatments (annealing, quenching, tempering) to improve their properties. After the traditional sectors consuming large volumes of aluminium, such as construction, public works and transport, the metal is found in many everyday applications. This dispersion complicates the traceability of flows and also hinders the recovery of waste for recycling. Once the finished products (cans, cars, window frames, household appliances, etc.) have reached end of life, the recovered aluminium is re-injected into one of the two major recycling channels: refining and direct recycling. Mixed with primary aluminium and manufacturing offcuts, the aluminium waste is re-utilised as "secondary" aluminium for a new cycle of use.

The whole sector is also strongly integrated with international trade. For example, although the rates may vary by a few percentage points each year, more than 50% of the primary aluminium produced is exported, whereas approximately 70% of the primary aluminium consumed in France comes from imports. This configuration implies that the evolution of international trade must be regarded as an important issue when building prospective scenarios, in the same way as the deployment of inert anode technology in the production process.

### MODEIRE tool: Modelling decarbonisation of the resource-energy industry

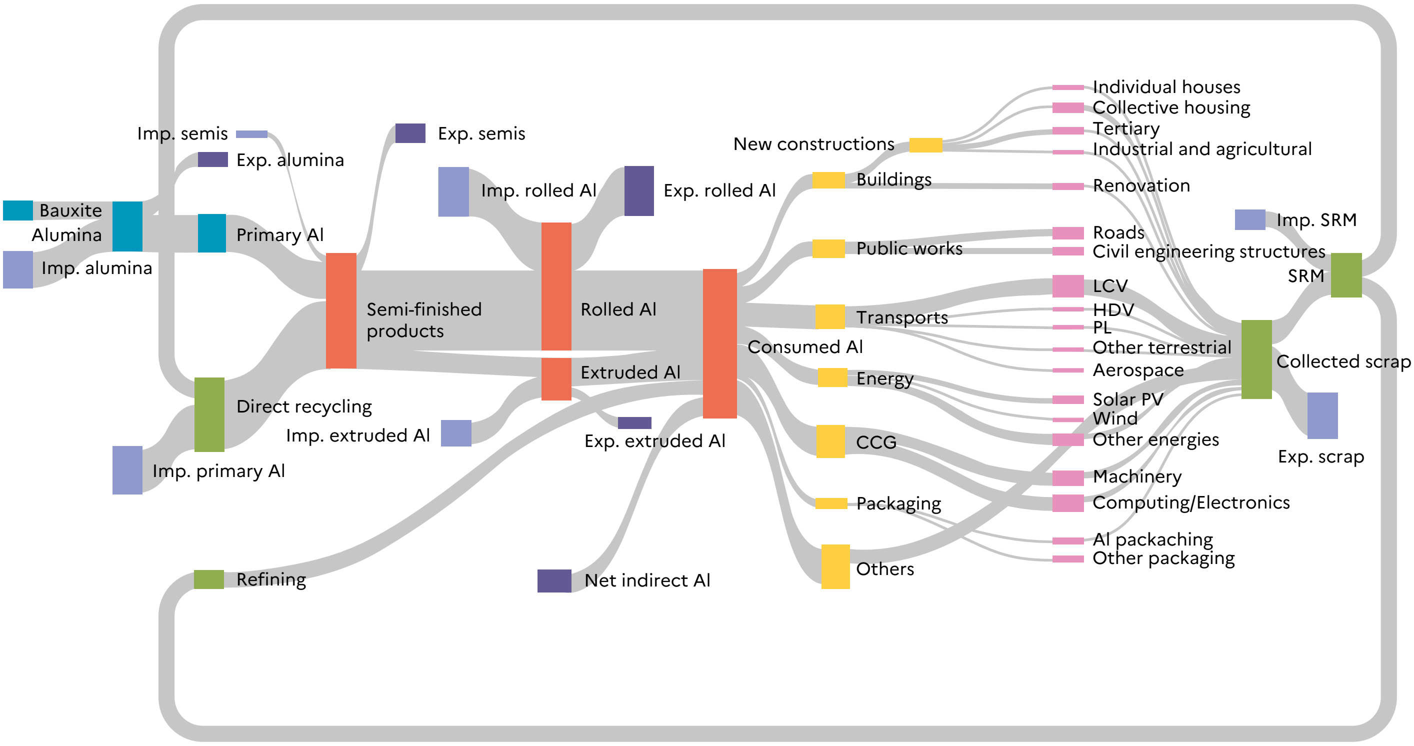
MODEIRE is the new version of the Excel modelling tool Pepit0 developed in partnership with the NEGAWATT ASSOCIATION and which aims to assess levels of demand for materials, especially those from the 9 most energy-intensive industrial sectors (steel, aluminium, cement, glass, chlorine, ammonia, ethylene, paper/cardboard and sugar), based on change scenarios for the consumer markets of these materials (mechanical, electrical, textiles, transport, etc.). These scenarios are based on assumptions made up to 2050 on a set of more than 600 parameters (demographics, recycling rate, per capita consumption of capital goods, distance travelled by vehicle, etc.). Used in other Sectoral Transition Plans, the tool estimates annual waste levels and now incorporates assumptions about the circular economy.

[11] Perspective d'Evolution de la Production Industrielle pour une Trajectoire 0 carbone (Prospects for changing industrial production for a zero-carbon pathway) - Tool developed by the negaWatt association on behalf of ADEME.

Note for the reader: On the upstream part of "aluminium consumed" each node corresponds to a stock of aluminium equivalent, supplied by imports and domestic production, from which there is one flow to export markets and another to the domestic market. The balance of indirect aluminium is an estimate of the tonnage of aluminium contained in products consumed by the macro-sectors. It is positive, because there is more aluminium in imports than in exports, and therefore feeds the aluminium footprint of French final consumption, distributed across the various uses.

➜ Picture by ALTEO Alumina/ALTEO Gardanne plant 4

**Figure 8. Sankey diagram for aluminium (source: ADEME, based on mapping of Pepit0[11] data).**



# 3.3. Introduction to technological drivers for decarbonisation

The main decarbonisation technologies for the aluminium sector are shown in Figure 9. A few additional drivers have been listed and described in the full report but are not included in the decarbonisation trajectories due to their very low level of maturity or, more simply, the lack of information about them in the literature (e.g. electrolysis of aluminium chloride, anodes based on bio-based carbon, electrolytic waste purification).

With regard to $CO_2$ capture technology in the aluminium industry, it can essentially be envisaged for primary aluminium production (in the electrolysis cells) or for alumina production. However, capture technology for the $CO_2$ from electrolysis cells is currently much less advanced, resulting in a relatively low TRL of around 3-4 for aluminium, while for other industries it is closer to 9 (e.g. cement, steel or electricity generation). The main difficulty associated with $CO_2$ from electrolysis lies in its very low concentration in the flue gases (less than 1%). This requires reconfiguring the cells to pre-concentrate the $CO_2$ (at least up to 4%) before capturing it, with an energy penalty that is admittedly still large, but more tolerable. Hence, there are also major R&D issues surrounding this technology.

➜ Picture by HYDRO/Jo_Michael_Alumina

**Figure 9. Main decarbonisation levers for the aluminium industry.**

**Lever 1**

Energy efficiency

As in any industry, there is a potential to improve energy efficiency. Many techniques are specific to the industrial sites (replacement of fans, prevent leakage in compressed air circuits...) and are usually part of current expenditures. The technologies that are most largely deployable are regenerative burners (equivalent to oxyfuel burners in terms of energy gains).

**Lever 2**

Fuel mix

Besides electricity, the aluminium industry also consumes natural gas for thermal usage. On of the solutions explored by the industry is the substitution with low-carbon vectors such as biogas or hydrogen. Despite constraints related to product quality, direct combustion of hydrogen is deemed technically possible on some process steps (alumina calcination, foundry) up to 20-30%.

**Lever 3**

Electrification

There are different electrification technologies either mature or still in R&D phase that can used at various process steps. These technologies yield emissions reduction by substituting fossil fuels, primarily natural gas. These technologies include Mechanical Vapor Recompression (MVR) for the alumina process or induction furnaces for recycling foundries.

**Lever 4**

Inert anode

The inert anode is a breakthrough technology designed for primary aluminium smelters. The pre-baked carbon anode that takes part in the reduction of alumina is replaced by an inert material. This way, instead of producing $CO_2$, the reaction releases oxygen. Several companies work on the development of the technology but has not yet reached commercial readiness. For more information, see chapter 3.2.

**Lever 5**

Carbon Capture and Storage (CCS)

This technology, not yet deployed on an industrial scale, aims to trap the $CO_2$ in an impermeable geological formation and can therefore theoretically cut out almost all of a site's emissions. It first involves capturing, purifying and concentrating $CO_2$ from industrial sites and then transporting it to a storage site. For the aluminium industry, the technology can apply to aluminium smelters and for alumina production plants.

# 3.4. Focus on inert anode technology

Alumina electrolysis produces $CO_2$ by consuming the carbon anode at a rate of approximately 1.5 $tCO_2/t_{aluminium}$ and accounts for about 90% of direct greenhouse gas emissions from primary aluminium production.
The principle of the inert anode is to prevent the reaction between oxygen contained in the alumina and the carbon of the anode to form $CO_2$. Instead, the expected chemical reaction would produce only liquid aluminium and oxygen.

$$2\,Al_2O_2 + 3\,C \rightarrow 4\,Al + 3\,CO_2 + \textit{heat} \Rightarrow 2\,Al_2O_2 \rightarrow 4\,Al + O_2$$

**The development of the inert anode remains highly confidential for the moment, making it difficult to find reliable information on this subject. In particular, the relatively low investment cost presented in the model should be viewed with great caution. Indeed, this figure of 1,590 EUR/talu.year for the cost of constructing a new inert anode smelter comes from an ADEME assumption based on the few available sources in the literature, not considered to be sufficiently robust[12, 13, 14].**

**The inert anode investment cost included in the model does not come from RIO TINTO or the ELYSIS consortium, who are both working on its development.**

➜ Picture by Aluminium Dunkerque/Secteur Carbone - Anodes

## A race for technological leadership...

Two major competing manufacturers are working on development of the inert anode, with a TRL currently estimated at 4-5 (Figure 10): the ELYSIS project, a partnership between RIO TINTO and ALCOA, and the RUSAL Group, the world's leading aluminium producer. The ELYSIS joint venture, launched in 2018, aims to develop an inert anode technology and market it by 2024. The project has already received a total investment of US$144m[15] (mainly for R&D) and notably received financial support of US$14m from Apple, for which aluminium represents 24% of the carbon footprint associated with the manufacture of its products. For its part, RUSAL has reportedly started testing an inert anode architecture at its Krasnoyarsk plant in Siberia. According to a 2019 press report, the Russian group was aiming to market its technology by 2021, while another more recent source indicates that large-scale deployment would not take place before 2030. ARCTUS METALS in Iceland is also developing an inert anode technology. Although the project appears to be much less well known and publicised than ELYSIS and RUSAL, the company has already managed to produce high-purity aluminium (99.9%) at laboratory scale with an electrolysis cell composed of vertical inert anodes and drained cathodes at an electrolyte temperature of 800°C. ARCTUS METALS also signed a cooperation agreement with TRIMET Aluminium in 2020 to pursue development to industrial scale and eventually convert its four electrolysis plants (Essen, Hamburg, Voerde in Germany and Saint-Jean-de-Maurienne in France).

[12] J. H. Magnusson et R. M. Falkenberg, Clean Aluminium Production Process, 2016 https://www.stjornarradid.is/library/02-Rit--skyrslur-og-skrar/Arctus_KIC_25%20aug%202016.pdff

[13] Climate Technology Centre and Network, "Inert Anode Technology for Aluminium Smelters", UNFCCC https://www.ctc-n.org/technologies/inert-anode-technology-aluminium-smelters

[14] J. Moya, A. Boulamati, S. Slingerland, R. van der Veen, M. Gancheva, K. Rademaekers, J. Kuenen and A. Visschedijk, "Energy Efficiency and GHG Emissions: Prospective Scenarios for the Aluminium Industry", Publications Office of the European Union, Luxembourg, 2015. https://publications.jrc.ec.europa.eu/repository/handle/JRC96680

[15] Million US dollars

➜ Picture by Yulia Grigoryeva/Shutterstock.com

## ...to develop a concept that is actually old...

The cell architecture composed of several vertical anodes and drained cathodes (as being developed by ELYSIS and ARCTUS METALS) now seems a more promising path than the installation of an inert anode on a conventional Hall-Héroult cell. The latter path was the subject of nearly 20 years of R&D (between 1990 and 2008) without real commercial success. It is also interesting to note that the inert anode is a technology that has already been imagined, theorised and tested for a long time (the first tests of inert anode materials date back to 1937, with the work of A. I. Belyaev and A. E. Studentsov). Charles Hall, one of the two inventors of the Hall-Héroult process, had already theorised the concept of an inert anode when he filed his patent in 1886. The fundamental problem with the inert anode is that it has to operate at a higher voltage than a Hall-Héroult cell, which results in overconsumption of electricity. To offset this energy penalty, the anode-cathode distance should be reduced, but this tends to create electromagnetic instabilities in the tank.

## ...and for which the key lies in the materials

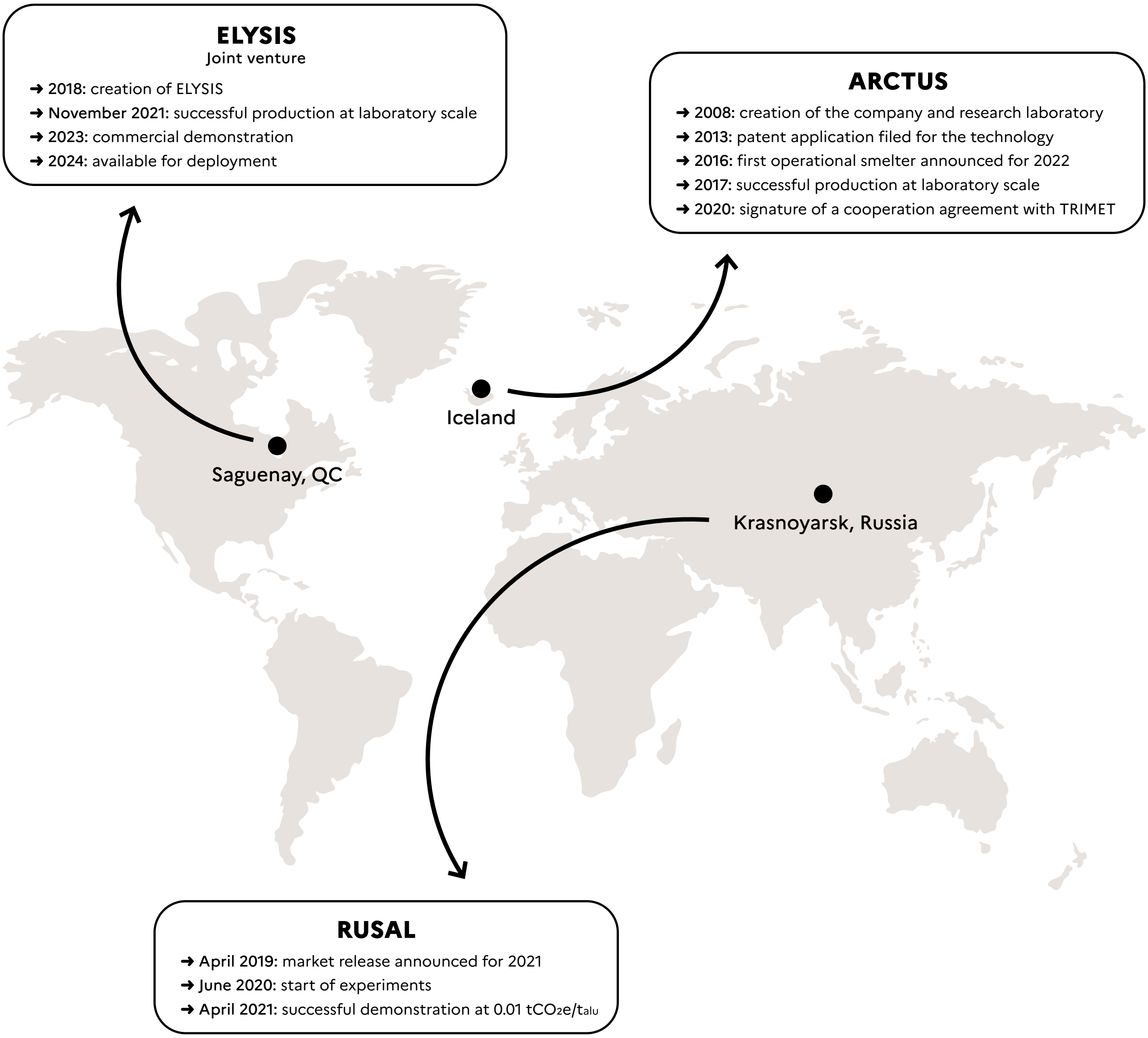
Among the technical difficulties related to its development, inert anode electrolysis diffuses many impurities into the liquid aluminium. It can corrode and have low thermal resistance. The correct operation of inert anode technology therefore depends largely on the choice of the materials that make it up. The search for materials with the required properties and also able to resist corrosion has focused on several paths detailed in the report: ceramics, metals and cermets.

Regardless of its composition, it appears that an inert anode technology will necessarily contain a number of metals (e.g. copper, iron, nickel, tin, antimony, etc.) which, in France, are now mostly imported. The volumes involved appear relatively small at first glance, but the impact of an industrial-scale switch to the inert anode on the consumption of these metals may require further assessment. In addition, and contrary to what its name might suggest, an inert anode does not have an unlimited lifespan. Some of its constituent materials diffuse into the aluminium as it is used (at least for metal-based technology). Just like a carbon anode, it must be replaced, but at a much lower frequency (about once a year[16]). For smelters, moving to the inert anode will thus likely result in them ceasing to manufacture anodes in house and instead having to procure them from external players who own and master the technology.

**The inert anode thus represents a potential radical change to the current operation of the aluminium industry, both from the environmental point of view and from the point of view of the new interdependencies between industrial players.**

[16] Source: V. B. and L. Kiss (2015) - Comparative analysis of the environmental impacts of aluminium smelting technologies.

**Figure 10. Major industrial players involved in the development of inert anode technology.**




➜ Picture by Aluminium Dunkerque/Secteur Electrolyse - série de cuves

➜ Picture by Aluminium Dunkerque/Secteur Fonderie - Fours

# 4. Staging barriers and drivers to decarbonisation by building two contrasting scenarios

## 4.1 Two contexts for transition that make it possible to achieve the SNBC target for an 81% reduction in greenhouse gas emissions

Given that availability of the inert anode and the evolution of international trade have been identified as the two most decisive parameters in the decarbonisation of the French aluminium industry, they have been used to build two contrasting and consistent transition universes.

Both scenarios meet the 81%[17] reduction target in 2050 but under different circumstances. They are primarily intended to outline the main challenges facing the sector by providing answers to the following questions: under what conditions can French manufacturers have access to the inert anode? If they cannot, what technological and industrial efforts would be needed? What is the potential of alternative solutions? What is the role of recycling in the transition of the sector? What impact would a European Carbon Border Adjustment Mechanism (CBAM) have on the French and European sector? How can ambitions for industrial sovereignty be combined with decarbonisation? What "no regrets" actions can be identified and implemented today? Under no circumstances do these scenarios claim to have the right

[17] With a 94% reduction, the "international cooperation" scenario goes well beyond the 81% target. This is linked to the particularly large gain from the inert anode which, combined with other technically feasible drivers in the other segments of the industry (alumina and direct recycling), makes it possible to achieve such a level of decarbonisation, close to neutrality in 2050.

[18] For more information, visit the dedicated website: https://transitions2050.ademe.fr/

answers or all the keys to the future development of the aluminium industry. They merely offer suggestions for possible paths given the issues identified.

Table 2 presents the main contextual elements that differ between the two scenarios, apart from the level of domestic demand. **The philosophy of the "international cooperation" scenario is based on a relatively favourable global geopolitical environment in which implementation of the CBAM, in line with its objectives, speeds up decarbonisation of the industry** in the main partner countries and ensures fairer competition, in particular through harmonisation of carbon pricing. The "cooperation" is also diplomatic and scientific: with the involvement of France, **the inert anode technology developed by the ELYSIS consortium is made commercially available to aluminium manufacturers.** The other inert anode projects, from RUSAL and ARCTUS METALS, are also reaching maturity. The carbon content of the French energy mix (mains electricity and gas) is evolving in line with the trajectory of the trend scenario in ADEME's prospective exercise "Transition(s) 2050"[18] (Figure 11).

By contrast, the "regional polarisation" scenario postulates growing tensions in international relations that will crystallise when the CBAM is implemented. The CBAM, seen as a form of European protectionism by third countries, does not produce the hoped-for incentive effects. This will result in regionalisation of trade. Due to competition, and also technical complications during the transition to industrial scale, French aluminium stakeholders do not have access to inert anode technology. **Recycling is thus given priority, while the decarbonisation of primary aluminium relies almost entirely on the mastery and deployment of technologies for $CO_2$ capture from the electrolysis cell.** Due to its similarity to the narrative of scenario S2 of ADEME's prospective exercise "Transition(s) 2050", it has been assumed that the carbon content of the French energy mix (namely electricity and gas) in this "regional polarisation" scenario evolves in line with the scenario S2 trajectory (Figure 11).

**Figure 11. Assumptions on the change in the energy mix carbon content for the different scenarios (source: ADEME Transition(s) 2050).**

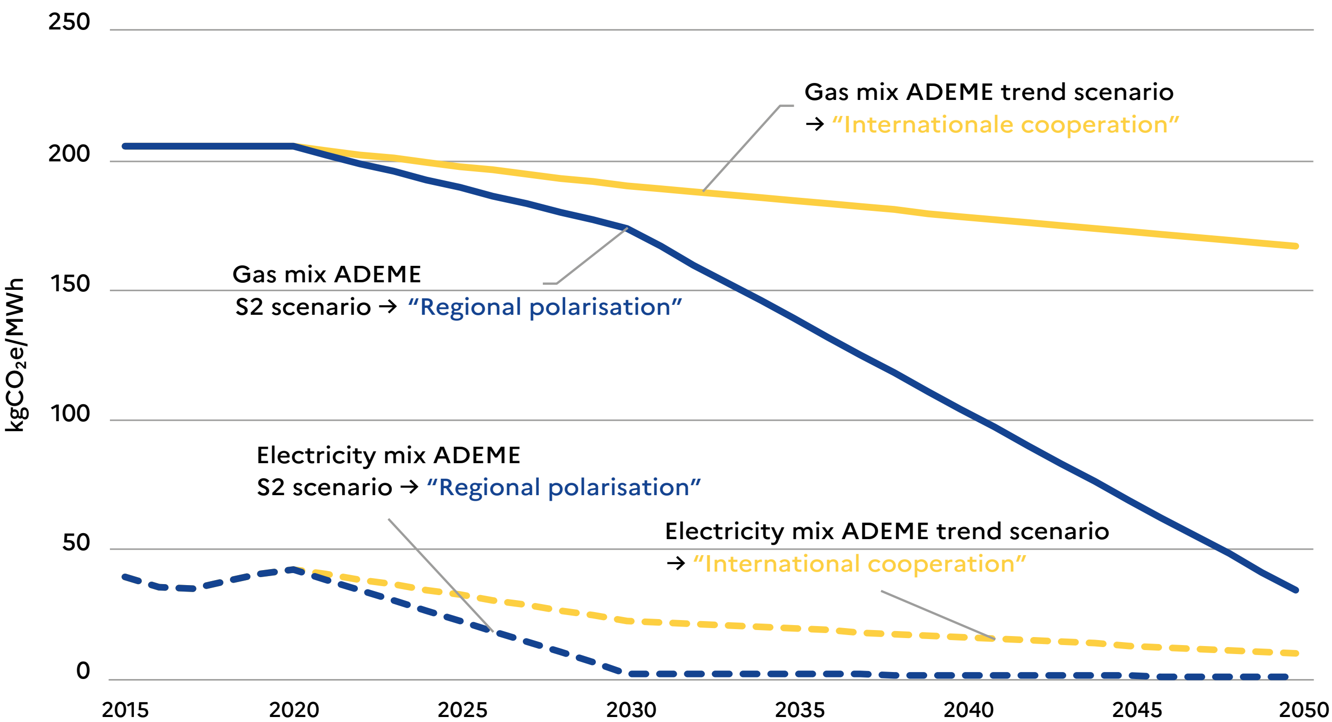


**Tableau 2. Summary of the main contextual elements for each scenario[20].**

| | "International cooperation" scenario | "Regional polarisation" scenario |
|---|---|---|
| Increase in domestic demand for aluminium | ★★★<br>In line with the transition contexts, the "market" evolution of these scenarios is more a matter of international trade than the domestic market. Hence, the assumed demand from the French market is considered to be identical for both scenarios and likely to increase. This increase in domestic demand is mainly driven by an acceleration in the renovation of buildings, transport infrastructure more geared towards rail, a trend towards lighter and electric vehicles, more connected lifestyles, a decline in plastic packaging in favour of other materials including aluminium, and the development of renewable energies. | |
| CBAM and opening of international trade | ★★★<br>Despite some of them changing direction, trade flows are generally expanding. The harmonisation of carbon pricing initiated with the introduction of the CBAM at EU borders promotes this openness and fairer competition between countries. New fiscal and regulatory measures are being taken to boost decarbonisation of industry abroad, thus preventing carbon leakage. As the trend remains towards business specialisation, alumina production is concentrated in bauxite-rich regions such as Guinea, Australia and Brazil, from which smelters can now obtain their supply. | ★☆☆<br>European industrial policy, and in particular the introduction of the CBAM, is seen as a form of protectionism by other countries. Access to the European market is more restricted and these third countries are gradually choosing to reduce their trade with Europe and redirect it on a more local scale. In particular, application of the CBAM will not have allowed third countries to catch up on carbon pricing and these countries will seek to circumvent the mechanism through "resource shuffling"[19] practices. For commercial and political reasons, the international landscape is divided into several major regional hubs, thus hindering attempts at international cooperation on technology. |
| Successful development of the inert anode | ★★★<br>By 2025, the technology has been mastered at industrial scale by the groups working to develop it. In the context of closer relations with certain countries that are developing the inert anode, France benefits from preferential access to the technology, which it will use to open a new smelter on its territory. However, this choice will create a new reliance on foreign companies to provide the technology. | ★☆☆<br>Despite some delays to the announced dates, the main industrial groups have mastered the inert anode but refuse to sell it to competitors (especially in Europe) or only under conditions that are far too restrictive given the competitive advantage it provides. The strategy of French and European smelters thus focuses on the development of carbon capture from electrolysis cells. |
| Scale of recycling | ★★☆<br>While not sufficient to meet all the demand, recycling is taking up an increasing share. Sorting and collection techniques are improving and secondary aluminium is highly valued and sought-after for its environmentally friendly credentials. The refining activity, its outlets significantly reduced with the disappearance of internal combustion vehicles, is gradually being transformed into direct recycling. International trade in waste continues to follow current trends. | ★★★<br>The European-wide circular economy strategy is gaining ground in France and the efficiency of collecting, sorting and recycling aluminium waste is significantly improving. In addition to its environmental benefits, recycling is ranked among the drivers for strategic independence in European policy-making. With an increasing amount of end-of-life waste and a more restricted supply of primary aluminium, refining remains a preferred recovery route. New outlets are opening up to the sector, particularly in the automotive and construction sectors. |

[19] Resource shuffling" is the practice of allocating or diverting existing low-carbon production for export to the European Union in order to circumvent a possible Carbon Border Adjustment Mechanism (CBAM).

[20] The star rating in no way represents an absolute value for the parameters and does not reflect value judgements. It simply compares aspects of the scenarios qualitatively and arbitrarily.

[21] At this stage, no geological storage capacity has been identified in the Fos-sur-Mer area (see ADEME opinion on the potential of CCS in France), so the deployment of a future $CO_2$ hub remains a speculative assumption. However, studies have already been carried out and are under way to assess storage potential in the surrounding area, particularly in the Mediterranean Sea. Italy is also developing the first storage project in the Adriatic Sea. Offshore storage could thus ultimately be a route for the manufacturers in the area.

# 4.2 Deployment of the inert anode in the context of "international cooperation": an ideal but uncertain scenario

In the "international cooperation" scenario, emissions are reduced by 94% in 2050, even with a doubling of domestic production (see Figure 12). The 81% reduction target is thus comfortably achieved. French primary aluminium production is increasing, resulting in the opening of a new inert anode smelter in 2030. Other existing smelters are being converted to an inert anode process at the same time. As announced in 2021, ALTEO Gardanne's alumina production site has shut down its Bayer process and processing is now limited to the calcination of imported alumina hydrate, with the site focusing on the production of specialty aluminas. Alumina calcination capacity has doubled between 2025 and 2030 to meet the growing demand for specialty aluminas for high-end applications (special glasses, ceramics, refractory materials, etc.). Taking advantage of the deployment of a $CO_2$ hub in the Fos-sur-Mer[21] area and by analogy with the cement process, the decarbonisation of alumina calcination kilns is achieved by adopting CCS-type technology as from 2040. Without the introduction of this technology, emissions would be reduced by 86% in 2050 instead of 94%. As regards direct recycling, energy efficiency measures (regenerative burners and/or oxy-fuel burners) are first adopted, then the plants are electrified and new capacity is opened from 2030 to meet the growing demand for aluminium.

With implementation of the inert anode only taking place after 2030, the reduction in emissions between 2015 and 2030 is only about 20%, which is insufficient given the 35% crossing point stated in the SNBC for the manufacturing industry. The final emissions level is reached around 2040 following the decarbonisation of the alumina segment using CCS. However, the drop in direct emissions is so steep following adoption of the inert anode from 2030 that cumulative emissions from the sector between 2015 and 2050 are lower than the SNBC carbon budget applied to the French aluminium industry (see Figure 5).

**Assuming that the inert anode is adopted, it is thus likely that the decarbonisation trajectory of the aluminium industry will take a stepwise shape. The challenge is to achieve this breakthrough as quickly as possible, to comply with the SNBC carbon budget.**

**Figure 12. "International cooperation" scenario**
**Change in GHG emissions from the French aluminium industrym[22].**

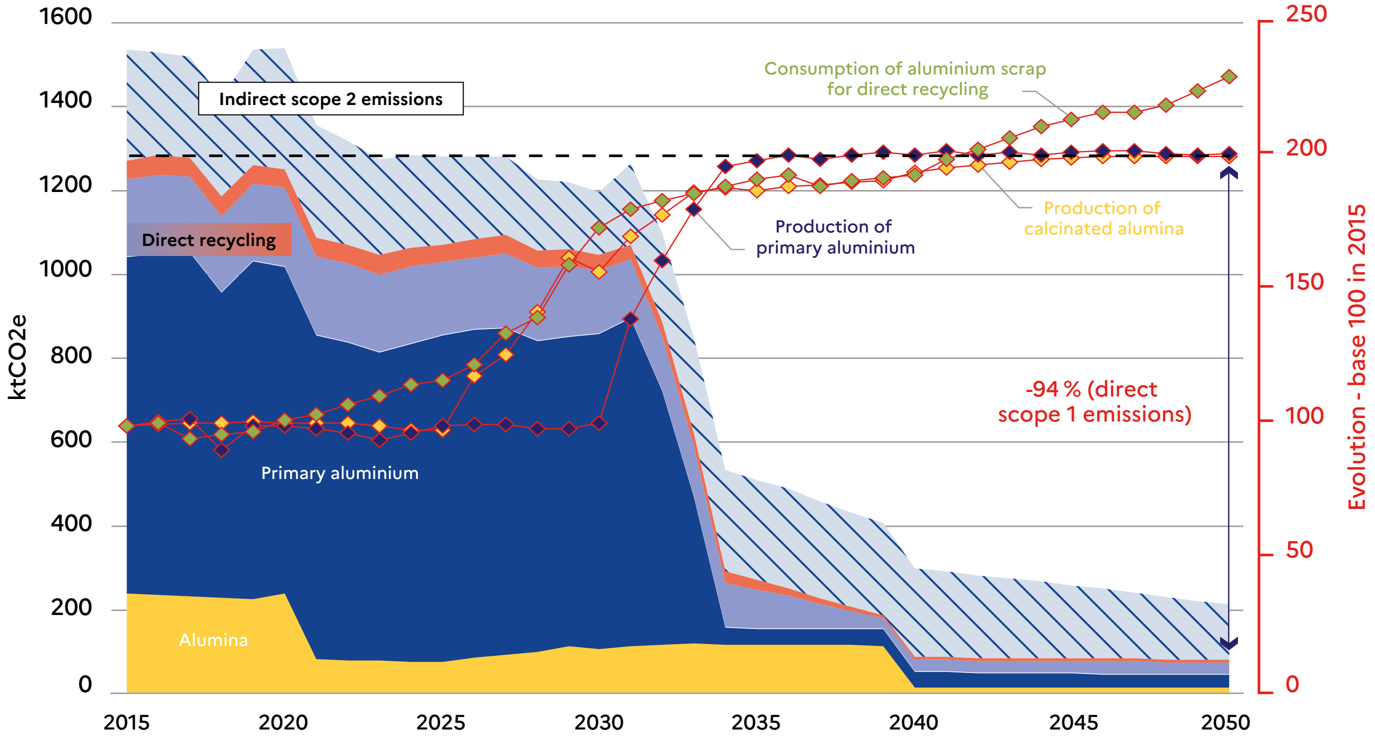
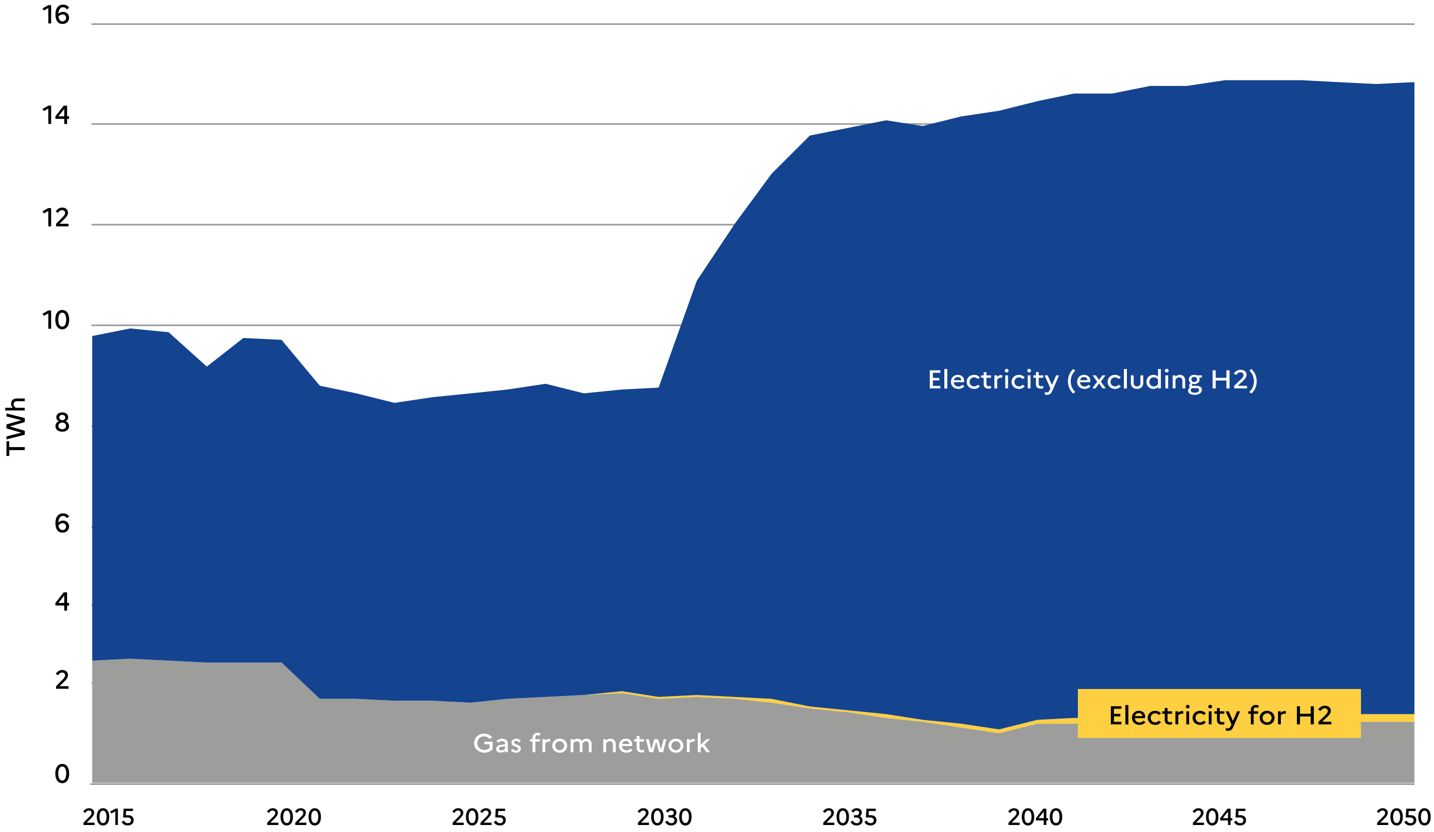


**Figure 13. "International cooperation" scenario**
**Change in energy consumption of the French aluminium industry.**




In 2050, the residual emissions (about 80 $ktCO_2e$) come from several sources. First, for alumina calcination, the capture rate has been set at 90% and hence a fraction of the $CO_2$ continues to be emitted to the atmosphere. There are also residual emissions linked to gas consumption for certain thermal needs, mainly at foundries and recycling sites, which is not fully decarbonised by 2050 in this scenario (see Figure 11).

The scope 2 indirect emissions related to electricity consumption are shown in Figure 12 for illustrative purposes only: they are not included in the 81% reduction target for direct emissions. However, the graph illustrates their significant size compared with direct emissions, even though the French electricity generation mix is considered highly decarbonised. Although the carbon content of the electricity generation mix is expected to decrease by 75% between 2015 and 2050 (see Figure 11), due to the increase in production and the trend towards electrification of processes (see Figure 13), these scope 2 emissions are only slightly reduced.

As Figure 13 shows, electricity consumption increases sharply in the "international cooperation" scenario from around 7 TWh in 2015 to over 13 TWh in 2050. This increase is chiefly linked to the opening of new electrolysis capacity and, to a lesser extent, the electrification of many recycling processes. Mains gas consumption is reduced by almost 40% due to the shut-down of the Bayer process and electrification of other processes.

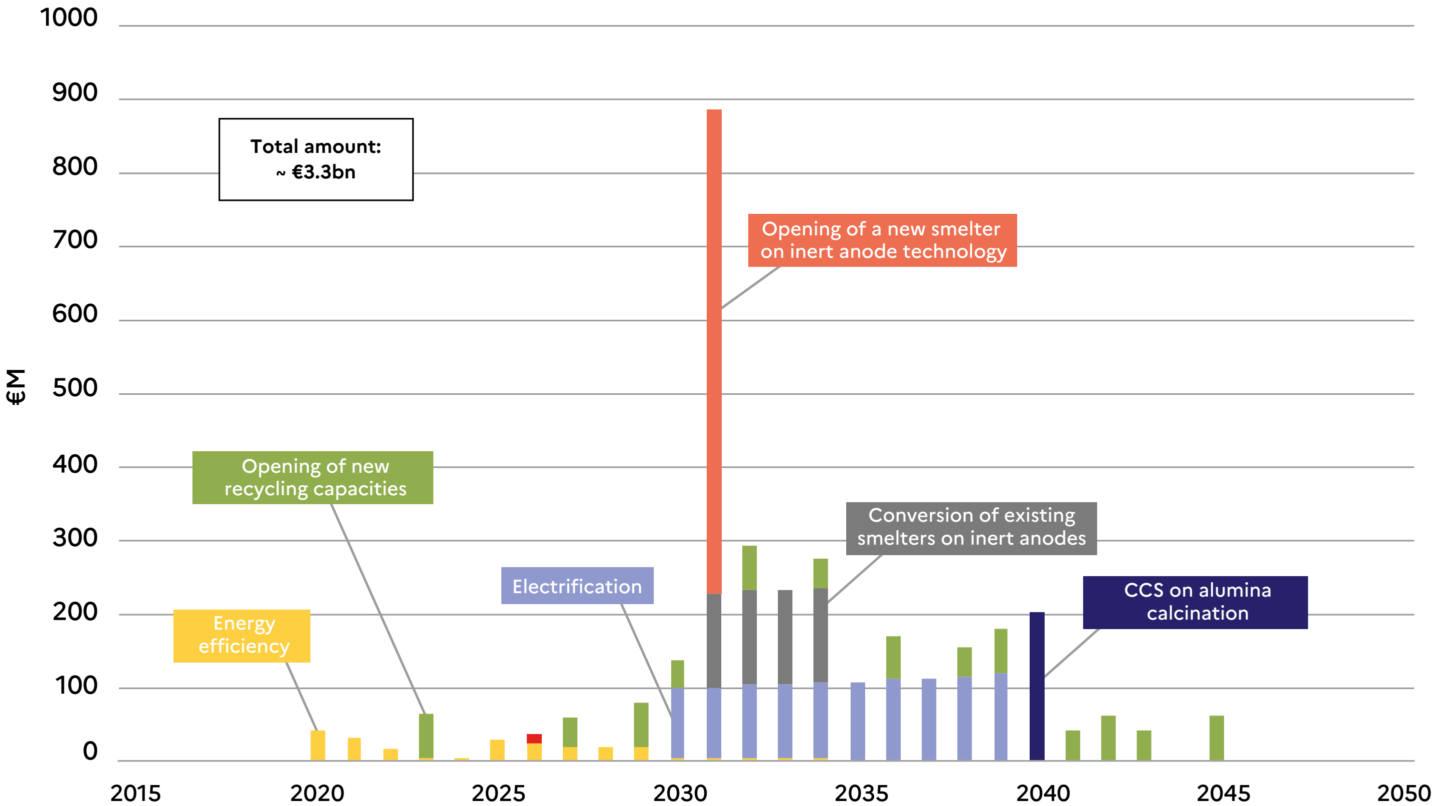
**Such a scenario will, of course, only be possible if low-carbon electricity generation and the associated infrastructure are sufficiently available and at a competitive cost for manufacturers.**

[22] Direct recycling has been modelled based on two "typical" plants: one recycling plant performing rolling and another performing extrusion.

The total amount of investment needed (Figure 14) to achieve this trajectory is around €3.3bn, of which 40% (€1.3bn) is related to the opening of new capacity (recycling and an inert anode smelter). The opening of the new inert anode smelter appears as an investment peak in 2031. It should be noted that this new capacity does not contribute to direct emissions reduction in the same way as energy efficiency or carbon capture and storage technologies, but it should be considered as an indirect support measure for decarbonisation in the context of an increase in demand.

➜ Picture by ALTEO Alumina/ALTEO R&D 5 bis

**Figure 14. "International cooperation" scenario**
**Investment time line for the French aluminium industry[23].**




[23] The costing of deployment of the inert anode is based on assumptions from literature sources that are not considered to be very robust and hence these economic results should be viewed with great caution. The cost of acquiring inert anode technology today remains a major source of uncertainty for aluminium stakeholders. Furthermore, no confidential information has been provided to ADEME by the industrial groups involved in the development of the inert anode.

➜ Picture by HYDRO/Halvor_Molland_Recycling_Postconsumed1

# 4.3. What industrial transformation is possible without the inert anode? A "regional polarisation" scenario to explore other drivers

The "regional polarisation" scenario was built under a dual constraint: achieving the 81% reduction target by 2050 (see Figure 15) and without using inert anode technology. It thus gives an idea of the technological and industrial means to be used to achieve the decarbonisation objectives in such a framework as well as the international context in which this could occur. The technological assumptions and industrial transformation described below are largely the result of these two input constraints.

Domestic demand for aluminium increases in line with the "international cooperation" scenario but domestic production changes in a different way as a result of international trade. As Europe has few primary resources (bauxite and alumina) within its borders, the regionalisation of trade means that Europe must rely less on primary aluminium. This is why, although new electrolysis capacity is opened in France (+135 kt/year) to meet demand, it remains lower than in the "international cooperation" scenario (+415 kt/year). The use of recycling is therefore proportionally higher, especially for direct recycling of waste, which more than doubles between 2015 and 2050. The flows of aluminium waste traditionally exported are gradually being redirected to domestic consumption. Onshoring therefore takes place at several levels in the value chain. At the same time, waste sorting technologies are being deployed downstream and facilitate the incorporation of recycled raw materials, for which the rate increases to 73% in 2040! On the other hand, this rate gradually decreases between 2040 and 2050, due to the decrease in waste production in the country, which is not offset by increased imports of waste. This estimate of the change in the amount of waste available and the impact on the Recycled Raw Materials (RRM) rate, highlights the limitations of setting a standardised target for the RRM rate, which may not correspond to the amount of waste available. Under the conditions of this scenario, waste has become a strategic resource with a stock that changes according to past consumption, and which can thus produce undesirable effects if a potential reduction in this stock is not anticipated. As for the new recycling plants, they are largely based on electrical technologies between 2025 and 2030. Recycling plants are gradually switching to electrification technologies for their processes until reaching a rate of 100% by 2050.

Alumina production remains broadly stable but, unlike the first scenario (see section 4.2), it is redirected to the production of metallurgical alumina to supply European smelters. As announced in 2021, Altéo Gardanne's alumina production site has shut down its Bayer process producing alumina from bauxite. However, to manage the upstream value chain, a Bayer process plant is reopened in France from 2030, according to the best existing environmental standards to minimise local impact. In a circular economy approach, some of the bauxite residues are also used in cement applications and for the extraction of certain metals (such as titanium and scandium). The new process works using electrical mechanical vapour recompression (MVR) technology, thus eliminating gas consumption and the associated direct emissions. Decarbonisation of the calcination step is achieved in part by injecting 25% low-carbon hydrogen in place of mains gas.

The decarbonisation of primary aluminium is achieved through the deployment of CCS technologies at sites located near or connected to storage areas. This is also the case for new primary aluminium facilities, which will be built with CCS technology already incorporated. To partially decarbonise, the foundries of the various smelters are injecting 30% low-carbon hydrogen as a substitute for mains gas. Recycling plants are gradually adopting electrical furnace technologies.

**Comparison of the two trajectories (see Figure 12 and Figure 15) shows that decarbonisation of the smelters by CCS remains less favourable than use of inert anode technology, though it does achieve the SNBC target of an 81% reduction in GHG emissions in 2050.**

In particular, the residual emissions in 2050 are much greater (approximately 250 $ktCO_2e$), largely due to the $CO_2$ that is not captured from the electrolysis cells. The capture rate has been set at 78%, which is already considered technically ambitious for the sector.

Despite an increase of almost 3 TWh/year in electricity consumption between 2015 and 2050 (see Figure 16), scope 2 indirect emissions fall almost to zero by 2030, here reflecting the change in the carbon content of the French electricity generation mix (see Figure 11). As with the "international cooperation" scenario, low-carbon electricity generation will have to be in line with this new demand and offer a competitive cost to manufacturers.

**Figure 15. "Regional polarisation" scenario**
**Change in GHG emissions from the French aluminium industry.**

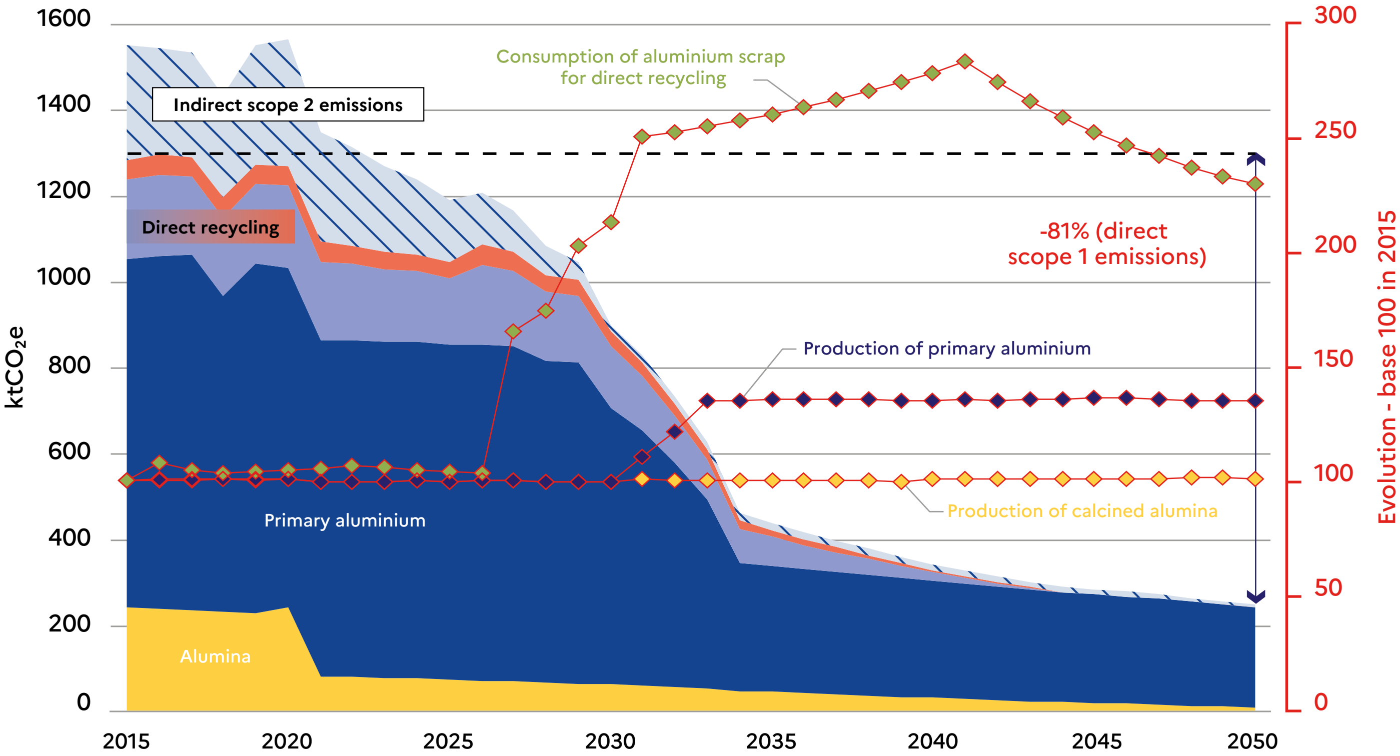
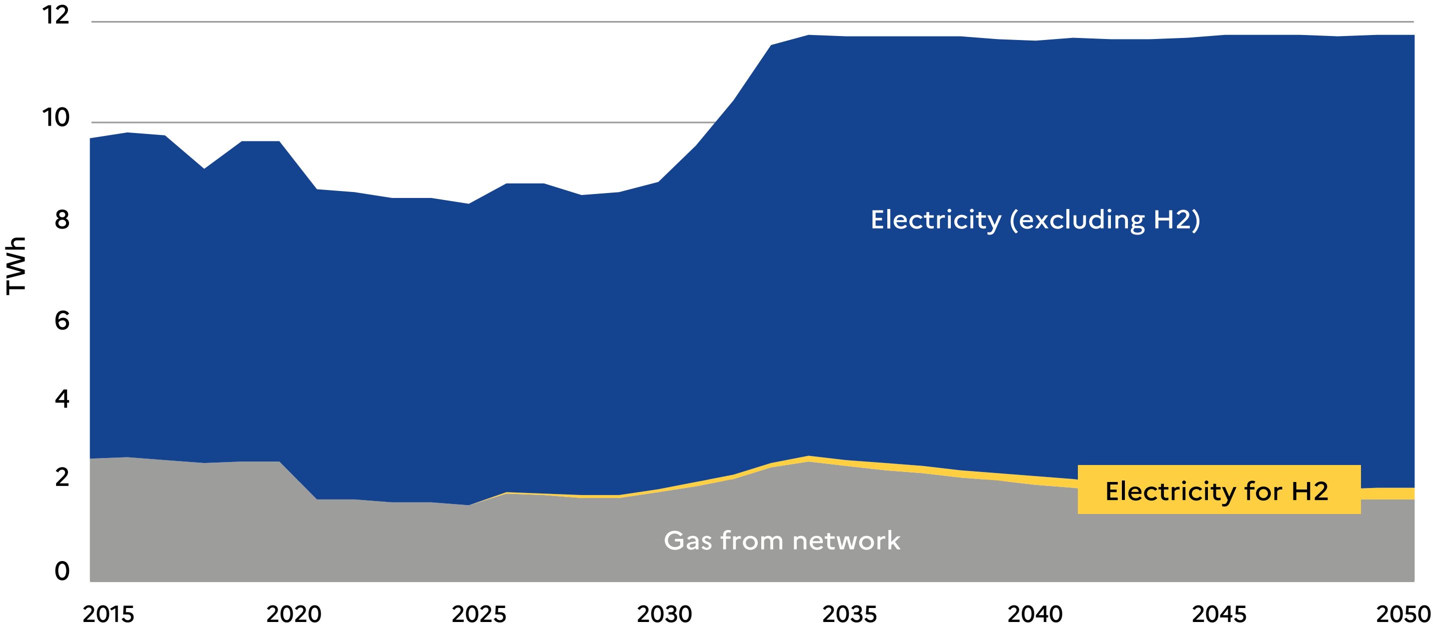
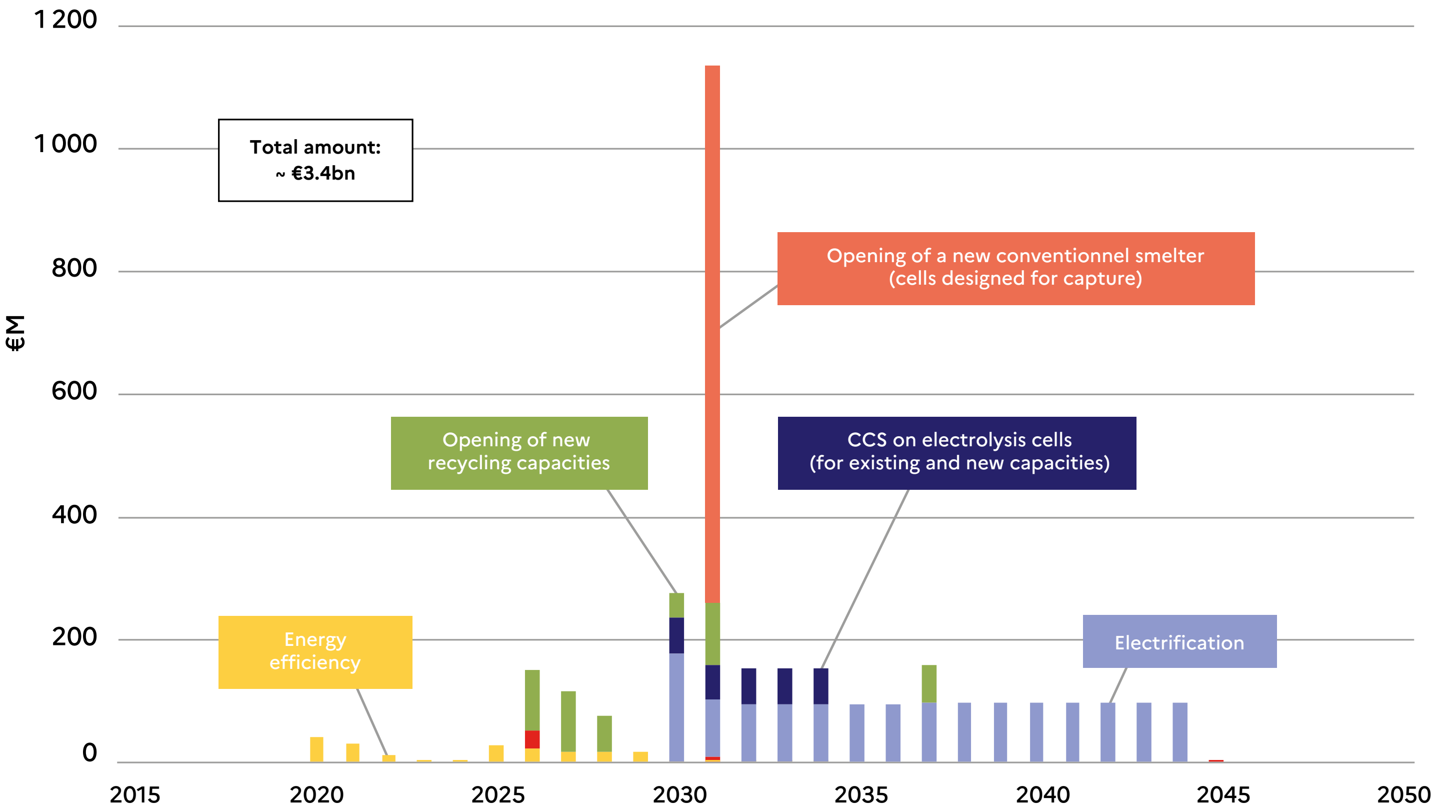


**Figure 16. "Regional polarisation" scenario**
**Change in energy consumption of the French aluminium industry.**




The total amount of investment needed (Figure 17) to achieve this trajectory is around €3.4bn, of which 40% (€1.3bn) is related to the opening of new capacity (recycling and a conventional smelter). The opening of a new smelter appears as an investment peak. It should be noted that this new capacity does not contribute to direct emissions reduction in the same way as energy efficiency or carbon capture and storage technologies, but it should be considered as an indirect support measure for decarbonisation in the context of an increase in demand.

**Figure 17. "Regional polarisation" scenario**
**Investment time line for the French aluminium industry.**



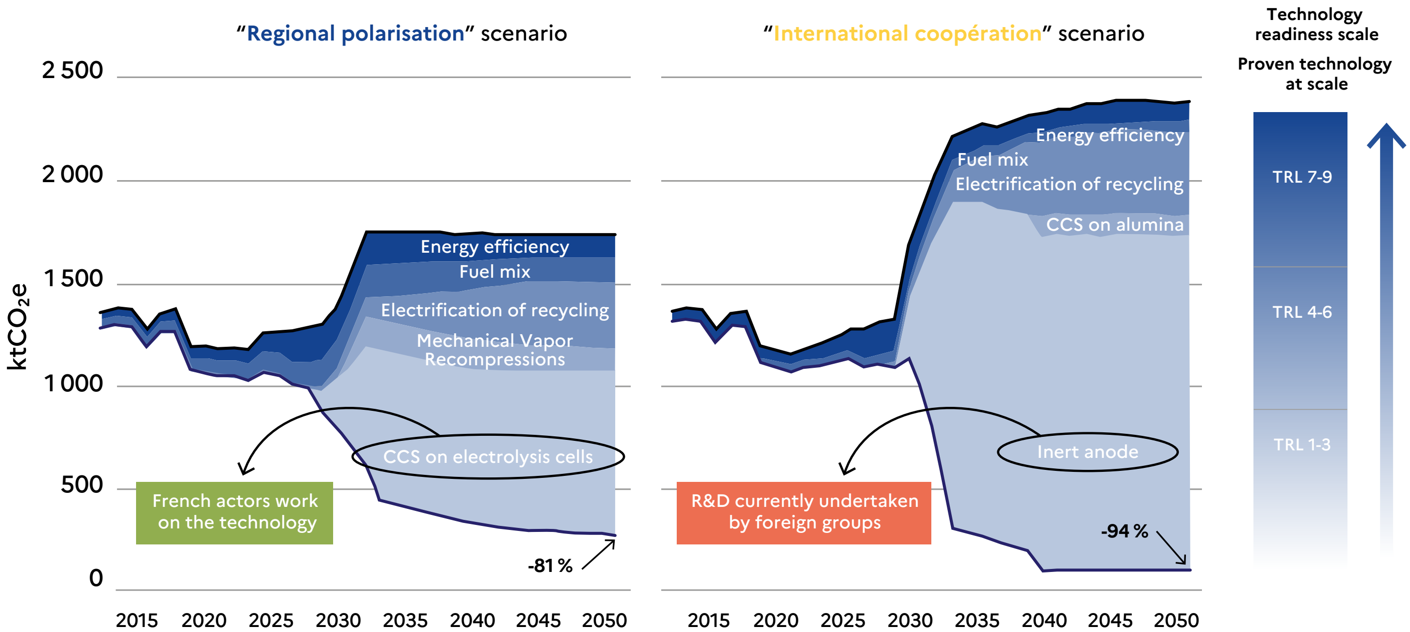
# 4.4. The technological bet of aluminium decarbonisation

Both scenarios achieve the 81% emissions reduction target at a high cost (see Figure 14 and Figure 17) and without using the same technologies. They are based on technological drivers that are not fully mature and that will take several years, or even decades, to reach a commercial stage. The risk that deployment on an industrial scale will be delayed, or even abandoned altogether, therefore remains all the greater given that the current maturity (measured by the TRL) is low. This is typically the case for the inert anode and capture of $CO_2$ from electrolysis cells (see sections 3.2 and 3.3), but also for other technologies such as large-scale mechanical vapour recompression, direct hydrogen combustion or high-capacity induction furnaces. Figure 18 shows the relative importance of each driver in the decarbonisation of both scenarios along with the associated technology readiness level. The graphs provide an understanding of the technological bet associated with each of the trajectories. Figure 18 clearly shows **the reliance of the "international cooperation" scenario on the inert anode and the reliance of the "regional polarisation" scenario on $CO_2$ capture.** Although they have similar levels of maturity, only capture is the subject of a research project in France, while the development of the inert anode is now mainly being carried out by foreign groups, and hence its availability to French stakeholders is not guaranteed. The uncertainty is all the greater as the inert anode technology would theoretically allow for gains in competitiveness compared with the conventional process (see section 5.3).

**The inert anode and capture from the electrolysis cell are thus key technologies in the decarbonisation of the French aluminium industry.**

Electrification is also a driver, particularly for recycling processes. As the recycling grows, it will also be increasingly subject to decarbonisation requirements. With energy-related emissions and the availability of some mature solutions such as induction furnaces or oxy-fuel burners, the decarbonisation of this segment appears to be technically more readily available than for primary aluminium. The main technological challenge for the recycling industry lies in the development of high-capacity electric furnaces, which provide higher productivity and lower costs. Today, for large production volumes, the choice of manufacturers is almost systematically focused on natural gas solutions. Induction furnaces are generally of interest for the low-volume production of certain alloys with a specific composition.

**Figure 18. Comparison of the "regional polarisation" (left) and "international cooperation" (right) scenarios - Abatement of GHG emissions from the French aluminium industry by technology associated with technology readiness level.**



# 5. Socio-economic analysis

## 5.1. Inert anode or CCS: impact on primary aluminium production costs

First of all, it is important to remember that the costing of deployment of the inert anode is based on assumptions from literature sources that are not considered to be very robust and hence these results should be viewed with caution. The cost of acquiring inert anode technology today remains a major source of uncertainty for aluminium stakeholders. Furthermore, no confidential information has been provided to ADEME by the industrial groups involved in the development of the inert anode.

For primary aluminium producers, the deep decarbonisation of the process is currently mainly envisaged through two technologies that at first sight seem to be in competition: $CO_2$ capture from electrolytic cells and the switch to the inert anode. While both can reduce a significant share of direct emissions, at least in theory, they are not economically equivalent. Cross-referencing several literature sources on the inert anode and CCS has allowed an estimate of the aluminium production cost for each of the technologies (see Figure 19). All the data and assumptions used to arrive at these production costs are detailed in the full report.

**Without a carbon price and CAPEX amortisation, the cost of producing aluminium at an inert anode plant would be 22% lower than that of a conventional smelter, while the cost for a CCS smelter would be 10% higher.**

**For primary aluminium production, the inert anode promises improved competitiveness compared with the conventional Hall-Héroult process.**

Compared with a conventional smelter, there are two main OPEX items that penalise CCS technology. First, the $CO_2$ capture entails an energy penalty. In the configuration modelled, the heat requirement is met using natural gas, with its consumption (and hence its contribution to the production cost) increased threefold per ton of aluminium. Then, once the $CO_2$ has been captured, it must be transported and stored, which adds €74/$t_{aluminium}$ to the production cost[25]. From the manufacturer's point of view, this "transport and storage" cost is recorded as an OPEX item, which in practice amounts to assuming that the industry pays for a network service provided by an outside company. Hence, even though transport and storage require material investment in infrastructure, they do not appear in the aluminium industry's investment time line.

In the case of an inert anode plant, carbon anode production workshop becomes obsolete since the anodes are now supposed to be made of an inert material, i.e. one that does not consume during electrolysis. Hence, the purchase of pitch and coke, the raw materials for carbon anodes (€258/$t_{aluminium}$) partly disappears to be replaced by a new OPEX item linked to the replacement of inert anode cells (€103/$t_{aluminium}$). This cost is linked to the fact that metallic inert anodes (those modelled here) slowly consume in practice over time.

[24] It should be noted, however, that the Norwegian Hydro group announced in 2022 that it was developing a new process for producing carbon-neutral primary aluminium through the electrolysis of aluminium chloride (AlCl3). Due to a lack of information, this process has not been modelled in the Sectoral Transition Plan. For more details on the "HalZero" project: https://www.hydro.com/en-US/media/on-the-agenda/hydros-roadmap-to-zero-emission-aluminium-production/halzero-zero-emission-electrolysis-from-hydro/

[25] This figure was calculated based on an assumption of the cost (in €/$tCO_2$) of transporting and storing $CO_2$ offshore by ship through a CCS hub similar to that in Dunkirk. These estimates should be treated with caution: they can depend greatly on the distance between the emitter and the sink, the type of environment in which the transport infrastructure is deployed (onshore or offshore, flat or mountainous, urban or rural, etc.) and the annual volume of emissions that passes through it. For further information: https://librairie.ademe.fr/changement-climatique-et-energie/81-captage-et-stockage-geologique-de-co2-csc-en-france.html

[26] Source: Arctus Metals (2017) – Modular Primary Aluminium Plant Based on Beck Cells with Multiple Vertical Inert Anodes and Wettable Inert Cathodes

➜ Picture by HYDRO/Halvor_Molland_PrimaryAluminium

**Inert anode technology is not completely "inert" as its name would suggest, and the anodes must be replaced periodically.**

It is thus necessary to change the anode and cathode approximately once a year, which generates a significant cost because of the expensive materials used to make them (in particular the drained cathode, which is coated with titanium diboride). Ceasing production of carbon anodes also leads to a slight decrease in natural gas and electricity consumption. Finally, it has been estimated that operation using an inert anode requires 2.5 times less labour than operation using the conventional Hall-Héroult process while other costs (maintenance, administration, etc.) are also halved[26].

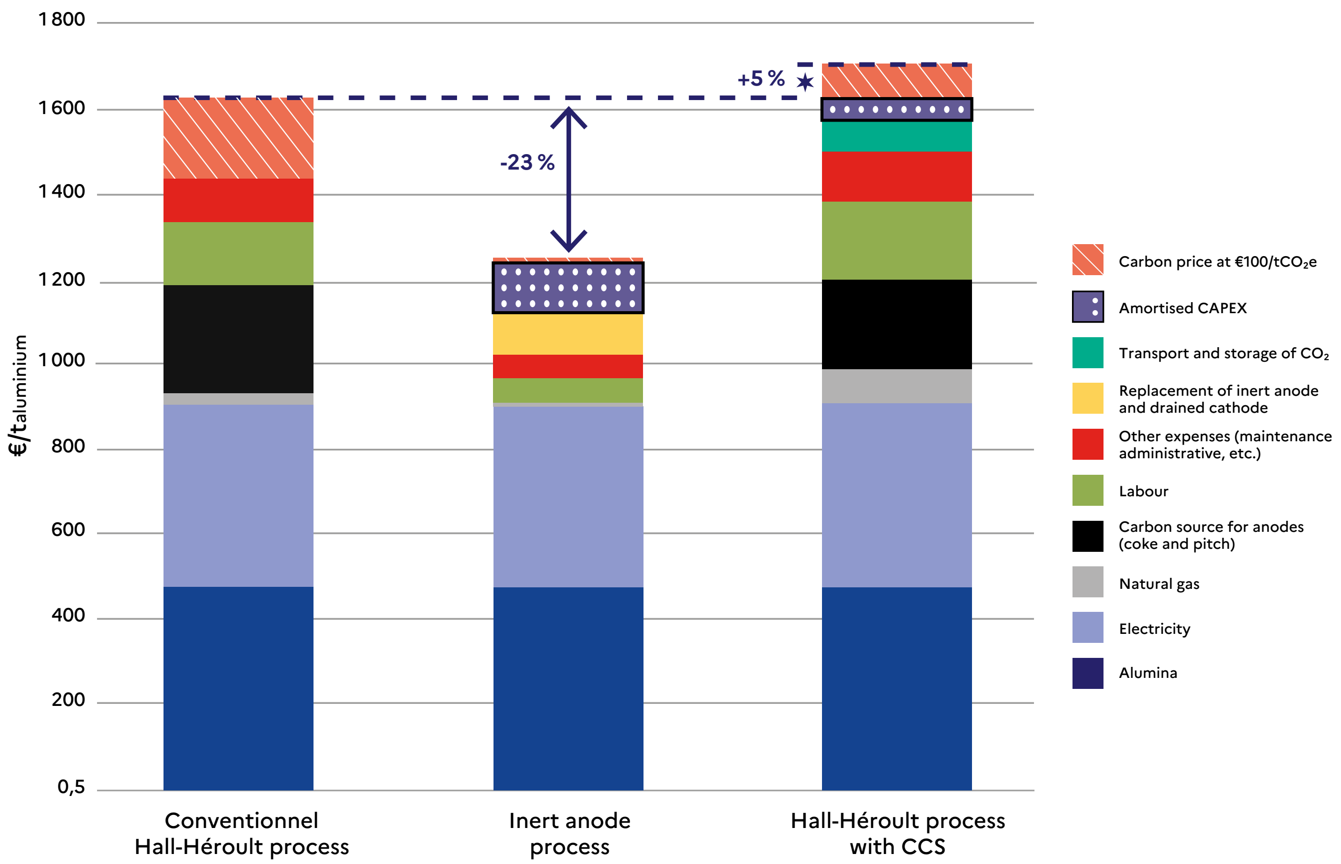
In addition to the standard operational costs (raw materials, energy, labour and administrative costs), Figure 19 shows the theoretical impact of a carbon price of €100/t$CO_2$. This increases the aluminium production cost by €192/t$_{aluminium}$ using the conventional Hall-Héroult process and by €84/t$_{aluminium}$ using the Hall-Héroult process with CCS. Given that it only concerns emissions from the electrolysis step, that the $CO_2$ capture rate is assumed to be 70% and that the energy penalty is offset using natural gas, **the abatement of direct emissions using CCS technology is only about 50%. A smelter with this technology thus remains relatively exposed to an increase in the $CO_2$ price, unlike an inert anode plant.** Since the inert anode eliminates almost all direct emissions, **the increase in the production cost associated to carbon pricing is almost negligible (about €10/t$_{aluminium}$) for an inert anode smelter.**

An estimate of CAPEX amortisation per metric ton of aluminium is also shown in Figure 19. This is the investment required to convert a conventional smelter to a process with CCS or the inert anode. The amortisation period was assumed to be 20 years at an interest rate of 7% for both technologies. Thus, even if the amortised CAPEX is higher for switching to the inert anode (€112/t$_{aluminium}$) than for CCS (€47t$_{aluminium}$), the production cost remains firmly in favour of inert anode technology, even for a conventional smelter.

**By incorporating a carbon price of €100/t$CO_2$ and CAPEX amortisation over 20 years, the cost of producing aluminium at an inert anode plant would be 23% lower than that of a conventional smelter, while the cost for a CCS smelter would be 5% higher.**

Furthermore, the $CO_2$ price at which the production cost of the Hall-Héroult process with CCS reaches that of the Hall-Héroult process without CCS is €175/t$CO_2$. In other words, it is only as from a carbon price of €175/t$CO_2$ that CCS technology becomes economically advantageous for the manufacturer compared with the conventional process. For the inert anode, the production cost remains lower than for the conventional process regardless of the $CO_2$ price.

Figure 19. Comparison of the production costs for a smelter using different processes by incorporating amortised CAPEX and a carbon price of €100/$tCO_2e$ (ADEME calculations based on literature sources).




## Putting the economic analysis into perspective with the cement STP

In the cement Sectoral Transition Plan, the analysis showed very strong dependence on $CO_2$ prices, with a potential double of the production cost in the extreme scenarios, and resulting spillover to the rest of the value chain (concrete and house construction prices). In the case of the aluminium industry, the findings are radically different. Extremely electro-intensive sites are chiefly vulnerable to an increase in the price of electricity, the main factor in the sector's international competitiveness. Given that primary aluminium is a relatively expensive material to produce (in the order of €1,000 to €2,000/taluminium), unlike cement, the share of the direct $CO_2$ emissions cost in the total production cost remains limited and to some extent "tolerable" for the manufacturer (see Figure 19).
In the case of the inert anode, the $CO_2$ cost would also become almost imperceptible in the overall production cost. In addition, given that aluminium is a globalised product with its price set on international markets, manufacturers individually have very little room for manoeuvre to pass on the rise in costs to the selling price, and hence little to be expected downstream in terms of cascade effects on the rest of consumers. Finally, some of the technical and economic data used for modelling the aluminium industry is extremely uncertain, in particular regarding the inert anode. For all these reasons, section 5.2 does not cover the impact on the value chain but instead focuses on sensitivity analysis of the abatement cost (in greater depth than the cement STP) to draw lessons from these factors specific to the aluminium industry. There is also an initial analysis of the change in jobs throughout the sector.

→ Picture by Aluminium Dunkerque/Parc métal - lingots

# 5.2. Sensitivity of abatement costs to price changes : inert anode vs CCS

The purpose of the abatement cost is to estimate the cost associated with deploying a technology to abate one metric ton of $CO_2$.

Given the high uncertainty surrounding price changes, and some assumptions related to the deployment of these technologies, the proposed abatement cost estimates for the inert anode and CCS are based on sensitivity tests rather than on values associated with each scenario.

An initial analysis was carried out to identify the sensitivity of the abatement cost to different variables tested on a variation from €0 to €100: the price per metric ton of $CO_2$, the price per MWh of gas (MWht) and the price per MWh of electricity for both main technologies (inert anode and CCS). Comparison of the box and whisker plots in Figure 20 clearly shows **the differentiating character of the change in gas price on the abatement cost of each technology[27].** The increase in energy consumption, particularly thermal, linked to the energy penalty of $CO_2$ capture, makes the abatement cost of CCS technology highly dependent on the price of gas. On reading the results, the $CO_2$ price also appears to be a decisive criterion for comparing the abatement cost of the two technologies. With a higher level of emission reduction for the inert anode, this criterion also seems to favour the deployment of this technology over CCS.

Conversely, a change in the electricity price does not seem to be a decisive factor in the choice of possible investment in one technology or the other. The repercussions of the change in electricity price relate more generally to the issue of the competitiveness of an electro-intensive process such as aluminium production (and the purchase of its electricity at a controlled long-term cost), and hence the ability of a manufacturer to fund such an investment.

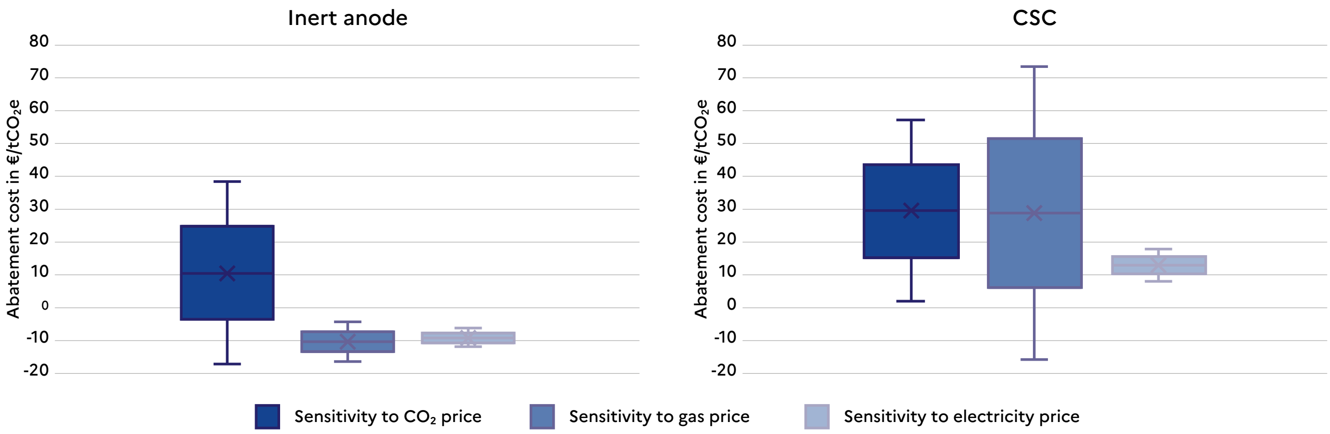
**Calculation formula and interpretation of the abatement cost**

$$Ca_i = \frac{\textit{Total costs}}{\textit{Total } CO_2 \textit{emissions avoided}} = \left[\sum_{t=1}^{D_i} \frac{(CAPEX_{i,t} + \Delta\, OPEX_t \times Q_t)}{(1 + r^{act})^{t-1}}\right] \times \left[\frac{1}{\sum_{t=1}^{D_i} Q_t \times (\Delta\, intCO_2)}\right]$$

where *Di* is the time over which OPEX savings and $CO_2$ emissions are calculated for technology i, *Qt* is the production level in year t, $r^{act}$ is the discount rate and $\Delta intCO_2$ is the variation in $CO_2$ emission levels per metric ton of aluminium following the deployment of technology i. **When the abatement cost of a technology is negative, its deployment results in OPEX savings that more than offset the initial investment (CAPEX).** In addition, the cumulation of these savings, and hence the probability that the abatement cost is negative, is all the more significant when $CO_2$ and/or energy prices are high, and when the duration over which these savings are calculated is long.

[27] Among the assumptions associated with the technologies, the CAPEX for the inert anode and the capture rate for CCS are the most uncertain. For the estimates, the assumption of CAPEX of €1,190/metric ton of primary aluminium has been adopted and reflects the estimate for investment on an existing site. For CCS, a $CO_2$ capture rate of 78% has been adopted. Estimates are based on an expected 10-year payback period for the investment. Where the $CO_2$ parameter is not tested, its price has been set at €83.5/$tCO_2$, and the gas price at €30/MWh where it is not tested. More information on the assumptions and sensitivity of abatement costs is available in the full report.

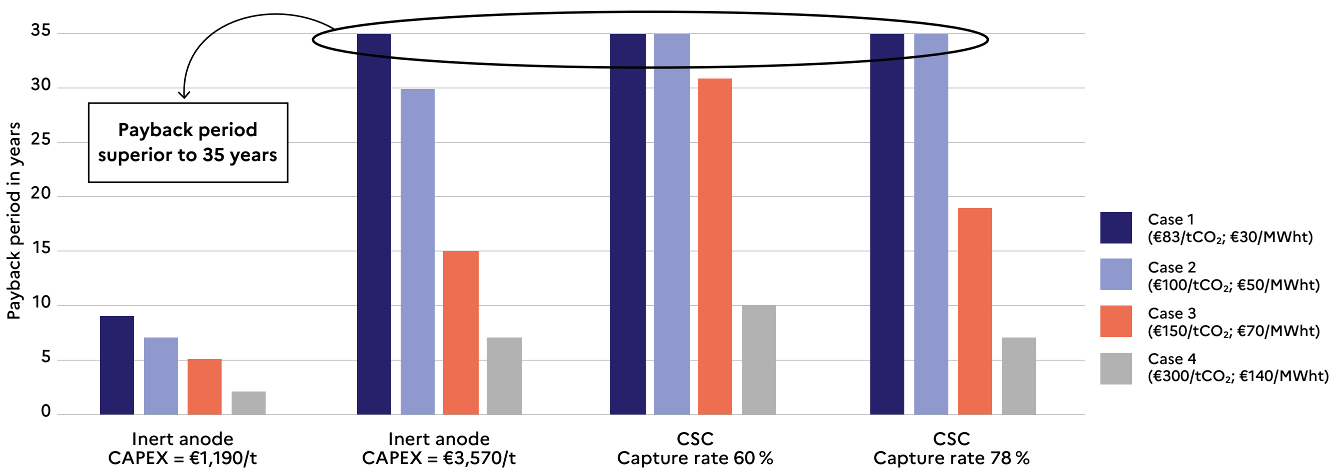
**Figure 20. Distribution of abatement costs for the inert anode (left) and CCS (right) by price variable ($CO_2$, gas, electricity).**




In the proposed configuration of the assumptions for these tests, the median abatement costs also appear to favour the inert anode (median abatement cost of CCS between €20 and €40/t$CO_2$ greater than for the inert anode).

To reflect a context in which prices are assumed to move in parallel and thus overcome one of the limitations of the sensitivity tests, **several price combinations are proposed. For each combination, the number of years taken for OPEX savings to cover the committed CAPEX is calculated, i.e. the expected payback period** (Figure 21). Since this exercise is not intended to estimate the change in these prices, the assumptions of "low" and "high" values are thus arbitrary and are essentially intended to cover a range of possibilities. Given the low sensitivity of these technologies to electricity prices, only changes in gas and $CO_2$ prices are considered.

**Figure 21. Estimated expected payback periods for the inert anode and CCS technology, by combination of $CO_2$ price and gas price.**




Several general observations are clear from reading the estimates in Figure 21:

- Investment expenditure of less than €1,200/metric ton of installed capacity for deployment of the inert anode at an existing site appears to be covered by all OPEX savings in less than 10 years, even with relatively low gas and $CO_2$ prices.
- For prices below €150/t$CO_2$e and €70/MWht, profitability seems difficult to achieve for CCS, even with a relatively ambitious capture rate of 78%.
- The reduction in payback periods for CCS with increasing prices indicates that the effect of $CO_2$ abatement on the abatement cost is greater than that of the additional gas consumption required for capture. However, in a situation where the gas price increases at a faster rate than the $CO_2$ price, the payback period would increase because of the energy penalty associated with CCS.

Ultimately, beyond the technical considerations, particularly those related to the date of deployment of the technologies, and as can already be observed in Figure 19 from the comparison of production costs, the trade-off between the inert anode and CCS seems to be very clearly in favour of the inert anode, except in a configuration where the CAPEX for this technology is greater than €3,500/metric ton and, at the same time, $CO_2$ and gas prices are very high[28].

# 5.3. Preliminary analysis on the impacts on employment by 2050

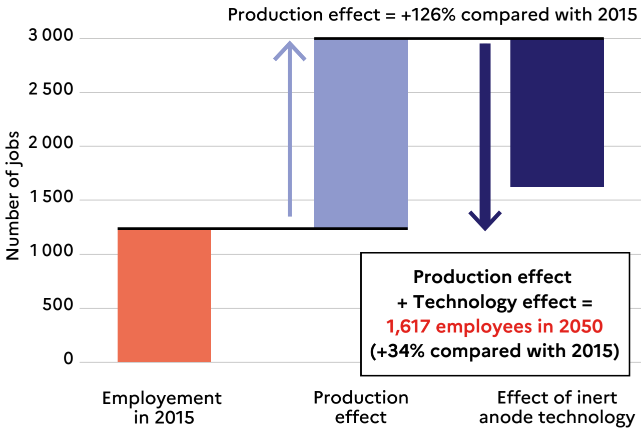
Quantifying the effect of transition scenarios on jobs in the sector relies heavily on production assumptions. This "production effect" is calculated on the basis of the average number of employees between 2011 and 2018 per metric ton produced. The results also assume constant productivity for each of the three production sectors and do not distinguish between production staff and support functions. Alongside this "production effect", it is also necessary to add the "technological effect", which is much more difficult to quantify given the lack of available data on this subject. Projection of the "technology effect" on jobs in both scenarios thus only takes into account the effect of the inert anode and CCS on primary aluminium and alumina production.

• For alumina production, the workforce is expected to almost double in the international cooperation scenario (+91%) to accommodate the twofold increase in calcined alumina production capacity and the deployment of $CO_2$ capture on site. This configuration could thus more than offset the consequences of shutting down the Bayer process in 2022. On the other hand, these favourable conditions for the expansion of calcination capacity have not been adopted in the assumptions related to the transitional context of the "regional polarisation" scenario, so job numbers are expected to remain stable in this scenario

• In both scenarios modelled, **the workforce related to primary aluminium production is assumed to grow significantly, with increases of 34% for the international cooperation scenario and 59% for the regional polarisation scenario, notably due to the opening of new capacity.** In contrast, the breakdown of the production effect and the technology effect illustrated in the Figure 22, highlights the main drawback of inert anode deployment, namely its impact on jobs. While the increase in production volume estimated for 2050 would more than double the workforce in primary aluminium production, the gradual switch to inert anodes on smelters limits this effect, as it leads to the cessation of carbon anode production. According to the existing literature on the subject, the average workforce required to produce 1,000 metric tons of aluminium is reduced by more than half on switching from the carbon anode to the inert anode.

In addition, the effect of $CO_2$ capture on primary aluminium production sites in the regional polarisation scenario plays only a marginal role in the estimated increase in workforce. Based on an article by O. Lassagne

**Figure 22. Change in the primary aluminium production workforce according to the production effect and the technological effect in the "international cooperation" scenario.**




et al. (2013) and internal calculations, fewer than a dozen additional jobs would appear to be required to deploy the technology on the sites, compared with more than 600 required to open new production capacity. Overall, in this regional polarisation scenario, the workforce could increase by 59% in 2050 compared with 2015.

• For the workforce on direct recycling sites, an increase seems inevitable given the high demand for aluminium and the increasing use of aluminium waste. With more than 6,200 employees in 2050 compared with just over 4,000 in 2015, estimates indicate an increase of almost 60% for the international cooperation scenario and 55% for the regional polarisation scenario.

**Taking into account alumina and primary aluminium production sites and direct recycling sites, the increase in the workforce in the aluminium sector is more than 50% in 2050 compared with 2015, for both scenarios.**

While it is difficult to quantify the effect of energy efficiency or electrification technologies on the size of the workforce, changes in skills would appear to be necessary in order to optimise the deployment of these technologies on sites. As with any structure undergoing change, challenges in terms of training and new skills are thus also likely to arise within the aluminium sector.

[28] These estimates may be updated as more accurate investment data becomes available, especially for the inert anode.

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## TABLES



## FIGURES

# Abbreviations and acronyms

**ADEME -** French Agency for the Ecological Transition
**CBAM -** Carbon Border Adjustment Mechanism
**CCG -** Capital and Consumer Goods
**CCS -** Carbon capture and storage
**GHG -** Greenhouse gas
**MEUR -** Million euro
**MUSD -** Million US dollars
**MVR -** Mechanical Vapour Recompression
**SNBC -** Stratégie Nationale Bas Carbone
**SRM -** Secondary Raw Material
**STP -** Sectoral Transition Plan
**TRL -** Technology Readiness Level

## ABOUT ADEME

At ADEME - the Agency for Ecological Transition - we are firmly committed to combating climate change and degradation of resources.

**On all fronts,** we mobilise citizens, economic players, and regions, empowering them to move towards a resource-efficient, carbon-free, fairer, and more harmonious society.

**In all areas - energy,** air, circular economy, food, waste, soils, etc., we advise, facilitate and help finance many projects, from research through to solution-sharing.

**At all levels,** we put our expertise and prospective capabilities at the service of public policy.

ADEME is a public institution under the supervision of the Ministry for Ecological Transition and Regional Cohesion, the Ministry for Energy Transition and the Ministry of Higher Education and Research.

**The collections**
## of ADEME

**FACTS AND FIGURES**
**ADEME the leader:** It provides objective analyses using regularly updated statistical indicators.

**KEYS FOR ACTION**
**ADEME the facilitator:** It produces practical guides to assist stakeholders in implementing their projects methodically and/or in accordance with the regulations.

**THEY DID IT**
**ADEME the catalyst:** Stakeholders talk about their experiences and share their know-how.

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**ADEME the expert:** It reports on the results of research, studies and collective achievements made under its auspices.

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**ADEME, focused on the future:** It provides a realistic, forward-looking vision of the issues involved in the energy and ecological transition to help everyone build a better future.

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EXPERTISES

# ALUMINIUM

## Summary report

Due to its electrolytic production process, the aluminium industry is known for being highly electro-intensive. However, unlike many producing countries, the low carbon content of the electricity generation mix in France makes the decarbonisation of its aluminium industry a unique exercise, as it mainly concerns scope 1 direct emissions. In this respect, the alignment of the sector with the target set by the French national low-carbon strategy (SNBC) – for an 81% reduction in greenhouse gas emissions in 2050 for French industry as a whole – faces technological and market challenges. The likely growing demand for aluminium to meet a wide range of applications (e.g. the automotive sector, packaging, networks) adds to the technical challenge. Building two contrasting scenarios that meet the SNBC target has highlighted the main uncertainties that influence decarbonisation of the French sector, namely the availability of inert anode technology and the evolution of international trade, in particular in the context of the implementation of the European Carbon Border Adjustment Mechanism (CBAM). Beyond the necessary investments, the aluminium industry will above all need visibility and guarantees: availability of the inert anode, energy prices, securing access to the available waste, etc. Recycling also represents an essential pillar of decarbonisation but remains conditional on improved sorting and collection of end-of-life waste. Finally, aluminium stands out as a very concrete example of the industrial sovereignty issues that have stirred public debate since the Covid-19 pandemic and the war in Ukraine. With a high dependence on imports and the future increase in aluminium requirements, projections to 2050 raise the question of the industrial model that is wanted for France and Europe.

**The Finance ClimAct project contributes to the implementation of the French national low-carbon strategy (SNBC) and European policy on sustainable finance. It aims to develop new tools, methods and knowledge to (1) enable energy-intensive industries to promote investment in energy efficiency and the low-carbon economy, (2) enable financial institutions and their supervisors to incorporate climate issues into their decision-making processes and align financial flows with climate-energy targets, and (3) enable savers to include environmental considerations when making investment choices.**

**The consortium, coordinated by the** Agency for the Ecological Transition, also includes the Ministry for the Ecological Transition and Regional Cohesion, the Financial Markets Authority, the Prudential Control and Resolution Authority, 2nd Investing Initiative, the Institute for Climate Economics, the Institute for Sustainable Finance and RMI.

**Finance and RMI.**

**Finance ClimAct is an unprecedented programme with a total budget of €18m, including €10 million in funding from the European Commission.**

**Duration:** 2019-2024

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