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Low-carbon transition pathways at the lowest cost

NOVEMBER 2016

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RÉPUBLIQUE FRANÇAISE

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de l'Environnement,
de l'Énergie
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contents

Low-Carbon transition pathways at the lowest cost

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foreword

The ministry has built an original tool that can model the transformations necessary to decarbonise the economy and create a dialogue between divergent world views on how to achieve the transition.

To reach the goal of cutting three quarters of greenhouse gas emissions by 2050, we know that we must mobilise emission abatement opportunities in all sectors of the economy (transport, buildings, energy, industry, agriculture and waste). These may be more efficient technologies, new sources of energy, but also behavioural changes. The challenge, within these sources, is to mobilise those capable of reaching the goal within a time frame which minimises the cost of transition.

This tool provides a coherent and transparent framework in order to, on the one hand, design, as an initial approach, aggregate or sectoral low-carbon transition scenarios, and on the other hand, point out the risks and the costs of undesirable technological lock-in, which would prevent the 75% emissions cut from being achieved.

It is designed to become a reference tool in the public debate on the transition to a low carbon economy.

Laurence Monnoyer-Smith
Commissaire générale au développement durable (General Commissioner for Sustainable Development)

Introduction

France has committed itself to decarbonise its economy with the objective of quartering its greenhouse gas emissions by 2050. In practice, this means mobilizing all the known emission reduction sources in the transport, building construction, energy, industry, agriculture and waste sectors in a way that minimizes the cost of transition.

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THE CHALLENGE OF LOW-CARBON TRANSITION

France has committed itself to decarbonize its economy. The Energy Transition for Green Growth Act (LTECV) confirmed the factor 4 objective by 2050. This entails quartering greenhouse gases emitted on national territory compared to the 1990 emission level. Thus emissions would be reduced to 140 MtCO2eq/year as opposed to 459 MtCO_2eq in 2014[#]. As France is already one of the OECD's less carbon-intensive countries, it thus wants to contribute by setting an example to the international effort in the fight against climate change. Many co-benefits also justify the low-carbon transition: energy security, air quality, new jobs, new markets, non-price competitiveness.

In practice, the factor 4 target implies a deep transformation of the productive system, which still relies, to a large extent, on fossil energies. Such a transformation is still possible. The potential of known emission reductions in the transport, construction, energy, industry, agriculture and waste sectors is sufficient to decarbonize the French economy. These reductions come in the form of more efficient technologies and new sources of energy as well as changes in behaviour. The challenge for public authorities and sectoral actors of the low-carbon transition is to mobilize, among these sources of reduction, those that make it possible to achieve the objective using a method of deployment and sectoral distribution that minimizes the cost of it.

The national low-carbon strategy (SNBC), foreseen by the LTECV (Law on energy transition for a green growth), was, when it was being drawn up, the object of a broad dialogue with the stakeholders, in particular the National Council for Ecological Transition (CNTE). The stakeholders will be involved in the SNBC monitoring and revisions to come.

In order to promote the acceptability and the appropriation of the sectorial objectives by those involved in the transition, the strategy is submitted for opinion to the National Council for Ecological Transition (CNTE) stakeholders. The prospective scenarios that were used for drawing up the SNBC are based on the sectorial expert reports, both meso and macro-economic modelisation work that takes account of the interactions between sectors and the effect of the low-carbon transition on economic activity and employment.

The building of a modelling tool for monitoring the dynamics of average abatement costs presented in this study of the CGDD, is a much more top down exercise. The tool provides more detailed information that is useful, however, as a first approach, for:

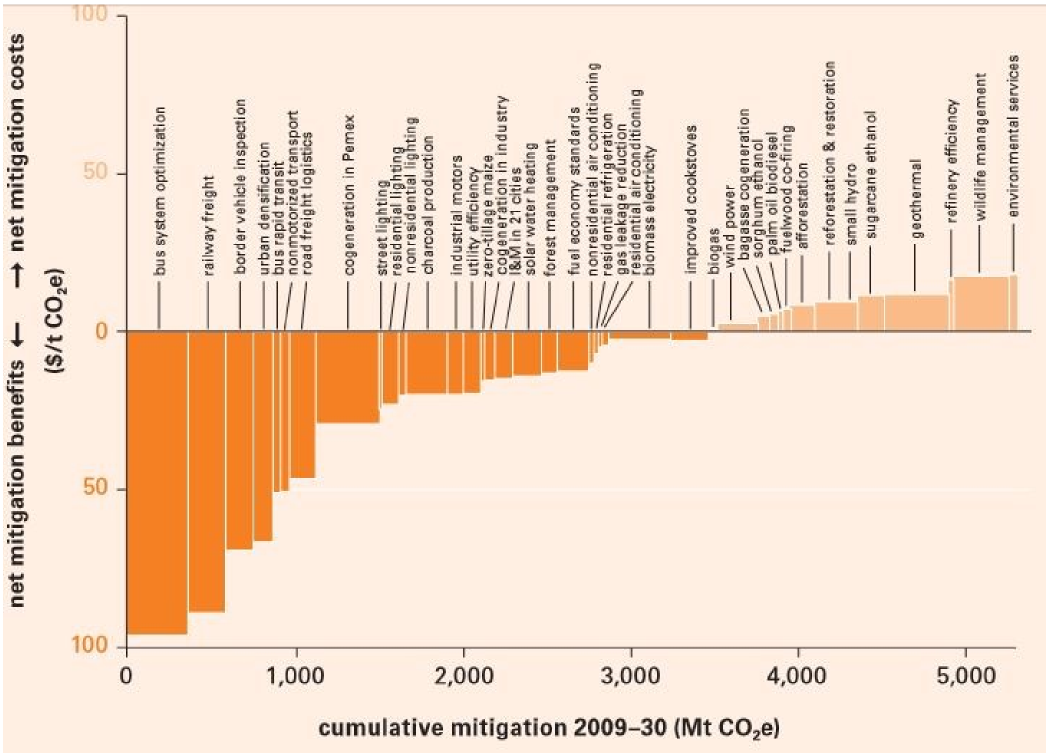
- fostering aggregated or sectoral low-carbon transition scenarios;
- offering useful elements for SNBC updates and defining future carbon budgets;
- assessing the coherence of the crossing points set by the low-carbon strategy with the long-term objective of factor 4 by pointing out the risks and costs of unwanted technological interlocks;
- defining efficient methods for deploying emission reduction measures;
- estimating the potential additional costs of a low-carbon trajectory compared to a business-as-usual scenario and thus calibrate subsidy levels to facilitate the transition.

[#] Emissions declared within the scope of the 2016 submission of the national inventory for the scope corresponding to the Kyoto protocol.

THE MARGINAL ABATEMENT COST CURVES

The marginal abatement cost curves (better known as *MACC*) are widely used to inform the climate debate on the available potential for greenhouse gas emission reductions and their costs. The success and the interest of these curves lies in their ability to summarise, in a single representation, a complex set of information: type of greenhouse gas emission reduction potentials, quantity of emissions avoided, ranking of measures according to their average cost over a given period. They exist at country level *(figure 1)* and even at world level (McKinsey, 2009).

Figure 1: Example of MACC drawn up for Mexico (Johnson et al., 2010)



Reading: The abscissa axis indicates cumulative quantities of greenhouse gas emission reductions between 2009 and 2030. The ordinate axis expresses the average cost over the same period of various emission reduction measures. These greenhouse gas emission reduction measures are classified along the abscissa axis in an order of increasing marginal cost.

These curves are often constructed with an "engineer" or "expert" approach, seeking to isolate the costs associated with a particular emission reduction measure or technology (unlike macroeconomic model-derived MACCs, which are constructed by varying a CO_2 price). If these curves allow for the simple representation of a set of measures ordered increasingly by the net cost compared to a business-as-usual scenario, the reading of the results has to be done keeping in mind the methodology for constructing the curve to avoid any over-interpretation of the results.

Finally, marginal abatement cost curves, as popularized by McKinsey, are constructed according to a "lowest cost first" logic for a fixed time horizon: these curves indicate a set of reduction measures to be mobilized continuously from today to the target year in order to minimize the total cost of abatement to achieve a given greenhouse gas reduction target. Nevertheless, these curves show a very static vision of emission reductions. They give an idea of the potential for emission reduction over a given period but do not give information about the paths to be taken to reach the objective set by the target year. In particular, interpreting a MACC as a "merit" curve that would depict measures from the cheapest to the most expensive would disregard/neglect all the temporal dimensions of the emission reductions deployment and consider that each potential can be instantly exploited.

It is regarding this last point, the too-static nature of the classic abatement curves, that the tool presented here can shed new light. In order to sequence a low-carbon transition strategy, public action needs a more comprehensive tool than marginal abatement cost curves that provide only a rough illustration of the relative costs of different emission reduction potentials. Prioritizing measures according to the marginal cost of emission reductions at a given date does not provide information on the starting dates for the exploitation of each measure or on the desirable rates of diffusion of the technologies. Establishing intermediate milestones for a GHG emission reduction strategy requires paying more attention to the temporal aspects of the mobilization of potentials.

Some methodological precautions are needed to interpret the results of a marginal cost abatement curve. The following questions must first be answered to avoid the main pitfalls (Kesicki & Ekins, 2012):

- What was the cost estimation method?
- What elements other than the impacts of climate change are not taken into account in the assessment framework?
- What interactions between measures have or have not been taken into consideration?
- What is (are) the temporal horizon(s) targeted by the cost curve?

CREATING A "DYNAMIC CURVE OF AVERAGE ABATEMENT COSTS" (TITAN, EX D-CAM) IN FRANCE

The SNBC, which aims at the long-term objective of factor 4 in 2050, proceeds step by step through five-years carbon budgets. It gives intermediate points of passage to different sectors according to objectives set out by law and the assessment of the social, technical and economic constraints that they face. Taken in isolation, the marginal abatement cost curves do not give any indication as to how to articulate these intermediate points with a long-term objective.

Vogt and Hallegatte (2011, 2014) developed a low-carbon transition planning tool based on abatement cost curves, which was designed to compare the potential of greenhouse gas (GHG) emission reductions and define all the measures to be mobilized over time to reach a target at the lowest cost by a given date. The graphical representation of the results brings together in the same figure *(see figure 2)*:

- an "average abatement cost curve" (CAM) with the average costs on the x-axis and the emission reductions on the y-axis (as opposed to the usual *MACC*);

- a temporal dynamic (D) emission curve that breaks down the evolution of emission reductions compared to a business-as-usual scenario in which emissions increase like economic activity. This curve is commonly called a *wedge curve*.

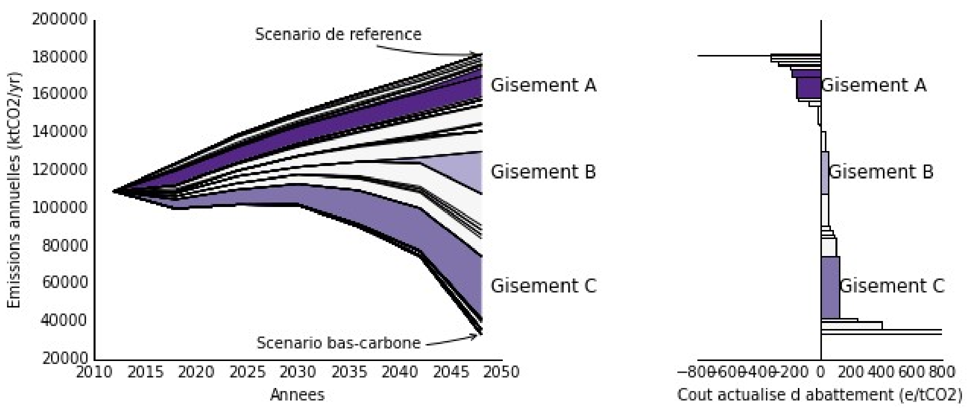
Each wedge corresponds to the deployment of an abatement measure *(A, B and C in figure 2)*, which, like the edge of a woodcutter, gradually carves a wedge in the emission level of the business-as-usual scenario. The average cost of each measure over the period considered is represented as a horizontal stick within the inverted CAM curve. The construction of the curves, on a sectoral or aggregate scale, is based on the estimation of costs for each emission reduction source in relation to a business-as-usual scenario in the evolution of GHG emissions. It is, in reality, these average costs that are ranked by ascending order in a marginal abatement cost curve.

Each of the mitigation measures/technologies is characterised by: (i) the potential for emission reduction at the time horizon considered, (ii) the deployment speed of the proposed technology, and (iii) a cost (varying over time) in relation to a comparable average technology of a business-as-usual scenario.

The quality of the database used to construct the TITAN curves is thus critical. Establishing this database must be discussed transparently between stakeholders of a low-carbon national strategy so that the TITAN curve delivers relevant and transferable messages. This tool can then provide useful points of comparison to the options chosen by the strategy.

In fact, it is possible to visualize, on the same graph *(figure 2)*, scenarios for the deployment of different measures (on the left, *wedge curve or dynamic abatement curve) associated with their cost (right, CAM curve) and at a given time horizon.* The analysis provides information on all the technological solutions to be mobilized in order to reach the fixed mitigation objectives and not on the merit order of their deployment.

Figure 2: Dynamic curve of average abatement costs



Reading: To the left of the figure, the wedge curve indicates the dynamics of deployment of the emission reduction deposits between 2010 and 2050 to reach the target set in the low-carbon scenario. The three main wedges are deposits A, B and C. On the right of the figure, the average abatement cost curve ranks these deposits according to a growing cost.

The tool is not intended to provide a hierarchy of solutions to be implemented, but to illustrate a set of measures that can be mobilized to divide by a factor of 4 the GHG emissions by 2050, and to reveal possible contradictions between the short-term and long-term objectives.

KEY MESSAGES DELIVERED BY THE TITAN TOOL

It is essential to clearly establish the perimeter of relevance of these curves, which depict a stylized image of a cost-efficient path of the low-carbon transition without providing an indication of the instruments for implementing such a transition. The visual appeal of these curves, and their resemblance to supply curves for power generation, may have led to misinterpretations in terms of merit order. The misuse of the term "marginal" may have encouraged promoters of these curves to deduce desirable levels of carbon tax from them.

The "enriched" version of the TITAN curves that links emission reduction dynamics to abatement measures is a better tool for representing emission reduction potentials to be mobilized during a low-carbon transition trajectory, but cannot be used to directly formulate policy prescriptions or specific methods for the deployment of a particular technology. All the barriers to the deployment of the measures are supposed to be captured by a parameter of "speed" of deployment, which remains, however, very inadequate given the real complexity of the sectors.

Therefore, they must be designed primarily as a tool for dialogue between the low-carbon transition stakeholders. By using different data sets based on divergent expertise, they can visualize the effects of different world views on both the pace and effective options to be mobilized for the low-carbon transition. The transparency of the database used is thus a key element for the credibility, acceptance and suitability of the tool.

Box 1: How to read and interpret a TITAN

To avoid any manipulation of messages from TITAN curves, it is essential to clarify what they can and cannot say.

TITAN curves cannot say:

- what the marginal abatement cost is, or the cost of the last ton of CO_2 avoided to reach a given target;
- that abatement measures must be implemented in order of merit (except for negative cost measures that must be mobilized from the outset to minimize the cost of any low-carbon strategy);
- the trajectory of the carbon tax which would trigger the set of measures required to reach a certain objective;
- the co-benefits of an abatement measure;
- the barriers that limit the deployment speed of measures.

On the other hand, TITAN curves can give the following messages:

- the average cost curve reveals potentials with negative costs, which may not be activated spontaneously (information deficit, downward cost trends over the period considered, difference in private / public discount rate, IRR lower than that of other investments deemed higher priority by companies) and should be deployed as quickly as possible (technology A of figure 2);

- the emission reduction options chosen to reach intermediate targets must avoid leading to a technological "lock-in" that would obliterate the future. For example, improving only the efficiency of conventional thermal vehicles to reach a medium-term objective may delay achieving full transport decarbonation if no R&D effort is provided in parallel for zero-emission vehicles. On the other hand, short-term options should prepare the following steps to reduce costs and maximize co-benefits.
- the association of dynamic curves and average costs makes it possible to highlight the efficient chronology of the technologies to be mobilized between today and the objective's target date, namely technology A and C immediately, followed by technology B.
- *Low-cost, slow-release technologies (technology C) have to be deployed at the same time as technologies with low or even negative abatement costs (and which may have equally slow diffusion) technology A), and even before measures with a lower average cost but which can spread more quickly (technology B) in order to reach the long-term objective. The TITAN curve facilitates this perspective and contributes to the dynamic coherence of emission reduction options.*

TITAN curves are thus exploratory instruments of a low-carbon strategy that allow the stages of an optimal deployment to be planned – from a cost-efficient perspective – of different reduction potentialof GHG emissions. The precise sequence of this deployment can only bi indicative, since it relies entirely on the the diffusion speed parameter, the calibration of wich is surrounded by wide uncertainties.

Introduction

Part 1

Methodology

The TITAN tool, developed by the CGDD, is popularized in English as "MACC" for *marginal abatement cost curves*) and is based on (i) the construction of a business-as-usual theoretical scenario that will serve as a reference point for low-carbon transition scenarios, (ii) a database on the potential, speed of deployment and cost of greenhouse gas emissions reduction sources available, and (iii) a model to minimize the costs of deploying measures to activate these sources of reduction.

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The TITAN tool is based on hypotheses, both about the business-as-usual scenario, and about all the greenhouse gases (GHG) abatement sources available.

CONSTRUCTING A THEORETICAL "BUSINESS-AS-USUAL" SCENARIO

Within the theoretical "business-as-usual" scenario, the technologies used in the different sectors are assumed not to evolve between 2012 and 2050. All sectors thus conserve the same energy intensity and the same carbon intensity: the same "technology of reference" is used over the entire period, which is characterized by the average of the unit costs and the unit emissions of technologies which provide the same service in 2012.

The evolution of each sector in the business-as-usual scenario is based on projected demand (expressed in kWh, in ton.km or passenger.km transported) up to 2050, taking into account the macroeconomic hypotheses that guide all scenarios of the National Low Carbon Strategy (SNBC): population, GDP growth and the spread of the value added between the different sectors[1]. No hypothesis implies a massive decline in industrial production or agricultural production.
The emissions are projected from this demand, maintaining the CO_2/2012 demand ratio. They are higher than the trajectories of trend scenarios (such as the "with existing measures" scenario of the SNBC) that already incorporate several emissions reduction measures.

The business-as-usual scenario technologies are thus in principle "frozen", but the model envisages the possibility of having (or not having) two types of costs, evolving over time:

- the cost of electric MWh may increase with the replacement of nuclear power plants by EPRs;
- the cost of housing construction which is not fixed at the average cost of the current fleet but changes according to the growing share of new dwellings, all of which are assumed in the business-as-usual scenario to show the characteristics of new dwellings in 2012.

This business-as-usual scenario leads to annual emissions of 561 Mt in 2035 compared to 464 Mt in the SNBC's "with existing measures" scenario (excluding LULUCF). It is therefore a fictitious scenario which, however, represents a less objectionable point of reference than a scenario which would integrate the effects of the existing measures. It also reveals that the existing measures do indeed have a downward effect on emissions.

[1] These hypotheses are only made for the 2010-2035 period in the SNBC. Over the 2035-2050 period, the macro-economicprojections of the European Commission ("Trends to 2050", 2013) were directly used.

INPUT DATA

GHG abatement sources

A series of GHG abatement sources have been identified for each sector based on a review of the academic and grey literature, as well as through complementary interviews with sector experts (AIE, 2015; ADME, 2012; INRA, 2013). These GHG abatement sources can thus correspond to more efficient technologies (the car at 2 l.100 km), changes in fuels (the electric car), changes in behaviour (carpooling, teleworking) and finally to changes in the structure of demand (modal shift towards public transport). In total, 578 emission reduction sources are taken into consideration.

Potential

Each of these GHG abatement sources has a maximum use potential, and a maximum deployment speed. The reduction potential will be determined by both the potential for use of the technology and the reduction of unit emissions compared to the reference technology. These unit emissions may decrease over time due to the energy efficiency associated with technical progress and the decarbonation of the energy source used. Only emissions over national territory are considered: the work is not done in life-cycle analysis (emissions related to the construction phases are not allocated, for example, to the residential or energy production sectors but to the industry sector).

Speed

Several methods have been used to estimate the deployment speeds. Each prospective scenario implicitly includes constraints regarding the diffusion of the GHG abatement sources it exploits. From these diffusion scenarios, a speed can then be extracted: it corresponds, for example, to the fastest diffusion scenario, which can serve as a reference value, integrating a wide set of constraints: regulatory barriers, barriers to social acceptability, technical constraints such as the need to develop a network or the lack of skilled manpower.

For some technologies with a rapid replacement rate (vehicles, heaters), it was considered that the whole fleet could be renewed over the typical lifetime of the technology (for example 15 years for the vehicle fleet). This limits the speed of diffusion in the short term, while in the long term the diffusion will result from the optimal moment to reach the objectives at the least cost.

For other technologies deployed on a global scale (carbon capture and storage, for example), the pace of diffusion is derived from international references. This entails assuming that research and development efforts in these sectors, which involve cost reductions and deployment on a commercial scale, are predominantly done at the global level, exogenously.

Cost

The measures also have an associated cost, which is broken down into an initial investment and an annual operating cost. Relative to the lifetime of the technology, the measurements have an updated cost, which allows 1) to obtain the additional cost compared to the average technology used in the business-as-usual scenario to provide an equivalent service (production of 1 kWh of electricity or heating of 1 m^2 of housing), and 2) comparing abatement technologies that have different lifetimes. The calculation for minimising the cost of reaching the objective (e.g.: -40% of CO_2 emissions eq in 2030 compared to 1990) is carried out from a public authority point of view. For this, unit costs are considered before tax and the discount rate chosen is 4.5%, which corresponds to the risk-adjusted public discount rate (Gollier report, 2011). In the results that follow, only the financial costs were taken into account (independently of externalities, or time savings for the transport sector for example). Finally, fossil resource prices are derived from the IEA's "New policies" scenario (2014).

There is no hypothesis about the carbon price in the European quotas exchange system. The reduction costs in the sectors subject to quotas are thus overestimated. There is also no hypothesis about the rising cost of the carbon component of taxes on the consumption of energy products, which leads to overestimating the costs of reducing emissions from diffuse sources (transport, individual heating). Introducing carbon pricing could be the subject of future development for the tool.

DYNAMIC (D) CURVE OF ANNUAL EMISSIONS ABATEMENT

Emissions after abatement (the left-hand graph regarding the figures presented below) are the result of a minimization of the discounted costs over the whole period of the abatement technologies which make it possible to reach an emissions target by 2050. Box 2 describes the optimisation programme used. The tool also makes it possible to seek to comply with other constraints linked to emissions, such as a CO_2 budget (i.e. cumulative emissions) over the 2012-2050 period, or sectoral or global intermediate crossing points. The additional constraints can be derived in particular from the Trajectory Committee (2011) report, which proposes intermediate and final targets in 2050 for each emitting sector, so as to reach a factor 4 in 2050. Other constraints included in the Energy Transition for Green Growth Act have also been imposed, such as the drop in nuclear power generation.

The optimization shows, for each sector, what the uses of all the technologies of the database are. In the business-as-usual scenario, these shares remain constant, whereas in the emission reduction scenario, more carbon-free technologies develop, with an associated additional net cost (or sometimes a profit). This approach is complementary to the scenario-creation exercise carried out upstream of the SNBC (Stratégie Nationale Bas Carbone or Low Carbon Development Strategy), which includes an assessment of the macroeconomic impacts of the constructed scenarios, and in particular the one used as a reference to the SNBC.

The emission differences between the two scenarios are broken down into different GHG abatement sources . One GHG abatement source is associated with each of the low-carbon technologies that can be deployed between 2012 and 2050. It takes into consideration both the diffusion of technology as a replacement for the technologies of 2012, and the reduction of its unit emissions over time.

Box 2: Description of the tool used to construct the curves

The tool is programmed using the free software python. It constructs, from the technology/measurement database and the business-as-usual scenario, a low-cost trajectory and produces the graphical representation of the "wedges" and associated average abatement costs. The minimization involves a variable that records, year by year, the use $a_{i,t}$ of each of the technologies/measures *i* at the date *t* input into the base. This optimization is made under several types of constraints (where c and e respectively denote the costs and the unit emissions).

The maximum potential for use of each of the technologies/measurements is:

From one year to the next, the increase in $a_{i,t} < A_{max,i}$ the use of technologies/measurements is limited by a max diffusion speed $V_{,i}$. The maximum diffusion speed is thus written as follows:

$$a_{i,t+1} \leq a_{i,t} + V_{max,i}$$

All the technologies in a sector have to respond to the projection of the demand for it:

$$\sum a_{i(secteur),t+1} = D_{secteur,t}$$

A constraint (GES_{max}) on total emissions in 2050, with the possibility of adding other crossing points, is introduced as follows:

$$\sum a_{i,2050} \cdot e_{i,2050} \leq GES_{max},$$

With, $e_{i,2050}$ the unit emissions for the technology i in 2050.

Constraints also exist regarding the equilibrium between supply and demand of the different energy vectors.

Minimizing costs to reach the GHG target in 2050 is then a sum of the type:

$$\sum_{i,t} \frac{a_{i,t} \cdot c_{i,t}}{(1+r)^t}$$

with r the discount rate chosen.

The vector $a_{i,t}$ which fulfills the constraints at the least cost thus chronicles the uses of each of the technologies over time.

The area occupied by a GHG abatement source (technology, behavior, ...) ("wedge") represents the cumulative emissions avoided over the 2012-2050 period that can be attributed to this measure or technology. This area is not proportional to the use of the technology over time but to the GHG reductions attributed to it by the LMDI method (see Box 3). This method takes into account the effect of the interactions over time between the energy efficiency and the carbon content of the energy on the potentials of the GHG abatement sources. For example, the potential for reducing telecommuting decreases with the energy efficiency of vehicles. The remaining area below the set of wedges represents the trajectory of residual GHG emissions over time in the "low-carbon" scenario analysed.

Box 3: Breakdown of the "LMDI" GHG abatement sources

The Log-Mean Divisia Index (LMDI) breakdown method is used to attribute emission reductions to different GHG abatement sources that can interact (change in the structure of activity, efficiency of new technologies, decarbonation of energy carriers). For example, reductions related to telecommuting or rail transport decrease as unit emissions from private cars decrease (see the evolution of "wedges" in figure 6, which depicts the transport sector). This interaction must be taken into account in order to allocate, over time, the emission reductions of the various GHG abatement sources in the transport sector.

The general method (Kesicki & Anandarajah, 2011) entails writing the total emissions E of a sector i as a sum of factors products, each associated with one of the technologies:

$E_i = \sum_j (a_i * s_{i,j} * f_{i,j} * e_{i,j})$

The factors being respectively: a_i the sector activity, $s_{i,j}$ the share of different technologies j used, $f_{i,j}$ the energetic intensity of each of them, and $e_{i,j}$ the CO_2 content of the energy.
The emission reductions are therefore broken down according to these four factors x_i before being attributed to the underlying technologies, following the general formula:

$$\Delta E_x = \sum_j (E_{i,BC} - E_{i,0})(\log E_{i,BC} - \log E_{i,0}) \cdot ln(x_{i,BC}/x_{i,0})$$

Where index 0 designates the business-as-usual scenario, index BC (for "bas carbone" meaning "low carbon") the low-carbon scenario, and E_x the emission reductions attributed to the factor x.

REPRESENTING THE AVERAGE ABATEMENT COSTS (CAM)

The net discounted cost of the tonne of CO_2eq avoided (IPCC, 2014) is associated with each measure. This cost corresponds to the ratio of the discounted total cost difference between the low-carbon technology and the corresponding technology used in the business-as-usual scenario and the (total discounted) emissions avoided by this measure. The costs and abatements incurred beyond 2050 (in particular for technologies with a long lifetime) are also taken into consideration.

Some technologies have costs that decline sharply over time, so that the discounted cost per tonne may be different from the marginal abatement cost in 2012 or in 2050 (e.g. the cost of electric vehicle batteries is divided by two after ten years). This reduction in costs is considered to be exogenous: it does not depend on how the technology spreads over the national territory.

Measures can be ranked for reading convenience according to increasing costs (top to bottom), but this is not a merit curve, which would prioritize the mobilization of GHG abatement sources. The abatement curves obtained show that the order of implementation of the measures does not necessarily follow that of the costs due to the limited and different deployment speeds of the GHG abatement sources . This order of implementation results from a minimization of costs over the entire period. **At intermediate crossing points, some GHG abatement sources with a relatively higher abatement cost than others must already be partially mobilized to ensure the long-term objective is reached**.

The height of the stick corresponds to the average cost per tonne of CO_2 eq avoided for this deposit over the entire period. Its width indicates the emissions avoided in the last year considered.

Box 4: Colour code used for all figures

- Behavioural GHG abatement sources
- Deposits linked to the structure of the demand
- Energy efficiency
- Change in energy source
- Decarbonation of energy vectors
- GHG capture and/or storage
- Others

Hatching: high cost uncertainties

Part 2

Sectoral curves of abatement cost dynamics

The TITAN tool explores decarbonation scenarios for each sector (energy, transport, buildings, industry, waste, agriculture), which enable the targets set by the national low-carbon strategy to be achieved at different time horizons.

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TITAN CURVE FOR THE ENERGY PRODUCTION SECTOR

Calibration of parameters and constraints used for optimisation

The European Commission's projection used for the business-as-usual scenario for the sole French energy sector provides an activity which stabilises over time. In order to obtain an aggregate curve across all sectors, output from the energy sector is adjusted to balance the demands of consumer sectors.

The curve of Figure 3 is calculated on this projection of the business-as-usual scenario in order to reach the sectoral target proposed by the trajectory committee (-96% emissions in 2050 from electricity, -85% from other energies). The energy sector includes both electricity and heat production, and the refinery.

For the electricity generation sector, all the means of production are not equal in view of the necessity of a constant balance between supply and demand. This balance is ensured by the presence of base capacities and peaking capacities. The latter, also called controllable capacities, are responsible for the bulk of the GHGs in the sector due to the mobilisation of fossil fuel stations. To represent the peak-to-base equilibrium, it has been simplified that a fixed part (16%) of the energy produced must be replaced by rapidly controllable capacities (fossil fuel stations, transfer and pumping station, dams). The choice of this ratio corresponds to what is observed today. Reducing GHG emissions in the energy sector is thus tantamount to removing carbon from the peaking capacities that are responsible for virtually all emissions of the energy sector.

The sector's target is to achieve an emission level in 2050 of 4.2 Mt/year, i.e. a 93% reduction in emissions compared to 1990 levels (60.1 Mt/year)

Results

Figure 3 shows that the emission reduction target is achieved by substituting fossil fuels to generate heat and electricity with biomass (through heat/electricity co-generation becoming widespread), biogas or synthesis gas and the mobilisation of carbon capture and storage (CCS). Almost all of the sources of emissions reductions used in 2050 have an average cost of less than €150/tCO_2. The dynamic emissions curve indicates that it is effective to initiate emission reduction efforts in 2025 and accelerate them in 2030.

The systematic use of BECCS technologies (bioenergy with carbon capture and storage) would even go beyond the target and produce negative emissions. TITAN

Figure 3: Dynamic curve of average abatement costs with a long-term target - Energy

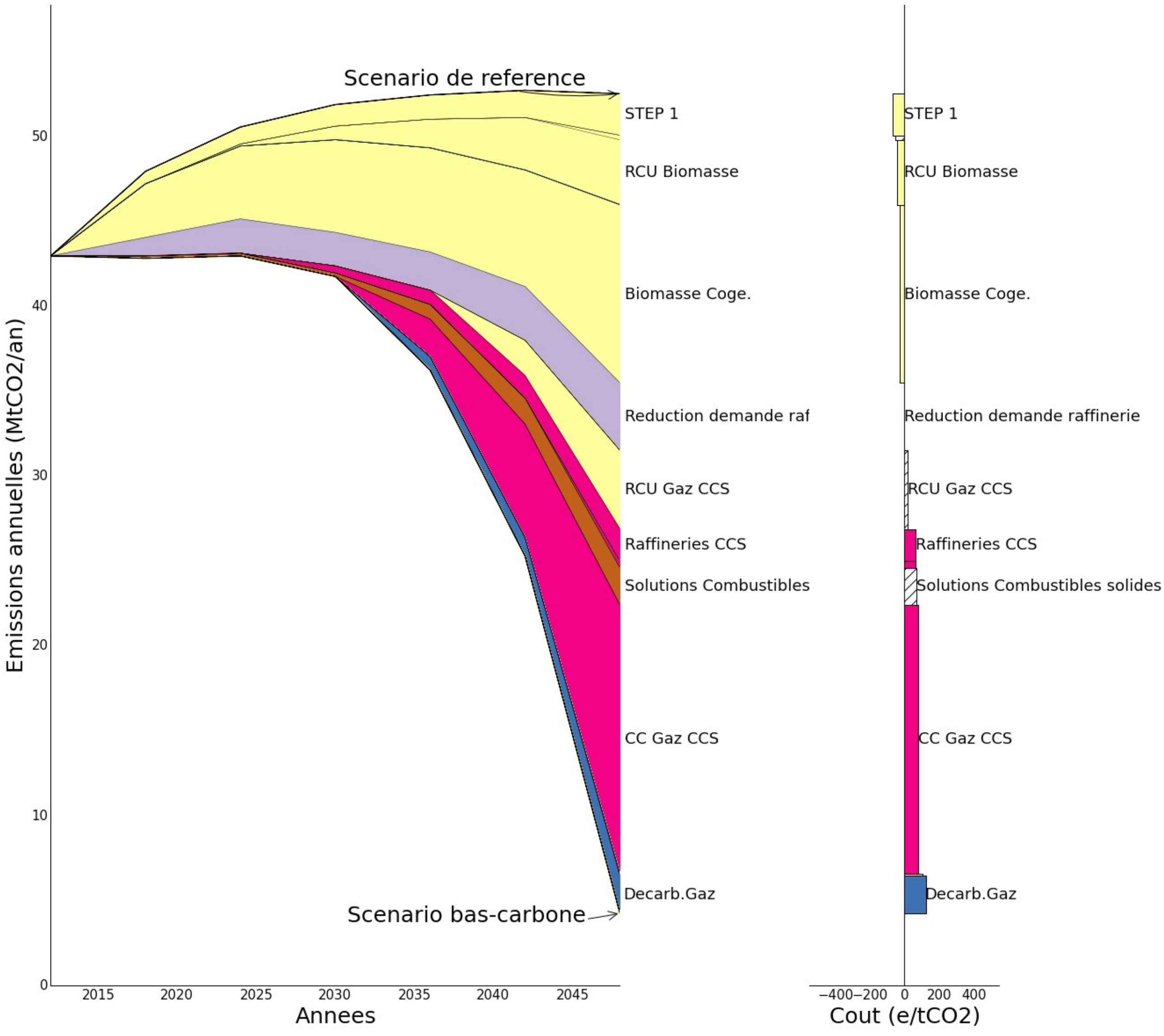
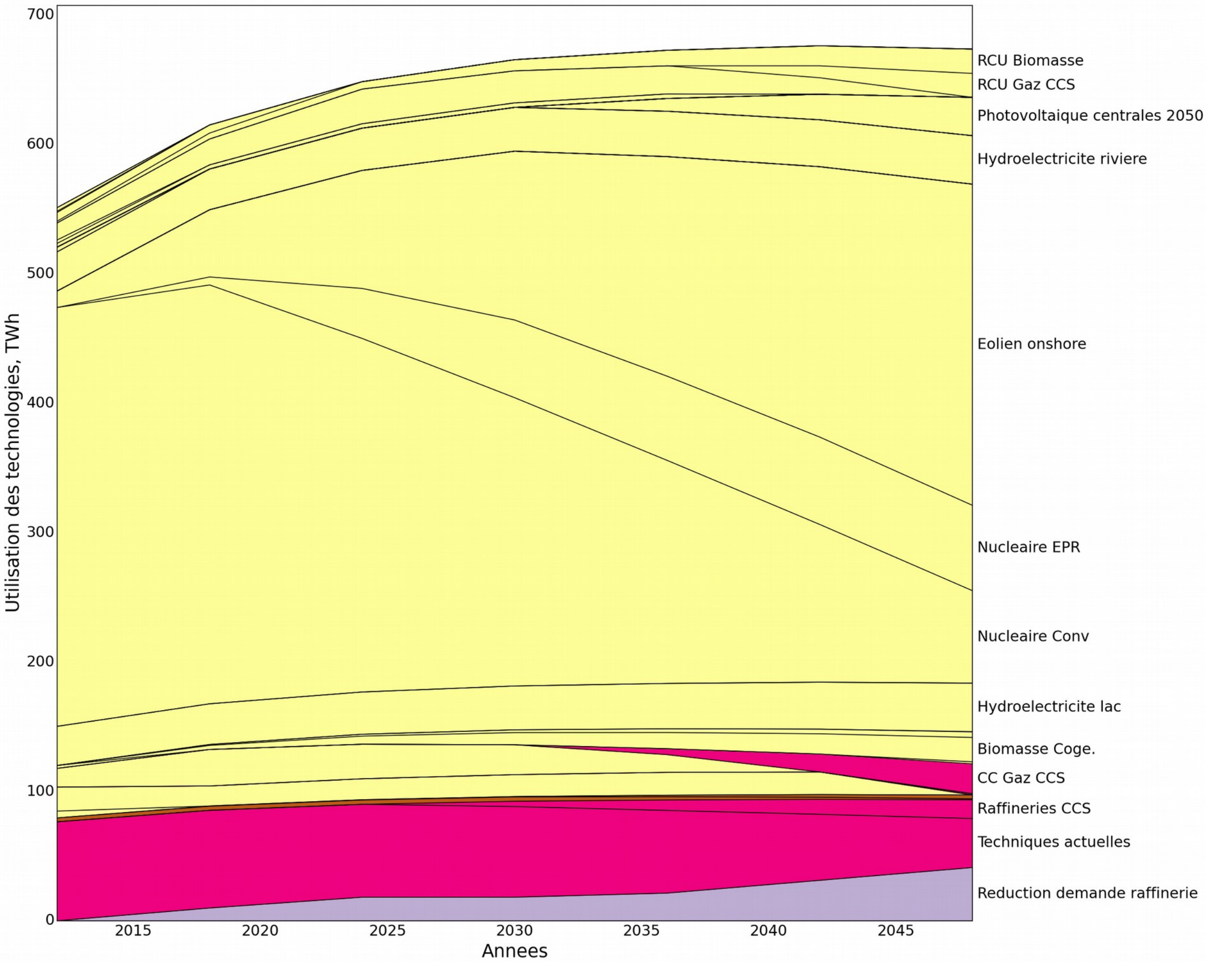


Figure 4: Trajectories of the use of different technologies of the electric power mix with constraints on emissions



It is important to note that the size of the sources shown in Figure 3 is not proportional to the physical quantity of energy produced and therefore does not reflect the share of technologies in the energy mix. Combined Gas Cycles are a significant source as these plants replace the coal and oil-fired power stations, which were responsible for a significant share of emissions in 2012. Since these technologies only concern peaking capacities, i.e. 16% of the mix, they represent only a small part of the total electrical power mix.

Figure 4 shows the total energy mix that results from cost minimisation. It thus reveals the technologies that provide the base capacities and do not appear in the TITAN insofar as they are non-emitting (nuclear, hydroelectric, wind, photovoltaic). The penetration of renewable energies is at the rate of the decrease of the share of nuclear energy in the electric power mix that will reach 50% in 2025 and remains constant until 2050.

Some of the reductions are also attributed to the use of non-fossil gas for electricity generation.

Similarly, nuclear power does not appear as a source of reduction in 2050, as its relative share in the electrical power mix decreases between 2012 and 2050. But the proportion of nuclear energy in final production remains significant.

The deployment of solar energy does not take place until 2030, as wind and hydroelectricity are already sufficient to cover demand in addition to the drop in nuclear capacity. It is important to note that, in this optimisation, the average cost of KWh in the business-as-usual scenario is assumed to be constant. However, since the gradual replacement of existing nuclear power plants by EPRs will lead to an increase in this average cost, this hypothesis leads TITAN to overestimate the energy sector's abatement costs. Given the strong uncertainties about the cost of KWh produced by EPRs (a possible doubling of costs compared to conventional power plants), it seemed simpler and clearer to keep the historical costs of nuclear power in the business-as-usual scenario that is purely analytical. This also helps to maintain methodological coherence with other sectors where technologies are assumed to be "frozen" throughout the period.

TITAN CURVE FOR THE TRANSPORT SECTOR (PASSENGERS AND FREIGHT)

Calibration of parameters and constraints used for optimisation

In 2012, the demand for transport was 860 billion passengers.km/year and 453 Gt.km/year. A projected growth of this demand of 0.4%/year for passengers and 1.5% per year for goods (as in the SNBC scenarios) is used to construct the business-as-usual scenario regarding emissions. In this scenario, the modal shares remain constant (80% for cars), as do the occupancy rates (1.53 passengers/vehicle) and the unit emissions of passenger cars (167 gCO_2/km), which leads to emissions of 172 $MtCO_2eq$/year in 2050.

The data include measures of (i) reduction in demand, (ii) modal shift, (iii) increased occupancy rates, (iv) improved vehicle efficiency, (v) changes in the energy used or decarbonation of the energy vector.

The emission target for 2050 is set at 42.5 $MtCO_2$/year, representing an emission reduction of 65% from the 1990 level of 121 Mt/year.

The unit emissions of each technology correspond to "actual" emissions of the vehicle under consideration, not the theoretical emissions measured over a test cycle.

Results

The results of the optimisation (Figure 5) show measures that reduce transport demand (negative cost measures), energy efficiency measures that reduce unit emissions from passenger cars, via hybrid vehicles or lower-consumption vehicles, measures that change energy carrier, via carbon-free vehicles and some (more costly) measures of modal shift to public transport.

Measures such as telecommuting (first hatched bar) or carpooling (presented under the light-duty vehicle load label) are by construction at negative cost, as they are supposed to avoid travel costs for the person who practices them. No cost (psychological or logistical) is associated with staying home to work or carpooling. Over time, due to the continued decline in average vehicle emissions, the emission reduction potential associated with these measures decreases and almost disappears at the end of the period.

The contribution of the least emissive vehicles (hydrogen and electric), considering their high abatement cost, remains modest before 2025 and then becomes mass-market until 2050. The date of the source's deployment, resulting from its optimisation, is conditioned by their limited deployment speed[2].

The deployment chronicle of these low-carbon vehicles is a good example of the dynamic issues involved in interpreting a TITAN, which makes it possible to justify sources with a relatively higher average cost being deployed before sources at a relatively lower average cost. For example, optimisation that would only achieve an intermediate target in 2030 (63 Mt, Figure 6) would not show hydrogen and electric vehicles in the TITAN because more efficient thermal vehicles would be sufficient to achieve the target. The optimisation with respect to the 2030 crossing point does not make it possible to anticipate the need for these vehicles in order to achieve the 2050 target and therefore the need to mobilise part of their source before 2030. In the absence of such an expectation, the cost to reach the final target in 2050 would be greater. Indeed, the lack of low-carbon vehicles in 2030 and the constraints on their speed of deployment will then prevent the deficit of this type of vehicles from being filled by 2050 (compared to the optimised scenario for the 2050 target), which will require the mobilisation of other more expensive technologies (metros, trams). This is why the "parts" associated with hydrogen and electric vehicles appear before 2030, while emissions remain high and other less costly solutions have not reached their maximum potential. Thus, **the only cost curve** (to the right of Figure 5) **does not make it possible to provide this dynamic information**.

[2] The source associated with the development of electric motorways that would allow electricity to be supplied via catenaries to diesel/electric hybrid heavy goods vehicles is not taken into consideration in this study. Other forthcoming CGDD works show that this type of infrastructure could be deployed from 2030 and could significantly contribute to the sector's emission reductions.

Figure 5: Dynamic curve of average abatement costs with a long-term target – Transport

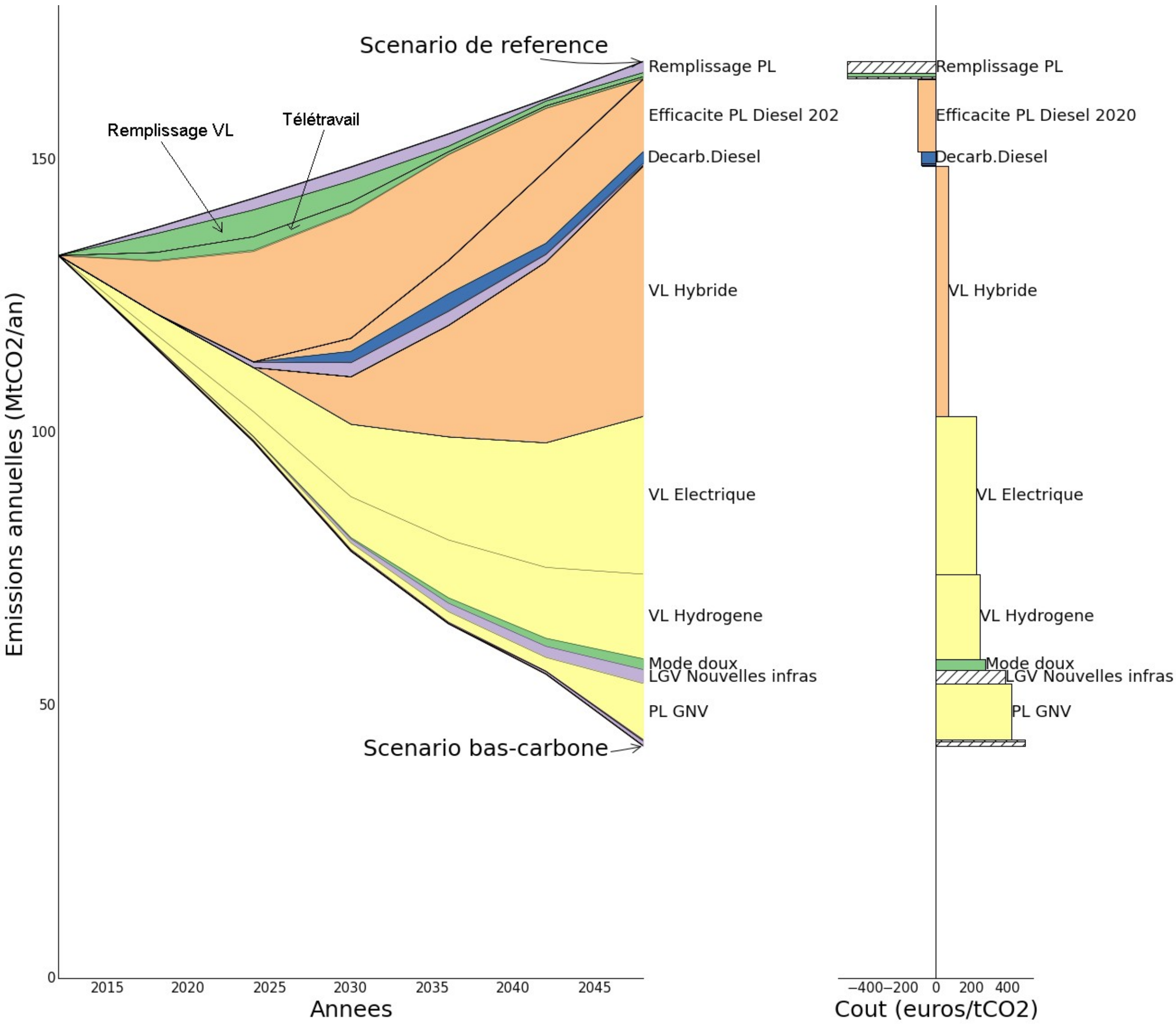


Figure 5bis: Cumulative sources of emissions reductions over the 2010-2050 period

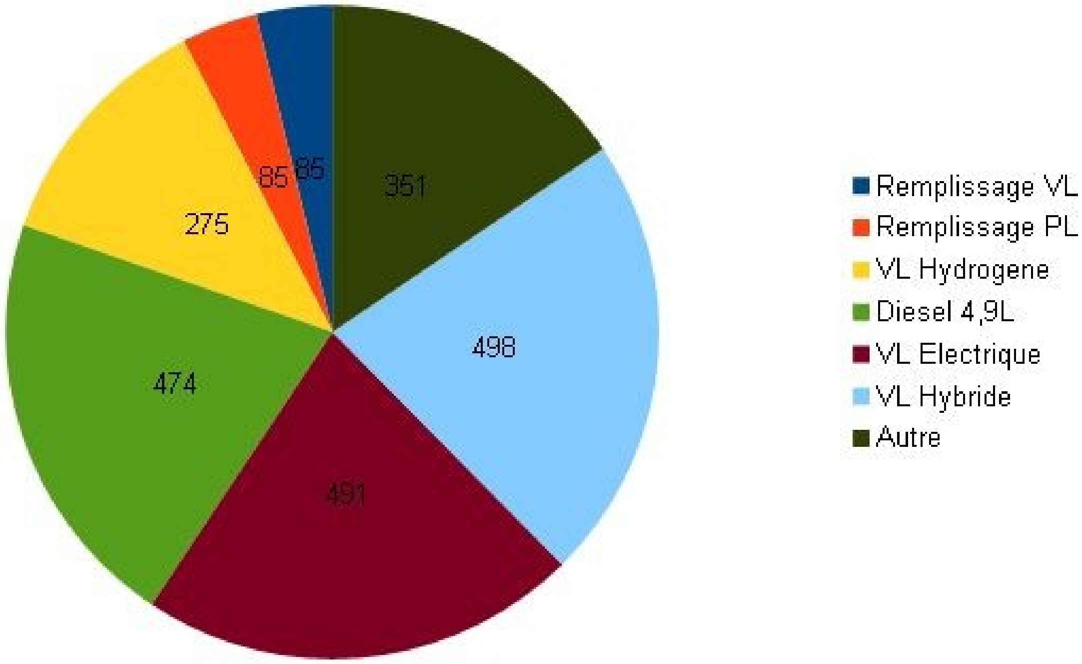


Figure 6: Dynamic and average cost abatement curve taking a medium-term target (2030) into account – Transport

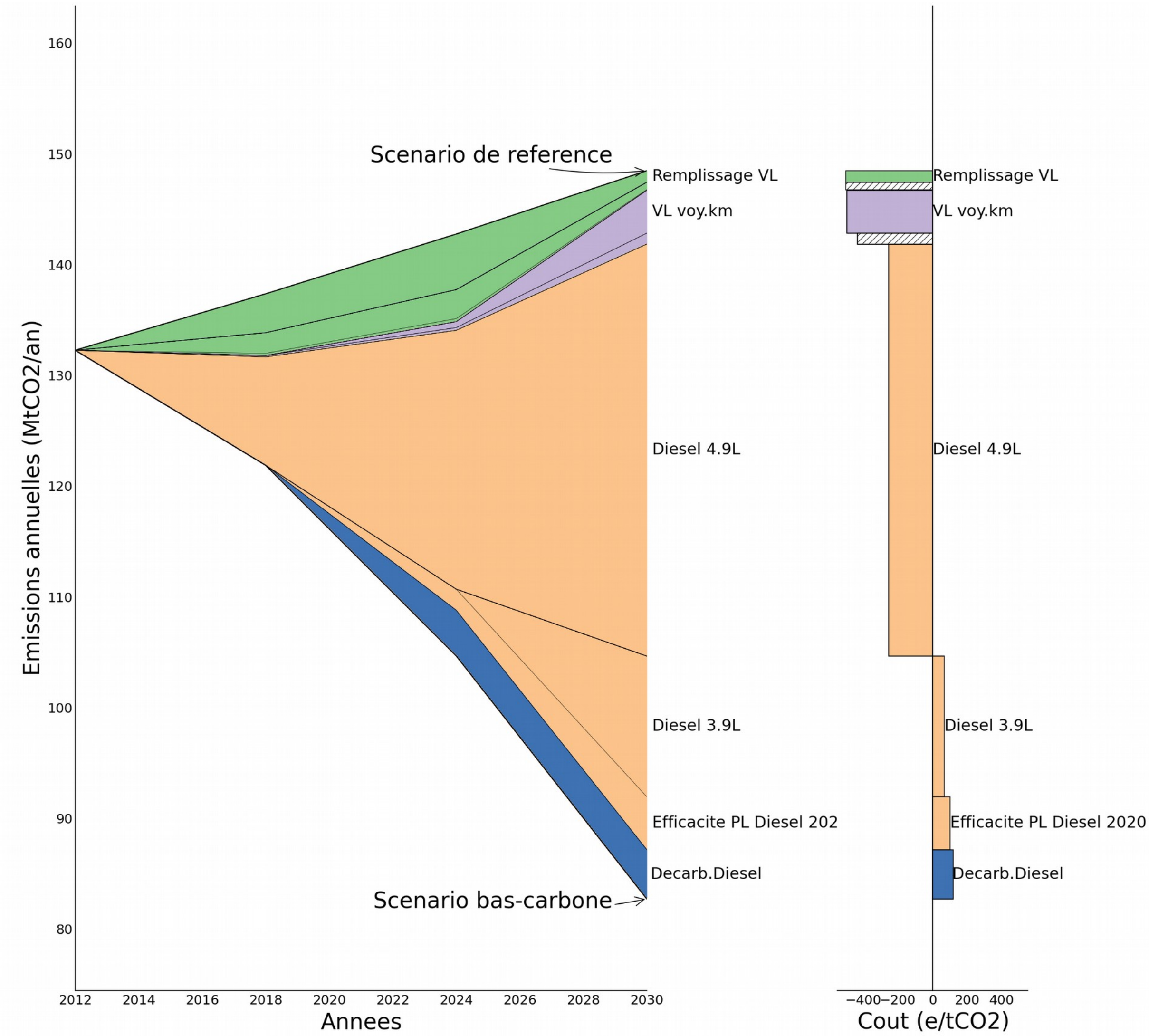


Figure 7: Type of measures implemented in 2030 according to the time horizon of the pursued target

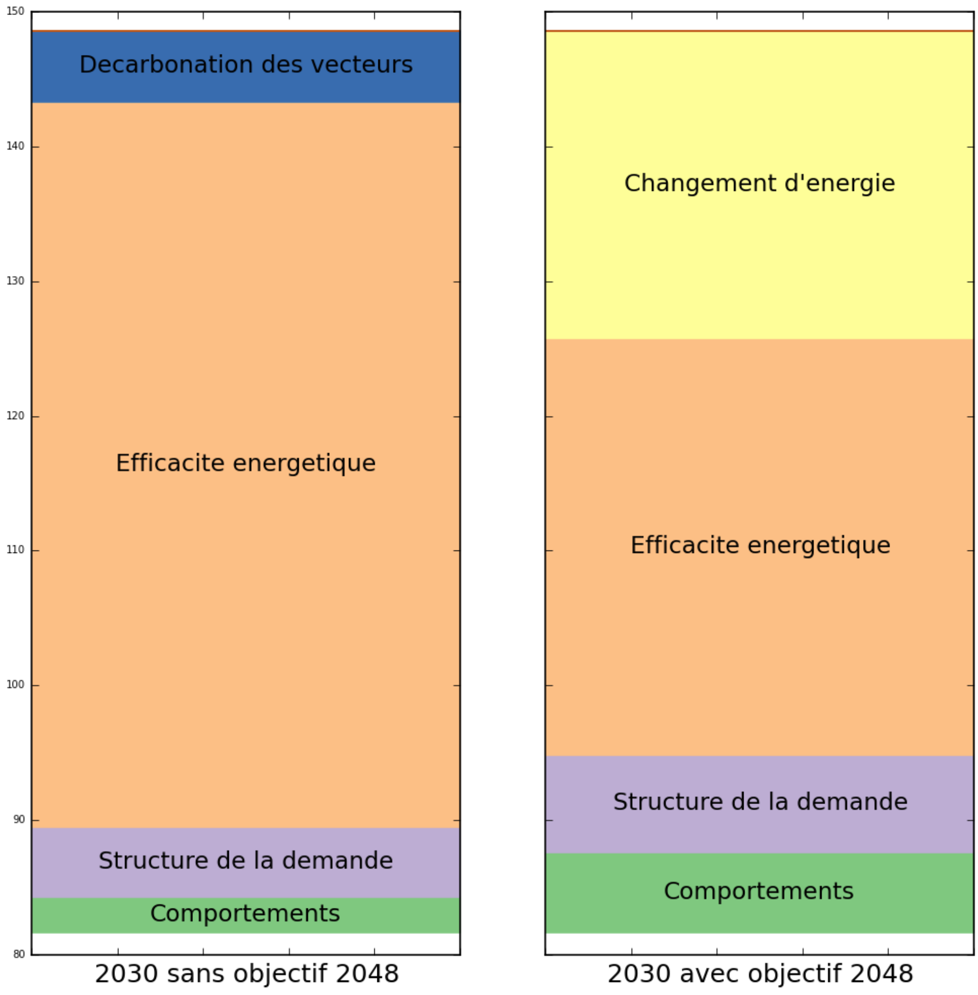
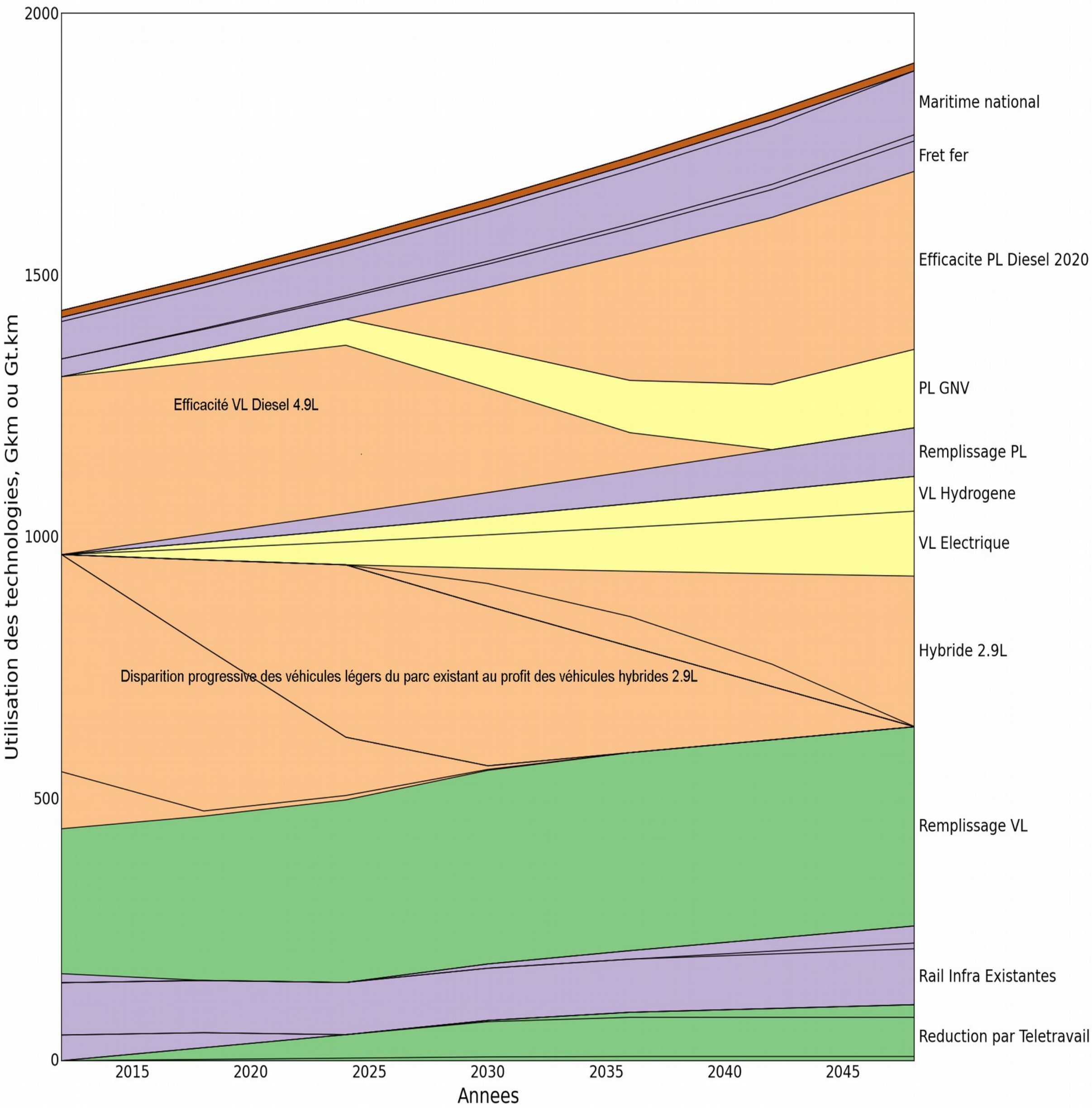


Figure 7, which compares the types of measures mobilised in 2030 with and without taking into account a long-term target, also shows these dynamic effects. In the absence of a long-term target, the 2030 target can be achieved by essentially mobilising energy efficiency measures (left-hand diagram). Optimising with respect to a long-term target distorts the structure of the sources at the crossing point (right-hand diagram). The contribution of energy efficiency is lower. While energy-change sources (electric or hydrogen vehicles), sources relating to the structure of demand (modal shift) and behavioural changes (vehicle load, telecommuting) are mobilised to a greater extent.

Figure 8, which shows the evolution of the use of technologies/measures in a low-carbon scenario by 2050, shows that some measures are only temporary. Their contribution to the emission reduction target in 2050 becomes zero but they have been usefully deployed between 2012 and 2050 to meet the transport demand while minimising the cost of the decarbonation target by 2050. This is the case for the penetration of 4.9 L diesel light-duty vehicles in the fleet, which are the main source of emission reductions until 2025 (see Figure 5bis on the cumulative emission reductions of the various sources) and whose contribution then reduces until cancellation in 2050 (source between HGV NGV and HGV load). Figure 8 shows that other types of vehicles, such as the current fleet of gasoline and diesel vehicles, are also disappearing without being sources of emission reductions. Their disappearance corresponds to their "natural" replacement by more efficient vehicles, in particular 2.9 L hybrid vehicles.

Figure 8: Use of different technologies or measures over time in the low-carbon scenario - Transport

(In G.km for the "passenger" part and in Gt.km for the "freight" part)



TITAN CURVE FOR THE WASTE SECTOR

Calibration of parameters and constraints used for optimisation

Four types of sources are considered to reduce GHG emissions from the waste sector:

(i) reducing the amount of waste produced;
(ii) increasing the recycling rate;
(iii) increasing the energy recovery of non-recycled waste (2/3 of non-recycled waste);
(iv) increasing the methane capture rate in storage centres (from 40% to 77%).

The majority of the data comes from the prospective exercise of the waste action plan conducted by the Ministry of the Environment in 2009.

For the part of the waste stored, emissions are not represented according to the kinetics used in the inventories. Each tonne of waste is expected to emit all of its GHGs in the year it is disposed of in a landfill.

The share of bio-waste among the waste that is landfilled (greater emitters of CH4), or among the waste recovered in energy (the biogenic part of CO_2 is not accounted for in emissions), is assumed to be constant: there is an additional source if the bio-waste content differs between incineration and storage.

For recycling, the avoided emissions counted are the amount of waste that is not disposed of in a landfill or that is not incinerated. The part related to the substitution of virgin material (raw material to manufacture steel for example) may appear in other sectors (less energy-intensive recycled steel).

The emission target for 2050 is set at 2.5 Mt/year, representing an emission reduction of 78% from the 1990 level of 11.5 Mt.

Results

To read the TITAN curves (Figure 9), it is important to remember that the avoided emissions on the ordinate axis are not proportional to the evolution of the quantities processed by each technology. The evolution of these quantities is presented in Figure 10. Figure 10 shows that treatment by incineration (second technologies from the top) becomes marginal at the end of the period and that landfilling according to the standards in force in 2010 completely disappears (fuchsia technology).

Figure 9 shows a decrease in the reductions associated with waste prevention and recycling (the first two parts starting from the top) at the end of the period. This is not due to a reduction in the recycling rate: the quantities of "non-produced" waste (compared to the business-as-usual scenario) or recycled waste continuously increase (Figure 10). But since unit emissions associated with waste destruction decreases, the amount of GHGs avoided per tonne of recycled waste also decreases.

The source associated with the capture of methane appears to be particularly significant since the emissions of the waste landfilled are then divided by approximately 3.

Figure 9: Dynamic curve of average abatement costs with a long-term target - Waste

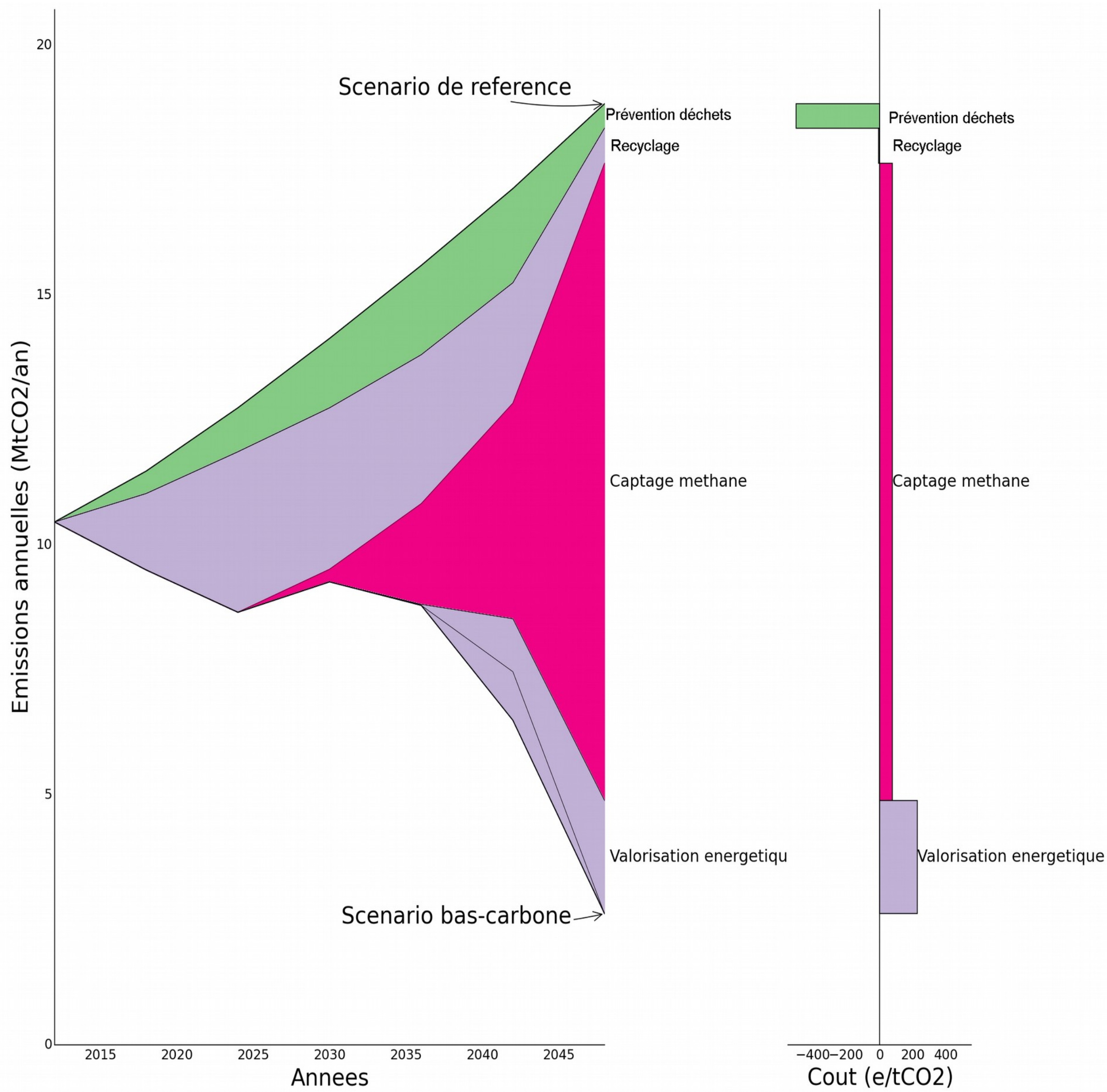
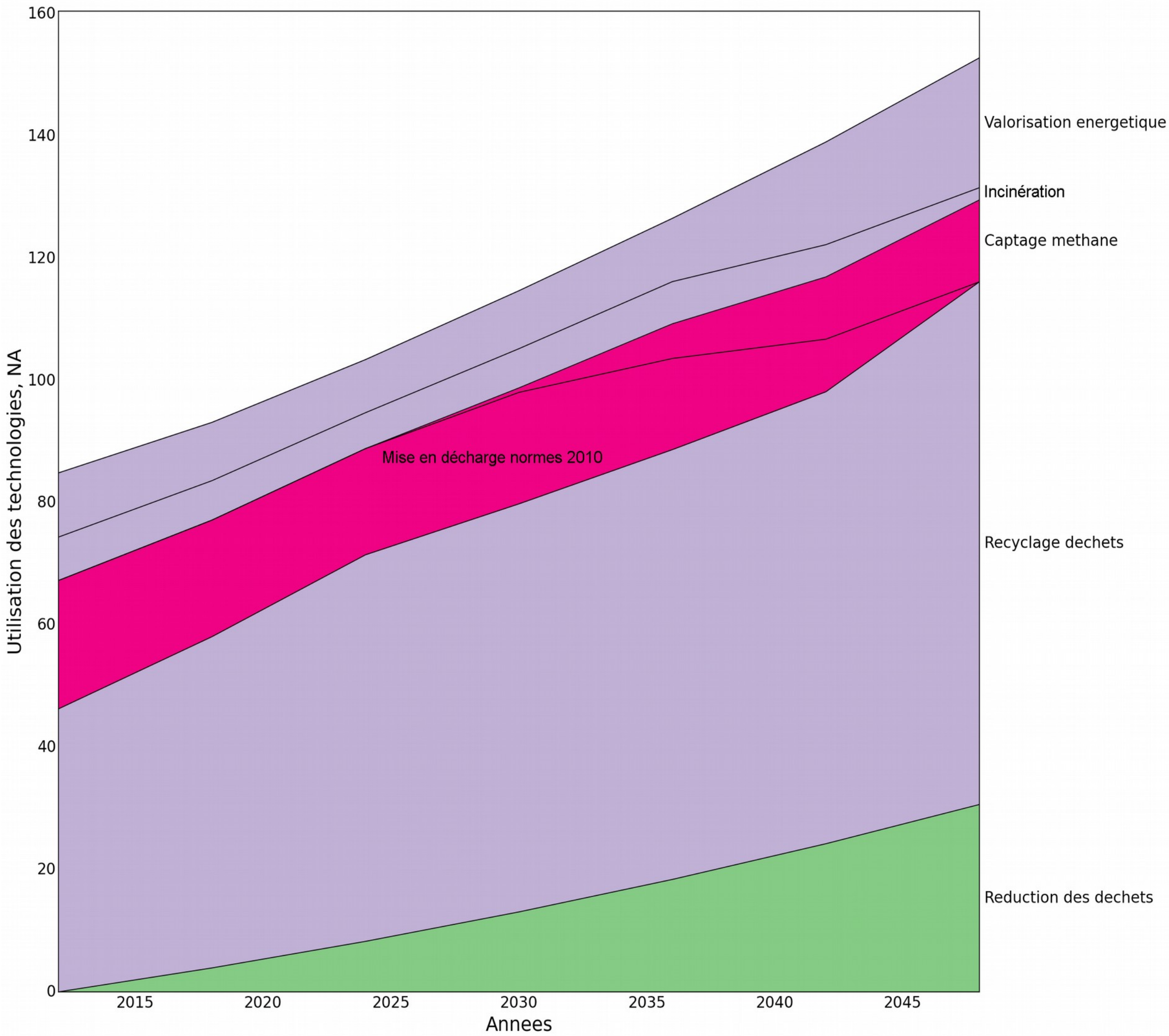


Figure 10: Quantities of waste treated by the different technologies considered over time in the low-carbon scenario - Waste



TITAN CURVE FOR THE BUILDING SECTOR (RESIDENTIAL AND TERTIARY)

Calibration of parameters and constraints used for optimisation

A large number of sources are considered for this sector, as the existing stock is disaggregated according to: the type of dwelling (single-family dwelling/multi-family dwelling), the heating energy used and the performance level of the building. For each combination, the sources include:

- the energetic refurbishment of the building, strong or moderate;
- the change of heating device for a more efficient appliance or for another type of heating energy.

The same type of measure may thus appear several times on the curve, as it does not apply to the same segment of the housing stock.

In new-build buildings, three levels of construction quality are considered (TR 2005, TR 2012 and TR 2020).

Other sources (in blue in Figure 11) correspond to the decarbonation of the main energy vectors (heat, electricity, gas).

Please note: Articulation with the energy sector

Some of the emissions related to the residential and tertiary sector are indirect emissions, through electricity and heat consumption. The sources linked to electrification, or to the energy efficiency on electrical substations or to the decarbonation of vectors depend strongly on the carbon content of the electricity. A potential is thus attributed to a "decarbonation of electricity" source which reduces the indirect emissions of the electricity consumed by the building. The costs and carbon content chronicle is calculated separately for the energy sector alone and depends on the target that has been assigned to this sector. The results are used here as input data to assess the indirect emission reduction potential of the building sector.

It is important to note that these emission reductions are not duplicated by those of the energy sector as a whole. They result from additional electricity production and therefore an additional decarbonation effort required from the energy sector.

The sources were calculated from:

- the final energy consumption of the current fleet (CEREN data);
- the expected gains on energy consumption by the energetic refurbishment of the building (Directorate-General for Energy and Climate (DGEC) assumptions);
- the yields of the different heating appliances considered (ADEME data);
- the GHG content of each of the energies used, which may be reduced over time. This evolution of the CO_2 content may be accompanied by a change in the cost of producing the associated energy (determined by the reduction curves of the “energy” sector).

As regards the behavioural aspects, no rebound effect on energy consumption was taken into consideration.

A unit cost is allocated to the building energetic refurbishments and to the heating appliances (assumptions used in the SNBC scenarios). For the potential, the maximum number of dwellings affected by each action was estimated from the synthesis of the reduction trajectories proposed under the DNTE[3].

For the construction of the business-as-usual scenario, the building park is assumed to be progressively enlarged by new constructions at the rate of 300,000 dwellings/year. The rates of equipment for the different types of heating appliances in these new dwellings in the business-as-usual scenario are those recorded in 2012 by the DPE (Energy Performance Diagnostics) Observatory. They are kept constant throughout the period. The construction quality level in this theoretical scenario is that of the TR 2005 (TR for “thermal regulation” for new buildings). The acceleration of this pace of new constructions, up to 500,000 dwellings/year, was considered as a source of GHG emissions reduction.

The same approach was used for the tertiary sector, but with a less disaggregated park (only one average performance level in 2012 for each of the heating energies considered).

The low-carbon trajectory considered optimises the costs over the period to reach an 85% reduction target for the residential-tertiary sector in 2050 compared to 1990. There is no overall target for the sector in terms of primary or final energy consumption, only the carbon criterion is taken into consideration.

The emission target for 2050 is set at 13.5 Mt/year (direct and indirect), representing an emission reduction of 85% from the 1990 level of 90 Mt/year.

Results

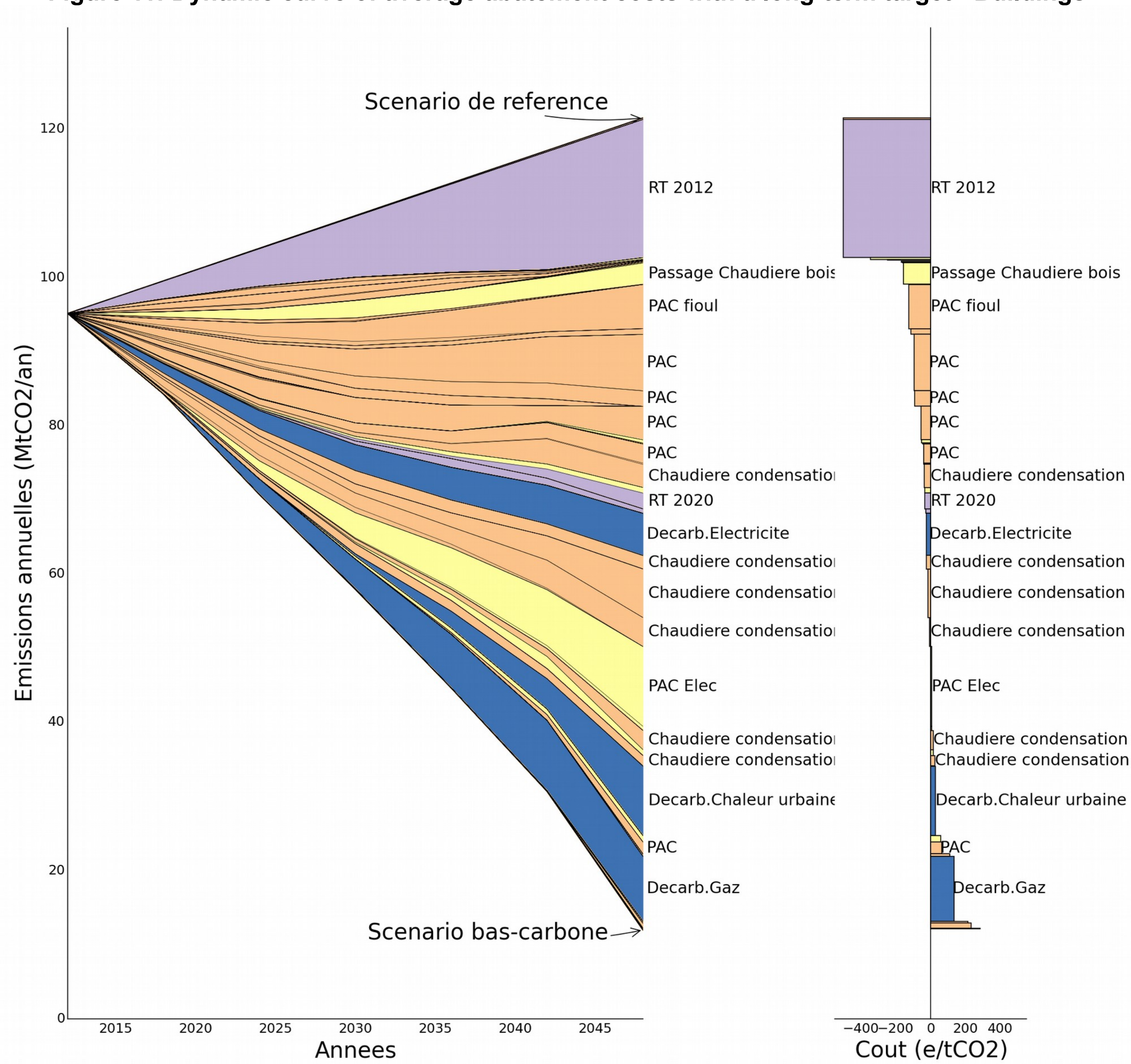
Identical sources of changes in heating appliances (heat pumps) appear several times in Figure 11 with variable (essentially negative) costs. This is due to the decomposition of the housing stock according to the heating energy used and the performance level of the building. Thus the cost of a heat pump varies with the initial performance level of the dwelling. The refurbishments indicated by the TITAN are even more onerous as the dwelling is more emitting at the outset. When the initial stock is in worse condition, the average abatement costs will cover a wider range of values.

Part of the GHG abatement sources (Figure 11) appears with a negative cost. This applies in particular to the application of TR 2012 for new constructions and several heating technologies. These negative costs may be linked to asymmetries of information on the energy savings achieved by these heating technologies, or to the use of a public discount rate (4.5%) which is lower than that used by a private economic agent.

Some expensive GHG abatement sources appear at the beginning of the period, given their very slow deployment speeds: this is the case for major energetic refurbishments. The cost curve (right), therefore, should not be read as the order of priority of the sources to be exploited. **The only cost curve (to the right of the figure) does not provide information related to the limited speed of energetic refurbishments or new constructions.**

3 Low hypothesis of new constructions, resulting from the synthesis of the trajectories of the National Debate from the National Debate on Energy Transition (DNTE) (Carbon 4, 2014)

Figure 11: Dynamic curve of average abatement costs with a long-term target - Buildings



TITAN CURVE FOR THE INDUSTRY SECTOR

Calibration of parameters and constraints used for optimisation

In the business-as-usual scenario of the industry sector, emissions from four sub-sectors are projected in relation to growth in the sectoral value-added industries:

- metals;
- chemistry;
- materials;
- other industries.

These four sectors had comparable levels of emissions in 2012.

The emissions considered combine both the use of fuels (category 1A) and those related to processes (category 2).

The main types of GHG abatement sources considered are:

- energy efficiency (main source: ADEME/CEREN study on energy-saving sources);
- change of energy source (main source: DNTE trajectories);
- decarbonation of energy sources (heat, electricity, gas, with data from the curves of these sectors);
- CO_2 capture and storage (main source: AIE).

Please note: Articulation with the energy sector

Some of the emissions related to the industry sector are indirect emissions, particularly through electricity consumption. The sources linked to electrification, or to the energy efficiency on electrical substations or to the decarbonation of energy vectors depend strongly on the carbon content of the electricity. A potential is thus attributed to a "decarbonation of electricity" GHG abatement source which reduces the indirect emissions of the electricity consumed by the industry. The costs and carbon content chronicle is calculated separately for the energy sector alone and depends on the target that has been assigned to this sector. The results are used here as input data to assess the indirect emission reduction potential of the industry sector.

Due to the low CO_2 content of electricity in 2050, indirect emissions are marginal.

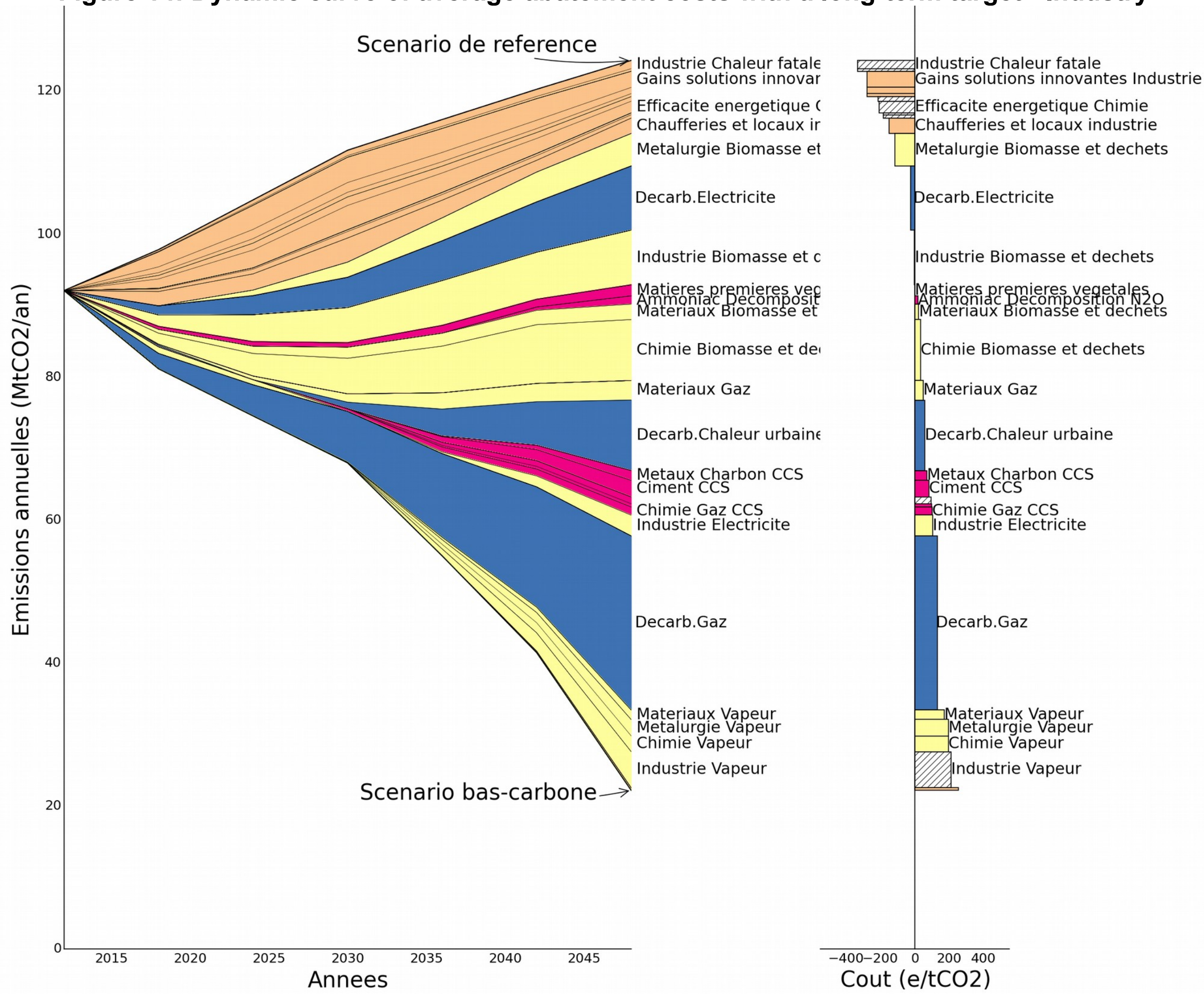
The emission target for 2050 is set at 22 Mt/year (direct and indirect), representing an emission reduction of 85% from the 1990 level of 148 Mt/year.

Results

Figure 14 shows that a significant portion of the reductions are related to the decarbonation of energy vectors used in industry (gas and electricity), which are in addition to measures specific to the energy change and efficiency sector.

In addition, carbon capture and storage appears from 2030 onwards, due to a lower abatement cost than other energy substitution measures.

Figure 14: Dynamic curve of average abatement costs with a long-term target - Industry



TITAN CURVE FOR THE AGRICULTURE SECTOR

Calibration of parameters and constraints used for optimisation

The potentials are derived from the abatement cost curve built by INRA (2013). The abatement curve was constructed for a given time horizon: sources in 2030. From these sources, the optimal time trajectories have been reconstructed: each of the identified actions could reach its maximum base in a given year, which made it possible to deduce a speed (the deployment kinetics have been simplified, since the diffusion used here is linear over time).

The measures concern both CO_2 emissions from energy use, N_2O and CH_4 emissions, as well as carbon storage components.

The emission target for 2050 is set at 56 Mt/year, representing an emission reduction of 50% from the 1990 level of 111 Mt/year.

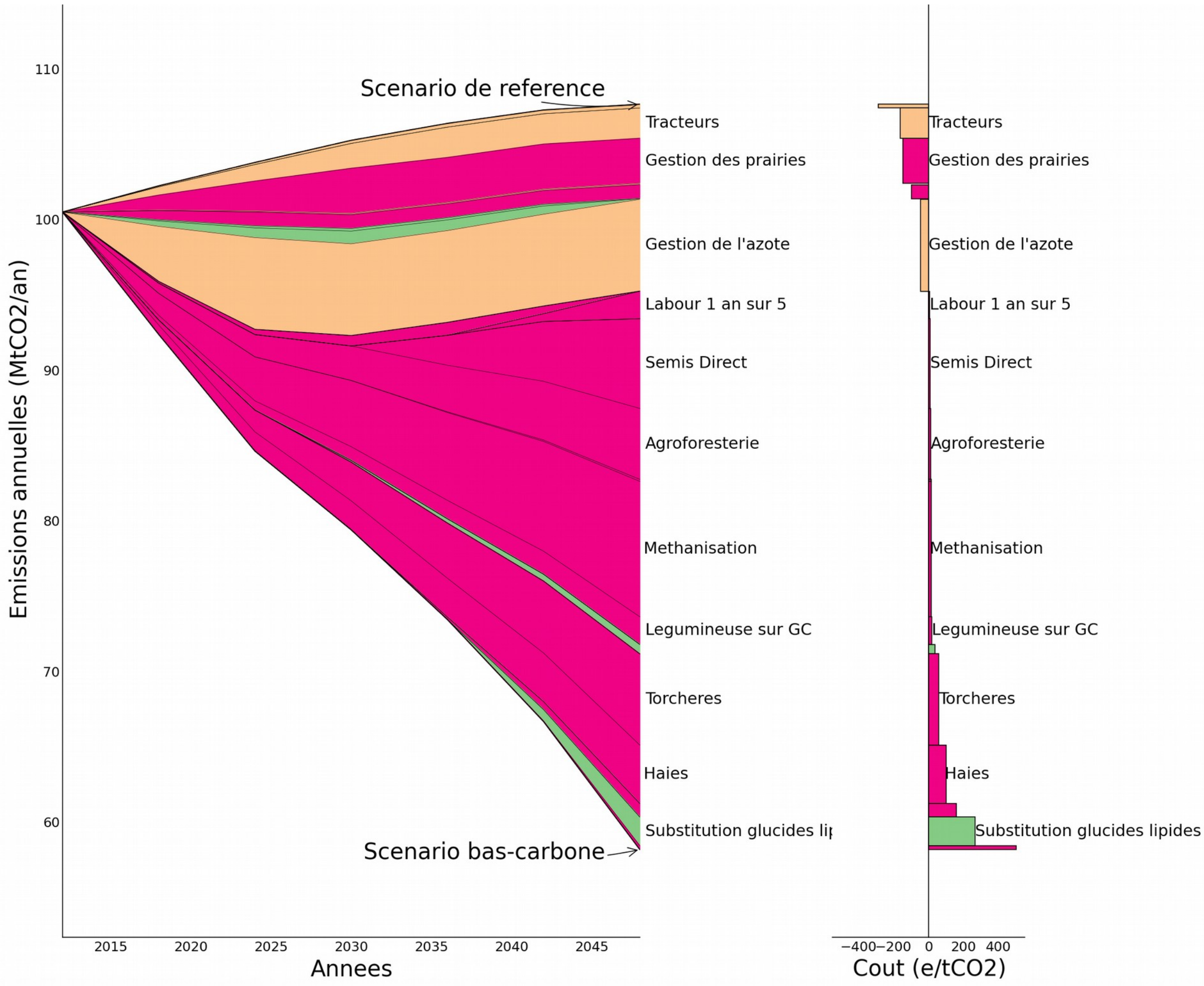
Note on the treatment of carbon storage measures:

Some of the measures presented here, such as changes in cultivation techniques, involve both identical annual reductions in emissions (such as fuel savings) and reductions that vary from year to year (such as increased carbon storage in soils or plants). For the latter, not all of the associated reductions were allocated to the year of implementation (inventory type approach) but were rather spread over 20 years.

Results

Since the fixed target (a two-fold reduction in emissions compared to 1990, i.e. 56 $MtCO_2eq$) represents, at the beginning of the period at least, a low constraint, some cost-effective measures are deployed as late as possible (such as ploughing one year out of five and no-till farming, buffer strip cropping) (Figure 15). Conversely, measures with negative costs appear at the beginning of the period. This chronicle of the mobilisation of GHG reduction sources represents the main difference with the scenarios for the dissemination of INRA actions, all starting in 2012.

Figure 15: Dynamic curve of average abatement costs with a long-term target - Agriculture



Part 3

Aggregate curve and key messages

The tool's aggregate approach changes the emission reduction effort allocated to each sector compared to the sector by sector approach. The effort required increases strongly in the energy sector and decreases in the industrial, transport and building sectors. The macro result of low-carbon transition does not show an obvious cost increase compared to the BAU scenario. The TITAN curves show indicative and exploratory transition pathways.

>

AGGREGATED TITAN CURVE WITH 75% (FACTOR 4) REDUCTION TARGET

Calibration of parameters and constraints used for optimisation

The aggregated version of the TITAN allows the design of a low-carbon pathway which minimises the costs of achieving the 75% reduction target by considering all abatement opportunities in all sectors at the same time. However for each sector, no carbon budget constraint (i.e. cumulated emissions over the period) has been imposed (either in 2030 or 2050). The detail of interactions between sectors consuming and producing energy can be found in Box 5.

Box 5: Energy sector and emissions tally

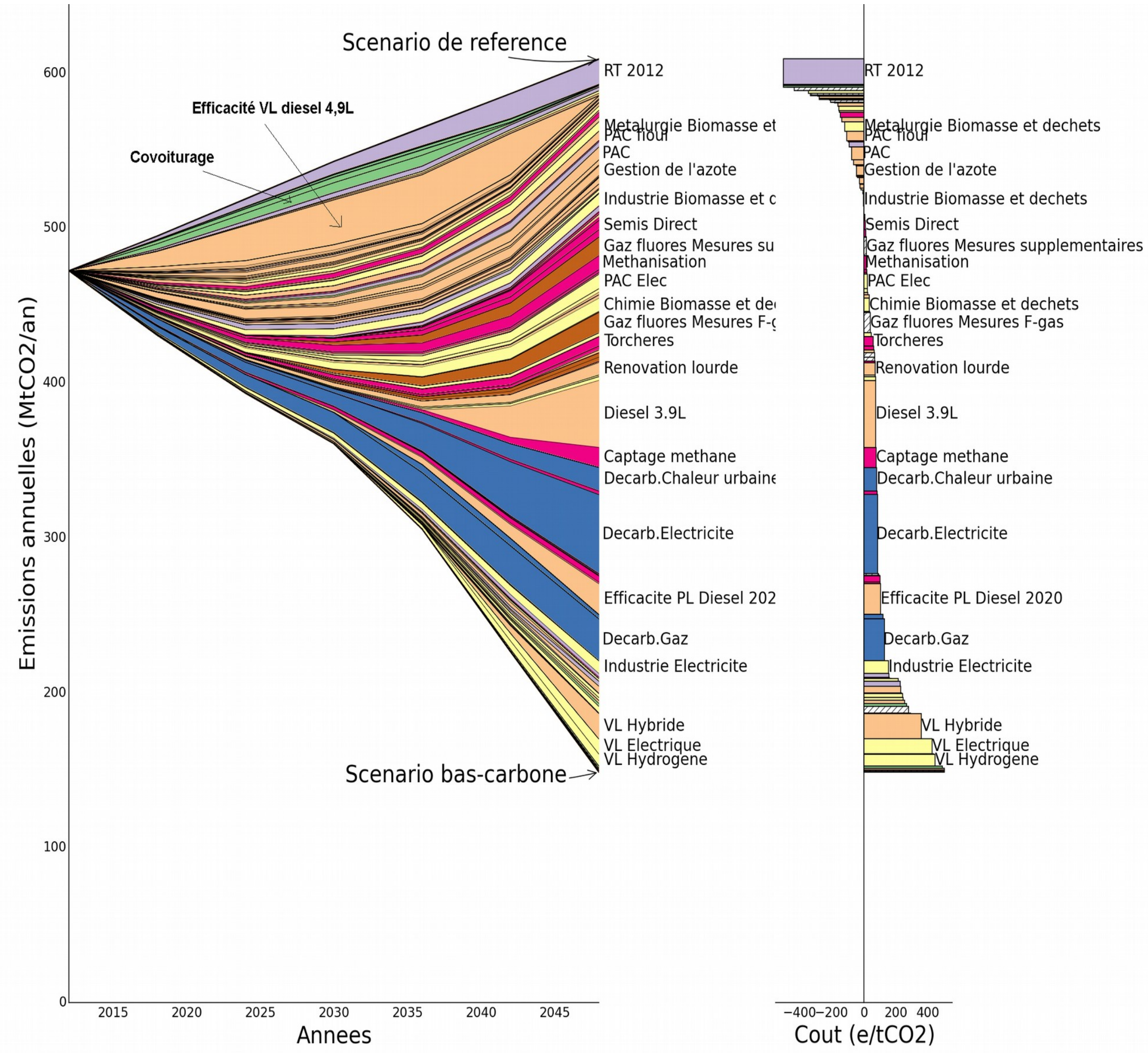
To draw an aggregated curve, the low-carbon transition of the energy sector (electricity and heat production) must, at the same time, ensure a balance between energy production and energy demand from the other sectors. Indirect emissions by these sectors are then reduced (for example, urban heating or electric heating), but the corresponding emission reductions are associated with energy production technologies. By contrast, the abatement opportunities associated with the move to electric power or heat (e.g. to replace gas) are indeed counted in the corresponding sectors (industry, residential, transport).

By balancing supply and demand, one can avoid the optimisations achieved in these sectors leading to massive electrification without energy savings, which would be achieved without any trade-off on the CO2 content or the production cost per kWh.

The change from heating oil to electricity leads to a change from direct emissions (category CRF 1A4, 'Residential combustion') to indirect emissions (category 1A1a 'Centralised Production of Electricity') *via* an increased demand for electricity, without the risk of being counted twice.

The 2050 emissions target has been set at 149 Mt/year, i.e. a 75% reduction in emissions ('Factor 4') compared to the 1990 level (596 Mt/year excluding LULUCF).

Figure 16: Dynamic average abatement costs curve with a long-term target – All sectors



USES

Identify sources with potentially negative costs

The appearance of an unexploited negative cost source in 2012 can be explained particularly by:

- information asymmetry;
- use of a lower public discount rate than the rates envisaged by the private sector;
- return on investment (ROI) rates below other investment opportunities for private individuals who do not seek to finance all profitable projects open to them;
- this measure may show a positive cost increase in 2012, but leads to profits over the whole period because of a decrease in the costs of certain technologies, because there is no technical progress in the BAU scenario.

Provide indications on the implementation sequence of the measures.

Figure 16, which shows the aggregated TITAN, is less legible than the sectoral TITAN's. It nevertheless illustrates all the phenomena observed in the sectoral results.

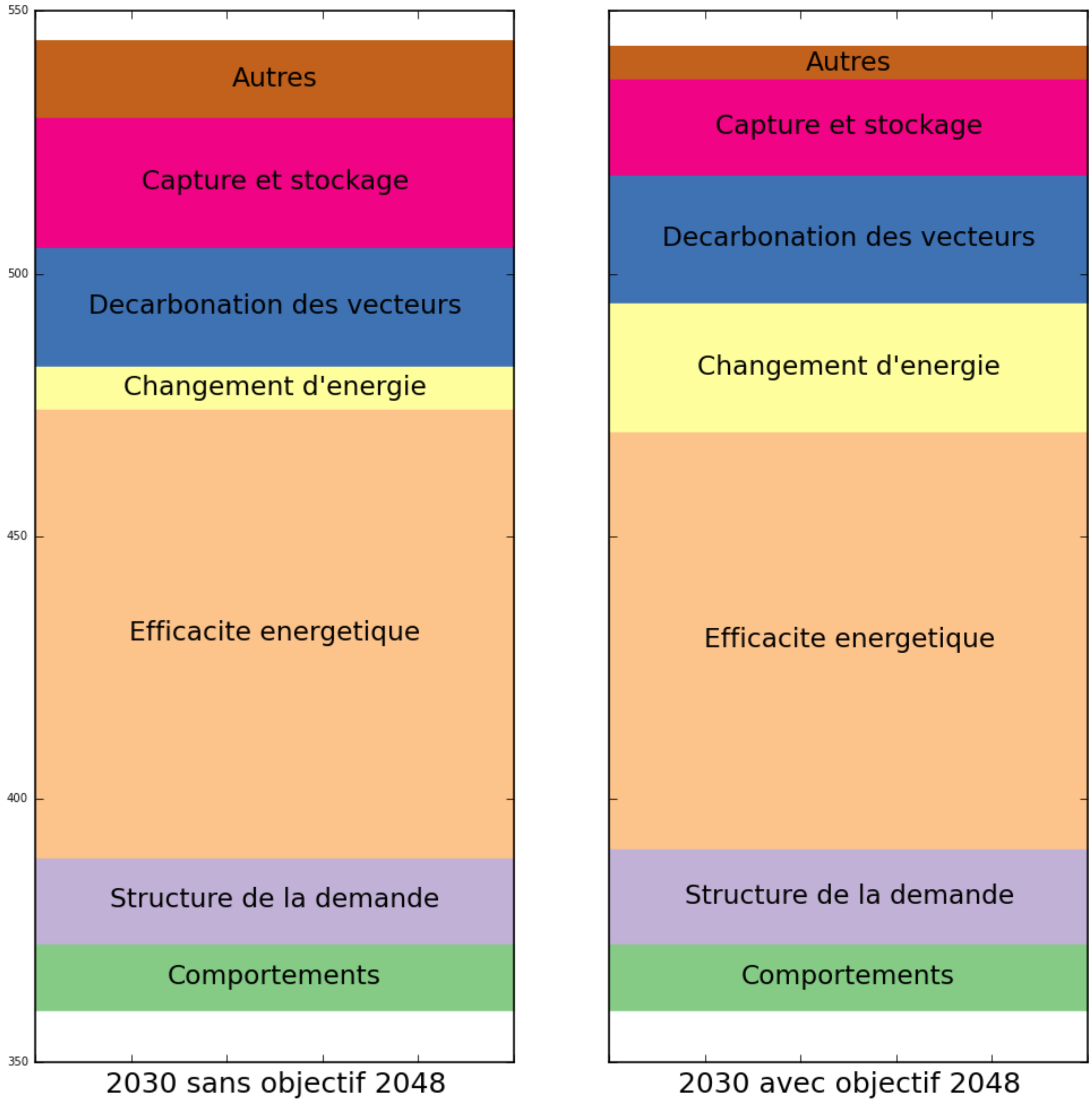
Negative cost sources are implemented as a priority. The contribution by behavioural measures tends to decrease over time because of growth in the energy efficiency of technologies.

The abatement opportunities are not mobilised in ascending order of their average cost, but according to their own timeframe, which depends on the optimised contribution of the opportunity to the emissions reduction target being pursued. The desired implementation date of a particular abatement source is determined by potential and dissemination speed. These dates give, specifically, an indication of the structure of reductions over time. They do not only concentrate on the lowest cost abatement opportunities, but also on high-potential, but slow to implement abatement opportunities (residential buildings renovation, pre-commercial stage technologies).

As the kinetics used are very rough, the resulting deployment timeframes should not be interpreted literally. However they clearly highlight the type of measure to be implemented at the very start of the period, although they are not necessary to achieve a medium-term target. This is particularly striking in the transport sector.

The aggregated structure of the abatement opportunities presented in figure 17 shows the changes in the structure of abatement opportunities according to the time horizon of the target. Taking into consideration that a long-term objective does indeed reinforce, in the medium term, the contribution from abatement opportunities linked to a change in energy type and demand structure, to the detriment of energy efficiency abatement sources.

Figure 17 - Types of abatements implemented according to the date of the target being pursued



Compare the sectoral efforts provided for in the aggregate scenario with the efforts defined by the SNBC (NATIONAL LOW CARBON STRATEGY)

Compared to sectoral scenarios, where optimisation is achieved according to constraints on the potential, speed of dissemination and abatement costs of the sector, in the aggregate sector, all abatement opportunities, whatever the sector, are in 'competition' to hit the 75% (Factor 4) target at the lowest cost, over the entire French economy. Thus, if a sector contains abatement opportunities at a lower cost than other sectors, whose potential has not been fully exploited, then optimisation can, beyond the sectoral target, enhance the mobilisation of these opportunities.

Table 1 shows that achieving the 75% (Factor 4) target at the aggregate level leads to more than doubling the effort required by the energy sector compared to what is aimed for in the SNBC (National Low Carbon Strategy), by massively exploiting negative emission abatement opportunities. This relieves the pressure on other sectors, chiefly industry, which sees its required effort reduced by 40%, then transport and lastly buildings. This result is directly linked to the existence of potential negative emissions in the energy sector. The abatement opportunity being considered is very large (in the order of 40 MtCO_2eq for a sector that emits today between 40 and 60 MtCO_2equivalent depending on the year). For this reason, the hypotheses on the potential, costs and speed of development of carbon capture and storage technologies, and the use of biomass for energy production are essential for understanding of the results, and their difference with the sectoral carbon budgets of the SNBC. In the SNBC, the potential of CCS technology is considered to be limited within the 2050 timeframe and is decisive only in the longer term. These results confirm that it is important to examine this technology more thoroughly, as it stands at the heart of debates on the potential of negative emissions, and these will be necessary in the longer term in any case, to comply with the 2°C target. They may also change fairly radically in the medium term sectoral emission reduction trajectories.

It is interesting to note that the aggregate TITAN trajectory requires less medium-term emission reduction efforts (184 million tonnes avoided in 2030) than the sum of efforts required by the sectoral TITAN (201 million tonnes avoided in 2030). This indicates a slight postponing of efforts into the future to attain the same aggregate 75% reduction target.

Table 1: Comparison between the breakdown of required effort (in millions of tonnes of CO_2 equivalent avoided) **provided for in the SNBC and the cost 'efficient' breakdown produced by the aggregate TITAN**

	Aggregated results from TITAN optimization		SNBC sectoral objectives	
	2030	2050	2030	2050
Energy	27	**103**	10	**48**
Industry	34	**61**	44	**102**
Agriculture	26	50	26	50
Buildings	41	**93**	50	**109**
Transport	45	109	66	126
Other	11	45	5	26
Total	**184**	460	**201**	460

ESTIMATING THE MACROECONOMIC COSTS OF LOW-CARBON TRANSITION

The optimisation used to draw the curves can give an indication of the total cost of use of the technologies/measures to be mobilised over the period in 4 scenarios: (i) Business-as-usual, (ii) optimised compared to the 2050 75% (Factor 4) target, (iii) optimised compared to an intermediary target in 2030, (iv) optimised without an emissions reduction target. The aggregate scenario without target provides another comparison point with the Factor 4 scenario, other than the theoretical BAU scenario. IN contrast to the BAU scenario, which freezes the cost of technologies/measures used in 2012, the un-targeted objective mobilises all the abatement opportunities which allow satisfaction of global demand at the lowest cost. This scenario thus mobilises all negative costs. Comparing the total cost of the Factor 4 scenario with the total cost of the un-targeted objective gives the upper limit of the net low-carbon transition cost, without entering into controversy about the existence or otherwise of negative costs.

Table 2 firstly presents the total cost of use of technologies/measures allowing satisfaction of global demand (energy, transport, buildings, industry) in these four scenarios, then the net cost (or profit) of transition compared to two scenarios: BAU and the un-targeted scenario.

Over the whole 2012 – 2050 period, the total cost of the Factor 4 scenario remains less than BAU because of the important number of abatement opportunities fundamentally linked to energy efficiency, implemented durably (buildings renovation), or temporarily (transitional use of more efficient thermal vehicles). The gap becomes smaller at the end of the period as more and more costly abatements are mobilised. Therefore, over the whole period, the low-carbon scenario provides a net gain compared to the BAU scenario. The difference between the un-targeted scenario and the Factor 4 scenario unsurprisingly shows costs rising over the whole period, reaching 62 billion euros in 2048, around 10% of total investment spending at this date.

Table 2: Total annual costs (in billions of euros) of use of technologies/measures in four scenarios, excluding externalities

	Total costs of scenarios (in G€)						
	2012	**2018**	**2024**	**2030**	**2036**	**2042**	**2048**
Total cost_BAU	207	234	261	289	316	343	370
Total cost_Factor4	207	210	226	246	274	315	362
Total cost_objective-2030	207	208	220	237			
Total cost_un-targeted	207	208	220	235	255	277	300
	Net costs of low-carbon transition (in G€)						
BAU – Factor 4	0	24	35	43	42	28	8
Un-targeted – Factor 4	0	-2	-6	-11	-19	-38	-62

To interpret these figures, it is important to remember that these costs result from optimisation, which does not take into account either the co-benefits or antagonistic effects of the measures on other public policy objectives, or the effects on development of economic circuits. In this sense it overestimates the costs of the low-carbon scenario. This effect is reinforced by the absence of a carbon price in the model. But the hypotheses made on the BAU scenario, which freeze the cost of the technologies/measures, also overestimate the cost of this scenario. A part of the average negative costs of the technologies/abatement measures arises from these hypotheses. It is probable that the 'real' BAU scenario would have exploited, at least partly, these negative cost abatement opportunities. A conservative way of measuring the net cost of low-carbon transition would be to consider only the positive average abatement costs, and just concentrate on the 'additional costs' compared to the BAU scenario. Here again, the sign of a net end-result is not immediately determinable. Changes to the demand structure and the energy efficiency of technologies in the low-carbon scenario can reduce global demand and therefore limit the additional costs compared to the BAU scenario because of a lesser use of technologies/measures.

LIMITATIONS OF THE TITAN CURVES

Several limitations have already been mentioned above: the simplified modelling of the electricity sector, the volume of emissions being considered. The following two are particularly important, and should be borne in mind while interpreting the dynamic average abatement cost curves as they are constructed here:

Simple kinetics

Deployment of each abatement opportunity has been extremely simplified, with a single deployment speed designed to summarise all brakes on deployment other than simple cost constraints. This means the deployment time frame of measures is fundamentally indicative, although it may highlight possible contradictions between medium and long-term objectives. Three important limitations should be mentioned:

- In this tool, the planner is a price taker for each abatement opportunity, which assumes the learning effects are exogenous. It is therefore difficult to use this type of approach to deliver refined messages on the sector research to be carried out.
- Furthermore, some technologies are associated with potentially irreversible choices – development of an energy distribution network for vehicles, choice of the optimal renovation level of a building, choices related to occupation of public space. Conversely, here there are no costs directly associated with a reversal of any of these choices.
- In the same way, there are no additional costs associated with the appearance of abatement opportunities, such as power stations in use for a considerably shorter time than the lifespan of the equipment.

Cost curves whose interpretation is not unequivocal

The individual costs of each measure can be used as a basis for discussion, but give no indication of the order in which measures are to be mobilised, for several reasons:

- arbitrage between measures must necessarily integrate elements which cannot be taken into account by the approach used: pursuing other public policy objectives, externalities, macroeconomic effects;
- costs by themselves are not sufficient to show the interdependence between certain abatement opportunities, and their timing;
- they are subject to uncertainties (in particular development up to 2050 related to technical progress or massive technology dissemination).

Furthermore, the optimisation achieved is only in terms of the financial cost of each abatement opportunity. This is a transition approach 'at the lowest cost', which omits the economic co-benefits of low-carbon transition in terms of activity levels, employment, or environmental externalities (particularly air quality). In this sense, the analysis tends to overestimate costs. *In contrast*, it tends to underestimate costs by discarding private transaction costs which may be added to the financial cost of the technologies.

CONCLUSION

This study by the CGDD (General Commission for Sustainable Development) presents an original tool for modelling the system changes to the French system of production necessary to reach the target of a 75% cut in GHG emissions by 2050 at the lowest cost.

The tool allows an initial approach to (i) elaborate aggregate or sectoral scenarios of low carbon transitions ; (ii) offer 'objectivised' points of comparison with the carbon budgets chosen by the national low-carbon strategy; (iii) assess the coherence of intermediary points with the long term 75% reduction objective, pointing out the risks of undesirable technological blockages; (iv) define efficient deployment time frames for emissions reduction measures according to their deployment speed.

But the results – given form by the TITAN cost curves – must be interpreted with caution. They depend on a database containing information on over 500 known emission reduction opportunities in the transport, buildings, energy, industry, agriculture and waste sectors. These opportunities take the form of more efficient technologies, new sources of energy, but also behavioural measures. Each opportunity features a potential, a speed of deployment and a cost. The deep uncertainties which remain as to quantifying these criteria for many opportunities reduce the precision of the results. They allow trends to be identified, but by no means would they be able to suggest precise time frames for the deployment of opportunities.

Thus the quality of the database which informs the TITAN curves is quite critical. In order to be able to evolve, this base must be discussed by stakeholders in the low-carbon strategy. The open and collaborative construction of the database is essential for the TITAN curves to deliver adoptable messages. The tool can then supply useful points of comparison with the options chosen by the national low-carbon strategy.

It has been designed to promote dialogue between diverging world views within a coherent framework. By using different data sets based on diverging expert opinions, the TITAN curves allow visualisation of the effects of different world views on the speed and efficient options to be mobilised to achieve low-carbon transition. The transparency of the database used is crucial to the credibility, acceptability and relevance of the tool.

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Appendices

Table1: GHG abatement sources in the transport sector

Name	Unit	Potential	2012 use	2050 use	CO_2 reduction in 2050 ($MtCO_2eq$)	Average cost (euros/tCO_2)	Cumulative CO_2reductions from 2012 to 2050 ($MtCO_2eq$)
Diesel 4.9 L, Improved efficiency of the current fleet of light-duty diesel vehicles to 4.9 L/100kmv	Gkm	79% of Light-duty vehicle.km	0	0	0	-316	479
Light-duty vehicle passenger.km	Gkm.trip	100% total mobility demand	800	859	0.2	121	45
Railway freight - New infras	Gt.km	13	0	11	0.2	500	9
Telecommuting	Gkm.trip	74	0	74	0.4	-500	42
Light-duty vehicle load/Carpooling	Gkm.trip	44% of the light-duty vehicle trip.km	277	380	0.7	-500	85
Non-motorised transport/ public bikes	Gkm, trip	24	0	24	2	488	22
HGV NGV	Gt.km	166	0	149	10.3	500	66
Diesel HGV Efficiency 2020	Gt.km	100% of HGVs	0	340	13.2	105	77
Light-duty vehicle Hydrogen	Gkm	15 % Light-duty vehicle.km	0	66	15.5	447	275
Heavy goods vehicle load, +10% in 2028	Gt.km	103	0	92	2	-433	85
Decarbonation Diesel	TWh	10,000	372	152	2.1	121	45
HSL - New infras	Gkm.trip	54	0	32	2.5	500	34
Electric light-duty vehicle	Gkm	28% Light-duty vehicle.km	0	124	28.9	425	491
Light-duty vehicle Hybrid with increased energy performance	Gkm	100% of LDV.km	0	288	46	277	498

Note to the reader: Electric light-duty vehicles could represent up to 28% of the car fleet in 2050. In 2012, these vehicles travelled zero kilometres. The TITAN predicts that they should cover 124 Gkm by 2050. This represents a reduction of 28.9 MtCO2eq in CO_2 emissions at that time, with an average cost per tonne of €425 saved. The cumulative emission reductions for the 2012 - 2050 period for electric vehicles are 491 $MtCO_2eq$

Table 2: GHG abatement sources in the waste sector

Name	Unit	Potential	2012 use	2050 use	CO_2 reduction in 2050 ($MtCO_2eq$)	Average cost (euros/tCO_2)	Cumulative CO_2reductions from 2012 to 2050 ($MtCO_2eq$)
Waste reduction	Mt	28% of solid waste	0	30	0.5	-500	39
Waste recycling	Mt	70% of waste produced	46	85	0.7	-5	82
Methane capture	Mt	100% of Discharge	0	13	12.8	76	77
Incineration recovery	Mt	66% of Non-recycled solid waste	17	23	0	236	5
Energy recovery of 100% of the heat induced by waste incineration	Mt	100% of Incineration recovery	10	21	2.3	225	13

Table 3: GHG abatement sources in the building sector

Name	Unit	Potential	2012 use	2050 use	CO_2 reduction in 2050 ($MtCO_2eq$)	Average cost (euros/tCO_2)	Cumulative CO_2reductions from 2012 to 2050 ($MtCO_2eq$)
Urban heat	Mm^2	15% of TR 2020	0	13	0.0	-52	0.8
Wood boiler	Mm^2	20% of TR 2020	0	8	0.0	500	0.5
Condensing boiler	Mm^2	100% of non refurbished	0	5	0.0	-138	1.5
Major refurbishment	Mm^2	83% of Electric powered collective dwellings	0	7	0.1	28	0.3
Intermediate refurbishment	Mm^2	50% of fuel LPG	0	60	0.1	-71	15.6
Wood boiler	Mm^2	20% of TR 2012	0	11	0.1	438	7.5
Condensing boiler	Mm^2	100% of non refurbished	0	10	0.1	-197	8.2
Heat pump	Mm^2	100% of non refurbished	0	0	0.1	284	
Condensing boiler	Mm^2	100% of non refurbished	0	1	0.1	-246	15.6
Urban heat	Mm^2	15% of TR 2012	0	21	0.1	-46	1.7
Condensing boiler	Mm^2	100% of non refurbished	0	4	0.1	-167	24.0
Gas boiler	Mm^2	100% of non refurbished	214	264	0.1	-160	0.7
Moderate refurbishment	Mm^2	100% of Electric powered collective dwellings	0	21	0.2	-38	1.6
TR 2012	Mm^2	392	0	134	0.2	-183	18.6
Boilers Efficiency	Mm^2	100% of single-family dwellings Wood	0	105	0.2	-500	3.7

Name	Unit	Potential	2012 use	2050 use	CO_2 reduction in 2050 ($MtCO_2eq$)	Average cost (euros/tCO_2)	Cumulative CO_2reductions from 2012 to 2050 ($MtCO_2eq$)
Major refurbishment	Mm^2	83% of Gas collective dwellings average	0	30	0.2	65	32.4
Passage Wood boiler	Mm^2	15% of non-refurbished	0	60	0.3	-343	1.4
Major refurbishment	Mm^2	42% of Gas	0	28	0.3	213	0.8
Heat pump	Mm^2	50% of non-refurbished	0	0	0.3	111	0.9
Passage Urban heating	Mm^2	15 % of non-refurbished	0	60	0.4	-51	1.9
Moderate refurbishment	Mm^2	50% of Elec	0	78	0.5	6	6.4
Heat pump	Mm^2	50% of non-refurbished	0	14	0.6	232	1.9
Heat pump	Mm^2	100 % of non-refurbished	0	4	0.8	-33	13.8
Major refurbishment	Mm^2	42% of Elec	0	100	0.8	-112	15.6
Passage Urban heating	Mm^2	15 % of non-refurbished	0	5	0.8	16	18.8
Heat pump	Mm^2	100 % of non-refurbished	0	2	0.9	57	13.1
Condensing boiler	Mm^2	100 % of non-refurbished	0	84	1.4	23	36.2
Heat pump	Mm^2	50% of non-refurbished	0	84	1.6	63	10.8
Condensing boiler	Mm^2	100% of non-refurbished	0	15	1.8	-23	45.0
Heat pump	Mm^2	50% of non-refurbished	0	15	2.1	-89	45.9
TR 2020	Mm^2	336	0	161	2.1	-33	17.6

Name	Unit	Potential	2012 use	2050 use	CO_2 reduction in 2050 ($MtCO_2eq$)	Average cost ($euros/tCO_2$)	Cumulative CO_2reductions from 2012 to 2050 ($MtCO_2eq$)
Condensing boiler	Mm^2	100 % of non-refurbished	0	130	2.6	14	23.5
Heat pump	Mm^2	100 % of non-refurbished	0	98	2.6	-38	45.3
Passage Wood boiler	Mm^2	20 % of non-refurbished	0	30	2.9	-155	66.3
Condensing boiler	Mm^2	100 % of non-refurbished	0	7	3.1	-37	42.4
Condensing boiler	Mm^2	100 % of non-refurbished	0	149	3.9	-6	77.4
Heat pump	Mm^2	50% of non-refurbished	0	149	4.5	-54	90.8
Electricity decarbonation	TWh	10,000	119	178	5.7	-24	118.2
Fuel Heat pump	Mm^2	100 % of non-refurbished	0	106	6.0	-125	99.7
Condensing boiler	Mm^2	100 % of non-refurbished	0	166	6.6	-16	64.5
Heat pump	Mm^2	100 % of non-refurbished	0	196	7.6	-93	132.9
Gas decarbonation	TWh	10,000	240	195	8.8	134	162.9
Urban heat decarbonation	TWh	10,000	17	35	9.3	28	67.9
Elec heat pump	Mm^2	100 % of non-refurbished	0	114	10.8	6	137.7
Construction of new dwellings complying with the requirements of TR2012	Mm^2	1,710	0	954	18.6	-500	316.2

Table 4: GHG abatement sources in the agriculture sector

Name	Unit	Potential	2012 use	2050 use	CO_2 reduction in 2050 ($MtCO_2eq$)	Average cost (euros/tCO_2)	Cumulative CO_2reductions from 2012 to 2050 ($MtCO_2eq$)
Protein intake reduction dairy cows	$MtCO_2e$	0	0	0	0.0	-94	3.8
Protein intake reduction Pigs	$MtCO_2e$	1	0	1	0.0	-84	18.7
Heated greenhouses	$MtCO_2e$	0	0	0	0.1	-144	2.2
Intercropping	Mha	0	0	0	0.1	15	1.2
Poultry buildings	$MtCo_2e$	0	0	0	0.3	-285	6.3
Buffer strip cropping	Mha	0	0	0	0.3	500	0.96
Adding nitrate to rations	$MtCO_2e$	0	0	0	0.6	37	7
Intermediate crops	Mha	4	0	3	0.9	158	7
Legumes in pastures	Mha	2	0	2	0.9	-96	28.5
Ploughing 1 year in 5	Mha	68% of Change in cultivation techniques	0	4	1.8	7	8.6
Large-scale farming legumes	Mha	1	0	1	1.8	18	33.1
Substitution of lipids carbohydrates	$MtCO_2e$	1	0	1	1.9	267	10.3
Tractors	$MtCO_2e$	2	0	2	2.0	-160	50
Pasture management	Mha	10	0	10	3.0	-145	81
Hedges	Mha	0	0	0	3.9	99	69.3
Agroforestry	Mha	0	0	0	4.7	13	82.8

Name	Unit	Potential	2012 use	2050 use	CO_2 reduction in 2050 ($MtCO_2eq$)	Average cost (euros/tCO_2)	Cumulative CO_2reductions from 2012 to 2050 ($MtCO_2eq$)
No-till farming	Mha	68% of Change in cultivation techniques	0	10	6.0	10	53.6
Flares	$MtCO_2e$	45% of Current Rations	0	5	6.1	59	94.9
Nitrogen management	Mha	12	0	12	6.1	-45	186.7
Methanisation	$MtCO_2e$	62% of Current Rations	0	8	9.0	16	158.4

Table 5: GHG abatement sources in the industry sector

Name	Unit	Potential	2012 use	2050 use	CO_2 reduction in 2050 ($MtCO_2eq$)	Average cost (euros/tCO_2)	Cumulative CO_2reductions from 2012 to 2050 ($MtCO_2eq$)
Metallurgy Gas	TWh	18% of metals energy	12	11	0.0	83	0.1
Energy consumption metals	TWh	4% of Energy demand metals	0	2	0.3	-181	7.6
Industrial engines	TWh	37% of Electrical industry	0	9	0.4	254	2.4
Co-generation industry	TWh	0% of Energy consumption Other industries	0	1	0.4	-331	7.7
Organisational gains Industry	TWh	2% of Energy demand Other industries	0	8	0.4	-276	18.3
Metals Gas CCS	TWh	33% of metallurgy Gas	0	3	0.5	97	4.8
Energy efficiency metals	TWh	7% of Energy demand metals	0	5	0.5	-181	21.6
Energy efficiency materials	TWh	19% of Energy demand materials	0	14	0.6	-212	28.5
Proven solutions gains Industry	TWh	5% of Energy demand Other industries	0	16	0.9	-276	38.1
Materials Gas CCS	TWh	28% of materials Gas	0	9	0.9	93	10.2
Chemistry Gas CCS	TWh	28% of Chemistry Gas	0	6	1.1	101	15.8
Ammonia decomposition N2O	Mt	100% of Ammonia	0	1	1.1	19	6.2

Name	Unit	Potential	2012 use	2050 use	CO_2 reduction in 2050 ($MtCO_2eq$)	Average cost (euros/tCO_2)	Cumulative CO_2reductions from 2012 to 2050 ($MtCO_2eq$)
Industry Free heat	TWh	2% of Energy consumption Other industries	0	4	1.2	-331	24.4
Materials Steam	TWh	12% of materials Thermal uses	0	4	1.3	171	10.8
Metals Coal CCS	TWh	33% of metallurgy Coal	0	1	1.4	69	8.2
Raw materials vegetables	TWh	12% of Non-energy chemistry	0	5	1.5	0	27.6
Energy efficiency Chemistry	TWh	18% of Energy demand Chemistry	0	23	1.6	-206	77.1
Boiler rooms and Industrial premises	TWh	12% of Energy demand Other industries	0	41	2.1	-150	76.9
Biomass and Waste materials	TWh	32% of materials Thermal uses	6	17	2.2	23	48.0
Chemistry Steam	TWh	12% of Energy consumption Chemistry	7	12	2.2	196	19.0
Innovative solutions gains Industry	TWh	13% of Energy demand Other industries	0	43	2.3	-276	99.1
Metallurgy Fumes	TWh	12% of metals energy	0	7	2.3	196	19.5
Cement CCS	Mt	28% of cement processes	0	4	2.3	83	20.9

Name	Unit	Potential	2012 use	2050 use	CO_2 reduction in 2050 ($MtCO_2eq$)	Average cost (euros/tCO_2)	Cumulative CO_2reductions from 2012 to 2050 ($MtCO_2eq$)
Materials Gas	TWh	100 % of materials Thermal uses	19	34	2.7	48	48.4
Electrical industry	TWh	50% of Energy consumption Other industries	61	87	2.9	105	29.1
Biomass and Waste Metallurgy	TWh	32% of metals energy	0	19	4.6	-116	75.9
Steam industry	TWh	12% of Energy consumption Other industries	8	23	5.1	210	36.4
Biomass and Waste Industry	TWh	32% of Energy consumption Other industries	26	64	7.7	-1	161.8
Biomass and Waste Chemistry	TWh	32% of Energy consumption Chemistry	0	32	8.5	35	172.2
Electricity decarbonation	TWh	10,000	122	122	9.0	-24	151.3
Urban heat decarbonation	TWh	10,000	17	48	9.9	59	95.4
Gas decarbonation	TWh	10,000	142	153	24.4	130	325.8

Table 6: GHG abatement sources in the energy sector

Name	Unit	Potential	2012 use	2050 use	CO_2 reduction in 2050 (MtCO2eq)	Average cost (euros/tCO_2)	Cumulative CO_2reductions from 2012 to 2050 (MtCO_2eq)
STEP 2	TWh	1	0	0	0.1	106	0.4
Lake hydroelectricity	TWh	37	30	37	0.3	-52	0.8
Coal with carbon capture and storage	TWh	3	0	1	0.4	65	1.2
CCS refineries	Mt	37% of Production refineries	0	14	1.9	61	21.1
Solutions Solid fuels	MtCO_2e	3	0	2	2.2	66	24.0
Gas decarbonation	TWh	10,000	41	72	2.2	124	18.0
STEP 1	TWh	4	0	4	2.4	-67	43.5
Urban heating network Biomass	TWh	65% of Urban heating	1	18	3.8	-43	45.7
Reduction demand refinery	Mt	41	0	41	4.0	0	74.8
Urban heating network Gas CCS	TWh	30	0	18	4.6	17	26.4
Biomass Cogeneration	TWh	19	0	18	10.5	-28	186.8
Combined Cycles Gas with CCS	TWh	30	0	23	15.8	77	100

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The Energy Transition for Green Growth Act confirmed the national target of factor 4 in 2050 and thus commits France to start the process of decarbonation of its economy.

In practice, the factor 4 target implies a profound transformation of the productive system, which still depends, to a large extent, on fossil energies. Such a transformation is still possible. The potential of known emission reduction sources in the transport, construction, energy, industry, agriculture and waste sectors is sufficient to decarbonize the French economy. These opportunities take the form of more efficient technologies, new sources of energy, but also behavioural changes. The challenge for public authorities and sectoral actors of the low-carbon transition is to mobilize, among these emissions abatement sources, those that make it possible to achieve the objective using a method of deployment and sectoral distribution that minimizes the total cost of it.

This CGDD study presents the TITAN tool for monitoring the average cost dynamics of emission reduction measures in France up to 2050.

Low-Carbon transition pathways at the lowest cost

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