Report

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The Value for Climate Action

A shadow price of carbon for evaluation of investments and public policies

Report by the Commission chaired by
Alain Quinet

FRANCE STRATÉGIE
ÉVALUER. ANTICIPER. DÉBATTRE. PROPOSER.

THE VALUE FOR CLIMATE ACTION

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FRANCE STRATÉGIE

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FOREWORD

The fight against global warming requires us to limit quantities of greenhouse gases present in the atmosphere, carbon gas in particular. In order to honour its commitments in this regard, France must significantly step up its efforts. It is well behind schedule as regards the trajectory it needs to follow if it is to achieve the goal of climate neutrality, or net zero GHG emissions ("Net-Zero"), inscribed in the 2015 Paris Agreement and the 2017 Climate Plan.

In order to decarbonize, investments must be made to reduce emissions. The choice of what investments to carry out must be made according to a cost per metric ton of emissions avoided. This is what the State is doing for its own investments, making it a rule to take account of a value of the metric ton of CO_2 (or equivalent) avoided in the socioeconomic analyses it carries out. This is the "shadow price" of carbon. The rule should be extended to all activities generating greenhouse gas emissions, in order to be able to provide a "value for climate action" applicable to them.

The Prime Minister requested Alain Quinet – who had already been responsible for an initial report on the subject in 2008 – to form a commission tasked with revising the shadow price, with support from France Stratégie's teams and taking account of the many developments that have taken place over the last ten years.

Alain Quinet's report provides a comprehensive overview of analyses enabling definition of a trajectory of values to be taken into account if we are to achieve the goal of net zero GHG emissions by 2050, given the current and foreseeable state of techniques available for reduction of emissions and carbon capture. The evolution of goals and techniques, together with the fact that we have fallen behind as regards the desirable emissions trajectory, requires significant upward revision of the target shadow price, which should be to the tune of €250 per metric ton of CO_2 in 2030, whereas the target set for the same year in 2008 was €100.

The report requests the public authorities to adopt policies enabling this value to be taken into account as widely as possible. The "Value for Climate Action" Commission recommends that tools be employed that go beyond simple price signals, combining all *instruments – including regulations and measures facilitating access to credit and fostering green investments – that might have equivalent effects. This pragmatic approach is necessary to enable effective implementation that takes account of all the economic and social consequences of these essential developments, and provides appropriate responses to them.*

Gilles de Margerie
Commissioner-General, France Stratégie

CONTENTS

INTRODUCTION

France's ambition is to eliminate greenhouse gas emissions on national soil by 2050. This is the "Net-Zero" goal: *net* zero greenhouse gas emissions from human activity, with residual *gross* emissions to be absorbed by carbon sinks – which include forests, grasslands and, further down the road, carbon capture and storage technology.

This ambition must translate into public and private investments, and more generally measures coming under public and private policy alike. Action must be taken across a broad agenda, but also in the right order, by setting joint priorities, channeling resources towards meaningful initiatives and making the call between swiftly rolling out mature technologies or awaiting new solutions enabled by the innovations in progress.

Putting a monetary value on mitigation activities means recognizing that there is value in taking action, as opposed to doing nothing. It means that human activity must take on board, "internalize" – beyond the "private" benefits – the collective benefits to be reaped from reducing greenhouse gas emissions. It provides a baseline for selecting and ranking the initiatives that are meaningful to the community.

The social value of mitigation activities is referred to as the shadow price of carbon in socioeconomic calculation jargon, as it is decided on by the State. It forms part of a long-term public strategy setting forth a shared vision of action to tackle climate change – in this instance the 2015 Paris Agreement and 2017 Climate Plan.

Carrying on a long-standing French tradition for economic calculation, and in the same vein as the previous commissions chaired by Marcel Boiteux (2001) and Alain Quinet (2008)[1], this report crowns the collaborative efforts of a commission made up of some 20 experts and economists on the environment from academia, international organizations and research centers, the economic and social sphere, non-governmental organizations and the government[2]. To draw up its proposals, the commission called on five modeling teams,

[1] General Commission of the Plan (2001), *Transports : choix des investissements et coût des nuisances*, report by the group chaired by Marcel Boiteux, Paris, La Documentation française; Center for Strategic Analysis (2008), *La Valeur tutélaire du carbone*, report by the commission chaired by Alain Quinet, Paris, La Documentation française.

[2] The list of commission members can be found in Appendix 2.

interviewed a number of specialists and organized a series of workshops for representatives of the economy's various sectors[1].

The social value of mitigation activities measures the value, for the community, of initiatives delivering on the net zero GHG emissions target

Through the 2015 Paris Agreement, the Parties have collectively agreed to achieve net zero GHG emissions by the latter half of the 21st century. The Agreement urges developed countries to reach this target before developing countries. This goal is grounded in the assessment by the Intergovernmental Panel on Climate Change (IPCC) of a shrinking of the carbon budget – i.e. the residual margins available for emitting greenhouses gases – if we wish to keep global warming to below 2°C. Based on past trends, we only have three decades' worth of emissions at our disposal: after that, we will be out of options – running the risk of serious and irreversible damage.

Action to tackle climate change and the resulting benefits for the community are not automatically factored into public and private stakeholders' financial profitability calculations. The shadow price of carbon makes up for this market failing: it gives an idea of the distance we still have to cover and, as such, expresses the value that society must attach to the public and private decarbonization initiatives we need to roll out to get there. These are the two sides of the same coin.

The rise in the social value of mitigation activities first and foremost gives an idea of the distance to be covered

For 2030, the time scale of the investments which have already been or are shortly due to be decided on, the commission puts forward a shadow price of €250 per ton of CO_2e, which is a substantial increase on the €100 target set in 2008. This rise reflects the limited nature of the carbon budget at our disposal; it lays bare the need to invest sustainably in low-carbon technology and the cost of such technology.

In the period post-2030, the value outlined here gradually falls into line with a Hotelling rule, which is to say the rule for properly managing a non-renewable resource, whose value is meant to grow at the discount rate – and is not therefore "crushed" over the long term under the effect of discounting. By 2050 it is expected to align with the estimated costs of the enabling technologies required for decarbonization – therefore a cautious range of €600 to €900/ton of CO_2e.

[1] The list of specialists interviewed can be found in Appendix 3.

The further the time scale extends beyond 2030, the more uncertain the forecasts. A lower carbon value at the end of the period – falling below €500 – would reflect closer international cooperation, ramping up the pace at which innovations are being produced and rolled out, and paving the way for disruptive technologies.

The rise in the social value of mitigation activities extends the scope of profitable initiatives for the community

The shadow price attributes a value to public and private decarbonization initiatives. It has traditionally allowed for public investments to be assessed and selected on the basis of their socioeconomic (and not just their financial) value. But its use must increase so as to shore up the definition of public policy priorities. With a shadow price of carbon of €250 in the period up to 2030, all initiatives costing less than €250 per ton of CO_2e avoided must be undertaken (retrofit of buildings on a large scale, roll-out of certain renewables for generating heat, for example). Otherwise there is a risk the target will not be reached. On the other hand, initiatives costing more than €250 today should only be undertaken if, by the time they are fully rolled out, the trajectory of shadow prices exceeds their cost.

More generally, a multi-year trajectory where the shadow price of carbon is concerned gives a long-term baseline – in a mindset of anticipating and planning for a world "without fossil fuels". A clear and credible trajectory gives everyone the opportunity to ascertain whether enough is currently being done to achieve the decarbonization target, and whether the right amount of resources are being harnessed at the right time. In this way it allows for investments with long payback periods, which are penalized by uncertainty or volatility.

Once the scope of profitable initiatives has been identified, the State or local authorities can choose to bear their costs directly via public investment. Where necessary, they can also steer private choices, via carbon pricing, subsidies for acquiring carbon-free equipment, risk-sharing mechanisms or regulations. In this context, the shadow price of carbon does not predetermine the right combination of available environmental policy tools. Instead it provides a baseline for checking that the "sum" of these tools for a given use is appropriately sized.

Moving towards a no-carbon economy is possible in return for far-reaching changes in terms of technology and use

Our research confirms, if proof were necessary, that France has not gone far enough in efforts to tackle climate change: whilst greenhouse gas emissions have fallen since 1990, our country is still behind schedule. Our research also points out that this delay can be made up by greater 'sobriety'[1] (equipment appropriately sized for its use), greater energy efficiency, better use of ground space and the large-scale roll-out of new carbon-free technologies.

Successfully decoupling GDP from greenhouse gas (GHG) emissions calls for a sustained investment drive

"Smart" decarbonization – without reducing GDP, without generating "carbon leakage" – requires investment, as of now, in clean technology and decarbonization of the capital stock in the broadest possible sense – encompassing factories, the energy generation capacity, farms, buildings and vehicle fleets.

Investment is the key: this is what will enable a decoupling between GHG emissions and GDP; it is also what will enable changes in behavior by bringing about alternative solutions.

But there is still a long way to go: we have slashed our greenhouse gas emissions by around 80 million tons since 1990; we need to bring this amount down another fourfold by 2050. The need to rechannel funding and investment towards carbon-free applications is well documented at international level, not least in recent studies by the OECD[2], the New Climate Economy Project[3] and the European Commission[4]. Our modeling efforts confirm this sustainable need for "green" investment: a significant proportion of current investment flows must be rechanneled towards tackling climate change whilst scaling up investments by around 1.5 GDP points a year. The investment required reflects a need not only for major projects (developing the grid and electricity generation capabilities) but also for a large number of smaller-scale projects bearing on existing assets (retrofit of buildings, conversion of fleets of vehicles powered by internal combustion engines into low-carbon vehicles, etc.) or new local assets (local facilities for generating renewables, electric vehicle charging points, etc.).

The role of public policy is also to support innovation. The goal to decouple emissions and GDP can partly be achieved by investing in existing technologies. But non-mature technologies also need developing, by seizing the opportunity to grow industrial sectors in France. Beyond 2040, innovation could open up new opportunities for increasing the size of carbon sinks (via CO_2 capture and storage), sustainable energy storage and extending the range of alternatives to oil.

[1] From the French term *sobriété*, referring to efforts to change our current excessive energy-consumption habits to more sustainable lifestyles and uses where we show greater energy restraint.
[2] OECD (2017), *Investing in Climate, Investing in Growth*, OECD Publishing, Paris.
[3] *Unlocking The Inclusive Growth Story of the 21st Century, 2018*
[4] *A European Strategic Long Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy, 2018*.

Post-2030, successfully achieving the low-carbon transition depends to a large extent on how closely the international community works together in tackling climate change.

By more effectively pooling the efforts of different countries it will be possible to:

- disseminate existing technologies more quickly, as attested by the positive momentum in terms of renewables, whose production costs are tumbling;
- foster the development of new technologies, absorb their initial cost over a broad base and therefore enable each country to benefit from learning-by-doing and economies of scale in the form of price reductions;
- avoid the risk of "carbon leakage", which is ineffective from a climate point of view and penalizing for the French economy. The most difficult sectors to decarbonize are also those which are highly globalized – long-distance freight transport and certain energy-intensive industries such as the chemical, steel and cement industries. This finding calls for the development of joint tools, at European level (including the emissions trading system/ETS, harmonization of energy taxation or a carbon inclusion mechanism for example) and, more broadly, at international level for international transport.

This commission's research is groundbreaking and seeks to show the way ahead, in that France is one of the very first countries in the world to have a shadow price of carbon driving a strong net zero GHG emissions ambition. Those signing this report hope that this proposal for a new trajectory for the shadow price of carbon will be used in the public policy and investment assessments and inform the debate on the necessary drivers and strategies for achieving the Climate Plan targets.

APPROACH, FINDINGS, USES

KEY MESSAGES AND RECOMMENDATIONS

By the 2015 Paris Agreement, the Signatory States have set themselves the collective ambition of achieving net zero GHG emissions – which is to say, a balance between greenhouse gas emissions by sources and removals by carbon sinks. The Intergovernmental Panel on Climate Change (IPCC) has recently confirmed that this objective is necessary if we are to keep temperature rise to below 2°C.

To contribute to the global response this calls for, in its Climate Plan of July 2017 France has set itself the goal of "net zero greenhouse gas emissions" (Net-Zero) by 2050, with residual gross emissions to be absorbed by carbon sinks – which include forests, grasslands and, further down the road, carbon capture and storage technology. This is a more ambitious goal than the "factor 4" (75% fewer emissions) enshrined in French legislation back in 2005. Efforts to reduce greenhouse gas emissions must therefore be stepped up imminently, as we are not on the right track.

To select the relevant measures, they should be valued in socioeconomic terms, i.e. in terms of their worth to the community. Specifically, the social value of mitigation activities (which is known as the shadow price of carbon in socioeconomic jargon) is the value that the community attaches to measures aimed at avoiding the emission of one ton of CO_2e.

Valuation of measures for tackling climate change has traditionally been practiced for the socioeconomic assessment of public investments. But such assessment would be worth extending to encompass all possible measures for setting the right priorities, encouraging meaningful action and sequencing this over time.

In 2008, an initial commission had outlined a trajectory for the shadow price of carbon. Ten years later, this work now needs updating: the climate policy objectives have factored in the worldwide delay in reducing greenhouse gas emissions and the need to strengthen the response: the technological opportunities for addressing the climate challenge and way forward in terms of international cooperation have become clearer, even if there is still much to be done.

A social value of mitigation activities grounded in the Paris Agreement and France's pledges

Several approaches may be harnessed in determining a social value of mitigation activities. The first, known as the cost-benefit approach, entails identifying the value of carbon which equalizes the marginal cost of damage linked to the emission of one ton of CO_2e and the marginal cost of reducing said damage. This approach, inspired by the landmark research by Arthur Pigou on externalities, was applied from William Nordhaus' initial work on the climate, and then adopted in the Stern report (2006) in particular. It leads to a calculation at global level of the damage that humanity will have to endure on account of the increasing concentrations in greenhouse gases – irrespective of the country producing the emission and the location of the damage.

This commission's so-called cost-effectiveness approach is complementary to that method. It involves identifying the value of one ton of CO_2e avoided, to be taken on board in all economic stakeholders' decisions and so ensure that France achieves climate neutrality[1] by 2050. Compared with a cost-benefit approach, this method gets round the uncertainties over the assessment of damage – on the basis of a legitimate objective reflecting collective preferences. The shadow price thus defined represents the value for society of measures aimed at reducing greenhouse gas emissions in line with the neutrality goal.

To conduct this approach, the commission began by characterizing the scope of France's pledges with a view to charting a relevant shadow price trajectory.

First, the goal in terms of net emission flows

The climate externality is a stock externality, to do with the level of concentration of greenhouse gases in the atmosphere. This is why consideration of this externality is expressed in terms of the carbon budget, i.e. of a limit of cumulative CO_2e emissions over time that must not be exceeded if we are to avoid temperatures rising further. The fifth IPCC report published in 2013 and 2014 showed that without specific efforts to reduce emissions, the global carbon budget to keep global warming below 2°C would be spent by the middle of the century.

The rapid shrinking of global carbon budgets is now leading to the stock objectives – responsible management of a multi-year carbon budget – being rounded off with flow objectives: a "net-zero" objective regarding human-driven greenhouse gas emissions. This net emission flow approach is now the norm:

[1] The commonly used term "climate" neutrality refers to a neutrality aim as far as all greenhouse gas emissions are concerned.

- it is the reference for the 2015 Paris Agreement, whose approach is grounded in the work of the IPCC;
- it is the reference for the IPCC's special report on the impacts of global warming of 1.5°C published in October 2018;
- it is the reference that France and several other – particularly European – countries have adopted (Norway, Sweden, Portugal and Spain among them). In France's case, the residual emissions emitted up to "net zero emissions" remain consistent with a carbon budget defined on the basis of our share in global emissions.[1]

Then, the time scale

France has set its sights on achieving net zero GHG emissions by 2050 – without waiting for the second half of the 21st century. This time scale is in line with the Paris Agreement, which urges the developed nations to take swift action. It factors in the need for early action to "phase out oil" and so as not to be caught off-guard should bad news come to pass. Finally, it addresses a concern for international fairness in the fight against climate change.

The "Net-Zero" goal for 2050 must obviously be interpreted as a goal to be upheld over the long-term – throughout the latter half of the century – which implies a sustainable decoupling of greenhouse gas emissions from GDP.

And finally, decoupling emissions from GDP

France is striving to map out a way forward where the move to net zero GHG emissions can be achieved without undermining growth. Aiming for a 2050 emissions target by restricting GDP would be costly – in terms of jobs and spending power – and ineffective on the climate front if this were to be associated with "carbon leakage", i.e. transferring production to countries with weaker climate ambitions, owing to losses in competitiveness.

The approach adopted thus meets two requirements: managing to decarbonize the economy by reducing greenhouse gas (GHG) emissions per unit of GDP; and investing to that end in energy efficiency and carbon-free technology.

This decoupling between emissions and GDP is already in progress: since 1990, GHG emissions in France have fallen by 16% while GDP has risen by nearly 50%. This is partly the result of efforts to make our electricity mix greener as well as energy saving efforts which are already beginning to pay off. The challenge now is to ramp up this

[1] Notwithstanding, therefore, the way in which the carbon budgets might be distributed between countries

decoupling over the next three decades, which calls for a considerable drive in terms of investment and changing our behavior.

Valuing mitigation activities based on the very best state-of-the-art

The fact is that no "turnkey" simulation tool currently exists for automatically generating a social value of mitigation activities. The commission puts forward a reasonable estimation based on the very best state-of-the-art, hinging on three key ingredients.

Ingredient no. 1: economic literature addressing the central question of distributing decarbonization efforts over time

With respect to managing a "carbon budget", an emissions and shadow price of carbon trajectory is recommended that enables compliance with the upper emissions limit at the least economic and social cost. In this context, the value of the shadow price of carbon must make it possible to honor the national pledge: its growth rate must lead to an effective distribution of efforts over time. In its basic version, the Hotelling rule recommends that the carbon value grow at the public discount rate – so a discounted shadow price that remains constant over time: provided that, from a starting point that is high enough to guarantee adequate total effort, this uniform valuation of activities guarantees their effective distribution over time.

The commission considered the Hotelling rule to provide a pertinent long-term guide, but that not applying it at the start of the period could be justified to smooth out the revaluation of the shadow price of carbon.

Ingredient no. 2: use of model simulations

Models allow an objective analysis of the carbon value, based on the target set, a detailed description of the technologies, behaviors and interactions between the various sectors of the economy and between France and its international environment.

Predominantly technology models define a trajectory representing the cost of reduction of one additional ton of CO_2e, the assumption being that this marginal cost will increase over time as it becomes necessary to leverage more expensive technologies. Macroeconomic models, meanwhile, can shed light on the investments and changes in behavior that are necessary for achieving net zero GHG emissions.

The commission felt that models painted a pertinent picture of the carbon value required over the period up to 2030, and even 2040, or alternatively until the reduction in emissions has approached the "factor 4" (i.e. GHG emissions have fallen by 75% compared with 1990). But the projections become increasingly less reliable the further along the time scale we go, the further the emissions fall and the closer we get to the point where their reductions become increasingly difficult and call for fundamental, non-marginal, changes that models calibrated on the past are no longer capable of predicting.

Ingredient no. 3: technological or technico-economic forecasting

Technological forecasting, such as the technology roadmaps produced by the International Energy Agency (IEA), or the exercises performed in France in laying the groundwork for the National Low-Carbon Strategy (SNBC), is a way of assessing the decarbonization potential of different technologies, their speed of deployment and their possible costs. To achieve a radical level of decarbonization, the shadow price of carbon must take into account a portfolio of enabling technologies for decarbonizing concentrated uses residual emissions – even if these have not yet been sufficiently developed and therefore remain relatively expensive.

Far-reaching changes to achieve the "net zero emissions" goal

The modeling work to date shows that there is significant scope for decarbonization at relatively affordable costs. Optimizing public transport systems, electrifying certain applications, developing certain thermal renewables such as green gases, or renovating buildings, for example, combine, in a good many cases, good environmental efficiency with low costs per ton of CO_2e avoided.

But radically decarbonizing the economy calls for further-reaching changes, at a time when the structure of energy systems is not evolving at any great pace and when greenhouse gas emissions are still difficult to bring down below certain limits for certain applications.

The main constructive insights to come to light from our research are as follows:

- achieving the "net zero emissions" goal will require both energy savings and decarbonization of the energy used;
- decarbonization will be gradual and depend to a large extent on investments aimed at "greening" existing capital (housing, commercial infrastructure, vehicles, etc.) or at providing new infrastructure (district heating, networks of electric vehicle charging points, public transport and so on);
- there is significant potential for abatement at no or low cost to be gained from greater 'sobriety', greater energy efficiency, small efforts and small investments. Once this potential has been exhausted, and unless technological breakthroughs are forthcoming, the cost of measures per ton of CO_2e avoided will increase as we progress in the transition to a carbon-free way of life and are obliged to rely on less mature technologies;

– by the 2050 milestone, the energy sector (which is already considerably decarbonized by the nuclear-renewables mix) may well have become completely carbon-free. It may even become a source of negative emissions if the development of bio-CCS (carbon capture and storage in the final stages of biomass-fired power plants), or direct capture of CO_2e in the air, is deemed "socio-technically viable". Residual gross emissions, which CO_2e sinks should be able to absorb, will in this case stem mainly from agriculture and a handful of industrial sectors.

A target value raised to €250 in 2030, in line with the most recent international estimations

In the commission's view, the 2030 time scale is likely to provide the best anchorage for a multi-year trajectory of the social value of mitigation activities, for two key reasons:

– the 2030 time scale – which is just over a decade away – is decisive for "anchoring" planning and catalyzing a wave of "low-carbon" investments;

– at this time scale, modeling can be grounded in reasonably sound economic and technological forecasting – even if this naturally continues to contain an element of uncertainty.

Based on modeling efforts to date, the commission recommends – starting with the current shadow price of €54 in 2018 – adopting a social value of mitigation activities of $€_{2018}$250 in 2030.

This value is a great deal higher than the current baseline value outlined by the commission in 2008 ($€_{2008}$100, so €110 in today's value). This mainly reflects the fact that we are behind schedule and the correlative increase in the level of ambition beyond the "Factor 4", both of which incur high abatement costs across several sectors of the economy, not least agriculture, some industrial sectors (cement, chemical industry or steel), and long-distance freight transport (by road, air or sea). The abatement costs also reflect the current inadequacy of the coordinated global response and the lack of international flexibility mechanisms available to the 2008 commission.

Beyond 2030, the trajectory mapped out is the result of two complementary approaches:

– forecasting on the costs of the enabling technology portfolio for successful decarbonization. The commission cannot predict whether a miracle new "backstop" technology (i.e. a substitute technology that completely does away with the need for fossil fuels, at a stabilized cost) will emerge. Neither does it postulate the emergence of a potential for negative emissions – i.e. an increase in the size of carbon sinks such that the carbon budget would swell and allow us some slack in terms of our response. But it does consider that a varied portfolio of enabling technologies (making more extensive direct use of carbon-free electricity or indirect use through hydrogen, or development of green gas and biomass) would make it possible to achieve radical decarbonization in return for relatively high switching prices;

– gradual calibration on a Hotelling rule. Between 2030 and 2050, growth of the shadow price will slow considerably to gradually align with a Hotelling rule for a public discount rate of 4.5%. This guarantees that the value of climate gains is not "crushed" by the discounting.

Ultimately, the commission recommends adopting a €$_{2018}$500 value in 2040 and a €$_{2018}$775 value in 2050. These fall within the range of the most recent carbon values outlined in the IPCC's latest special report, dated October 2018.

The value of the global response

When defining a trajectory for the social value of mitigation activities, the uncertainties over the valuations must be factored in – and these are only going to grow the further in to the future we go and the greater the scope for technological and diplomatic options becomes.

Sensitivity analyses show that the trajectory mapped out is based upon reasonably reliable modeling work with a 2030 time scale. Post-2030, our sensitivity analyses indicate that the values set out could be revised downwards were international cooperation to speed up the pace at which innovation is produced and disseminated.

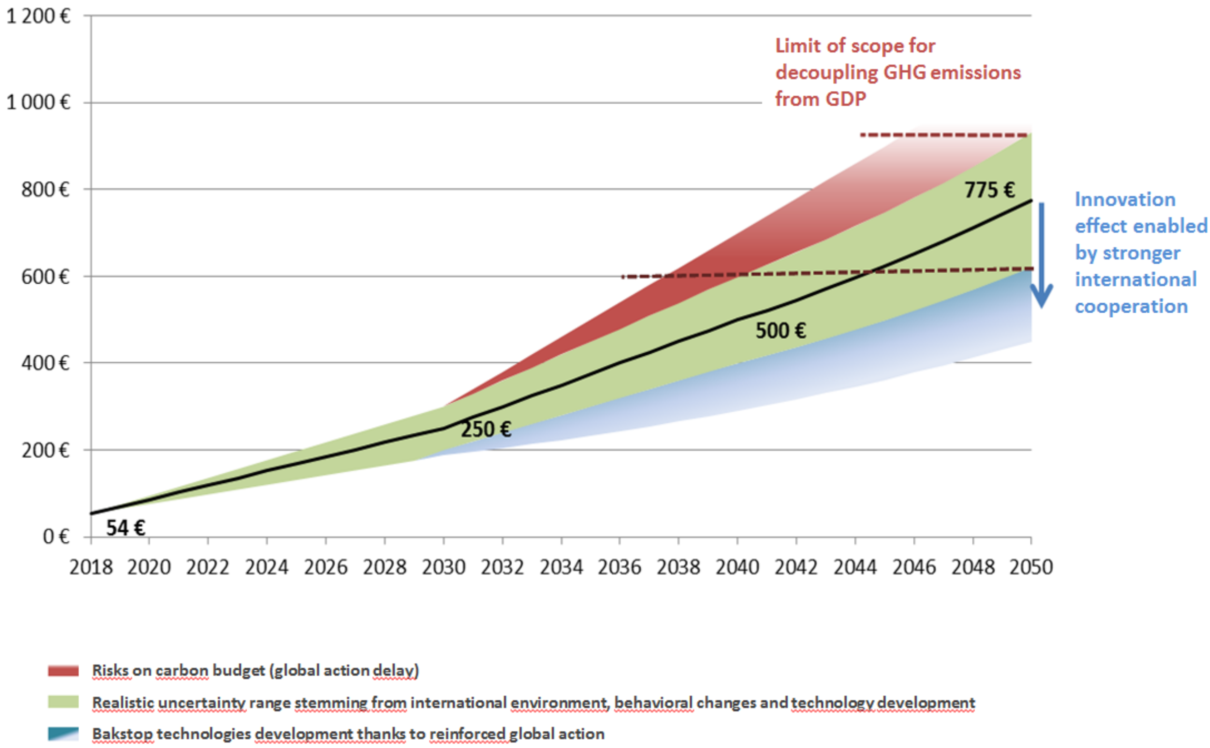
The sensitivity of the results to the cost of technology is closely tied in with the underlying hypotheses of international cooperation. At industrial level, research and innovation efforts geared more towards decarbonization solutions would help to drive down the cost of technologies – as can currently be observed for renewables. When a number of research institutions and companies across different countries embark on innovation programs, there are gains to be had for each country taken individually: for each country benefits from the emergence and global spread of innovations and the fall in the cost of technologies enabled by learning-by-doing and economies of scale.

At the end of the day, whilst a scenario where technological breakthroughs are enabled through stronger international cooperation would likely have little effect on the 2030 shadow price of carbon, it would, however, allow for a significant downward revision of this value between 2030 and 2050 to be considered. This could amount to around €450 by 2050 in this favorable scenario.

The uncertainty over the costs of mitigation technologies (and over the damage caused by climate change) makes a sequential approach even more necessary, whereby policies are gradually revised as more information comes to light. This has three consequences:

- it confirms the merits of a shadow price, ensuring consistency in the assessment of *all* potential mitigation options, without showing a preference for one over another;
- it requires uncertainty to be taken on board when determining the shadow price – which the trajectory and associated ranges endeavor to do, as illustrated in the chart below;
- it also implies that the shadow price is not set in stone, but revised at regular intervals (every five to ten years) based on new, game-changing information – not least about the true costs of mitigation.

Social value of mitigation activities



Universal use of the social value of mitigation activities

Achieving far-reaching decarbonization calls for changes both in behavior and technology. Such changes are within our grasp, as long as we set a broad spectrum of measures in motion, including positive price signals, an investment program that widens the scope of carbon-free applications and innovation efforts at international level.

This concerns industry across the board today. Radically decarbonizing the economy requires a much broader "base" of public and private options for tackling climate change

– even if abatement sources obviously vary considerably from one sector to the next, in terms of volume, unit price, potential for substitution and speed of decarbonization.

All greenhouse gases are concerned today – not just CO_2. This is because a quarter of greenhouse gas emissions concern other gases than CO_2. The challenge is not only to reduce energy-driven emissions but also emissions associated with industrial processes, waste processing, agriculture or land use.

A clear multi-year trajectory to enable investment and innovation

The key to a successful energy transition lies in the establishment of a capital stock allowing for the creation of business without emitting greenhouse gases, i.e. enabling GDP to be decoupled from emissions. In line with a number of previous studies, chief among which those by the OECD, the New Climate Economy Project and the European Commission[1], our research clearly points to a need to redirect investment and funding towards low-carbon projects.

The additional net investment needed for a successful move to a low-carbon future is at least 1 GDP point per year over the 2030 time scale and 1.5 to 2 GDP points per year over the 2040 time scale – with part of existing investment flows having to be rechanneled towards the formation of "green" capital.

Our research brings two, more specific, facts to light:

– to enable investment and innovation, public and private stakeholders must have access to a clear and stable trajectory for the shadow price of carbon which guides their planning and allows for their coordination: each stakeholder must start making plans, as of now, for the phasing out of oil and the running out of carbon budgets;

– the necessary investments bear first and foremost on a host of individual choices, involving housing, mobility or decentralized energy generation for example. Steps must be taken to remove the various traditional barriers to investment (insufficient R&D, limited access to information and loans), redirect financial flows and organize a fair sharing-out of financing and technological risks between the public and private sectors.

[1] OECD (2017), *Investing in Climate, Investing in Growth*, OECD Publishing, Paris; New Climate Economy Project (2018), *Unlocking The Inclusive Growth Story of the 21st Century*; European Commission (2018), *A European Strategic Long Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy*.

A guide for action

The social value of mitigation activities lays bare the sheer distance we still have to cover (represented by the marginal abatement cost of greenhouse gas emissions) and reflects the value to be given to measures enabling us to go this distance – i.e. to close in on the "Net-Zero" goal.

A reference for determining the collective priorities

The primary purpose of the social value of mitigation activities is to provide a reference for an updated assessment framework addressing four key questions:

- is the country on the "right" track to decarbonization – i.e. on course to ultimately meet the "Net-Zero" goal? The answer to this question can be found in a quantitative monitoring of emission flows per sector and of carbon sinks;
- does the observed trajectory enable the goal to be achieved at the best cost? This is where the shadow price of carbon comes in as a useful guide, insofar as it enables a definition of the scope of relevant action for the community. A higher shadow price of carbon extends the scope of profitable action for the community: all of the initiatives – whether public or private – costing less than the shadow price of carbon (so they present a lower socioeconomic abatement cost than the shadow price) should be taken wherever possible. When this cannot be done, the barriers and obstacles to such action must be identified;
- are the initiatives ranked by merit order? All sorts of measures can be taken to achieve the target, but they must be undertaken in the right order. Low-cost drivers for reducing CO_2 emissions must be leveraged as a priority, before more costly measures are taken. This is where the merits of a multi-year trajectory for a shadow price of carbon that rises over time become clear, as it can guide the activation at the right time (so not too early and not too late) of effective action, with account taken of the required investment timeframes;
- do private stakeholders initiate measures of their own accord, or do these require public intervention? In some cases, measures are cost-free and sometimes even generate gains. This is often the case with "cutting down", i.e. 'sober', mentalities, equipment-sharing strategies and certain efforts to achieve greater energy efficiency. In other cases, the externality is not factored in and requires public intervention in the form of investment or incentives and regulatory measures.

A reference for assessing the effectiveness of sector-specific action and public investment projects

Within this general assessment framework, it would be well worth using the social value of mitigation activities systematically in socio-economic project assessments. The various measures being considered to tackle climate change present wide-ranging cost-effectiveness ratios, you see. To be more exact, two key indicators would enable use of this value to guide the allocation of rare resources for society.

- The first indicator is a general one, and concerns the socioeconomic abatement cost, i.e. the full cost (so purchase and use) of a measure undertaken to reduce one additional ton of CO_2e. The shadow value provides a benchmark to which the different abatement costs can be compared; measures which have a lower abatement cost than the shadow cost are profitable for the community. But abatement costs must be calculated according to stable, transparent rules, and this is still not the case. Efforts to standardize and harmonize such calculations are recommended.

- The second, more specific, indicator is the calculation of the socioeconomic profitability of public investment projects. In this respect, the shadow price can help to steer projects by attributing a monetary value to the emissions avoided. Socioeconomic assessments of public investment projects adhere to a set of clearly established rules, but their use must extend beyond the fields it has traditionally been applied in, primarily transport and public buildings.

Revaluation of the shadow price of carbon must form part of a complete picture of the "climate" impact of projects. Over and above revising the shadow price of carbon upwards, it will also be necessary to revise the whole of the assessment framework: the reference scenarios, consideration of the climate risk in the discount rate and of the climate impacts throughout projects' lifetimes. Reassessing projects must make it possible to rank them better with a view to redefining an investment program that is more compatible with the Net-Zero goal.

A reference for anticipating the necessary changes

A multi-annual price trajectory, running from now until 2050, maps out the course ahead for "phasing out oil" and should prompt us to anticipate this transition, to plan for it. Such planning should prove beneficial in the coordination of public and private policy: if we are to develop electric car use, we need to install a network of electric vehicle charging points and change the vehicle fleet.

In addition to guidance with the spadework, incentives or recommendations are often necessary to kick-start meaningful action when private stakeholders do not initiate this of their own accord. In the same vein as the approach taken by the OECD and Stern-Stiglitz

Commission[1], this commission believes that it is important, well before any specific measures are taken, to ensure public policies square with the goal to tackle climate change – especially when it comes to land, urban planning and transport policies. For example, it is important not to make long commutes inevitable for workers on account of poor land regulation, "excessively" high property prices or a lack of infrastructure; instead, cities must be compact with sustainable travel networks.

In this realigned context, the road to a low-carbon future will be lined with a range of measures – carbon pricing, subsidies, measures for accessing credit, technological risk sharing and regulations – each one enabling the next milestone to be reached. It is not possible to settle for rolling out just one of these measures as each one comes with its relevant points and stumbling blocks. Carbon pricing is a way of supporting the profitability of "green" investments and steering innovation in the "right direction". And yet it is hampered by its redistributive effects and by the risks of lost industrial competitiveness. Whilst regulations can guarantee results, they can lead to high compliance costs for some stakeholders and hinder innovation. Subsidies, meanwhile, may generate free-riding and represent a cost for taxpayers.

The shadow price of carbon is not "earmarked" for a particular measure, and the commission does not claim to settle the issue of the right combination of measures. What it recommends is that it be possible to gauge – against the shadow price of carbon, on a use-by-use basis – whether the combination envisaged is appropriately sized. And this involves genuine assessment work, for the various measures are combined without it being possible to add them together strictly speaking. The clearer the State is on the abatement costs of CO_2 emissions per use, the better it will be able to calibrate its actions to help the switchover to carbon-free technologies.

[1] OECD (2015), *Aligning Policies for a Low-carbon Economy*, OECD; Stern-Stiglitz (2017) Commission, *Report of the High-level Commission on Carbon Prices*.

To help stakeholders to make sense of the new shadow price trajectory and put it into practice, we recommend doing the following

1. Make the trajectory outlined for the social value of mitigation activities official, to get stakeholders preparing along the same lines and thus enable investments to "decarbonize" the economy.

2. Make this price the reference for a stronger framework for assessing decarbonization measures, so as to be able to determine the priorities of public policy.

- Under France Stratégie's leadership, standardize the rules for calculating socioeconomic abatement costs so as to be able to compare the various sector-specific measures for achieving decarbonization.

- In addition to decarbonization, take better account of the co-benefits associated with the fight against climate change: improvement in air quality, and therefore health, by reducing local pollution, preservation and enhancement of biodiversity; better diets; less sensitivity to oil price shocks – and even technological breakthroughs.

- Use the shadow price of carbon as a reference for assessing the most relevant sector-specific decarbonization measures, by thinking in terms of socioeconomic abatement costs, so as to provide a more solid basis for setting public priorities.

- Based upon the multi-year trajectory outlined, assess in what order these measures would best be rolled out for most effectively achieving the goal for net zero GHG emissions in 2050.

3. Revise the framework for the socioeconomic assessment of public investments and come up with a new series of projects accordingly.

Ask France Stratégie to update the framework for the socioeconomic assessment of public investments for the purposes of:

- clarifying the reference scenario(s) allowing the national net zero GHG emissions goal to be reached, and which should be used in project assessments;

- value public projects based on their contribution to the net zero GHG emissions goal and their "option value", i.e. the flexibility they allow in the strategy's delivery;

- specify the rate at which the costs and climate gains of projects are to be discounted, with particular account taken of the correlation between the benefits of decarbonization investments and future economic growth;
- take better account of the emissions generated and/or avoided during the development stages of projects during assessments – in addition to those already counted during their operation;
- be more systematic in performing socioeconomic assessments of all public investment projects (including those financed by the local authorities), bearing in mind the fact that achieving net zero GHG emissions will rely, in no small part, on a large series of small-scale projects;
- ask the General Secretariat for Investment (SGPI) to draw up, based on these updated assessments, a new program of R&D and public investment projects.

4. Explain and address the implications in terms of redistribution and competitiveness.

The value of a reduction in emissions of one ton of CO_2e is the same for society irrespective of the sector where such reduction has been achieved. It gives an idea of the distance we still have to go, but does not predetermine how we should go about covering this distance nor how efforts (particularly financially speaking) should be distributed between the various public and private stakeholders. This distribution would be worth clarifying, with two aims in mind in particular:

- assess on a use-by-use basis the implications of carrying out decarbonization measures, in terms of redistribution and competitiveness;
- factor these implications into public policy design, not least with a view firstly to helping stakeholders with no immediate alternative available to phase out solutions reliant on carbon, and secondly to avoiding "carbon leakage" in sectors exposed to international competition.

5. Calculate a European shadow price, in order to highlight the relevance of a net zero GHG emissions goal at European level.

A European shadow price could particularly serve a purpose in assessing projects financed by the EIB or European funds, for the assessment of European policies – including the ETS – and stronger European cooperation.

KEY FIGURES

Global carbon budget

- Enabling maintenance of global warming below 2 C with 66% probability: 1,320 GtCO_2eq;
- Enabling maintenance of global warming below 1.5 C with 66% probability: 570 GtCO_2eq.

Source: IPCC Report on Global Warming of 1.5 C, 2018

French trends 1990-2017

- GDP: +47%
- Greenhouse gas emissions: -15%

Sources: World Bank (GDP in volume); Inventory of Greenhouse Gas Emissions – United Nations Framework Convention on Climate Change

French greenhouse gas emissions in 2017 (France, all GHGs)

- 466 MtCO_2eq (millions of metric tons of CO_2 equivalent)
- i.e. 7 tCO_2eq per inhabitant

Sources: CITEPA, 2018 indicators; INSEE

Sources of greenhouse gas emissions (taking all GHGs together)

- Energy (production and use): 69%
- Agriculture (apart from energy): 17%
- Industrial processes: 10%
- Waste treatment: 4%

Source: France Stratégie calculations, based on data provided by the General Directorate for Energy and the Climate (DGEC), 2015 inventory, and data from models

Economic sectors' share in French CO_2 emissions due to energy use/production (69% of GHG emissions)

- Transport: 38%
- Building: 21%
- Industry: 20%
- Energy production: 18%
- Agriculture: 3%

Source: France Stratégie calculations, based on data provided by the General Directorate for Energy and the Climate (DGEC), 2015 inventory, and data from models

Emissions under ETS/Emissions outside ETS

The Emissions Trading System covers 45% of all greenhouse gas emissions and 23% of French emissions.

Sources: European Commission and Ministry for the Ecological and Inclusive Transition

Size of carbon sinks

The current size of carbon sinks connected with land-use, land-use change and forestry (LULUCF) is assessed at around 40 $MtCO_2eq$.

Source: General Directorate for Energy and the Climate (DGEC)

The proposed value for climate action

- 2018: $€_{2018}54/tCO_2eq$
- 2020: $€_{2018}87/tCO_2eq$
- 2030: $€_{2018}250/tCO_2eq$
- 2040 : $€_{2018}500/tCO_2eq$
- 2050 : $€_{2018}775/tCO_2eq$

Source: Commission on the Value for Climate Action

GLOSSARY

Abatement cost

Difference in discounted cost between decarbonization action and the reference carbon equivalent solution, compared with greenhouse gas emissions avoided by the action.

Anthropogenic greenhouse gas emissions

Greenhouse gas emissions relating to human activity.

Climate neutrality or “net-zero GHG emissions”

Gross greenhouse gas emissions are fully compensated by carbon absorption by sinks.

Cost-benefit approach

Approach aiming to simultaneously determine the optimal trajectory for reduction of greenhouse gas emissions and the cost of such emission abatement, by continuous equalization of the marginal abatement cost for one metric ton of greenhouse gas and the discounted value of future marginal damage caused by one metric ton of greenhouse gas emitted today. The carbon value ensuring such equality is known as the “social cost of carbon”.

Cost-effectiveness approach

Approach aiming to determine the minimum cost of reducing greenhouse gas emissions, for a set emission reduction target. The value for climate action or shadow carbon price results from this approach.

Decarbonization

Actions aiming to reduce greenhouse gas emissions.

Decoupling of GDP emissions

Reduction of emissions that is not due to reduction in the GDP.

EU-ETS market

European Union Emissions Trading System.

Marginal abatement cost

Cost of reduction of one extra unit (metric ton) of greenhouse gas.

Socioeconomic calculation

Calculation aiming to evaluate the interest of a project for the whole national community.

Socioeconomic discount rate

Rate used in socioeconomic evaluations to discount a project's future gains and costs. The socioeconomic discount rate is generally lower than a private investor's discount rate.

Socioeconomic viability of investments

Evaluation, in monetary terms, of an investment's' viability for the whole national community. Gains generated by the community include effects that do not go through the market, including effects on the environment for which no prices exist, but excluding financial flows constituting simply monetary transfers between operators within the national community.

Value for climate action or shadow carbon price

Value that the community places on actions enabling avoidance of the emission of one metric ton of CO_2 equivalent.

CHAPTER 1

THE GLOBAL CONTEXT: WHAT HAS CHANGED IN THE LAST TEN YEARS

Since the work carried out in 2008 by the first Commission on the shadow price of carbon, the global context of the fight against climate change has undergone far-reaching changes.[1] The backdrop is now that of continuous drift in global greenhouse gas emissions (GHGs). The IPCC's fifth report, published in 2013 and 2014, helped provide an accurate picture of the reality of climate change and its multifaceted consequences. The Panel's work shows that the carbon budget available to humankind (i.e. our GHG emission margin) in order to limit the rise in temperatures to 2°C will be exhausted by the end of the next three decades, and even before then if we want to limit the rise in temperatures to 1.5°C.[2]

In this "race against the clock", progress has been made on the technology front as well as with regard to environment policies:

- the field of technological possibilities for decarbonization has broadened, with the steep drop in the cost of renewable electrical energies, the maturity of such technologies as electric mobility, and fresh perspectives in the key fields of energy and hydrogen storage and CO_2 capture and storage;
- national policies combating climate change have gradually gained in scope and consistency in several regions of the world. According to World Bank statistics, 46 countries and 25 territorial authorities have set a price for carbon, on a basis representing 20% of global greenhouse gas emissions. By restarting the negotiation process that had been deadlocked since COP15 in Copenhagen, the 2015 Paris Agreement provided an opportunity to renew the commitment made by the 196 signatory countries to keep the rise in temperatures below 2°C.

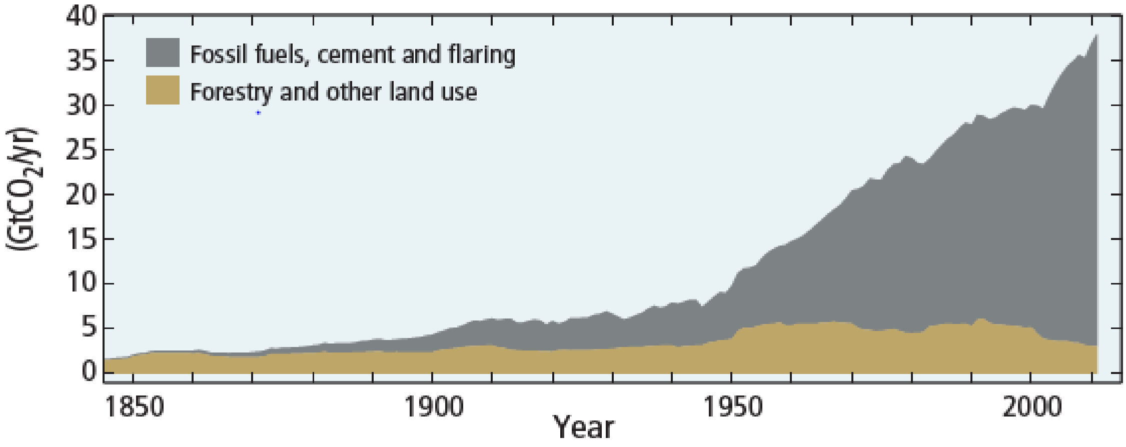
[1] Centre for Strategic Analysis (CAS) (2008), *La valeur tutélaire du carbone*, Report by the mission chaired by Alain Quinet, Paris, *La Documentation française*.
[2] IPCC (2018), *Global Warming of 1.5°C, Summary for Policymakers*.

Without claiming to cover the full complexity of debates on the scientific, technological, economic and social issues of climate change, this chapter endeavors to characterize the major international developments that a national carbon valuation initiative must necessarily take into account.

1. The world is not on the right trajectory

Global GHG emissions started to increase significantly in the 1950s (see Figure 1). Although there was a relative slowdown in the 1990s, the development of emerging countries, in particular BRICS (Brazil, Russia, India, China and South Africa), has since led to fresh acceleration of GHG emissions.

Figure 1 – Global anthropogenic CO_2 emissions per year and cumulative CO_2 emissions by period



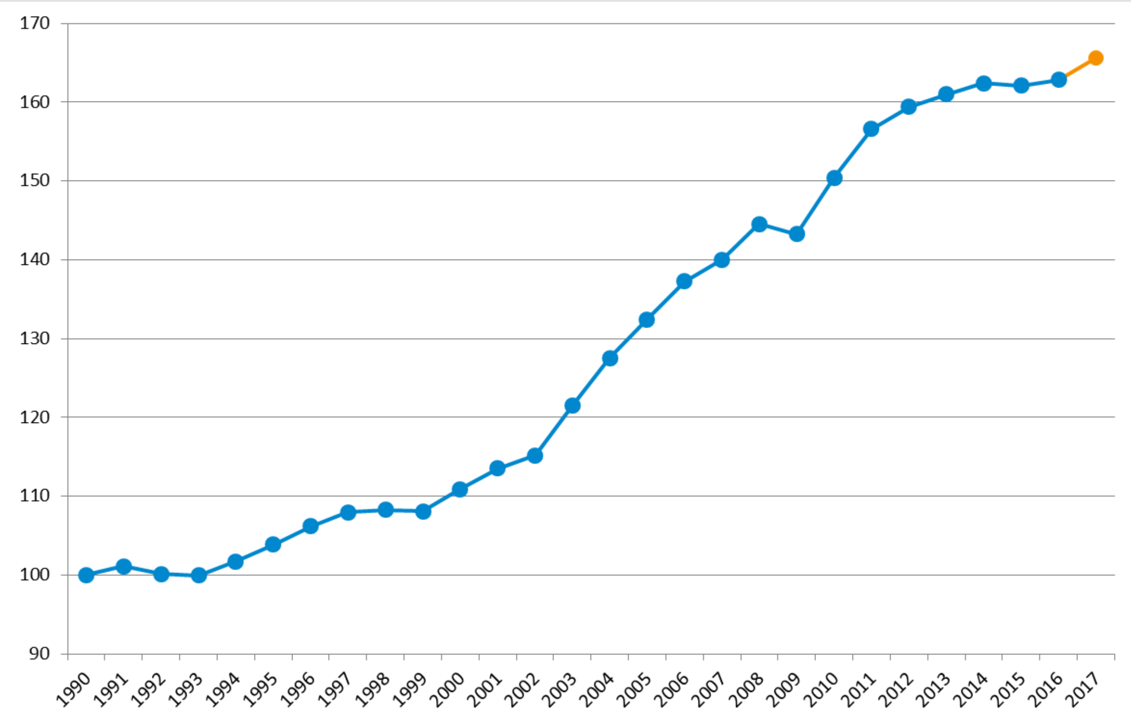
Interpretation: emissions connected with fossil fuel combustion, cement works activities and flaring are represented in grey; emissions connected with forestry activities and other land uses are in brown.

Source: IPCC (2014), Climate Change 2014, Synthesis Report, Summary for Policymakers, p.3

Despite the environment policies implemented, mainly in Europe, global GHG emissions have continued to increase, except during the 2007-2008 financial crisis.[1] Taking all GHGs together and including land use and forestry sectors, there was an increase of almost 70% between 1990 and 2018.

[1] Between 2008 and 2009, the global GDP calculated in constant dollars fell by 1.73% and global GHG emissions decreased by 0.9% (sources: World Development Indicators and Global Carbon Project).

Figure 2 – Annual growth of global GHG emissions, base 100 in 1990)



Sources: Corinne Le Quéré et al. (2018), Global Carbon Project, Earth System Science Data, 10, pp.405-448, (orange point: estimation); Canadell P., Le Quéré C. et al. (2018), "Carbon emissions will reach 37 billion tonnes in 2018, a record high", The Conversation, 5 December.

1.1. Risks of serious irreversible damage

The part that human activities play in global warming has been rigorously established. The IPCC's most recent report asserts more clearly than its predecessors that climate change is now having observable effects: "Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems".[1]

The IPCC's successive reports have also been increasingly specific in documenting the risks of serious irreversible damage that humankind is running. "Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems".[2] Climate change will amplify existing risks to natural and human systems and create new ones: a downturn in agricultural yields, rising water levels, and an upsurge in extreme events. As may be expected, the thresholds above

[1] IPCC (2014), *Climate Change 2014, Synthesis Report, Summary for Policymakers*.
[2] *ibid*.

which such risks may materialize are difficult to determine, as is any exact location of damage.

Inset 1 – Greenhouse gases

The Paris Agreement's commitments bear on seven GHGs (CO_2, CH_4, N_2O, HFC, PFC, SF_6 and NF_3). Three-quarters of all GHG emissions are CO_2 emissions.

These gases are characterized by their lifespan and warming power. Global warming potential (GWP) expresses a given gas' impact on global warming in comparison with CO_2, within a given timeframe (usually 100 years). This enables conversion of different gas masses into a single unit, the metric ton of CO_2 equivalent (t CO_2eq), which represents the mass of CO_2 required to generate the same impact on global warming as a metric ton of the gas under consideration.

Hence, over 100 years, a metric ton of methane has a global warming potential of 25, which means that one metric ton of methane emitted today would contribute as much to global warming measured in 100 years as 25 metric tons of carbon dioxide emitted today. One metric ton of methane therefore corresponds to 25 t CO_2eq.

Table 1 – Greenhouse gases: lifespan, warming potential, distribution and sources of emissions

		CO_2	CH_4	N_2O	Fluorinated gases			
					HFC	PFC	SF_6	NF_3
Atmospheric concentration	2014	397 ppm	1 823 ppb	327 ppb	> 157 ppt	> 6,5 ppt	8,2 ppt	< 1 ppt
	2005	379 ppm	1 774 ppb	319 ppb	> 49 ppt	> 4,1 ppt	5,6 ppt	-
Life expectancy		*	9	131	for a period of weeks, or for several thousands of years			
Global warming potential over 100 years		1	25	298	[124 ; 14 800]	[7 390 ; 12 200]	22 580	17 200
Global GHG emissions by substance (% of total 2010 emissions)		74	17	7	2			
Main sources of anthropogenic emissions		Fossil fuel burning, industrial processes, deforestation	Wastes, agriculture and livestock farming, industrial processes	Agriculture, industrial processes and fertilizers	Sprays, cooling, industrial processes			Manufacture of electronic components

ppm: part per million ppb : part per billion ppt: part per trillion.

Remark: a million metric tons of carbon (1 MtC) = 3.664 million metric tons of CO_2.

* The lifespan of carbon cannot be represented by a single value as this gas is not destroyed over the course of time. It migrates between the oceans, the atmosphere and the terrestrial system. Some excess CO_2 is rapidly absorbed (by ocean surfaces, for example) but the rest will stay in the atmosphere for several thousand years due to the slowness of the process that transfers carbon to ocean sediments.

Sources: Chiffres clés du climat, France, Europe et Monde*, 2016 and 2018 editions, General Commission for Sustainable Development (CGDD) and I4CE, Datalab, Ministry for the Ecological and Inclusive Transition; United States Environmental Protection Agency Climate Change Indicators: Greenhouse Gases, www.epa.gov/climate-indicators/greenhouse-gases; United States Environmental Protection Agency Climate Change Indicators: Global Greenhouse Gas Emissions Data, www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data; World Development Indicators, World Bank; Technical Interprofessional Centre for Atmospheric Pollution Studies (CITEPA), www.citepa.org/fr/air-et-climat/polluants/effet-de-serre/perfluorocarbures*

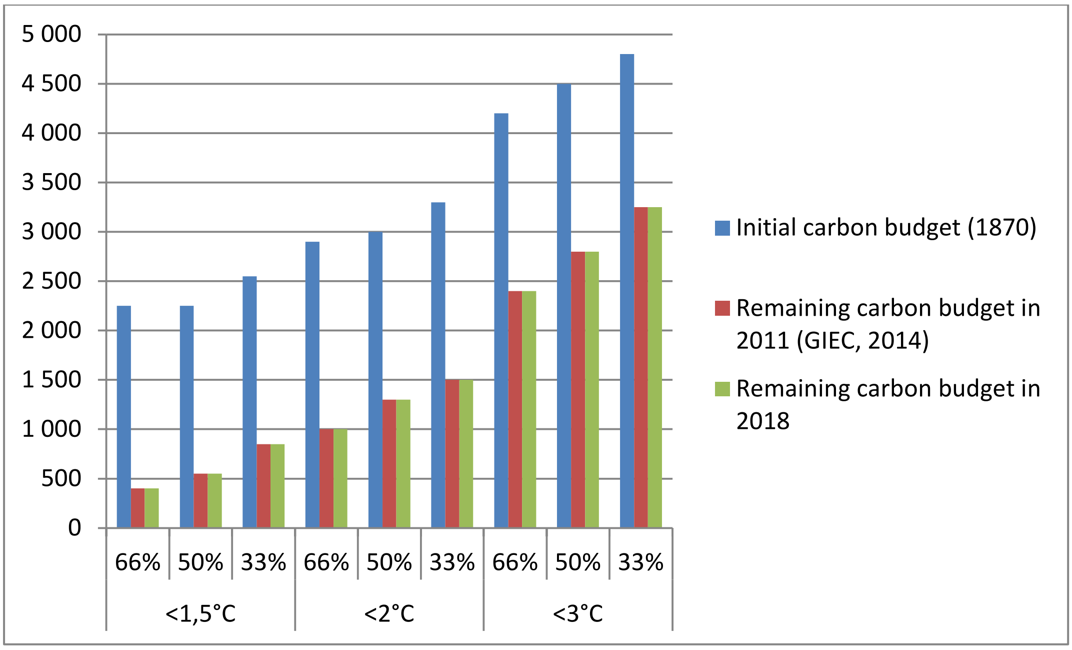
1.2. A global carbon budget rapidly approaching exhaustion

The carbon budget is defined as the total quantity of carbon that can be emitted for a given maximum rise in temperatures (1.5°C or 2°C) in order to stay below such limit with a given probability. Given the uncertainties of climate models for a given temperature target and probability, measurement of the carbon budget itself is surrounded by uncertainties and is a recurrent subject of debate. This report does not aim to provide an account of such debate, and much less to take a position, but rather to characterize the general messages emanating from the work brought together and summarized by the IPCC.

The IPCC's fifth evaluation report published in 2014 and its 1.5°C Special Report, which has just been issued, elucidates the issues involved in keeping a rise in the earth's surface's temperature "significantly below" 2°C compared with the preindustrial era, with 1.5°C being a more desirable target:

– The deadline is now expressed in decades. A large proportion of the carbon budget available to us at the beginning of the industrial era has already been consumed (see Figures 3 and 4); residual carbon budgets will be exhausted well before the end of this century, and well before fossil fuel deposits are exhausted;

Figure 3 – Initial carbon budget and carbon budgets remaining in 2011 and 2018



Source: France Stratégie calculations based on IPCC (2014), Climate Change 2014. Synthesis report, p.64

– the carbon budget (in other words the stock of GHG emissions that must not be exceeded) will be exhausted within two or three decades at the current rate of emissions; if we wish to keep warming below 2 degrees;[1]

– the fight against climate change and the 2°C target require "net-zero emissions" by the second half of the 21st century, in other words, containment of gross emissions at the level of carbon sinks;

– between the present day and the second half of the 21st century, economies must converge towards sustainable "net-zero emissions" if the target is 2°C. If the aim is to limit the temperature rise to 1.5°C, global neutrality must be achieved by 2050.

If we go into the details of IPCC scenarios, the number of decades still available depends on the temperature goal and the probability we give ourselves of not overstepping that goal. It also depends on methodological choices over the period in question and estimated sizes of carbon sinks (oceans and forests in particular).

[1] The IPCC's abovementioned 1.5°C Report mentions the possibility, with attached risks, of temporarily exceeding the carbon budget and then, by making use of carbon capture and storage (CCS) technologies, returning to trajectories compatible with Paris Agreement goals.

The IPCC's fifth report for 2013-2014 shows that carbon budgets compatible with a temperature rise limited to 2°C would be exhausted in the next three decades. Based on the results of the IPCC's fifth report bearing on carbon budgets calculated in 2011, it is possible to estimate the carbon budget available today, according to the climate goal. In order to update 2011 estimations, we have incorporated emissions between 2011 and 2017 into the calculation (see Table 2).

Table 2 – Carbon Budgets

Global warming target	**< 1.5°C**			**< 2°C**			**< 3°C**		
Probability of compliance with temperature rise goals	**66%**	**50%**	**33%**	**66%**	**50%**	**33%**	**66%**	**50%**	**33%**
Initial carbon budget (reference year 1870)	2,250	2,250	2,550	2,900	3,000	3,300	4,200	4,500	4,800
Carbon budget remaining in 2011 (Fifth IPCC report 2014)	400	550	850	1000	1,300	1,500	2,400	2,800	3,250
Carbon budget remaining in 2018	153	303	603	753	1,053	1,253	2,153	2,553	3,003
Years left before exceeding the budget at present rate of emissions (hypothesis of 37 $GtCO_2$/year)	4	8	16	20	28	34	58	69	81

Sources: France Stratégie calculations based on IPCC (2014), Climate Change 2014. Synthesis report, p.64; a presentation by K. Anderson of the Tyndall Center for Climate Change Research; and Le Quéré C. et al., Global Carbon Budget 2018, Earth Syst. Sci.

The IPCC's recent 1.5°C Special Report provides an upward revision of carbon budgets extended by some ten years, on different methodological bases to those used in previous reports.[1]

[1] Any upward revision of the carbon budget should be considered with caution as a great many uncertainties exist.

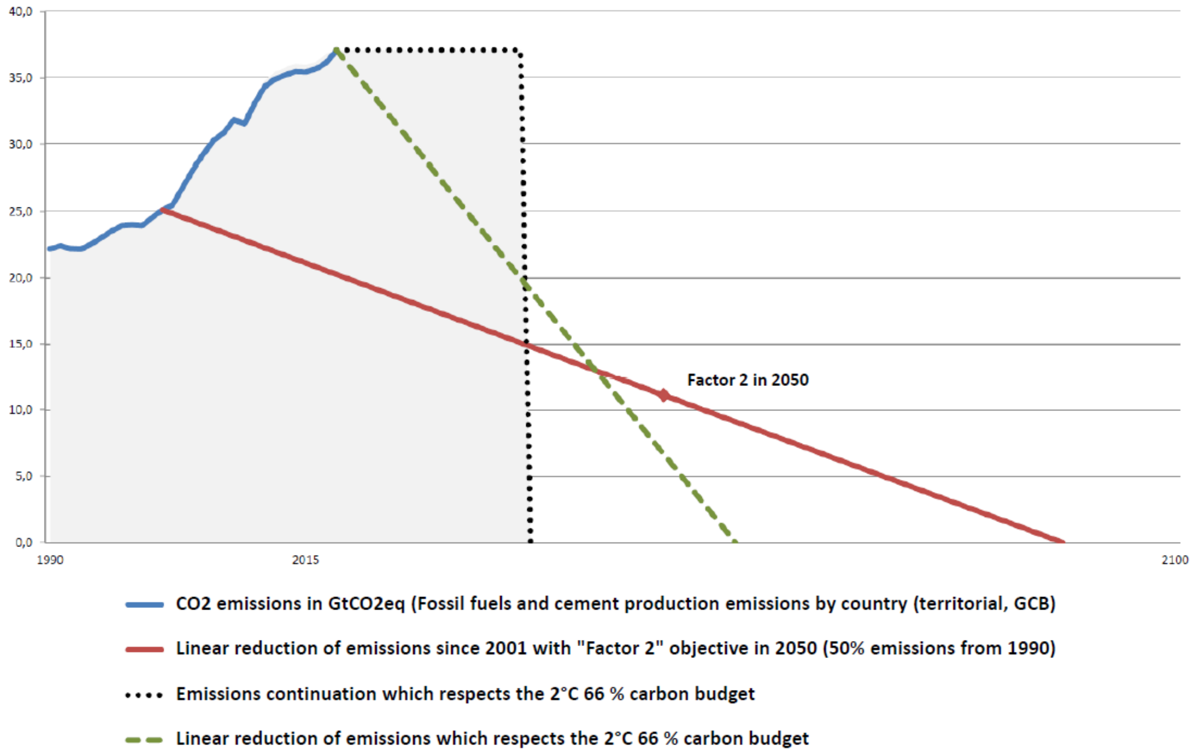
Table 3 – Carbon Budgets AR5 (fifth IPCC Report) and SR 1.5 (1.5°C Special Report) remaining in 2018

	AR5						1.5 SR					
Anthropogenic warming target	<1.5°C			<2°C			<1.5°C			<2°C		
Probability of compliance with temperature rise goals	66%	50%	33%	66 %	50%	33%	66%	50%	33%	66%	50%	33%
Carbon budget remaining in 2018	153	303	603	753	1,053	1,253	420	580	840	1,170	1,500	2,030

Sources: France Stratégie calculations based on IPCC (2014), Climate Change 2014, Synthesis report, Table 2.2, p.64, and IPCC (2018), SR 1.5, Chapter 2, Table 2.2, p.22

Leaving uncertainties aside, the general message may be summarized in stylized fashion in the graph below: we are not on the right trajectory, global emissions are increasing and the carbon budget is diminishing. In such a context, achieving net zero GHG emissions – net-zero carbon sink emissions before the end of the century – should logically become the new basis for strategies on the fight against climate change.

Figure 4 – Comparison of global goals with trajectories complying with the 2°C carbon budget (with 66% probability)



Source: France Stratégie simulations based on United States Environmental Protection Agency Climate Change Indicators: Global Greenhouse Gas Emissions Data

1.3. IPCC scenarios for achieving net zero GHG emissions

In its 1.5°C Special Report published in October 2018, the IPCC considers that it would be necessary to achieve zero emissions around 2050. This means that remaining emissions would have to be compensated by eliminating CO_2 from the atmosphere. With this in mind, its summary for decision-makers highlights four typical scenarios (P1 to P4) enabling the rise in temperatures to be limited to 1.5°C. The scenarios are differentiated according to two criteria: demand for energy and size of carbon sinks. The greater the demand for energy, the more the sizes of carbon sinks must be increased, by resorting to carbon capture and sequestration, and the higher the marginal emission abatement cost, as carbon capture and storage (CCS) technologies are expensive.

- In scenarios P1 and P2, final energy demand decreases or is stable (relative to 2010). In this context, net zero GHG emissions can be obtained by abatement of gross emissions and recourse to natural carbon sinks such as permanent grasslands and forests without any significant use of CCS technologies. However, scenario P2 assumes increased international cooperation.

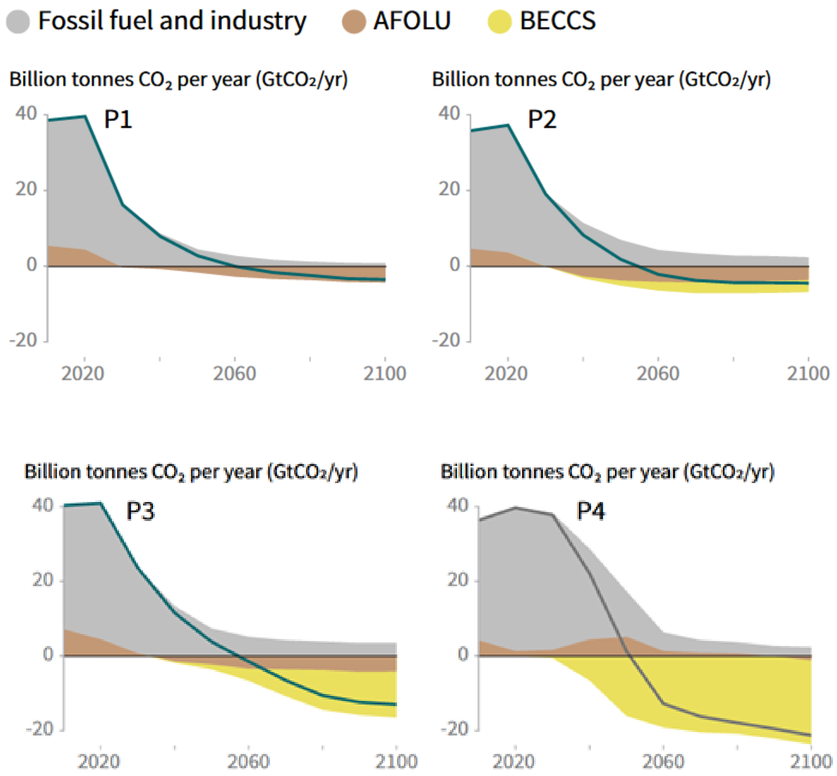
- In scenarios P3 and P4, final energy demand increases. Reduction of gross emissions is more difficult and slower, and temperatures temporarily overshoot the 1.5°C limit. In addition to natural sinks, net zero GHG emissions requires recourse to artificial carbon sinks. Among CCS technologies, the IPCC highlights BECCS as a critical technology as it enables achievement of negative emissions.[1] [2]
  - the BECCS solution enables negative net CO_2 emissions. CO_2 emissions from combustion of biomass are captured and stored, while the stock of biomass is renewed (when a tree is cut down to obtain fuelwood, another is planted in its place);
  - The greater the potential of BECCS, the more room there is for maneuver on gross emissions. Mass recourse to BECCS is itself conditioned by increased international cooperation.

Only the first two scenarios do not involve temporary overshooting of the target, later correction of which is conditioned by development of CCS technologies.

1 BECCS (Bioenergy with Carbon Capture and Storage) is the use of biomass as energy input, whose CO_2 emissions are captured and sequestered.

[2] Scenarios P2 and P4 emphasize the importance of international cooperation enabling achievement of net zero GHG emissions more rapidly, in 2050. Increased international cooperation plays a major role in financial and technological transfers.

Figure 5 – Characteristics of four typical emission reduction scenarios



Interpretation: AFOLU stands for Agriculture, Forestry and Other Land Use; BECCS is the acronym for Bioenergy with carbon capture and storage.

Source: IPCC (2018), Global Warming of 1.5°C, Summary for Policymakers, p.16

2. The field of technological opportunities is expanding

Climate change calls for a change in lifestyles, habits, and some of the assets and technologies we make use of today. For the last decade or so, the field of technological opportunities has been significantly expanding, even though there are still major uncertainties about deployment speeds and innovation costs.

2.1. A more promising technological future

In its work for the energy sector (*World Energy Outlook* and *Energy Technology Perspectives*[1]), the International Energy Agency (IEA) highlights the portfolio of critical technologies that will have to be deployed on a wide scale at global level in order to achieve the Paris Agreement's goals.

[1] www.iea.org/weo, www.iea.org/etp.

The portfolio is first of all made up of technologies enabling gains in energy efficiency in all sectors of the economy. Digital technologies will play a key role, for example, via the real-time management and regulation capacities they provide to improve energy efficiency in housing units, tertiary buildings and factories, and to optimize grids. Use of digital technologies could also result in increased energy consumption, in a proportion that would depend on the employment and regulation of such uses, for autonomous vehicles, for example.[1]

The portfolio should then go on to cover all existing and future technologies enabling energy decarbonization. In this respect, the IEA's report *Energy Technology Perspectives 2017* specifies that three developments will be of critical importance:

– decarbonization of electricity production, with joint progress in variable renewable electrical energies (wind power and solar PV), controllable decarbonized means (hydroelectricity, nuclear power and biomass) and low-carbon resources (fossil fuels with CCS), and improvement of electricity storage capacities;

– electrification of uses: either by more extensive direct use of decarbonized electricity in transport, building and industry, or by indirect use via hydrogen produced in decarbonized procedures making use of electricity and electrolysis of water. The hydrogen vector may itself have direct uses (fuel cells, for example) or indirect uses in synthetic gases and fuels ("power-to-liquid" and "power-to-gas");

– development of bioenergies, next-generation biofuels in particular.

Finally, the portfolio will include CO_2 capture and storage technologies, BECCS in particular. BECCS will potentially enable generation of negative emissions, and therefore compensate difficult-to-abate residual emissions from various industrial and agricultural processes, as well as from sea and air transport.

Four main lessons are to be learned from the IPCC report:

– the field of decarbonization technologies is expanding, even though it would be unwise today to rely on the appearance of a "backstop" technology with no major development constraints, enabling us to do away with fossil fuels entirely. Decarbonization of certain sectors will be a long and difficult process. Such is the case with air transport and sea freight transport and is also true of a number of industrial sectors, including cement, steel and chemicals. In these sectors, we shall have to count on disruptive technologies (such as hydrogen) or on development of CCS technologies if we are to achieve significant decarbonization;

– Information currently available suggests that the technologies most likely to enable us to achieve total decarbonization by the end of the period will be expensive, possibly as much as €500 to €800 per metric ton of CO_2 eliminated. The costs of technologies

[1] International Energy Agency (2017), *Energy and Digitalization*, IEA Publications, October.

mentioned here do not take account of the costs of deployment and adjustment of capital stock, so marginal abatement costs may be higher than technology costs *sensu stricto*;

- the *Energy Technology Perspectives 2017* (or ETP) Report emphasizes the importance of international cooperation. There is all the more chance of innovations emerging and disseminating if a large number of countries and enterprises commit to innovation policies designed to "green" their activities. Learning-by-doing and economies of scale should then enable more rapid and greater reductions in the price of technologies.[1] Multilateral cooperation can foster this "Schumpeterian" innovation process and give developing countries easier access to green technologies;
- finally, the ETP Report emphasizes the interdependence of technologies.[2] "Combining different technologies will enable provision of reliable and affordable energy services while reducing emissions."

The IEA's work has been corroborated by other scientific studies. As an illustration, one of the Report's complements summarizes a recent article published in *Science,* by a network of some thirty scientists, synthesizing margins of technical progress inasmuch as they can be assessed today.[3]

2.2. Major uncertainties on technology costs by 2050

The broadening of the field of technological possibilities is potentially good news in the fight against climate change, but it must be incorporated "without naivety" in any foresight exercise, for two reasons.

Firstly, technological progress is not automatically "green" and very much depends on price signals – the incentive to look for fossil fuel substitutes is dependent on anticipated

[1] See the *Complements* to this Report for simulations of learning effects and their consequences on reduction costs per metric ton of CO_2: Complement 15, "*Valeur tutélaire du carbone : quelques considérations techno-économiques*" (Shadow Value of Carbon: a few techno-economic considerations), by François Dassa and Jean-Michel Trochet.

[2] This argument concerns all sectors, from energy to industry via agriculture and forestry. The IEA stresses the fact that "Energy technologies are interdependent and must therefore be developed and deployed in parallel" (ETP Report 2017, see Complement 13 to this Report) and "A significantly strengthened and accelerated policy response is required to achieve a low carbon energy future. Early action to reduce emissions and avoid lock-in of emissions-intensive infrastructure will be essential if future temperature increases are to be kept to 2°C or below. The scale of effort needed to achieve net zero GHG emissions by 2060 in the B2DS highlights that there would be almost no room for delay; all available policy levers would need to be pulled, and soon." (ETP Report ETP 2017, p.20).

[3] Davis S.J. *et al.* (2018), "Net-zero emissions energy systems", *Science,* vol.360, Issue 6396, eaas9793.

and observed evolution of their prices[1] – as well as on the effectiveness of public policies supporting R&D. These must overcome the effects of “dependence on the past”, which pushes companies to focus on fields in which they already possess solid knowledge.

Secondly, there are still major uncertainties regarding the potential for development of new technologies and their marginal costs. Such uncertainties include the potential of carbon capture and sequestration (CCS), which determines carbon sink sizes and consequently the available margin for “absorption” of gross emissions. The CCS process consists of trapping molecules before, during or after the combustion stage in order to avoid their being liberated into the atmosphere. The technologically convincing experiments underway must be continued at demonstrator level, in order to reach the required industrial size. There are also other obstacles to overcome: for example, it may well be necessary to deploy a network interconnected between European countries to transport CO_2 to sequestration zones in the North Sea, which seems to possess the most promising storage potential. More generally, we still have to remove the uncertainty surrounding major potential sequestration areas.[2]

A more systemic field of uncertainties bears on the potential for each technology’s development. Each technical solution has its limitations:

– such limitations may be both physical and in terms of energy. Available physical resources must exist in sufficient quantity, such as water for hydroelectricity, underground pockets for CCS, and small metals[3] for manufacture of decarbonized energy sources. Access to and production of resources also requires increasing energy expenditure despite developments in production techniques.[4] New energy technologies’ content in materials and energy alike must be taken into account in carbon evaluation of “green” technological products, as their net impact on GHG

[1] Dechezleprêtre A. (2016), “How to reverse the dangerous decline in low-carbon innovation”, *The Conversation*, 24 October.

[2] International Energy Agency (2017), *Energy Technology Perspectives 2017. Catalyzing Energy Technology Transformations*, p.31 ff. CCS makes a 14% contribution to emission reduction to transition from the Reference Technology Scenario (RTS) to the 2°C Scenario (2DS) and a 32% contribution during transition from 2DS to the Beyond 2°C Scenario (B2DS), coming to around 18% from RTS to B2DS.

[3] Also called critical, strategic or rare metals, setting aside a few nuances. Unlike iron or bauxite, these metals are produced in small quantities and are less present in the earth’s crust. They are particularly sought-after for their properties and applications in new energy technologies.

[4] This effect comes under the second principle of thermodynamics. It may be approached via the Energy Return on Investment (EROI) ratio, which measures the quantity of usable energy per unit of energy expended to obtain such energy. It calculates the difficulty of extracting energy from the environment. It establishes that net energy available for human activities is decreasing. The same goes for metal resource production: more and more energy is needed to produce the metal resources used in production of renewable energies. See Court V. and Fizaine F. (2017), “Long-term estimates of the Energy-Return-on-Investment (EROI) of coal, oil, and gas global productions”, *Ecological Economics*, 138 (2017), pp.145-159.

emissions may be less than their "gross" impact.[1] Understanding and evaluation of this energy/material loop is essential to consideration of technologies' contributions and therefore of the value for climate action;

- new energy-efficient technologies may generate "rebound effects", a tendency to make greater use of more efficient equipment – important effects in the field of mobility and, to a lesser extent, housing;
- limitations may finally be a matter of conflicts of use: for example, biomass may be put to a wide range of uses (food supply, sequestration, heat needs, etc.) that require arbitrations on land use. Similarly, limitations may be to do with acceptability, as is evidenced by the degree of opposition to deployment of onshore wind turbines.

These uncertainties are reinforced by the persistence and even widening of the gap between the stated aims of national and international mitigation policies on the one hand and the actual results of such polices on the other. Although this "implementation gap" still requires detailed analysis, it is a clear expression of the existence of major obstacles to action – at least in the short term – largely to do with three issues:

- in a context where actors do not always have decarbonized alternatives available to them, handling of redistributive questions relating to climate policies is subjected to constraints regarding access to credit and competitiveness;
- social and institutional barriers to rapid deployment of "low carbon" options – for upgrading existing buildings' energy efficiency, for example – along with vocational training and sector structuring issues at supply level, and the landlord/tenant dilemma at demand level;
- lack of funding in a context where there is no lack of available savings but inadequate investment in "low carbon" actions as perceived risks are still high; also in a context where there is limited room for budgetary maneuver. The question is therefore how to come up with the best means for directing private savings to "low carbon" investment.

3. The climate economy provides a framework for effective mitigation of climate change

This Report does not claim to describe the whole theoretical context and the debates that analysis of the consequences of climate change and conditions for an effective mitigation policy have given rise to among economists. Here, it is more a matter of highlighting advances made over the last decade – advances on which the valuation of climate action initiative might draw.

[1] The concept of "grey energy" may be deployed. It signifies incorporated energy to which the energy used in deployment of the good is added; during the good's use and up to its end-of-life recycling.

3.1. Economic analysis of the mitigation of a global externality

Environmental economics broach climate as a collective good to be preserved or as a negative externality (CO_2 emissions) to be internalised in the functioning of markets. It is a particular kind of externality as global warming is brought about by accumulation of GHGs in the atmosphere. Damage is therefore connected with stocks of GHGs rather than with the emission flows that supply them (as is the case with classic externalities). Correlatively, it takes a great deal of time to reduce concentration.

In this context, the cost-benefit approach to the climate problem aims to determine the socially optimal trajectory of GHG emissions at global level, by continuous equalization of the marginal abatement cost for one metric ton of greenhouse gas and the discounted value of future marginal damage caused by one metric ton of greenhouse gas emitted today. When such equality is obtained, we are insured against two risks: that of making undue efforts with little social benefit, and that of not making enough effort although costs to bear are low and benefits considerable.

However, cost-benefit analysis remains difficult to apply operationally insofar as calculation is extremely sensitive to choices of certain key parameters (valuation of damage, discounting, threshold effects, etc.) that are still poorly understood or provided by foresight exercises[1]:

- the main difficulty in this type of approach lies in estimation of the marginal damage curve, on which it is hard to obtain a consensus.[2] The IPCC's work has largely consolidated disaster risks[3] but accurate determination of tipping points remains highly uncertain;
- the effects of temperature variations on the economy are hard to evaluate. Some of the damage caused is of a commercial nature – potential loss of GDP due to limitation of natural resources and destruction of productive capital in the event of a disaster. But some is also non-commercial, concerning loss of biodiversity and risks of destruction of societies and ecosystems;
- the consequences of uncertainty are amplified by the existence of a whole range of inertias, one might even say irreversibilities, in the climate system and technical, economic and social systems alike.

[1] See Inset 2.
[2] Somewhat provocatively, Robert Pindyck states that "when it comes to the damage function, we know virtually nothing – there is no theory and are no data that we can draw from"; Pindyck R. (2017), "The use and misuse of models for climate policy", *Review of Environmental Economics and Policy*, vol. 11(1), pp.100-114.
[3] See Working Group I's contribution to the IPCC's Fifth Evaluation Report, 2014.

Despite such limitations, the most detailed cost-benefit analyses, such as those carried out with the PAGE model developed by Chris Hope and Cambridge University[1] and used for the Stern Report[2], or carried out using highly aggregated simple models, such as the DICE model developed by William Nordhaus[3], have played a major part in increasing awareness of the scale of the problem and the cost of inaction in definition of effective mitigation policies.

3.2. A "toolbox" to achieve decarbonization at the lowest cost

Complementing or substituting for cost-benefit analysis, a second approach consists of setting a GHG emission or concentration goal and then determining the optimal mitigation trajectory for achieving it at the least cost.

This "cost-effectiveness" approach frees economists from the need to evaluate and discount damage, insofar as the marginal damage curve is replaced by an emission target. Its relevance is based on accurate assessment of marginal abatement costs, i.e. costs of GHG emission reduction connected with the portfolio of available and foreseeable technologies.

Inset 2 – The cost-benefit approach and the cost-effectiveness approach

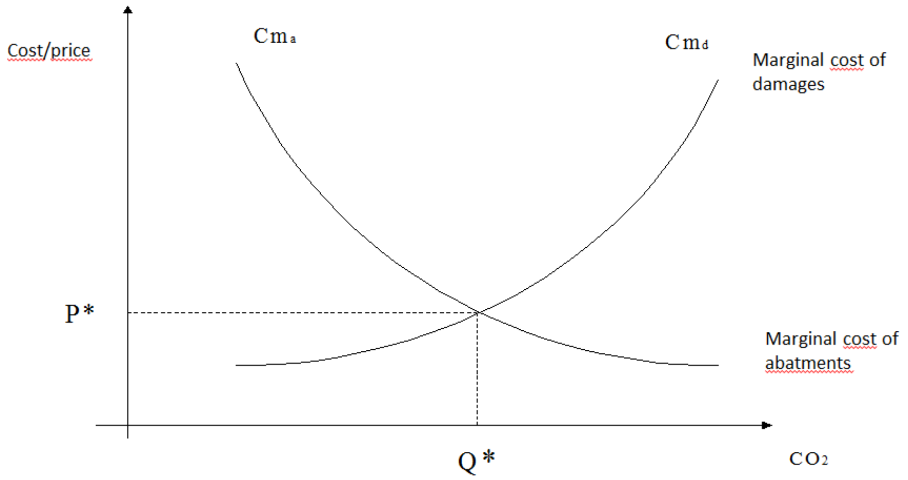
The cost-benefit approach

In this approach, effectiveness requires minimizing the overall cost of climate change – made up of emission abatement costs and residual damage costs – and deducing the optimal emission trajectory from it. The approach leads to continuous ensurance of equality between the marginal cost of damage caused by the emission of an extra metric ton of CO_2 into the atmosphere and the marginal cost of reducing CO_2 emissions.

This principle acts as the basis for cost-benefit analysis, as is illustrated by the simplified graph below, presenting the marginal damage cost curve and the marginal abatement cost curve. The higher the concentration of CO_2, the higher the cost of damage resulting from a supplementary emission; the lower the concentration of CO_2, the higher the marginal abatement cost. Equalization of marginal costs enables arrival at an optimal emission quantity Q* and the related price p*.

[1] Hope C., Anderson J. and Wenman P. (1993), "Policy analysis of the greenhouse effect: An application of the PAGE model", *Energy Policy*, 21 (3), pp.327-338.
[2] Stern N. (2006), *Stern review: The Economics of Climate Change*, United Kingdom.
[3] Nordhaus W. D. (1993), "Reflections on the economics of climate change", *Journal of Economic Perspectives*, 7(4), pp.11-25.

Figure 6 – Cost-benefit approach

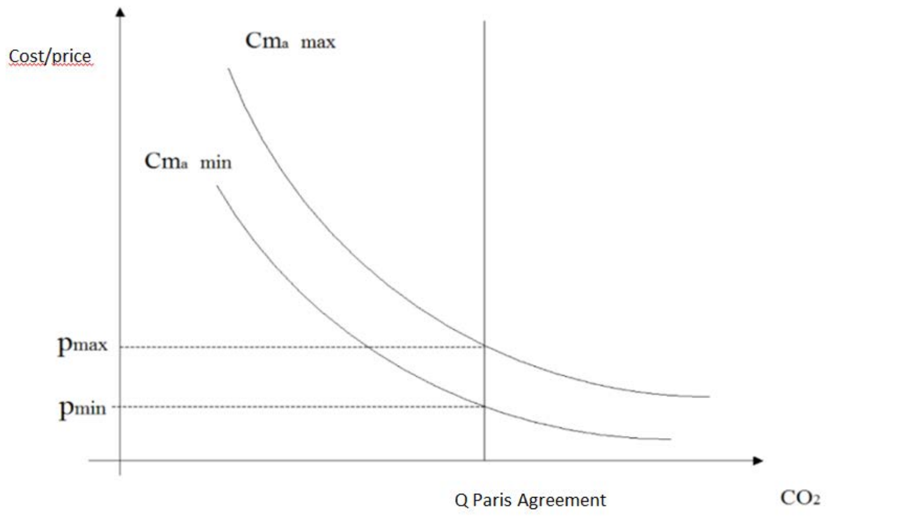


Source: France Stratégie

The cost-effectiveness approach

A second approach consists of *ex-ante* definition of an emission reduction goal falling within the reasonable ranges resulting from cost-benefit analysis. Once the goal has been defined at policy level, economic analysis can take the target into account and work on the cost-effectiveness component alone.

Figure 7 – Cost-effectiveness approach



Source: France Stratégie

Equilibrium value mainly depends on two variables:

– level of emission reduction goals. The more ambitious the goal, the higher the marginal abatement cost;

– available emission-reduction technologies. The more effective the technologies, the lower the marginal abatement costs.

Complementarity of approaches

Each approach has its own merits and drawbacks:

– The cost-benefit approach assumes that you can estimate and discount damage flows resulting from global warming, based on hypotheses of atmospheric concentration of GHGs and temperature rises. The controversies that surrounded publication of the Stern Report testify to the sensitiveness of results to the various parameters selected, in particular the calibration of the relationship between temperature and damage, and the discount rate;

– the cost-effectiveness approach requires determination of a target emission reduction scenario and simulation of the log of values in order to do so. One difficulty lies in modelling learning curves on technologies and hypotheses on future innovations.

The two approaches are complementary. The cost-benefit approach seeks to define the optimal level of greenhouse gas concentration in the atmosphere, while the cost-effectiveness approach seeks to associate a carbon value representative of marginal costs of abatement with a given goal. Finally, if the reduction level set is optimal, carbon values provided by the two approaches should converge.

In this context, cost-effectiveness analysis provides a number of structuring factors for definition of a multiyear carbon value trajectory compatible with compliance with climate goals:

– carbon value mainly depends on level of ambition, decarbonization technologies available to achieve such ambition, and level of international cooperation. All things being equal, a more demanding goal requires mobilization of more expensive technologies, which increases carbon value. Conversely, favorable expectations regarding future deployment and costs of decarbonization technologies reduce need for initial effort.

– the slope in a carbon value's trajectory reflects a rationale of optimization of an exhaustible natural resource. Logically enough, the price of an exhaustible natural resource will increase as it is consumed, due to its growing scarcity. More specifically, the owner of the resource will continue to arbitrate between leaving the resource in the subsoil or extracting it and placing revenue from it on financial markets. If he knows what reserves are available, and future prices, from the start, the owner should extract his resource so that income from the nonrenewable resource (selling price minus extraction cost) increases at the same rate as the interest rate. Similarly, in the case of carbon, the budget set is exhausted gradually, just like a reserve of raw materials. To consume this margin, it must be equivalent to emitting or abating one metric ton of CO_2 today or in a year's time; which implies that the value of a metric ton of CO_2 rises like the discount rate. This so-called "Hotelling" rule preserves the future as it ensures that the discounted value of carbon remains constant and is not overwritten by the value of time.

However, the simplest version of the Hotelling rule does not exhaust the question of choice of distribution of decarbonization efforts over time.

Economic arguments advocate a pace of growth in value slower than the discount rate and consequently, with an unchanged climate goal, for a higher initial value:

– *prudence*: like a prudent household that accumulates precautionary savings for when its future income becomes less certain, it may be socially desirable to increase initial abatement efforts in order to provide "precautionary savings" in a context of major initial uncertainty, whatever its origin, in order to absorb any bad news;

– *the innovation dynamic*: via cumulative effects (such as increasing returns to scale, learning by doing, etc.), early deployment of mature technologies enables future reduction of abatement costs.

Conversely, other arguments advocate greater progressivity of actions:

– an early action may occasion high costs due to immediate possibilities for adaptation on the part of economic actors. Existing capital and investments already made may rapidly become obsolete (with a risk of "stranded costs"). There would be consequent major job reallocations, with professional transition issues into the bargain. Substitution solutions would not be systematically available;

– control of redistributive effects between sectors and stakeholders also argues for progressivity of efforts. Account should be taken of various sectors' exposure to international competition, and certain households' special vulnerability and unequal access to decarbonized alternatives.

Although these principles help guide thought, the climate economy does not provide a "turnkey" recipe as there are still a great many uncertainties. Advances in modeling enable calibration of reasonable orders of magnitude. However, three families of parameters are currently lacking in order to come up with a sufficiently detailed representation of interactions between the economy and the fight against climate change:

- measurement of spillover effects of innovations. A coordinated global effort would foster emergence of a critical mass of green innovations and, via the effects of learning and scale, would enable each country to benefit from wider, less costly access to effective decarbonization technologies in return. However, we do not yet possess a looped representation of such spillover effects enabling calibration of the effect of global technological advance on marginal abatement costs;

- macroeconomic issues involved in climate policies, in particular when thought is given to major efforts.[1] Transition to a low-carbon economy involves a major investment effort, in support of the GDP but also in order to finance it. In order to minimize the economic and social cost of transitions, we need to quantify the economic and financial closure induced by the need "for green investments", potentially stranded costs on unamortized polluting investments, the scale of required reallocations, and measures taken to limit losses of competitiveness and/or losses of the most exposed actors' purchasing power;

- the level of the discount rate that governs the slope of carbon value's multiyear trajectory. In addition to the traditional debate on the various parameters contributing to formation of the discount rate, the question of taking account of risk and, more specifically, the correlation between economic risk and climate risk; is yet to be elucidated. The "climate beta"[2] of a program combating climate change may actually increase or reduce the discount rate, depending on the nature and sign of the correlation between economic risk and climate risk.

4. The institutional context is more promising, although there is still inadequate international cooperation

The past few years have seen construction of operational tools for combating climate change: at evaluation level, with development of several reference frameworks on carbon value, and at environmental level with introduction of price signals and regulations. These

[1] For further thought on these issues, see Tirole J. (2009), *Politique climatique, une nouvelle architecture internationale* (Climate policy, a new international architecture), Report no.87 for the *Conseil d'analyse économique* (CAE – Council of Economic Analysis), and Autume A., Schubert K. and Withagen C. (2016), "Should the carbon price be the same in all countries?", *Journal of Public Economic Theory*, 18(5), pp.709-724.

[2] The climate *beta* measures how much mitigation of climate change affects the aggregate consumption risk borne by future generations (seer Dietz S., Gollier C. and Kessler L. (2018), "The climate beta", *Journal of Environmental Economics and Management*, 87, pp.258-274 *Centre d'analyse stratégique* (CAS – Center for Strategic Analysis) (2011), *Le calcul du risque dans les investissements publics* (Calculation of the risk in public investments), Report by the Mission chaired by Christian Gollier.

operational tools were developed in a context of reinforced multilateral cooperation, with the 2015 Paris Agreement.

4.1. The 2015 Paris Agreement

Following the successive failures of various climate agreements and the failure of the "burden-sharing" initiative, which sought to share the carbon budget and efforts to be made, during the Copenhagen Conference, the Paris Agreement brought fresh impetus to the fight against climate change.[1]

In order to "hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels", the Paris Agreement enshrined the ambition to achieve net zero GHG emissions. Stakeholders agreed to comply with a net-zero emissions goal in the course of the second half of the 21st century.

Shared but differentiated responsibility and net zero GHG emissions are evoked in Article 4 of the Paris Agreement: "Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty."

With the Paris Agreement, signatory States, through "nationally determined contributions" (NDCs), undertook to define national climate strategies setting goals for reduction of their emissions or, for a number of emerging and developing countries, limiting their carbon intensity. NDCs enable measurement of States' contributions and must be revised upwards on a regular basis. Thus far, measures included in NDCs are leading to a dip in global GHG emissions but have not yet led to any overall establishment of a net zero GHG emissions trajectory and are consequently still inadequate.[2]

[1] The American withdrawal, which will take place after the mandate of the current President, has not altered signatory States' determination to combat climate change.

[2] See for example the Interdisciplinary Group's overview of national contributions, published in Benveniste H. O., Boucher C., Guivarch C., Le Treut H. and Criqui P. (2018), "Impacts of nationally determined contributions on 2030 global greenhouse gas emissions: Uncertainty analysis and distribution of emissions", *Environmental Research Letters*, 13(1), pp.1-10. According to the Climate Action Tracker Institute (consulted on 15 July 2018), the "commitments" scenario, which includes NDCs deposited between the Paris Agreement and November 2017, anticipates – by means of the many hypotheses on evolution of emissions country by country post-2030 – warming of 3.16°C or more with a 50% probability. The "commitments" scenario anticipates warming of between 2.6°C and 4°C. The average of 3.16° is close to the 3.4°C average of current trends excluding NDCs.

The Paris Agreement also encourages international cooperative approaches (Article 6.4) between countries to achieve the net zero GHG emissions goal. For advancing towards a world with net zero emissions requires international cooperation in order to facilitate transfers of low-carbon technologies, skills and funding, etc., which may encourage climate action and reduction of its cost.

4.2. Development of new reference frameworks for carbon value

Several modeling exercises have been carried out at international level, as well as at national level by various countries, in order to calculate carbon values compatible with a set climate target. Such values derive from a cost-benefit rationale – the term used here being the "social cost" of carbon – or from a cost-effectiveness rationale – in which case the term used is the "shadow price" of carbon, or value for climate action.

International carbon values: IPCC estimations

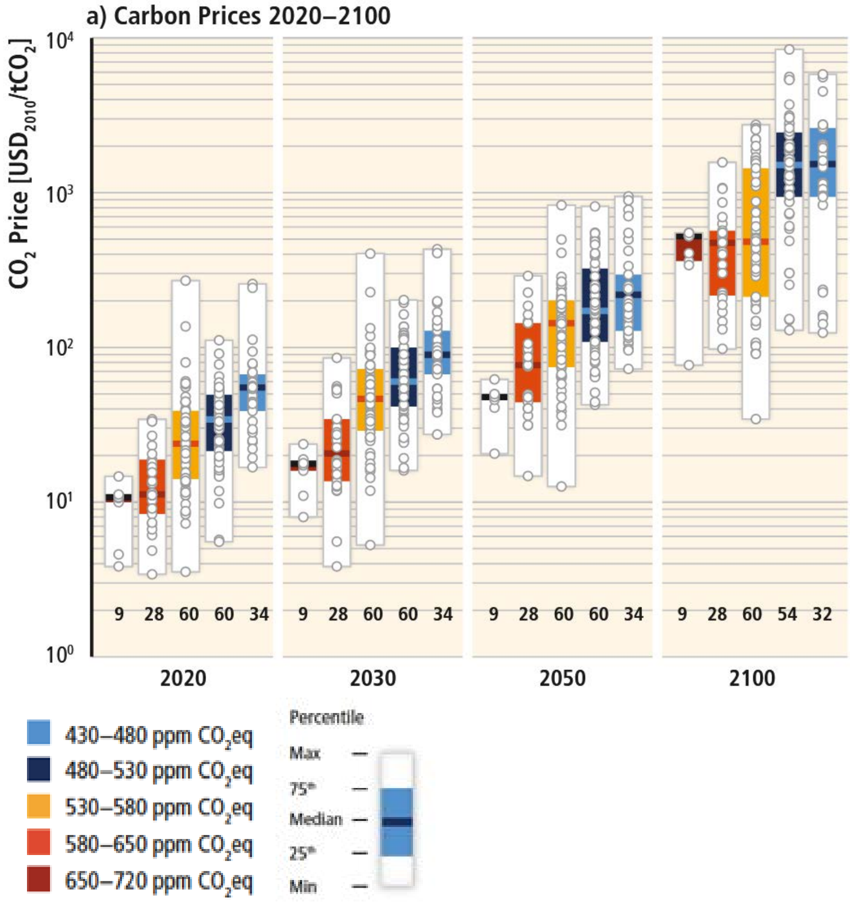
In its Fifth Report, published in 2014, the IPCC provided estimated ranges of carbon prices, understood as the aggregated costs of mitigation, depending on the size of the carbon budget set. Hence, Figure 8 shows that minimization of abatement costs results in a CO_2 price (in $\$_{2010}$) of:

- by 2030, around \$12/tCO_2eq for a 650-720ppm scenario[1] and \$100/tCO_2eq for a 430-480ppm scenario[2];
- by 2050, around \$15/tCO_2eq for a 650-720ppm scenario and \$200/tCO_2eq for a 430-480ppm scenario.

[1] 650-720ppm ("parts per million") CO_2eq correspond to an unlikely warming of 2°C and more likely than unlikely warming of 3°C above preindustrial temperatures.

[2] 430-480ppm ("parts per million") CO_2eq correspond to a more unlikely than likely warming of 1.5°C and likely warming of 2°C above preindustrial temperatures.

Figure 8 – Evolution of overall mitigation costs over time and according to emission scenario



Note: the number of scenarios considered is indicated below the bars.

Source: IPCC, Fifth Report, Working Group III, Chapter 6, p.450

The IPCC's Special Report on Global Warming of 1.5°C, published in October 2018[1] presents the results of modeling exercises simulating carbon price ranges obtained in the context of cost-effectiveness analysis. These prices, which represent marginal abatement costs, vary substantially according to models and scenarios, and, logically enough, increase with warming mitigation efforts made. The ranges obtained – which must be understood as resulting from models – are as follows:

[1] IPCC (2018),*Special Report on Global Warming of 1.5°C*.

Table 4 – Carbon prices

Warming goal	2030	2050	2070	2100
Higher-2°C	$\$_{2010}$15-220/t$CO_2$eq	$\$_{2010}$45-1,050/t$CO_2$eq	$\$_{2010}$120-1,100/t$CO_2$eq	$\$_{2010}$175-2,340/t$CO_2$eq
Below-1.5°C	$\$_{2010}$135-6,500/t$CO_2$eq	$\$_{2010}$245-14,300/t$CO_2$eq	$\$_{2010}$420-19,300/t$CO_2$eq	$\$_{2010}$690-30,100/t$CO_2$eq

Source: IPCC (2018), Special Report on Global Warming of 1.5°C, Chapter 2, p.152

Carbon values used at national level

In the United Kingdom, the former Department of Energy and Climate Change (DECC), now the Department for Business, Energy and Industrial Strategy (BEIS), published a carbon valuation in 2009, based on a cost-effectiveness approach. The long-term target set by the Climate Change Committee (CCC) is an 80% reduction in 2050, compared with 1990 (the aim being consistent with an anticipated temperature increase of 2°C), with very little risk of reaching 4 C.[1] It results in a carbon value of £$_{2007}$70/tCO_2eq in 2030 and£$_{2007}$220/tCO_2eq in 2050.

Since 2012, BEIS has published its short-term carbon value estimation for sectors covered by the European Union Emissions Trading System (EU-ETS). Calculation of carbon value is therefore based on estimations of future prices and, in its most recent publication, results in a value of £$_{2017}$4.56/tCO_2eq for 2020 and £79.43/tCO_2eq for 2030.[2]

In the United States, the Environmental Protection Agency (EPA) and other federal agencies use a social cost of CO_2 to evaluate the impacts that policies implemented have on the climate.[3] Since 2009, an Interagency Working Group (IWG) has been tasked with harmonizing this value and, since 2016, updating it in collaboration with a Committee from the National Academies of Sciences, Engineering and Medicine. The EPA adopts a cost-benefit approach, while recognizing that models used (DICE – Dynamic Integrated Climate Economy – developed by William Nordhaus, PAGE – Policy Analysis for the Greenhouse Effect – developed by Chris Hope, and FUND – Climate Framework for Uncertainty, Negotiation and Distribution – developed by Richard Tol[4]) do not take account of all the physical, ecological and economic impacts of climate change that appear in the literature, due to lack of information on the exact nature of such damage and the time it took to carry out modeling after such literature was published. Discounting plays an extremely important

[1] In October 2015, the UK Government set new goals (limiting global warming to 1.5°C and 2°C) and tasked the CCC with developing new strategies to achieve them.
[2] BEIS (2018), *Updated Short-Term Traded Carbon Values*, January.
[3] EPA (2017), *Regulatory Impact Analysis for the Review of the Clean Power Plan: Proposal*, U.S. Environmental Protection Agency.
[4] Tol R.S.J. (1996), “The Climate Framework for Uncertainty, Negotiation and Distribution”, in Miller K.A. and Parkin R.K. (eds.), *An Institute on the Economics of the Climate Resource*, University Corporation for Atmospheric Research, Boulder, pp.471-496.

role in this evaluation and values are provided for various discount rate values (5%, 3% and 2.5%). In order to pay special attention to very unlikely extreme events, the value (for a 3% discount rate) of the 95th percentile of distribution of the social value of CO_2 is also included. Values obtained are presented in the Table below.

Table 5 –Social cost of carbon, 2015-2050 (in $\$_{2007}$ per metric ton of CO_2)

	Discount rate and statistics			
Year	5% average	3% average	2.5% average	High impact (3% 95th Pct)
2015	$11	$36	$56	$105
2020	$12	$42	$62	$123
2025	$14	$46	$68	$138
2030	$16	$50	$73	$152
2035	$18	$55	$78	$168
2040	$21	$60	$84	$183
2045	$23	$64	$89	$197
2050	$26	$69	$95	$212

Source: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis, Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, August 2016

Since 2017, calculation is carried out for two discount rates, 3% and a new, very high value of 7%. In addition, only national damage is taken into account, rather than global damage as has been the case up to now. It therefore results in a much lower social cost of carbon calculated for the United States alone, of between $\$_{2007}1$ (for a 7% discount rate) to $\$_{2007}5.6$ (for a 3% discount rate) for 2020.[1]

In Germany, a study by the German Environment Agency (UBA) uses a cost-benefit approach to provide an evaluation of social costs of damage. Recommended values are as follows.[2]

Table 6 – Social cost of carbon (€$_{2016}$/tCO_2eq)

	2016	2030	2050
1% pure rate of time preference	180	205	240
0% pure rate of time preference	640	670	730

Source: Matthey A. and Bünger B. (2018), Methodological Convention 3.0 for the Assessment of Environmental Costs, Costs Rates, German Environment Agency.

[1] See EPA, Table 3-7 p.44 (2017), making $\$_{2011}6$ for a 3% discount rate and $\$_{2011}1$ for a 7% discount rate, which we have converted into $\$_{2007}$.
[2] Matthey A. and Bünger B. (2018), *Methodological Convention 3.0 for the Assessment of Environmental Costs, Costs Rates*, German Environment Agency.

4.3. Implementation of carbon pricing tools

According to the survey carried out by the World Bank, 46 countries and 25 territorial authorities have introduced carbon pricing.[1] Such pricing now covers 20% of global greenhouse gas emissions, leaving 80% of emissions free of any pricing system.

- Most current carbon prices are significantly lower than the ranges defined by the Stern-Stiglitz High-Level Commission on Carbon Prices. The Stern-Stiglitz Report (2017) recommends carbon pricing of between \$40 and \$80/tCO_2 by 2020 and between \$50 and \$100/tCO_2 by 2030.

- The second edition of the OECD study explains that 42 OECD and G20 countries accounting for 80% of global carbon emissions price carbon emissions attributable to energy use.[2] The "effective carbon rate" calculated corresponds to the sum of three components: taxes specifically targeting fossil fuels, taxes on carbon, and emissions trading prices. If we use the €30 per metric ton of CO_2 reference, the pricing deficit for all 42 countries falls from 83% in 2012 to 76.5% in 2018.[3]

4.4. Reference values for carbon revised upwards overall at global level

There are now a large number of studies on carbon valuation available, summarized and aggregated in the Table below. Two main trends are to be seen in recent evaluations:

– valuation exercises are increasingly based on cost-effectiveness approaches: this is due to methodological difficulties inherent in the cost-benefit approach and the need to take account of more demanding goals over shorter time horizons;

– exercises resulting in higher carbon values as time goes by, reflecting the accumulated delay and growing need for early action in the face of risks of serious irreversible damage.

[1] The World Bank only covers pricing in the survey and leaves aside the regulatory instruments that are nonetheless necessary to any climate policy.

[2] OECD (2018), *Effective Carbon Rates 2018: Pricing Carbon Emissions Through Taxes and Emissions Trading*, OECD Publishing, Paris.

[3] Two reference levels are considered: €30/tCO_2, which is a low estimation of the costs of carbon today; and €60/tCO_2, which is an intermediate estimation of such costs in 2020 or a low estimation for 2030.

Table 7 – Summary table of prices or values (in €$_{2017}$/tCO_2eq)

	Target	Geographical area	2010	2015	2020	2030	2050
Quinet Report (2008), *La valeur tutélaire du carbone*	Factor 4	France			**€61**	**€109**	**€163-380**
Carbon Valuation in UK Policy Appraisal: A Revised Approach, DECC (2009)	2°C	United Kingdom			ETS Sectors**:** **€29** Non-ETS sectors: **€70**	**€82**	**€257**
German Environment Agency (2012)		Germany		**€640**			
Fifth Report by the Intergovernmental Panel on Climate Change (IPCC) (2014)	430-480ppm CO_2eq (1.5°C more unlikely than likely, 2°C likely) 650-720ppm CO_2eq (2°C unlikely, 3°C more likely than unlikely)	World				650-720ppm **€11** 430-480ppm **€95**[1]	650-720ppm **€14** 430-480ppm **€190**
Norwegian Public Roads Administration (Smith and Braathen, 2015)		Norway		**€23**		**€88**	
Environmental Protection Agency, Interagency Working Group (2016)	Cost-benefit analysis	United States		**€10-€100**		**€15-144**	**€25-201**
Stern-Stiglitz Report by the High-Level Commission on Carbon Prices (2017)	2°C	World			**€38-76**	**€48-95**	
Guivarch and Rogelj, *Carbon price variations in 2°C scenarios explored*, work document (2017)	2°C	World				**€14-342**	**€43-949**
Rogelj *et al.*, *Scenarios towards limiting global mean temperature increase below 1.5°C*, Nature Climate Change (2018)	1.5°C	World	**€47-€157**			**€126-416**	**€334-1,102**
Special Report on Global Warming of 1.5°C, IPCC (2018)	Below 1.5°C Higher 2°C	World				**€128-5,217** **€10-190**	**€232-12,330** **€43-911**

Note: conversion of foreign currency from years other than 2017 into €$_{2017}$ was carried out via conversion into 2017 foreign currency and then into €$_{2017}$. Data used was consulted on 8 October 2018.

Source: France Stratégie

[1] The IPCC highlights price corridors rather than an average level.

CHAPTER 2

THE COST-EFFECTIVENESS APPROACH

In 2008, special socioeconomic evaluation work was carried out in France on valuation of climate action over the long term. Ten years on, it requires updating: climate policy goals have become more ambitious since then, there are more precised perspectives for international cooperation, and increased technological opportunities.

In order to carry out an update, this Report relies on a comprehensive approach which, in addition to available theoretical and empirical developments, incorporates original modeling work and foresight analysis of available decarbonization technologies.

This chapter presents the various stages in the approach: formulation of the French goal on which the cost-effectiveness approach is based (Section 1), foresight tools (Section 2), specifications (Section 3) and the reference scenario (Section 4).

1. The approach is based on France's climate commitments

In practice, the term "carbon value" may refer to several rationales. The first consists of calculating the social cost of GHG emissions, i.e. the cost connected with emission of one metric ton of CO_2 equivalent. This rationale, inspired by Arthur Pigou's key work on externalities and given formal expression in the Stern Report (2006), leads to calculation of the damage suffered by humankind due to the increase in GHG concentrations, independent of an emission's country of origin and location of damage.

As highlighted in Chapter 1, a great many uncertainties surround the monetary evaluation of damage necessary to cost-benefit analysis. Without disputing the legitimacy of the cost-benefit approach, its implementation in the national context comes up against two difficulties of principle:

- firstly, uncertainties on valuation of damage are too great to develop a reference designed to guide short- and medium-term political action;
- secondly, with regard to global externalities, it is difficult to restrict a cost-benefit assessment to the borders of a given territory.

This Commission's approach is therefore based on a complementary rationale. It does not consist of evaluating the social cost of damage produced by emission of one metric ton of CO_2eq on French territory, but rather of identifying a carbon value consistent with the goal of net zero GHG emissions by 2050.

In order to implement this cost-effectiveness approach, the Commission has endeavored to provide an accurate picture of the scope of French commitments, so as to come up with an appropriate multiyear shadow value trajectory.

1.1. The "Net-Zero Emissions" goal

The climate externality is a stock externality, connected with the level of GHG concentration in the atmosphere. This is why its consideration is expressed in carbon budgets, in other words, in upper limits of CO_2eq emissions accumulated over time and not to be exceeded if we are to keep temperature rises below a certain threshold.

The rapid exhaustion of global and French carbon budgets has now led to complementing stock goals – prudent management of a multiyear carbon budget – with a flow goal: a "net-zero" goal of GHG emissions connected with human activities, as residual gross emissions are likely to be absorbed by anthropogenic carbon sinks such as forests and grasslands, and, over the longer term, by technological carbon sequestration systems.

- This is what the 2015 Paris Agreement does, basing its approach on the work carried out by the IPCC. In its Fifth Report, published in 2013 and 2014, the IPCC showed that the global carbon budget enabling limitation of the temperature rise to 2°C or, yet better, to below 2°C, would be exhausted by the middle of the century if there was no reduction in emissions.
- The IPCC's 1.5°C Special Report published in October 2018 highlights the pertinence of the "net-zero emissions" anchorage as a logical consequence of carbon budget exhaustion.
- What applies at global level also applies in France, which accounts for around 1% of global emissions. The French goal of achieving net zero GHG emissions by the middle of the century is in line with the global goal of keeping warming below 2°C or even 1.5°C.

De facto, France's accumulated emission flows up to the "net-zero emissions" goal in 2050 is leading to carbon budget consumption consistent with our share in global emissions.

1.2. By 2050

France has set itself the goal of decarbonization by 2050, without waiting until the second half of the 21st century. Its goal is consistent with the Paris Agreement, which calls upon developed countries to commit to rapid efforts. It incorporates the need for early action to prevent risks of serious irreversible damage.

The 2050 goal should be understood as a goal that must be supported over the long term, throughout the second half of the century. In other words, the final goal is not simply to target 2050 itself, but rather to keep gross emission flows compatible with sink absorption capacities over the long term.

In this respect, the French goal remains cautious as regards size of sinks and *a fortiori* France's potential recourse to negative emission solutions by geological storage of carbon[1], which would help smoothen efforts and allow short-term overshooting of the emission ceiling set.

1.3. Decoupling emissions and human activities

France aims to map out a path enabling successful transition to net zero GHG emissions without negatively impacting economic activity and living standards. Seeking to achieve an emissions goal in 2050 through compression of the GDP would be costly in terms of jobs and purchasing power and inefficient as far as climate is concerned – with reduction produced by "carbon leakage", i.e. relocations of production to countries with lower climate ambitions, due to loss of competitiveness.

The approach meets two requirements:

- decarbonizing by reducing GHG emissions per production unit rather than reducing production itself;
- reducing emissions per production unit by investing in energy efficiency and decarbonized technologies, not by relocating carbonized production units.

Initial decoupling is already underway: GHG emissions have decreased by 16% since 1990, while the GDP has increased by 47%. Even though a proportion of this decoupling is the consequence of French deindustrialization, capital "greening" actions are starting to pay off. The challenge is to increase decoupling over the next three decades, which will require major investment efforts by constitution of "green" productive capital.

[1] For example, with energy use of renewable biomass, accompanied by geological storage of carbon emitted. The IPCC's reports start to resort to this solution in 2050 and beyond in 2°C scenarios, and make wide use of it in 1.5° scenarios (*Special Report on Global Warming of 1.5 °C*, October 2018).

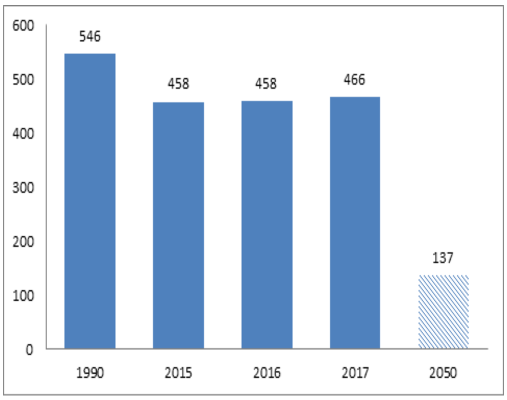
Inset 3 – French commitments, from Factor 4 to climate neutrality

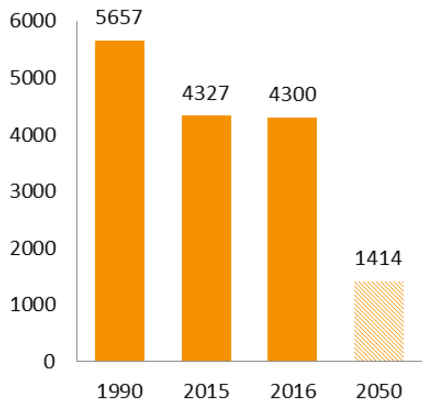
Factor 4

The term “Factor 4” refers to the Head of State’s commitment in 2003 to divide national greenhouse gas emissions by 4 by 2050 compared with 1990. The Grenelle de l’environnement confirmed this goal in 2007.

Between 1990 and 2015, France reduced its GHG emissions by 15% and the EU by almost a quarter. Over the same period, France’s GDP grew by 47%. Of course, this must be seen in the light of the deindustrialization phenomenon and the increase in fossil fuel prices, but it also testifies to initial success in the fight against climate change.

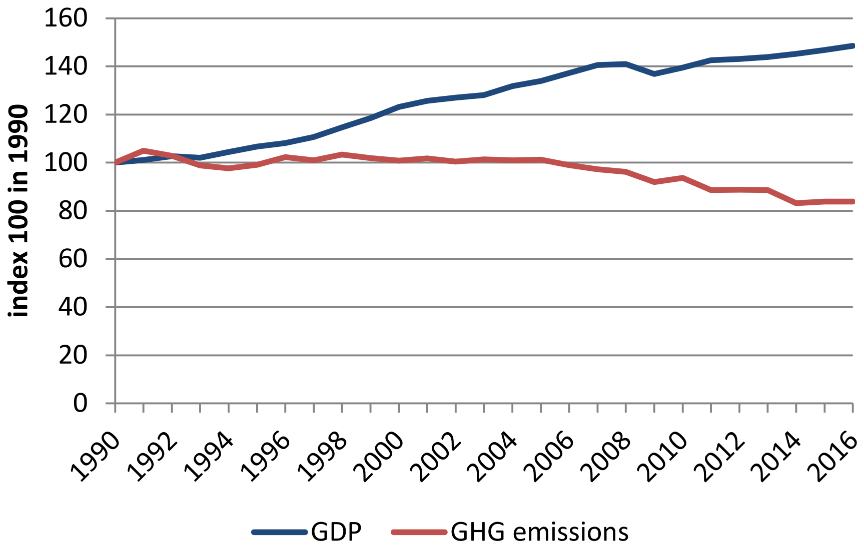
Figure 9 – GHG emissions recorded and Factor 4 in France (in blue) and in the EU (in orange) in millions of metric tons of CO_2 equivalent ($MtCO_2eq$) apart from land use, land-use change and forestry (LULUCF)





Sources: CITEPA (Technical Interprofessional Centre for *Atmospheric Pollution Studies), 2018 indicators 2018, and European Environment Agency (2018), Annual European Union Greenhouse Gas Inventory 1990-2016 and Inventory Report, Submission to the UNFCCC Secretariat, 27 May*

Figure 10 – Evolution of GHG emissions and the GDP in France (base 100 in 1990)



Sources: World Bank (GDP in 2010 constant dollars); Emissions Greenhouse Gas Inventory – Detailed data by Party – United Nations Framework Convention on Climate Change

However, as our carbon budget is rapidly running out, the French goal was revised in 2017, switching from a "Factor 4" rationale to a rationale of net zero GHG emissions by 2050.

Climate neutrality

The 2017 Climate Plan, adopted in the wake of the Paris Agreement, makes the goal of net zero GHG emissions by 2050 explicit. So far, a number of developed and developing countries have committed to net zero GHG emissions by 2050 at the latest[1].

Climate neutrality is a comprehensive approach. It takes all GHGs into account and applies to all sectors.

It is a "net" approach to carbon sinks. A sector whose emissions are lower than its sequestration and capture capacities, as is now and will continue to be the case for the forestry sector, could eventually compensate other sectors' non-abated emissions. Climate neutrality prioritizes reduction of greenhouse gas emissions at source insofar as the potential for increase in the sizes of carbon sinks, natural

[1] However, there are differences in ways of achieving net zero GHG emissions. France anticipates a significant contribution from its carbon sinks, forest and agricultural sinks in particular, whereas Norway does not exclude the possibility of purchasing carbon credits. Other countries that have announced a neutrality goal include Sweden, Portugal, the Marshall Islands and Spain.

(forests, wetlands and land use) and artificial (CCS and CCU[1]) alike, remains limited up to 2050.

Finally, net zero GHG emissions is a national “production” approach rather than a “consumption” approach or carbon footprint that takes account of the carbon content of imports. Imported emissions are anyway difficult to evaluate in a context where global value chains are breaking apart.

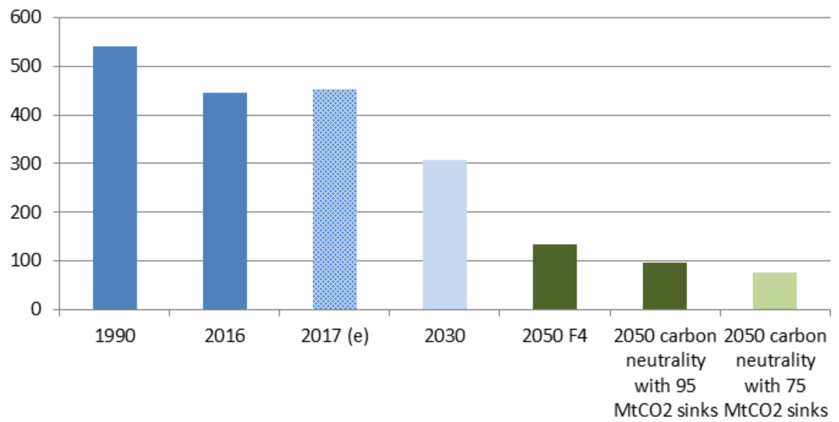
From one ambition to another

Dividing 1990 emission levels by 4 by 2050 – a 75% reduction – leaves 25% residual emissions, which will have to be reduced or sequestered in order to achieve net zero GHG emissions.

Sinks connected with land use, land-use change and forestry (LULUCF) were estimated at 40 $MtCO_2eq$ in 2016 (as against 29 $MtCO_2eq$ in 1990). The hypothesis adopted is that their sequestration capacity may reach 75 to 95 $MtCO_2eq$ in 2050. Natural sinks would be complemented by 20 $MtCO_2eq$ of sequestration capacities coming from the expected development of carbon capture and storage technology. Consequently, French carbon sinks, including CCS, would be able to absorb 95 $MtCO_2eq$ to 115 $MtCO_2eq$ in 2050.

All in all, the net zero GHG emissions scenario represents a *Factor 6* or *7* depending on sinks’ real potentials.

Figure 11 – French emissions and emissions targets



Interpretation: the “95 scenario” refers to an agricultural and forest sink of 95 $MtCO_2eq$ to which 20 $MtCO_2eq$ of CCS is added. In each scenario, the CCS hypothesis selected is 20 $MtCO_2eq$.

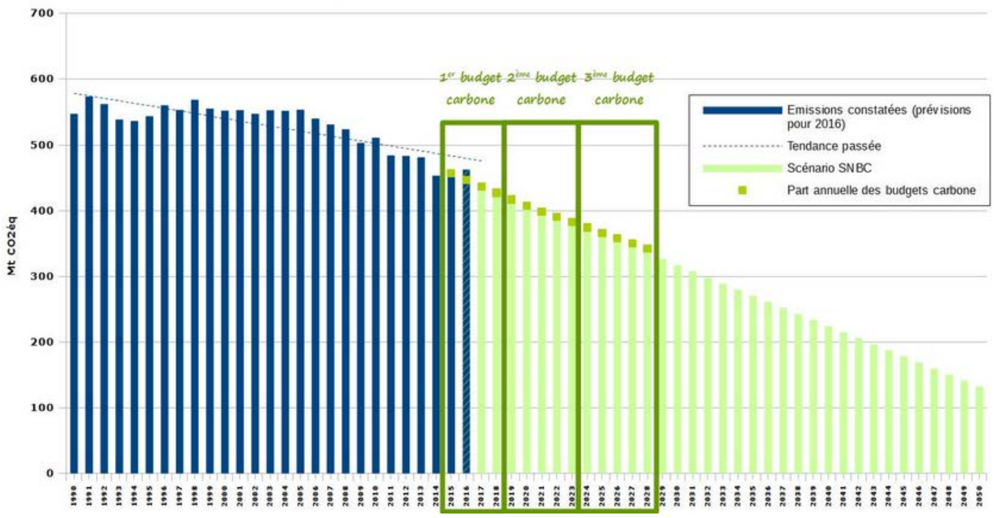
Source: CITEPA (2018), National inventory report for France under the UN Framework Convention on Climate Change and the Kyoto protocol, Appendix 7, March

[1] This is a climate change mitigation technology that captures CO_2 and injects it deep into the subsoil; CCU stands for Carbon Capture and Utilization. CCU is a climate change mitigation technique that aims to capture and then use CO_2 in various industrial processes.

French carbon budgets

French carbon budgets[1], determined in the context of the *Stratégie Nationale Bas Carbone* (SNBC – National Low-Carbon Strategy), are GHG emission ceilings set for successive four- or five-year periods. They should therefore not be confused with those estimated by the IPCC. These ceilings define a specific trajectory for reduction of the country's emissions in order to achieve medium- and long-term targets. They determine the GHG emission limits that France has set itself. Three initial carbon budgets were defined in 2015, covering the periods 2015-2018, 2019-2023 and 2024-2028. They are organized by major field of activity, [2] on an indicative basis. The first carbon budget, set at 442 $MtCO_2eq$, is organized in the following indicative fashion: 127 $MtCO_2eq$ for transport, 76 $MtCO_2eq$ for buildings, 86 $MtCO_2eq$ for agriculture, 80 $MtCO_2eq$ for industry, 55 $MtCO_2eq$ for energy production and 18 $MtCO_2eq$ for waste.

Figure 12 – Evolution of GHG emissions in France and the first SNBC's goals



Source: *www.ecologique-solidaire.gouv.fr/suivi-strategie-nationale-bas-carbone*

2. The Commission's approach draws on a number of foresight instruments

It has to be said that no "turnkey" simulation tool exists that mechanically generates a multiyear shadow carbon price trajectory. The Commission puts forward a reasonable

[1] Few countries have set themselves carbon budgets. The United Kingdom was the pioneer in this respect.
[2] Transport, residential/tertiary buildings, industry, agriculture, energy production and waste.

estimation based on the latest findings, incorporating four key ingredients into an overall argument:

- **First ingredient: simulation and foresight exercises carried out using various models** enabling objective assessment of shadow carbon price depending on given ambition levels, economic context, available technologies and sink potentials. This approach consists in using paradigms specific to each model to evaluate a multiyear carbon value trajectory that keeps us on a path to emission reduction in line with the French goal. In formal terms, sectoral macroeconomic models model price increases relating to carbonized options and show how different sectors adapt to the increase and invest in decarbonization. Techno-economic models utilize detailed descriptions of technologies to evaluate the cost of deploying necessary technologies.

- **Second ingredient: technological and techno-economic forecast exercises**, such as those carried out at global level by the International Energy Agency (IEA) and at French level during preparation of the National Low-Carbon Strategy (SNBC), enabling assessment of the costs of various decarbonization technologies – and consequently prices for switching from carbonized solutions to decarbonized solutions. The more ambitious the goal, the more need there is to mobilize an extensive technology portfolio which also includes technologies that are not yet mature but will be necessary to achieve the goal. Such technological foresight exercises are surrounded by uncertainties that increase as the time horizon lengthens. In addition, this approach does not enable account to be taken of the economic impacts of these technologies.

- **Third ingredient: economic and social literature devoted to the central question of decarbonization burden-sharing over time**. In its basic version, management of a “carbon budget” leads to recommendation of a discounted carbon value based on the maximum emission abatement cost and which remains constant over time, which expresses a lack of difference between emitting today and emitting tomorrow once the emission ceiling is complied with. In theory, this rule, known as the Hotelling rule, guarantees that the value of a limited resource does not go down over time due to discounting (as it increases at the discount rate) and that burden-sharing over time is effective. De facto, with perfect information available, this rule would enable optimization of deployment of technologies, sequencing of efforts and the emission reduction trajectory.

- **Fourth ingredient: exchanges with stakeholders**, including researchers, economists, representatives of union and employers’ organizations, various professional federations, and representatives of administrations concerned, in order to assess the pertinence of the trajectory and implementation conditions.

3. Specifications are based on a series of reasonable hypotheses

3.1. The characteristics of climate neutrality taken into account by the Commission

The Commission defined specifications in line with the goal of "net-zero emissions" of greenhouse gases on French territory by 2050 as required by the Climate Plan of July 2017:

- emissions considered are all emissions taking place on French territory, net of sinks available on the national territory. In concrete terms, the goal includes emissions in Metropolitan and Overseas France but excludes emissions connected with manufacture abroad of products imported into France. By extension, the goal excludes any transfer of climate effort to other countries, for example by "compensating" emissions on national territory by carbon sinks abroad. More generally, the report does not postulate implementation of an integrated framework – global carbon market or global carbon price – that would enable optimization of global abatement costs and which, in doing so, would contribute to reducing the carbon value required in France;
- the goal bears on all sectors, without *ex ante* integration of sectoral goals, as one metric ton of carbon emitted or avoided is the same whatever its sector of origin. This choice of method enables determination of the least expensive strategy for achieving a given emission reduction goal, by mobilizing the least expensive sources of abatement without any sectoral preconceptions;
- the goal covers all greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorine compounds (HFC, PFC, SF_6 and NF_3). Definition of a shadow price for carbon in this context therefore involves reasoning in carbon equivalents for these GHGs. Carbon equivalents are defined on the basis of the global warming potential (GWP) of the gas under consideration compared with that of CO_2 (see Table 1).

The value for climate action as evaluated by the Commission is a gross valuation that does not take account of any eventual co-benefits relating to reduction of GHG emissions. For example, air quality improvement following the decrease in emissions of fine particles brought about by a reduction of internal combustion vehicles' share in road transport is not valued in the approach adopted (see Inset 4).

Inset 4 – Co-benefits

Climate policies may have positive effects in addition to limiting global warming, known as co-benefits[1]. They are defined as collateral advantages – including in economic, social, environmental, health, progress and development terms – of implementation of mitigation policies.

The main co-benefits identified in the literature are:

– better protection of ecosystems and biodiversity;

– improvement of health connected with reduction of local pollutions and better diet;

– greater security of energy provision;

– reduction of inequalities thanks to better allocation of resources;

– the effects of technological externalities.

At global level, the main co-benefit relating to the fight against climate change is the improvement of air quality enabled by reduction of coal production. This co-benefit does not concern France, and the decision has been made not to take co-benefits into consideration in light of this key fact, and a number of other reasons:

– *they are difficult to quantify in monetary terms*. Some co-benefits can be directly expressed financially, while others can only be approximated or even not be quantified at all or expressed by a monetary equivalent;

– *There is no general rule enabling their integration into carbon value.* How a co-benefit is taken into account depends on its nature. Some can be explicitly separated from the effects of GHG emissions and covered by other policies (regulations on vehicles' exhaust pipes, for example), while others cannot be separated from policies combating global warming;

– co-damage must also be considered. Even though there are more co-benefits than there is co-damage, you cannot record the former without the latter (wind farms have an impact on landscape, electric battery production generates pollution, etc.).

[1] For more exact understanding of co-benefits, refer to Cassen C., Guivarch C. and Lecocq F. (2015), "*Les cobénéfices des politiques climatiques: un concept opérant pour les négociations climat?*", *Natures Sciences Sociétés*, supplement (Supp. 3), pp.41-51. doi:10.1051/nss/2015017.

3.2. The simulation's time horizon

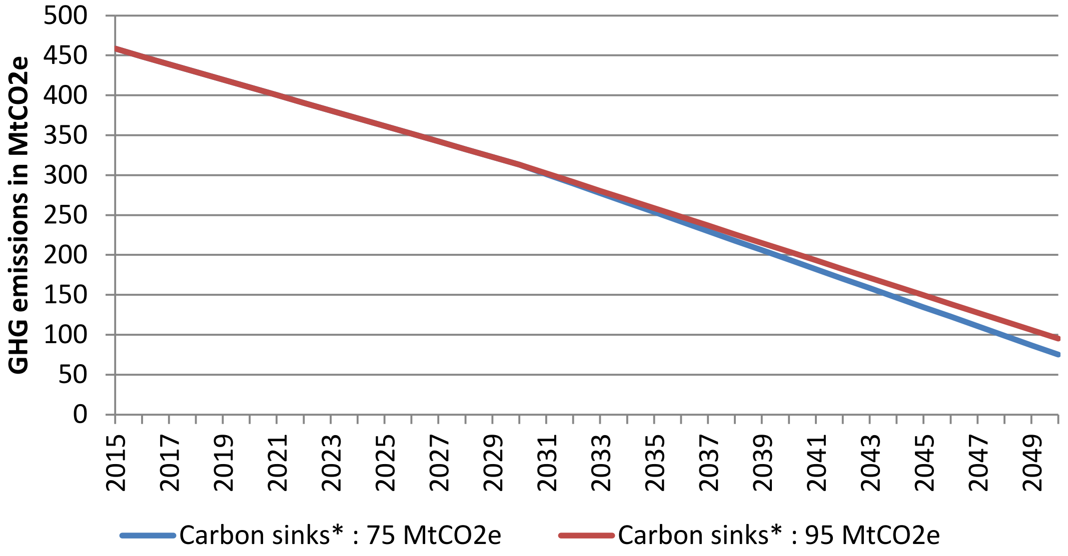
In order to achieve a net-zero emissions goal by 2050, the Commission has set itself a smoothed emission reduction trajectory with an intermediate point in 2030 (-43% of gross emissions compared with emissions in 1990, consistent with the official French goal) (see Figure 13).

Smoothing out the GHG emission trajectory takes account of:

- A French share in the global carbon budget enabling global warming to be kept below 2°C, and possibly even 1.5°C, consistent with the share of France's GHG emissions in global emissions.
- The fact that decarbonization action must be progressive in order to minimize adjustment costs[1], which could well be multiple:
  - time taken for installation of capital;
  - effects of saturation and bottlenecks: when demand for a good or a service (electric vehicles, for example) increases sharply, there may be short-term difficulties in meeting it;
  - vocational training and retraining needs: widespread launches of building renovation projects involve training and supply-structuring actions;
  - stranded costs: the change in scale in emission reduction involves shortening the lifespan of certain existing facilities. For example, thermal power plants will have to be closed before the end of their productive lives, which will require decommissioning of such units and more rapid investment to replace them.

[1] The techno-economic and macroeconomic models utilized in the context of this Commission do not enable optimization of a GHG emission reduction trajectory and require its *ex ante* definition. However, the theoretical model presented in the Report's Complements show that, when adjustment cost is taken into account, the optimal emissions trajectory is in the form of an S-curve relatively close to a linear reduction (see Complement 1, "*Un modèle avec capital d'abattement pour l'évaluation du carbone*" by Boris Le Hir, Aude Pommeret and Mathilde Salin).

Figure 13 – Target trajectory of emission flows



** Carbon sinks associated with LULUCF*
Source: France Stratégie, authors' calculations

The goal of net-zero GHG emissions in France, presented in the Climate Plan, targets 2050 but will have to be maintained over the long term. This has two major consequences:

- full account must be taken of the benefits provided by a technology throughout its lifespan in order to assess its pertinence. Hence, identification of technologies to deploy by 2050 must incorporate their benefit in terms of metric tons of CO_2eq avoided that they may procure after 2050 when their lifespans are long enough. If we do not take account of the residual value of technologies after 2050, we run the risk of regarding various technologies useful to achievement of the 2050 goal as non-viable, or of overestimating carbon value in 2050;
- secondly, it is likely that constraints on maintaining net zero GHG emissions will evolve. In particular, carbon sinks associated with land use, land-use change and forestry (LULUCF sinks) and CO_2eq capture and storage will not necessarily provide the same margins after 2050, which may lead to modification of target gross emissions. It is therefore probable that maintenance of net zero GHG emissions after 2050 will require prior deployment of more ambitious technological changes than those simply enabling compliance with the 2050 target.

4. Calculation of a carbon value trajectory is based on original modeling work

4.1. General categories of models used

Carrying out a series of simulations is essential for the determination of a carbon value trajectory. Three major categories of models can be used to construct a carbon value:

Integrated assessment models (IAMs) represent the full cycle of interactions between human activities and the environmental sphere (blue circle in Figure 14) in a single numerical system. Design of such models mobilizes a wide range of disciplinary fields (climatology, geophysics, biology, economics, engineering, etc.). The main relationships described are those that link economic activities and anthropogenic greenhouse gas emissions in climate systems and the impacts of climate change on socioeconomic systems. Such models enable definition of the types and proportions of desirable actions to mitigate global warming, and therefore follow a cost-benefit rationale as described in Chapter 1 of this Report. Nordhaus' DICE model[1] is an emblematic example of an IAM.

The cost-effectiveness approach adopted here does not require modeling of the environmental sphere as the emission reduction goal is regarded as fixed. Only the system's technological and macroeconomic components, along with GHG emission flows, need to be modeled (part surrounded by the green dotted-line circle in Figure 14).

Techno-economic models provide a detailed description of one or more sectors' production technologies. Most of these so-called "engineer's" models concentrate on one specific field. For example, the TIMES and POLES models utilized by the Commission aim to provide the most comprehensive representation of the energy system, which includes production technologies and technologies connected with energy use, and enable consistent management of their potential substitutions. Hence, they can provide detailed information on the energy offer, the energy mix and technologies utilized, emissions, etc. The main purpose of such models is to define the energy system's structure depending on a given macroeconomic context, availability of resources, public policies, and detailed information on available technologies. These models are not "looped" economically and consequently cannot take account of the effects of macroeconomic or intersectoral retroactions.

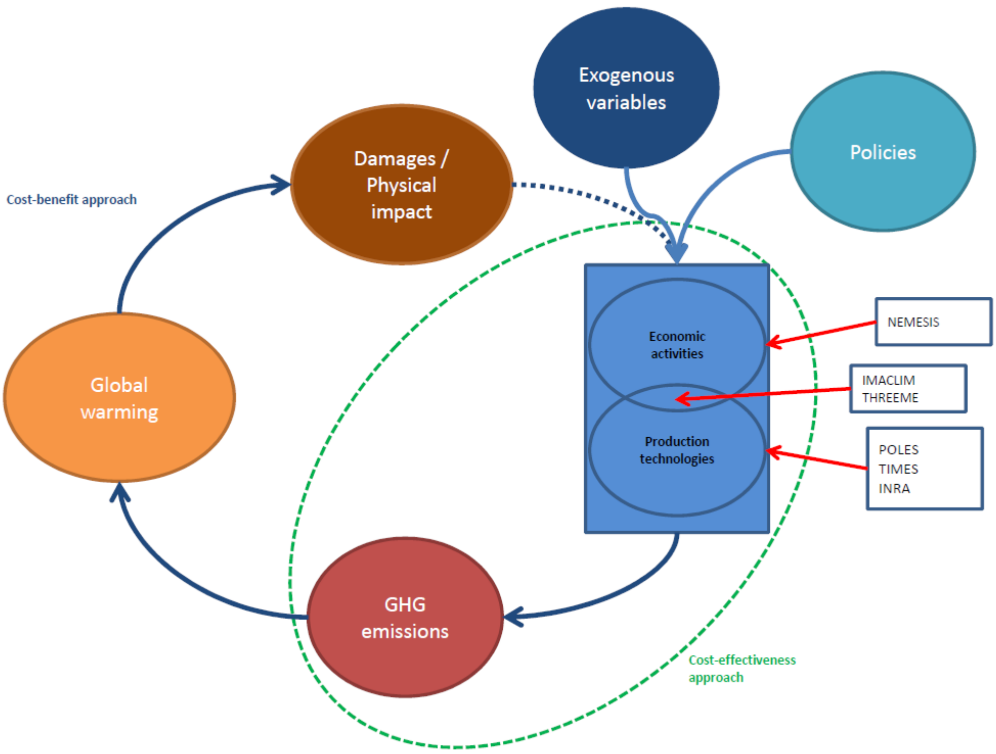
Conversely, **macroeconomic models** provide information on an environmental policy's effects on the economy, while giving a more summary description of the technologies involved. These models enable endogenization of the macroeconomic effects of retroaction, as well as substitution mechanisms between production factors and consumer goods. Hence, they highlight the impact that such a goal might have on

[1] Nordhaus W. (2017), "DICE/RICE models - William Nordhaus - Yale Economics".

competitiveness, production and employment. Among the models utilized by the Commission, IMACLIM, ThreeME and NEMESIS are in this category, with the first two integrating some techno-economic aspects.

Inset 5 below gives a brief individual presentation of models utilized by the Commission; they are described in greater detail in the Complements to this Report.

Figure 14 – Diagram of modeling



Source: France Stratégie, authors' representation

Inset 5 – Presentation of models utilized[1]

Techno-economic models

TIMES-France[2] is a demand-driven intertemporal optimization model of the French energy system: based on a representation of subsectors of the whole energy sector, its aim is to determine a choice of technologies that satisfies demand while minimizing the French energy system's total discounted cost over a given time period, and taking account of reduction of greenhouse gas emissions in the energy system. In this model, the total cost integrates

[1] The five models utilized in the context of the Commission are described in greater detail in the Complements to this Report; here, we are only covering their general characteristics.

[2] Other versions exist with different geographical coverages, including a global version.

investment costs, running, operational and maintenance costs, and the value of equipment buyback at the end of the model's time horizon.

POLES-Enerdata[1] is an energy system simulation model. It is a recursive dynamic model that calculates its variables year by year with adaptive expectations. It covers a wide geographical field as it is a regionalized global model. It divides the world into 54 individually modeled zones – including the 28 EU countries and four neighboring countries (Norway, Iceland, Switzerland and Turkey) – and 12 regions representing other countries that are not modeled individually. POLES is also capable of endogenous calculation of energy demand, supply and prices on various regional markets, as well as sectoral emissions of six greenhouse gases.

Macroeconomic models

IMACLIM-R France[2] is a dynamic recursive computable general equilibrium (CGE) model that represents the French economy in fifteen economic sectors. It also includes endogenous techno-economic modules to represent evolution of the electricity mix, stocks of residential buildings and fleets of vehicles (and therefore mirrors some of the characteristics of techno-economic models as regards technological details and induced technical progress). Expectations are in general adaptive except on the carbon value trajectory, for which expectations may be assumed to be either adaptive/myopic (agents extrapolate future and current values) or perfect.

ThreeME is a macroeconomic multisectoral computable general equilibrium model of Neo-Keynesian inspiration, designed to evaluate macroeconomic impacts of public policies, energy and environmental policies in particular. It describes the French economy in 37 sectors, including 17 energy sectors, and also integrates techno-economic aspects. It is a dynamic recursive model with adaptive expectations. Energy consumption partly depends on the evolution of housing, vehicle and capital-goods stocks and their characteristics.

NEMESIS is a system of sectoral econometric models developed for each of the European Union's 28 Member States. It is intended for quantitative forecasting and analysis of economic policies, so-called "structural" policies in particular, which have medium- and long-term effects (research, environment, energy, taxation, budget, etc.). It disaggregates the economy into thirty production sectors. It is again a dynamic recursive model (resolution by annual steps) with adaptive expectations.

[1] Three versions of the POLES model exist: POLES-Enerdata, POLES-JRC (European Commission) and POLES-GAEL (University of Grenoble). The model utilized by this Commission is the POLES-Enerdata model, which, for simplicity's sake, will be referred to as POLES in the rest of the document.
[2] A global version exists, which describes the global economy in twelve regions, and other country versions (including Brazil).

4.2. Models that need to be completed in order to cover all GHGs

For the most part, the models that have just been described only take account of energy-induced CO_2 emissions. These only account for 70% of total GHG emissions, yet the net zero GHG emissions goal concerns all GHGs. Three "blind spots" in the models must therefore be covered: non-energy agricultural emissions, emissions from industrial processes, and emissions connected with waste treatment. As there are only limited possibilities for modeling the last two types of emissions[1], hypotheses on possible reductions have been developed without using models. As regards non-energy agricultural emissions, reduction possibilities have been established on the basis of a techno-economic model developed by INRA. Figures on emission reductions in the various sectors are presented in the next chapter.

4.3. The general principles of simulation and foresight exercises

Models' inputs and outputs

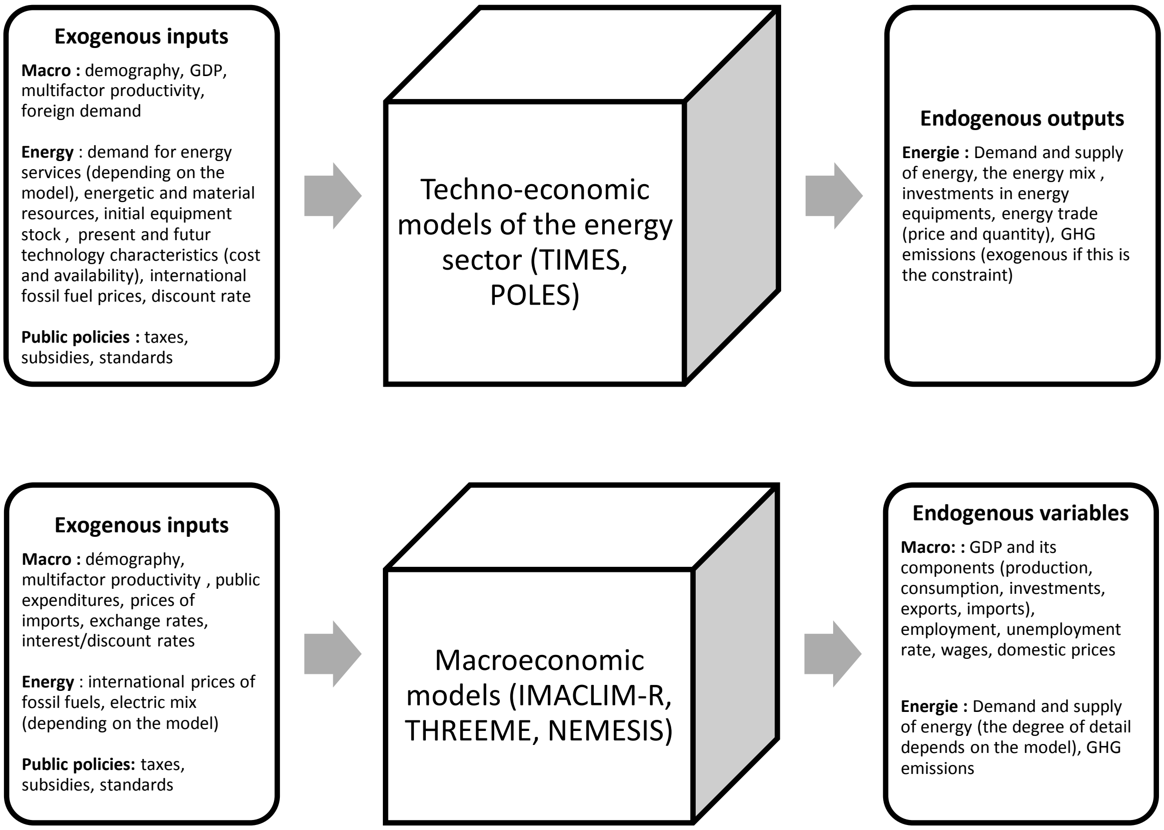
A model of whatever kind integrates a set of equations enabling calculation of "endogenous" variables, based on "exogenous" variables, which, by definition, are not calculated but imposed on the model. Obviously, it is only possible to interpret a model's results if we understand what "enters" the model (exogenous variables) and what "goes out" (endogenous variables: the output of the model). The nature of these ingoing and outgoing variables is largely connected with the category of model.

In techno-economic models of the energy sector, most macroeconomic variables are exogenous and imposed on the model with no retroactive effect. Therefore, such models do not enable analysis of macroeconomic variations. However, they provide detailed descriptions of the energy mix, investments in energy equipment, energy production and use (although energy service demand is exogenous in some models), energy trade (prices and quantities) and GHG emissions (except in cases where they are constrained).

In macroeconomic models, a large number of macroeconomic variables are endogenous. However, technological mixes are potentially exogenous and, above all, characterization of technologies is much less detailed.

[1] Only the ThreeME model provides information on emissions from industrial processes. It integrates emissions connected with the firing of nonmetallic mineral products, which accounts for most emissions connected with industrial processes.

Figure 15 – Indicative diagram of models' inputs/outputs

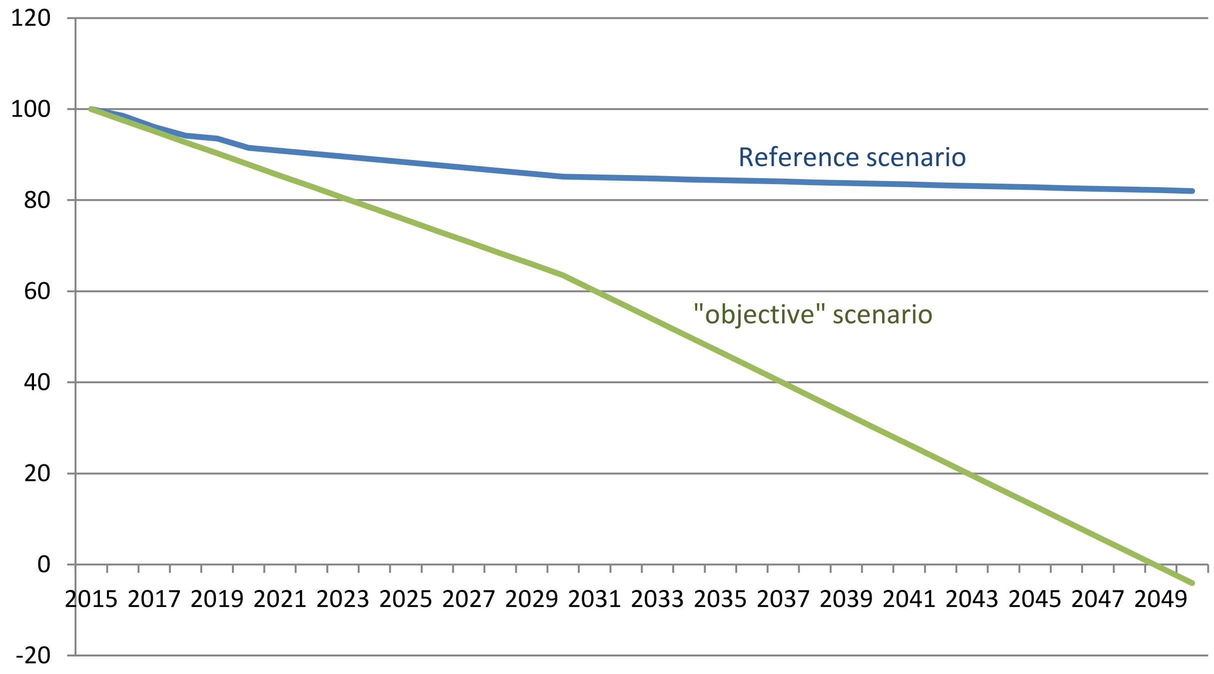


Note: as the list of exogenous and endogenous variables differs greatly from one model to another, including in models in the same category, this diagram is only provided on an indicative basis.

Variational gap analysis

These models were utilized here to determine a carbon value relating to transition from a reference scenario presenting a spontaneous emission trajectory in the absence of a new climate policy to an "objective" scenario resulting in net zero GHG emissions in 2050 (see Figure 16).

Figure 16 – Variational gap analysis



Source: France Stratégie, authors' calculations

What carbon value in models reflects

Carbon value is defined as follows depending on category of model (see also Inset 6):

– carbon value as defined by **techno-economic models** is a marginal abatement cost. It is determined by **the cost revealed *ex post*** of compliance with GHG emission constraints on the trajectory, in other words, the cost of the technological system to deploy in order to abate the quantity of emissions imposed by the constraint;

– carbon value as defined by **macroeconomic models** represents **the relative price of carbonized products** that makes decarbonized technologies competitive.

Inset 6 – Carbon value according to different model specifications

Techno-economic models use a detailed description of technologies – their cost, speed of development and arrival at maturity, related constraints – to evaluate optimal deployment cost of the technologies necessary to comply with the set emission reduction trajectory. Sectoral macroeconomic models model an implicit price in the form of a rise in the relative price of carbonized products and show how the various sectors adapt to the rise, invest in emission-abating technologies and decarbonize. The first category of models therefore defines carbon value as the optimal marginal cost of the effort required to abate an extra one metric ton of emission, whereas macroeconomic models define it as the price signal enabling decentralization of compliance with the constraint.

Consideration of expectations is another major model differentiation factor.

TIMES model, which belongs to the techno-economic category of models, is a demand-driven intertemporal optimization model: it functions with perfect expectations. The model optimizes the energy system across the whole period by minimizing the system's discounted total cost. Unlike adaptive expectation models, it can therefore end up deploying more expensive technologies over the short term that would enable reduction of future costs by, for example, avoiding the effects of technological lock-in. Technologies are not necessarily deployed individually in merit order. For this reason, the carbon value calculated by this type of perfect expectation techno-economic model tends to be higher than those calculated by adaptive expectation models over the short term but more moderate over the long term; as the value's entire trajectory is further optimized.

IMACLIM model, which belongs to the category of dynamic recursive macroeconomic sectoral models, is based on adaptive expectations but can make hypotheses of adaptive/myopic or perfect expectations of future carbon value. In the first case, agents simply extrapolate the current value (which evolves over time). In the second case, everything happens as if the carbon value trajectory was known in advance by all economic agents, with other economic indicators remaining imperfectly anticipated. It is the prospect of a higher future carbon value that leads agents to act now. For example, for an individual who has to replace a vehicle with a lifespan of several years, if it is forecasted that carbon value will increase rapidly over the coming years, it might be best to opt now for an electric vehicle rather than a less expensive one that runs on petrol, even though the present carbon value is still low (the discounted full cost of the first option over duration of use would be lower and the investment finally cost-effective). IMACLIM model was used under the two hypotheses (perfect and adaptive expectations on carbon value) so as to illustrate their impact on the shadow carbon price trajectory.

4.4. Modeling technical progress

There are only two possible ways of reducing an economy's GHG emissions: either you reduce production or you reduce the quantity of GHG emissions per production unit. A neutrality goal aiming to reduce emissions without compromising French wellbeing, growth and competitiveness leads to prioritizing the second possibility.

In order to decouple GHG emissions and a country's GDP[1], again two options are possible:

- **reducing, on the territory, the weight of activities that emit the most** in favor of cleaner activities. The main drawback of such a policy is that it leads to "carbon leakage", i.e. relocations. Such a policy would potentially have a zero or even negative net effect on GHG emissions at global level, as reduction of French emissions could be compensated by an increase in those of countries exporting carbonized products;
- **constituting a decarbonized capital stock**[2] enabling the decoupling of GDP and GHG emissions. This is why modeling of technical progress is essential to apprehending an economy's decarbonization possibilities as pertinently as possible.

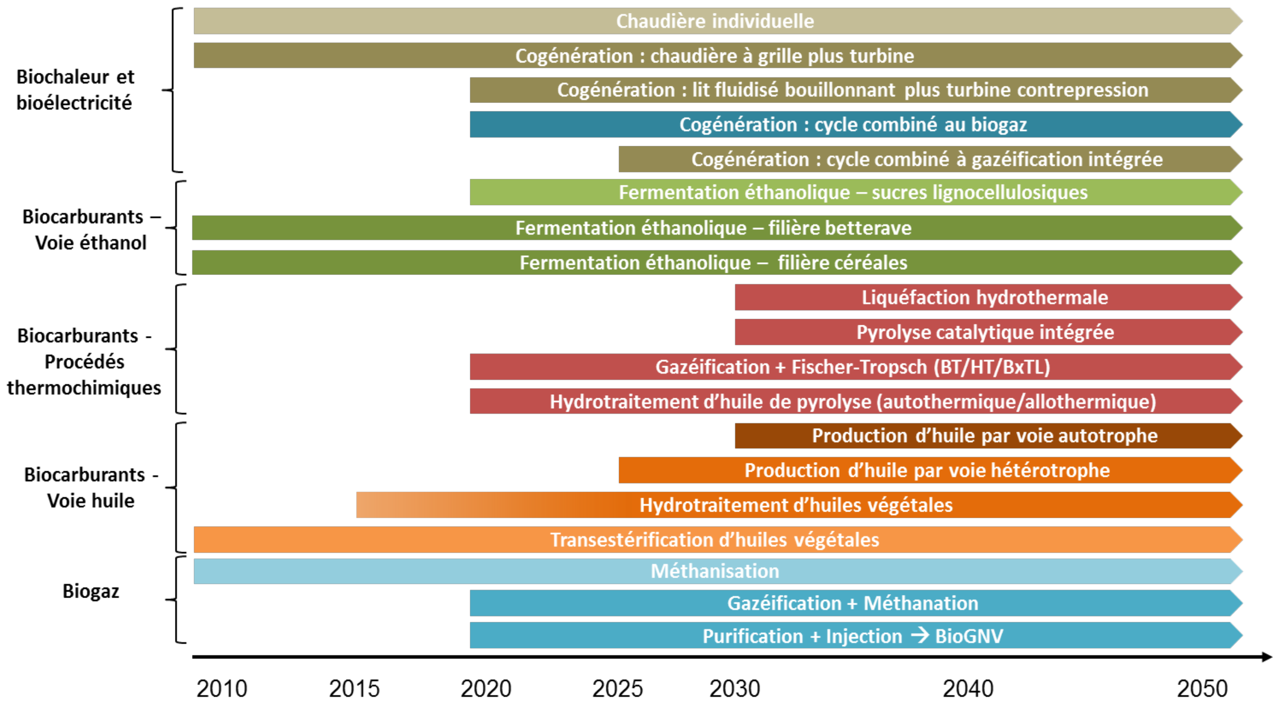
Techno-economic and hybrid models are those that model technological changes in the various sectors in the greatest detail. Specifically, they are models of technological choices subject to constraints: they incorporate a matrix of available present and future technologies, the dates on which such technologies become available, evolution of their cost over time and their potential sources (see Figure 17). They also take account of a number of constraints relating to these technologies (e.g. widespread adoption of electric vehicles leads to new constraints in the transport sector, in particular with regard to installation of charging stations and infrastructures, etc.). This "topology" of various technologies is established on the basis of meticulous expert assessment for each sector and use.

In techno-economic and hybrid models, a proportion of the technical progress made may be "endogenized" by **learning effects** (induced technical progress) of two kinds:

- according to "learning by researching", investing in R&D leads to lower technology costs. However, available data do not enable integration of this technical progress driver into techno-economic models[3];
- according to "learning by doing", the more a technology is deployed on a wide scale (i.e. the greater accumulated installed power is), the more its cost decreases. This form of technical progress is more easily integrated into models, with the help of "learning curves" that describe the reduction in cost of each technology depending on its level of deployment. POLES model integrates such learning curves (see Figure 18) and therefore endogenizes a part of technical progress.

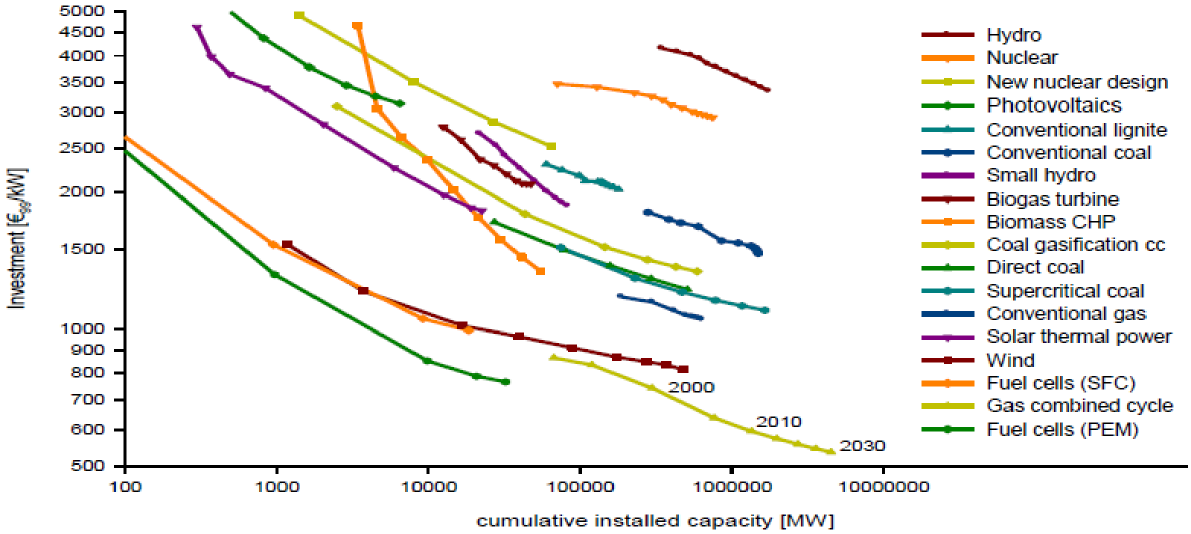
[1] In a production approach with no carbon footprint.
[2] The term "green" is used inaccurately but for simplification's sake to refer only to decarbonization of the economy and not to other environmental aspects.
[3] This would in particular require R&D data per technology, data which does not exist or at most is extremely rare (it is rather data per economic activity that exists).

Figure 17 – Example of technological foresight provided as input in techno-economic models



Source: Center for Applied Mathematics (CMA), TIMES model

Figure 18 – Example of "learning by doing" curves



Source: Enerdata, POLES model

Hypotheses on agents' expectations have a major influence on the dynamics of adoption of technologies. Depending on model, technological choices can be made by agents with so-called "adaptive" expectations (POLES models), when they only have present information, which they tend to extend, only partly anticipating technological developments and their future cost. Conversely, they may be made by agents with so-called "perfect" expectations (TIMES model), who possess full present and future information and process it in optimal fashion. Expectations lead to investment in technologies that are more expensive at the beginning but which enable achievement of the final goal at less cost. The Commission used models that take both types of hypotheses on expectations into account: POLES considers agents with adaptive expectations while TIMES postulates that they have perfect expectations[1].

5. The reference scenario

The reference scenario is the one that describes:

– the way in which the economy, technological systems and French emissions would evolve spontaneously in the absence of a new climate policy;

– the context in which the objective scenario will have to be achieved.

Changes required to achieve net zero GHG emissions by 2050 are evaluated on the basis of this baseline.

This section describes the reference scenario's key factors: climate polices taken into account, economic growth, energy efficiency, energy mix, and the international context.

5.1. A "neutral" international environment

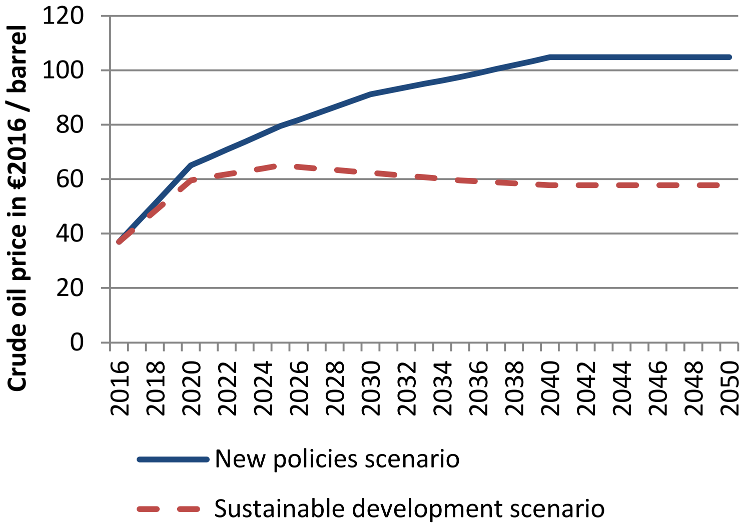
The analysis carried out here is an analysis with an unchanged global scenario. In other words, we are not comparing a situation in which France and the rest of the world decarbonizes with a baseline situation in which neither one nor the other reduces their emissions; but rather a situation in which France decarbonizes with a situation in which it makes no special decarbonization efforts, in a given international context. The path to take in order to transition from the reference scenario to the decarbonization scenario remains no less dependent on hypotheses on such international context.

This being so, in carrying out this exercise it was first of all decided to take an agnostic point of view on the international context in the reference scenario, setting aside extreme scenarios; and, secondly, to test results' sensitivity to the international context's various channels of influence, in order to evaluate the order of magnitude of underlying uncertainties.

[1] Sensitivity tests at expectations' time horizons were carried out using TIMES.

- Fossil-energy price projections adopted came from the IEA's "New Policies Scenario"[1], which is based on the hypothesis that countries comply with the commitments defined by nationally determined contributions (NDCs) made prior to COP21. Such commitments correspond to mobilization that is still not enough to keep warming below the 2°C threshold. An alternative hypothesis was tested out to evaluate the sensitivity of results to it: the IEA's "sustainable development" scenario in which global mobilization is assumed to enable limitation of global warming to 2 C. In this scenario, as demand for fossil fuels is lower, their price is revalued downwards (see Figure 19). It was made no special hypotheses as regards the prices of other resources, and the impact of any eventual rise in the price of resources necessary to decarbonization technologies comes down to that of an increase in the cost of such technologies.

- **Figure 19 – Crude oil prices, IEA scenarios**



Source: World Energy Outlook 2017 by the IEA up to 2040; reprocessing: linear interpolation between 2016, 2025 and 2040 prices; prices frozen after 2040

- These simulation exercises do not assume that a substitute technology for carbonized technologies, of moderate cost and with unlimited potential (a so-called "backstop" technology), could be deployed to abate emissions. The impact of this cautious choice is easily justified over the short and medium terms.

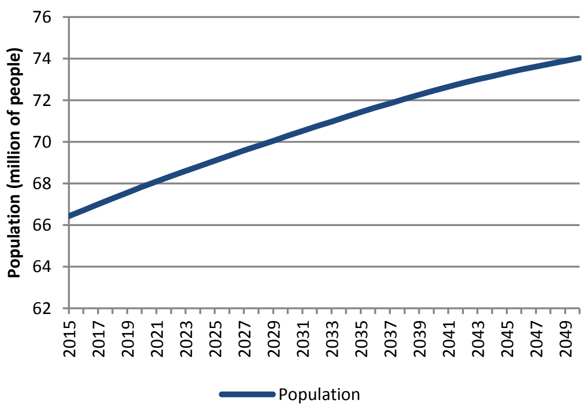
Evaluation of uncertainties underlying these factors is described in the Report's next chapter.

[1] International Energy Agency (2017), *World Energy Outlook*.

5.2. A hypothesis of 1.6% average annual growth

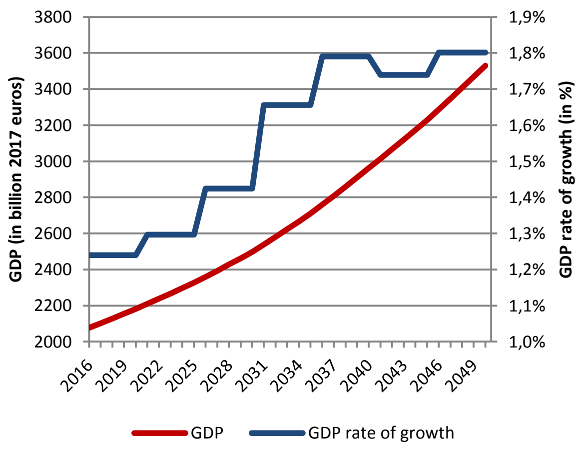
Demographic and macroeconomic hypotheses (homogenized across models) are taken from projections made by leading national and international public institutions. French demographic evolutions are based on INSEE's projections (see Figure 20), and the economic growth hypotheses on projections in the European Commission's 2015 Ageing Report, hypothesizing average annual growth of 1.6% over the period (see Figure 21). For macroeconomic models, this trajectory is endogenous but compatible with this order of magnitude.

Figure 20 – Demographic projection in the reference scenario



Source: INSEE; central scenario of 2013-2070 population projections for France

Figure 21 – GDP projection in the reference scenario



Source: European commission, Ageing working group, Ageing Report 2015

5.3. A reference scenario without price signals on carbon

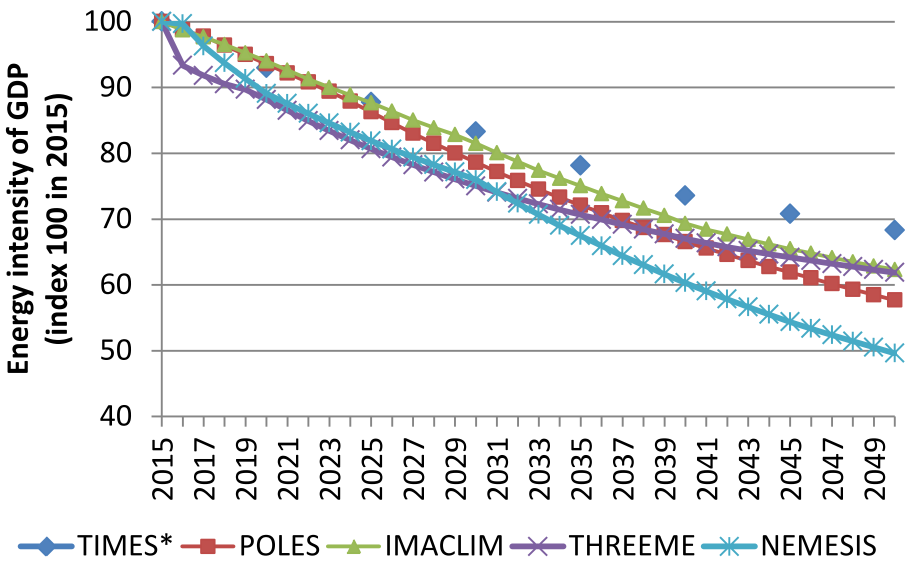
The reference scenario does not integrate new public policies combating GHG emissions apart from those in force in 2017. For the reference scenario, it was decided to deactivate those corresponding to an explicit price-signal (a decision expressed in particular by setting carbon pricing and ETS prices at zero) but to keep other public policies, on building construction standards in particular, which do not only reflect climate goals. As not all models describe all public policies explicitly, this choice was implemented depending on their ability to identify such policies.

5.4. A favorable trend of gains in energy efficiency

Much of the economy's decarbonization will be brought about by a reduction in production's energy intensity but, here again, any future increase in energy efficiency cannot be wholly attributed to low-carbon transition. Only the trend in improvement of energy efficiency is retained in the reference scenario.

Figure 22 represents the spontaneous evolution of the GDP's energy intensity obtained by the various models for the reference scenario. It shows that major gains are anticipated in national production's energy efficiency, even before special climate actions are implemented, of between 30% and 50% from 2015 to 2050 depending on the model.

Figure 22 – Evolution of the GDP's energy intensity in the reference scenario



Note: the GDP's energy intensity is calculated here by the final total energy consumption to GDP ratio, indexed at 100 in 2015.

* TIMES model does not enable endogenization of energy service demand. Sectoral demand for energy service was based on ThreeME simulations with some adjustments in order to reflect sectoral specificities.

Source: Authors' calculation based on models' simulation results

5.5. GHG emissions calculated by models

On the basis of their respective configurations and the hypotheses described above, models defined the trend in evolution of energy-induced GHG emissions. Figure 23 represents this spontaneous evolution of CO_2 emissions obtained by the various models in the reference scenario. The Figure shows significantly different trajectories and consequently variations in totals of emissions to abate across models.

Figure 24 connects spontaneous emission evolution to that of the GDP. The Figure shows a significant trend towards decoupling of emissions from the GDP in the reference scenario in most models, this decoupling being associated with the downward trend in energy intensity.

Figure 23 – Energy-induced CO_2 emissions in the reference scenario

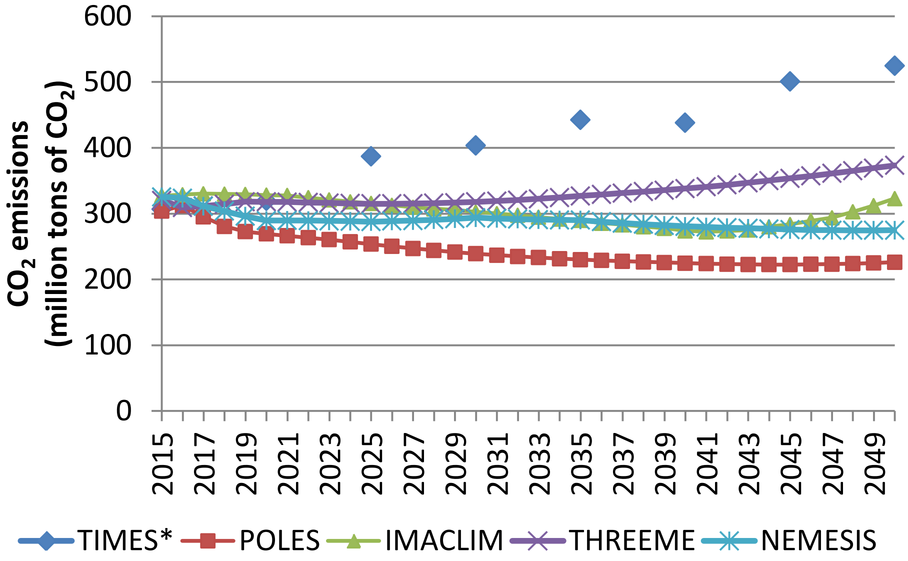
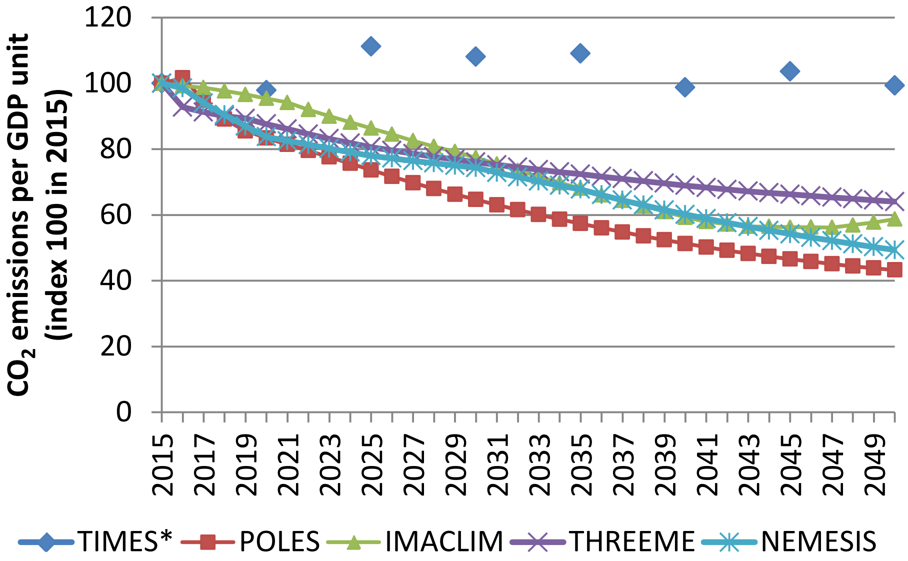


Figure 24 – Energy-induced CO_2 emissions per unit of GDP in the reference scenario



Note: emissions considered here are only energy-induced CO_2 emissions.

* TIMES model does not enable endogenization of energy service demand. Sectoral demand for energy service was based on ThreeME simulations with some adjustments in order to reflect sectoral specificities. TIMES model is also the model enabling the most exhaustive removal of carbon policies, therefore tending to increase the economy's carbon intensity in the reference scenario compared with other models.

Source: Authors' calculation based on models' simulation results

CHAPTER 3

RESULTS OF VARIOUS FORESIGHT EXERCISES

This chapter presents the “gross” results of the various approaches implemented by the Commission. These results constitute the “ingredients” useful to construction of the shadow carbon price trajectory proposed in the next chapter. Foresight work carried out in targeted fashion is described in the first part, along with the sensitivity of results obtained to major structuring hypotheses: the international context, size of sinks, behaviors and technical progress.

The second part describes the major economic issues of transition to net zero GHG emissions as exposed by foresight exercises. The Commission does not present the macroeconomic or social impacts of low-carbon transition, insofar as such impacts very much depend on the exact design of environment policy measures. Nonetheless, our work sheds light on conditions for successful transition and the nature of underlying sectoral reallocations.

1. All approaches converge towards substantial revaluation of the value for climate action

1.1. Models

Carbon values obtained by models

Utilization of simulation models enables integration of a GHG emission reduction trajectory into our technological and economic environment, in order to better understand how behaviors and technologies are changed in order to follow the trajectory leading to the “Net-Zero” goal. Such models are widely used in international evaluations of carbon value. The IPCC in particular bases many of its global carbon price estimations on series of simulations carried out with a wide range of models, in accordance with methodologies very similar to those adopted by the Commission[1].

Table 8 below brings together carbon values obtained by the various models utilized by the Commission: the two techno-economic models TIMES and POLES and the three sectoral macroeconomic models IMACLIM, ThreeME and NEMESIS.

The Commission made use of a wide variety of models, with a view to defining a reasonable range of shadow carbon prices that would not be dependent on any particular specification. Models used are mainly differentiated on the basis of two criteria: model category (techno-economic or macroeconomic) and account taken of perfect or adaptive expectations (of the future carbon value and/or of all economic signals).

Table 8 – Carbon Values defined by models

		Shadow carbon price for sinks of between 75 $MtCO_2eq$ (in orange) and 95 $MtCO_2eq$ (in blue) (€$_{2016}$/tCO_2eq)									
		2030		**2035**		**2040**		**2045**		**2050**	
Techno-economic	**TIMES**	322	**288**	293	**285**	375	**465**	661	**1,054**	1 365	**2,451**
	POLES	253	**351**	384	**547**	575	**845**	907	**1,400**	1958	**3,513**
Macro-economic sectoral	**IMACLIM***	168	**168**	168	**168**	168	**168**	440	**489**	1 453	**3,132**
	IMACLIM (myopic)**	228	**--**	288	**--**	537	**--**	1,337	**--**	3 328	**--**
	ThreeME	143	**143**	226	**402**	363	**1 128**	428	**1,626**	511	**2,389**
	NEMESIS	185	**185**	360	**393**	655	**784**	1,358	**1,934**	--	**--**
	Average	221		319		551		1,058		2,233	
	Minimum-maximum	143	**351**	168	**547**	168	**1 128**	428	**1,934**	511	**3,513**

* Model used with a hypothesis of perfect expectation of shadow carbon price for values for sinks between 85 $MtCO_2eq$ and 95 $MtCO_2eq$.

** Model used without hypothesis of perfect expectation of shadow carbon price for values for 95 $MtCO_2eq$ sinks.

Note: for each year, the left-hand column corresponds to the most favorable sink hypothesis (95 $MtCO_2eq$) and the right-hand column to the least favorable sink hypothesis (75$MtCO_2eq$)[2]

The average of models' results should be considered with due caution given the models' structural differences of functioning.

Source: models' simulations

On the basis of the various modelings, the Table above highlights two salient points.

- By 2030, models display carbon values between €143 and €351. Disparities are moderate and mainly connected with model category: the TIMES and POLES techno-

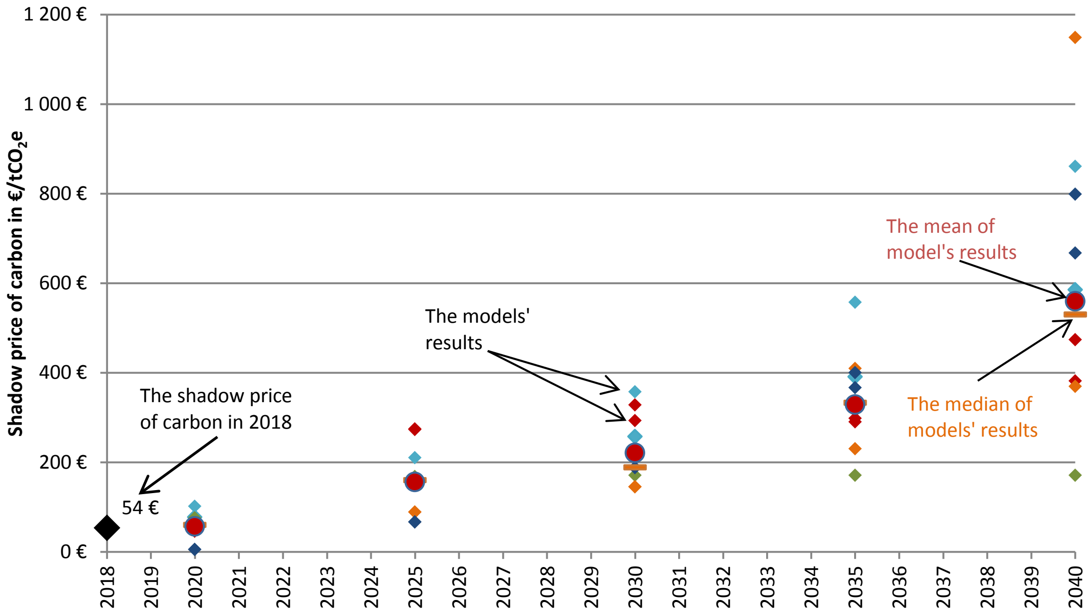
[1] See for example the IPCC's Fifth Report (2014) and Chapter 2 of the recent *Global Warming of 1.5°C* report.

[2] TIMES attributes a lower short-term value in the least optimistic case (€288 as against €322) but the increase in this value over the end of the period is significantly higher than under the optimistic sinks hypothesis.

economic models display higher values than the IMACLIM, ThreeME and NEMESIS macroeconomic models (respective averages of €300 and €165).

- Although they are constructed on completely different principles, all models display a growing carbon price trajectory throughout the period from today to 2050, at a pace considerably greater than the discount rate, as would be recommended by a Hotelling rule. Such growth rate reflects two distinct phenomena:
  - the choice of smoothing out GHG emission reduction efforts across the whole of the period, as the carbon value trajectory reflects the increase in marginal abatement costs in the process of decarbonizing the economy;
  - The difficulty of simulating a deep decarbonization scenario at the end of the period, as models of all kinds have a hard time simulating the radical changes required for deep decarbonization of the economy, so that the carbon value obtained tends to "take off" in order to try and achieve the goal.

Figure 25 – Carbon values obtained by models up to 2040



Source: simulations by models

Model results exploitable up to Factor 4

Apart from their specification differences, the models provide reasonably convergent and robust orders of magnitude over the first part of the projection period. However, as the time span lengthens, models have increasing difficulties in simulating the GHG reductions required to achieve net zero GHG emissions. This is partly explained by their intrinsic limitations:

- some models are "conservative" by nature: they refer to observation of past behaviors and are unable to describe more systemic changes. As regards demand, this limitation is expressed in stable and moderate relative price elasticities, even when models approach the "zero emissions" zone;
- as regards supply, models are unable to fully apprehend all the fundamental aspects of the innovation process. In particular, they only partially integrate learning effects connected with deployment of technologies (learning by doing) or with R&D investments on such technologies (learning by researching). This limitation makes it especially difficult to project future switching prices of technologies that are not mature today but will be essential to achieving net zero GHG emissions. *A fortiori*, apart from an incremental progress trend, models cannot anticipate disruptive innovations;
- finally, as simulations are done assuming policy remains unchanged, models do not incorporate structural changes in organization of space and land use.

All in all, as is shown in Figure 26, which presents carbon value levels depending on emission levels reached (in percentages of 1990 levels) for the various models:

- **cutting emissions by half compared with 1990 involves highly convergent carbon values between models, of between €175 and €250**. Results remain convergent up to an emission reduction level to the tune of 60% compared with 1990. Values at this level are between €300 and €450 /tCO_2eq[1];
- **disparities between results increase but remain partially explicable up to around 2040, when we get close to Factor 4** – i.e. division of emissions by four compared with 1990;
- **then, the shadow price trajectory slope increases sharply in all models, and disparities between models increase significantly,** expressing the difficulty, even impossibility, of achieving net zero GHG emissions on the basis of mechanisms included in these models alone.

Besides simple observation of the "leap" in the simulated carbon value, at the end of the period macroeconomic models describe a decarbonization more related to decrease in production than to decoupling between production and GHG emissions[2].

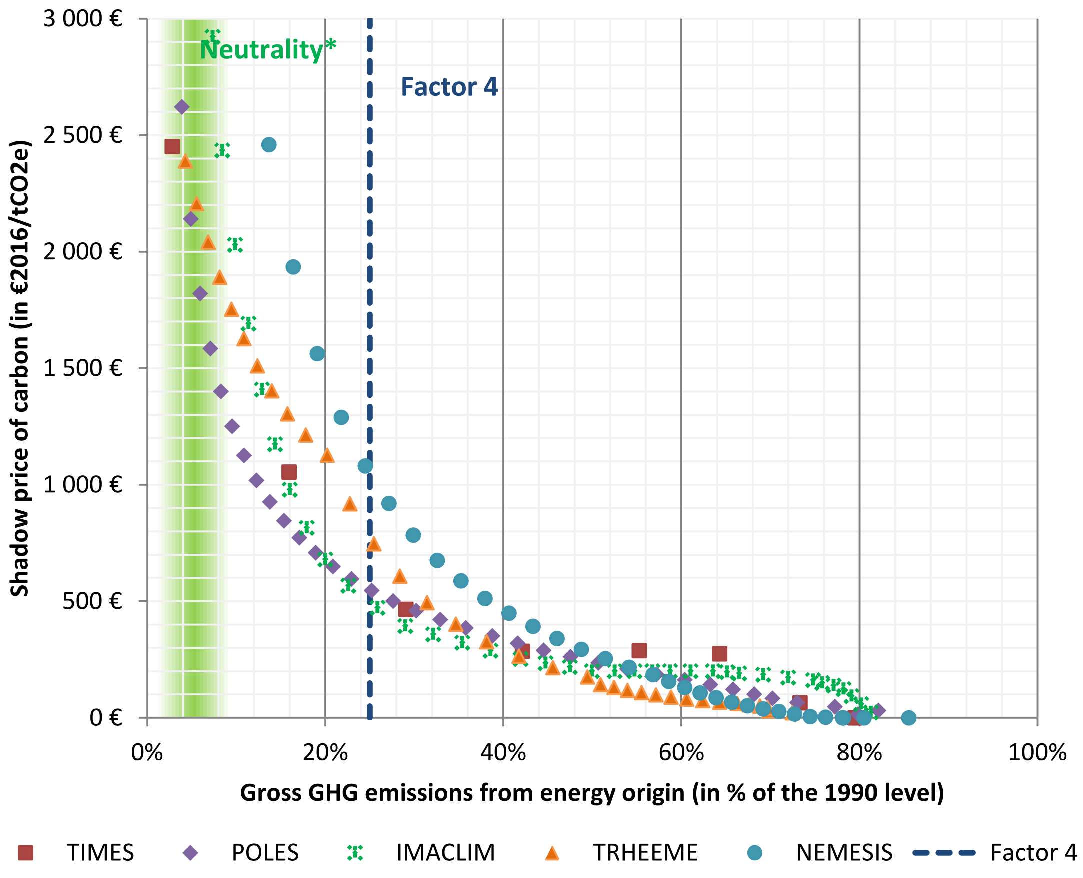
---

[1] We exclude the IMACLIM model here, as the carbon value/emission level relationship it obtains is too dependent on the trajectory owing to expectations.

[2] By considering the equation $E = E/Y \times Y$, with E the GHG emission flow and Y the GDP, the contribution of decoupling corresponds to the contribution of the variation of E/Y in the variation of E

On the basis of this results analysis, **the Commission reckoned that the models used provided a robust perspective of the shadow carbon price trajectory required up to emission reduction close to Factor 4** (division of GHG emissions by 4 compared with 1990), but that exploitation of results produced beyond that point in order to evaluate shadow carbon price was not pertinent. The capacity for deep decarbonization of the economy to achieve net zero GHG emissions requires enabling policies (land use and development in particular), innovation and international coordination, all of which are more difficult to model.

Figure 26 – Models' carbon values depending on emission levels achieved compared with 1990



Note: for ease of interpretation, values displayed here are those obtained by simulations with the hypothesis of LULUCF sinks of 75 $MtCO_2eq$ (85 $MtCO_2eq$ for IMACLIM); curves obtained by trajectories with a hypothesis of 95 $MtCO_2eq$ sinks differ little from those displayed here, except for ThreeME.

The curve corresponding to the IMACLIM model represents the myopic version; the version with perfect expectations on carbon value does not enable establishment of this curve.

* Climate neutrality corresponds here to the goal of energy-induced emission reduction compatible with hypotheses of sinks of between 75 $MtCO_2eq$ and 95 $MtCO_2eq$.

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and that of the variation of production to the variation of Y.

Source: authors' calculation based on models' simulation results

1.2. Technological foresights

Technological foresight exercises are carried out at global level, in particular by the International Energy Agency (IEA), with regard to technologies connected with energy production and use, as well as at national level in a number of countries, including the United Kingdom and Germany and by France in the context of preparation of the *Stratégie Nationale Bas Carbone* (SNBC – National Low-Carbon Strategy). Such exercises enable assessment of probable dates of emergence of various decarbonization technologies, their speed of deployment and evolution of their costs – and, finally, switching prices of carbonized uses to decarbonized uses (see Inset 7 below).

Foresight studies on available technologies serve to identify the most expensive marginal technologies required for deep decarbonization of human activities. By 2050, carbon value should logically reflect the probable cost of the most expensive enabling technologies to achieve the goal.

The Table below draws on a variety of sources to present abatement costs relating to a selection of enabling technologies for energy-induced emissions. According to these results, a large number of technologies might be deployed at less than €100/tCO_2eq by 2050. Technologies enabling significant increases in abatement potential, such as "Power to X" technologies, are more expensive, between €300 and €600 per metric ton of CO_2eq abated.

Reducing non-energy-induced emissions in the agricultural sector by 33% compared with their 1990 level – i.e. achieving the target set for 2030 – would require mobilization of technologies whose abatement costs would be somewhere between €250/tCO_2eq[1] and €500/tCO_2eq[2]. Achieving the -50% goal in the sector compared with 1990 emissions should therefore involve yet higher costs.

For all sectors, abatement costs connected with technologies only represent direct costs, under the hypothesis of optimal utilization of such technologies, and do not integrate constraints relating to their deployment: modification of the production system, sectoral reallocations, professional retraining and transitions, and the effects of tension on these technologies if they have to be used intensively. Given the models' results, taking such

[1] Technology 7A: modification of animal feed by replacing sugars with unsaturated fats and use of additives in ruminants' feed in order to reduce protein content in rations.

[2] Technology 4C: introduction of grass strips acting as buffers. See Pellerin *et al.* (2017), "Identifying cost-competitive greenhouse gas mitigation potential of French agriculture", *Environmental Science & Policy*, 77, pp.30-139.

transition constraints and costs into consideration could well increase direct costs by as much as 30%.

The Commission has adopted the hypothesis that, with a shadow price ranging from €600 to €900/tCO₂eq at end of period, it is possible to make a portfolio of enabling technologies cost-effective in achieving the "Net-Zero" goal. Of course, these cost levels are subject to major uncertainties, and, for the sake of caution, do not assume the emergence of an inexpensive high-potential disruptive technology.

Table 9 – Abatement costs relating to a selection of enabling technologies for energy-induced emissions

Technology		**Cost per tCO_2**	**Source**	
Natural gas combustion + CCS	Includes €10/t for transport/storage	€40-73 /t	IEAGHG 2017	Technical Report, Overview Book
Electricity, gas or coal + CCS		< €100 /t	IEA 2017	IEA ETP 2017, figure 6.16
Cement works = CO_2 capture	First range with oxy-combustion Second range with post-combustion	$55-70 /t $90-150 /t	IEA 2018	Technology Roadmap Low-Carbon Transition in the Cement Industry
Steelworks + CO_2 capture		$60-80 /t	IEA 2011	Technology Roadmap CCS in Industrial Applications
Biomass electricity + CCS	Biomass electricity plant = CO_2 capture with negative net emissions of -75 g/kWh	$250 /t	IEA 2017	IEA ETP 2017, figure 6.16
H2 + capture	Hydrogen manufactured by vapo-reforming = CCS	€47-70 /t	IEAGHG 2017	Technical Report February 2017
Power to gas	Electrolytic H_2 = capture of CO_2 for combustible gas or liquid formation	€307/t	DENA 2018	Deutsche Energie Agentur Leitstudie. Impulse für die Gestaltung des Energie systems bis 2050 Integrierte Energiewende
Power to liquid		€311 /t		
CO_2 air capture	Direct air capture (DAC) of CO_2	€85 /t**		
Power to gas	H_2 by electrolysis and methanation for heating uses (natural gas substitute)	€570 /t**	Agora Energie-wende	Agora SynKost Study et FVVH1086 Renewables in Transport 2050 – Kraftstoffstudie II
Power to liquid	H_2 by electrolysis and processing into fuel for mobility (oil substitute)	€470 /t**		

* Target cost per metric ton of CO_2 captured, accessible in 5-10 years for some and by 2040-2050 for others.

** Calculation based on Agora Energiewende data and hypotheses on electricity cost (€80/MWh), an electrolyzer used 8000 hours/year, and absence of H_2 storage.

Source: contribution by F. Dassa and J.-M. Trochet, EDF (see Complements)

Inset 7 – Certain sectors are dependent on technologies that are not yet mature

Technology watch exercises teach three major lessons.

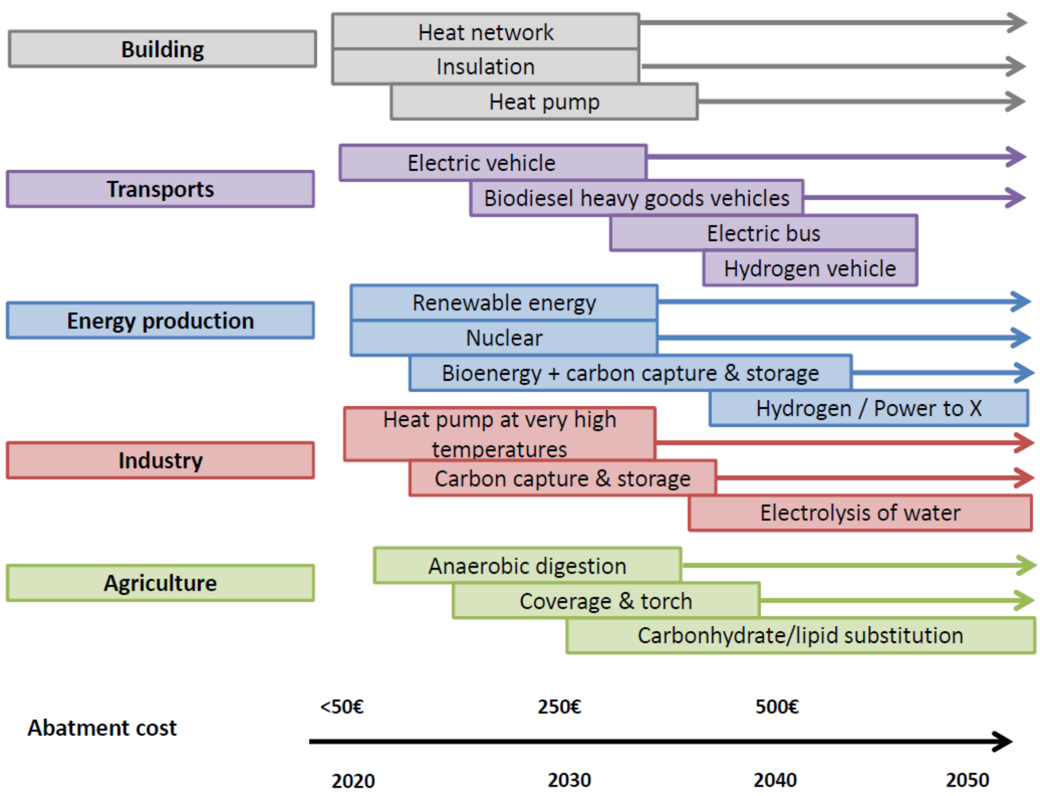
Almost half of GHG emission reductions will be able to be carried out using technologies with abatement costs below €250/tCO_2eq.

A great many solutions can be deployed as from today at very limited cost, in particular in the building sector, energy production, industry and agriculture. Only sector saturation could slow down deployment of these solutions.

However, deep decarbonization of certain sectors depends on technologies that are not yet mature, with abatement cost projections that are still very high even by 2050 (over €500/tCO_2eq).

The cost of deploying these non-mature technologies is still surrounded with major uncertainties and varies depending on source. The Table below, which was mainly inspired by work carried out by the IEA, proposes a few orders of magnitude for abatement costs directly connected with new decarbonization technologies. These direct costs do not take account of sectoral and macroeconomic costs connected with their large-scale deployment in the economy.

Figure 27 – Costs of deploying various technologies



*Sources: orders of magnitude defined by the Commission on the basis of various sources: Carbone 4 (2018), "*Comment décarboner en profondeur et sans tarder le bâtiment, les transports et l'industrie?*"; IEA (2017), "Energy Technology Perspectives 2017"; Pellerin et al. (2013), "*Quelle contribution de l'agriculture française à la réduction des émissions de gaz à effet de serre? Potentiel d'atténuation et coût de dix actions techniques*" Final Report, INRA*

1.3. Sensitivity of results to sinks, behaviors and costs of technologies

Structuring hypotheses in evaluation of the carbon value trajectory have been subjected to sensitivity tests:

- the actual total of emissions to abate; connected in particular with LULUCF sink hypotheses;
- the international context of the fight against climate change;
- actors' behaviors;
- technical progress.

This section presents the results of these sensitivity analyses.

Sensitivity of the value to the abatement goal

Sensitivity to LULUCF sinks

All simulations are carried out under at least two hypotheses of LULUCF sink potentials, one at 95 $MtCO_2eq$ and the other at 75 $MtCO_2eq$[1]. In each scenario, sink load capacity increases gradually until it reaches its maximum potential in 2050. Table 3 shows the relative gaps in carbon value obtained depending on these sink hypotheses. By 2030, disparities in sink capacities remain moderate between scenarios and there is low variability in carbon value depending on hypotheses, of around +/-5%. It then increases as sink disparities widen, reaching an average order of magnitude of +/-10% to 20% in 2040. After 2040, dispersion of models leads to highly variable and not at all robust disparities. However, sensitivity of around +/-20% or over would seem very probable.

[1] 85 $MtCO_2eq$ for IMACLIM.

Table 10 – Variations in carbon value depending on sinks' probable potentials

		2030	2035	2040
Techno-economic models	TIMES	6%	1%	11%
	POLES	16%	17%	19%
Macroeconomic models	IMACLIM*	0%	0%	0%
	ThreeME*	0%	28%	51%
	NEMESIS	0%	4%	9%

Interpretation: this Table shows the extent of relative variations of carbon value around a central value for hypotheses of LULUCF sinks of between 75 $MtCO_2eq$ and 95 $MtCO_2eq$. The carbon value in 2040 obtained by the POLES model can vary by +/-19% around the central value (85 $MtCO_2eq$) depending on LULUCF sink potentials (from +/-10 $MtCO_2eq$ around 5 $MtCO_2eq$). As model results are only regarded as pertinent up until 2040, results for later dates are not presented.

*The zero variations displayed by the IMACLIM model are biased compared with other models by expectation mechanisms that defer such variations to end of period. The extent of disparities in values deduced from ThreeME simulations under various sink hypotheses is also hard to explain.

Results' sensitivity to the international context of the fight against climate change

Degrees of mobilization and levels of international cooperation in combating global warming influence French carbon value via at least four channels:

- the possibility of sharing national efforts to control emissions (in particular via the effects of an international emissions trading system and exploitation of foreign carbon sinks);
- price of resources, fossil fuels in particular;
- the country's terms of trade and competitiveness;
- and innovation.

Analysis of results' sensitivity to hypotheses made on the international context have therefore been broken down so as to identify their sensitivity to each of the above channels.

The possibility of international cooperation

Coordinated action on the part of several countries enables efficient burden-sharing by making a priority of exploiting low-cost sources. A number of France's emission reduction actions could potentially rely on foreign sources. In this case, it would be possible to compensate certain GHG emissions on French soil by emission reduction projects abroad, rather than eliminate all emissions produced on our territory if the marginal abatement cost proved very high.

If a "club" of countries decided to organize better integration of efforts, carbon value could be moderated, either because they could make use of foreign sinks or because they could purchase CO_2 allowances rather than make more expensive efforts[1]. Taking such a possibility into account requires postulation of higher carbon sinks. As an example, a flexibility mechanism enabling use of foreign wells for 10 $MtCO_2eq$ would reduce the value by around 10%.

The price of fossil fuels

A global context in which there were greater efforts to limit global warming would result in reduction of demand for fossil fuels and therefore of their prices. Yet if such energies cost less, it would be an incentive to make more use of them. This "rebound effect" necessitates application of larger-scale abatement actions in order to counter it. Baseline hypotheses adopted on fossil fuel prices are based on the IEA's central scenario, which only corresponds to compliance with national commitments[2], which are not enough to keep global warming below 2°C. It is therefore probable that, in a context where the world stepped up its action in the fight against warming, fossil fuel prices would be at lower levels than those envisaged in this scenario. Different versions have been created using TIMES and NEMESIS models, by adopting the IEA scenario's fossil fuel price hypotheses in which global efforts enable warming to be kept below 2°C[3].

Switching from a hypothesis of oil prices at €91 in 2030 and €105 in 2040 to a hypothesis of prices at €62 in 2030 and €58 in 2040 – a reduction of between 30% and 45% – would lead to a €3 to €15 rise in carbon value in 2030 and a €34 to €50 rise in 2040 (see Table 11). Carbon value would therefore seem to show relatively little sensitivity to uncertainties on fossil fuel prices, with variations of less than 10%.

Besides bringing about a drop in fossil fuel prices, reinforced global action could also lead to tensions on the market for the raw materials required for production of low-carbon technologies and drive up their prices. This second mechanism is not specifically evaluated in this analysis and would increase the rise in carbon value brought about by the drop in oil prices.

[1] Tirole J. (2009), *Politique climatique, une nouvelle architecture internationale*, Report no.87 for the Council for Economic Analysis (CAE).
[2] The IEA's "New policies scenario".
[3] The IEA's "Sustainable development scenario".

Table 11 – Increase in carbon value when hypotheses on fossil fuel prices are taken into account

		2030	2040
TIMES	Gap in €	+ €3 to €20	+ €34
	Gap in %	+ 1% to 7%	+ 7% to 9%
NEMESIS	Gap in €	+ €14	+ €50
	Gap in %	+ 7% to 8%	+ 6% to 8%
Oil price	"New policies" price scenario	€91	€105
	"Sustainable development" price scenario	€62	€58
	Gap in €	– €29	– €47
	Gap in %	– 32%	– 45%

Note: comparison of the carbon value obtained depending on whether fossil fuel price hypotheses are those of the IEA's "New policies" or "Sustainable development" scenarios. The gaps presented are defined as follows:

Gaps in euros: CV (Sustainable development) – CV (New policies).

Gaps in percentage: [CV (Sustainable development) – CV (New policies)]/ CV(New policies).

Gaps vary depending on sink scenarios.

Competitiveness

The third channel of influence has to do with variations in competitiveness. Reinforced international action would result in protecting the competitiveness of exposed French sectors and reduce the risk of "carbon leakage". This is a key economic issue but would have little impact on shadow carbon price as there would be no overall change in efforts to achieve "net-zero emissions".

Innovation

Innovation is probably the international context's most important vector of influence on the shadow price of carbon. Strong global mobilization would lead to a broadening in the scope of R&D efforts, greater probability of fresh discoveries being made, and large-scale deployment of resulting innovations, with significant cost reductions into the bargain.

Results' sensitivity to technological foresights

In a strong international cooperation scenario enabling the Paris Agreement to be fully implemented with a goal of keeping global warming below 2°C or even 1.5°C, decarbonized technologies would be deployed on a wide scale and benefit from reductions in cost that would be all the more significant the higher their learning rates were. The learning rate (LR) expresses the reduction in cost relating to each doubling of the accumulated number of facilities produced. In general, it is between 5% and 25%[1] and reflects a scale effect (amortization of R&D fixed costs) along with learning effects (greater production efficiency).

The shadow price of carbon very much depends on the pace at which technologies – and, more generally, technological systems – are deployed. Figure 28 provides a stylized representation of determination of a shadow price trajectory, and, at the same time, mobilization of technologies in merit order depending on emissions to be abated and cost of available technologies T1, T2 and T3 (left-hand Figure): when shadow carbon price becomes higher than the abatement cost connected with technology Ti, the latter can be deployed. The emission reduction trajectory is determined by deployment of these technologies (right-hand Figure).

In this context, an innovation can have two kinds of impact:

- it may lower the shadow price trajectory compatible with compliance with the same budget (or the same trajectory);
- it may also enable earlier deployment of the technology concerned.

The sensitivity analysis presented here is based on two types of case studies: intermediate or "mid-term" technologies, and technologies that are not as yet mature, referred to as "ultimate" technologies as they would enable us to take the "final step" in decarbonization of the economy.

The case of "mid-term" technologies or incremental innovations

Figure 28 illustrates the impact of a reduction in the cost of a technology that is to be deployed "mid-term": the technology in question (T2) can be deployed earlier on and emissions reduced earlier. More expensive technologies (T3) can be deployed later while complying with the same carbon budget. Consequently, the shadow price trajectory can be lowered, as there is only a moderate effect on end-of-period value.

The case study, details of which are provided in Complement 12 to this Report[2], bears on the transport sector and presents the impacts of various global scenarios on the relative cost-effectiveness of three competing technologies: vehicles with internal combustion engines (ICE), battery electric vehicles (BEV) and fuel-cell electric vehicles (FCEV). The

[1] Photovoltaic panel modules have recorded a more than 20% learning rate over the last thirty years, and wind energy a rate of around 15%. For a review of learning rates, see for example Rubin *et al.* (2015), "A review of learning rates for electricity supply technologies", *Energy Policy*, vol. 86, November, pp.198-218.
[2] See Complement 12, "*Valeur tutélaire du carbone et environnement international de décarbonation*" (Shadow price of carbon and the international decarbonization environment) by Patrick Criqui.

sensitivity analysis carried out consisted of comparing switching prices of decarbonized technologies according to hypotheses i) of deployment of such technologies at global level, and ii) of learning rates of between 15% and 25%. It shows that, for a given carbon value, a favorable global scenario (Beyond 2°C) combined with a high learning rate (25%) results in making non-GHG-emitting technologies (BEV and FCEV) less expensive that the GHG-emitting technology (ICE) much earlier than a less ambitious global scenario (NDCs) combined with a moderate learning rate (15%).

Learning effects can therefore lead to significant reduction (over more than 50% in this example) of the carbon value required to activate clean technologies in this sector, in particular if there is a favorable international scenario.

The case of a technology representative of "ultimate" abatement costs or a disruptive innovation

The impact of a disruptive innovation is all the greater when it bears on less mature and the most expensive technologies with major abatement potential.

Its impact on the shadow price of carbon depends on numerous factors: the extent of the reduction in costs, of course, as well as the potential of the technology concerned and the date it appears on the scene. The impact of this type of technological advance leads to early deployment of "ultimate" technology (T3) and, if the cost reduction is known about early enough, to further extension of previous efforts (T1 and T2) (see Figure 30, left), while still complying with the same carbon budget (Figure 30, right).

Unlike the previous case, innovation in ultimate technologies makes a much steeper fall in end-of-period shadow price of carbon possible, as such technologies have high abatement potential and a significant price differential with other technologies. Hence, drops of a quarter or even a third in the value by 2050 would be conceivable in a favorable context of more intensive international cooperation in combating climate change.

The possible order of magnitude is illustrated in the inset below. The case study evaluates the abatement cost connected with "power to gas" technology enabling storage of energy in accordance with the various plausible scenarios for deployment of this technology identified in technological foresight studies and with a learning rate ranging from 5% to 20%.

Inset 8 – Foresight illustration of a non-mature technology: "power to gas"

According to current "best available technology" hypotheses, it is now possible to produce methane from electrolytic hydrogen (and decarbonized electricity) for €207/MWh gas (order of magnitude) – almost ten times more expensive than the wholesale price of natural gas today.

The current implicit cost of one metric ton of CO_2 avoided thanks to this technology would therefore be €770.

According to international cooperation scenarios (joint hypotheses on volumes deployed and learning rates), abatement costs connected with this technology could be much less in 2050.

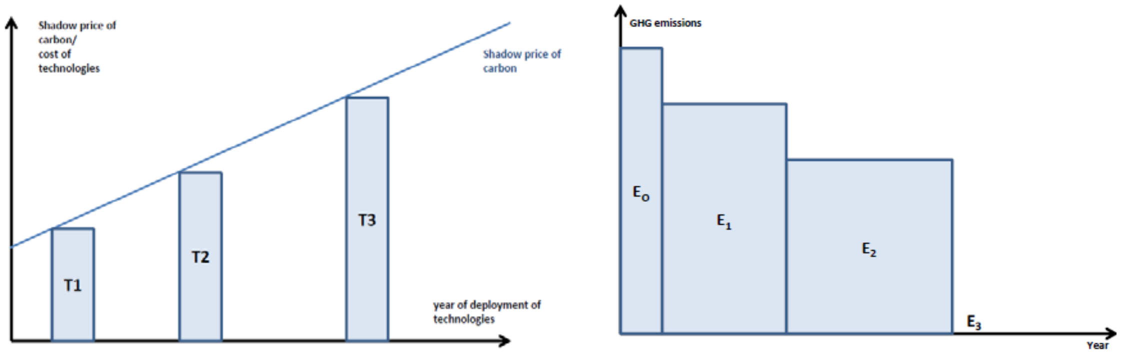
In the case of a 3°C scenario where there is inadequate cooperation and restrained technical progress (5% learning rate), the cost relating to avoided CO_2 emissions would be close to €600/tCO_2eq (electrolyzers and methanation reactors would be 25% less expensive, with a total cost of €170/MWh).

However, in a 2°C scenario, involving wider deployment of the technology and under optimistic hypotheses on technical progress (20% learning rate), the cost relating to avoided CO_2 emissions could go down to €470/tCO_2eq (equipment prices could fall by 75%).

Sources: calculations carried out on the basis of data from Frontier Economics Ltd 2018, "The Future Cost of Electricity-Based Synthetic Fuels", commissioned by Agora Energiewende and Agora Verkehrswende; FVV 2016, "Renewables in Transport 2050", Forchungsvereinigung Verbrennungskraft-maschinen e.V.; and hypotheses on the cost of electricity and the discount rate (4.5%).

Figure 28 – Deployment of technologies and emission reduction in the initial scenario

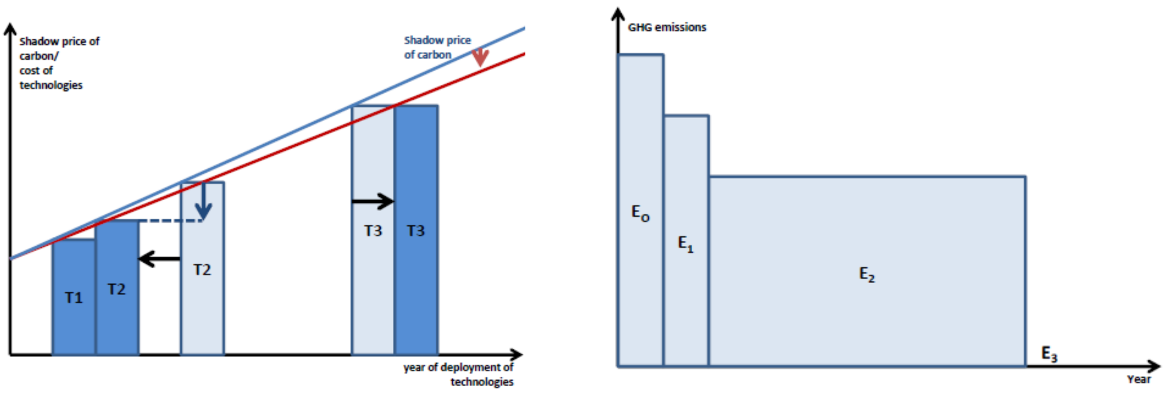
Order of deployment of technologies | GHG emissions



Source: France Stratégie, the authors

Figure 29 – Impact of an innovation on an intermediate technology

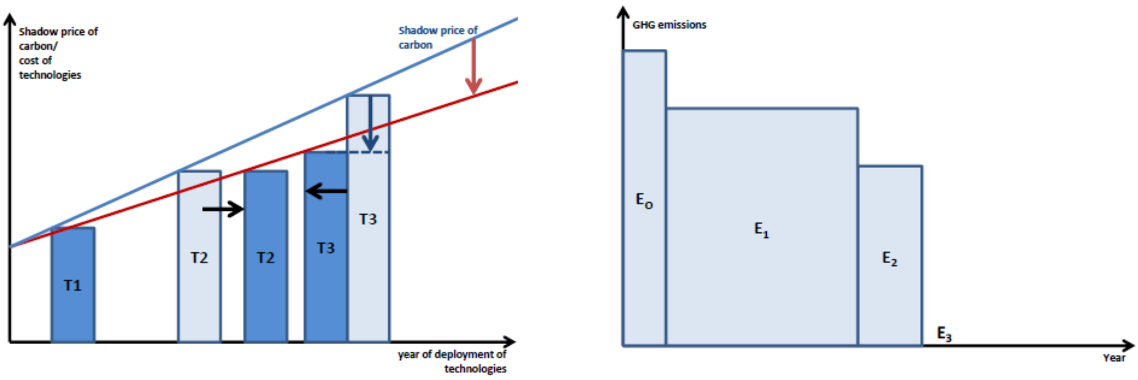
Order of deployment of technologies GHG emissions



Source: France Stratégie, the authors

Figure 30 – Impact of an innovation on “ultimate” technologies

Order of deployment of technologies GHG emissions



Note: E0+E1+E2 = B where B is France’s carbon budget, identical in all three cases.

Source: France Stratégie, the authors

Sensitivity of results to agents’ behaviors

The macroeconomic models used are estimated or calibrated on economic agents’ present and past behaviors. Therefore, by their very construction, they cannot correctly anticipate changes in agents’ behaviors in the face of a major challenge. Yet it is possible that if there is growing societal awareness of the issues involved in combating climate and effective public awareness-raising action, there will be increased sensitivity to the relative price.

Sensitivity tests were conducted with the NEMESIS model, considering an increase in substitution elasticities between energy products, i.e. an increase in economic agents’ reaction to relative prices of energy. In these variants, households and companies substitute decarbonized energies for fossil fuels more quickly when relative prices are modified. Variants with a twofold and 50% increase in such elasticities are considered. For a twofold increase:

– at household level, substitution elasticity between carbonized and decarbonized energy sources is increased by around 0.4 to 0,8;

– at company level, substitution elasticity between electricity and other energies is increased by between 0.7 and 1.4 and, for other energies, substitution elasticity is between 0.5 and 1.

Sensitivity tests suggest that such an increase in sensitivity to carbonized energy prices would enable a reduction of between 20% and 30% in carbon value for a twofold increase in substitution elasticities, and 15% for a 50% increase in these elasticities (see Table 12).

Table 12 – Carbon value sensitivity to change in agents' behavior

	Impact on shadow price
Doubling of elasticities	One third fall in value
Elasticities increased by 50%	Around 15% fall in value

Source: authors' calculations based on simulations by the NEMESIS model.

The change in behavior considered corresponds to an increase in agents' sensitivity to energy prices. Its implementation is expressed by a twofold or 50% increase in substitution elasticities between energy products.

Summary of areas of uncertainties

Sensitivity of results to the various sources of uncertainties analyzed is recapped in the following Table.

Table 13 – Summary of sensitivity tests

	Variant	Impact on shadow price		
		2030	2040	2050
LULUCF sinks / purchase of allowances abroad	+/- 10 $MtCO_2eq$ of sinks around the central hypothesis of 85 $MtCO_2eq$	Gap of around +/- 5% around central value	Gap of around +/- 10 to 20% around central value	Probable gap of +/- 20% round central value
Fossil fuel prices	Taking account of the IEA's Sustainable Development scenario (-€47, half as much in 2040 compared with the "New Policies" central scenario)	Around 6% to 8% increase in shadow price		
Competitiveness	No variant modeled	Impact on macroeconomic variables, not on shadow price		
Technological progress	Non-model case studies. Taking account of alternative scenarios with learning rates varying from 5% to 20% for marginal technologies and more or less intensive international technological deployments	Low impact	Moderate impact	High impact. Possible fall of over a third in shadow price compared with central hypotheses
Agents' behavior	50% increase in substitution elasticities between carbonized and decarbonized energies	The 50% increase in substitution elasticities between energies shows a drop of around 15% in shadow price		

Source: France Stratégie, the authors

2. Investment is key to successful transition to climate neutrality

2.1. Sectoral evolutions

Structure of reductions by emission source

Although carbon value is uniformly applied to all emissions, emission reductions are not distributed proportionately between emission sources, due to very different abatement possibilities. Whereas energy-induced emissions may be almost completely eliminated, it is highly unlikely that those of agricultural origin can be reduced by more than half, those from industrial processes by more than three-quarters, and those from waste treatment by more than four-fifths compared with 1990 levels. Under hypotheses of LULUCF sinks of between 75 $MtCO_2eq$ and 95 $MtCO_2eq$, total reduction of gross emissions to achieve net neutrality in 2050 would therefore correspond to achievement of a Factor 6 to over 7 compared with 1990. Table 14 and Figure 31 present the assumed distribution of efforts in order to achieve climate neutrality by GHG emission source.

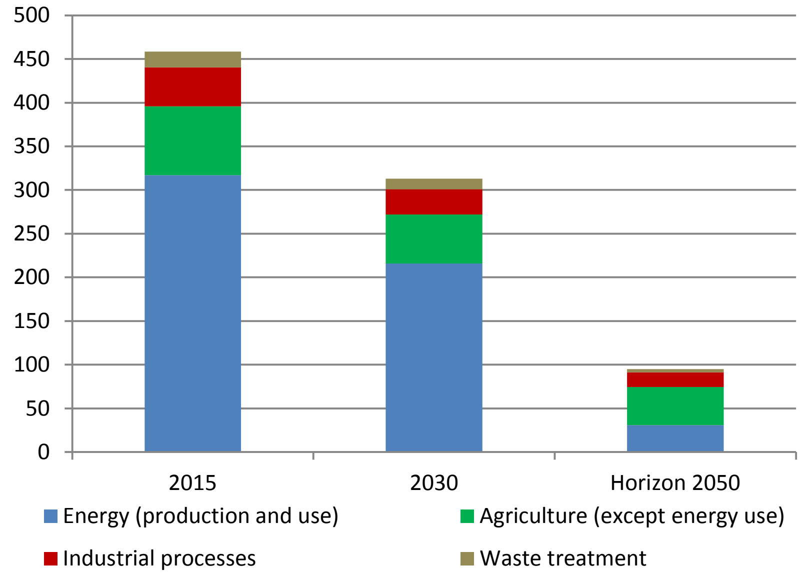
Table 14 – GHG emission reductions by emission source

Emission source	Emissions 1990	Emissions 2030		Emissions 2050	
	$MtCO_2eq$	$MtCO_2eq$	% of 1990 emissions	**$MtCO_2eq$**	% of 1990 emissions
Agriculture (apart from energy)	83	56	67%	43	52%
Industrial processes	67	29	43%	17	26%
Waste treatment	19	12	63%	4	21%
Energy	377	214	57%	11-31 depending on sinks	3%-8% depending on sinks
Total	546	311	57%	75-95 depending on sinks	14%-17% depending on sinks

Note: sinks correspond to LULUCF sinks.

Source: France Stratégie, authors' calculations based on information provided by the DGEC, CGDD and INRA

Figure 31 – Annual emission flows by emission source* (in $MtCO_2eq$)



* Under the hypothesis of 95 $MtCO_2eq$ LULUCF sinks.

Source: France Stratégie, authors' calculations based on information provided by the DGEC, CGDD and INRA.

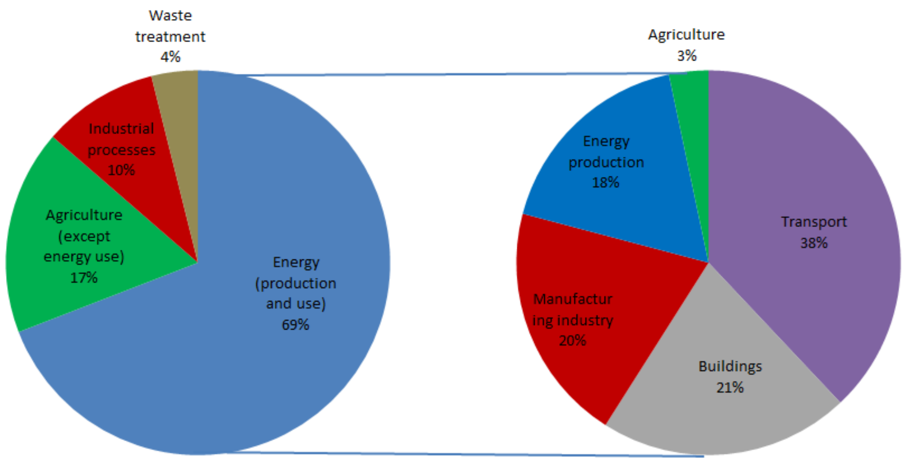
Sectoral breakdown of efforts to reduce energy-induced emissions

In 2015, GHG emissions connected with energy use and production accounted for around 70% of total GHG emissions apart from LULUCF (see Figure 32), 317 $MtCO_2eq$ in all. The transport sector is the largest emitter, accounting for 38% of energy emissions, over a quarter of all GHG emissions. Next in line are (residential and tertiary) buildings and the manufacturing industry, each of which accounts for around 15% of total emissions (over 20% of energy emissions), followed by the energy production sector; accounting for 12% of total emissions (18% of energy-induced emissions).

Achieving net zero GHG emissions in 2050 would involve reduction of energy-induced emissions to no more than 11 to 31 $MtCO_2$ in 2050 according to LULUCF sink hypotheses, a reduction of 90% to over 97% compared with 2016. Such deep energy decarbonization, at use and production levels alike, involves significant reductions in all sectors (see Figure 33).

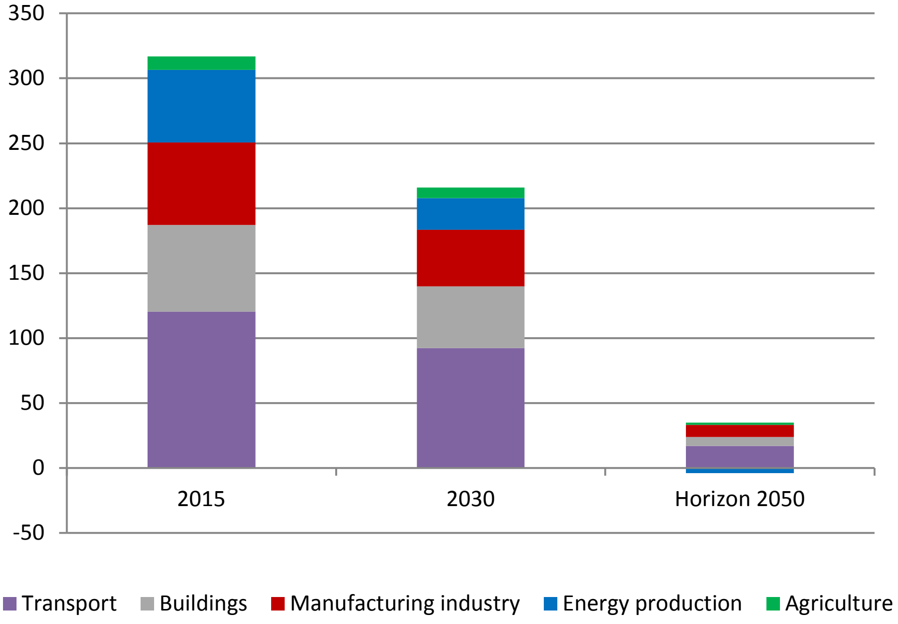
- The energy production sector could achieve negative emissions with the help of BECCS deployment, which would enable absorption of other sectors' emissions.
- Other economic sectors would all decarbonize in major proportions.
- In volume, the transport and tertiary/residential building sectors would concentrate the largest totals of GHG emission abatements to achieve.
- The dynamics of sectoral decarbonization differ significantly depending on model: some models decarbonize all sectors in parallel, while others decarbonize economic sectors successively (see Figure 34).

Figure 32 – Breakdown of emissions by source in France in 2015



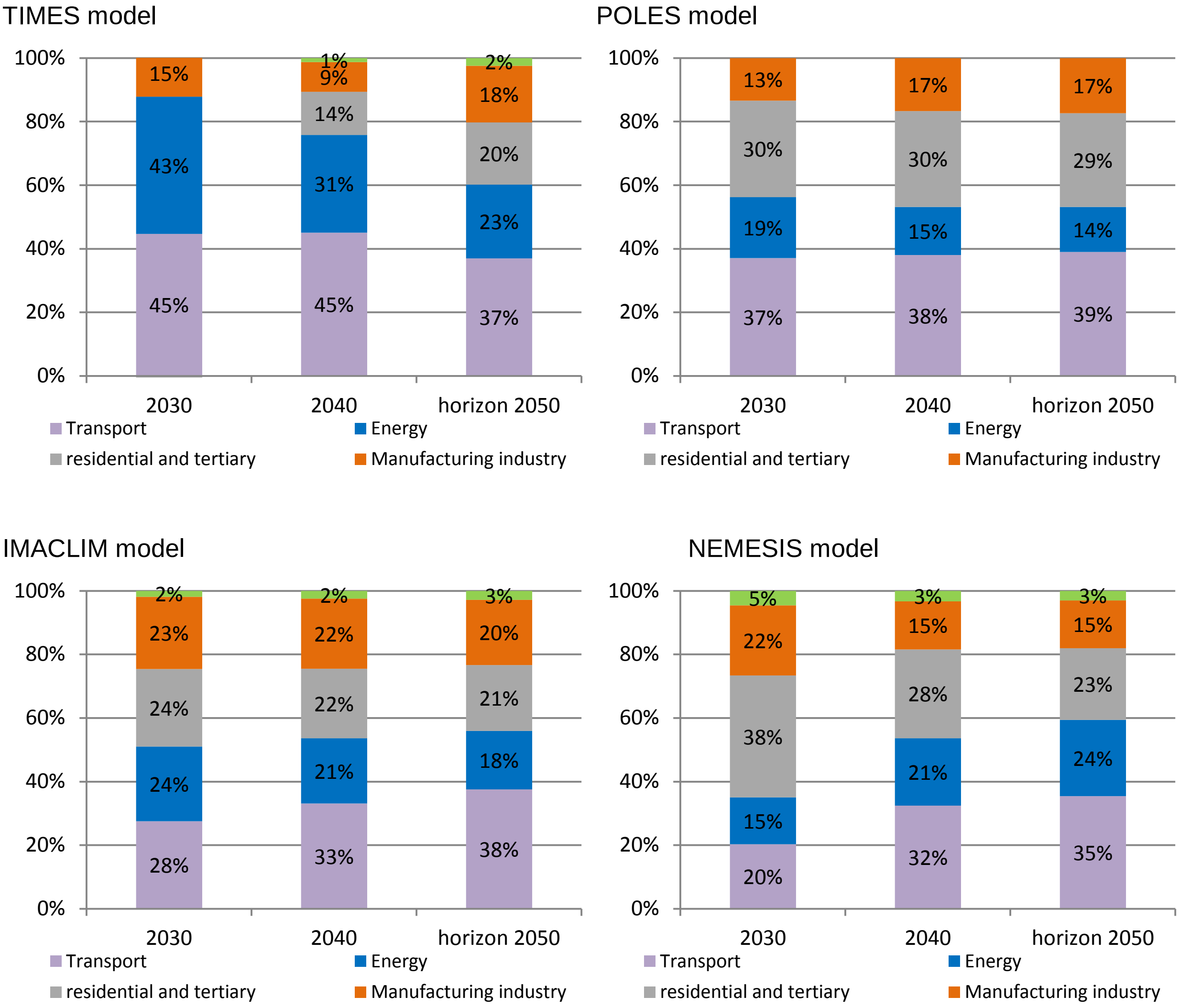
Source: DGEC figures, 2015 inventory and data from models

Figure 33 – Sectoral decarbonization of energy-induced emissions (indicative average of models in millions of metric tons of CO_2)



Source: authors' calculations based on data from models

Figure 34 – Sectoral contributions to energy-induced CO_2 emission reduction (in percentages of total reduction)



Source: simulations by TIMES, POLES, IMACLIM and NEMESIS models

2.2. The main levers of convergence towards climate neutrality

Decarbonization of the French economy will not only be based on efficient allocation of actions between sectors, but also within each sector:

– on a combination of two levers: improvement of energy efficiency and decarbonization of energy used;

– on investment expenditures enabling "greening" of capital already in use and constitution of new "green" capital.

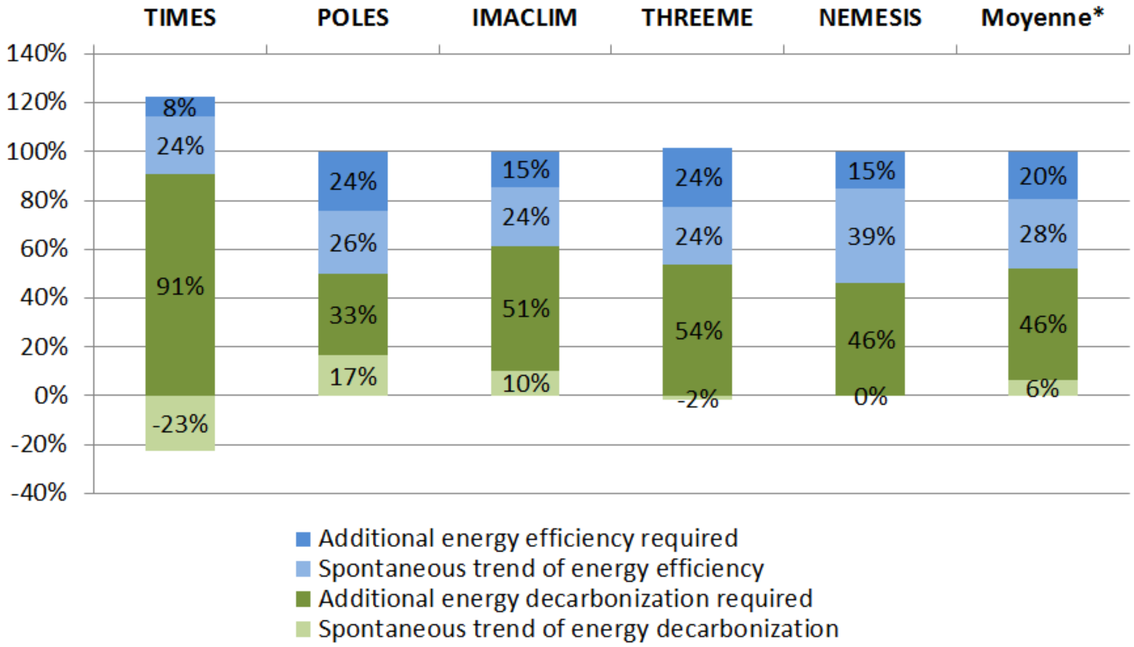
Net zero GHG emissions of the energy system is made possible by energy savings as much as by energy decarbonization

Models estimate that, in order to be efficient, reduction of emissions per unit of GDP by 2040 compared with 2015 should result (see Figure 35)[1]:

- for one half (48% according to the models' average), from improved energy efficiency – an improvement of no more than 20 points would require additional measures;
- and for the other half (52% according to the models' average) from energy decarbonization – such decarbonization being almost totally connected with climate policy

The first half, regarding energy efficiency; is expressed by changes in equipment, production methods and behaviors. The second, regarding energy decarbonization, is expressed in practice by a change in the energy mix reducing the share of fossil fuels in favor of renewable energies. Both levers involve major investments.

Figure 35 – Share of energy efficiency and energy decarbonization in decoupling of emissions and the GDP by 2040 compared with 2015



Interpretation: according to the IMACLIM model, reduction of emissions per unit of GDP by 2040 compared with 2015 is 61% the result of energy decarbonization, 10 points of which would be achieved without additional climate policy, and 49% the result of reduction in energy consumption.

* As demand for energy services is exogenous in TIMES, the average is calculated without taking this model into account.

Source: authors' calculations based on models' simulation results

[1] Models' results differ relatively little from this average, except for the TIMES model, however, for which demand for energy services is exogenous, and which consequently underestimates the importance of energy efficiency.

Major investment needs

Investment efforts may be considered at several levels.

- The first level is ***gross investments***, representing all investments made with the explicit aim of decarbonization. Setup of a windfarm, for example, is a *gross investment*. A great majority of such investments actually consist of redirecting existing investments and only a much smaller part constitutes additional investments to be made. Modeling exercises – in the context of this Commission as in most work published – do not enable direct evaluation of levels of investments to be redirected and consequently of gross investments. Various more in-depth studies suggest that redirected investments account for around three times the total of green investments. However, this estimation remains subject to a great many uncertainties[1].

- The second level is ***net green investments of substitution effects (apart from redirected investments)***, insofar as "clean" investments are partly made instead of "GHG-emitting" investments. In the example above, investment in a windfarm may be made in the place of investment in a coal-fired plant. Therefore, *net investment* is not measured by the cost of the windfarm but by the difference in investment cost between the windfarm and the equivalent coal-fired plant.

  Net investment of substitution effects is the direct surplus of investment required for decarbonization. Its total may be obtained using techno-economic models, by comparing the total of investments made in the "Net-Zero" scenario with those made in the reference scenario. Figure 36 presents the scale of investment flows obtained by the TIMES model. The investment surplus in the entire energy system (production and use) gradually increases as constraint becomes more pronounced, as such growth reflects a linear emission reduction and increasing abatement cost. According to this model, emission reduction will require supplementary annual investments in energy production and use of over 1 GDP point in 2030 and around 1.5 points in 2040. This would represent a 25% increase in energy investment in 2030 and a 30% increase in 2040. Sectors contributing the most are transport, building and energy production, electricity in particular. These investment totals only reflect investments in the energy system (production and use); they do not include investments necessary for decarbonization of agriculture, industrial processes and waste treatment. In addition, as models do not integrate the spatial aspect, they either do not take account of or undervalue certain investments, including those in infrastructures. Knowing that energy investments only concern

[1] Dasgupta D., Espagne E., Hourcade J.-C. *et al.* (2016), "Did the Paris Agreement plant the seeds of a climate consistent international financial regime?", *Note di Lavoro*, no.50, FEEM.

three-quarters of abatements to be achieved and that they may be underestimated, a highly approximate hypothesis of homothety to other sectors results in estimation that, **in total, such investment could reach 2 GDP points by 2040: it would then account for 10% of total investment in France, around 60 billion euros a year**. This order of magnitude is comparable with evaluations made at international level:

– the OECD evaluates global investment required to keep below 2°C at 6.9 trillion dollars a year over the next fifteen years, a 10% increase in average annual investments in infrastructures[1];

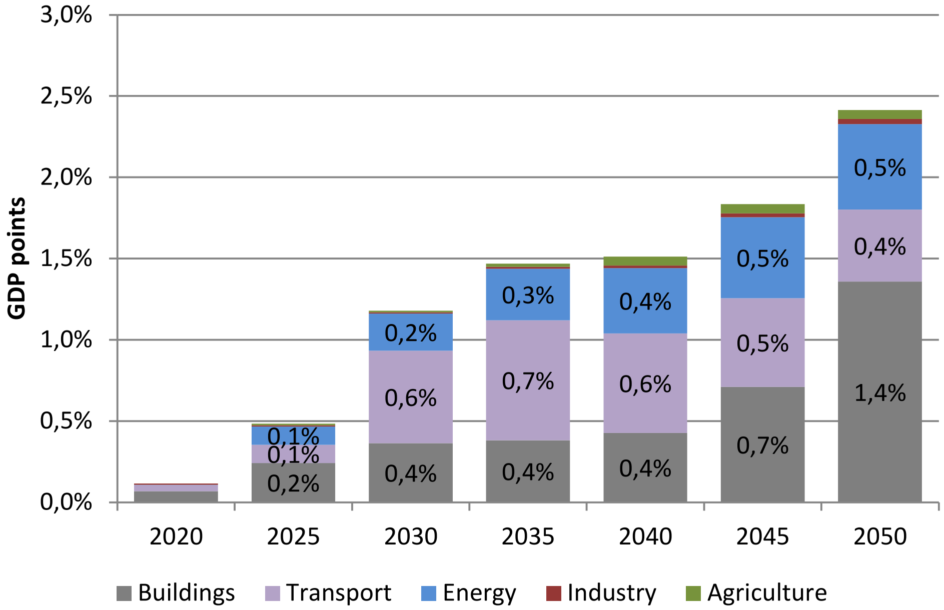
– the New Climate Economy Report[2], which draws on various studies[3], evaluates the increase in global investment in infrastructure at 5% in order to make such capital low carbon intensive;

– more recently, the IPCC, in its 1.5°C Report, estimates that by 2035, 2.5% of the global GDP will have to be devoted to low-carbon investment every year;

– and the European Commission[4] evaluates the increase in annual investment in energy production and use at up to 1.2% of the GDP between 2030 and 2050 if we are to achieve the “net-zero emissions” goal at European level (an annual average of between 175 and 290 billion euros over the period, depending on scenario). Investment would gradually increase to reach 1% of the GDP in 2035 and peak at 2% around 2040.

[1] See OECD (2017), *Investing in Climate, Investing in Growth*, and New Climate Economy Project (2018), *Unlocking The Inclusive Growth Story of the 21st Century*.
[2] New Climate Economy (2016), *The Sustainable Infrastructure Imperative. Financing for better growth and development*.
[3] Bhattacharya A. *et al.* (2016), *Delivering on Sustainable Infrastructure for Better Development and Better Climate*, and Global Commission on the Economy and Climate (2014).
[4] European Commission (2018), *A Clean Planet for All. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy*.

Figure 36 – Surplus investment in the system compared with the reference scenario

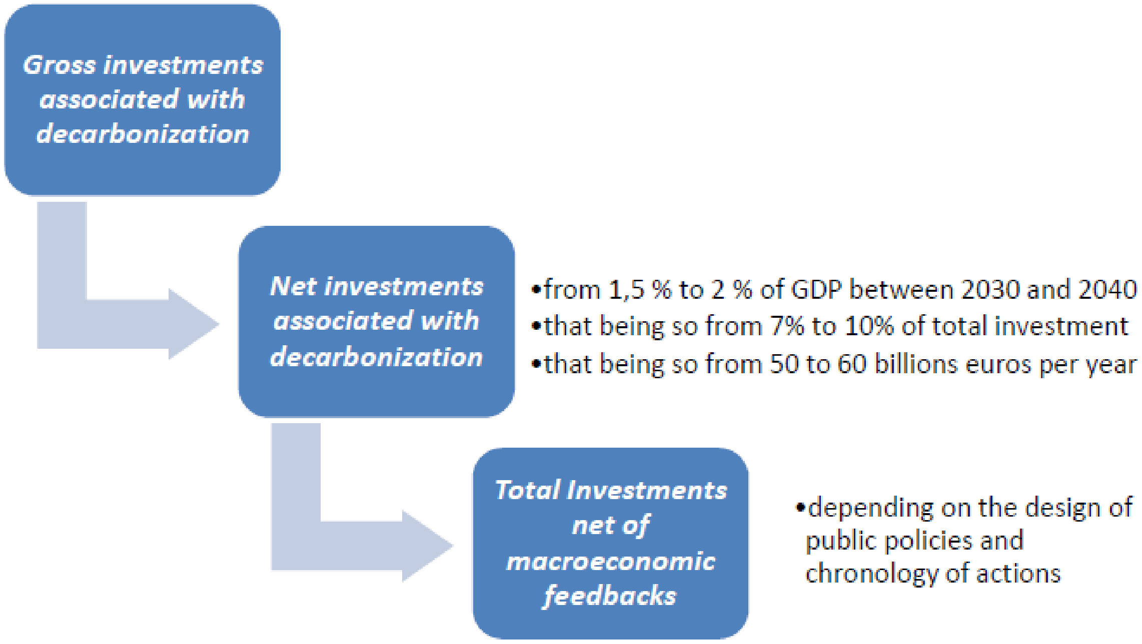


Source: TIMES model simulation (hypothesis of LULUCF sinks of 85 $MtCO_2eq$)

- The third and final level is ***total net investment of effects of macroeconomic feedbacks*** (crowding out, Keynesian revival, etc.). In addition to the previous level, this integrates two distinct effects:
  - *the crowding-out effect*: by mobilizing major financial resources, supplementary (or more costly) investments may crowd out investments elsewhere in the economy. When an economic actor – household or company – invests in a sustainable technology, it potentially abandons other investment expenditures. Once such crowding-out effects are taken into account, only about half of green investments would constitute a real increase in macroeconomic investment;
  - *Possible lever effects of the policy implemented*: Over the short term, instruments mobilized in the context of the policy to combat greenhouse gas emissions may generate Keynesian revival effects, and, over the longer term, enable reduction of market imperfections (via introduction of more pertinent legislation, more efficient recycling of tax revenues, etc.). Such lever effects may then result in increased macroeconomic investments. Their scale is entirely dependent on the policy implemented.

Finally, the real investment surplus at national level, resulting from all the effects identified, remains closely connected with the macroeconomic and financial context, design of public policies and chronology of actions.

Figure 37 – Investment needs



CHAPTER 4

THE VALUE FOR CLIMATE ACTION

On the basis of the results of the various approaches used, their comparative advantages and their complementarity, the Commission proposes a multiyear value trajectory up to 2050. This chapter explains the choices adopted and aims to evaluate and delineate the uncertainties surrounding this trajectory. Finally, it presents a number of macroeconomic evaluations of actions underlying the proposed trajectory.

1. The proposed trajectory is based on a value of €250 in 2030

1.1. A single trajectory for the whole economy

The value for climate action should constitute a single reference for the whole economy, even though savings opportunities and carbon abatement costs differ from one sector to another. *A priori* adoption of different "baseline" values in order to design decarbonization policies in the various sectors would come down to admitting that we are prepared to invest €1000 to obtain emission reductions in a sector that might only require €250, or €100 in sectors where abatement costs are lower, probably sectors that are high emitters and possess major reduction opportunities. A single reference is an incentive to mobilize decarbonization sources whose abatement costs are and will be lower than the "shadow" price, and, more generally, to proceed by merit order.

1.2. A multiyear trajectory based on a value of €$_{2018}$250/tCO_2eq in 2030

The 2030 anchor point

The Commission considers that 2030 is the ideal anchor point on a shadow carbon price trajectory, for three fundamental reasons:

– 2030 (a time horizon of just over ten years) is decisive in order to "anchor" expectations and initiate a public and private "low-carbon" investment program;

- by 2030, modeling work may draw on reasonably robust and reliable economic and technological foresight factors, even though they will naturally still be surrounded by uncertainties;
- decarbonization actions to be undertaken by 2030 will be useful to France, whatever the level of international climate cooperation.

Although the carbon value set for 2030 by the 2008 Report was €$_{2008}$100/tCO_2eq (€$_{2018}$110/tCO_2eq), the Commission proposes to revise it substantially upwards, setting it at €$_{2018}$250/tCO_2e. This high value bears witness to the length of the road yet to be travelled and expresses the cost of the technologies required to achieve the goal.

Linear catch-up from the present to 2030

The Commission chose to start out from the current shadow carbon price (€$_{2018}$54/tCO_2eq, from the 2008 Report). This does not mean that this initial value is an "optimal" point. It reflects the strategy of smoothening reduction of greenhouse gas emissions adopted in the specifications. In this context, models take account of this gradual reduction of emissions via two dynamics:

- the expectation dynamics, which leads actors to initiate investments and actions on the basis of future carbon values;
- the capital adjustment dynamics, which leads the same actors to take account of adjustment costs and therefore gradually adapt the stocks of assets to emission reduction requirements.

Starting from this initial €$_{2018}$54/tCO_2eq point, the value for climate action therefore increases sharply to reach the target levels for 2030 and 2040.

A shadow carbon price trajectory based on the costs of decarbonization technologies

After 2030, the proposed multiyear shadow carbon price trajectory integrates the result of these various approaches:

- model simulations that remain robust up to around 2040, when reduction levels approach Factor 4;
- foresight on the cost of the portfolio of enabling technologies required for successful decarbonization. The Commission does not assume the emergence of any new miracle disruptive "backstop" technology[1], i.e. a technology enabling total

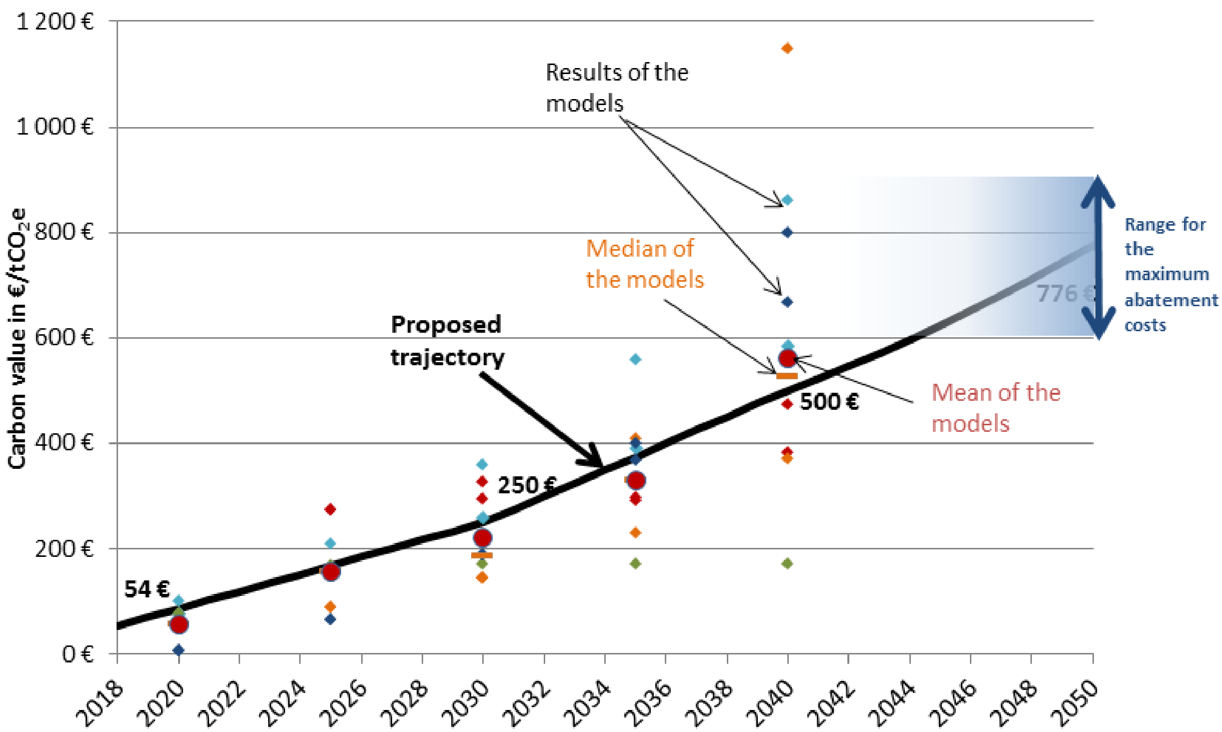
[1] A technology is regarded as "backstop" when it has almost unlimited potential as well as being inexpensive.

abandonment of fossil fuels or massive abatement of GHG emissions at moderate cost. It considers that the portfolio of enabling technologies (for example, more extensive direct use of decarbonized electricity or indirect use via the hydrogen vector produced in decarbonized fashion by electrolysis of water[1]) would enable achievement of complete decarbonization with relatively high switching prices (of over €600-900/t in 2050);

– calibration on a Hotelling rule as from 2040 for a 4.5% public discount rate, as this would guarantee that the value of climate gains is not overwritten by discounting.

This trajectory ends up with a value of $€_{2018}500/tCO_2eq$ in 2040 and $€_{2018}775/tCO_2eq$ in 2050.

Figure 38 – Trajectory proposal



Source: France Stratégie

[1] Direct or indirect use, *i.e.* by reconstitution based on hydrogen and a carbon source to be captured from liquid and gas carbonized combustibles ("power to liquid" and "power to gas").

2. The trajectory is revised upwards, in line with the most recent modeling works

2.1. Revaluation of the trajectory due to exhaustion of French and global carbon budgets

The construction of the shadow price of carbon is carried out in a different context from that in which the 2008 evaluation was made. Several factors now require modification of the trajectory defined ten years ago (see Figure 41).

Two factors require significant revaluation of the shadow price.

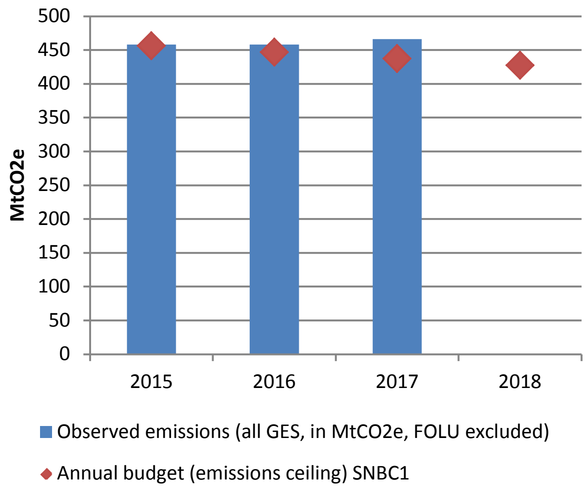
- **Exhaustion of the carbon budget**:

– at global level, the available carbon budget is much lower than it was ten years ago, a result of delayed action and the IPCC's more pessimistic estimation of available room for maneuver if we are to contain the rise in temperature;

– at French level, we have also been very slow to take action on behalf of the climate since 2008 (see Figure 39), even though the economic crisis contributed to a decrease in our GHG emissions (see Figure 40). We therefore need to commit to a shadow carbon price "catch-up" period between now and 2030, in order to make the investments and innovation efforts necessary to transition possible and cost-effective;

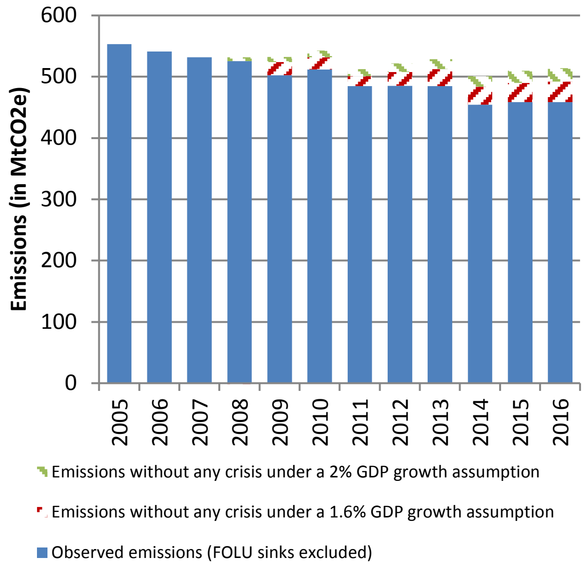
– France's recently adopted goal of "net" climate neutrality in 2050 is more ambitious than the Factor 4 goal, as it now corresponds to a reduction factor of between 5 and 7 depending on the sink hypotheses adopted.

Figure 39 – The delay in meeting the goals set by the SNBC in 2015



Source: SNBC and CITEPA (with provisional estimation for 2017)

Figure 40 – The crisis' potential contribution to reduction of past GHG emissions



Source: authors' calculations based on data provided by CITEPA, UNFCCC (2018) and INSEE

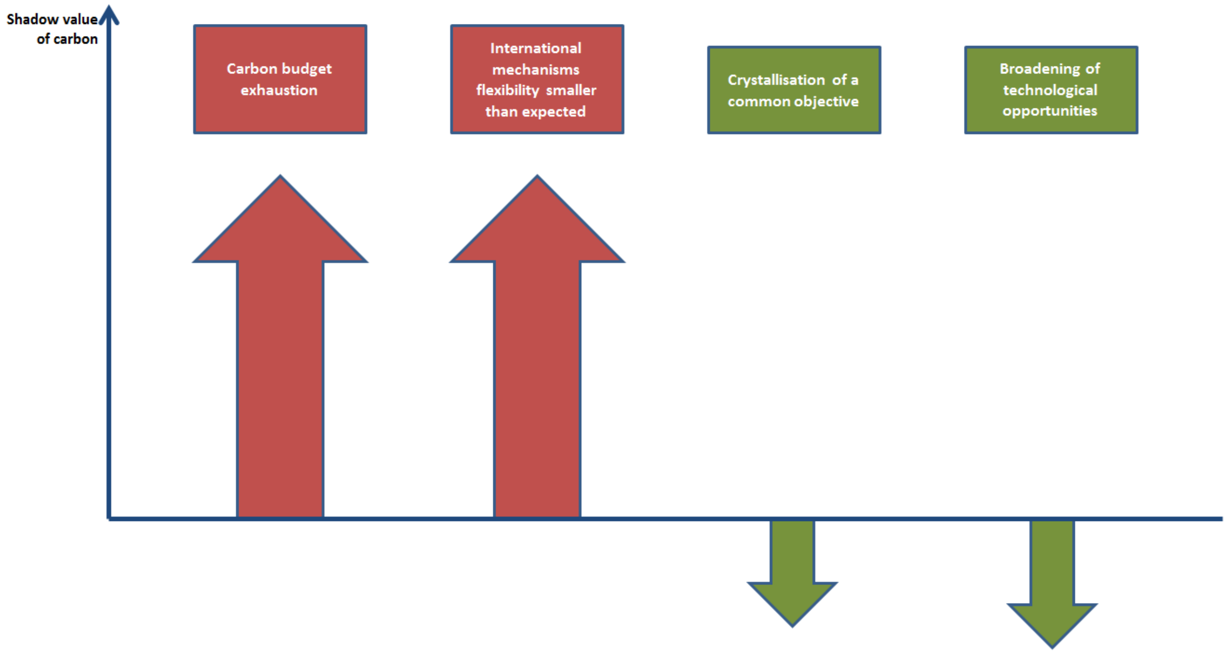
- **The very limited character of international flexibility mechanisms (carbon price and ETS).** In contrast to 2008, in constructing the trajectory, the Commission deemed it prudent not to integrate the possibility of compensating a surplus of emissions by purchasing rights to emit abroad. There are no concrete prospects with regard to international flexibility, which, all things being equal, increases the need for investment on national soil.

Conversely, other more recent factors have come into play contributing, to a lesser extent, to moderation of the value for climate action:

– the 2015 Paris Agreement, which gives concrete expression to a common goal, as well as to national commitments that are undoubtedly not yet enough to achieve it;

– a widening in the field of technological opportunities (as documented by the IEA for example), whose potential effects will be felt at the end of the period.

Figure 41 – What made the shadow price of carbon evolve



Source: France Stratégie

2.2. A trajectory consistent with the most recent international work

The shadow price of carbon proposed here is within the range of carbon values identified in the IPCC's most recent report of October 2018, a range that was itself revised substantially upwards in order to take account of the risks of rapid exhaustion of carbon budgets (see Chapter 1). As in the summary of the IPCC's Special Report of October 2018, evaluations based on a scenario in which there is low probability of exceeding 2°C come within a range of $\$_{2010}$15 to 1,300/t$CO_2$eq in 2030, while those based on a scenario in which warming would be limited to 1.5°C with moderate probability come within a range of $\$_{2010}$40-1,200/t$CO_2$eq (see Table 15). The extent of these value ranges reflects the variety of modelings, uncertainties on the present and future decarbonization technologies portfolio, and the reference scenarios considered.

Table 15 – Carbon values from the IPCC's 1.5°C Special Report (non-discounted values in $\$_{2010}/tCO_2eq$)

		Value range order of magnitude		Average values	
Scenario	Description	**2030**	**2050**	**2030**	**2050**
Below 1.5°C	Probability of exceeding 1.5°C less than 34%	130 – 5,500	240 – 13,000	1,472	3,978
1.5°C low	Probability of exceeding 1.5°C between 34% and 50%	40 – 1,200	120 - 4000	334	1,026
1.5°C high	Probability of exceeding 1.5°C between 50% and 67%	15 - 700	100 – 3,300	129	586
Lower 2°C	Probability of exceeding 2°C less than 34%	15 – 1,300	70 – 3,500	164	518
Higher 2°C	Probability of exceeding 2°C between 34% and 50%	15 - 200	45 - 950	56	169

Source: IPCC's Special Report for value ranges, and authors' calculations based on IPCC data (available on the IIASA website) for averages

3. More intense international cooperation would result in lower abatement costs

3.1. Technological and behavioral uncertainties

The proposed baseline trajectory falls within the context of global action enabling compliance with the Paris Agreement's commitments, if not keeping warming below 2°C. In this context, as from 2030 the proposed trajectory is subject to a range that increases over time, reflecting uncertainties on the cost of technologies, carbon sinks and changes in actors' behavior.

The range is dimensioned by evaluation of the uncertainties presented in the previous chapter with regard to size of carbon sinks and the cost of the most enabling decarbonization technologies identified in foresight work. It is also based on results' sensitivity to hypotheses on private actors' behavior (conservative or increased elasticities).

- In this context, the upper end of the range corresponds to a situation marked by major behavior inertias and incremental technical progress.

- The lower end of the range would correspond to a situation marked by more rapid deployment of new decarbonization technologies and changes in the behavior of all actors concerned, reflecting increased societal awareness of the issues involved in the fight against climate change.

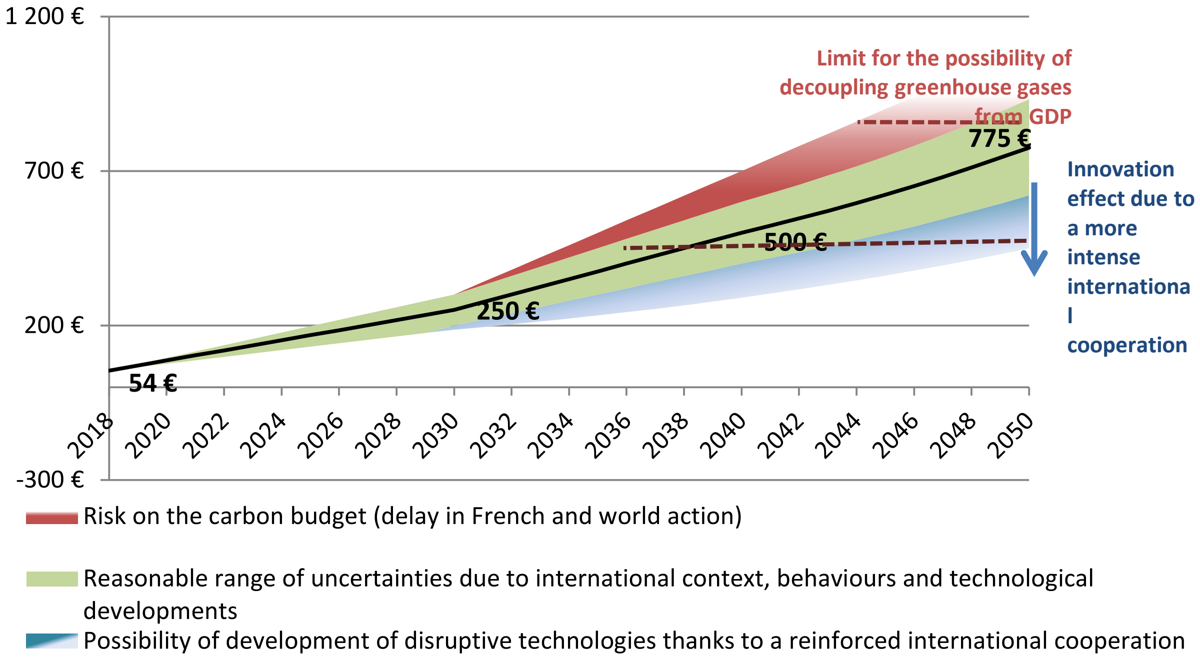
3.2. The value of international action

Apart from the central range, two areas of uncertainty may be elaborated on in order to highlight how important intensive international cooperation is up to 2050.

- The first area of uncertainty, expressed by the blue area in Figure 42, represents the medium- to long-term impact of more ambitious international action on the French shadow price of carbon. In this area, the “club” of countries signatory to the Paris Agreement would commit itself more strongly to compliance with net zero GHG emissions goals and foster development of disruptive technologies with low abatement cost and major long-term potential (technologies like “Power to X” and DAC (direct air capture of CO_2) could well be candidates). In the event of development and wide-scale global deployment of such technologies, the marginal abatement cost could be revised significantly downwards. On the basis of optimistic hypotheses on learning curves, it is estimated that the cost could fall to around €450/tCO_2eq.

- The second area of uncertainty is expressed by the red area. It is related to the risk of delay in international mobilization. Awareness of such a risk should lead to earlier investment in expensive technologies and a consequent more rapid rise in shadow price. Beyond the threshold corresponding to the maximum abatement cost connected with technological solutions (uncertain but estimated at between €600-900/tCO_2eq), it would be of no purpose to further increase the shadow price of carbon. This would lead to rapid mobilization of over-costly technological solutions or changes in behavior, with possible losses in wellbeing, GDP and competitiveness.

Figure 42 – Uncertainties surrounding the shadow carbon price trajectory



Source: France Stratégie

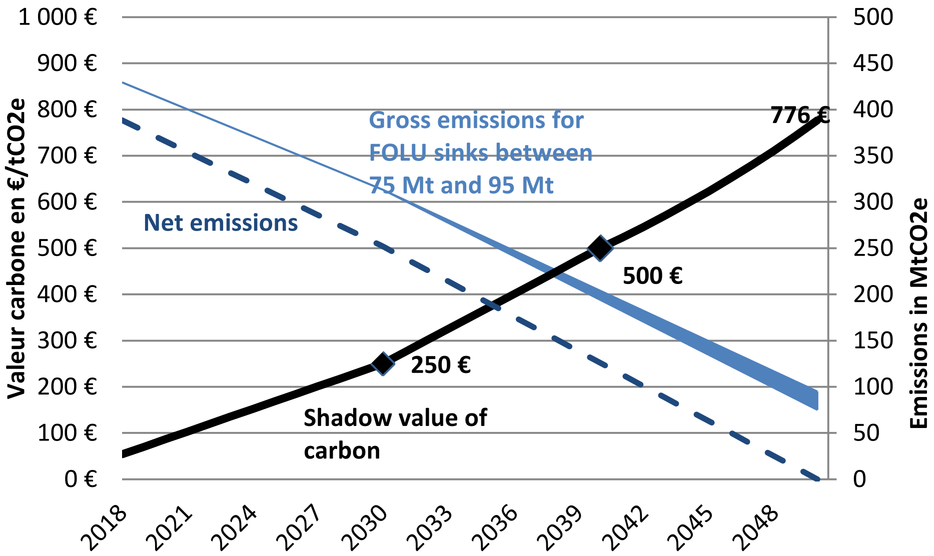
4. Valuation of decarbonization actions

The shadow carbon price trajectory acts as a reference for setting the value for climate action. Such valuation may be applied at microeconomic level to identify projects and actions useful to the fight against climate change, as elucidated in the following chapters devoted to uses. By way of example, this part proposes a macroeconomic valuation of potentially cost-effective actions combating climate change, socioeconomic gains relating to such actions, and the social cost of residual emissions.

4.1. Amount of cost-effective decarbonization actions

The relationship defined by the emission-reduction trajectory and the shadow carbon price trajectory (see Figure 43) is the result of a critical mass of decarbonization actions.

Figure 43 – A decrease in emissions concomitant with an increase in carbon value



Source: France Stratégie, authors' calculations

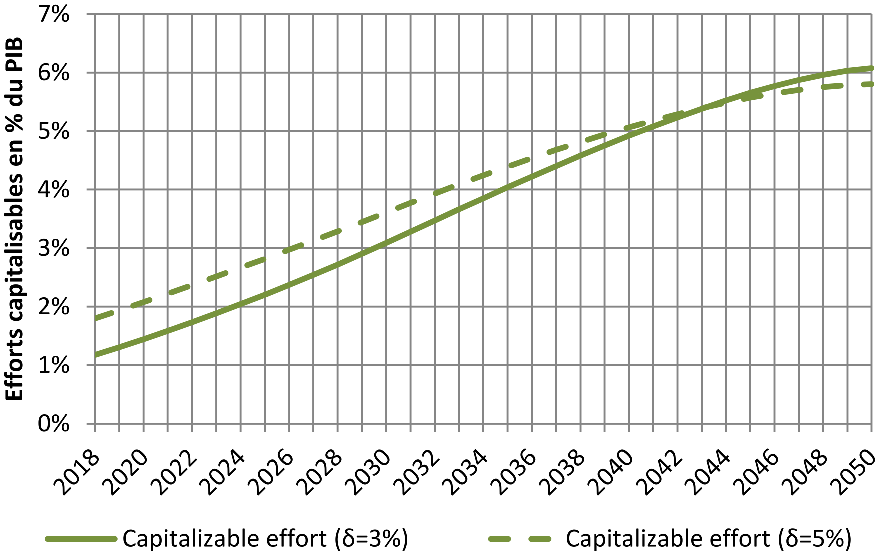
The carbon value trajectory aims to set a socioeconomic value for "actions" seeking to reduce greenhouse gas emissions so as to constitute a "green capital" enabling decarbonization of the economy. Actions resulting in emission reduction may be regarded as capitalizable inasmuch as their effects are long-term and increase future capacity to emit smaller quantities of GHGs. Changing modes of transport, thermally renovating a building and changing the energy production mix are all types of initial efforts in the form of investments or changes in behavior.

Such decarbonization actions may therefore be compared with economic investments, even though some of them go beyond the scope of simple physical investments measured by national accounting.

The amount of such capitalizable actions may reach 3% to 3.5% of the GDP in 2030, 5% in 2040 and 6% of the GDP in 2050 (see Figure 43 and Inset 9 for calculations). According to the simulation results presented in the previous chapter; only about half would constitute investment expenditures in the sense of national accounting (1.5% to 2% of GDP between 2030 and 2040).

These figures give orders of magnitude for totals of actions that the proposed shadow price trajectory should make cost-effective in order to constitute a "*decarbonized capital"* enabling achievement of net zero GHG emissions by 2050.

Figure 44 – Amount of capitalizable efforts or annual cost of efforts required (in percentage of the GDP, according to decommissioning rate δ)



Note: the amount of capitalizable efforts is calculated here under the hypothesis that all abatement efforts are made in the form of investment, in the widest sense of the word, whose decommissioning rate would be between 3% and 5%.

The calculation is based on a hypothesis of LULUCF sinks of 95 $MtCO_2eq$, a 4.5% discount rate and annual GDP growth rate of 1.6%.

Source: France Stratégie, authors' calculations

Inset 9 – Calculation of the value of abatements and the annual efforts amount to achieve them

Calculations of the social value of abatements and the amount of annual efforts are carried out on the basis of the following hypotheses:

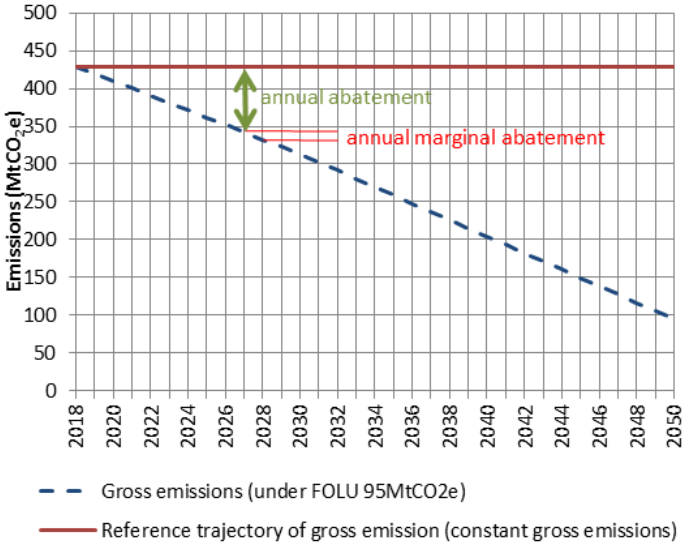
– a constant gross emission flow (no sinks) in the reference scenario (which is relatively consistent with the results provided by energy emission models);

– a linear reduction of emissions (with a slight break in the slope in 2030), i.e. constant annual marginal abatement to the tune of 10 to 11 Mt of CO_2eq, depending on sink hypotheses (75 $MtCO_2eq$ or 95 $MtCO_2eq$);

– a growing shadow carbon price as described in Figure 42: $€_{2018}250/tCO_2eq$ in 2030; $€_{2018}500/tCO_2eq$ in 2040; and $€_{2018}775/tCO_2eq$ in 2050. Post-2050, shadow price is then regarded as constant[1].

[1] This hypothesis is not exactly the same as the one adopted in the section on use in this Report, which considers that the shadow value should increase to 4.5% by 2060, but is used here as an illustration.

Figure 45 – Annual reduction efforts



Source: France Stratégie, authors' calculations

We have to distinguish *annual abatement* (or total annual abatement) described by the disparity in emission levels between the reference scenario and the scenario aiming for net zero GHG emissions in 2050 (double green arrow in Figure 45), and the *marginal annual abatement* defined by the increase in total annual abatement (double red line in Figure 45).

Whereas total annual abatement grows continuously throughout the period, marginal abatement remains constant as emission reduction is linear.

If abatements are entirely achieved by capitalizable efforts, such efforts made in each period must enable an increase in the annual marginal abatement's CO_2eq emission abatement.

Investment in T is assumed to be dimensioned so as to increase the abatement capacity E_t of e compared with the period T-1, as this capacity is decommissioned by δ in each period. Such investment must therefore correspond to an abatement capacity of $e + \delta * E_{T-1} = e \times [\delta(T-1)+1]$. The maximum cost-effective investment amount relating to such abatement capacity is equal to the gain defined by the discounted value of these emission reductions:

$$I_T = \sum_{t=T}^{\infty} \left(\frac{e \times [\delta(T-1)+1] \times V_t}{(1+a)^{t-T}} \times (1-\delta)^{t-T} \right)$$

$$= e \times [\delta(T-1)+1] \times \sum_{t=T}^{\infty} \left[\left(\frac{1-\delta}{1+a} \right)^{t-T} \times V_t \right]$$

The curves in Figure 44 are obtained with $a = 4{,}5\%$and δ between 3% and 5%.

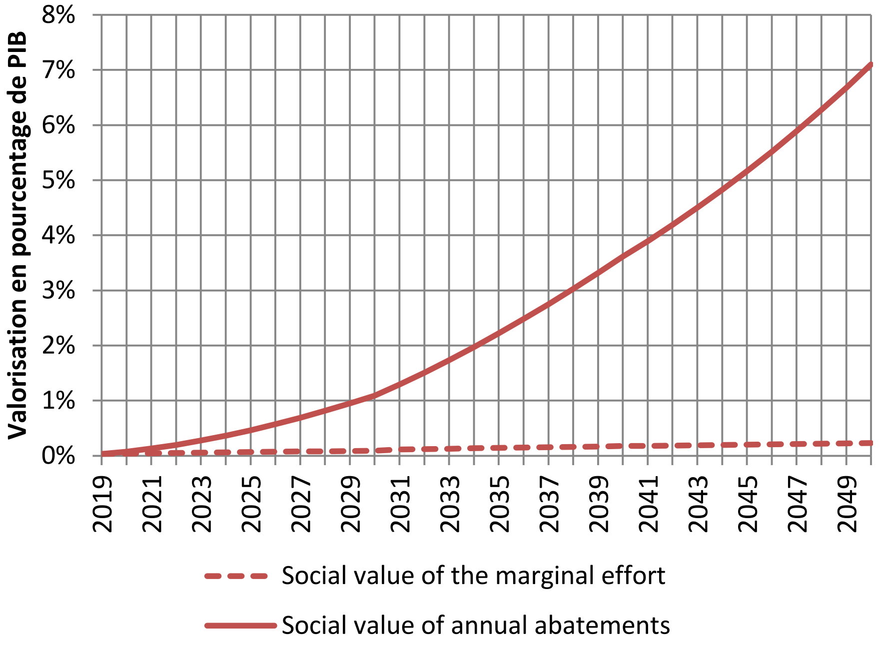
4.2. Value of emissions avoided by actions undertaken

The shadow carbon price enables evaluation of the value for the community of actions enabling avoidance of emission of one metric ton of CO_2 equivalent.

The socioeconomic value created by emissions avoided in year *t* can be measured by the total of emissions eliminated over year *t* (annual abatements represented in Figure 45) multiplied by the same year's shadow carbon price.

Under the calculation hypotheses described in the Inset; the social value of emissions avoided in year *t* would be equivalent to about 1% of the GDP in 2030, 3.5% of the GDP in 2040 and 7% of the GDP in 2050 (see Figure 46). This value increases over time as terminal emissions are more difficult to abate, making actions undertaken more valuable.

Figure 46 – Valuation of abatement efforts through the shadow carbon price trajectory (measured in percentage of GDP)



Source: France Stratégie, authors' calculations based on hypotheses described in the Inset

4.3. The socioeconomic cost of residual greenhouse gas emissions and the value of sinks

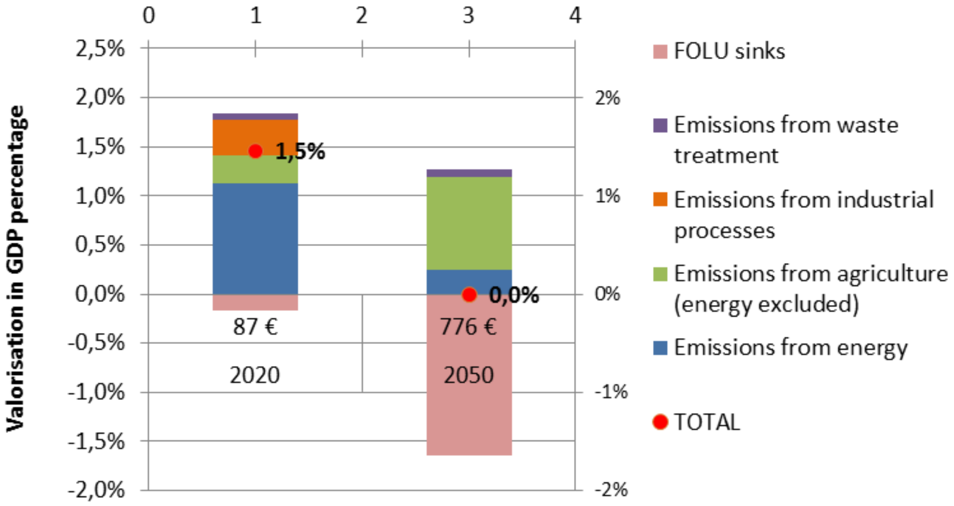
With the proposed trajectory's values, total valuation of net GHG emissions – which corresponds to the socioeconomic cost of residual GHG emissions[1] – would reach 1.5%

[1] Our premise is that carbon budgets have been defined in line with a cost-benefit approach and, consequently, that the cost-effectiveness approach employed here enables us to deduce a social cost of emissions.

of the GDP in 2020. This evaluation provides a measurement of the cost of non-action in 2020.

At the same time; due to the rise in shadow carbon price and the increase in sink capacities, the socioeconomic value of sinks enabling absorption of residual emissions proving difficult to abate would increase continuously over the period, to around 0.5 GDP points in 2030, 1.1 GDP points in 2040 and 1.6 GDP points in 2050 (see Figure 47 and Table 16).

Figure 47 – Valuation of sinks through the proposed trajectory (in percentage of the GDP)



Source: France Stratégie, authors' calculations

Table 16 – Cost of residual emissions and valuation of sinks (in percentage of the GDP)

	2020	**2050**
Shadow carbon price	**€87**	**€775**
Energy-induced emissions	**1.1%**	**0.2%**
Agriculture-induced emissions (apart from energy)	0.3%	1.0%
Emissions from industrial processes	0.2%	0.4%
Emissions from waste treatment	0.1%	0.1%
LULUCF sinks	-0.2%	-1.6%
Total	**1.5%**	**0.0%**

Value of emissions = Carbon value (€/tCO_2eq) * level of emissions (tCO_2eq)/GDPx100.

Source: France Stratégie, authors' calculations based on the shadow carbon price trajectory, the emission reduction trajectory and GDP projections[1]

[1] Projections from the 2015 Report 2015 by the European Commission's Ageing Working Group. Projections on which models are based.

CHAPTER 5

A REFERENCE FRAMEWORK FOR VALUING THE CLIMATIC IMPACTS OF PUBLIC INVESTMENT PROJECTS

France has a long tradition of public economic calculation evaluating public investment projects' full potential impacts on wellbeing. Such economic calculation is distinct from the usual financial calculations in three essential ways: it adopts the widest possible conception of a project's advantages for the community (lives saved, time gained, pollution avoided, etc.); it measures these advantages – and costs – over the long term; and it discounts them at a lower rate than a private investor's, reflecting the State's capacity to withstand and dilute risks.

Over the last ten years or so, socioeconomic analysis has come to take better account of environmental issues involved in projects, climate issues in particular:

- investment projects' contribution to the fight against climate change was better clarified with formalization of a shadow carbon price trajectory in 2008;
- the time horizon for projects' evaluation was increased in order to take better account of their long-term, even very long-term structuring effects;
- indexation of shadow carbon price on the public discount rate, in application of the Hotelling rule, has led to supporting carbon valuation up to distant time horizons, in order to avoid it being overwritten by the value of the time.

The new shadow carbon price trajectory proposed in this Report should provide an opportunity to take a new direction.

Taking all projects together, public investment in France was to the tune of 76 billion euros in 2016, i.e. 3.4% of the GDP, mostly carried out by regional and local authorities. National and local public investment projects should be making major contributions to achievement of decarbonization goals, whether by optimizing emissions due to energy consumption (thermal renovation of extensive and often antiquated property assets, etc.), facilitating deployment of renewable energies in towns (heating networks, networks of electric-vehicle charging stations, etc.[1]) or by decarbonizing mobility (transport infrastructures fostering modal shifts). Some public investments may be preliminary to implementation of decarbonization solutions by private actors (switching from gas to biomass heating via a heating network, switching to electric vehicles or use of public transport). Yet it has to be said that most public investment projects still “escape” transparent adversarial evaluation procedures. To extend the field of evaluation is a mean to better prioritize projects and target public money on the most relevant projects.

Revision of shadow carbon price, which in its turn is connected with revision of goals, requires renovation of the whole evaluation system: new reference scenarios taking account of the decarbonization goal, new carbon values, a new discount rate, and taking account of greenhouse gas emissions throughout project lifespans – from their development to end of service life, even if this extends beyond 2050.

1. Socioeconomic evaluation of projects must be extended and reinforced

1.1. All public operators are concerned

These days, all civil investment projects financed by the State, its public institutions, public health establishments and healthcare cooperation bodies are subject to obligatory prior socioeconomic evaluation. Furthermore, those for which public operators’ contributions exceed 100 million euros and represent over 5% of the project’s value net of tax are subject to an independent counter-assessment overseen by the Secretariat-General for Investment (SGPI) (see Inset 10).

Projects promoted by regional and local authorities, however, are not obligatorily subject to socioeconomic evaluation or counter-assessment. Extending the field of socioeconomic analysis to territorial authorities’ major projects, in full respect of the principle of free administration, would improve transparency of and consistency in local projects’ contributions to achievement of the national decarbonization goal. De facto, regional and local authorities have a key role to play in reduction of GHG emissions, in particular in development of local heating and transport networks.

[1] Even though deployment of such networks is not necessarily the responsibility of the public authorities and may also be overseen by private operators.

Inset 10 – Current obligations regarding socioeconomic evaluations and methodological aspects

These days, all civil investment projects financed by the State, its public institutions, public health establishments and healthcare cooperation bodies are subject to obligatory prior socioeconomic evaluation (Article 17 of the Public Finance Programming Law of 31 December 2012). Decree 2013-1211 of 23 December 2013 stipulates that:

- if the contribution of the abovementioned public projects exceeds a threshold of €20M net of tax, the project must be declared to the inventory and the socioeconomic evaluation file must contain certain specific information;
- if the contribution of the abovementioned public actors exceeds a threshold of €100M and represents at least 5% of the investment project total value net of tax, the socioeconomic evaluation is subject to an independent second assessment overseen by the Secretariat-General for Investment.

Evaluations and counter-assessments must be communicated to Parliament.

The general methodology for carrying out socioeconomic evaluations is presented in the Report issued in 2017 by the expert group on socioeconomic evaluation chaired by Roger Guesnerie[1], which draws on the 2013 Report by the Group chaired by Émile Quinet[2]. In particular, the 2017 Report presents the formula for an investment's socioeconomic net present value (NPV).

Simplified[3] and isolating the "greenhouse gas emissions" component, it is written as follows:

$$NPV = \sum_i \frac{\Delta market\ gains_i - \Delta market\ costs_i}{(1+a)^i} + \sum_i \frac{\Delta non\ market\ gains_i - \Delta non\ market\ costs_i}{(1+a)^i} + \sum_i \frac{\Delta emissions_i * VT_i}{(1+a)^i}$$

[1] France Stratégie (2017), *Guide de l'évaluation socioéconomique des investissements publics*, drafted under the authority of the Expert Committee on methods of socioeconomic evaluation of public investments, chaired by Robert Guesnerie.

[2] Commissariat-General for Strategy and Foresight (CGSP) (2013), *Évaluation socioéconomique des investissements publics*, Report by the Mission chaired by Émile Quinet.

[3] In particular, without taking account of the investment's residual value and by assuming that the discount year is the year the work started. Public expenditures take account of the opportunity cost of public funds (OCPF).

With:

- $\Delta emissions_i$- *Δmarket-costs* market-cost gap, compared with the baseline option;
- *Δemissions* variation of greenhouse gas emissions in year *i*, in differential to the baseline option;
- VT_i shadow carbon price in year *i*;
- *a* the public discount rate adopted for socioeconomic evaluations;
- sums bear on construction and operation years;
- non-market gains and costs do not include valuation of greenhouse gas emissions;
- market and non-market gains and costs diverge from the baseline options.

This formula differs from classic financial evaluation in that it takes the viewpoint of the community as a whole rather than of any single specific actor, takes externalities into account, and is based on a socioeconomic discount rate rather than a private discount rate.

In addition, various sectoral technical aspects are specified in complementary texts (including documents of use to the Directorate-General for Transport, Infrastructure and the Sea (DGITM) concerning transport infrastructures) or are likely to be so following publication of the 2017 Report.

1.2. All fields of public action are concerned

The traditional sphere for application of socioeconomic calculation is transport, which concentrates a great many public projects and mobilizes major budgets. As is illustrated in the Table below, socioeconomic calculation has been gradually extended to other fields over the past few years, including large public buildings (universities) and various other infrastructures (heating networks) – a recent development that needs to be reinforced.

One of the advantages expected from extension of the field of socioeconomic evaluations, in particular as far as carbon impacts are concerned, is that it will enable better prioritization of public projects, targeting those with more evident climatic virtues. On the basis of evaluations already available, it is clear that gains in terms of greenhouse emission reduction compared with a project's cost are highly discriminatory. Hence, such gains are particularly high in a number of collective railway and research projects. Conversely, and unsurprisingly, taking account of GHG emissions reduces the value of the motorway projects presented below (see Table 18).

Table 17 – Number of counter-assessments carried out by the SGPI, median values of projects concerned

Projects counter-assessed	2013	2014	2015	2016	2017	2018 Q2	All	Median value (€M)
Hospitals	5	2	7	2	2	2	**20**	**193**
Transport	1	2	5	4	3	0	**15**	**1,700**
Higher education and research	0	8	2	0	0	0	**10**	**178**
Other	0	1	2	3	4	0	**10**	**311**
Total	**6**	**13**	**16**	**9**	**9**	**2**	**55**	**288**

Source: Secretariat-General for Investment (SGPI)

Table 18 – Weight of carbon in evaluation of major public investment projects

Sector	Investment	Cost	NPV[1]	Carbon impact on the basis of the 2009 shadow price trajectory	Carbon/ Cost
		(€$_{2015}$M)	(€$_{2015}$M)	(€$_{2015}$M)	%
Energy	Geothermal heating and cooling network on the Saclay Plateau	47	23	7	15%
Railway	Modernization of the Serqueux-Gisors line	344	786	472	137%
GPE	Grand Paris Express program	21,815	28,449	6,825	31%
Research	Microcarb (equipment for measurement of CO_2 emissions by satellite)	142	31	105	74%
Motorway	Rouen East bypass	841	787	-78	-9%
Railway	Charles de Gaulle Express	1,714	3,056	76	4%
Motorway	Castres-Toulouse motorway link	275	559	-52	-19%
Building	Reconstruction of the Bordeaux-Gradignan prison	107	21	1	1%
Railway	HPGVSE – modernization of the Paris-Lyon line	350	2,156	396	113%

Source: Secretariat-General for Investment (SGPI)[1]

[1] Including the opportunity cost of public funds, representing the opportunity cost of mobilizing public money on a specific project. See Commissariat-General for Strategy and Foresight (2013), *Évaluation socioéconomique des investissements publics*, report by the mission chaired by Emile Quinet.

The shadow carbon price trajectory proposed in this Report, revised sharply upwards, should accentuate project prioritization: under the strong hypothesis of an unchanged reference scenario, there would be greater discrimination between greenhouse gas-emitting and non-emitting projects, as is illustrated in purely indicative fashion by the Table below. Evolution would not be homothetic for all projects insofar as the chronology of emissions avoided or generated plays a major role in calculation.

Table 19 – NPV component connected with consideration of greenhouse gas emissions in evaluation of major public investment projects (with reference scenario unchanged)

Investment	With the current shadow price trajectory	With the proposed shadow price trajectory *
	(€$_{2015}$ M)	(€$_{2015}$ M)
Geothermal heating and cooling network on the Saclay Plateau	7	14
Modernization of the Serqueux-Gisors line	472	856
Grand Paris Express program	6,825	12,599
Microcarb (equipment for measurement of CO_2 emissions by satellite)	105	296
Rouen East bypass	-78	-345
Charles de Gaulle Express	76	75
Castres-Toulouse motorway link	-52	-241
Reconstruction of the Bordeaux-Gradignan prison	1	2
HPGVSE – modernization of the Paris-Lyon line	396	361

* Without modifying the reference scenario, by way of illustration.

Source: Secretariat-General for Investment (SGPI) calculations

2. The entire evaluation framework should be revised in the light of the climate neutrality goal

The shadow carbon price currently used in socioeconomic evaluations comes from the 2009 report[2], complemented by the 2013 France Stratégie report on socioeconomic evaluation[3]. In order to ensure that public investment decisions are consistent with the new net zero GHG emissions goal, we propose to update this trajectory on the basis of this Report's proposals.

1 Reports online on the SGPI website: www.gouvernement.fr/Rapports_CE.
2 Centre for Strategic Analysis (2009), *La valeur tutélaire du carbone*, report by the Commission chaired by Alain Quinet.
3 France Stratégie (2017), *Guide de l'évaluation socioéconomique des investissements publics*, *op.cit.*

Upward revision of the shadow carbon price trajectory must be accompanied by an update of the methodology for evaluation of emission projects, taking three questions into consideration: choice of reference scenario and taking account of risks involved, carbon value after 2050, and taking account of emissions generated during the construction phase.

2.1. Valuation of the contribution of economy decarbonization projects should include risk analysis

In order to evaluate a project's contribution to decarbonization of the economy, three factors have to be taken into account:

- the baseline situation in which the project is to be carried out and the uncertainties surrounding it;
- the project's flexibility in adapting itself to any change in the baseline situation;
- the correlation between gains generated by the project and economic growth.

Baseline situation and related uncertainties

Socioeconomic calculation does not evaluate a project's absolute value but rather its contribution to collective wellbeing compared with a situation in which the project would not have been undertaken. This assumes that sector-by-sector reference scenarios are available describing the evolution of main parameters (economic, technological and social trends) in the sector under consideration, along with a baseline option, i.e. a description of alternatives in the project's absence. The gains a project provides therefore very much depend on the hypotheses adopted to describe the situation in which it was not undertaken.

In current socioeconomic practices, reference scenarios and options are not constructed "on the fly": they are scenarios of convergence towards an official decarbonization goal, under the hypothesis of an alignment of public polices to achieve such goal.

Inset 11 – Decarbonization included in the reference scenario: example of a railway project

How important construction of the reference scenario is may be illustrated by the example of a railway project whose carbon gains require valuation. Such gains are essentially due to a modal shift: evaluation sets a value on emissions that will not be emitted by users who switch from road or air travel to rail travel. But from the present day up to 2050, what car population does one take into consideration in order to make these calculations? If the car population has not been decarbonized, the project provides major carbon gains via the modal shift. If, however, the car population becomes fully electrified, there will be no metric tons of carbon to evaluate at the end of the period, whatever the shadow carbon price happens to be in the same year (assuming that electricity itself is totally decarbonized). The railway project's advantages with regard to reduction of greenhouse effects due to the modal shift from car to train are therefore zero after 2050[1]. The only gain left is to do with the shift from air to rail. Therefore, increase of carbon value over the long term does not automatically involve an increase in valuation of a project's carbon gains, in particular for distant time horizons. Everything depends on the reference scenario under consideration and the way in which one evaluates the risk that the decarbonization goal will not be achieved.

As choice of reference scenario is of crucial importance as regards the aim to achieve total decarbonization of human activities in 2050, analysis of a project's contribution to decarbonization must take account of uncertainties regarding achievement of net zero GHG emissions in 2050. Net zero GHG emissions is an ambitious goal, not a foregone conclusion. When you evaluate a project in a decarbonized baseline environment, it is prudent to take account of the risk that decarbonization may be slower than anticipated[2], which would have a retroactive impact on the project's interest.

At this point in time, the Commission is not making any specific recommendations on how to take such uncertainties into account, leaving it to France Stratégie's expert group on socioeconomics to come up with the right project analysis reference framework. It considers that such expert assessment work should take three requirements into account.

- Reference scenarios should integrate the new net zero GHG emissions goal and the fact that public policies will foster decarbonization, as this is unlikely to be exclusively based on public investment projects. In this respect, the expert group will be able to draw on the SNBC's sectoral scenarios.

- The "insurance" value of certain structuring projects should be monetized. The important thing is to avoid a situation where projects useful to decarbonization are not carried out solely because we have taken convergence towards net zero GHG emissions for granted. This question is of particular importance for projects whose

[1] This does not mean that carbon value is zero by this time: if we examine a coal-fired plant project instead of a railway project, it is important that carbon value in 2050 is not zero in order to discourage investment in the coal-fired plant.

[2] This may happen even when the carbon value calculated to achieve this goal is incorporated into all public policies, if the shadow carbon price initially calculated is too low.

contribution to decarbonization cannot be regarded as marginal (major urban-planning or transport network projects, for example) and which provide public and private actors alike with alternative uses to those based on carbonized energies.

- Consistent by-sector versions of the decarbonization goal must be developed, a task which assumes that reference scenarios per major sector are:
  - adopted in consultation with all public actors concerned, with France Stratégie responsible for coordination;
  - made explicit in public reference documents usable by contracting authorities;
  - regularly revised to incorporate new information, bearing in particular on changes in behaviors and the technological offer;
  - taken into account by the Secretariat-General for Investment (SGPI) in its roles as investor and coordinator of public investments.

The questions raised by evaluation of projects and their confrontation with a reference scenario lead more generally to the subject of taking risks into account in project value. We recommend that France Stratégie's report prepared under the aegis of Christian Gollier[1] is further developed in two ways: to take account of projects' option value and the rate at which benefits and costs of projects combating climate change are discounted.

Better integrating a project's option value in order to take account of the irreversibility of certain decisions[2]

The fight against climate change calls for early action to prevent the risk of serious irreversible damage. With regard to projects with potentially very long lifespans, it is also pertinent to maintain some flexibility. There is a risk of regarding already known solutions as "indispensable", deploying them on a wide scale on the basis of too short-termist or mechanical socioeconomic analyses and discouraging innovation enabling emergence of potentially more effective solutions, so creating a technology lock-in. Such flexibility can take two forms:

- fostering early implementation of projects with flexible uses. For example, a heating network may be supplied by a variety of heat sources: it is therefore not necessary to know which sort of renewable heat will be prioritized in the future in order to be certain of the interest of this type of infrastructure;

[1] Centre for Strategic Analysis (2011), *Le calcul du risque dans les investissements publics*, report by the Mission chaired by Christian Gollier.
[2] Bureau D. and Gollier C. (2009), "Évaluation des projets publics et développement durable", CEDD, *Références économiques pour le développement durable*, no.8.

- sequencing certain decisions over time in order to take better account of new information. For example, before widespread deployment of a given transport network (electric motorway, network of charging stations for a specific type of vehicle, etc.), it may be useful to make sure that no alternative technology would enable more efficient obtainment of similar results.

Continuing work to better integrate risks in definition of shadow carbon price

The discount rate used to evaluate projects and, more generally, public policies with long-term consequences depends on a variety of parameters (pure preference for the present, expected per capita GDP growth, marginal wellbeing gains connected with increased consumption, precautionary approach). The discount rate must also be refined to take account of systemic risks that the State cannot protect itself against and which are impossible to share, starting with macroeconomic risk.

As the complement to Christian Gollier's report[1] makes clear, the question of correlation to macroeconomic risk is of particular importance in determining the discount rate applicable to projects devoted to combating climate change. In practice, this rate may be increased or decreased depending on the nature of uncertainties:

- if the main uncertainty on growth is to do with the pace of technical progress enabling decarbonization, there is a risk of strong growth generating large quantities of emissions. The marginal benefit of a project combating climate change will then be positively correlated with the GDP (positive "climate beta");
- if the main uncertainty on growth is to do with the extent of damage caused by climate change, then projects combating such disturbances support economic growth. A negative climate beta will reduce the discount rate and lead to higher valuation of investments enabling reduction of GHG emissions.

Better evaluation of this correlation between climate risk and macroeconomic risk, as the complement to Christian Gollier's report proposes, conditions full understanding of risks and the choice of discount rate applicable to long-term projects.

2.2. Long-term impacts of projects combating climate change

Over recent years, developments in socioeconomic evaluation have led to better account being taken of long-term impacts: discount rates have been revised downwards; evaluation time horizons have been extended; and as far as combating climate change is concerned, the Hotelling rule guarantees that long-term benefits are not "overwritten" by discounting.

[1] See Complement 3, "On the efficient growth rate of carbon price under a carbon budget".

In this context, and even though our proposal is aligned on 2050 as a time horizon, evaluation of projects whose lifespans extend beyond this horizon need to include a post-2050 “rule of the game”. Even in a decarbonized environment, setting a value for carbon will still be a requirement in order to ensure sustainability of the decoupling between GDP and emissions and valuation of negative emissions.

In this context, we recommend prolongation of the Hotelling rule for a decade after 2050, with growth of the shadow price kept at 4.5% a year. By this time horizon, decarbonized capital stock will have been constituted and amortized. Moreover, modeling that adjusts the Hotelling context to take account of constitution of decarbonized capital[1] shows that you only need to stabilize shadow carbon price in order to maintain incentives to renew this capital over time.

2.3. Taking account of projects’ entire lifespans

It is pertinent to take account of emissions generated and/or avoided through projects’ entire lifespans, from construction phase to dismantlement phase, if any.

These days, carbon evaluation concentrates on emissions avoided or generated following entry into service of a financed investment, but does not include carbon emissions induced by infrastructure works. These may be major, contributing to exhaustion of France’s carbon budget. Underground transport projects, for example, induce major emissions during digging of tunnels, which are seldom taken into account in socioeconomic evaluations.

The Commission recommends that socioeconomic assessments incorporate impacts relating to capital works. Without going into a complete life-cycle analysis, it is useful for evaluation of projects’ “carbon viability” to check that emissions generated during the construction phase are offset by the emission reductions expected following entry into service.

[1] See the Complements to the Report, Complement 1, “*Un modèle avec capital d’abattement pour l’évaluation du carbone*” (A model with abatement capital for carbon evaluation), by Boris Le Hir, Aude Pommeret and Mathilde Salin. Stabilization of the shadow price is obtained when (i) there is no technical progress that reduces the cost of the technologies necessary to achievement of decarbonization in 2050, (ii) the cost of abatement does not increase with economic growth, and (iii) carbon sinks are stable (if carbon sinks are reduced after 2050, maintenance of net zero GHG emissions will involve further action on gross emission reduction, which may require mobilization of more expensive technologies than those utilized to obtain initial net zero GHG emissions in 2050, and the shadow price may continue to rise as a result).

Conclusion

Socioeconomic evaluation provides an analytic framework essential to assessment of a project’s contribution to wellbeing and the fight against climate change. Shadow carbon price acts as an objective basis for orientation of public investment choices towards the “Net-Zero” goal. Of course, the framework requires making methodological choices that are open to discussion and has major limitations, but it is the best method so far enabling integration of a project’s various aspects into a single analysis, in particular integration of economic, social and ecological approaches into a single evaluation.

Socioeconomic evaluation aims to guide public choices, not restrict them. Evaluations provide decision-makers with “food for thought” independent of lobbies’ positions; it never aims to automate choices or act as a substitute for definition of strategic priorities.

CHAPTER 6

A COMPASS FOR INVESTMENT AND ACTION

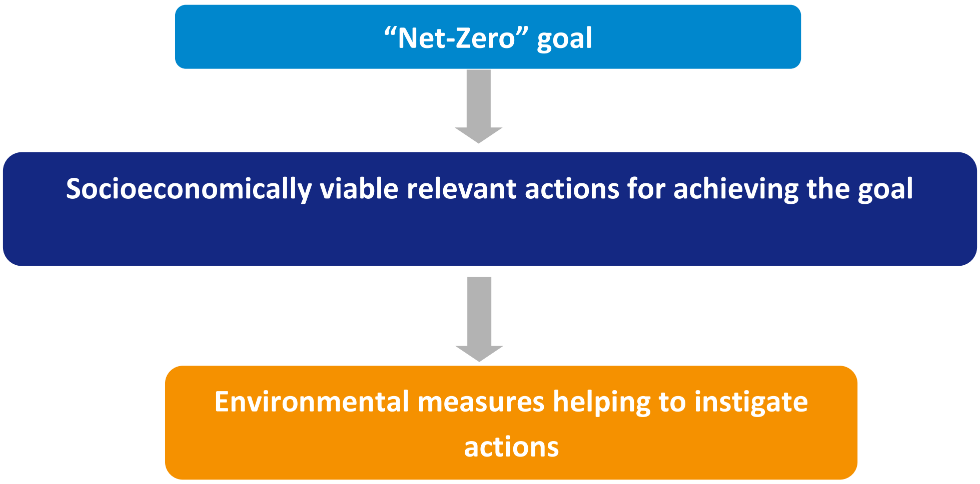
The value for climate action or shadow carbon price is the basic ingredient in an evaluation framework providing answers to three fundamental questions:

- is the country on the "right" decarbonization trajectory, i.e. on the road enabling it to finally achieve the "Net-Zero" goal? The answer is provided by quantitative monitoring of emission flows per sector and carbon sinks;
- does the trajectory observed enable the goal set to be achieved at the best cost? In order to answer this question, the abatement cost of the various sectoral decarbonization actions (thermal renovation of buildings, deployment of decarbonized vehicles; reduction of agricultural emissions, etc.) may be compared with the shadow price trajectory. Such comparison should help set public policy priorities;
- are actions implemented by merit order? Means of reducing GHG emissions at low cost must be mobilized first, before more expensive actions are carried out. A multiyear shadow carbon price trajectory acts as a guide to implementation of effective actions at the right time – not too early and not too late – by taking account of the time it takes to make investments and decreases in costs due to learning effects.

This chapter proposes a general framework for evaluating sectoral decarbonization actions, as well as environmental policy measures in support of actions deemed to be pertinent for the community. It shows the structuring role that shadow carbon price can play in construction and implementation of the proposed evaluation framework.

1. The value for climate action enables specification of sectoral decarbonization actions useful to the community

In order to achieve the “Net-Zero” goal, it is first of all necessary to define relevant sectoral actions to carry out. The question then arises as to what measures may be necessary to instigate such actions.



A sectoral decarbonization action in whatever form may be regarded as an investment, as it represents an initial effort that results in sustainable reduction of the quantity of CO_2eq emitted. Such investments may be measured in euros per metric ton of CO_2eq avoided, which is referred to as abatement cost. It is this cost that has to be compared with the shadow carbon price trajectory in order to evaluate whether the decarbonization action is relevant from the community’s point of view. If an action that reduces emissions by 1 tCO_2eq a year for ten years represents a cost of €100 per metric ton of CO_2eq avoided and the average discounted shadow price is €150 per metric ton, it may be regarded as relevant for the community. More generally:

- any decarbonization action whose abatement cost is lower than the average of the shadow carbon price discounted over the action’s duration is relevant for the community;
- other actions induce additional costs compared with more efficient pathways if no other dimensions are taken into account.

1.1. Evaluation of the socioeconomic costs of abatement

Although socioeconomic evaluation has traditionally focused on public investments, it should be extended to all actions. Public investments alone cannot ensure successful low-carbon transition: they should rather be seen as facilitators by providing private actors – companies and households – with decarbonized alternatives.

The reference instrument for evaluating decarbonization actions is the abatement cost, which is defined as the discounted cost gap between the decarbonization action and the equivalent carbonized reference solution, relating to greenhouse gas emissions avoided by the action. The cost gap is discounted as the abatement cost incorporates costs connected with the initial investment as well as costs relating to the investment's use throughout its lifespan. This Report does not discount emissions, so the abatement cost only depends on total volumes abated, not on any exact record of abatements.

In general terms, the formula for calculation of the socioeconomic cost of abatement is as follows:

$$AC = \frac{\Delta investment\ cost + \Delta operating\ cost - \Delta cobenefits}{\sum_i \Delta emissions_i}$$

With:

- *AC*: abatement cost;
- Δ*investment cost*: potential additional investment costs compared with the reference carbonized technology;
- Δ*operating cost*: potential additional costs of equipment operation compared with the reference carbonized technology, discounted at the socioeconomic discount rate;
- Δ*cobenefits*: potential co-benefits of the decarbonized solution compared with the reference carbonized technology, discounted at the socioeconomic discount rate;
- $\Delta emissions_i$: lower greenhouse gas emissions over year *i*, compared with what they would be with carbonized technology, estimated for the equipment's entire lifespan.

The formula may also be written in the following equivalent form:

$$0 = -\Delta investment\ cost - \Delta operating\ cost + \Delta cobenefits + \sum_i \Delta emissions_i * AC$$

This formula is very close to the formula measuring the socioeconomic net present value (NPV) gap between decarbonized and carbonized investment (with VCA_i as the shadow carbon price for year *I* and with *a* as the socioeconomic discount rate):

$$\Delta NPV = -\Delta investment\ cost - \Delta operating\ cost + \Delta cobenefits + \sum_i \frac{\Delta emissions_i}{(1+a)^i} * VCA_i$$

Which, when the shadow price grows at the discount rate, is written as:

$$\Delta NPV = -\Delta investment\ cost - \Delta operating\ cost + \Delta cobenefits + \sum_i \Delta emissions_i * VCA_0$$

Hence, if the shadow price grows at the socioeconomic discount rate, a sectoral decarbonization action is socioeconomically viable when its abatement cost is lower than the investment year's shadow price. If the shadow price increases at a different pace, the abatement cost must be compared with the average of the discounted shadow price (weighted by annual emission reductions).

In order to be able to compare the abatement costs of various possible sectoral actions, a common core set of evaluation rules must first of all be defined. In this context, special attention must be paid to the baseline situation. The impact that electric renewable energies have on emissions is not the same depending on whether they replace GHG-emitting gas-fired or coal-fired plants or decarbonized nuclear power stations. Similarly, the production cost gap is not the same depending on whether you compare the electric renewable energy source with a gas-fired plant or nuclear power station. It is also necessary to take as much account as possible of emissions over the equipment's entire lifespan (for example, account must be taken of emissions during manufacture of an electric vehicle's battery).

The abatement cost calculated here is a socioeconomic abatement cost, from the viewpoint of community interest. This has three major consequences:

- the costs considered exclude financial impacts of taxes and subsidies, insofar as these represent monetary transfers within the community, with no net impact on an investment's socioeconomic performance;
- account must be taken of a decarbonization action's co-benefits (such as reduction of local pollution and noise levels due to deployment of electric vehicles). Co-benefits must be evaluated on the basis of the shadow prices set for such externalities, and deducted from the abatement cost;
- finally, the rate at which costs and gains should be discounted is the public discount rate, not the financial market rate.

Evaluations of socioeconomic abatement costs enable priorities to be set on the basis of cost-effectiveness analysis. Sectoral decarbonization actions can therefore be classified depending on their abatement costs:

- Inset 12 below presents evaluations of abatement costs drawn from a few recent studies. **Actions with zero or negative abatement costs**, in particular because they do not require any significant investment: when there are no additional costs for the community in a switch to decarbonized technology or behavior, or possibly when there is a gain in carrying them out without even valuing avoided emissions. Such actions should therefore be undertaken immediately, subject of course to their operational feasibility and implementation of any support measures required, in particular at social level:

- in terms of 'sobriety'[1]: purchase of a vehicle better suited to one's needs rather than a larger, more powerful vehicle when buying a new car (as purchase price and fuel bills are lower for the same use), or manual optimization of a building's heating in the daytime (as the heating bill may be reduced without having to install any special apparatus);
- in terms of sharing: recourse to carpooling[2].

- **Actions with positive but relatively low abatement costs**, less than €100/tCO_2eq. These include various actions bearing on thermal insulation, installation of heat pumps, or a switch to electric buses in densely populated environments.
- **Actions whose abatement costs are between €200/tCO_2eq and €250/tCO_2eq**. These include adoption of electric vehicles to replace internal combustion vehicles.
- **Actions whose abatement costs remain high** given the current state of knowledge, such as use of decarbonized hydrogen in transport, industry and energy production, or carbon capture and sequestration. Abatement costs may be revised downwards later in the event of technological progress or a rise in fossil fuel prices.

Inset 12 – A few recent studies on abatement cost

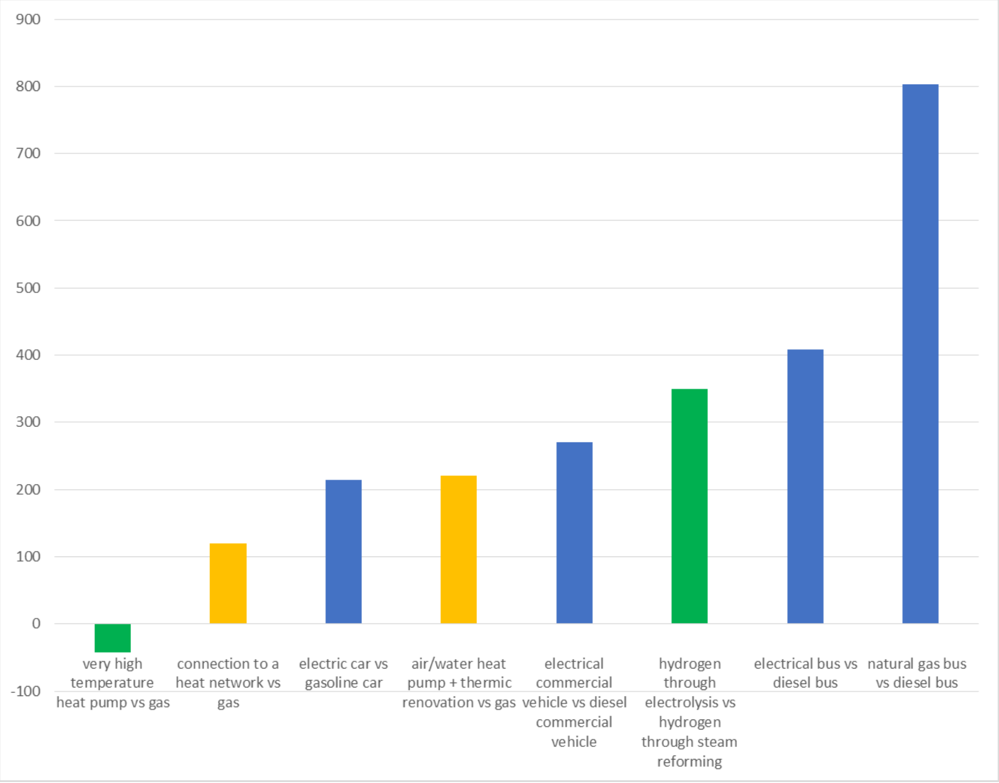
This Inset presents examples of abatement costs taken from three sources: a publication by the Carbone 4 consultancy (see Figure 48), a contribution from the General Commission for Sustainable Development (CGDD, see Figure 49), and a calculation carried out on the basis of a study by the Directorate-General of the Treasury (see Figure 50). Technological fields vary, as do certain hypotheses and levels of detail, so results are not always comparable. In particular, only the CGDD's contribution incorporates the co-benefits of decarbonization actions. In addition, in contrast to the two other examples presented, Carbone 4's study presents abatement costs calculated without discounting avoided emissions.

Carbone 4's study

The Carbone 4 consultancy's evaluations illustrate the extreme heterogeneity of abatement costs from one sector to another as well as within a single sector. They also illustrate the existence of negative abatement costs (very high-temperature heat pumps for certain industries).

[1] See definition in the Introduction.
[2] When it does not require setup of special infrastructures.

Figure 48 – Public abatement cost by Carbone 4, in €/tCO_2eq, for an investment made today

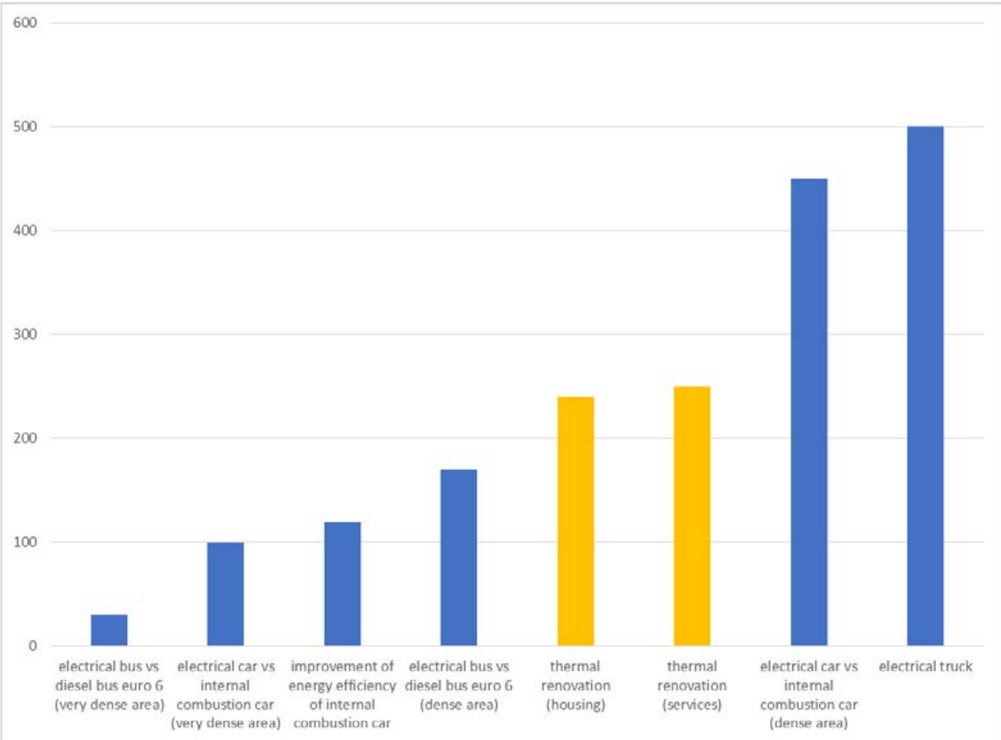


Source: Carbone 4, decarbonization barometer, November 2018. Orange: housing; blue: transport; green: industry. The method employed does not take account of co-benefits but integrates emissions connected with manufacture of batteries for electric vehicles. In the calculation, emissions in the denominator are not discounted. The socioeconomic abatement cost calculated for a given investment period can be compared with the average discounted shadow carbon price over the same period (weighted by emissions avoided by the project or year-by-year measurement), i.e. the abatement cost can be compared with the initial shadow carbon price when the later increases at the same pace as the discount rate.

The study by the General Commission for Sustainable Development (CGDD)

The CGDD's contribution presents evaluations of net abatement costs of co-benefits. Hence, taking account of the cost of local pollution and noise enables more accurate evaluation of the abatement cost of electric vehicles when their use is targeted on very densely populated urban areas, compared with a use in urban areas that are only densely populated: electric vehicles' abatement cost would fall from around €450/t in a densely populated area to €100 €/t in a very densely populated area, and the cost of electric buses from €170/t to €30/t.

Figure 49 – Abatement cost according to the contribution provided by the CGDD, in €/tCO_2eq, for an investment made in 2020



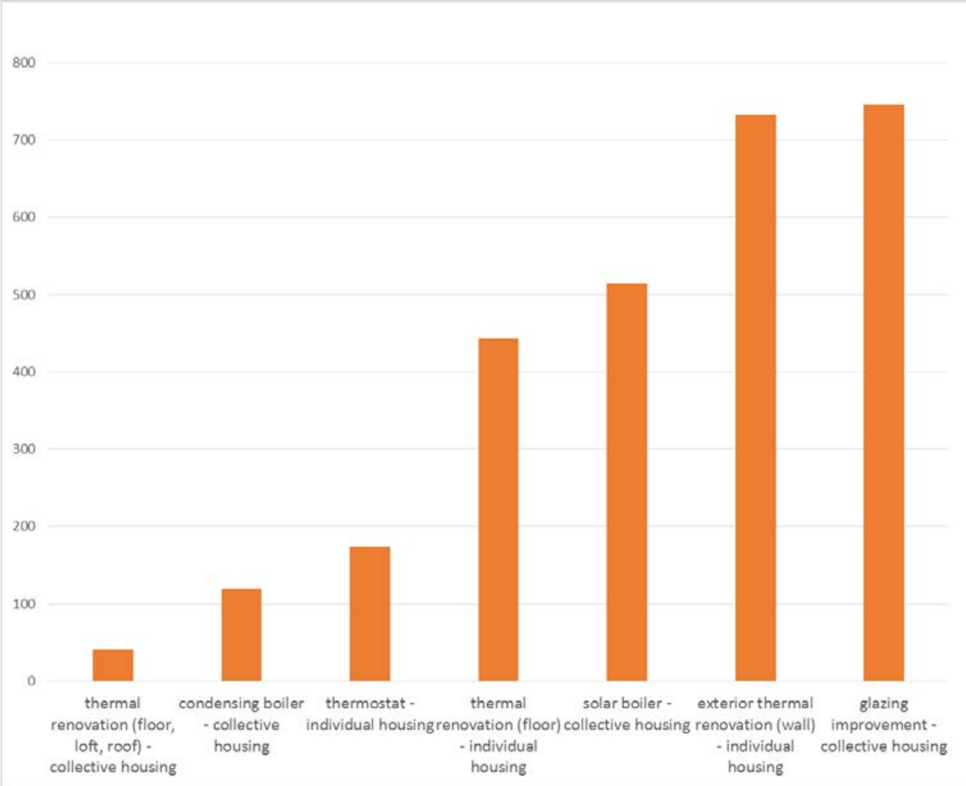
Source: CGDD 2019, contribution to this Report. Orange: housing; blue: transport. For details, see the Report's Complements. Some calculations take account of the opportunity cost of public funds, and others take account of local pollution. Emissions connected with manufacture of batteries for electric vehicles are taken into account. In the calculation, emissions in the denominator are discounted. The socioeconomic abatement cost calculated for a given investment period can be compared with the average shadow carbon price over the same period (weighted by emissions avoided by the project and discounted).

The CGDD's contribution also illustrates the impact that technical progress and evolution of fossil fuel prices may have on evolution of abatement costs. Hence, the abatement cost of electric heavy-goods vehicles may be halved between 2020 and 2030 (falling from €500/t to €250/t) under the combined effect of lower battery costs and an increase in oil prices.

Calculations applied to renovation of housing units, on the basis of a study by the Directorate-General of the Treasury

The abatement costs presented below are calculated on the basis of a study bearing on discounted energy savings enabling various renovations to be carried out.

Figure 50 – Abatement costs, calculations based on a DG Treasury work document, in €/tCO_2eq, for an investment made today



Source: calculations based on "Barrières à l'investissement dans l'efficacité énergétique: quels outils pour quelles économies?", Les Cahiers de la DG Trésor, *no.2017-02, March, p.15. The document's figures in €/MWh cumac (accumulated and discounted) have been converted into €/tCO_2 assuming that the reference equipment is a gas boiler, insulation measures have a thirty-year lifespan, with a twenty-year lifespan for condensing boilers and solar water heaters, and twelve years for thermostats. In the calculation, emissions in the denominator are not discounted. The method employed does not take account of co-benefits and a 4% discount rate was adopted in the initial document and for calculations presented here.*

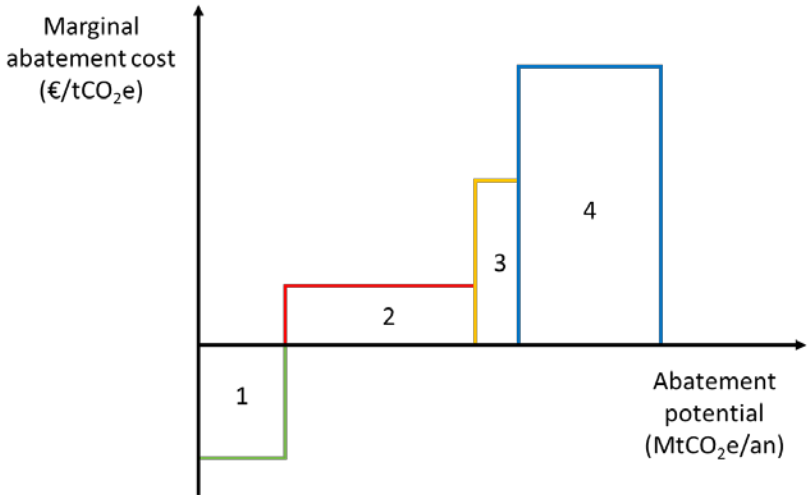
All in all, it is important to define and stabilize evaluation rules in order to facilitate comparisons, set the right priorities and define a merit order for pertinent actions.

1.2. A dynamic approach to merit order

A decarbonization action's abatement cost can be compared to the average discounted shadow carbon price throughout the equipment's lifespan: if it is lower than the shadow price, the sectoral action is useful from the community's point of view and should be implemented.

In order for decarbonization strategy to be effective the general rationale behind deployment of technologies is to proceed by merit order, i.e. to make a priority of mobilizing technologies whose abatement cost (in €/tCO_2eq) is lower than the discounted average shadow price[1] throughout their lifespan, and then mobilize more expensive technologies over the course of time. This merit order may be represented by marginal abatement cost curves (see Figure 51), ranking decarbonization actions according to their increasing costs (on the ordinate) while indicating each action's GHG emission abatement potential (on the abscissa)[2]. These curves represent a group of actions to be mobilized progressively between the present day and the target year, with a view to minimizing the total abatement cost enabling achievement of net zero GHG emissions in 2050.

Figure 51 – Marginal abatement cost



Source: from Vogt-Schilb A., Hallegatte S. and de Gouvello C. (2014), "Marginal abatement cost curves and quality of emission reductions: A case study on Brazil", Climate Policy, Taylor

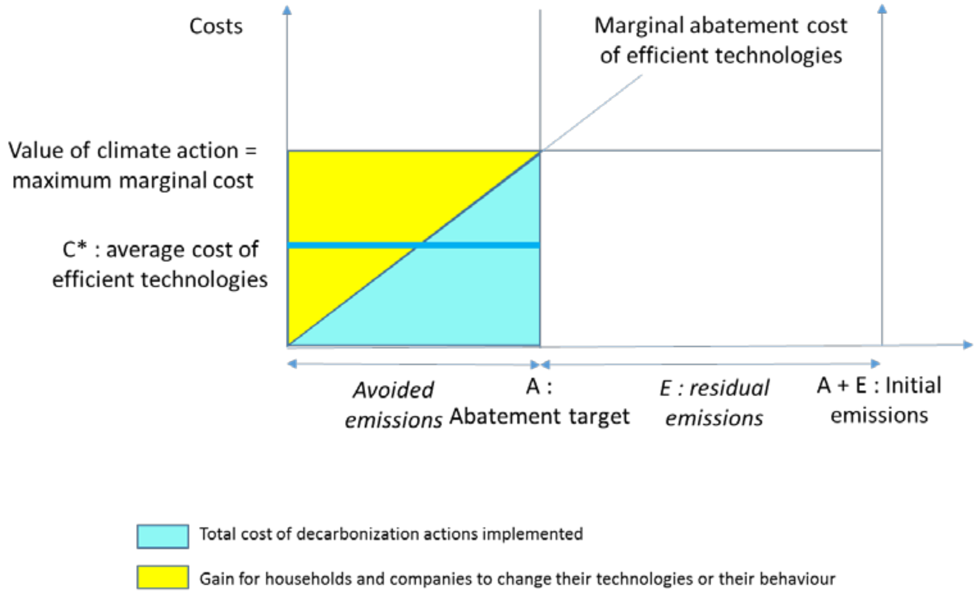
The graphs in Inset 13 below show the interest of such prioritization of actions, which reconciles ecological efficiency and economic efficiency.

[1] Weighted by annual emission reductions.
[2] Vogt-Schilb A., Hallegatte S. and de Gouvello C. (2014), "Long-term mitigation strategies and marginal abatement cost curves: A case study on Brazil", *Policy Research working paper*, no.WPS 6808, Washington DC, World Bank Group.

Inset 13 – Value for climate action and selection of pertinent actions

As illustrated in Figure 52 below, if a merit order rationale is properly applied in selection of actions, the community will achieve emission reductions up to a volume A[1] by implementing the least expensive actions. The total implementation cost is represented by the blue area.

Figure 52 – Case of mobilization of decarbonization actions by merit order

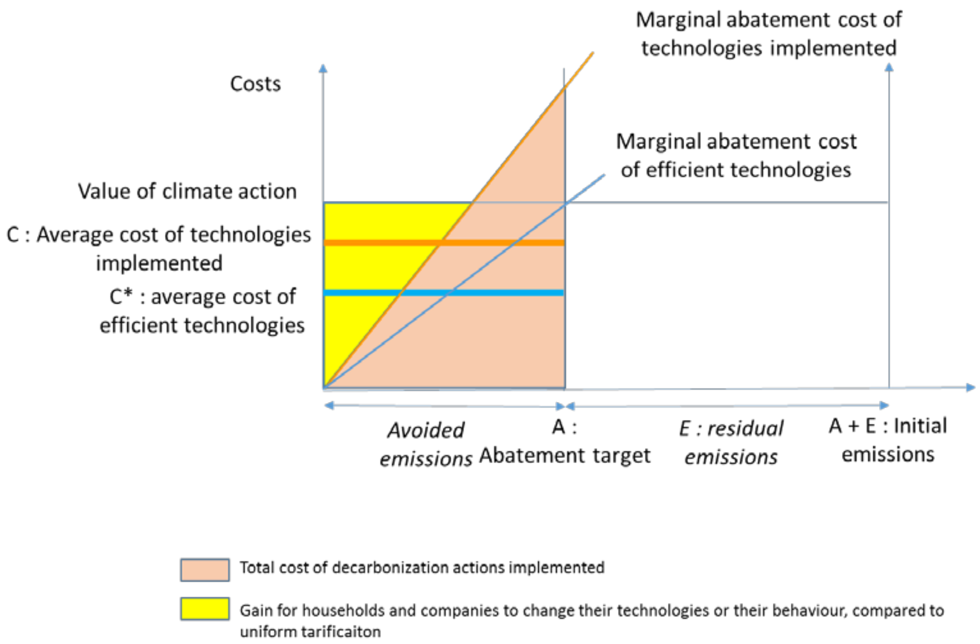


Source: France Stratégie

Figure 53 illustrates a case in which decarbonization actions are not initiated in merit order, with certain actions' abatement cost exceeding shadow price. The total cost of decarbonization actions implemented is equal to the area below the marginal abatement cost of technologies actually mobilized (orange diagonal), when the same results in terms of abatement (A) could have been achieved much more cheaply: an approach by merit order would have led to a cost equal to the area of the triangle below the marginal abatement cost of efficient technologies (blue diagonal). In other words, for the same abatement volume A, the average cost of decarbonization actions carried out (C) is higher than the average cost that would have been obtained if more efficient actions had been mobilized (C*).

[1] For simplification's sake and by way of illustration, we assume in this Inset that the decarbonization action only produces its effects for one year, enabling comparison of the abatement cost with the shadow price, rather than with the average shadow price over several years.

Figure 53 – Case in which actions are not mobilized by merit order



Source: France Stratégie

This traditional illustration of merit order must be refined in order to take account of the time taken to deploy the various actions concerned and learning effects. It is not always best to wait until the full potential of technologies with the lowest abatement costs has been exhausted before going on to invest in more expensive technologies.

- We need to take account of time constraints weighing on deployment of decarbonization investments, whether with regard to speed of installation of electric-vehicle charging stations across the territory or the speed at which the housing stock is renovated, which depends in particular on how many people are trained in these fields as well as the speed at which stocks of vehicles and machines are renewed.
- Account must also be taken of the potential of technical progress that early deployment of a technology may harbor, via learning effects[1] and economies of scale.

This dynamic vision of merit order leads in particular to recommend early initiation of investments that take time to carry out and whose benefits are spread over the long term. In this respect, the proposed shadow carbon price trajectory, marked by a sharp increase in value up to the balance points of 2030 and 2040, should obviously not be interpreted

[1] Perissin-Fabert B. and Foussard A. (2016), *Trajectoires de transition bas carbone au moindre coût*, Thema Analyse, Perissin-Fabert B. and Foussard A. (2016), *Trajectoires de transition bas carbone au moindre coût*, Thema Analyse, Ministry of the Environment, Energy and the Sea.

as an incentive to defer initial efforts. This Commission, like its 2008 predecessor, takes it upon itself to “contravene” the Hotelling rule at the start of the period, on the basis of two considerations:

- in order not to create a “leap” in the initial level of shadow carbon price, it is legitimate to accept a period seeing rapid growth in such value up to the balance points of 2030 and 2040;
- Shadow carbon price may act as a “compass” for decarbonization investments. Yet such investments have two major characteristics that make them more sensitive to the future value of carbon than to its immediate value:
  - they are decisions that are spread over time, at the pace at which buildings, housing units, factories and stocks of vehicles are renewed;
  - they are long-term decisions: either an investment has a long lifespan or it has to be renewed when it comes to the end of its life in order to maintain the asset over time. Hence, benefits must be valued throughout the asset’s lifespan, not only during its very first years of entry into service.

These two considerations go hand-in-hand with a requirement: the emission reduction trajectory and related climate action value trajectory must be clear and credible, in order to be anticipated and taken into account in public and private investors’ decisions.

1.3. A reference extended to the whole economy

The value for climate action constitutes a single reference: the value of one non-emitted metric ton of CO_2eq is the same for society, whatever sector the reduction originated in.

In the perspective of a “net-zero emissions” goal, shadow carbon price serves as a reference for the widest possible scope of actions, as all society’s activities are concerned.

- In order to achieve deep decarbonization of the economy, we need to extend the field of public and private actions combating climate change, to cover all emissions connected with industrial processes, agriculture, land use and waste treatment, and stimulate development of carbon sinks.
- All greenhouse gases (carbon dioxide, methane, nitrous oxide and fluorine compounds) must be taken into account and all sectors of the economy must reduce their greenhouse gas emissions. The land-use sector requires special attention as it can enable development of natural carbon sinks while providing biomass for energy use.
- All public and private actors are concerned:
  - the State, regional and local authorities, and public institutions;

- private actors: companies, climate funding actors, and households. It is a whole multitude of individual choices, investments and changes in habits added together that will enable achievement of the net zero GHG emissions goal.

2. The private value of actions must be brought closer to their socioeconomic value

Certain decarbonization actions useful to society are viable from a private point of view, and can therefore be initiated without any special public involvement. These are actions whose financial appraisal, taking account of investment costs and use costs, is favorable to decarbonized technology. In such cases, private viability goes hand-in-hand with socioeconomic viability.

However, decarbonization actions that are pertinent from the community viewpoint are not always financially viable for private actors. This is often the case when no public policy enables internalization of the emission reduction goal. Lack of deployment on the part of private operators may also be connected with lack of information on abatement opportunities, limited access to credit in order to invest, or risks of development of new technologies considered as too great.

In such situations, public measures are required in order to bring private values of decarbonization actions closer to their value to the community: a public investment enables deployment of a new low-carbon infrastructure, a regulation may make the action compulsory, a tax on CO_2 may improve a decarbonized technology's competitiveness, a subsidy helps finance acquisition of the technology, a guarantee may enable sharing of development risks, etc.

2.1. Deep decarbonization of human activities is necessarily based on a range of complementary measures

When decarbonization actions useful to society are not implemented spontaneously, it is up to the State to identify the most pertinent levers to trigger them. The question of the panoply of measures fostering decarbonization actions falls outside the scope of this report, as it involves redistributive, social, budgetary and industrial issues among others. The value for climate action provides a measure of the road to travel and helps define the scope of sectoral actions and investments viable for the community, without prejudging measures required to initiate such actions and investments. This may be illustrated by highlighting two very different possible rationales behind construction of this panoply of measures.

The first consists of giving price signals a central role. If carbon pricing is set at the level of the maximum marginal abatement cost consistent with the decarbonization goal sought, it is certain that climate goals will be achieved under economically efficient conditions: actors will be encouraged to carry out all decarbonization actions of lower cost than the tax, and high-cost actions will be set to one side without the State needing to know actors' abatement costs or oversee their actions in detail. In addition, companies will be encouraged to innovate in order to propose decarbonized solutions.

This rationale belongs to a world where all public policies are already aligned on the net zero GHG emissions goal. Among other things, this would assume that:

- urban-planning and mobility policies are consistent with each other, in order to reduce travel needs;
- actors have decarbonized alternatives available to them (suitable infrastructure networks and technological solutions) and resources for funding viable decarbonization investments (access to credit, facility, and public guarantees covering various risks involved);
- the State is able to separate the question of implementing effective carbon pricing from that of dealing with its distributive effects and impacts on competition, for example by adopting compensatory provisions.

The second rationale consists of considering that transition to net zero GHG emissions should be based on alignment of all public policies on the "Net-Zero" goal and "smart" aggregation of complementary measures. This is the approach adopted by the OECD[1] and the Stern-Stiglitz Commission[2].

This Commission has also adopted the second rationale. Carbon pricing is essential to establishing accurate ecological prices, making decarbonization projects viable and stimulating the search for innovative solutions. But even though its initial aim is to act as an incentive, carbon pricing is also subject to constraints as, it may affect household purchasing power and company competitiveness under conditions that existing redistribution mechanisms do not always manage to compensate. Action therefore needs to be taken on a wider front if we are to achieve deep decarbonization of human activities, including:

- aligning the regulatory framework on a higher level of climate ambition, in particular in the fields of urban-planning (in order to control land and real-estate prices in cities), buildings' energy and environmental performance, releases from industrial facilities, and automobile construction;
- stimulating research and development;

[1] OECD (2015), *Aligning Policies for a Low-carbon Economy*, Council Meeting at Ministerial Level, OECD Publishing, Paris.
[2] Stern N. and Stiglitz J.(2017), *Report of the High-Level Commission on Carbon Prices*, Carbon Pricing Leadership Coalition.

- improving decarbonized technologies' competitiveness compared with carbonized technologies;
- if necessary, sharing technological development and initial deployment risks via guarantee mechanisms, as proposed, for example, in Pascal Canfin and Philippe Zaouati's report *Pour la création de France Transition*[1].

2.2. Evaluation of all decarbonization measures implemented should be reinforced

Quite large numbers of measures encouraging decarbonization often accumulate for a given use (utilization of a car, a heating system, an industrial or agricultural facility, etc.). For example, energy efficiency and pollution standards, the bonus-malus system for acquisition of new vehicles, the vehicle conversion bonus, fuel taxation, and possible future low-emission zones and congestion charges all combine to reduce emissions from private vehicles. Such accumulation is not a problem in itself, as each measure targets a specific incentive at the time of purchase or use. We still need to have an aggregated view of incentives and obligations deployed if we are to evaluate whether or not such aggregation ensures the viability of actions whose abatement costs are deemed acceptable by the community. We must make sure that the cumulation of measures is enough, and that the implicit cost of compliance with standards, which is less transparent than price signals, is not too high for all or some of the actors concerned. It has to be said that there are not enough such evaluations available at this point in time. The Commission recommends that they be carried out, while emphasizing that they are not a matter of simple additions but require development of a rigorous evaluation framework.

Evaluating incentives

If we wish to analyze whether the aggregation of measures initiates actions whose socioeconomic abatement cost is deemed relevant, we cannot simply take into account price signals sent by taxes, emission allowance markets, subsidies and the implicit cost of regulations. Developing an aggregated analysis requires painstaking work. As the OECD has demonstrated[2], it requires:

- use-by-use determination of emission reductions achieved as a result of decarbonization actions initiated by all measures. In some cases, evaluation may be quite simple (for example, an obligation to replace one piece of equipment with another). In other cases, calculation requires account to be taken of changes in

[1] Canfin P. and Zaouati P. (2018), *Pour la création de France Transition. Des mécanismes de partage de risques pour mobiliser 10 milliards d'euros d'investissements privés dans la transition écologique*, Report to the Minister for the Ecological and Inclusive Transition and the Minister of Economy and Finance, December.
[2] OECD (2014), *Effective Carbon Prices*, OECD Publishing, Paris.

actors' behavior (for example, carbon pricing will reduce GHG emissions to an extent that depends on actors' consumption elasticity to energy prices) or of an interaction between two actions (for example, two regulations each enabling a 50% reduction in a housing unit's energy consumption do not result in a 100% consumption reduction);

- account to be taken of the difference in kind between incentives to invest in and to use a new piece of equipment. In theory, both such incentives should be taken into account when an investment choice is made as they condition its viability, even though, in practice, a subsidy or bonus/malus system for the investment may be more visible and incentivizing than user charging. Once the purchase has been made, only measures bearing on use can contribute to emission reduction (for example, once a vehicle has been purchased, only fuel taxation and any possible restrictions on vehicle use have any effect on residual emissions). Therefore, the two measures have different bases for emission reduction and analysis of their impact requires account to be taken of purchase elasticity and usage elasticity.

Evaluating redistributive effects

All environmental policy measures have redistributive effects. It is worth expanding on those that are hidden.

Carbon pricing orients investment efforts to actors whose abatement costs are lower than price signals. Such incentives may induce unwanted redistributive effects that must be evaluated in order to be able to develop mechanisms for compensation and for the best targeted diffusion of decarbonized alternatives.

Regulations impose potentially highly heterogeneous abatement costs between actors, with hidden redistributive effects that are more difficult to detect than in cases of pricing. It is essential to clarify the redistributive effects of regulations and the implicit costs they impose on the various categories of actors, as is done for taxation.

Subsidies reduce the burden on investors as it is taken on by the community[1]. If they are poorly targeted, however, subsidies may lead to the community having to bear the cost of actions that would have been carried out anyway by private actors, a situation referred to as the "deadweight effect". Here again, the redistributive effects from taxpayers to subsidy recipients require clarification.

Evaluating industrial impacts

In the same vein, the industrial impact of public measures must be better clarified. Taking early decarbonization action may result in the appearance of new actors in sectors that are not yet fully mature (such as renewable energies, waste management and thermal

[1] To finance a subsidy, effort may be required by the present community (financing through taxation or reduction of other expenditures) or by the future community (loans).

renovation). However, implementation of carbon pricing or standards may raise production costs and bring the risk of "carbon leakage", i.e. relocation of production in countries less involved in the fight against climate change. A rise in production costs may also lead companies to reduce their margins and investment capacities.

Close attention was paid to companies' competitiveness in development of the European Union Emissions Trading System (EU ETS), which covers major industrial facilities and electricity production. The market was designed to enable efficient distribution of effort among companies subject to the ETS and protect companies with high exposure to international competition, via the free allowances system. However, the market was not calibrated to achieve net zero GHG emissions at European Union level, which helps explain part of the significant gap between the shadow carbon price proposed by this Commission and the ETS allowance price. In order to clarify the terms of the debate, this gap calls for complementary work for:

– an aggregated evaluation of incentives and regulations that French companies are currently subject to;

– a European evaluation of a carbon value compatible with a target of net zero GHG emissions in 2050.

For SMEs that are exposed to international competitions but are not in the ETS market, support mechanisms may also be pertinent. They may take the form of investment aid schemes, preferably intended for companies experiencing financial difficulties in adapting (subsidies, over-amortization schemes, etc.). They may also take the form of technical support to optimize production processes and so reduce emissions (energy audits, materials audits, etc.). The Inset below presents two examples of support mechanisms.

Inset 14 – Two examples of support mechanisms: *certificats d'économies d'énergie* and the "*TPE-PME, gagnantes sur tous les coûts!*" scheme

Certificats d'économies d'énergie (CEEs – Energy Savings Certificates) benefit households and businesses alike, enabling funding of energy efficiency actions by limiting remaining sums to be paid by beneficiaries. The mechanism consists of requiring energy suppliers (electricity, gas and fuel) to earn a certain number of certificates, depending on their sales volumes. In order to obtain the certificates, suppliers must finance approved renovation actions for third parties (households or businesses). The mechanism is doubly virtuous: it enables businesses to reduce the cost of energy efficiency work they undertake and which will result in lower energy bills, and it encourages energy providers to be as efficient as possible so as to obtain certificates as inexpensively as possible. However, businesses still have some way to go as far as appropriation of the mechanism is concerned.

The "*TPE-PME, gagnantes sur tous les coûts!*" (VSEs/SMEs, winning on all costs!) scheme, managed by France's Agency for Environment and Energy Management (ADEME), consists of prefinancing audits for companies with fewer than 250 employees in the industry, distribution, catering and craft sectors, in order to help them optimize their flows of energy, materials, waste and water. Companies pay ADEME a flat fee, but only if they have made substantial savings following provision of its support. The scheme's effectiveness was clearly demonstrated on an initial sample in 2016 (with an average of 50,000 euros saved per company per year).

3. Synthesis: How to use the value for climate action

On the basis of these various factors, we can outline "instructions" for proper use of climate action value, consisting of three major steps:

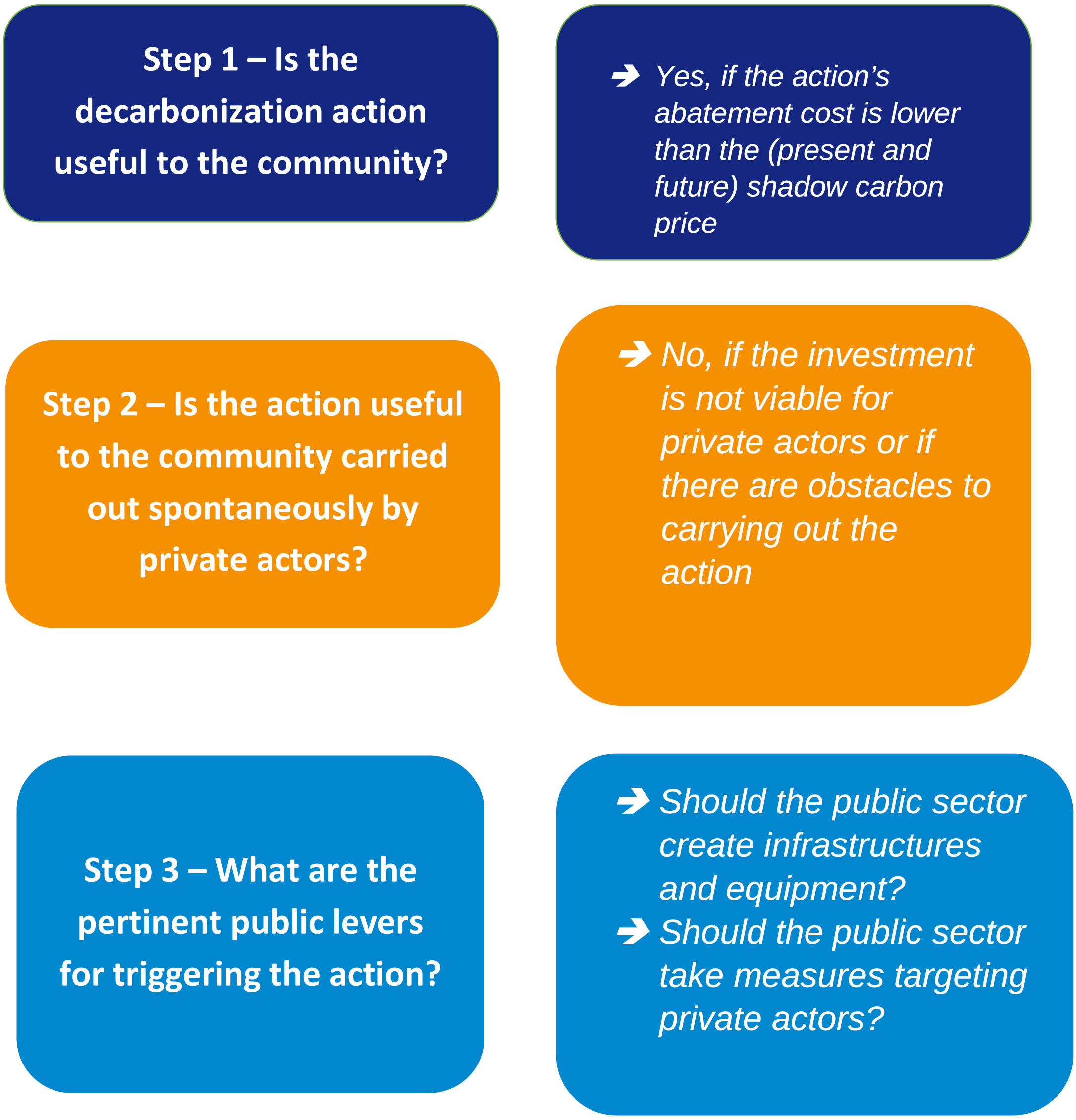
– the value for climate action must be mobilized upstream, during development of the decarbonization strategy, in order to define the scope of viable actions and, in consequence, public policy priorities;

– sufficiently detailed understanding of abatement costs per use or per technology must then enable identification of which actions among those that appear pertinent will be undertaken spontaneously by private actors and which will require public intervention;

– a pertinent combination of public measures must then be decided on to provide effective leverage. In its decision-making process, the State should attach particular importance to socioeconomic evaluation of public investment projects and ensure that any accumulation of taxes, subsidies and regulations on a single given use provides sufficient incentive for initiation of useful actions. Whether or not the financial burden is shared among actors largely depends on choice of measures, their funding, and support mechanisms.

The three steps are illustrated in the schema below.

Schema – Instructions for proper use of value climate for action



GENERAL CONCLUSION

The Commission’s work highlights the need for major revaluation of carbon value to realign it with a higher level of ambition. We believe that such revaluation is essential in order to put our country on the right trajectory.

After 2030, as the time horizon grows longer, the proposed trajectory naturally remains surrounded by growing uncertainties, in particular as regards marginal abatement costs of greenhouse gas emissions. Such uncertainties lead us to recommend that work on shadow carbon price be reviewed at regular intervals – at least every ten years – in order to take account of changes in the international economic and technological context.

We also believe that it is essential to “beef up” at least four aspects of the research program on the climate externality’s socioeconomics, without waiting for the next review.

- Modeling work should now integrate exhaustion of available carbon budgets and the global and French goal of net zero GHG emissions. The new context and new goals require that existing models be expanded, by extending them to all sectors, uses and greenhouse gases, and refining analysis of investment behaviors. They also need to be able to describe various possible technological futures, based on more detailed descriptions of scale and learning effects.

- The shadow carbon price trajectory is crucially dependent on the underlying discount rate. Here, as a precaution, we have adopted the 4.5% public discount rate as a reference, but the question of taking risk into account, and the “climate beta” value in particular – i.e. the correlation between climate risk and macroeconomic risk – deserves further work.

- The evaluation framework for sectoral actions is still in its infancy. It is essential to develop a clear, shared methodological framework in order to be able to evaluate the socioeconomic abatement cost of different actions. Such work requires full understanding of co-benefits (air quality in particular) inasmuch as different goals are often sought simultaneously.

- The evaluation framework for public investment projects should be substantially updated and expanded. Updated as evaluation of public investment projects useful to decarbonization must be carried out in a radically new context: post-2050 net zero GHG emissions. Special attention must be paid to the reference scenario, as it is this choice as much as the choice made on revaluation of carbon value, which will determine projects' socioeconomic viability. Expanded as evaluation of investment projects is still essentially confined to the transport and building sectors and should be extended to other major sectors, starting with energy.

Last but not least, evaluations of shadow carbon price would benefit from equivalent calculations made by our main European partners or by the European Commission. In addition to the methodological progress it would foster, comparison of different values would enable best use of the gains made due to closer international cooperation and could contribute to design of the European Union's long-term climate policy and related instruments, with net zero GHG emissions as their goal.

APPENDICES

APPENDIX 1
MISSION LETTER

The Prime Minister

22 February 2018

Alain Quinet
General Inspector of Finance
FRANCE STRATEGIE
20, Avenue de Ségur
75007 PARIS

Dear Mr Quinet,

Setting a monetary value for greenhouse gas emissions and the efforts undertaken to control them is an essential component of ecological transition. Such value enables efficient orientation of investment choices, research and development, and funding by the State and local authorities, as well as by enterprises and all economic and social actors.

Signature of the Paris Agreement constituted a major diplomatic turning point and obliges us to act now in order to keep rises in temperature below 2°C compared with preindustrial levels. This is the sense of the goal, set in the Climate Plan in July 2017, of achieving climate neutrality in France by 2050.

In addition to consolidation of climate goals, a number of reasons necessitate a review of the shadow price of carbon you defined in 2008, including economic conditions and energy prices. Issues with regard to the energy mix have also evolved significantly. And finally, recent economic work on carbon prices carried out at international level has brought new factors to bear in thought given to the social value of carbon.

I should therefore like you to form a Commission to revise the shadow price of carbon, as you did in 2008. The Commission, to be composed of experts and representatives of social partners and non-government organisations, will propose a new trajectory consistent with France's climate goals. It will also formulate recommendations to extend use of such value in definition and evaluation of public policies, as well as in choices of private investment and financing.

You will draw on the assistance of France Stratégie's teams in order to complete this mission.

In order for the new shadow price to be fully integrated into the version of the National Low-Carbon Strategy that will be subject to consultation in the second half of 2018, you will provide me with a provisional version of your report at the end of June 2018, presenting the shadow carbon price trajectory. You will provide me with your final report in November 2018.

Yours sincerely,

Edouard PHILIPPE

APPENDIX 2

MEMBERS OF THE COMMISSION

Émilie Alberola, Climate Policies and Market Mechanisms Manager, Eco'Act

Luc Baumstark, Mission Officer, Secretariat-General for Investment (SGPI)

Dominique Bureau, Delegate-General, Economic Council for Sustainable Development (CEDD), President of the Committee for the Green Economy (CEV)

Xavier Bonnet, Inspector-General, National Institute of Statistics and Economic Studies (INSEE)

François-Nicolas Boquet, Director of Environment and Energy, French Association of Private Enterprises (AFEP)

Stéphane de Cara, Research Director, National Institute for Agricultural Research (INRA)

Pierre-Yves Chanu, Confederal Advisor, General Confederation of Labor (CGT)

Thierry Chapuis, Delegate-General of the French Gas Association (AFG), acting on behalf of the Movement of French Enterprises (MEDEF)

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Mireille Chiroleu-Assouline, Professor of Economics, Paris School of Economics

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François Dassa, Director of the Prospective and International Relations Mission, EDF

Meike Fink, “Action Climat” Network

Nathalie Girouard, Head of the Environmental Performance and Information (EPI) Division, OECD

Alain Grandjean, co-founding partner, Carbone 4

Thibault Guyon, Deputy Director of Sectoral Policies, Directorate-General of the Treasury

Gilles Lafforgue, Professor of Economics, Toulouse Business School

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Mines ParisTech (TIMES model)

Nadia Maizi
Ariane Milliot

Seureco (NEMESIS model)

Paul Zagamé
Baptiste Boitier

Enerdata (POLES model)

Sylvain Cail
Morgan Crenes
Quentin Bchini

Other people who contributed to the Commission's work

Isabelle Cabanne, DGEC

Stéphane Crémel, CGDD

Silvano Domergue, CGDD

Mathilde Salin, France Stratégie

APPENDIX 3

HEARINGS

Individuals heard

The following individuals were heard over the course of the Commission's work, during select committee meetings, plenary sessions and special theme-based workshops.

Boris Bailly, Associate Director and founder, I Care & Consult

Emmanuel Combet, economist in the Economy and Forward Planning Department, ADEME

Jean-Pierre Deflandre, teacher at the IFP School's Exploration Production Centre, researcher and project leader in the field of CO_2 storage

Quentin Deslot, Mission Officer, Ministry for the Ecological and Inclusive Transition's Department for Combating the Greenhouse Effect

Luisa Dressler, economist working at the OECD's Centre for Tax Policy and Administration

Araceli Fernandez, energy technology analyst, International Energy Agency

Gaël Giraud, Chief Economist at the French Agency for Development (AFD), Affiliate Professor of Economy and Finance at ESCP Europe, Catholic University of Louvain, and Chad

Christian Gollier, Professor of Economic Sciences, Director-General of the Toulouse School of Economics

Olivier de Guibert, Deputy Head of the Ministry for the Ecological and Inclusive Transition's Department for Combating the Greenhouse Effect

Stéphane Hallegatte, Senior Economist at the World Bank, Climate Change Group

Yann Kervinio, Forests and Oceans Mission Officer, Ministry for the Ecological and Inclusive Transition

Isabelle Le Nir, Director of the Interpretation Techniques Department, Schlumberger, President of EVOLEN's Geosciences Committee

Carole Le Jeune, National Federation of Agricultural Workers' Unions (FNSEA)

Cédric Léonard, Head of the Market Models and Economic Studies Department, RTE

Valérie Quiniou, Vice-President of Total's Climate Team

Jean Tirole, Professor of Economic Sciences, Director of the Toulouse School of Economics, Guest Professor at MIT and Director of Studies at the School of Advanced Studies in Social Sciences (EHESS)

Presentations of the Commission's work

- Before the National Council for Ecological Transition (CNTE), 12 April 2018
- Before the SNBC Information and Orientation Committee, 4 May 2018
- Meeting with union organizations (CFDT, CFE-CGC, CGT, FO and CFTC), 19 June 2018
- The French Association of Environmental and Resource Economics (FAERE) Annual Colloquium, 31 August 2018
- Colloquium on "Conditions for adherence to ecological taxation", I4CE, National Assembly, 2 October 2018

APPENDIX 4
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