What Value Do We Attach to Climate Action?

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Abstract – In the course of policy-making to mitigate the effects of climate change, economists seek to attach a monetary value to actual or foregone carbon emissions. Charting a long-term pathway for carbon prices involves measuring the most cost-effective way to reduce emissions, assigning value to long-term investment, and having a benchmark against which to set priorities. The carbon neutrality target, as set out in the 2015 Paris Agreement, calls for higher carbon values in monetary terms than those historically obtained under Factor 4 targets derived from a cost-benefit approach. This paper looks at developments in carbon values over time, with an emphasis on their underlying methodologies and the role of uncertainty in valuation. It then sets out how carbon values can be used in policy-making to mitigate the effects of climate change.

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Our climate, considered by the founding fathers of economics as a free good, available in unlimited quantities, has gradually moved back into the category of economic goods, i.e. goods that are scarce. In a 1972 paper entitled "Is Growth Obsolete?", William Nordhaus and James Tobin launched a critique of Meadows' "The Limits to Growth", published in the same year under the auspices of the Club of Rome, which predicted the depletion of our natural resources. They argue that in the future, scarcity will not be in raw materials or energy sources – as prices will rise to prevent their over-exploitation – but in public goods, available at no cost and thus subject to excessive exploitation. In conclusion, they point to the need to focus on conserving free natural resources ("fresh air") rather than conserving "chargeable" natural resources: "There is no reason to arrest economic growth to conserve natural resources, although there is good reason to provide proper economic incentives to conserve resources which currently cost their users less than true social cost."

In the wake of Tobin & Nordhaus, a small group of economists began to model the economics of climate, to define the conditions of protecting earth's climate balance as a fragile public good. Climate economics addresses four essential aspects of climate change:

- Externality: unfettered markets distort price signals, because economic agents may emit greenhouse gases (GHGs) at no cost and overlook the impact of their emissions on current generations ("tragedy of the commons") and future generations ("tragedy of the horizon"). Where economists and decision-makers are aware of the externalities, as described in Pigou (1920), GHG emissions exceed all other known externalities in terms of their scale and impact;

- Externality as a global phenomenon: one ton of CO_{2e}[1] emissions has the same impact on climate, regardless of geographic origin. Historically, rich countries have imposed this externality on poor countries; however, the opportunities for reducing emissions at low cost, such as by addressing coal production, can now mostly be found in emerging countries. Designing effective and equitable incentives to overcome "free-rider" problems is one of the major challenges facing climate economists (Tirole, 2009; d'Autume *et al.*, 2016);

- Inertia of climate externality: global warming is caused by an accumulation of GHG emissions in the atmosphere. GHG levels rise through emissions and fall through natural absorption (by seas, forests and other carbon sinks). The concentration of CO_2 alone was approximately 280 ppm before the start of the industrial revolution; today, it is over 400 ppm. The rise in global temperatures has already reached one degree Celsius. However, when emissions already accumulated are accounted for, temperatures are expected to rise by a further 1-3 degrees Celsius by the end of this century (IPCC 2014). The discount rate used to appraise the damage takes on particular importance in view of the lengthy time frames (Stern, 2006; Dasgupta, 2008);

- Uncertainty: the fight against climate change is confronted with multiple interrelated causes of uncertainty: scientific uncertainty, regarding the extent of temperature increases caused by higher concentrations of GHGs in the atmosphere (climate sensitivity); uncertainty over the impact of climate change, in particular the thresholds (or tipping points) beyond which systemic changes are at risk of occurring; uncertainty regarding technology that can be deployed to offset emissions and mitigate their impact. This uncertainty means that combatting climate change calls for a precautionary approach (Pyndick, 2006; Weitzman, 2007). Furthermore, incorporating the risk of serious and irreversible damage generates an option value for the most flexible solutions, i.e. those that facilitate changes in public policy in response to new information (Arrow & Fischer, 1974; Henry, 1974).

These four characteristics of climate change highlight the scale of the challenges faced by economists who carry out research in this area. Within a short period, climate economists have managed to adapt their traditional "toolbox" for addressing economic problems – managing externalities (Pigou, 1920), managing exhaustible resources (Hotelling, 1931), long-term welfare considerations (Ramsey, 1928), socio-economic value (Dupuit, 1844) – to a new and much larger problem. Economics has incorporated advances in climate science and other physical sciences, social sciences and decision-making, in order to model the impact of global warming on human activity, as well as the economic cost of addressing this phenomenon. It now boasts a rigorous methodological approach that has been the subject of numerous academic literature reviews, for example Pindyck (2013) and Heal (2017).

1. Tons of greenhouse gases (e.g. carbon dioxide, methane, nitrous oxide, etc.) are expressed here in equivalent tons of CO_2 (or CO_{2e}) warming potential.

There are, of course, points of contention within the profession, arising both from the scientific uncertainties that continues to undermine the accuracy of models (Stern, 2013; Pindyck, 2017) and the need to use traditional economic methods beyond their usual scope of application, as can be seen with the discount rate, which is used to give a present value to damage or actions that may last for decades or even centuries (Gollier & Weitzman, 2010).

Such debates are crucial to making progress towards a deeper economic understanding and analysis of climate issues. However, consensus has been reached around one point: no ecological transition is possible, and no credible policy to mitigate climate change can exist, if pollution remains cost-free and people remain unaware of the damage they impose on others. In other words, given the multitude of human activities and actors, minimum pricing of carbon is a necessary, though not sufficient, condition to effectively combat climate change (Stern & Stiglitz, 2017).

The goal of this paper is to shed light on how economists have gone about calculating the monetary value of a ton of actual or foregone CO_{2e} emissions and to provide an overview of the past and currently used estimates. This form of valuation is an essential benchmark if the aim is to determine the economic cost of pathways to be taken, as well as to define the range of appropriate actions and calibrate public policy regarding mitigation.

As no formal market price for carbon has been established, the value of carbon has been modelled by university researchers and public authorities. This paper sets out the range of carbon values consistent with meeting the targets set under the 2015 Paris Agreement, internationally and domestically (in France), in the context of the second committee for carbon shadow pricing in 2019 (Quinet, 2019). These levels exceed the threshold of \$100 per ton of CO_{2e}, which raises additional questions. For example, how can these levels be reconciled with the lower and uncertain values derived from cost-benefit models? How can such values be incorporated in public policy-making?

Combatting Climate Change and the Depletion of Carbon Budgets

Carbon valuation can involve two approaches: “cost-benefit” and “cost-effectiveness”.

The cost-benefit approach involves arriving at an overall discounted valuation of all short, medium and long-term damage caused by the emission of one tonne of CO_{2e}. The comparison between the marginal cost of damage and the marginal abatement cost[2] will determine the socially optimal path to reducing emissions. The value of carbon, known in this approach as “social cost of carbon”, assigns a monetary value to the social cost of damage and, correspondingly, the welfare gain from a reduction in emissions. Adopting this approach acts in principle as a hedge against two risks: making too much effort for too little social benefit; and not making enough effort to attain a high benefit despite a low associated cost.

With the “cost-effectiveness” approach, an abatement target is exogenously set, and the level and trajectory of carbon values are set in order to reach that target in the most efficient way possible. In this case, the price of carbon is the dual variable of the quantitative constraint – for this reason, it is known as the shadow price of carbon. This approach may appear as a second best to the cost-benefit approach, but it abstracts from discussions over the cost and discount rate of damage and has a sound methodological basis – as applied to optimal management of non-renewable resources.

Carbon Budget Management

As the climate externality is related to the level of GHG concentration in the atmosphere, targets are expressed in terms of the carbon budget, i.e. the maximum net cumulation of CO_{2e} over a given period, at or below which rises in temperatures are restrained.

With this approach, the carbon value level depends on the size of the carbon budget, available carbon sinks, decarbonisation technology, achievable behavioural changes, as well as the availability of international flexibility mechanisms (e.g. purchasing emissions permits on international markets, availability of carbon sinks in other countries, etc.)

The slope of the carbon value trajectory is consistent with optimisation of a scarce natural resource. The price of the scarce resource will increase in step with its consumption due to its

2. The abatement cost is defined as the discounted cost difference between the decarbonisation action and the alternative baseline solution, equal to the greenhouse gas emissions prevented by the action. The cost difference is discounted as the abatement cost includes costs linked to the initial investment, but also costs linked to the purpose of that investment.

increasing scarcity. Specifically, the value of a ton of CO_{2e} is intended to increase along with the discount rate (Schubert, 2008; Chakravorty *et al*., 2008). This rule of optimisation, known as Hotelling's Rule (Hotelling, 1931), holds that the price of carbon rises at the interest rate thereby protecting future values (see Box). Correspondingly, it protects against the risk of creating an incentive to postpone efforts, as would be the case if the price grew faster than the discount rate – known as the "green paradox" (Sinn, 2015).

Applying Hotelling's Rule raises a number of operational issues. Research carried out in France by the most recent committee for shadow carbon pricing (Quinet, 2019) highlights the twin problems of setting a discount rate and managing the underlying investment dynamics (Gollier, 2019; Le Hir *et al*., 2019).

Gollier (2019) argues that the discount rate must include, in addition to the risk-free rate, a "climate beta", i.e. a risk premium that factors in the impact of climate policy on macroeconomic performance, specifically the incidence of the covariance between the marginal abatement cost and aggregate consumption.

Uncertainty over the carbon budget supports a higher initial value and a growth rate of value below the discount rate, in order to seamlessly absorb mid-point revisions to the carbon budget. This rationale is based on the negative correlation between the marginal abatement cost and consumption. Where the carbon budget revised downwards, this increases the marginal abatement cost (assumed to be increasing) and restricts consumption possibilities. If, on the other hand, the carbon budget is higher than initially envisaged, the marginal abatement cost will be lower and consumption higher. The negative correlation between the abatement cost and consumption leads to a negative "beta". This reasoning also applies where uncertainty affects decarbonisation technology: in the event of unforeseen advances,

Box – **Simple Theoretical Model of Carbon Budget Management**[(a)]

We make the following assumptions:

- Economic agents derive utility $U(R_t)$ from consumption of fossil fuels in time *t*;

- A discount rate ρ applies a weighting factor to these levels of utility as a function of time.

We then seek to solve the maximisation problem for an aggregate of all utility values derived over time through consumption of the fossil fuel.

$$Max \int_0^{\infty} e^{-\rho t} U(R_t) dt$$

Utility is maximised subject to three constraints:

$$\dot{S}_t = R_t$$

$$\dot{M} = \varepsilon R_t - \alpha M_t$$

$$M_t \leq Z$$

S_0, M_0, given that

The first constraint assumes that the extraction and consumption of resource *R* reduces finite stock *S* (existing global resources), for which the value is known in time *t*.

The second constraint assumes that the concentration of CO_2, *M,* increases with the level of emissions, which themselves are proportional to extraction of *R* (with a constant coefficient ε) and decreases with natural absorption of CO_2 (which is equal to a fraction α of the atmospheric concentration of CO_2).

The third constraint assumes that the atmospheric concentration must not exceed a level considered dangerous, denoted by *Z*.

Each constraint is allocated a coefficient in order to solve the equation, for which the economic rationale is as follows:

- $\lambda_t > 0$, denoting the implicit price of the resource (scarcity rent);

- $\mu_t > 0$, denoting the implicit value of the carbon inventory (carbon price);

- $\omega_t > 0$, multiplier linked to the concentration constraint. It adopts a zero value where the constraint is not met, and a positive value otherwise.

Under optimal conditions, the following relationships hold:

$$U'(R_t) = \lambda_t + \varepsilon \mu_t, \ \frac{\dot{\mu}_t}{\mu_t} = \rho + \alpha - \frac{\omega_t}{\mu_t}, \ \frac{\dot{\lambda}_t}{\lambda_t} = \rho$$

Scarcity rent increases on the optimal path at discount rate *r*:

$$\lambda_t = \lambda_0 e^{\rho t}$$

The carbon price increases on this optimal path at the discount rate plus the rate of natural carbon absorption in the atmosphere:

$$\mu_t = \mu_0 e^{(\rho + \alpha)t}$$

(a) *Report on carbon shadow pricing (Quinet, 2008).*

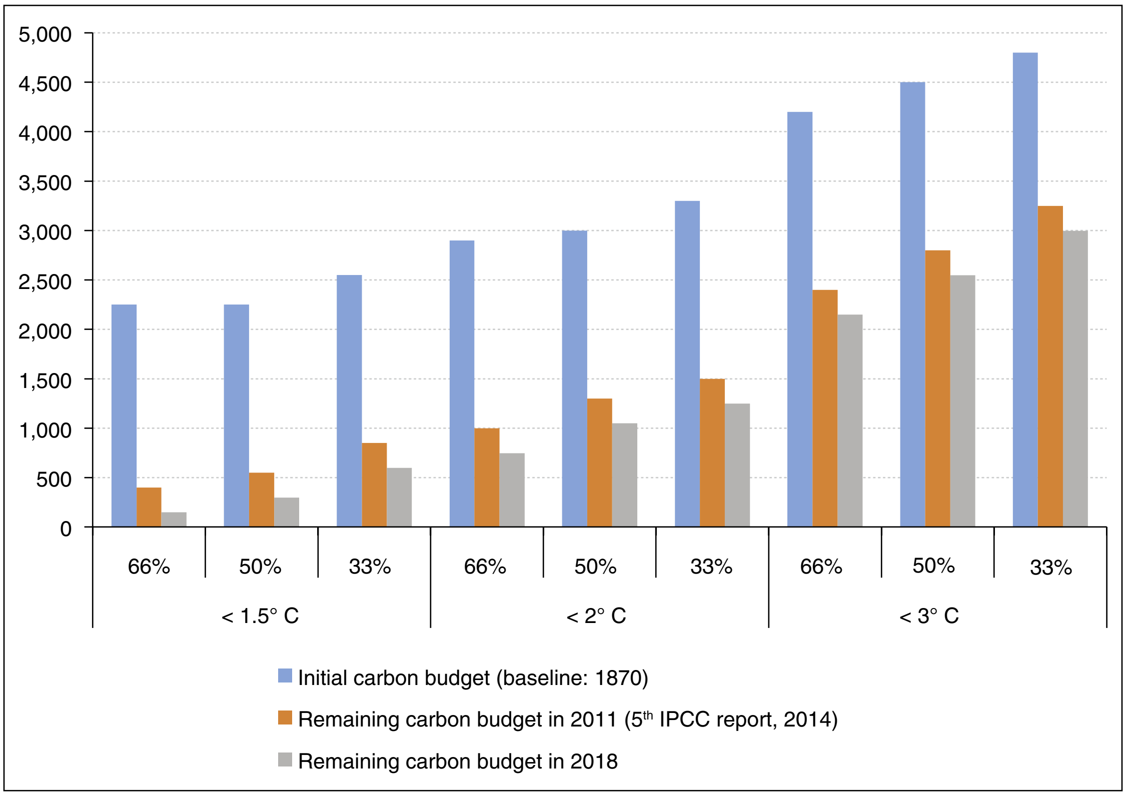
the future marginal abatement cost will be lower and consumption higher.

On the other hand, where macroeconomic conditions are the main cause of uncertainty, the correlation between the marginal abatement cost and consumption is positive. Where growth is higher than forecast, emissions will be higher, as will the marginal abatement cost as a consequence, resulting in a positive "beta" value. In this configuration, the benefit from an investment to reduce emissions increases over time, and is higher than the discount rate – returns from this investment thus take the form of a risk premium. The initial value of carbon is therefore lower and its growth rate higher than the discount rate.

The model put forward by Le Hir *et al.* (2019) develops Hotelling's Rule further by considering two stocks: the carbon budget, which depletes over time; and enterprises' productive capital, which is expected to gradually become "greener". Each stock is assigned a value – the value of carbon and the cost of capital allocated to carbon abatement. An unexpected downward revision to the carbon budget would result in an immediate and costly adjustment to the capital stock. This risk acts as an incentive to plan abatement and "green economy" investment activity, and thereby increase the initial value capital allocated to abatement.

The well-defined cost-effectiveness analytical framework must confront a new challenge, namely the rapid depletion of carbon budgets, as illustrated in Figure I below, which sets out the size of carbon budgets for three maximum-temperature targets and a range of probabilities. The fifth report of the IPCC, published in 2013 and 2014, demonstrated that in the absence of specific efforts to reduce emissions, the global carbon budget to limit temperature increases to 2°C would run out by the middle of the century (IPCC, 2014). The IPCC also noted that a conservative estimate of the potential volume of negative emissions would make the second half of the 21st century a viable target for achieving carbon neutrality, i.e. a balance between gross GHG emissions and carbon sinks such as forests, permanent grasslands and, in the longer term, technological solutions for geological carbon sequestration. These findings underpinned the 2015 Paris Agreement.

Figure I
Available carbon budgets under temperature minimisation targets (billions of tons of CO_2)



Notes: The percentages refer to probabilities of meeting temperature increase targets.
Sources: Quinet (2019).

Depleting the carbon budget by the middle of the century leaves little time for adjustments, which may have significant implications for designing an economic framework for transition:

- It is necessary to rapidly develop and deploy decarbonisation technology, for which the cost and emissions reduction potential are largely unknown at present. In certain sectors (e.g. steel, chemicals, long-distance freight, etc.) technical solutions aimed at achieving full decarbonisation do not exist, hence the critical role of carbon sinks in order to reach net zero emissions;

- It is necessary to minimise as far as possible the number of stranded assets, i.e. unamortised assets that emit GHGs which must be decommissioned in order to achieve carbon neutrality, such as coal-fired power plants. This means that efforts must be progressive enough to prevent decommissioning of existing assets and firm enough to dissuade the construction of new polluting assets;

- To reach net-zero emissions, it is necessary to engage in long-life or very-long-life investment projects (e.g. railway lines or electricity transmission lines). The residual economic value of new installations and equipment that can meet a net-zero emissions target by 2050 but that have not fully depreciated by that time must be considered when calculating their economic viability.

Sharp Upward Revisions in Carbon Values

Carbon values linked to decarbonisation targets are subject to significant upward revision in response to a dwindling carbon budget and more stringent targets. Table 1 below gives the mean world carbon prices based on simulations carried out by the IPCC, recognising that the dispersion is high around these mean values. Predictably, values rise as the urgency of decarbonisation increases. In addition, in the "1.5°C" scenarios, values pass the $100 mark by 2030, before "taking off" after 2030.

The table highlights the difficulties associated with modelling the transition towards a carbon-neutral economy. Models give plausible values through to 2030 and 2040, or alternatively until emissions have fallen broadly in line with "Factor 4" scenarios (i.e. reductions in greenhouse gas emission levels by a factor of four from 1990 levels). The robustness of model output declines as the years progress, the level of emissions falls and we approach the level at which reductions become harder to achieve and require structural, non-marginal changes, which models calibrated on the cost of existing or foreseeable technologies can no longer predict. Lastly, it is noted that the slope of value trajectories between 2030 and 2050 is markedly higher than under Hotelling's Rule, which suggests that the need for initial effort is underestimated.

A New and Robust Carbon Value Path for France That Meets the Carbon Neutrality Target

Under collective efforts set down by the Paris Agreement, France, in its Climate Plan of July 2017, set a target of net zero emissions in GHGs by 2050, with residual gross emissions to be absorbed by carbon sinks and any available carbon sequestration technologies. This target is more ambitious that the previous "Factor 4" target (reduction in emissions to one-quarter of their 1990 levels).

The cost-effectiveness approach offers a way of determining a carbon value for France in line

Table 1
Carbon value under IPCC calculations (in $ 2010 per ton of CO_2)

Scenario	Content	Carbon value in 2030	Carbon value in 2050
1.5°C	Probability of exceeding 1.5°C less than 34%	1,472	3,978
1.5°C low	Probability of exceeding 1.5°C between 34% and 50%	334	1,026
1.5°C high	Probability of exceeding 1.5°C between 50 and 67%	129	586
Lower 2°C	Probability of exceeding 2°C less than 34%	164	518
Higher 2°C	Probability of exceeding 2°C between 34% and 50%	56	169
Above 2°C	Probability of exceeding 2°C more than 34%	21	63

Notes: In each scenario, average value for a range of models and simulations.
Sources: IPCC (2018).

with this target. Following on from early research by Marcel Boiteux on shadow pricing, i.e. monetary values to be assigned by the State to welfare gains and losses (Boiteux, 2001), an initial study was carried out in 2008 to assign values to actions intended to prevent emission of one ton of CO_{2e} in respect of the Factor 4 target. The baseline was set at €100 (at 2008 values) per ton of CO_{2e} in 2030, subsequently rising under Hotelling's Rule to €250 (at 2008 values) in 2050 (Quinet, 2008). Ten years later, a second report (Quinet, 2019) updated this benchmark to account for the worldwide lag in reducing GHG emissions, the 2015 Paris Agreement, and potential advances in technology.

A Carbon Trajectory Based on State-Of-The-Art Analysis

It should be noted that no ready-made simulation exists that can mechanically produce a carbon value path. The new report puts forward a coherent carbon value trajectory established collaboratively by France's leading climate economists, which is of the highest attainable standard. In addition to the general principles of climate economics, it features two specific elements:

1) Simulations from five different models (Times, Poles, IMACLIM, ThreeME and NEMESIS). The cost-effectiveness approach adopted here does not require a model for the damage curve as the emissions reduction target is set by the Paris Agreement of 2015. Under this approach, only technological and macroeconomic dynamics, along with GHG emissions flows, are modelled. These models produce a path that reflects the marginal cost of reducing one ton of CO_{2e}, i.e. the marginal abatement cost, which tends to increase over time as the deployment of more cost-intensive technological solutions becomes necessary. These models make it possible to detail the investment and behavioural changes required to achieve carbon neutrality;

2) Forward-looking studies into technological and techno-economic solutions. Studies such as those carried out by the International Energy Agency (IEA, 2017), are used to assess the decarbonisation potential of various technologies, their speed of deployment and their cost. Based on this research, the report does not predict the arrival of "backstop" technology, i.e. replacement technology that can completely bypass fossil fuels at a stable cost. It does however postulate that a limited number of carbon sinks will emerge. To reach a target of full decarbonisation, it assumes that a portfolio of functional technologies (e.g. more widespread and direct use of carbon-neutral electricity or indirect use via the hydrogen energy vector, development of CO_2 capture and storage solutions) could be leveraged to achieve full decarbonisation through relatively high fuel switching prices.

A Target Value Increase from €100 to €250 in 2030

The report considers that a timescale of 2030 serves as the preferred anchor for a carbon value trajectory for two key reasons: firstly, a 10-year horizon is determinant in "anchoring" expectations and initiating an upsurge in "low-carbon" investment; secondly, with this timescale, the basis of economic forecasts and technological outlooks are relatively sound, although they of course remain uncertain.

Based on the modelling work completed, the report recommends the adoption of a carbon value of €250 (at 2018 values) in 2030, based on the current value of €54 in 2018, which therefore entails a catch-up phase. After 2030, growth in the carbon value reduces progressively, aligning with Hotelling's Rule at a public discount rate of 4.5% from 2040 onwards. The price in 2050 is €750.

A Value in Line with IPCC Estimates

The value proposed in 2030 is significantly higher than that of the current benchmark taken from the 2008 report (€100 at 2008 values, €110 at current values). This primarily reflects the lag and the corresponding increased ambition beyond "Factor 4", which entail high abatement costs or technological breakthroughs in a number of economic sectors, particularly agriculture (notably the need to adapt crop and livestock farming), in some industrial sectors (the need to find substitutes or disruptive technologies in essential production such as cement, chemicals and steel), and in long-distance transport (land, sea and air travel). The increase in carbon values also reflects the lack of international cooperation and flexible mechanisms at international level.

The value of carbon in France is within the range of values indicated in the IPCC's latest October 2018 report for targets under two degrees (see Table 1), which were revised sharply upwards to factor in the risk of rapid depletion of world carbon budgets.

An Outcome that is Sensitive to International Cooperation and Innovation

Determining a carbon value trajectory must account for uncertainty which increases further into the future as the scope for technological developments and diplomatic ini-tiatives expands. After 2030, the values suggested by the model may be revised downwards to reflect behavioural changes by actors who fully incor-porate combatting climate change into their practices, or the availability of a broader portfolio of decarbonisation technologies.

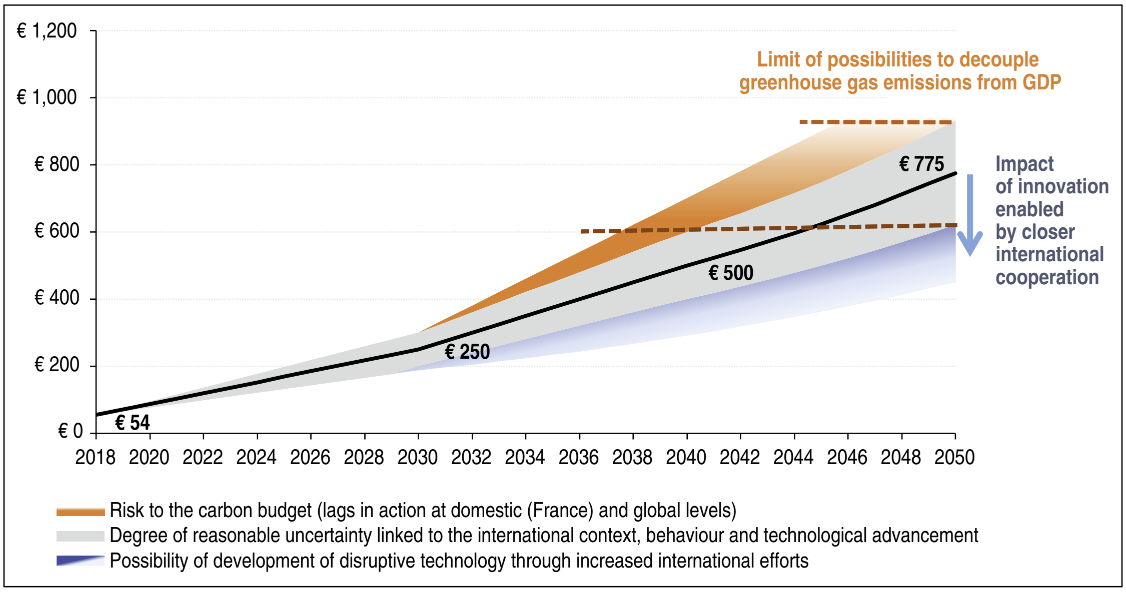
The sensitivity of results to the cost of technology is closely related to underlying assumptions of international cooperation. Research and innovation efforts that place greater focus on decarbonisation and are simultaneously engaged in multiple countries would have a powerful impact in terms of reducing the cost of tech-nology, as can be seen at present in the case of renewable energy. Where multiple research bodies and companies in a number of countries become engaged in innovation projects, this should produce gains for individual countries: each country benefits from the emergence and dissemination of innovation throughout the world, along with the reduction in the cost of technology facilitated by learning effects and economies of scale, the so-called international spillover effects.

Overall, the assumption of technological breakthroughs through closer international cooperation would undoubtedly have little effect on the value of carbon in 2030, but would accommodate an expected sharp reduction in the carbon value beyond 2030 (from €750 to €450; see grey area in Figure II below). On the other hand, a deficit in international cooperation would not justify an upward revision in the already-high baseline carbon value in France (see orange area in Figure II below); any such revision would not stimulate the deployment of additional technologies within the same short timescale and could lead to restrictions in business activity and employment, with no sustainable benefit from the fall in the carbon intensity of human activity.

Issues Related to Upward Movement in Carbon Values

Cost-effectiveness approaches adopted either nationally or globally have resulted in much higher carbon values. These increases reflect the depletion of carbon budgets. They raise two basic questions: how do we reconcile these results with the lower values produced using cost-benefit approaches, and how can they be incorporated into public policy aimed at reaching the stated targets?

Figure II
Carbon price path - France



Sources: Quinet (2019.

Coordinating the Results from Cost-Effectiveness and Cost-Benefit Approaches

To understand the cause of the emerging gap between carbon values reached using cost-effectiveness approaches and those using a cost-benefit approach, it is instructive to set out the three main elements in calculating the marginal cost of damage.

Monetary Value of Damage

Modelling climate externalities essentially depends on two parameters: climate sensitivity, i.e. the increase in temperatures caused by increasing concentration of GHGs in the atmosphere; and the climate damage function, which captures the impact of rising temperatures on welfare. The cost of damage or cost of inaction is expressed in monetary terms but consists of both market costs (e.g loss of productivity and GDP, lower agricultural yields, destruction of productive capital due to natural disasters, etc.) and non-market costs (e.g. loss of biodiversity, destruction of ecosystems, etc.), to which we assign a monetary value. Assigning a value to damage is therefore subject to considerable uncertainty: how do we aggregate such a wide range of impacts and give a monetary value to what are in part non-market damages? Is the damage function multiplicative (i.e. is damage correlated to the level of GDP) or additive (i.e. is damage independent of the level of GDP)? What degree of convexity does the damage curve exhibit?

Discounting for Damage Caused Over Time

The marginal cost of damage caused in the future by the emission of one ton of CO_{2e} today must be discounted in order to be tracked to its present value. Over the very long term – a horizon much longer than that used in financial markets – the discount rate involves ethical choices: pure time preference, aversion to intra- and intergenerational inequality, assessing the long-term outlook and its attendant uncertainties (Stern, 2006; Gollier, 2012; Dasgupta, 2008). This is especially important in the context of global warming, given that large-scale changes are at risk of occurring by the end of the century.

Accounting for the Risk of Serious and Irreversible Damage, Over and Above Marginal Damage

Consideration of catastrophic risk leads, in various forms by way of an option value, to an increase in the mean value of damage (Hery, 1974; Weitzman, 2014).

Applying Cost-Benefit Analysis to Combatting Climate Change: Mission Impossible?

Cost-benefit analyses, which usually serve as the basis for all meaningful economic thought, have ultimately been few in number. The Stern report in 2006 generated discussion over the main parameters in cost-benefit calculations (Weitzman, 2007; Nordhaus, 2007; Sterner & Petersson, 2008). However, only a handful of integrated assessment models have been used in major international studies, notably DICE (Nordhaus, 2018), FUND (Anthoff & Tol, 2014) and PAGE (Hope, 2006).

These models are intended to overcome the major methodological issues that heavily influence the conclusions that they reach. In fact, ranges for the social cost of carbon are relatively broad – between \$30 and \$150 per ton of CO_{2e}. Table 2 sets out a non-exhaustive list of figures for the

Table 2
Social cost of carbon (per ton of CO_2)

	2015	2020	2050
DICE (values in \$ 2010)			
Discount rate of 4.25%	30	35	98
Discount rate of 2.5%	111	133	242
US IWG (values in \$ 2007)			
Discount rate of 3%	36	42	69
Discount rate of 2.5%	105	123	212

Sources: Nordhaus (2018), US Interagency Working Group (2016).

social cost of carbon from two recent major studies, and underlines the sensitivity of these figures to the choice of discount rate:

- Output from the DICE model, from updated research by Nordhaus (2018). This model is transparent in its assumptions and output;

- Analysis by the United States Interagency Working Group for the environment, based on the use of DICE, FUND and PAGE models (USIWG, 2016).

How can divergences between the cost-benefit and cost-effectiveness approaches be interpreted? Do they suggest that cost-benefit models minimise the cost of damage, or, conversely, that climate policy targets underestimate the cost of emissions reduction?

Traditionally, economists have sought to adjust for the difference in orders of magnitude in both approaches by using a low discount rate in cost-benefit analysis. This is the approach used in the Stern report, which features a very low time preference, systematically leading to carbon values close to valuations based on Factor 4 targets. It should be noted that valuations of carbon using cost-benefit approaches are more sensitive to the discount rate than those using cost-effectiveness approaches, where analysis covers much longer time horizons. Cost-benefit approaches tend to apply a discount factor to damage inflicted over a very long time horizon of between 100 and 200 years. Cost-effectiveness analyses generally look at much shorter time horizons, typically between one and three decades (2030 or 2050). As we have seen, using these approaches, the discount rate determines the slope of the carbon price path, not its initial level directly.

In addition to the discount factor, recent economic research suggests that cost-benefit approaches tend to underestimate the cost of damage and therefore apply much larger carbon budgets than those implicit in new climate change targets. Three interrelated reasons for underestimation exist:

- Models generally do not take account of all potential damage, some of which are difficult to assign a monetary value to because they have no direct impact on GDP and asset values, or do not factor in the most recent, more pessimistic valuations (Aufhamer, 2018);

- Climate change has traditionally been assumed to affect GDP through productivity, dwindling capital stock and destruction from natural disasters. However, an emerging body of research suggests that the growth rate can also be affected by a reduction in the capital stock or productivity gains, in particular in poor countries and countries vulnerable to climate change (Moore & Diaz, 2015; Dietz & Stern, 2015);

- Models use damage curves that are mildly convex, thereby underestimating the risk of disaster in the case of marked increases in temperature.

In this respect, a more fundamental criticism applies to the degree of relevance of cost-benefit analysis, which compares the marginal cost of action and inaction, typically using normal probability distributions. However, climate change includes non-marginal risks of catastrophic damage, with probabilities of occurrence considerably higher than those obtained from a normal distribution (Weitzmann, 2014; Van der Ploeg & de Zeuw, 2014). In his Dismal Theorem, Weitzman (2011, 2014) describes a scenario in which the social cost of carbon tends to infinity, where the probability of catastrophe falls at a slower pace than the scale of catastrophic damage increases. Weitzman considered the implications of this outcome “absurd”: current generations cannot devote all of their resources to disaster risk prevention, and the conditions under which the Dismal Theorem holds are undoubtedly highly restrictive. However, the message of caution when implementing and interpreting cost-benefit assessments remains valid: the value of emission reductions should not only be measured by the damage prevented but also by the reduced probability of the occurrence of irreversible catastrophes.

In this context, the IPCC scientific community has been guarded about the use of cost-benefit approaches, preferring instead to keep to the definition of maximum temperature thresholds for preventing the risk of serious and irreversible damage. Overall, the main argument for more ambitious mitigation policies than those based on the cost-benefit model output lies in the finding that both GHG concentrations and damage are irreversible.

The irreversibility of GHG concentrations is linked to current levels of technological advancement. Negative emissions technology may reverse GHG inventories, but the prospect of such a development remains wholly speculative at this point, and the prudent approach would be to expect a dwindling and/or depleted carbon budget.

Even if one assumes that emissions become partially reversible in the future, some of the damage caused will be irreversible, meaning that the services currently offered by nature that will have disappeared will not be able to be replaced by technological substitutes. Front-loading and increasing efforts provides an option value against the risk of being without any room for manoeuvre in the future; if an unforeseen but favourable event occurs, it will still be possible to reduce the level of subsequent abatement when compared with forecasts; however, when faced with the carbon budget constraint, an unforeseen and unfavourable event will in all cases produce damage (Bureau, 2017).

Highlighting the limitations of existing cost-benefit approaches does not mean that the economic and social costs of mitigation to meet these thresholds should be ignored. A cost-effectiveness approach makes it possible, through a carbon value trajectory, to measure the economic effect of mitigation actions and their merit order, the required decarbonisation investment and the risk of stranded costs to meet a given climate target.

Translating Carbon Value into Public Policy

The value of carbon sets a baseline for calibrating climate policy: all actions that entail an abatement cost below the baseline must be undertaken as they are socially and economically viable.

The leading mitigation policy instrument is uniform pricing applied to all global emissions (Tirole, 2009): the broader the scope, the more opportunities exist for abatement at low cost. This efficiency rule does however pose difficult questions in terms of equity. Applying a single global price for carbon not only raises the issue of free-riding, but also of financial compensation: advanced countries carry a large share of the responsibility historically for global warming, yet the main actions to reduce emissions, in particular the elimination of coal, focus on emerging countries. Where financial compensation schemes are not in place between countries, the uniformity of the carbon price cannot ensure equitable outcomes (d'Autume *et al*., 2016). At present, the 2015 Paris Agreement relies on an accumulation of quantitative commitments by nation states, which is a more pragmatic method of achieving harmonisation of climate mitigation policies internationally, but without the decentralised coordination of efforts that a single global carbon price would allow.

Minimum pricing for carbon is necessary. The operational question is the correct level with respect to two considerations, the first of which is social: can carbon pricing be aligned with a high baseline value? The second consideration is economic: can carbon pricing be enough to realise substantial decarbonisation of human activity?

Questions regarding the correct price and the complementarity of instruments for reducing carbon emissions are the subject of a large body of research in climate economics. The terms of the debate are now clear: pricing aligned to the value of carbon would be relevant in a world where public policy is closely aligned on the carbon neutrality objective and where market imperfections are non-existent or already overcome. This would assume:

- Close coordination of land and urban planning policies and transport and mobility policies (that people are not forced to commute long distances due to excessive property costs, towns and cities are compact and have sustainable transport networks, etc.);

- Actors have zero-carbon alternatives (suitable infrastructure, technological solutions) and a means of funding profitable decarbonisation investment (access to credit, guarantees against certain types of risk, etc.);

- The State is able to address its distributive effects of a carbon tax or its impact on competitiveness.

A more refined analysis would view the transition to carbon neutrality as dependent on alignment of all public policies regarding "net-zero emissions" and a "smart" aggregation of additional measures. This has been argued by the OECD (2015) and in the Stern-Stiglitz report (2017); to remain on the right pathway towards carbon neutrality, there needs to be a minimum global price of carbon to ensure transparent pricing and the profitability of decarbonisation initiatives, and to encourage research into innovative solutions. However, the scope of action to achieve substantive carbon reductions from human activity is much broader, including in particular:

- Building a regulatory framework that facilitates optimal land use (increasing population density in towns and cities, and minimising commuter journeys);

- Subsidies for "green" R&D in addition to pollution charging to overcome instances of market failure and the tendency of companies to limit innovation to their own field of expertise (Acemoglu *et al.*, 2017) ;

- Investment in public infrastructure and low-carbon buildings; risk sharing where necessary with respect to zero-carbon technologies through guarantee schemes, and facilitating access to credit.

According to Stern & Stiglitz (2017), a minimum price of carbon should fall between \$50 and \$100 per ton of CO_{2e} by 2030. It should be noted that, in light of statistics published by the World Bank and the OECD, much progress remains to be made towards minimum pricing. A 2019 survey by the World Bank showed that 46 countries and 25 territorial authorities have introduced carbon pricing. However, such arrangements only cover 20% of global greenhouse gas emissions, with the remaining 80% outside the scope of any pricing mechanism. The OECD (2018) measures the Carbon Pricing Gap, i.e. the carbon price deficit of OECD countries and the G20 by comparison with a baseline of €30 per tonne of CO_2: in 2018, the deficit was 76.5%.

Without revisiting the discussion around the correct choice of climate policy instrument, it should also be noted that public policy-makers require key information over and above the baseline price of carbon, in order to develop a climate policy.

Adopting a high price of carbon requires a detailed appreciation of the potential winners and losers in order to design the most suitable carbon offset mechanisms. It does not however require a detailed understanding of the abatement costs across different economic sectors. It is the economic agents themselves who, through an intimate knowledge of their own abatement costs, decide to incur a tax or to reduce their emissions.

Where the government opts to use non-tariff instruments – typically regulations or subsidies – detailed knowledge of abatement costs becomes essential to efficiency: too low a level of subsidy or light-touch regulation is inefficient; too high a level of subsidy creates rent-seeking; overly stringent regulation may impose compliance costs in excess of the baseline value of carbon. Appropriate calibration of climate policy therefore depends on the capacity of the government to know and track in detail the actual abatement costs. This requirement is particularly important, given that available research indicates that the cost of decarbonisation actions are widely dispersed among economic actors within each sector, which is not surprising: one solar energy plant or one wind farm generates very different abatement costs depending on its location and the structure of the pre-existing energy system.

It is possible to make a generic classification of decarbonisation actions by each sector based on their abatement cost (Gillingham & Stock, 2018):

- Actions with zero or negative abatement costs, in particular because they do not involve significant investment or generate immediate savings. Such rare instances of a "free lunch" primarily entail restraint, e.g. purchasing a vehicle based on need rather than a larger, more powerful car when changing vehicle, adding a dose of ethanol into petrol, manual optimisation of a building's heating through the day, or carpooling;

- Actions with positive abatement costs that are lower than the baseline value of carbon. These are actions that are not financially viable but appropriate for communities, and should be encouraged;

- Actions whose abatement costs remain high, based on current knowledge, such as the use of carbon-free hydrogen for transport, industry or energy production, or carbon trapping and sequestration.

In the latter example, abatement costs should be assessed dynamically: an action might entail a high initial cost but also have the potential to reduce the cost over time through economies of scale and learning effects (Vogt-Schilb *et al.*, 2014). This can be seen in the case of photovoltaic solar panels and in electric vehicle development. Some actions fall into intermediate scenarios and are thus the subject of discussion: the transition from coal to gas generates significant short-term GHG savings but involves installation of appliances that emit CO_{2e} in the long term; nuclear energy substantially reduces GHGs, but the associated abatement cost tends to increase over time.

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Amid uncertainty over the timing, scale and apportionment of damage, analysis of the economic literature suggests that it is undoubtedly too soon to use cost-benefit analysis to calibrate precautionary actions. The near-term challenge is "buying flexibility". Setting a specific target today makes it possible to cover the risk of serious and irreversible damage, with the option to make subsequent adjustments to the mitigation path in the event of "good news" regarding climate or "backstop" technologies.

Under the 2015 Paris Agreement on climate, the parties have set a target of achieving carbon neutrality, i.e. GHG emissions and the absorption capacity of carbon sinks to be in balance – by the second half of the 21st century. In working collectively towards this target, France, like other European countries, has set this same target for 2050. This ambition must be reflected in behavioural changes, investment and, more generally, concerted action from the public and private sectors. In this regard, assigning a monetary value to carbon means assigning value to actions to protect the climate, emphasising that decarbonisation actions have a collective value. Once a carbon value trajectory is established, all public and private actors have a medium-to-long-term reference point for determining the appropriate actions to take and to implement them in order of merit. □

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