The Social Cost of Global Warming and Sustainability Indicators: Lessons from an Application to France

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Abstract – In order to meet the Paris agreements, significant financial resources must be incurred, which are evaluated here using a macroeconomic model combining a criterion of intergenerational distribution of the climate effort and assumptions on decarbonisation technologies. The results show that, for France, the current greenhouse gas emissions trajectory is unsustainable, in the sense that in order to reach the carbon neutrality commitment in 2050, the annual level of climate spending would have to increase very substantially, to 4.5% of GDP from the current 1.9%. These evaluations make it possible to deduce a social price of carbon or a value for climate action, which has been increased significantly compared to previous evaluations such as those of the Stiglitz-Stern commission, in line with the results of the Quinet Commission in 2019. Such evaluations of the emissions trajectory and the social price of carbon could be the entry point for environmental economic accounting that includes the degradation of natural assets caused by economic activities.

JEL Classification: Q01, Q54, Q56, E01, E21, O13
Keywords: sustainability, climate change, carbon price, adjusted net savings

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While the global temperature has experienced a very clear increase since the 1980s, the scientific consensus is now established and recognises that human activities have an impact on global warming through greenhouse gas (GHG) emissions. In exchange, global warming will cause damage to human societies and natural environments, and the risks of abrupt and irreversible damage increase with the degree of warming.

In this context, the international framework for combating climate change has been considerably strengthened in recent years, particularly with the Paris Agreements in 2015 (COP 21) which define a shared goal of limiting the rise in the average temperature of the planet to "well below 2°C above pre-industrial levels". This goal is based in particular on the work of the IPCC, which shows that the risks of damage become very high in scenarios involving a rise in temperature above 2°C (IPCC, 2015). Various nations are also beginning to make individual commitments by setting targets for reducing GHG emissions within a certain time. In the case of France, the goal of achieving carbon neutrality in 2050 was set by law in 2019 and the climate goals are reflected in the National Low Carbon Strategies (*stratégies nationales bas carbone* - SNBC), which consist of a GHG emissions reduction trajectory and measures to be implemented to achieve that objective. These strategies give rise to implementing decrees that set three-yearly carbon budgets (annual quantities of emissions that must not be exceeded). The scale of the efforts needed to achieve these goals, their distribution over time and the consequences for standards of living and their sustainability remain points of debate.

Thus, the question of the climatic sustainability of growth arises and the aim of environmental economic accounting is precisely to provide the data that allows this key issue to be analysed. Unlike traditional areas of national accounting, in which values, prices and volumes are measured, environmental matters are characterised by the absence of prices or by the fact that the latter do not reflect the value of assets (natural resources, biodiversity, the climate, etc.) or liabilities (pollution and global warming). Environmental economic accounting involves replacing market prices with a social value. In this respect, the Paris Agreement constitutes a turning point in the sense that the objective of human societies, in terms of climate, can now be considered fixed: to limit global warming to 2°C and to achieve carbon neutrality by 2050. In the language of environmental economic accounting, this Agreement is the benchmark for placing a value on carbon.

Translating our shared climate goal into action requires being able to predict the different possible economic and climatic trajectories in accordance with individual efforts. Using a macroeconomic model, created on the basis of realistic assumptions on decarbonisation technologies and the distribution of efforts across generations, we evaluate the optimal emission reduction trajectories for France and the world, as well as a measurement of the annual climate change mitigation effort. This model also makes it possible to determine a carbon value in France, revisiting the results of the Quinet Commission (Quinet, 2019). By significantly raising the carbon price in comparison with previous evaluations, the report of the Quinet Commission was an important moment in the debate on the social valuation of climate action. Our results go even further in this direction and lead us to consider the Quinet prices as minimums, in view of the goal of achieving carbon neutrality by 2050.

Modelling GHG emission reduction trajectories allows us to evaluate climate sustainability. However, it is more complex to measure sustainability in a general sense. The Commission on the Measurement of Economic Performance and Social Progress had, moreover, abandoned this ambition and its report recommended separating the two dimensions of economic sustainability and environmental sustainability (Stiglitz *et al.*, 2009), thus rejecting approaches such as those based on inclusive wealth or adjusted net savings, which seek to evaluate overall sustainability by massing all the economic and natural "capital" that is transferred from one generation to the next.

However, progress concerning the carbon price and the estimation of decarbonisation technologies invites a review of the subject, by re-evaluating overall sustainability in France and worldwide, when the degradation of natural capital is valued using the new carbon price estimates.

After a description of the simplified climate economics model (section 1), we will focus on evaluating climate sustainability by comparing the actual trajectory of GHG emissions to that which would be required to meet the goals set by the Paris Agreements and by measuring the scale of the effort required (section 2). We will then look at the resulting estimates of the social value of climate action (section 3), followed by addressing the issue of sustainability in a broad sense, through an evaluation, at both national and global level, of adjusted net savings and inclusive wealth (section 4), before concluding.

1. Evaluating the Effort to Combat Climate Change and Distributing the Effort across Generations: Analytical Framework

Evaluating the sustainability of the economic development trajectory essentially entails making future projections, both medium and long term, and therefore requires the use of modelling. There are many models, both national and international, that integrate environmental concerns, whether centrally or peripherally. They can comprise several hundred equations and are all useful for simulating, in the short or medium term, the impact of targeted or sector-specific measures. Their sophistication also has a cost, which is to make it more difficult to identify the assumptions that fundamentally determine their results. As Robert Solow noted in the introduction to his "A Contribution to the Theory of Economic Growth" (Solow, 1956), the strength of an economic model sometimes lies less in its complexity than in its ability to formulate central assumptions that offer the right compromise between simplicity and realism. It is on these central assumptions, which form the core of the integrated economy-climate model reactor, that we focus here (Figure I).

1.1. Greenhouse Gas Production and Emissions

In this spirit of focusing on the critical factors, here we consider a stylised model of an economy with capital K_t and labour L_t as factors of production and a Cobb-Douglas production function: $Y_t = K_t^{\alpha}(A_tL_t)^{1-\alpha}$. The work and technical progress A_t are exogenous and grow according to an exponential law.[1] In each period, households save a proportion s_t of the national income, feeding into the stock of capital, which depreciates each year at the rate of δ. The law for the development of physical capital is therefore: $K_{t+1} = K_t + s_tY_t - \delta K_t$

The interconnection between the climate and the economy is essentially reflected in two elements:

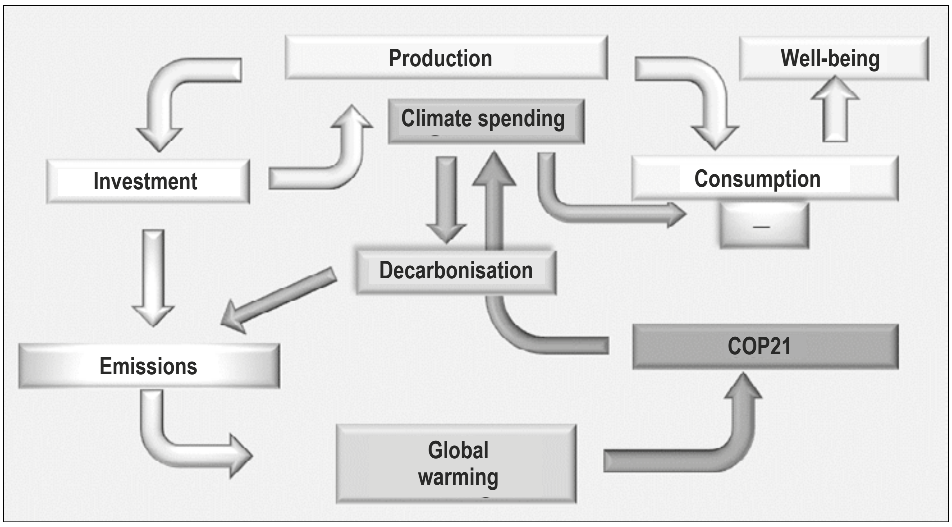
(i) economic activities are responsible for greenhouse gas emissions $E_t = \sigma_t Y_t$, where σ_t represents the carbon intensity of the economy;

(ii) climate spending D_t, in favour of decarbonisation technologies, can reduce carbon intensity and thus limit the growth of emissions. This spending reduces consumption by the same amount $C_t = Y_t - s_tY_t - D_t$.

In each period, the public authorities have the opportunity to act on the two levers that are $\Lambda_t = D_t / Y_t$, the proportion of climate spending in GDP and s_t, the savings rate. They do so by seeking out the economic trajectory, compatible with the climate

1. For the global model, the annual population growth rate decreases gradually over time, to reach a global population of around 10 billion inhabitants in 2050.

Figure I – **Main determining factors of the model**



objective, which maximises a previously defined inter-temporal utility function.

1.2. Damage Function and Climate Target

One of the central issues is to evaluate the optimal GHG emissions target. The pioneering work of Nordhaus (1977), who built a Dynamic Integrated model of Climate and Economy (DICE), provides some initial elements of an answer. By precisely expressing the damage function as a function of global temperature, this type of model makes it possible to calculate an optimal trajectory, both economic and climatic. The greenhouse gas emissions goal appears endogenous to the overall model: this is the cost-benefit approach (Figure II-A).

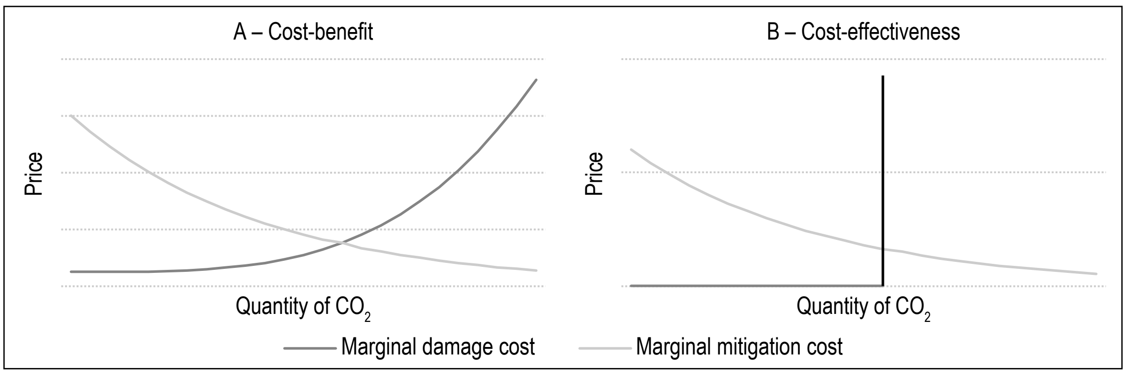
While this approach is natural from a theoretical point of view, it is particularly difficult to implement in practice due to the extreme difficulty of determining a monetary value for climate damage. There are commercial costs (such as the erosion of productivity and destruction of productive capital), but there are also non-commercial costs (such as the loss of biodiversity and destruction of ecosystems) that are much more difficult to value properly. In addition to marginal damage, there is the issue of the risks of serious and irreversible damage, or even collapse, which are generally not taken into account. The result is an underestimation of the damage and, consequently, economic policy recommendations that accommodate an unreasonable level of global warming. This is the case for the damage function of the DICE model, which is certainly quadratic as a function of temperature, but with such a low coefficient that the climatic optimum is achieved for a temperature of around +4°C compared to pre-industrial levels, which seems particularly optimistic, especially in view of the latest work of the IPCC.

In this respect, there is a before and an after 2015. The work of the IPCC has made it possible to form a scientific consensus on the consequences of global warming and the need to limit warming since the pre-industrial era to 2°C, which implies a cap on emissions over a certain time period. Other models therefore treat as given the goals of limiting the rise in temperature set by the international community (IPCC, Paris Agreements, etc.) and, accordingly, of reducing GHG emissions. This is particularly the case, out of necessity, with national models, since climate balances only make sense at global level. This second category of model is used to evaluate national and/or global trajectories. The principle is to set an exogenous protective goal of reducing emissions, then to quantify the spending trajectory necessary to achieve that goal. The damage function is therefore implicitly defined by the climate goal: before reaching the goal, the damage is zero or only slightly increasing; it becomes infinite if the goal is passed. We then speak of a cost-effectiveness approach (Figure II-B).

For France, the climate goal is currently defined by the 2019 Energy-Climate Law. The goal is to achieve net zero emissions (NZE), i.e. carbon neutrality, by 2050, by combining a division of emissions by a factor of around F=7 compared to 1990 levels and a doubling of the capacity of the carbon sink,[2] increasing it from 40 to

2. Reservoir that stores atmospheric carbon using a natural or artificial mechanism. Carbon sinks are essentially the oceans and forests, as well as CO_2 capture and sequestration projects.

Figure II – **Cost-benefit and cost-effectiveness approaches**



Reading note: Graph A shows the shape of the curves for the marginal damage cost (increasing with the quantity of CO_2 emitted) and mitigation (decreasing with the amount of CO_2 emitted). Graph B shows a new shape for the damage cost curve, which becomes infinite from a certain emission threshold, corresponding to the exhaustion of the carbon budget.

80 million tonnes per year. This goal follows on from an initial goal of dividing emissions by a factor of F=4 by 2050 in comparison with 1990 emissions levels, defined by the 2015 Energy Transition Law.

1.3. Technologies for Mitigation and Decarbonisation of the Economy

As the difficult issue of damage valuation is discarded by the *ex-ante* definition of an emission reduction goal, it is indeed the development of decarbonisation technologies that becomes a central assumption of the model. What is the cost of the GHG emission reduction technologies, known as the "mitigation cost", that will need to be used? In other words, what is the law for the development, between now and 2050, of the carbon intensity of the economy as a function of climate spending?

There is a broad consensus based around the idea that, the lower the carbon intensity, the more costly it is to reduce emissions, simply because the cheapest decarbonisation techniques are implemented first. This invites us to use a general law for the development of carbon intensity in accordance with climate spending that takes the following form: $\sigma_{t+1} = \sigma_t \left(1 - \varepsilon(\sigma_t)\Lambda_t\right)$, where $\varepsilon(\sigma_t)$ is a growing function of σ_t. At a given level of GDP, the lower the emissions, the more expensive it is to "mitigate" a given amount of CO_2. Here we use a simple functional form: $\varepsilon(\sigma_t) = \varepsilon\sigma_t^{\theta-1}$ where ε and θ are the parameters to be defined.

Two approaches are theoretically possible for assessing these parameters. The first approach is macroeconomic and econometric. It would consist of inter-temporal and inter-country regressions. Unfortunately, to date, the lack of sufficient data on climate spending does not allow this. This underlines how useful it would be if progress could be made very quickly in establishing environmental economic accounting. There is already a framework, the System of Environmental Economic Accounting (SEEA), which is a set of standards defined by the UN Statistical Commission and modelled in its architecture on the SNA (System of National Accounts) which governs the public accounts of nations.

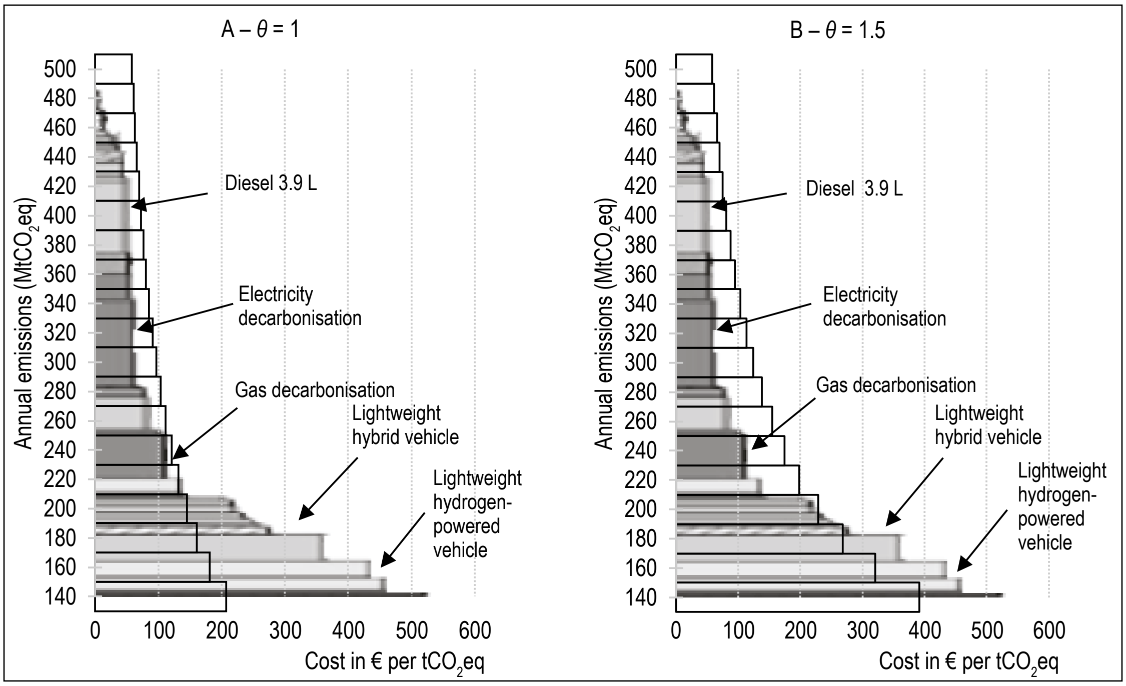
The other approach is microeconomic and parametric, based on the average mitigation cost curves for economy decarbonisation technologies. As its name suggests, this method consists of calculating the cost/effectiveness ratio of the different technologies (housing insulation, wind power, hydrogen-powered cars, etc.), which is the ratio between the total costs of implementation and the total emissions avoided. This method is implemented in France by the Ministry for the Environment using the TITAN model (formerly D-CAM), which ranks technologies in ascending order of cost and derives a curve comparing unit cost and total mitigation potential.

Figure III compares the average mitigation costs obtained from the technico-economic studies and those obtained with our carbon intensity development assumption for both cases $\theta = 1$ or 1.5, with a value of $\varepsilon\sigma_0^{\theta-1} = 1.5$.[3] This approximation tends to validate both the nature of the mitigation equation and the value of the parameter ε. For example, the technologies planned by the SNBC in the area of annual emissions of around 150 $MtCO_2eq$ (e.g. lightweight hydrogen-powered vehicles) have an average mitigation cost of €450, which is quite close to the average macroeconomic cost for $\theta = 1$ (€370). In general, our development assumption is consistent with the available microeconomic evaluations.

Some studies also presuppose the discovery of a so-called "backstop" technology that can be deployed on a large scale to absorb greenhouse gases and that is partly an alternative to reducing emissions. Such technologies, particularly bioenergy with carbon capture and storage (BECCS), are currently being tested. They aim to generate so-called negative CO_2 emissions by intercepting the release of CO_2 into the atmosphere and redirecting it to geological storage sites. Nevertheless, the path to widespread use of such technology remains very long, making this possibility rather uncertain in the medium term. Furthermore, there is no consensus regarding the cost of such a technology, with estimates in the literature ranging from one hundred to several thousand euros per tonne of CO_2, or on the possibility of large-scale deployment. In view of our study period of up to 2050, which is relatively short given the time required to industrialise production of such technology, we assume that its use will remain marginal.

3. *To determine a value for this parameter, we proceed from the observation that emissions per € of GDP have fallen by an average of 2.5% per year over the last ten years, which is a slight acceleration of the reduction compared to the previous two decades (2% per year). Climate spending, in turn, is evaluated at €41.4 billion for France in 2018, or 1.8% of GDP, which is a slight increase compared to the beginning of the decade (€34.4 billion, or 1.6% of GDP). It is on this basis that we can estimate a value $\varepsilon = 1.5$, which is equal to the ratio between the average reduction in the carbon intensity of GDP over 2013-2018 (2.5%) and the average climate spending between 2011 and 2017 as a % of GDP (1.7%).*

Figure III – **Comparison of average technico-economic (D-CAM) and macroeconomic mitigation curves for cases $\theta = 1$ and $\theta = 1.5$**



Reading note: The solid bars represent the average mitigation costs of the different D-CAM technologies calculated by the CGDD; the hollow bars trace the average mitigation cost corresponding to the macro-technological equation $\dot{\sigma}_t / \sigma_t = -\varepsilon \sigma_t^{\theta-1} \Lambda_t$.
Sources: Baptiste-Perrissin & Foussard (2016) for D-CAM, authors' calculations.

1.4. Optimality and Intergenerational Equity

Once the climate goal has been defined, the path to take towards that goal must be determined, taking into account the intergenerational equity of the climate spending trajectory that allows for emissions reduction. Which generations should pay for the climate? Is it preferable to make the entire adjustment now, being prepared to lower per capita consumption today and then returning to an upward trajectory in the future, or would it be better to spread the adjustment over the first decade, for example, if there is a greater preference for the present?

It is customary in the models to formalise this issue by using the framework set out by Hotelling (1931) on the economic analysis of exhaustible resources. The "Hotelling rule" stipulates that the income drawn from an exhaustible resource must develop exponentially, at a rate equal to the interest rate, until the resource is exhausted.[4]

This approach leads to two pitfalls. First of all, while the carbon budgets allocated to each country under the Paris Agreement are akin to an exhaustible resource, the fact that decarbonisation technologies exist means that governments have the option to somewhat "extend" the resource. Thus the Hotelling rule does not apply directly, but this pitfall is easily overcome by integrating the additional control variable of climate action into the optimal programme. The second pitfall is a type of contradiction between the method and the goal. Since the Brundtland Report (1987), the goal has been to promote sustainable development, defined as a form of development that meets the needs of current generations without compromising the ability of future generations to meet their own needs. It is paradoxical in this context to define the corresponding economic programme as the maximisation of the inter-temporal satisfaction of current generations.

4. The interest rate r is in turn determined by Euler's canonical equation, which is $r = \rho + n + \tau\gamma$ where ρ is the rate of preference for the present, n is the population growth rate and γ is the rate of technical progress, while τ is the inverse of the elasticity of the utility function. The Euler equation derives from a Ramsey optimisation programme for the present and future utility flow for consumption $\sum_{t=0}^{T} \beta^t u(c_t)$, where c_t is the per capita consumption, u is a concave function and β is a discount factor that reflects a preference for the present. For clarification, with a preference rate of 2%, a technical progress rate of 1%, a population growth rate of 1% and an elasticity of utility of consumption of 0.5, Euler's canonical equation results in an r rate of 5%.

The Brundtland doctrine is more in line with the idea, formalised by Arrow *et al.* (2012), that a sustainable trajectory is one in which well-being should not decline. If monetary satisfaction of generation t is equated with $V_t = \left[C_t / L_t\right] / \left(1+\rho\right)^t$, where ρ is a parameter taking into account the effects on perceived monetary well-being of the passage of time alone (Easterlin, 1974), then, as in the steady state C_t / L_t growing at the rate of γ, $V_t = \left[C_0 / L_0\right]\left[(1+\gamma)/(1+\rho)\right]^t$ is increasing when ρ is less than γ and decreasing if it is not. The more ρ is high and the lower the technical progress, the more disadvantaged future generations will be. If the public authorities aim to achieve Brundtland-style sustainable development, they can express it by setting a parameter $\rho = \gamma$ in the collective utility.

A relatively simple way to express this idea is to define the programme of the public authorities as the determination of the level of the control variables (climate spending Λ_t and savings rate s_t) making it possible to maximise monetary well-being, equated to the discounted per capita consumption of the worst-off generation.

In analytical terms, the aim is to maximise the inter-temporal utility defined by:

$$\max_{\Lambda_t, s_t}\left\{\min_t\left[C_t / L_t\right] / \left(1+\rho\right)^t\right\}$$

When this parameter is equal to the growth of technical progress and the savings rate is constant over the period, this optimisation programme also leads to a ratio of Λ_t for climate spending over GDP constant during the period. In this specific case, the optimal path to the goal follows an intuitive notion of generational equity, according to which the effort required at each date follows a uniform distribution over time. It would therefore be a matter of making the adjustment from the initial period, or at least as quickly as possible, and then ensuring that all generations have a constant level of climate spending as a percentage of GDP.

With the assumptions described above (exogenous emission goal, law for the development of carbon intensity and the intergenerational equity criterion), we are equipped to examine the issue of sustainability in its various aspects, both climatic and economic. In particular, we will define the concept of the climate sustainability of the economy according to an equity/effectiveness approach, starting from the concept of a sustainable trajectory corresponding to a trajectory that satisfies the following two conditions: *(i)* compliance, by 2050, with a ceiling goal for annual greenhouse gas emissions; *(ii)* a distribution of climate efforts over time that protects future generations.

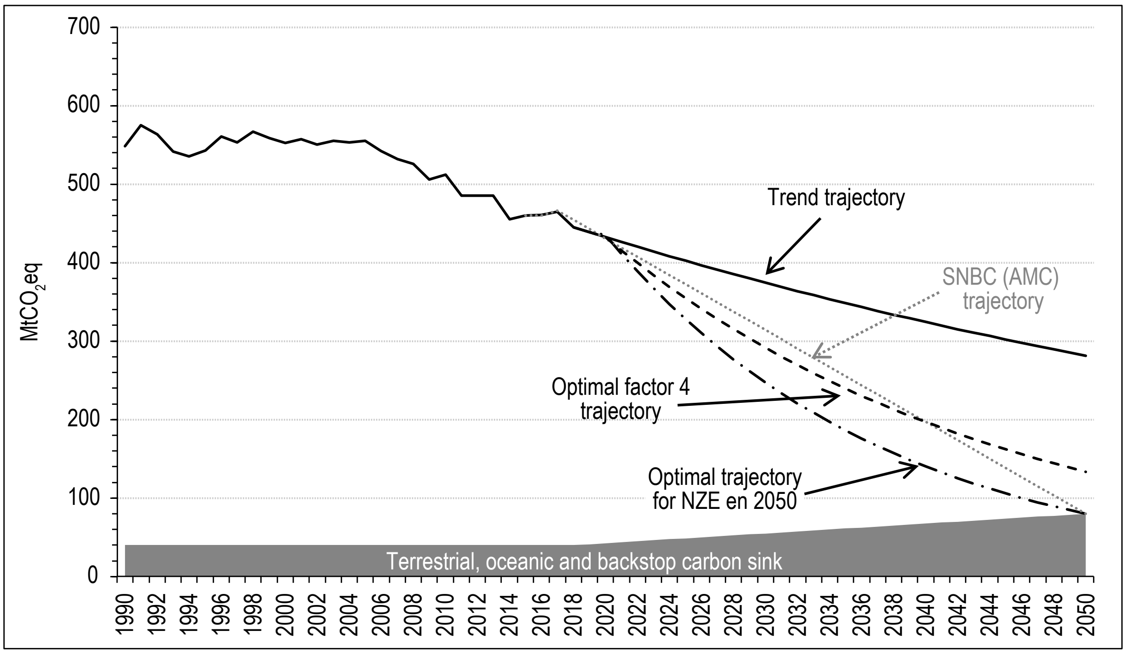
2. Carbon Emissions Trends that are Currently Incompatible with our Climate Commitments

2.1. CO_2 Emission Reduction Trajectories

To begin, we describe the results for France corresponding to the assumption $\theta = 1$ concerning the decarbonisation technologies, i.e., let us recall, in which climate spending mitigates the carbon intensity of production according to the relationship $E_{t+1} / Y_{t+1} = E_t / Y_t \ (1 - \varepsilon\Lambda_t)$. This optimal trajectory is plotted (Figure IV) for reductions by factors 4 and 7 of SNBC-1 and 2. The graph also plots (a) the trend trajectory assuming 1.5% annual growth and a decline in carbon intensity consistent with the maintaining of the current climate effort and (b) the AMC trajectory as notified to the European Commission (with AMC standing for "*avec mesures complémentaires*" in French, referring to a scenario with complementary measures that have not yet been approved). The accumulated levels of emissions per sub-period are also provided in Table 1. It is specified that the emissions in question are in all cases emissions within the national territory, also called the "national inventory". These emissions are those that are the subject of international commitments and it is for this reason that they are used in this article; however, they should be distinguished from the notion of a "carbon footprint", which measures the emissions related to our lifestyle, including greenhouse gas emissions associated with our imports.

Past achievements and the trend trajectory appear to be well above the two optimal trajectories by a factor of 4 and 7 and the SNBC budgets. The first budget for SNBC-1 was slightly exceeded (458 $MtCO_2eq$ compared with the planned 440 $MtCO_2eq$) and, above all, the trend scenario would then clearly diverge from the planned trajectories: 2030 would be at 68% of the 1990 level instead of 57% of the SNBC-2 and 2050 would be 3.5 times higher than the carbon neutrality goal (281 $MtCO_2eq$ instead of the planned 80 $MtCO_2eq$). In addition, the AMC scenario notified to the European Commission would meet the carbon neutrality goal, but at a quasi-linear pace, therefore making it different from the optimal scenario of intergenerational equity defined above.

Figure IV – **Greenhouse gas reduction trajectories in France**



Reading Note: Assuming the reduction in emissions by 2050 by a factor of 4, emissions in 2030 are expected to be 53% of 1990 levels. As at the same date, this percentage should be 45% for a target of net zero emissions in 2050, while the trend trajectory suggests a ratio of 68%.
Sources: CITEPA, authors' calculations.

Table 1 – **Planned, trend and optimal carbon budgets by sub-period**

Période	Planned emissions (low carbon strategy)	Actual and trend emissions	Optimal emissions (Factor 4 in 2050)	Optimal emissions (Neutrality in 2050)
2015-2018 (1st budget*)	422	458	458	458
2019-2023 (2nd budget*)	399	427	417	408
2024-2028 (3rd budget*)	359	397	346	311
2029-2033 (4th budget**)	300	369	285	234
2034-2038 (AMC***)	244	343	235	177
2039-2043 (AMC***)	185	320	194	133
2044-2048 (AMC***)	127	298	160	101
2050 (AMC***)	80	281	137	80

Sources: *SNBC2015, **SNBC2020, *** 2019 Government projection with complementary measures.

In the steady state, it is possible to formulate a simple rule that makes it possible to gauge whether the carbon trajectory is meeting its goal by dispensing with the solution of a model. In this case, economic activity grows at a constant rate g, and the optimal trajectory of carbon emissions, as we have just defined it, obeys a simple law of decreasing at a constant rate that we call Γ. Indeed, if climate spending represents a constant proportion Λ of GDP, the carbon intensity σ decreases at a constant rate of $\varepsilon\Lambda\%$, since $d\sigma/\sigma = -\varepsilon\Lambda$. As a result, GHG emissions decrease at a constant ratew of $\Gamma = \varepsilon\Lambda - g$. The value to be assigned to Γ is then deduced directly from the GHG reduction factor F in relation to the starting year, and from the number of years T before the set deadline, with condition $(1+\Gamma)^T = F$ leading to $\Gamma = F^{1/T} - 1$. Thus, for France, where the aim is to reduce emissions from 439 to 80 $MtCO_2eq$ between 2019 and 2050, F=5.48 of a T duration of 31 years, $\Gamma = 5.48^{1/31} - 1 = 5.6\ \%$. This means that once emissions are decreasing by less than 5.6% per year, climatic sustainability is not ensured, in the sense that either carbon neutrality will not be achieved on time or the effort is too spread out over time.

This rule is not fully an accounting rule: it is indeed a case of moving from point A to point B in time *T*, but with a rate of progression resulting from the equity rule defined above, constant as a percentage and therefore in level, moving faster at the beginning and slower at the end than the straight line. Nevertheless, it is very useful for providing clarification and determining orders of magnitude, because it tells us how much the GHG emissions should be decreased immediately and sustainably to restore a sustainable trajectory (in the same way as sustainability indicators, such as the tax gap).

Using the variant $\theta = 1.5$ for the decarbonisation technologies would imply a slightly modified distribution of effort (Figure V). In this case, the rule just stated does not apply, the rate of reduction is not constant and simulations must be used. Unsurprisingly, however, the bearish profile of the new trajectory is more pronounced at the beginning of the period.

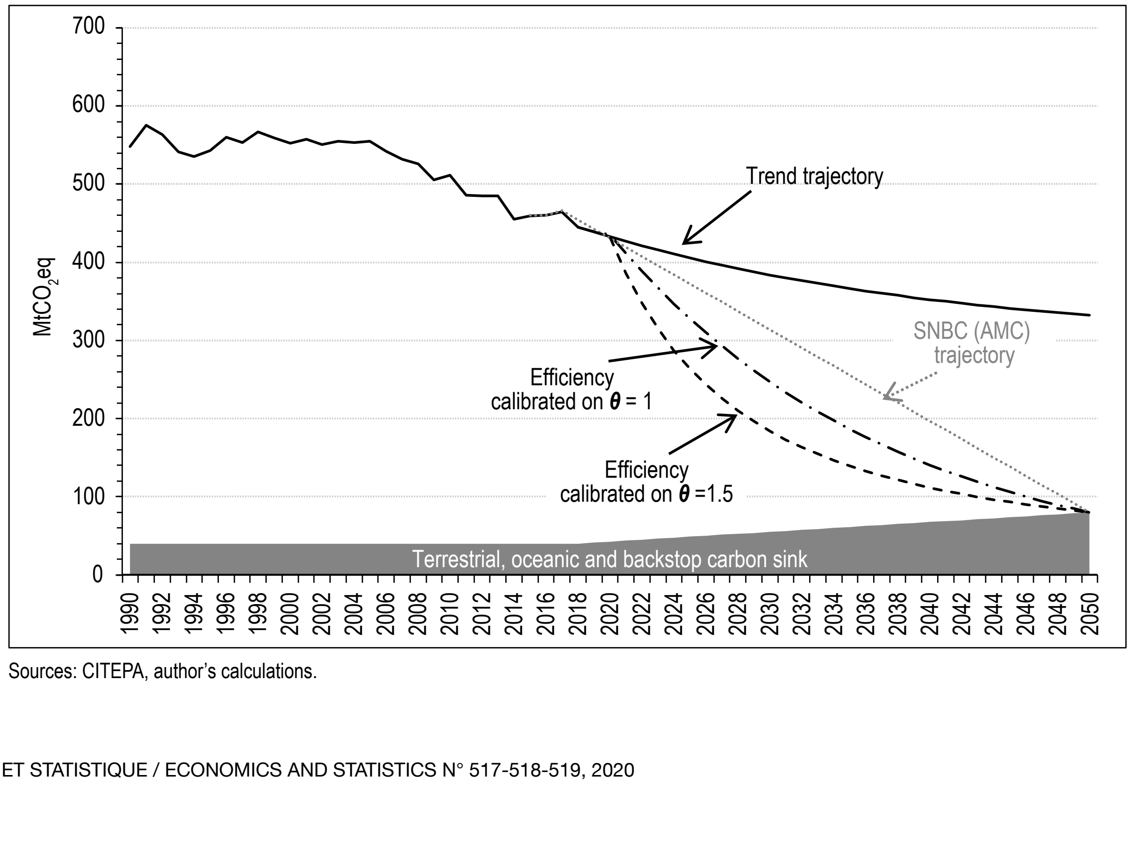
We can come back here to the recommendations of the Stiglitz Commission on Carbon Prices (Stiglitz *et al.*, 2009) for the measurement of sustainability. It recommended that the "environmental aspects of sustainability deserve a separate follow-up based on a well-chosen set of physical indicators. In particular, there is a need for a clear indicator of our proximity to dangerous levels of environmental damage". The monitoring of GHG emissions is perfectly in line with this goal as far as the climate challenge is concerned and it conveys a message that appears here without appeal: in terms of climate, our trajectory is not sustainable. France, although not the worst placed among the richest countries, emits ten times more GHG (439 $MtCO_2eq$) than it absorbs (40 $MtCO_2eq$). The projections show a likely downward trend in the coming years, but one clearly insufficient for a return to equilibrium in the time necessary. At global level, the situation appears even more critical: the trend is upward, whereas emissions need to be divided by a factor of 4 by 2050 to contain warming at 1.5°C.

Finally, it should be recalled that, despite a drop in the carbon inventory, France's footprint has continued to grow, which means that emissions produced within the national territory have been gradually replaced by imported emissions. Figure VI shows the different possible projections depending on whether France (France NZE + World BAU), the rest of the world (France BAU + World NZE) or both (France NZE + World NZE) respect the climate goals of achieving carbon neutrality by 2050 (see Online Appendix C1, link to the Online Appendices at the end of the article).

2.2. Climate Spending

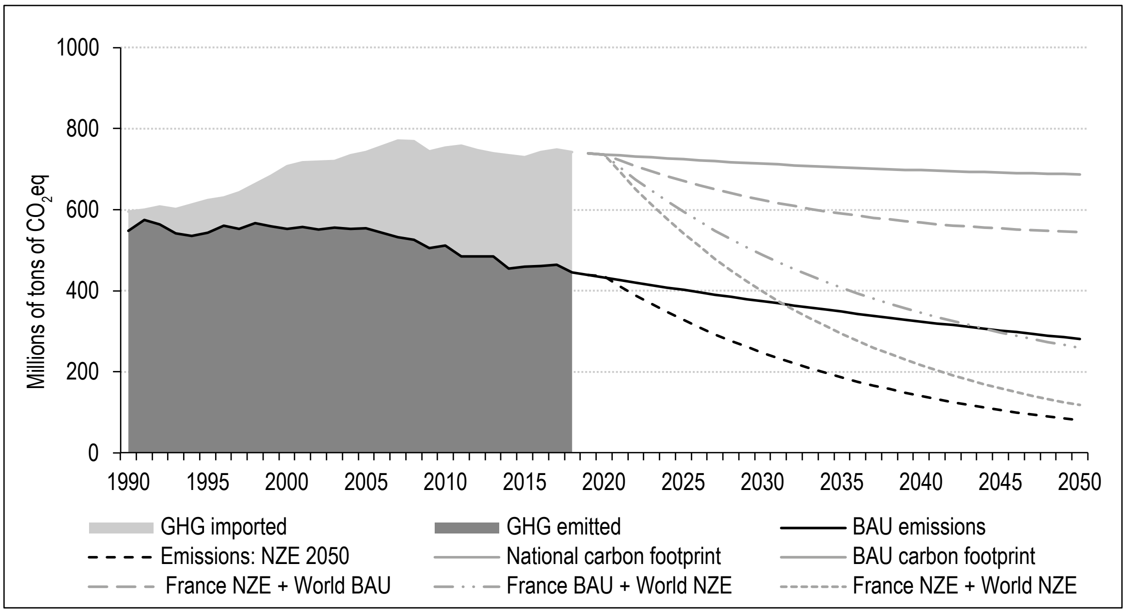
With the trajectories for returning to carbon neutrality having been established, our model

Figure V – **Optimal trajectories towards carbon neutrality by efficieny of decarbonisation technologies**



Sources: CITEPA, author's calculations.

Figure VI – **France's carbon inventory and footprint**



Sources: INSEE, CITEPA, authors' calculations

makes it possible to directly quantify the costs of adhering to them. For France, annual spending associated with the optimal trajectory would amount to 4.5% of GDP, corresponding to around €100 billion,[5] which represents an increase of more than a factor of 2 compared to the current spending evaluated, for the state, businesses and households, with just over €45 billion spent in 2018 (1.9% of GDP) by the Institute for Climate Economics (I4CE, 2019). This represents a significant, but not impossible, effort: in relation to the population, the amount is around €1,500 per capita instead of the current €600.

Again, we can reveal a simple rule for economies in a steady state, between the optimal national carbon effort and economic growth. It should be remembered that in this case and where $\theta = 1$, the constant rate Γ of reduction of GHG emissions is equal to $\varepsilon\Lambda - g$. As a result, the effort that ensures compliance with the goal is $\Lambda^* = [g + \Gamma] / \varepsilon$. This relationship teaches us, for example, that the current effort of 1.9% of GDP, if not increased in the coming years, would not be compatible with achieving carbon neutrality by 2050 unless GDP falls at a rate of 2.7% per year.[6]

These results are sensitive to the assumptions used, particularly concerning decarbonisation technologies, the rule for intergenerational effort sharing and also the economic growth rate, which is considered exogenous in this model. Table 2 illustrates the sensitivity of the level of annual effort required under the growth and energy efficiency scenarios.[7] Thus, the annual climate spending may increase from around €65 billion in 2018 (zero growth and optimistic on efficiency) to €165 billion (growth of 1.5% and prudent on efficiency).

At global level, although the emission reduction factor required to achieve carbon neutrality is slightly lower than that required for France, the projected growth is higher and, in the end, the global financial effort would be of the same order and even slightly higher than that to be made nationally, as percentage points of GDP: our model results in a climate effort rate of 5.1% of global GDP, compared to 4.5% at national level for France. In contrast, the change in scale is much larger, with global climate spending likely to be less than 1% of global GDP at present.[8]

5. Very precisely, €105 billion in 2019, which would then develop in value like the GDP.

6. Indeed, $g = \varepsilon\Lambda - \Gamma = 1.5 * 1.9\% - 5.6\ \% = -2.75\%$

7. The results are tested for a value of ε ranging from 1 (prudent scenario) to 2 (optimistic scenario), with the so-called "central" scenario corresponding to ε = 1.5.

8. $681 billion in 2016, according to the 2018 report of the Standing Committee on Finance (SCF) of the Conference of the Parties (COP) of the UNFCCC (SCF, 2018), for a global GDP of $76,000 billion, which equates to 0.9%. It should be noted that this figure is consistent with a value of ε_M=1.5, as it implies a reduction in carbon intensity of 0.9X1.5=1.25 per year, which is more or less the trend observed (-1.2% per year over the 2008-2018 period).

Table 2 – **Sensitivity of climate spending (as a % of GDP and in billions of € in 2018) to the growth and energy efficiency assumptions**

Energy efficiency scenario \ Growth scenario	1.5%		1.0%		0.0%	
Prudent	6.9 %	(€157 bn)	6.4 %	(€147 bn)	5.6 %	(€129 bn)
Central	4.5 %	(€104 bn)	4.3 %	(€97 bn)	3.7 %	(€85 bn)
Optimistic	3.4 %	(€77 bn)	3.2 %	(€72 bn)	2.8 %	(€63 bn)

2.3. Saving Strategies

To conclude this section, here we examine four variants that depart from the assumption of a constant savings rate and vary the rules for the development of consumption and climate effort (Figure VII).

The first column (scenario S1) corresponds to the trajectories that we have described so far: as the exogenous savings rate is constant, both GDP and capital remain on their regular growth path, hence a constant *K/AL* ratio, where *AL* represents labour plus the factor of technical progress. By construction, the consumption per unit of efficient labour remains constant after the initial adjustment, which implies a constant discounted standard of living $V_t = \beta^t C_t / L_t$ with $\beta = 1/(1 + \rho)$.

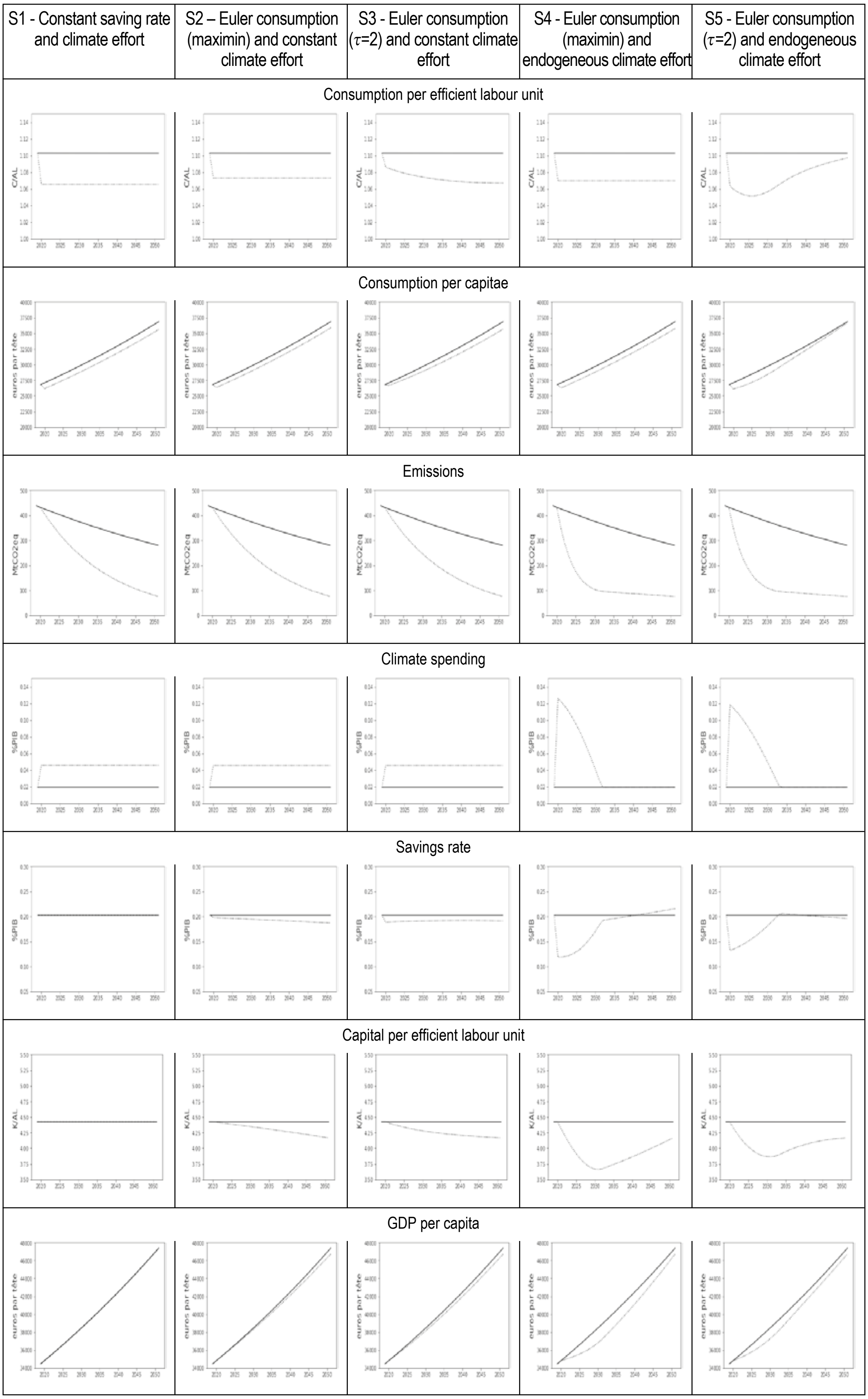
Scenarios S2 and S3 maintain the assumption of a constant climate effort rate, but with an endogenous savings rate, which varies across time. More precisely, the savings rate is the consequence of the choice of consumption, which derives from an intertemporal optimisation programme. The two scenarios are different in the choice of the utility function that will be maximised (see Online Appendix C2). In the second scenario (S2), this is a max/min type of optimisation, which implies a constant level of consumption by unit of efficient labour, once the initial adjustment is realised. The savings rate is gradually reduced to bring capital to its new steady state,[9] which corresponds to a slight decrease of the average standard of living compared to the reference trajectory. In the third scenario (S3), the consumers seek to maximise $\sum_{t=0}^{T} \beta^t \frac{c_t^{1-\tau}}{1-\tau}$, with a finite parameter τ[10] involving a substitution between current and future consumption (in contrast to the Brundtland approach of the public authorities which corresponds to an infinite τ). They chose to reduce more strongly their savings in the initial period to smooth the downfall of consumption caused by a constant climate effort over the period.

The fourth and fifth scenarios (S4 and S5) make the climate effort rate endogenous. The difference between scenarios S4 and S5 lies in the rule for the development of consumption per efficient work unit resulting either from a max/min type of optimisation programme (S4), or that of more impatient consumers (S5). If the end point is the same for both emissions and the capital goal, trade-offs can be made over time between investment, climate effort and consumption. The optimal trajectory corresponds to a much faster decarbonisation, with carbon neutrality being achieved by 2030; this assumes a higher climate effort until that time in the reference scenario, and lower thereafter; this effort is cushioned, symmetrically, by an immediate reduction in the savings rate, before it returns to its initial trajectory. The growth of both GDP per capita and capital per capita is slowed down before, once decarbonisation is complete, resuming its course towards the new steady state. This latter trajectory, due to the scale of the adjustments it implies, is undoubtedly not the most likely, but it has the merit of showing the possibility of a faster reduction in CO_2 emissions – thus further limiting global warming – without harming standards of living, by taking action on the savings rate.

All the scenarios presented here display a reduction in consumption per capita the first year during the initial adjustment, due to a significant rise of climate effort. This initial effort in consumption is largely offset later on

9. As the savings rate is endogenous, in order to solve the optimal public authority programme, it is necessary to define the economic output goal. Our simulations here are based on the goal that the economy, in 2050, will be in its new regular state, integrating a permanent decarbonisation effort equal to the optimal effort of the period 2020-2050. The need to decarbonise the economy increasingly constantly means reducing total factor productivity and thus reducing the optimal K/AL ratio.
10. τ set at 2, the standard value in the literature.

Figure VII – **Economic and climatic trajectories under different savings scenarios**



by an increase of consumption by capita, which grows like technical progress. Nevertheless, in order to prevent the risk that growth is lower than expected, or decarbonisation more expensive, there is a clear interest to bring forward the efforts at the beginning of the period. If our utility function invites to do all the ajustment efforts as quickly as possible, the adjustment can also be smoothed on several years to avoid the negative initial shock in consumption per capita.

3. A New, Higher Carbon Price, in Line with the Goal of Achieving Carbon Neutrality by 2050

3.1. The Social Value of Climate Action

Based on evaluations of the overall cost of the decarbonisation strategies, it is then possible to move on to the determination of a carbon price. It is known that market mechanisms are of little use in placing a value on the cost of CO_2 emissions. The fundamental reason for this is that CO_2 has no extraction cost, unlike, for example, the gas and mining industries: because it is neither sold nor purchased, CO_2 has no price. Since 2005, there has been a European market for CO_2 quotas, the EU Emissions Trading System (EU ETS). However, firstly, it concerns only around 5,000 companies, representing 45% of emissions, and, secondly, the allowances allocated to them are insufficiently binding for the price on this market to reflect a social value. Thus, between 2013 and 2018, the CO_2 allowances, known as EUAs (European Union Allowances) traded at around five euros per tonne of CO_2.

At what level, then, should the carbon price be set? It is necessary to go back to the basics of the climate economy. CO_2 emissions have a cost because they are responsible for global warming and, therefore, cause damage to the economy. Climate action has value because investing in decarbonisation technologies will prevent future generations from suffering the now well-documented negative consequences of rising temperatures. This is why the Quinet Commission wished to refer to the notion of the "value of climate action" (Quinet, 2019).

This general principle being set, the term of "social" price of carbon can correspond to a number of notions, which need to be considered with caution in comparisons, as well as in the use that can be made from the estimated valued of the models. Talking of a social price requires before all to clarify what is meant by "social". In other words, what is the objective fixed by the society with regard to climate change, that the fixation of such carbon price can contribute to. There are essentially two approaches: an "accounting approach" and a "cost approach". The first one, based on the volume-price split of the optimal climate spending, consists in dividing such spending by the current GHG emissions, allowing thus to measure at which price to charge, implicitly or explicitly, carbon emission in order to reach the target of carbon neutrality in a equitable repartition of efforts among generations. The second approach consists in dividing the optimal climate spending by the cumulated flow of current and future emissions avoided. It is thus a logic of incentives targeting the evolution of behaviours towards decarbonisation: it is the viewpoint of the Quinet Commission, aimed at integrating the climatic dimension in the measurement of socio-economic cost of investments.

The two notions are of course linked, and can be made consistent with each other. We will nevertheless put forward the first approach, which seems to be the most effective and robust, given the uncertainty in the measure of the cumulated flow of avoided emissions, and notably the actualisation rate.

In practice, the social value of carbon covers a very wide range of climate policies, ranging from carbon taxes and emission allowances to the imposition of thermal standards for buildings, the cost of which is covered partly by the owners and partly by public support such as tax cuts, and the financing of public transport by local authorities and their transport authorities. To confuse the social value of carbon with a carbon tax is to confuse policies to combat global warming with their funding. Furthermore, both in France and everywhere else, carbon taxes so far represent only a minority share of the climate effort.

3.2. Estimates of the Social Cost of Carbon

With the meaning of the notion of the social value of climate action – or the social cost of carbon – having been clarified, its calculation follows directly from its definition, as this value – according to the "accounting approach" – must verify equality at every point of the optimal trajectory: $P_t^{co2}E_t^* = \Lambda_t^* Y_t^*$ where E_t^*, Y_t^* and Λ_t^* refer to emissions, GDP and climate effort along this trajectory, respectively. Stated in this way, the social value of carbon would amount for France to around €250 in 2020, €500 in 2030, €1,010 in 2040 and €2,050 in 2050 for the objective of carbon neutrality (Table 3).

Table 3 – **Social value of climate action for the objective of carbon neutrality in 2050**

	2020	2030	2040	2050
National values (€/ton of CO_2eq)				
Model results				
Accounting approach	247	501	1,014	2,052
For the record, with the objective of Factor 4 in 2050	*188*	*320*	*547*	*937*
Cost approach (actualisation rate of 5%)	127	258	522	1,057
Values retained by the Quinet Commission 2019				
Cost approach	88	250	500	775
Models used by the Quinet Commission				
ThreeME Model		143	1,128	2,389
NEMESIS Model		185	784	(*)1,934
POLES Model		351	845	3,515
TIMES Model		228	465	2,451
Global values (€/ton of CO_2eq)				
Model results				
Accounting approach	72	161	359	801
IPCC Estimates				
IPCC 1.5°C		284	497	872
IPCC 2°C		139		440

(*) Value for the year 2045.
Sources: Quinet Commission (2019), authors' calculations

The models used nationally as well as those used by the IPCC, also tend to produce even higher evaluations. Our estimates for the objective of carbon neutrality correspond to a quasi-doubling of the social value of carbon compared to the factor 4 goal that prevailed until 2018. This can be understood easily if we come back to the formation of this value: since $P_t^{co2} E_t^* = \Lambda_t^* Y_t^*$, the price ratio P_t^{F7} / P_t^{F4} can be decomposed as a product $\left[\Lambda_*^{F7} / \Lambda_*^{F4}\right] \times \left[\mathrm{E}_t^{*F4} / \mathrm{E}_t^{*F7}\right] \times \left[\mathrm{Y}_t^{*F7} / \mathrm{Y}_t^{*F4}\right]$. In a scenario where the two GDP trajectories would be the same, we would have $P_{2050}^{F7} / P_{2050}^{F4} = 7/4 \times \left[\Lambda_*^{F7} / \Lambda_*^{F4}\right]$. Given that effort Λ_*^{F7} is obviously higher[11] than that, Λ_*^{F4}, corresponding to a factor of 4, P_{2050}^{F7} is approximately equal to $2 \times P_{2050}^{F4}$. Let us stress that this doubling of the price does not necessarily mean a doubling of the optimal climate spending because, at the same time, the GHG reduction is also faster.[12]

If we now measure the social value of carbon according to the "cost approach" and with an actualisation rate of 5% on the measure of future avoided emissions, we obtain the amounts of €127 in 2020, €258 in 2030, €522 in 2040 and €1,057 in 2050. The orders of magnitude are comparable to those proposed by the Quinet report, specifically €250 in 2030, €500 in 2040 and €775 in 2050.[13] Our simulations tend to confirm the very strong revaluation made by the Quinet report (Quinet, 2019), as opposed to the estimates commonly accepted previously, such as the one proposed in 2017 by the Stiglitz-Stern Commission (Stigltiz *et al.*, 2017),[14] which was €70 to €100 in 2030, not to mention the values still used by the World Bank (World Bank, 2011) or the UNDPD (UNU-IHDP, 2012) : $30 or €25.5, to calculate net savings and adjusted net savings, to which we will return later and which seem out of scale.

11. *For France,* Λ_*^{F7}*=4.5% and* Λ_*^{F4}*=3.5%.*

12. *For France,* $\Lambda_*^{F7}/\Lambda_*^{F4}$*= 4.5 / 3.5 = 28%;*

$P_{2050}^{F7} / P_{2050}^{F4} = 7/4 \times [4.5/3.5] = 2.25.$

13. *While the Quinet Commission re-evaluates the social price of carbon in light of the new neutrality goal, it considered that the results of the technico-economic and macro-sectoral models used become less sound from 2040, or even 2030, and therefore decided to cap the price afterwards, in view of the technological uncertainties in the medium term.*

14. *The authors have nevertheless clarified that their estimated cover only one part of the social value of carbon:* "This commission concludes that the explicit carbon-price level consistent with achieving the Paris temperature target is at least US$40–80/t$CO_2$ by 2020 and US$50–100/t$CO_2$ by 2030, provided a supportive environment policy is in place" *(Stiglitz* et al. *2017, p. 3).*

Finally, we estimate a global carbon price, which is a priori not the same as the national price. In fact, if we start from the definition of the social value of carbon, the ratio between the global and national levels can be written as follows:[15] $P_t^{MD} / P_t^{FR} = \left[\Lambda_*^{MD} / \Lambda_*^{FR}\right]\left[\sigma_t^{*FR} / \sigma_t^{*MD}\right]$. However, as we have seen, global and national climate efforts represent a comparable proportion of GDP (5.1% and 4.5%, respectively), the same cannot be said for carbon intensity (CO_2/GDP ratio), which is 720 g per € of GDP[16] at global level, compared with 189 g per € in France, which is a ratio of 1 to 3.8. The global value comes out of our simulations at €161 per tonne of CO_2 in 2030, €359 in 2040 and €801in 2050, which is broadly in line with the simulations of the IPCC. Indeed, the average IPCC values for the goal of limiting the temperature increase to 1.5°C (i.e. a scenario with a 33% probability of exceeding 1.5°C), a goal that would require achieving carbon neutrality in 2050, come out at €284 in 2030, €497 in 2040 and €872 in 2050.

3.3. Carbon Price Accounting

Continuing with our endeavour to express simplified rules under the assumption of stable growth at rate g, we can establish two new rules concerning the social value of climate action, according to the "accounting approach". To obtain a reduction Γ in emissions at a given date, if GDP grows at the rate g, a reduction in the carbon intensity of production is needed at the rate of $d\sigma/\sigma = \Gamma + g = r$. Since $d\sigma/\sigma = -\Lambda\varepsilon$, this requires constant climate spending when expressed as a percentage of GDP of $\Lambda = r/\varepsilon$. We deduce therefore an initial price, which is equal to the initial spending per tonne of GHG emitted, is $P_0^{co2} = (r/\varepsilon) \times (Y_0 / E_0)$. On any given date, this same price will be $P_t^{co2} = (r/\varepsilon) \times (Y_t / E_t) = (rY_0 e^{gt}) / (\varepsilon E_t e^{-\Gamma t})$ or even $P_t^{co2} = P_0^{co2} e^{rt}$ and a price that thus increases at the rate r, with this growth reflecting the increasing difficulty of continuing to reduce emissions as carbon intensity declines.

Two new rules can therefore be established. The first is that, as at the initial date, the social value of carbon is at least equal to $P_0^{co2} = (r/\varepsilon) \times (Y_0 / E_0)$, where Y_0 and E_0 are the initial GDP and level of CO_2 emissions, respectively. The second is that, along this trajectory, the social value of carbon follows a law of exponential growth at the rate $r = g + \Gamma$, where g is the GDP growth rate and Γ is the annual percentage reduction in emissions goal.[17]

The latter rule is similar to a Hotelling rule, which stipulates that the price of a scarce resource must develop exponentially, to compensate for scarcity. It specifies the rate of development. In the case of France, this rate is 7.4% for the factor 7 goal and 5.5% for the factor 4 goal. By way of comparison, the Quinet Commission uses a rate of 7.2% between 2030 and 2040 and the averages of the simulations used by the IPCC corresponding to r=5.5% between 2030 and 2050 (see Table 3); in contrast, the underlying rates of TIMES, POLES, NEMESIS and ThreeME are significantly higher (between 12% and 13% for the first three and 16% for ThreeME), reflecting either a rule of equity less favourable to future generations, or a more optimistic view regarding the progressiveness of decarbonisation costs, or a combination of the two.

3.4. Towards a Concept of Climate Debt?

Once the social cost of carbon has been defined, it becomes possible to consider several monetary indicators to describe the climate situation, beginning with two "climate debt" indicators.

It is possible to start by examining, following a forward-looking approach, the costs to be paid in the future to return to the goal trajectory, i.e. the discounted cumulative sum of future climate spending needed to achieve the goal. In other words, this is the amount of financial resources that would need to be held in reserve to achieve the goal without having to drain future incomes. This is an important concept because it reflects the idea that every euro not spent on climate investment today will be passed on to future generations. Here we will use the term implicit climate debt to refer to this indicator.[18] This is, in effect, a forward-looking concept, similar to the concept of implicit liabilities used for other types of public spending, such as pensions, the discounted equivalent of the stream of future spending necessary to honour a commitment made. In the scenario of achieving carbon neutrality by 2050, with a rate

15. *Indeed,* $P_t^{MD,FR} = \Lambda_*^{MD,FR} Y_t^{*MD,FR} / E_t^{*MD,FR} = \Lambda_*^{MD,FR} / \sigma_t^{*MD,FR}$.
16. *The ratio is 613 g per \$ which, assuming the dollar converts to €0.85, equates to 720 g per €.*
17. $\Gamma = F^{1/T} - 1$, *see above.*
18. *Implicit debt is a cumulative sum not to be confused with the annual mitigation effort. By way of analogy, if we differentiate between the annual mitigation effort as a percentage of GDP and the effort actually achieved today, we come closer to the notion of a tax gap or discounted funding gap, which reflects the amount as a percentage of GDP for the improvement of the structural balance that would have to be made in a sustainable manner to bring the public debt back to a sustainable trajectory.*

of preference for the present equal to the rate of growth of the economy, the implicit climate debt amounts to around 150% of 2018 GDP, and can be measured at first order simply by the number of years to achieve neutrality multiplied by the annual climate spending as a percentage of GDP.

Another approach for "climate debt" would follow a backward-looking approach, by measuring the costs not paid in the past, as these terms are often used to express the notion that the burden of past inaction is passed down to future generations. As this debt has neither a creditor nor a debtor, its definition is normative. Nevertheless, once a value of climate action is defined for the future, it is a natural candidate to be used to value insufficient past efforts. Consequently, we propose defining climate debt as the sum of past net emissions, valued at the current social price of carbon according to the "accounting approach".[19] This corresponds to the simple idea that, regardless of when the CO_2 was emitted, it contributes to climate disruption in the same way[20] and it must be valued at the same level. This concept can also be linked to the idea of debt that developed countries, "historical" polluters, would have accumulated towards to less developed countries, which remains a fundamental question when it comes to the repartition of decarbonisation efforts at global level. Climate debt since 1990 has been estimated at €3,475 billion, which is also close to 150% of GDP and represents around €50,000 per capita. This debt can then be projected and compared to a climate debt ceiling corresponding, for example, to the level making it possible to achieve the goal of +2°C (Figure VIII).

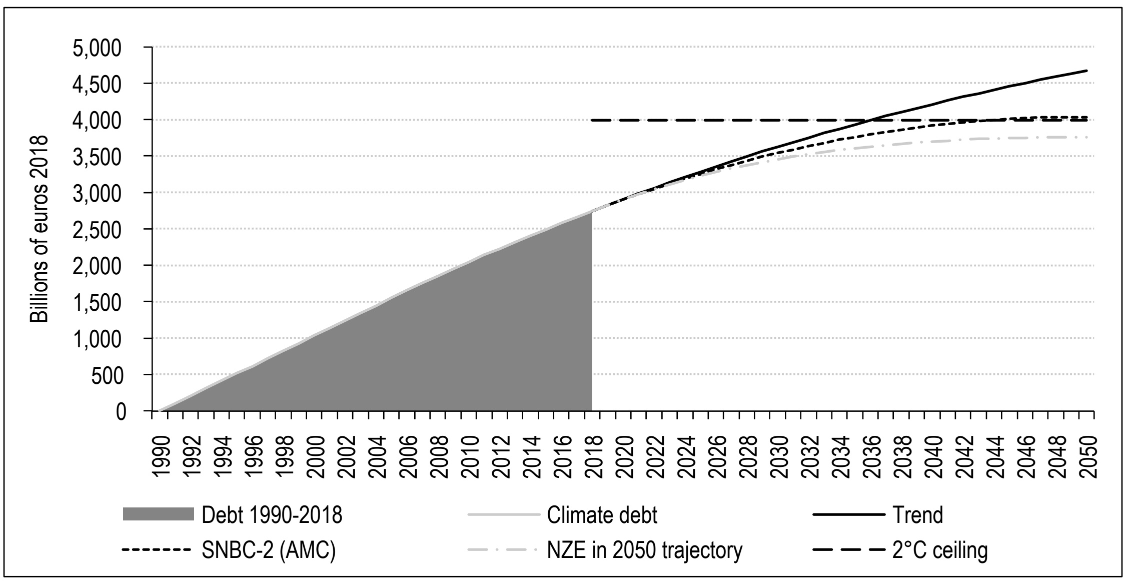
The development paths of these two indicators are linked. Indeed, each year the unpaid costs (resulting in positive gross emissions) will be added to the costs of returning to carbon neutrality. They may also be monitored year after year, based on an official carbon price set by the public authorities and updated each time the database of the national accounts changes. Indeed, the climate debt indicator can constitute a steering tool for public authorities from an equity/efficiency perspective: it makes it possible to measure both the deviation from the carbon neutrality goal and the fair distribution of the effort between generations, with an insufficient effort in one year having to be compensated for in the following year(s).

19. Formally, as at date t_0, its accumulated variation $\Delta D_{t0}^{\tilde{T}}$ is defined in relation to an initial date $\tilde{T}$ by $\Delta D_{t0}^{\tilde{T}} = \int_{\tilde{T}}^{t0} P_{t0}^{co2}\left(E_s - \bar{E}\right) ds$,

where E_s are the GHG emissions as at date s and $\bar{E}$ is the terrestrial and oceanic carbon sink. Financial climate debt can therefore be calculated simply as the accumulative sum of net emissions (physical "debt"), multiplied by the social value of carbon.

20. This amounts to disregarding the time taken for GHGs to disappear spontaneously, which is legitimate, as this is effectively a very long time in view of the time periods considered here.

Figure VIII – **Climate debt since 1990 (backward looking approach)**



Sources: CITEPA, authors' calculations.

4. A Net Savings Rate Adjusted for the Social Climate Cost That is Now Negative, a Sign of a World That Would Gradually Become Poorer

4.1. Beyond Climate: Broader Approaches to Sustainability

The answer to the question of whether the current emissions regime is compatible with meeting national commitments is, therefore, clearly no. We are far from the goal trajectory for greenhouse gas emissions. If we consider that failure to respect these commitments exposes us to major environmental risks, it can be said that we are consuming more natural resources than nature is capable of bearing. With the exception of a few climate sceptics, this assessment is widely shared: the notion of strong sustainability of economic development, which requires that each generation leave natural, physical and human capital at least equal, in each of these dimensions, to that which it has inherited, is not being fulfilled in respect of the environmental dimension.

Is it useful to supplement this message with indicators measuring what the literature describes as "weak" sustainability? This is what the indicators do when aggregating the developments of these different types of assets, leaving room for the idea that a decline in one type of asset could be offset by an increase in another. In reality, this is not the case for the climate, if the damage is irreversible, because then a marked deterioration of the environment cannot be offset by an accumulation of physical capital. It is this observation that calls for the selection of several sustainability indicators, isolating in particular those having a vital impact for mankind (pollution and global warming), as proposed in the Stiglitz report. However, this should not stop us from looking also at global sustainability indicators.

Enriching national accounts with such indicators is nevertheless a long-standing issue and there has been no shortage of proposals to do so. Conceptually, Hicks (1946) introduced the notion of real income, which he defined as the maximum consumption allowed without deteriorating the capital stock, which can therefore be interpreted as a concept of sustainable consumption. It was the Brundtland Commission (1987) that definitively placed it on the international agenda, defining it as the need to "satisfying the needs of the current generation without compromising the capacity to satisfy the needs of future generations". It was during this period that Cobb & Daly (1989) introduced an indicator of sustainable well-being, the ISEW (Indicator of Sustainable Economic Welfare) – also called green GDP – which includes the cost of environmental deterioration as well the issues of leisure and human capital. However, green GDP does not resolve the issue of global sustainability. To do so, "what we need", as the Stiglitz report pointed out, "is an evaluation of the distance between our current situation and the sustainable goals [...] in other words, we need indicators of over-consumption or under-investment" (Stigltiz *et al.*, 2009, p. 73), with both notions being understood in a broad sense.

The analytical framework linking inclusive wealth and adjusted net savings is best suited to solve this issue (see Online Appendix C3). Measuring sustainability in this way is precisely the objective that the World Bank has been pursuing since the 2000s by calculating an "adjusted" net savings indicator for most countries (World Bank, 2006, 2011, 2018). That work is based on the Hicksian idea that a sustainable trajectory, defined as a trajectory in which monetary well-being – comprehensive wealth – never decreases, is one in which the adjusted net savings are always positive. In concrete terms, the adjusted net savings (ANS) calculated by the World Bank can be written in the form GS - FCC + EDU - ENV, where GS is gross national savings, FCC is fixed capital consumption, EDU is education spending,[21] and ENV is the cost of environmental damage. Five factors are taken into account for the latter: the depletion of forest, oil and mining resources, global warming and air pollution.

The World Bank estimates global adjusted net savings at 10.7% in 2016, for gross savings of 25.9%. Environmental deterioration only accounts for -2.6% of GDP. Despite the apparent breadth of the spectrum of damage taken into account, the adjustments made by the World Bank to measure environmental deterioration are very small at global level. They are virtually imperceptible in the case of France.[22] In particular, the financial valuation of global warming is greatly underestimated, based on a social price

21. ANS, in contrast, does not take into account the depreciation of educational capital (which leads to an overestimation of educational savings in developed countries) or the quality of education.

22. For France, the ANS figure is 7.1%: gross savings is 20.3%, from which 17.7% is deducted for fixed capital consumption, equating to 2.2% of the net savings; education spending has a positive impact accounting for 4.9% of GDP, while the environment contributes negatively, with -0.4%.

of carbon of only €25.5 per tonne of CO_2.[23] This issue should therefore be re-examined here in light of the new evaluation of the social price of carbon that we have just reviewed.

4.2. Net Savings Adjusted for Climate Repair Costs

Here, we focus on climate issues. The data are taken from the World Bank's database for net savings EN_t and greenhouse gas emissions E_t; the carbon sink $\bar{E}$ is based on the SNBC-2 at national level,[24] and remains constant at 10 $MtCO_2eq$ at global level. With a view to simplify, the carbon price used – for France and at global level – is the average IPCC value for the objective of +1.5°C, "backcasted" for 2019, i.e. \$180 per $MtCO_2eq$ or €153 per $MtCO_2eq$ (Figure IX).

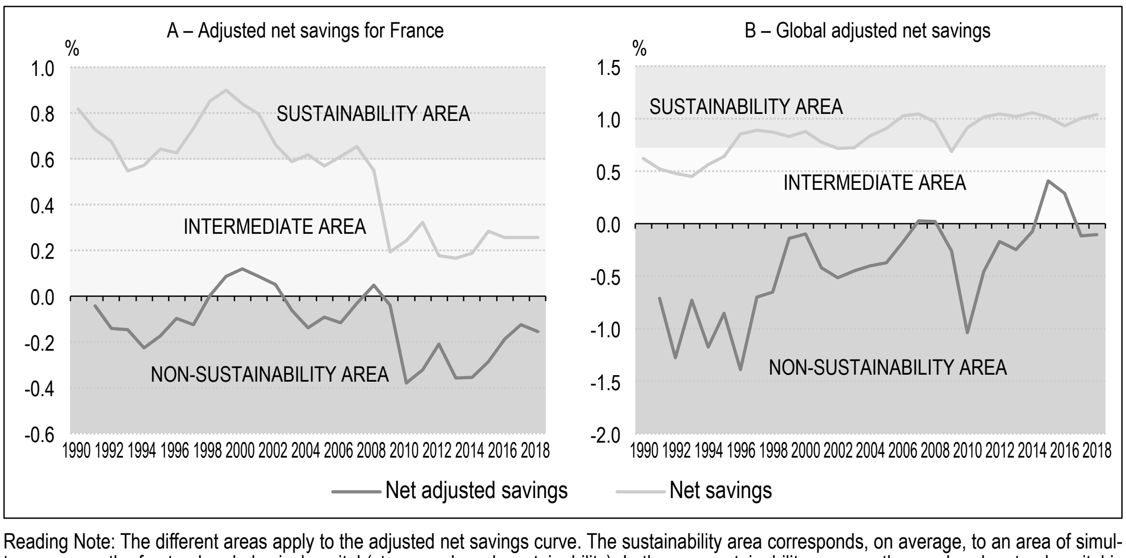
The adjusted net savings rate then appears negative at global level. Even if, after reaching a low point close to -13% in 1996, it has since recovered, mainly due to the rise of the Chinese economy, which has a high savings rate, it remains significantly negative on average over the last two decades. In France, the adjusted net savings rate has also been negative since the beginning of the 1990s. Contrary to the conclusions of the World Bank,[25] growth thus appears to be unsustainable, even in the so-called "weak" sense of the term, i.e. considering the substitutions between physical and natural capital. Not only are we using more resources than nature is capable of regenerating, but the wealth we leave behind does not compensate for the costs of repairing climate damage.

4.3. Inclusive Wealth, Integrating Climate Debt

The stock concept of inclusive wealth can be associated with this concept of flow. Inclusive wealth is defined as the sum of the different forms of capital weighted by the implicit price of each of them. Here we consider physical capital and climate "capital". The capital stock is created using a permanent inventory from 1975, i.e. by assuming a capital/output ratio of 2.8 in 1975. This calculation is performed using net savings data from the World Bank.

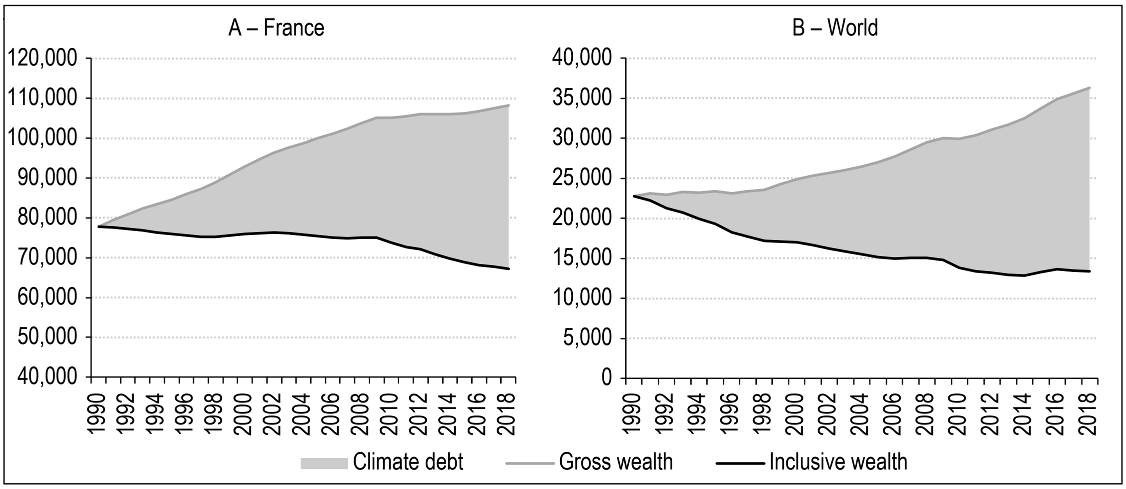
23. *In the rest of the article, we will express all carbon "prices" in euros per tonne of CO_2. Carbon prices sometimes also refer to a price per tonne of carbon and not CO_2. The shift from the first to the second is done by multiplying by 0.275: as the atomic mass of carbon is 12 and that of oxygen is 16, there is 12/44 of a tonne of carbon in a tonne of CO_2. A price of €20 per tonne of carbon is therefore equivalent to a price of €5.5 per tonne of CO_2.*
24. *40 $MtCO_2eq$ in 2020, rising slightly to 80 $MtCO_2eq$ in 2050.*
25. *The main reason for the discrepancy with the World Bank estimates is a difference in the assessment of the carbon value. The World Bank also takes into account, contrary to this article, the accumulation of human capital, which is valued at the level of public education spending. This choice may seem optimistic in the sense that it seems more appropriate to use permanent inventory methods, considerably reducing the impact on adjusted savings, particularly when the school-leaving age stops rising, as has been the case in France for the past two decades. Furthermore, it is more than likely that the positive valuation of the accumulation of human capital would be more than offset by the negative consideration of biodiversity loss - the other major environmental concern - without altering the message of the unsustainability of the current economic trajectory.*

Figure IX – **National and global adjusted net savings (in % of GDP)**



Reading Note: The different areas apply to the adjusted net savings curve. The sustainability area corresponds, on average, to an area of simultaneous growth of natural and physical capital (strong and weak sustainability). In the non-sustainability area, on the one hand, natural capital is declining and, on the other, the repair costs are higher than the increase in income (strong and weak non-sustainability). In the intermediate area, adjusted net savings are positive but below the average net savings value – this means that natural capital is declining overall (weak but not strong sustainability).
Sources: World Bank Data, authors' calculations.

Figure X – **National and global wealth integrating climate debt (in euros per inhabitant)**



Sources: World Bank Data, authors' calculations.

The climate is taken into account from 1990 onwards. This is a normative choice consistent with the one we have made for the evaluation of climate debt and, of course, with the choice of the COPs since Kyoto to make it the reference for all the processes associated with them. It can also be considered that from that date, the fight against global warming became a social goal, and that continuing to emit more GHGs than the planet is able to absorb has become a debt for future generations.[26]

In 2019, readjusted inclusive wealth per capita amounts to approximately €57,500 in France and €13,175 at global level, corresponding to wealth (capital) of €109,000 for France and €31,450 at global level, respectively (Figure X). The difference represents the financial value of carbon debt since 1990. In both cases, wealth, extended to include natural resources (in this case, the climate), is in decline, which has been more pronounced in France since the 2008 crisis due to the drop in gross savings, with that drop being more attenuated at global level due to the emergence of China.

Inclusive wealth is constructed as the cumulative sum of adjusted net savings over time. Adjusted net savings measure instantaneous sustainability, which is interesting in itself. However, one year of negative net savings can be compensated the following year by a positive year; inclusive wealth takes into account developments in both the medium and long term. In our construction there is a very simple relationship between inclusive wealth, capital and financial climate debt (according to the backward looking approach), with the first being simply the difference between the other two. These latest results shed new light on the work that concluded that most rich countries were sustainable, based on these adjusted net savings and inclusive wealth indicators. A correctly calibrated carbon price indeed leads to the opposite conclusion.

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In this article, we have endeavoured to re-evaluate the issue of the climate sustainability of economic development, at national level for France and globally. On a theoretical level, considerable progress has been made since the late 1990s, with an important milestone around the work of the Stiglitz Commission (Stiglitz *et al*, 2009).

In the language of the theories of well-being and sustainability, COP 21 and its continental and national iterations have placed a social value on climate action. Societies now consider CO_2 emissions beyond terrestrial and oceanic absorption capacities as a cost for future generations. And this gives mitigation efforts a value, the value of climate action. The other essential factor for assessing climate sustainability is of a technico-financial nature. Translating the CO_2

26. Another option would be to go further back, to the moment when GHGs exceeded the capacity of the global carbon sink, i.e. in the 1950s to 1960s.

emission reduction goals into financial terms requires knowing the cost of the techniques and technologies in relation to their potential to decarbonise the economy. In this respect, too, the magnitudes are now beginning to be better established, contributing to the reliability of both macro-sectoral and technico-economic models.

Therefore, we have proposed a macroeconomic framework that makes it possible to evaluate the optimal GHG emission reduction trajectories with constraints in terms of intergenerational equity and the development of decarbonisation technologies. This dual movement to clarify the climate goal and technico-financial knowledge seems sufficient for us to be able to assign a reasonably reliable price to carbon. We have demonstrated that this value for France should be positioned, for the objective of carbone neutrality, at around de €120 to €250 today; €250 to €500 in 2030; €500 to €1,000 in 2040; €1,000 to €2,000 in 2050. These estimates are globally consistent, in terms of their order of magnitude, and when we analyse comparable concepts of social price of carbon, with the IPCC estimates or those established by the Quinet Commission (2019) and the models on which they are based: they constitute the high end of the range. To meet France's climate commitments, i.e. to achieve carbon neutrality by 2050, the climate spending effort should be increased to 4.5% of GDP each year. The global effort should be on a comparable scale (5.1% of global GDP).

Finally, these increased social values of carbon shed new light on the evaluation of the sustainability that we are accustomed to describing as weak, i.e. the – otherwise rightfullly controversial – issue of determining whether, despite everything, and thus despite the environmental damage, the balance for future generations would be "positive", given the continuous improvement of the average standard of living. The global net savings rate, adjusted to take account of climate damage, is negative over the entire period under review. Over the past three decades, the world is thought to have become poorer not richer, with the cost of human activities on the climate being thought to have outweighed the accumulation of both private and public capital. Inclusive wealth, aggregating natural and physical capital, is in decline. Even in the weak sense of the term, we are on a trajectory of unsustainability and, in reality, we have been on it for several decades, and only a change of scale in the economy's decarbonisation policies is likely to correct it.

We can only stress, for a definitive conclusion, the implications of recent advances and clarifications, both theoretical and empirical. Determining a value for the carbon price is a major issue for steering public policies, and the implementation of environmental economic accounting, would be likely to shed light on the public debate. However, such public accounting would also be useful for guiding individual choices on consumption, production and travel. One possibility would be to set a social value for climate action or a social cost of carbon by law,[27] which would also specify how the value is to be used, which could range from systematic labelling or inclusion in the business accounting standards to more binding measures, such as inclusion in public procurement contracts or setting a minimum price for CO_2 emissions allowance trading. ☐

27. We have distinguished the social value or carbon from the carbon tax. As a matter of fact, the carbon tax is only one of the possible levers of climate policies and raises significant questions of fiscal justice without establishing the behavioural effects, which would assume price elasticities to be established.

Link to the Online Appendices : https://www.insee.fr/en/statistiques/fichier/4770154/ES-517-518-519_Germain-Lellouch_Online_Appendices.pdf

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