On the Way to Net Zero. But Which Way?

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Abstract – Based on an optimal investment choice model, we describe the optimal transitions to carbon neutrality that are in line with climate-related constraints such as one-off greenhouse gas emission caps or a cap on cumulative emissions. We show that *i)* the early scrapping of brown capital – greenhouse gas emitters – cannot occur with one-off targets; *ii)* in order to limit global warming to a given level, the explicit introduction of such a constraint in the form of a cumulative emissions total not to be exceeded minimizes the associated economic cost, resulting in an initially high level of scrapping with limited cumulative emissions. Well-chosen regular emissions caps from the first year result in a similar trajectory; *iii)* with a given cumulative emissions constraint, delaying the transition increases both costs and scrapping; *iv)* the total annual investment during and after the transition is lower than that of the initial state.

JEL: Q01, Q54, Q56, E01, E21, O13
Keywords: climate change, Ramsey model, green technology, dynamic model

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The fight against global warming demands significant efforts in order to limit greenhouse gas (GHG) emissions. With the signing of the Paris Agreement in 2015, 196 parties (195 states + the European Union) entered into an agreement to take the necessary measures in order to limit the increase in the global average temperature to well below 2°C, and preferably to below 1.5°C, above pre-industrial levels. According to the IPCC (Intergovernmental Panel on Climate Change), the achievement of carbon neutrality across the globe by 2050 is crucial if we are not to exceed 1.5°C of global warming, and it must be achieved by 2075 for a maximum of 2°C (IPCC, 2022). In order to comply with the Agreement, each of the signatory parties has established its own roadmap, based on commitments that together are expected to lead to an emissions-neutral world. In France, this is the French Strategy for Energy and Climate (*Stratégie française sur l'énergie et le climat*, SFEC),[1] which proposes a pathway to net zero emissions (NZE) of greenhouse gases in 2050. This strategy also includes meeting an interim target set by the European Union of achieving a reduction in net emissions of 55% in 2030 when compared with 1990 (Fit for 55 package).

The increase in global temperatures follows the increase in the amount of GHG in Earth's atmosphere in a near linear manner:[2] the most obvious solution for managing the fight against global warming would therefore be to place a cap on total future emissions resulting directly from human activities. To this end, the IPCC estimates remaining 'carbon budgets' to limit global warming to a given level (e.g. 1.5 or 2°C) with a certain degree of probability (IPCC, 2022): these budgets represent caps that the cumulative total of net future GHG emissions (i.e. gross emissions minus the amount that the planet is able to absorb) must not exceed if we are to keep global warming to below a certain level with a given probability.

It is clear from the strong relationship between temperature and the stock of GHGs in the atmosphere that it will only be possible to stabilise global warming if the stock of GHGs in the atmosphere is no longer increasing, in other words, if the world is 'carbon neutral': gross GHG emissions must be balanced with the carbon sink, i.e. the planet's ability to absorb carbon (whether natural in the form of oceans, the ground and vegetation or artificial in the form of carbon capture and sequestration technologies). National decarbonisation strategies, which often aim to achieve carbon neutrality, are often presented as responses to the objective of limiting global warming to below 1.5°C (and to a maximum of 2°C). However, there are many different pathways to achieving carbon neutrality by a given date, all of which result in cumulative net emissions that may differ significantly at the end of the transition. In theory, the world can become carbon neutral after emitting any amount of GHGs. In particular, there is no guarantee that the trajectories aimed at achieving carbon neutrality by 2050 are consistent with limiting global warming to 1.5°C (or 2°C).

If we are to achieve carbon neutrality, we must undertake significant actions to decarbonise consumption and production methods through the use of three main levers: reduced consumption, efficiency (in particular energy efficiency) and the decarbonisation of production. The latter two levers involve the replacement of carbon-based technologies with clean, low or zero-emission technologies (electric cars, renewable energies, energy-efficient housing and even agrobiology). The majority of these technologies already exist. In the future, technological progress is expected to bring new developments that will make green production methods more competitive than their carbon-based counterparts.

The transition may require the premature scrapping of brown capital to meet carbon limitation targets, creating worthless assets referred to as 'stranded assets'. These assets include natural resources (stocks of coal, natural gas and oil still in the ground), physical assets (coal-fired power stations, blast furnaces) and financial assets (stocks and bonds in extraction or energy-intensive industries). The NGFS (2022) has designed a set of global decarbonisation scenarios, which vary depending on the intensity of the efforts made and how soon they are implemented: orderly (immediate and increasing efforts between now and 2050), disorderly (no effort before 2030 followed by a rapid catch-up) or disorderly and ineffective (insufficient efforts that vary from one country to the next). IRENA (2017) estimates stranded assets at one percent of 2019 GDP for each year between 2019 and 2050 in the event of a disorderly transition, twice as

1. *The SFEC is comprised of the Energy and Climate Programming Law (*Loi de programmation énergie-climat*, LPEC), the National Low-carbon Strategy (*Stratégie nationale bas carbone*, SNBC), the Multi-annual Energy Programming (*programmation pluriannuelle de l'énergie*, PPE) and the National Adaptation Plan for Climate Change (*plan national d'adaptation au changement climatique*, PNACC).*
2. *For example, the IPCC (2022) estimates the climate sensitivity (i.e. the average global temperature increase that would occur if the amount of GHGs in the atmosphere were to double) at an average of 3°C. This linear relationship between the increase in the stock of GHGs and the increase in temperatures can also be used as a projection by means of modelling (see Figure SPM.10, IPCC, 2023).*

much as with an orderly transition. This estimate compares two scenarios: immediate transition aimed at achieving the 2°C target and delay of the transition to 2030, while still aiming for the 2°C target. The amounts of stranded assets, calculated as the difference between the two scenarios, would mainly involve the construction sector in the European Union.

Here, we propose a stylised macroeconomic model aimed at clarifying the challenges associated with the transition from carbon-based production processes to other, cleaner processes at the national level in France, and at evaluating the impacts of the various decarbonisation strategies, such as the introduction of a remaining carbon budget constraint that must be complied with and/or the establishment of annual emissions caps. We start by addressing the following questions: which investment strategy should we follow if we are to comply with a carbon budget that is compatible with an ambitious limitation of global warming? What are the economic and environmental differences between a policy based on the capping of cumulative emissions and policies limiting annual flows (such as NZE and Fit for 55)? How much will each decarbonisation strategy cost? What is the cost of delaying decarbonisation? Would the transition necessarily lead to the scrapping of brown capital and, if so, to what extent and when?

Our toy model is in line with the report by Pisani-Ferry & Mahfouz (2023), which encourages the development and use of stylised models to shed light on the key challenges of the energy transition. Such models are not intended to replace existing detailed models (they would not be accurate enough, for example, to evaluate a decarbonisation pathway in as detailed a manner as the SFEC does); rather, they are used to shed light on specific issues, based on limited sets of assumptions, even if that means subsequently comparing them with the results of the detailed models and analysing the differences between them. Thanks to the fact that it records both brown and green investments, the results of our model shed new light on the situation. While Pisani-Ferry & Mahfouz (2023) favour a bottom-up approach involving the aggregation of investment needs by sector, our modelling approach results in the calculation of investment series at the macroeconomic level (top-down) in response to constraints and taking account of the general equilibrium effects.

In line with Rozenberg *et al.* (2020) and Acemoglu *et al.* (2012), the model takes account of two forms of capital, depending on whether their use for production produces GHGs (brown capital) or not (green capital). The quantities of these two types of capital used in the economy depend on the constraints on carbon emissions, which are set exogenously. In this context, the decarbonisation of the economy is achieved by gradually replacing brown capital with green capital. These two forms of capital are involved in the production process, but may offer different levels of productivity and are not perfectly substitutable. A portion of the annual production is used for household consumption, with the rest being used for brown and green investments. Consumption, brown and green investments and stranded capital[3] trajectories are decided upon by a social planner, whose aim is to maximise intertemporal welfare while subject to emissions caps. The investment is irreversible: the planner cannot turn brown capital into green capital or consumption. However, it is possible for them to scrap all or some of the brown capital at any time, unlike in Rozenberg *et al.* (2020), where brown capital can only be underutilised.[4]

To achieve decarbonisation, the planner can replace the obsolete brown capital with green capital at the same rate at which it is depreciating. If a significant reduction in emissions is required, this strategy is insufficient, as the reduction in emissions is limited by this natural depreciation. The planner can then dispose of the brown capital, thereby reducing future production. The model examines the evolution of the investments and capital stocks depending on the type and severity of the constraints imposed by each decarbonisation scenario. Calibration is performed for France, with an initial estimate of brown capital that is based on the national accounts and the I4CE climate investment trajectories (2022). These investments represent the amount necessary in order to replace the surplus brown capital (that which exceeds the capacity of the carbon sink), which makes it possible to estimate its initial value and its replacement cost. Unlike Rozenberg *et al.* (2020), our model is calibrated at the French national level.

3. Fossil and renewable energies are not directly modelled as inputs, but are instead incorporated into the aggregated, consumed or invested good. The installed capital, whether it be brown or green, includes that which is necessary for energy production: some of the brown capital produces fossil fuels (natural gas and coal) and some of the green capital produces alternative energies (nuclear and renewable).

4. We do not introduce the possibility of underutilising the capital. Climate constraints aim to transform the economy in a way that ensures that it functions normally while complying with emissions caps. The underutilisation of capital could circumvent policies aimed at decentralising the centralised equilibrium, a possibility that the legislator must anticipate. However, this strategy is not relevant for the central planner looking for optimal transition trajectories.

The results of the simulations must be interpreted with caution, as they are intrinsically linked to the modelling framework and the parameters selected, some of which are still not well known in the literature. A bottom-up approach could result in different conclusions regarding the stranding of assets highlighted in certain simulations. The numerous robustness analyses performed also reveal that the results obtained are sometimes sensitive to parameterisation. The aim, therefore, is to propose orders of magnitude, with a certain set of assumptions, of the efforts involved in the transition and their spread over time, as well as an illustration of the economic mechanisms at play when different mitigation policies are put in place. In addition, the model remains highly stylised and reveals the centralised equilibrium; it fails to take account of the decentralisation instruments of this centralised equilibrium and the market imperfections that could complicate the achievement of this equilibrium in a decentralised world. As a result, the simulations likely represent a lower bound of the costs of the transition. Lastly, the results in terms of global warming are based on the assumption that cumulative emissions will also remain below the budget corresponding to that level of warming in other countries. Indeed, the action in France only provides information about France's contribution to global efforts to limit global warming.[5] The results are also based on the estimated remaining carbon budgets and the projected relationship between temperature and GHGs at GHG levels higher than those observed. The equivalences between cumulative GHG emissions in France and global warming are provided purely for illustrative purposes.

Our simulations allow us to compare the consequences of the various decarbonisation objectives on the optimal trajectory of brown and green investments and stranded assets in France, between 2022 and 2050 (target year for the achievement of carbon neutrality). A reference scenario, one of climate inaction, is established, in which there are no limits on emissions. Next, four decarbonisation scenarios are assessed, all of which share the 2050 NZE objective, with the following targets: 1) only the NZE objective, 2) a 55% reduction in net emissions in 2030 when compared with their 1990 level (Fit for 55), 3) Fit for 55 in 2030 and a 90% reduction in net emissions in 2040, and 4) the introduction of a national carbon budget that is compatible with the most ambitious objective set out in the Paris Agreement (+1.6°C of warming). Following this, a series of scenarios is presented that aims to evaluate the impacts of intensifying targeting via annual emissions caps, with targeting every ten, five and then two years. Lastly, three delayed transition scenarios are evaluated, based on the date on which the optimal intertemporal management of the remaining carbon budget is commenced (2023, 2028 or 2033).

With optimal trajectories and using stated equivalents between emissions and global warming, the ZEN scenario is compatible with global warming of 1.8°C, the Fit for 55 scenario with 1.75°C, and Fit for 55 + 90 with 1.65°C. Of the various scenarios studied, it is with the intertemporal management of a carbon budget that the increase in green investment takes place at the earliest stage. Brown investment disappears from the first year, thereby initiating the transition quickly. Conversely, with the NZE objective alone, brown investment survives for several years, delaying the transition. It only begins to disappear from 2027 onwards, at the same time as a green investment finally begins to come into play. The addition of the Fit for 55 target in 2030 makes it possible to significantly advance the transition and to accelerate the phasing out of brown investment; however, it also gives rise to the appearance of an undesirable stop and go phenomenon: brown investment reappears temporarily in 2030 and continues for a short time after this, before finally disappearing for good. The addition to this latter scenario of a target of reducing net emissions by 90% by 2040 eliminates this phenomenon: the brown investment does not restart again just after 2030, nor does it recommence after 2040.

These initial scenarios also allow us to illustrate a fundamental finding of the model: anticipatory stranding of assets is never an optimal solution with one-off emissions caps, so the stranding of brown capital is not seen until 2050 with just the NZE objective alone, in 2030 and 2050 with the addition of Fit for 55, and in 2030, 2040 and 2050 with an additional cap in 2040. These one-off constraints do not lend themselves naturally to spreading the efforts over time, which may complicate their implementation. On the contrary, the optimal management of a carbon budget over time goes hand-in-hand with strandings, which can occur every year and may be substantial during the first year with an ambitious climate goal.

5. The model describes the emissions produced by national production, i.e. the national GHG inventory, which is the set of figures used for the purposes of international commitments. The national inventory differs from carbon footprint, which is the emissions linked to national consumption (excluding the emissions linked to exports and including those linked to imports).

Another thing that the model teaches us is that, in all of the transition scenarios, the overall investment is lower, on average, than was initially observed. Indeed, the carbon constraint shifts the production frontier such that, in the final, post-transition state, less capital is mobilised for production, since the increase in green capital does not compensate for the reduction in brown capital that has been forced by the constraint. When compared with the initial situation, the total amount of investment is therefore lower in the final equilibrium state, and it also appears to be lower on average during the transition in all scenarios studied.

In order to achieve a given maximum global warming target (a given cumulative amount of emissions), the explicit introduction of this constraint, in the form of a remaining carbon budget, will make it possible to reduce the associated economic cost to a minimum. A trajectory similar to that of an optimal trajectory associated with compliance with a carbon budget may be achieved with emissions caps that are spaced at regular intervals and that are applied from the first year and selected based on the emissions from that optimal trajectory. When faced with an ambitious climate goal, bringing these interim milestones closer to one another in terms of time reduces the drift that can occur between those milestones.

Lastly, the later the transition takes place, the more it costs. We compare delayed transition scenarios:[6] NZE objective initially, followed by the commencement of the transition from a certain date to comply with the remaining budget compatible with global warming of 1.6°C. The later this date, the greater the proportion of the budget that has already been consumed and the more the stock of brown capital needs to be reduced in order to achieve very low GHG emissions over the remaining period until 2050. Therefore, during the year in which the transition is made to the management of the remaining carbon budget, stranding is twice as high if the policy change comes in 2028 as opposed to in 2023, and three times higher if the change is made in 2033. Consumption is, on average, 1% lower during the transition period in the event that the policy change is delayed to 2033 rather than 2023.

With all the different types of constraints on GHG emissions, the optimal trajectories often result in very significant stranding of assets during a given year. It is likely that, in order to reduce the resulting intergenerational conflicts, the effort will be smoothed over time. We therefore introduce a cost of stranding capital into the utility function, quadratic in the quantity of stranded capital. The stranding is then spread over time to a greater or lesser extent depending on the amount of these costs, reflecting a more realistic situation in terms of both their amounts and their temporal profile. With high stranding costs, which limit the reduction of brown capital at the start of the period, emissions fall more slowly than with moderate or zero costs, which means that the economy must be closer to neutrality at the end of the period in order to compensate for the increase in emissions at the beginning of the period.

We describe the way in which the model works in Section 1, then we describe our various findings in Section 2, before setting out our conclusion. A literature review positioning the contribution of this model in relation to the state of the art is available in the Online Appendix (link to the Online Appendix at the end of the article).

1. Presentation of the Model

1.1. Productive Sector

Each year t, the economy evolves in accordance with the following stages:

1. At the start of year t, the available capital is K_{t-1}^{i} ($i = b$ (brown) or v (green)), resulting from the accumulation of capital up until the previous date. At this time, an amount of brown capital, ϕ_t^b, may be scrapped (stranded capital), such that only the remaining brown capital $K_{t-1}^{b} - \phi_t^b$ is used for production.
2. A quantity of goods is produced, depending on the brown capital that is still available, plus the green capital, $Y_t = F\left(K_{t-1}^{b} - \phi_t^b, K_{t-1}^{v}, \bar{L}\right)$, where $\bar{L}$ represents the population, which is assumed to be stable and constant over time for the purposes of this calculation. If desired, and as is often the case in Ramsey models, the presence of the labour factor allows for positioning in a framework where the returns to scale are constant, while also taking account of the reduction of returns on capital.
3. Once production is complete, the levels of consumption C_t and investment I_t^i $(i = b, v)$ can be chosen with the following constraint: $C_t + I_t^b + I_t^v \leq Y_t$.
4. A fraction δ of the capital disappears.

6. *Our delayed transition scenarios differ from those of IRENA (IRENA, 2017) with regard to the pre-transition period. In the IRENA scenario, it is a case of business as usual until 2030. In our simulations, however, the pre-transition period follows a NZE trajectory, which is already compatible with the 1.8°C goal (according to our simulations), but that is not sufficient to meet the 1.6°C target.*

Lastly, the investment dynamics bring about an accumulation of brown and green capital represented by the following equations:

$$\begin{cases} K_t^b = (1-\delta)\left(K_{t-1}^b - \phi_t^b\right) + I_t^b \\ K_t^v = (1-\delta) K_{t-1}^v + I_t^v \end{cases}.$$

In our modelling, these two forms of capital are not mutually exclusive: they coexist within the economy. At steady-state equilibrium, their respective share depends on their productivity and their substitutability. The use of brown capital for production results in GHG emissions, while the use of green capital does not. Therefore, the gross emissions for year t are equal to $e_b\left(K_{t-1}^b - \phi_t^b\right)$, where e_b is the average emissivity, i.e. the emission of GHGs generated by the use of one unit of brown capital.

The NZE objective allows brown capital to survive beyond 2050, but in a way that is limited by the capacity of the carbon sink, as the emissions will simply saturate it. In the model, a portion of brown capital, referred to as 'residual', is calculated such that its emissions precisely saturate the sink. As this sink is considered to be constant, the residual capital is also constant, with a residual brown investment offsetting its depreciation each year. The residual brown capital is expressed as $\underline{K}^b$, and the non-residual as $\tilde{K}_t^b$, where $K_t^b = \tilde{K}_t^b + \underline{K}^b$. The amount of residual brown investment is $\delta \underline{K}^b$, and the net emissions e_t are those emitted by the non-residual brown capital (which is the only capital affected by stranding): $e_t = e_b\left(\tilde{K}_{t-1}^b - \phi_t^b\right)$.

The capital accumulation dynamics are in line with the Ramsey model (Ramsey, 1928; Mercenier & Michel, 1994), with a trade-off between current consumption and investment, which will be used for future consumption. With two types of capital, a new consideration emerges: replacing brown capital with green capital while preserving consumption. This can be achieved by allowing the brown capital to be phased out naturally and gradually replacing it with green capital. Such replacement decisions naturally result in a reduction in the potential of the economy, in so far as they do not come about as a result of the relative efficiency of the two types of capital. The urgency of the transition may require a more rapid reduction in emissions than the depreciation of brown capital, implying its early withdrawal. The following section provides details of the constraints on emissions and the incentive to eliminate brown capital more or less quickly.

1.2. Constraints on Emissions

The ambitions to combat global warming are reflected in the constraints on net GHG emissions. Their introduction prioritises green capital in the productive process, at the expense of brown capital.

Three types of constraint are taken into consideration:

1. The NZE constraint: this is common to all decarbonisation scenarios and determines the terminal steady state. From year T_E: $K_t^b = \underline{K}^b$, after the planner has disposed of the non-residual brown capital at the beginning of T_E: $\phi_{T_E} = K_{T_E-1}^b - \underline{K}^b$.

   $\forall t \geq T_E, e_t = 0.$

2. A carbon budget, based on cumulative net emissions and compatible with limiting global warming to a given level:

   $$\sum_{t=t_0+1}^{T_E} e_t \leq E_{max} \qquad (1)$$

   where t_0 is the base year and the date on which the constraint was introduced into the economy. In the applications, we start with $t_0 = 2022$ and, in the majority of situations, we consider a carbon budget that is compatible with a probability of keeping global warming to below 1.6°C or 1.8°C of 50%.

3. One-off constraints on net emission flows during year t_l, such as $e_{t_l} \leq \overline{e}_{t_l}$. For example, Fit for 55 in 2030: $e_{2030} \leq 0.45 \times e_{1990}$.

The model is based on the assumption that, once known, the constraints are perfectly anticipated, thereby allowing the planner to establish trajectories of brown and green investments for the entire period. In a way, the announcement of the constraints brings about an immediate economic shock, with the model precisely describing the consequences of that shock. The following section explains how investment decisions are taken.

1.3. Social Planner's Program

We assume that the investment and consumption decisions are taken by a social planner, who maximises the discounted intertemporal sum of utilities derived from consumption on each date ($u(C_t)$), subject to constraints. The equilibrium is reached by solving the following program, together with the constraints set out below:

$$\max_{\substack{\tilde{I}_{t_0+1}^b,\ldots,\tilde{I}_{T_E}^b \geq 0 \\ \phi_{t_0+1}^b,\ldots,\phi_{T_E}^b \geq 0 \\ I_{t_0+1}^v,\ldots,I_t^v,\ldots \geq 0}} \sum_{t=t_0+1}^{+\infty} \frac{u(C_t)}{(1+\rho)^{t-t_0}}.$$

• Balance between resources and use:

$$F\left(K_{t-1}^b - \phi_t^b, K_{t-1}^v, \overline{L}\right) = C_t + \tilde{I}_t^b + \delta \underline{K}^b + I_t^v.$$

What is produced with the installed capital (from which the stranded capital ϕ_t^b is taken) is used for consumption and investment in brown (including residual) or green capital on date t.

- Accumulation of brown and green capital:

$$\begin{cases} K_t^b = \tilde{K}_t^b + \underline{K}^b \\ \tilde{K}_t^b = (1-\delta)\left(\tilde{K}_{t-1}^b - \phi_t^b\right) + \tilde{I}_t^b \\ K_t^v = (1-\delta)K_{t-1}^v + I_t^v \\ 0 \le \phi_t^b \le \tilde{K}_{t-1}^b \end{cases}.$$

These equations describe the accumulation dynamics of non-residual brown capital and green capital. The residual brown capital remains constant: it is only invested ($\delta \underline{K}^b$) for the purposes of renewing it.

- Accumulation of net carbon emissions: $E_t = E_{t-1} + e_t$, where $e_t = e_b\left(\tilde{K}_{t-1}^b - \phi_t^b\right)$.
- NZE constraint: $\phi_{T_E}^b = \tilde{K}_{T_E-1}^b$, then $\forall t \ge T_E$: $\tilde{K}_t^b = \tilde{I}_t^b = 0$ and $K_t^b = \underline{K}_b$, and $\forall t \ge T_E + 1$: $\phi_t^b = 0$.
- One-off constraints on annual emissions:

$$e_{t_l} \le \overline{e}_{t_l}, \phi_{t_l}^b = max\left(\tilde{K}_{t_l-1}^b - \frac{\overline{e}_{t_l}}{e_b}, 0\right).$$

- Carbon budget that is not to be exceeded (equation (1)).

This program can be reformulated in a recursive form as shown below, on each date t (Stokey *et al.*, 1989), by defining:

$$V\left(I_t^b, I_t^v, \phi_t^b \middle| K_{t-1}^b, K_{t-1}^v, E_{t-1}\right) = u(C_t) + \frac{1}{1+\rho} W\left(K_t^b, K_t^v, E_t\right)$$

where the variables $\left(K_{t-1}^b, K_{t-1}^v, E_{t-1}\right)$ are the state variables, allocated from one period to the next by the control variables $\left(I_t^b, I_t^v, \phi_t^b\right)$, and where:

$$W\left(K_{t-1}^b, K_{t-1}^v, E_{t-1}\right) = \max_{I_t^b, I_t^v, \phi_t^b} V\left(I_t^b, I_t^v, \phi_t^b \middle| K_{t-1}^b, K_{t-1}^v, E_{t-1}\right)$$

is the value achieved by the indirect utility function, once optimised in relation to the control variables, while retaining the same constraints as those set out above.

The program is then fully solved by defining the initial values of the state variables and allows for a single solution under the standard assumptions of the regularity and convexity of utility and production functions (Stokey *et al.*, 1989).

1.4. Steady-State Solutions

In the absence of carbon constraints, brown and green capital coexist in steady-state equilibrium where they are not perfectly substitutable in the production process. Their respective levels, K_0^v and K_0^b, are then solutions to the equations (see Online Appendices S1 and S2 for the working):

$$\rho + \delta = \frac{\partial F}{\partial K^b}\left(K_0^b, K_0^v\right) = \frac{\partial F}{\partial K^v}\left(K_0^b, K_0^v\right).$$

With an initially steady-state economy and carbon constraints announced on date t_0, levels of installed brown and green capital at the start of year $t_0 + 1$ correspond to their steady-state level at the end of year t_0. Only on this date does the planner make investment and consumption decisions that are compatible with the carbon constraints, thereby bringing the economy out of its original state.

Between $t_0 + 1$ and T_E, the various carbon constraints can be applied (especially on a one-off basis), generating shocks within the economy.

Beyond T_E, the NZE constraint comes into play and the environment stabilises again. The only remaining brown capital is the residual brown capital ($\underline{K}^b$), which saturates the carbon sink. In the long term, a new steady state is reached, such that the total investment keeps consumption at a constant level. The final green capital obtained in this manner (K_∞^v) is the solution to the equation:

$$\rho + \delta = \frac{\partial F}{\partial K^v}\left(\underline{K}^b, K_\infty^v\right).$$

1.5. Calibration

1.5.1. Functional Forms

The production function takes brown and green capital and labour as inputs: $Y = F\left(k\left(K^b, K^v\right), \overline{L}\right)$, where $F\left(k, \overline{L}\right) = k^\alpha \ \overline{L}^{1-a}$, where $\overline{L} = 1$ by normalisation, and k is the synthetic capital function. It is assumed that brown and green capital are combined according to technology with a constant elasticity of substitution σ (CES). Thus:

$$Y = F\left(k\left(K^b, K^v\right), 1\right) = \left[\left(\left(a_b K^b\right)^{\frac{\sigma-1}{\sigma}} + \left(a_v K^v\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}\right]^\alpha.$$

The CES form allows for the coexistence of brown and green capital in investment decisions.

For utility, the conventional approach is to select a logarithmic form: $u(C) = \ln(C)$.

The forms chosen are therefore highly concave (provided that $\sigma > 1$ in the production function), which guarantees the existence of a steady-state solution to the planner's program, as well as a convergence on this solution.

1.5.2. Initialisation and Structural Parameters

The values of GDP and the total installed net capital start from 2019, a year for which the economic figures are well known; however, 2022 has been selected as the base year from which to launch the simulations (Table 1).

Table 1 – **Initial and observed values of model quantities**

Variable	Starting levels
GDP	2.426 trillion euro
Brown capital	4.481 trillion euro
Green capital	3.667 trillion euro
Gross GHG emissions	404 $MtCO_2eq$

The GHG emissions are taken from national inventories for 2022 in order to take account of the decarbonisation of the economy since 2019 (SDES, 2023).

The respective shares of green and brown capital within the overall capital[7] are estimated based on the climate investment reports issued by I4CE (2022).[8]

In our approach, the brown capital corresponds to emissive goods or their emissive element. For example, within a home, an oil-fired boiler and poorly insulated walls are brown capital, while the rest of the home is green capital. If it is not possible to separate the emissive elements from the non-emissive elements, the entire object is considered a brown investment. This means that decarbonising transport involves the replacement of petrol and diesel cars with electric cars, but this is not simply a case of swapping the engines: this means that petrol and diesel cars are entirely brown capital. The distinction between brown and green capital relies entirely on existing technologies: due to the GHG emissions generated by its production activities, a cement plant is considered brown capital; however, when combined with an efficient decarbonisation technology, such as a CO_2 capture and storage system, it would become green.

The elasticity of substitution σ between brown and green capital is set at three, a value that is consistent with the Value of Climate Action (*valeur de l'action pour le climat*, VAC) in 2050 set out in the report by A. Quinet (2019)[9] and in line with existing empirical estimates.[10] The parameter α is deducted from the amounts of GDP and brown and green capital in the initial year:

$$\alpha = \frac{(\rho+\delta)\left(K_{2019}^{b}+K_{2019}^{v}\right)}{Y_{2019}}.$$

The values of parameters a_b and a_v are deduced from the first-order conditions in the initial steady-state situation.

We use a capital depreciation rate of 5%, which is similar to that estimated based on the 2019 national accounts data, by looking at the ratio of the consumption of fixed capital to the installed fixed capital. The discount rate of 2.5% comes from the extended Ramsey rule, as was the case for É. Quinet (2013), taking account of uncertainties concerning future economic growth. This value is a compromise between those proposed by Stern (2006) (1.4%) and Nordhaus (2007) (4.5%), and falls within the range of reference values for OECD countries, which ranges from 0% (the Netherlands) to 3.5% (United Kingdom) (OECD, 2019).

Table 2 shows the values used for the various parameters in the basic specification.

Sensitivity analyses are performed for these various parameters in order to put the main messages taken from the basic specification into perspective (see Online Appendix S4).

Unless otherwise stated, the carbon budget used is 3.93 $GtCO_2eq$, which corresponds to a global warming target of 1.6°C with a 50% probability of success. It is derived from the planetary carbon budgets estimated by Lamboll *et al.* (2023). France's share of the global budget is considered to be equal to its share of the world population in 2019 (0.88%). The equivalences between carbon budgets for France and global warming are provided in Online Appendix S3.

7. INSEE's balance sheets do not allow brown and green capital to be measured directly. For example, in the case of energy, it is not possible to separate green energy (renewable and nuclear) from brown energy (natural gas and coal-fired power plants).

8. The I4CE (2022) trajectories are based on five scenarios that are consistent with the NZE in 2050 objective: the SNBC scenario and the four 'Transitions 2050' ADEME scenarios. We chose ADEME scenario 3, 'Green technologies' for calibration, since its philosophy is similar to that of our model. We assume that all Panorama investments are made with the intention of replacing brown capital with green capital (for example, replacing gas or oil-fired boilers with heat pumps and replacing petrol and diesel cars with electric cars). The value of brown capital in 2019 is considered to be the same as the cost of its future replacement by green capital, i.e. the total climate investments made between 2019 and 2050. For that reason, 55% of the capital is estimated to be brown at the beginning, with the rest being green.

9. With an elasticity of substitution of three and a carbon sink of 85 $MtCO_2eq$, compatible with the natural sink provided for by A. Quinet (2019) of between 75 and 95 $MtCO_2eq$, the mitigation cost in 2050 appears very similar to the VAC arrived at by A. Quinet (2019), namely 775 €/tCO_2.

10. Papageorgiou et al. *(2017) propose an elasticity of substitution of two between brown and green inputs in the electricity sector and close to three for the rest of industry, based on a macroeconomic estimate involving 26 countries between 1995 and 2009 (not including France). Jo (2022) finds elasticities of between two and five based on data from manufacturing companies in France, between 1995 and 2015. However, our definition of brown and green capital is broader than that used by the literature, which focuses on specific production sectors, while we include all business sectors. This means that empirical estimates are not sufficient to provide an elasticity value that is perfectly suited to our model.*

Table 2 – **Parameter values of the calibrated model**

Structural parameters	Value	Range of values analysed in the robustness tests
σ	3.00	1.5–5.5
e_b	0.09	Derived parameter
α	0.39	Derived parameter
a_b	3.07	Derived parameter
a_v	2.77	Derived parameter
ρ	0.025	0.005–0.04
δ	0.05	0.01–0.10
Carbon sink	35	5–80
$\frac{K^b_{t_0}}{K^b_{t_0}+K^v_{t_0}}$	55	40–90

Notes: e_b is expressed in kgCO_2eq/€, the carbon sink in MtCO_2eq, the initial share of brown capital within the total capital as a %. The remaining figures do not have units. Derived parameters are calculated on the basis of the other parameters. Robustness analyses are available in Online Appendix S4.

2. Results

Our simulations compare the consequences of the various decarbonisation objectives on the optimal trajectory of brown and green investments, stranded assets and consumption in France, between 2023 and 2050 (target year for the achievement of carbon neutrality). A reference scenario, one of climate inaction, is established, in which there are no limits on emissions. By comparing this scenario with others, we are able to highlight the impact of mitigation policies. This comparison only provides a partial analysis of welfare since the damage to the climate, and therefore its mitigation to a greater or lesser extent in the scenarios with climate constraints, are not modelled. Next, four decarbonisation scenarios are assessed, all of which share the 2050 NZE objective, with the following targets: 1) only the NZE objective, 2) a 55% reduction in net emissions in 2030 when compared with their 1990 level (Fit for 55), 3) Fit for 55 + a 90% reduction in net emissions in 2040,[11] and 4) the introduction of a national carbon budget that is compatible with the objective set out in the Paris Agreement (+1.6°C of warming).

Next, a series of scenarios evaluates the impacts of an increase in the intensity of targeting via annual emissions caps, with targeting every ten, five and then two years. Lastly, three delayed transition scenarios are evaluated, based on the date on which the optimal intertemporal management of the remaining carbon budget is commenced (2023, 2028 or 2033), following on from a period in which only the NZE constraint is applied.

All of the decarbonisation scenarios have a similar profile in the long term, as they all converge on the same steady-state situation in line with the NZE objective. From 2050 onwards, their economic trajectories are very similar, with consumption and GDP that are both lower than in the scenario where no action is taken.

In theory, the Fit for 55-style one-off maximum GHG emission targets only apply for one year, so they do not limit subsequent emissions in principle. Our simulations show that after having stranded the brown capital on the date on which the emissions cap was introduced, the optimal approach may be to reinvest in brown capital immediately afterwards. This behaviour wastes resources and only reduces emissions very slightly. This is a direct consequence of the wording of the climate policy, which only caps emissions for one year. In practice, rather than stranding and then reinvesting in brown capital, companies likely underutilise their brown capital in the target year, with limited stranding (Rozenberg *et al.,* 2020). This avoidance behaviour does not provide information on the transition as such, as led by the social planner, but on the public policies implemented with a view to achieving it. However, our study primarily aims to shed light on the centralised equilibrium of the transition rather than its decentralisation. In the various scenarios, we therefore model one-off targets such as caps that also apply in subsequent years, thereby better reflecting the spirit of the legislation that aims to bring about net zero emissions in 2050. For

11. In order to reach the NZE in 2050 objective, the European Commission recently proposed the introduction of an interim target, in 2040, aimed at reducing GHG emissions by 90% when compared with 1990 (https://commission.europa.eu/news/recommendation-2040-target-reach-climate-neutrality-2050-2024-02-06_en). Unlike the Fit for 55 *target, this new target is still at the proposal stage.*

example, under Fit for 55, net emissions are not permitted to exceed 45% of their 1990 level, whether that be in 2030 or later.

2.1. Scenario Without Carbon Constraints

In this scenario, no constraints are imposed on emissions, neither in terms of flows nor stocks. In 2022, the base year, the economy is on a balanced growth path where green and brown investments coexist, due to their imperfect substitutability within the production process. In the absence of technical progress and demographic growth, the economy remains stable and never deviates from the steady-state equilibrium, which represents the initial situation. The various components of GDP remain at their 2022 levels throughout the trajectory. Emissions increase in a linear manner, which results in the rapid depletion of the carbon budget over a period of around ten years.

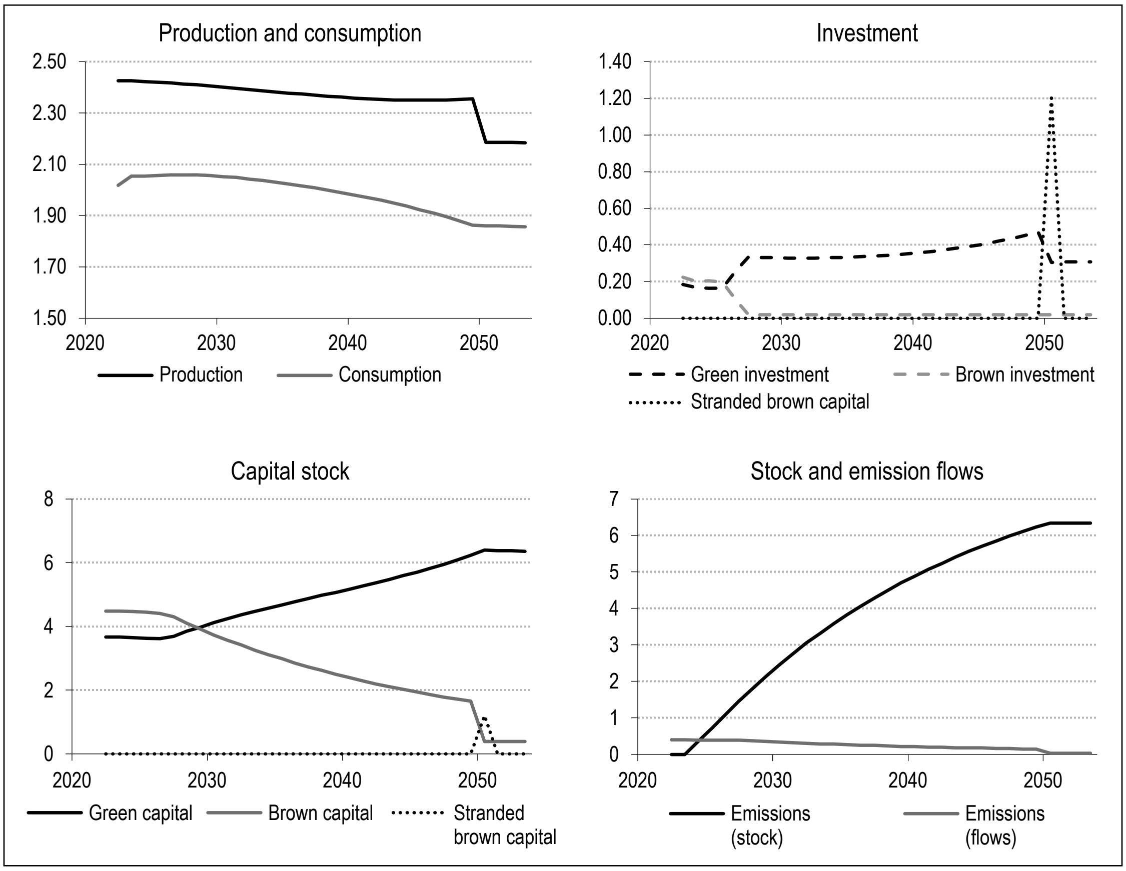
2.2. Annual Emissions Caps Versus Compliance with a Carbon Budget

2.2.1. Net Zero Emissions From 2050

Where the only constraint that is applied is the goal of achieving carbon neutrality by 2050 (ZNE), brown investments start to decline from 2025 onwards (Figure I), when compared with the scenario without any carbon constraints. Their decline is rapid as, from 2027 onwards, they fall to the rate that only ensures the renewal of the residual brown capital. The green investment evolves in the opposite direction: while it initially remains stable at its initial level, it increases significantly between 2025 and 2027 before stabilising. Green investment then begins to gradually increase again as 2050 approaches, which makes it possible to smooth out consumption and to mitigate its decline brought about by the significant stranding of brown capital in 2050. Indeed, this brings about the sharp decarbonisation of the economy and a rapid reduction in production capacity, which is offset by more green capital.

The transition from brown to green therefore takes place relatively late: it takes several years for the NZE 2050 constraint to truly get the transition under way. Indeed, the further the constraint is in the future, the more the brown capital acquired during the first few years depreciates naturally before the NZE deadline. The additional productivity of brown capital,

Figure I – **NZE 2050 scenario**



Notes: GHG emissions are in $GtCO_2eq$; for the other variables, the unit is trillion euro.

accumulated over a long period of time, makes the remaining large fraction of brown capital that is stranded in 2050 to achieve neutrality profitable.

2.2.2. Fit for 55 *in 2030 + NZE from 2050*

The addition of an interim emissions target in 2030 brings about the immediate disappearance of the brown investment, the amount of which only ensures the renewal of the residual brown capital from 2023 (Figure II). At the same time, the green investment is increasing. This therefore results in the transition being brought forward to a point in time that is earlier than in the NZE scenario and begins from the first year.

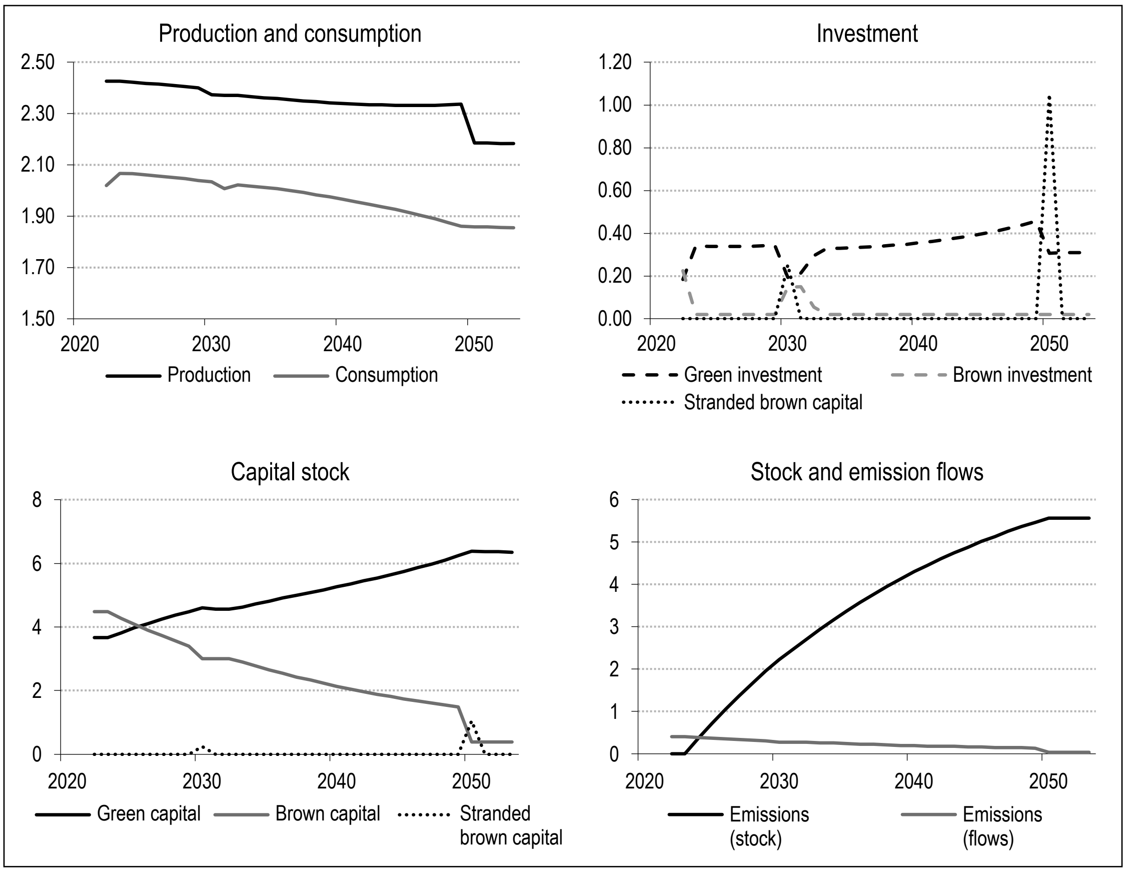
However, the fact that the emissions cap does not reduce any further after 2030 has a pernicious effect. Indeed, once the brown capital has depreciated sufficiently to meet the new constraint, it once again becomes profitable to invest in brown capital for a few more years after 2030. This results in a sawtooth trajectory: the brown investment initially disappears, reappearing again once the impact of the constraint lessens, before disappearing permanently in 2033.[12]

2.2.3. Fit for 55 *in 2030 +−90% in 2040 + NZE from 2050*

The introduction of an additional target to the Fit for 55 scenario in 2040, aimed at reducing net emissions by 90% when compared with their 1990 levels, brings about further stranding of capital, this time in 2040 (Figure III). This is actually the most significant stranding within the trajectory at almost four times greater than that which occurs in 2030. This highlights the scale of the effort that still needs to be undertaken after 2030, even if the Fit for 55 challenge has previously been a success. Reflecting the rapid decline in the stock of brown capital, emissions fall and remain low throughout the 2040s.

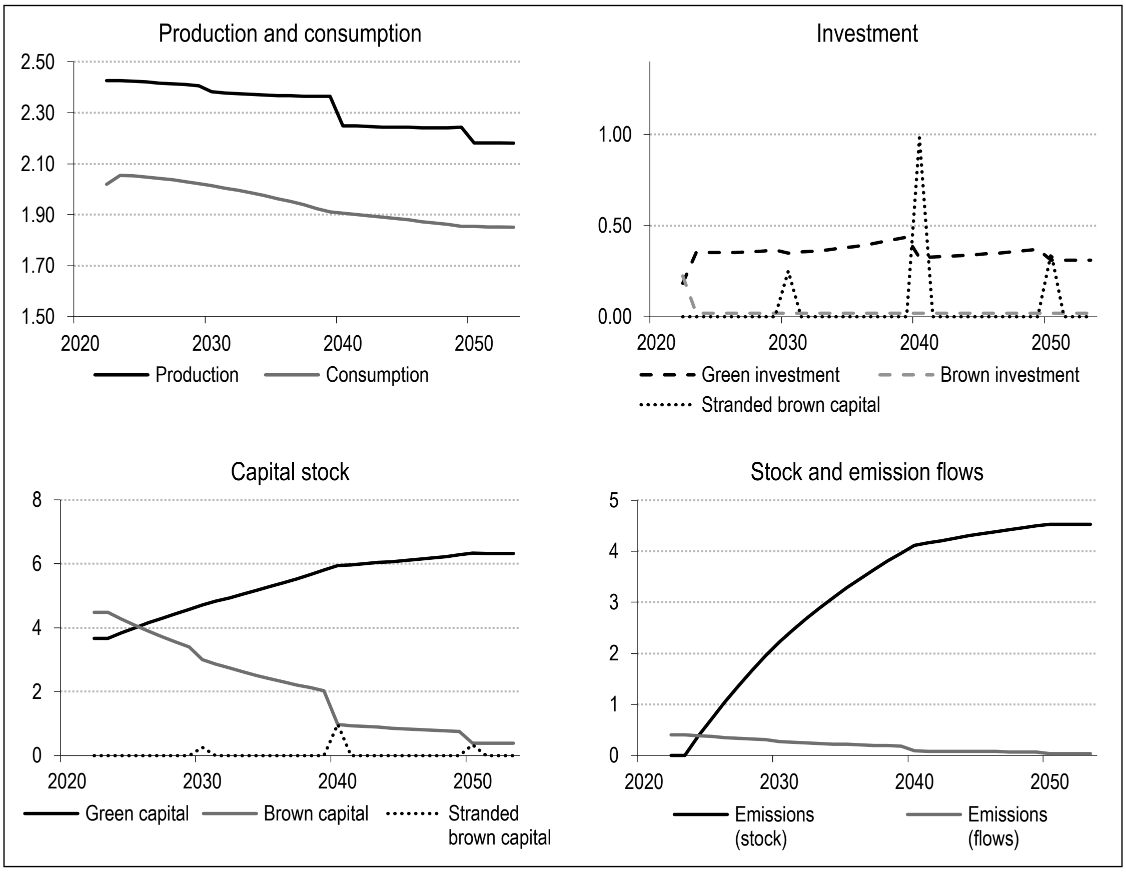
12. *In simulations not discussed here, we applied the Fit for 55 constraint in 2030 only and not in the following years, which would reflect a literal interpretation of this commitment: in 2030, green investment ceases while brown investment increases sharply; from 2032, brown investment falls once again to the level at which the residual brown capital is stabilised. The brown capital increases in 2031, then stagnates when the* Fit for 55 *constraint is also applied in the subsequent years. Although the increase in brown capital after 2030 is moderate when compared with that shown in Figure II, it is accompanied by additional emissions that amount to a cumulative total of 0.15 GtCO$_2$eq by 2050.*

Figure II – **Fit for 55 scenario**



Notes: cf. Figure I.

Figure III – **Fit for 55 and target of −90% in 2040**



Notes: cf. Figure I.

2.2.4. Carbon Budget at 1.6°C + NZE from 2050

The simulation presents the optimal decarbonisation trajectory for meeting the national carbon budget for 1.6°C (i.e. 3.93 $GtCO_2eq$) while also meeting the NZE in 2050 objective. In this regard, there are therefore two constraints: one on emission flows (NZE from 2050) and the other on stock (the cumulative emissions should remain below the budget).

Revealing the constraint in 2023 triggers an immediate transition. From that date on, the green investment takes off, while the brown investment (not including the renewal of the residual brown capital) disappears for good (Figure IV).

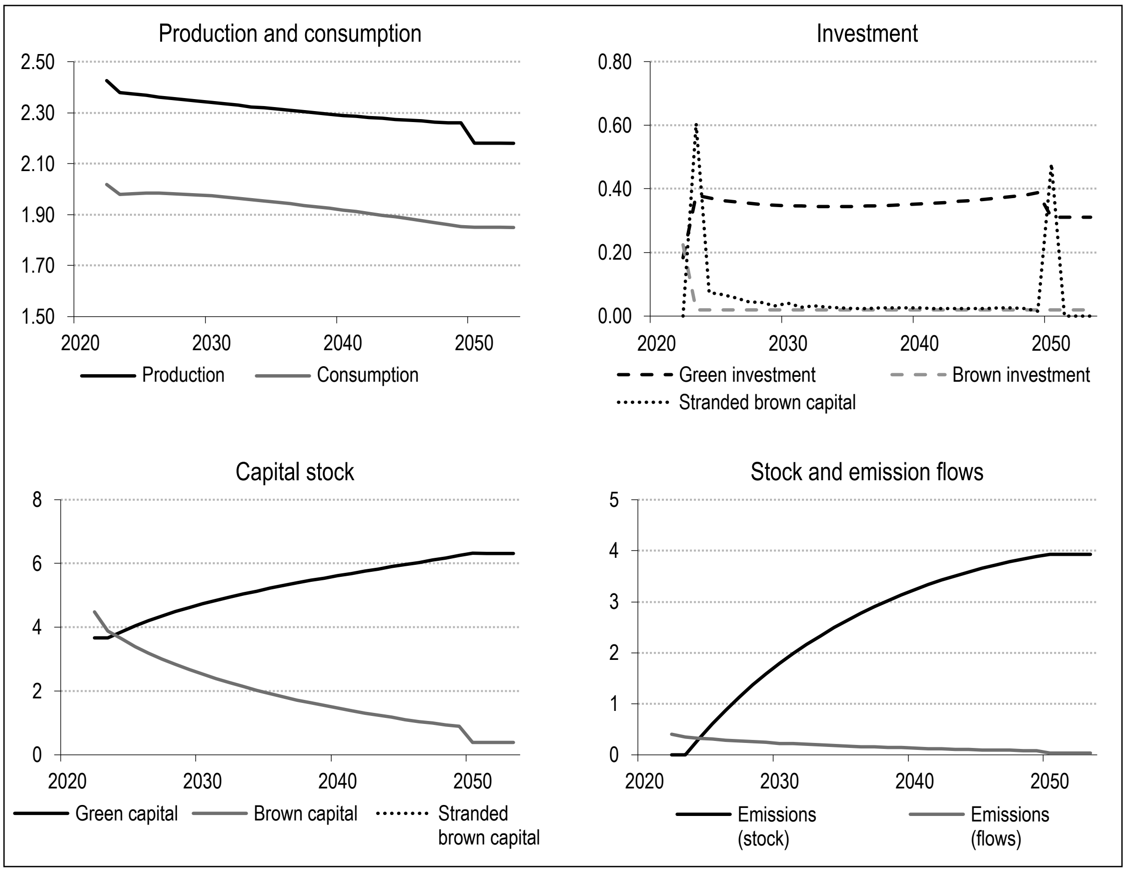
Furthermore, this disappearance of brown investment is not sufficient to adequately reduce GHG emissions. Regular stranding of capital takes place, but primarily at two points: first, on a massive scale during the first year (14% of the initial brown capital) and then again in 2050 (11% of the initial brown capital) to achieve neutrality.

The results obtained with this scenario are sensitive to the carbon budget target E_{max} used (Figure V). The lower the carbon budget, the higher the stranding and green investment. As long as the carbon budget remains below 5.5 $GtCO_2eq$, the (non-residual) brown investment remains constant at zero. With slightly higher carbon budgets, the (non-residual) brown investment becomes positive during the first few years, but remains moderate. When the carbon budget exceeds the cumulative emissions of the NZE scenario (6.3 $GtCO_2eq$), this budget is no longer binding and only the NZE constraint applies, meaning that the trajectories are therefore those of the NZE scenario.

2.2.5. Lessons From Different Climate Mitigation Policies

Anticipatory stranding cannot occur with one-off emissions targets (NZE, Fit for 55, −90% in 2040). The brown investment may decrease or stop before the constraint on emissions comes into effect, but stranding assets ahead of the constraint is never the optimal approach. Intuitively, if we assume that there is anticipatory stranding in the optimal trajectory

Figure IV – **Carbon budget scenario (3.93 GtCO$_2$eq)**

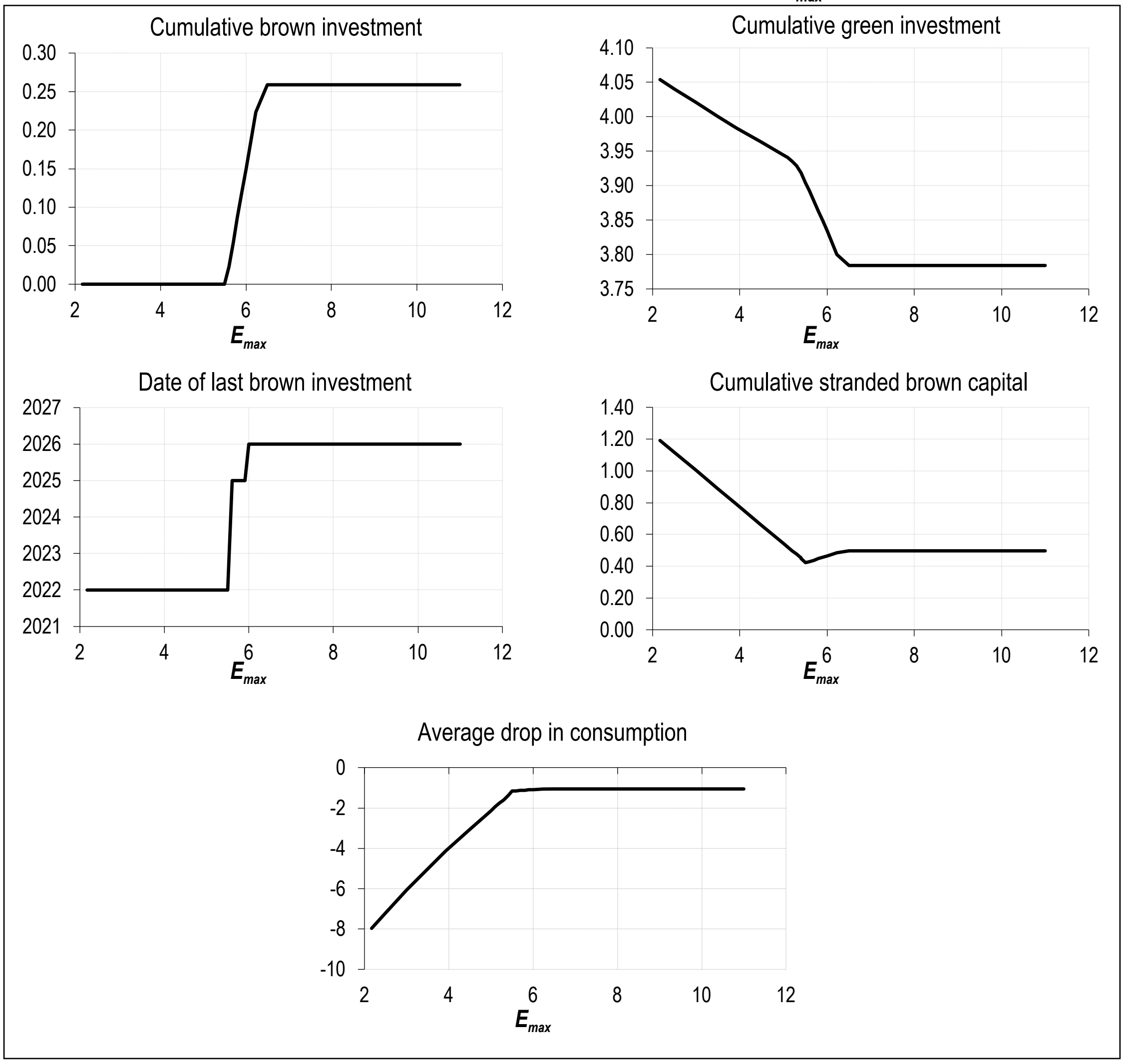


Notes: cf. Figure I.

associated with a one-off emissions target, then if we retain the same green and brown investment trajectories and don't strand in advance but only in the year when the constraint becomes binding, to meet that target, then this new trajectory complies with the emissions constraint and offers a strictly higher discounted consumption. Indeed, in this case, consumption is significantly higher between the date of early stranding and the date on which the constraint comes into effect, since the brown capital and therefore the production are significantly higher in this case, with identical investments. In fact, in the NZE scenario, stranding is not observed until 2050; in the Fit for 55 and NZE scenario, stranding only takes place in 2030 and 2050; and when the 2040 constraint is added, stranding of brown capital occurs in 2030, 2040 and 2050. Conversely, compliance with a constraint on cumulative emissions is accompanied by stranding each year, on an especially large scale during the first year. The economic intuition underlying this finding is important for economic policy: with one-off targets, there is no economic pressure to strand assets ahead of time, which does not allow for a sufficient spread of efforts over time and results in significant stranding in a specific year, which is difficult to implement in practice as the generation concerned may seek to delay some of the fall in production to a future date, thereby also postponing compliance with the climate constraint.

The NZE scenario is compatible with global warming of 1.8°C, the Fit for 55 scenario with 1.75°C, and the Fit for 55 + 90 scenario with 1.65°C (see Online Appendix S3). By design, the carbon budget complies with cumulative emissions consistent with a given level of warming. These findings are based on at least two key assumptions, in addition to the modelling and calibration: *i)* the cumulative emissions also remain below the budget corresponding to that level of warming in other countries. Indeed, action in France only provides information about France's contribution to global efforts to limit global warming. The equivalences between cumulative GHG emissions in France and global warming are primarily provided by way of illustration, *ii)* the decisions made are optimal within the framework of the model, but there is an infinite number of other trajectories that could

Figure V – **Sensitivity analysis: carbon budget (E_{max})**



Notes: The average drop in consumption represents the average difference, as a %, in consumption when compared with its initial value over the period from 2023 to 2050. Cumulative brown and green investment and stranding are in trillion euro.

also satisfy the constraints; for example, the scenario in which there are no carbon constraints until 2049 followed by a mass stranding that enables the brown capital to be reduced to the level of the residual capital would meet the NZE constraint; in this case, the cumulative emissions would be significantly higher than the 6.3 $GtCO_2eq$ produced by the optimal trajectory for compliance with the NZE constraint. However, that trajectory would not be optimal, as the consumer would prefer to smooth out the sharp drop in consumption that would then take place in 2050 by consuming less before this date in order to increase the stock of green capital.

When it is long-lasting, **the decarbonisation of the economy produces a greater effect on the climate the longer it is in place**, as the amount of avoided cumulative emissions is higher. Therefore, the carbon budget corresponding to global warming of 1.6°C (3.93 $GtCO_2eq$) is exhausted in 2036 with the NZE objective, in 2038 with the Fit for 55 target and in 2039 with the additional target of −90% in 2040 – if no action is taken, it will be exhausted in 2033. Although the dates of exceeding this carbon budget are close for these different scenarios, the stronger constraints have nevertheless placed the economy on a trajectory of lower GHG emissions, which manifests as lower global warming in 2050. The cumulative emissions between 2023 and 2050 are 39% lower in the NZE scenario than with no constraints, and the difference can only increase from there, since the NZE trajectory no longer emits any GHGs from 2050 onwards, unlike the initial situation. Cumulative emissions fall by a further 12% with the Fit for 55 target, and by a further 19% with the 2040 target. Lastly, compliance with a carbon budget reduces these cumulative emissions by 13%

when compared with the Fit for 55 + 90 + NZE scenario (the differences in the cumulative emissions between the two scenarios are represented by the space between the emissions flow curves, Figure VI, or can be measured directly as the distance between the curves showing cumulative emissions, Figure VII).

From an economic standpoint, **these various climate policies have different impacts on welfare** (Table 3). The NZE, Fit for 55 and –90% in 2040 scenarios involve a smaller loss of utility and discounted cumulative consumption than in the carbon budget scenario aiming to limit global warming to 1.6°C. This is only a partial view of the situation since the impacts of the damage caused by global warming are not modelled: the analysis focuses purely on the effects of the transition policies. The overall impact of the Carbon Budget at 1.6°C scenario on utility, which is the most effective means of limiting global warming to this level, is likely considered to be positive by the signatories of the Paris Agreement in 2015, which aimed to limit global warming to below 2°C, and if possible to below 1.5°C.

Figure VI – **Emission flows for the Carbon budget, NZE, Fit for 55 and Fit for 90 scenarios**

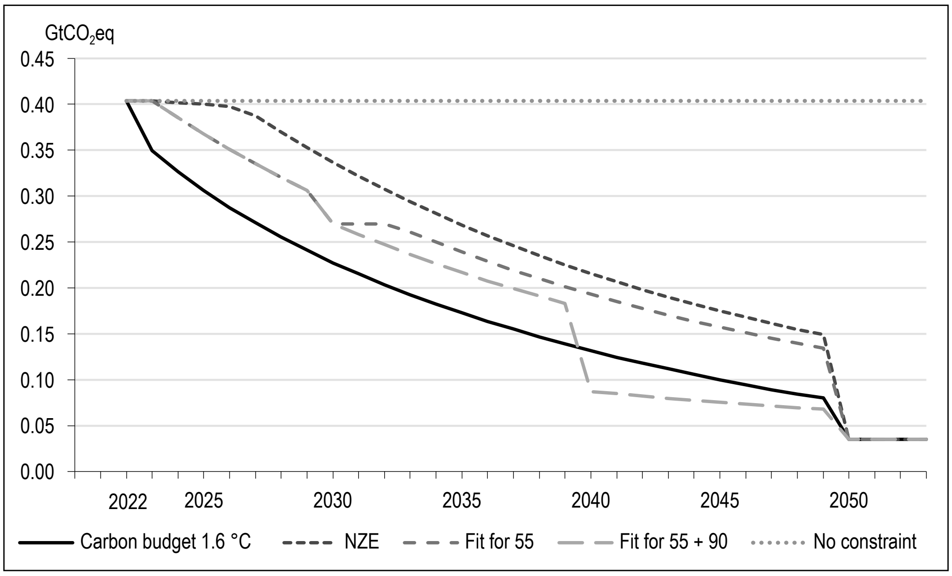
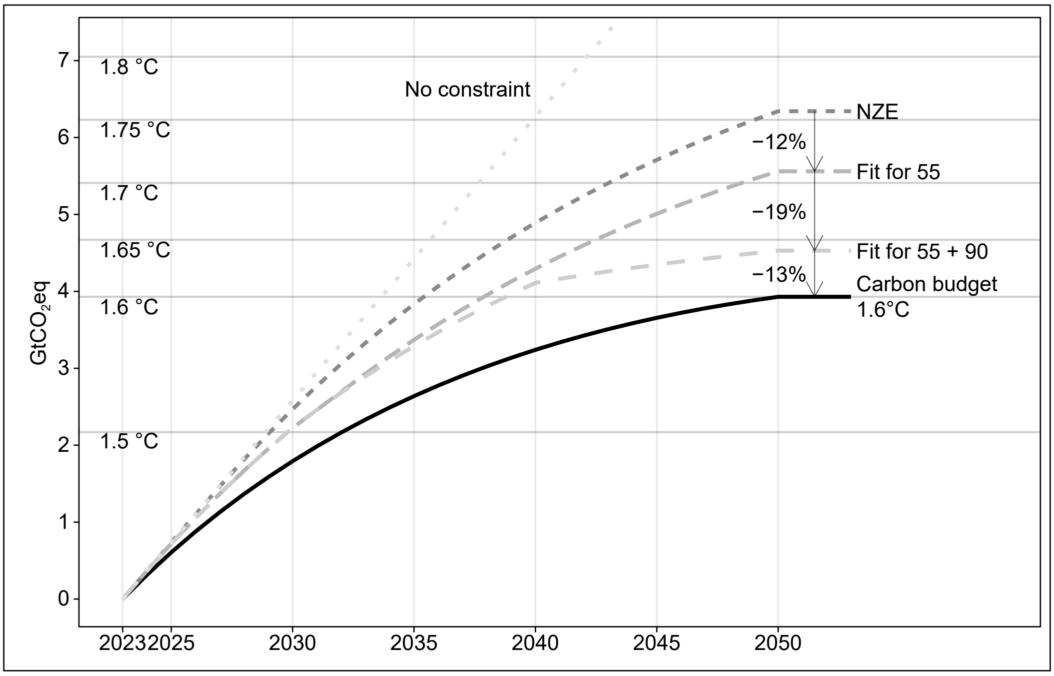


Figure VII – **Cumulative emissions for the carbon budget, NZE, Fit for 55 and Fit for 90 scenarios**



To first order, the more ambitious the climate goal, the more economic harm is suffered (and the greater the gains from causing less damage). Therefore, compliance with a carbon budget at 1.6°C triggers the stranding of brown capital much earlier and on a much larger scale than is the case with one-off targets or compliance with a less restrictive carbon budget, which reduces production and consumption.

However, to second order, different policies aimed at achieving a given climate target have a greater or lesser impact on welfare. If we look at it from another angle, at a given loss of welfare, the trajectory of investments and stranding can be optimised in such a way as to reduce the emissions generated by production and therefore the damage to the climate. Therefore, the NZE scenario and compliance with a carbon budget at 1.75°C generate the same level of welfare and cumulative consumption across the period as a whole, but cumulative emissions up until 2050 are slightly higher with the NZE scenario than with the carbon budget scenario (6.3 vs 6.2 $GtCO_2eq$). By design, the carbon budget scenario maximises welfare under the constraint of complying with the carbon budget, which ensures that, at a given level of cumulative GHGs, this scenario offers a smaller loss of utility than with one-off emissions constraints. In particular, early stranding may take place in a carbon budget scenario, which is not the case for these one-off constraints.

The one-off target scenarios delay the transition when compared with the budget scenario, resulting in a greater accumulation of brown investments, which are both higher and longer-lasting. As regards stranding, as more brown capital is accumulated, there are also more assets to be scrapped at the end of the period, as it is not just the initial capital that is affected by stranding in these scenarios, but also the capital that has been accumulated along the trajectory.

In all of the transition scenarios, the overall investment is lower, on average, than was initially observed. Indeed, as the production function is a concave function of capital, and as the capital stock determined by its marginal productivity must equal $\rho + \delta$ (Section 1.4), the green and residual brown capital stock in the final, post-transition state is below the initial brown and green capital stock. When compared with the initial situation, the total amount of

Table 3 – **Emissions and economic figures according to the various carbon emission constraints**

	Without carbon constraints	Carbon budget 1.6°C and NZE	Carbon budget 1.75°C and NZE	NZE	Fit for 55	Fit for 55 + 90
Cumulative emissions in 2050 ($GtCO_2eq$)	10.33	3.93	6.23	6.34	5.56	4.53
Difference in intertemporal utility when compared with the scenario without constraints (%)	-	−6.94	−4.54	−4.53	−4.95	−6.09
Brown capital	4,482	1,254	1,722	1,745	1,582	1,408
Green capital	3,667	5,679	5,493	5,477	5,575	5,712
Brown investment	224	19	32	34	25	19
Green investment	183	334	320	319	326	337
Total investment	407	354	353	353	352	356
Stranding of brown capital	0	36	15	15	18	25
Consumption						
Level	2,018	1,893	1,925	1,925	1,920	1,904
Difference when compared with the scenario without constraints	-	−126	−93	−93	−99	−114
Difference when compared with the scenario without constraints as a %	-	−6.22	−4.60	−4.60	−4.89	−5.64
GDP						
Level	2,406	2,227	2,258	2,259	2,252	2,241
Difference when compared with the scenario without constraints	-	−179	−148	−147	−154	−165
Difference when compared with the scenario without constraints as a %	-	−7.45	−6.14	−6.11	−6.41	−6.86

Notes: The figures shown (with the exception of the percentages and the first row) are discounted annual averages. The difference in utility is the difference (as a %) in the discounted intertemporal utility when compared with the scenario without carbon constraints. Units in billion euros, unless specified otherwise.

investment is therefore lower in the final equilibrium, and it also appears to be lower on average during the transition in all scenarios studied. The overall investment may occasionally be higher than in the initial state (which is the case in the NZE and Fit for 55 scenarios, for example as 2050 draws nearer).

2.3. Emissions Targets Every Ten, Five or Two Years + NZE From 2050

Rather than complying with a carbon budget, the various different countries around the world have, in practice, opted for emissions targets with a specific date on which they are to achieve carbon neutrality, with some also setting interim targets such as Fit for 55. However, as our simulations have shown (Section 2.2), targets that are set too far in the future result in a transition that comes too late and to jolts in efforts, with relaxation as soon as a target is achieved, which is not efficient. An obvious solution is then to introduce another interim target, in the case of Europe between 2030 and 2050: even before it becomes binding and strongly reduces emissions in 2040, the 2040 target lowers the emissions trajectory during the 2030s by preventing brown investment from recommencing in early 2030 (Figure VIII).

The introduction of interim emissions targets can therefore make it possible to bring the trajectories more into line with the optimal trajectories for achieving a given climate objective. Indeed, if emissions caps are introduced each year from 2023 to 2049 that correspond to the emissions of the 1.6°C carbon budget scenario, the solution obtained coincides with the optimal trajectory for this carbon budget (Table 4). To determine how important it is to bring the one-off targets closer together, we develop a number of scenarios that meet one-off emissions targets, spaced at regular intervals of ten, five or two years and selected based on the emissions from the optimal scenario for complying with the given carbon budget.

Figure VIII – **Regular emissions targets, carbon budget 1.6°C**

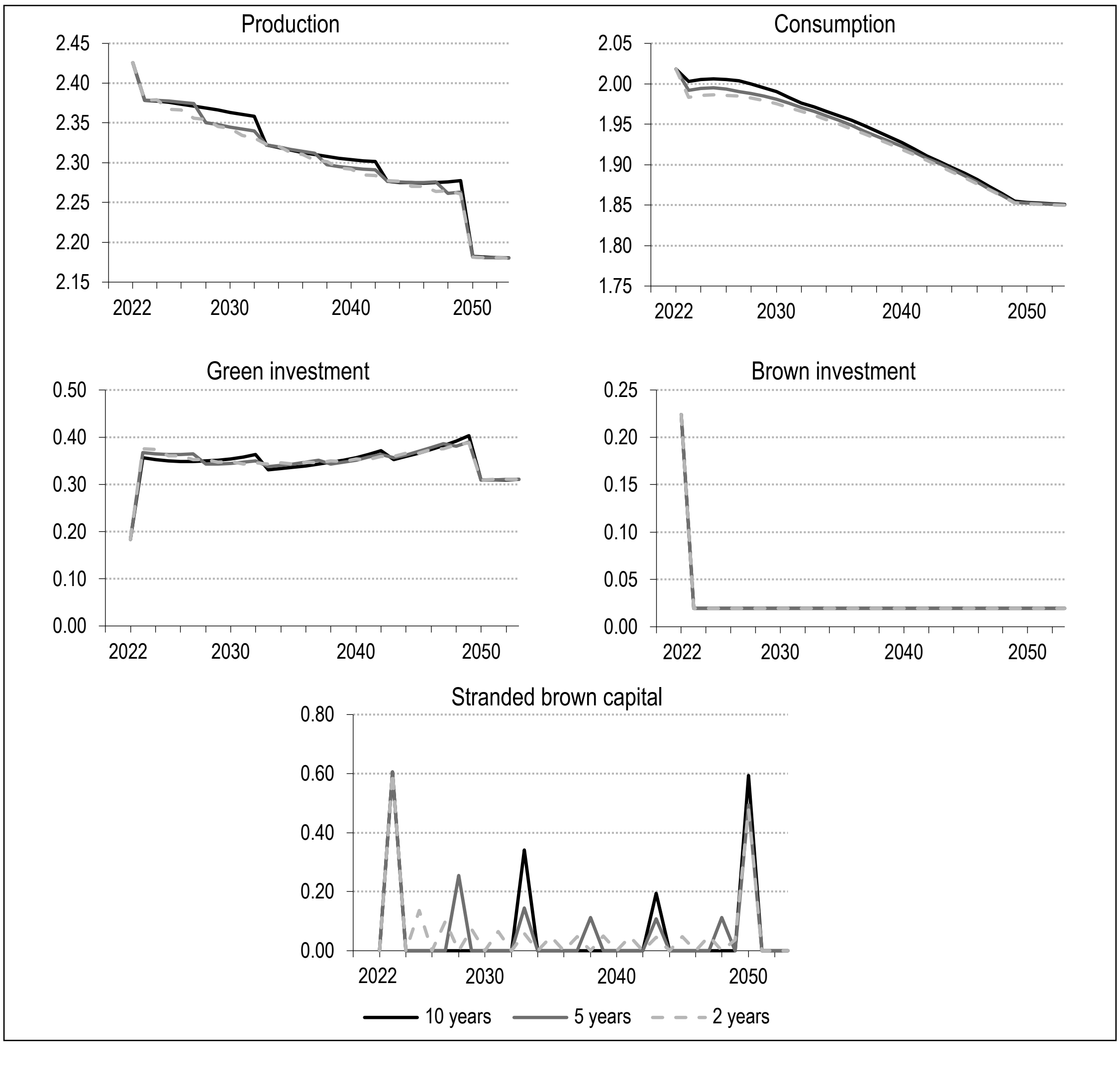


Table 4 – **More closely spaced one-off emissions targets bring the economy closer to the optimal trajectory for complying with the carbon budget at 1.6°C**

	Targets			
	Annual	Every two years	Every five years	Every ten years
Cumulative emissions in 2050 ($GtCO_2eq$)	3.93	3.97	4.08	4.25
Difference in intertemporal utility when compared with the scenario without constraints (%)	−6.94	−6.88	−6.70	−6.44
Brown capital	1,254	1,263	1,286	1,321
Green capital	5,679	5,678	5,673	5,663
Brown investment	19	19	19	19
Green investment	334	334	334	333
Total investment	354	354	353	352
Stranding of brown capital	36	36	34	32
Consumption				
Level	1,893	1,894	1,896	1,899
Difference when compared with the scenario without constraints	−126	−125	−122	−119
Difference when compared with the scenario without constraints as a %	−6.22	−6.18	−6.07	−5.89
GDP				
Level	2,227	2,228	2,230	2,232
Difference when compared with the scenario without constraints	−179	−179	−177	−174
Difference when compared with the scenario without constraints as a %	−7.45	−7.42	−7.34	−7.22

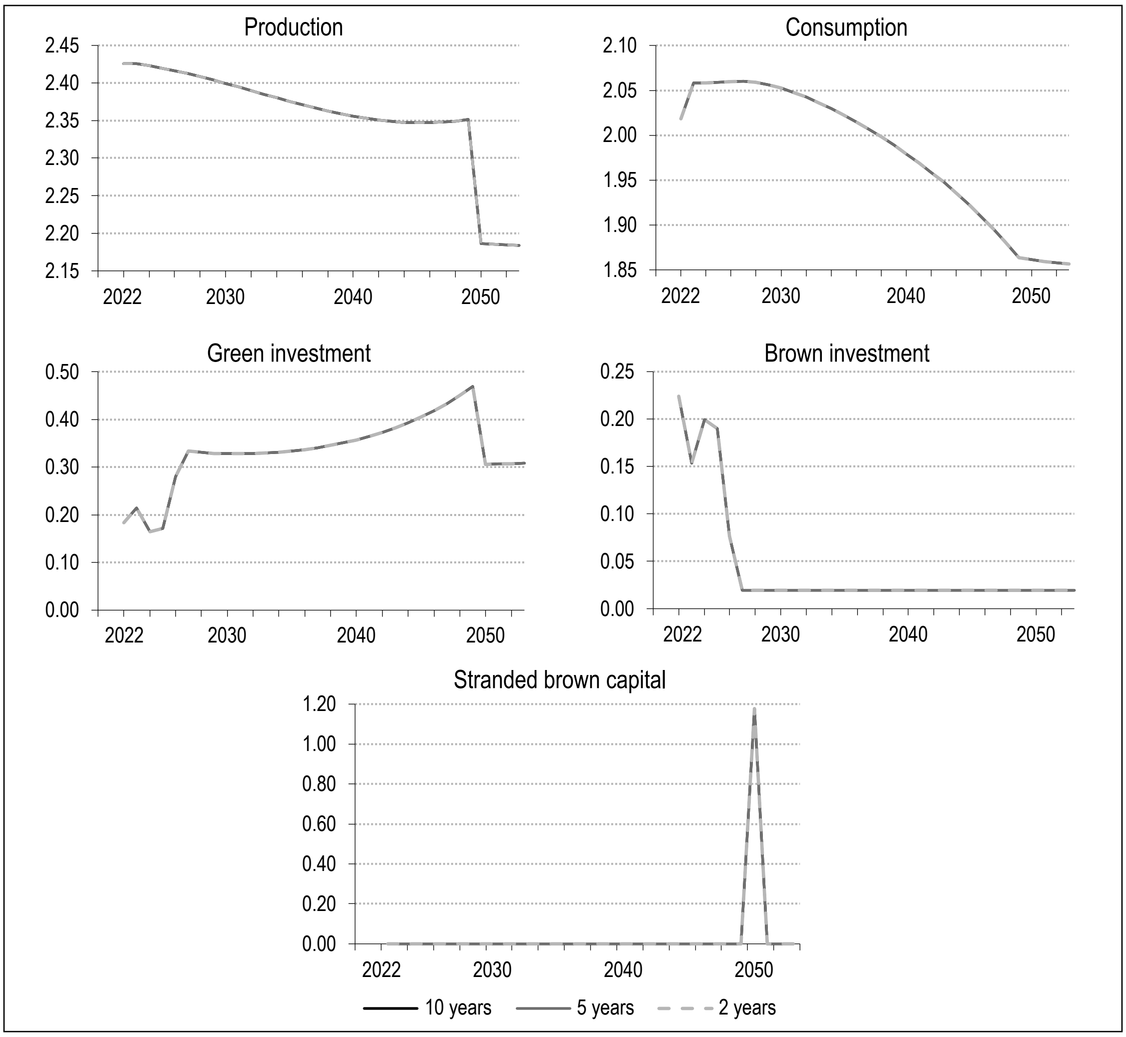
Notes: The emissions targets are also set the same as the emissions for the optimal trajectory for complying with a carbon budget of 3.93 $GtCO_2eq$, consistent with limiting global warming to 1.6°C. Annual targets result in the same solution as compliance with the carbon budget (Carbon budget 1.6°C and NZE column in Table 3). The figures presented (with the exception of the percentages) are discounted annual averages. The difference in utility is the difference (as a %) in the discounted intertemporal utility when compared with the scenario without carbon constraints. Units in billion euros, unless specified otherwise.

Frequent interim targets appear to be important for meeting ambitious targets, but not for targets that are not as ambitious. In scenarios complying with a high carbon budget, greater than 5.5 $GtCO_2eq$, there is no anticipatory stranding (from 2023 to 2049); the solutions for the scenarios with milestones every ten, five or two years, selected in accordance with the emissions from the corresponding carbon budget scenario, coincide with that of the carbon budget scenario (Figure IX with a carbon budget at 1.75°C of 6.23 $GtCO_2eq$). Therefore, the fundamental problem with the one-off target instrument, in that it cannot trigger stranding until the constraint comes into effect, is no longer an issue when the carbon budget is high and there is no anticipatory stranding in the trajectory of the carbon budget scenario. Conversely, in scenarios with a lower carbon budget, early stranding of capital takes place.[13] The solutions corresponding to the interim milestones set at ten, five or two years then deviate from the optimal carbon budget, especially when *i)* the carbon budget is small and early stranding is high, and *ii)* these milestones are spaced further apart from one another. Therefore, if we start with a carbon budget of 1.6°C, the cumulative emissions for 2023–2050 will reach 4.25 $GtCO_2eq$ with ten-yearly targets, almost 10% higher than the 3.93 $GtCO_2eq$ of the associated carbon budget. These cumulative emissions reach 4.08 $GtCO_2eq$ with targets every five years and barely exceed the carbon budget with targets every two years. These differences in the pathways do not come from brown and green investments, which are very similar in the various simulations, but from the stranding of brown capital, which does not take place until the emissions cap comes into effect: stranding is lower when targets are more spread out, which results in a higher average amount of productive capital throughout the period, and therefore higher production, consumption and utility.

Ultimately, it seems that, in order to achieve a given maximum global warming target, the explicit introduction of this constraint, in the form of a remaining carbon budget, will make it possible to reduce the associated economic cost to a minimum. A trajectory similar to that of an optimal trajectory associated with compliance with a carbon budget may be achieved with emissions caps that are spaced at

13. This anticipatory stranding begins in 2034 and remains present until 2050 with a budget of 5.4 $GtCO_2eq$.

Figure IX – **Regular emissions targets, carbon budget 1.75°C**



regular intervals and that are applied from the first year and selected based on the emissions from that optimal trajectory. When faced with an ambitious climate goal, bringing these interim milestones closer to one another in terms of time reduces the drift that can occur between those milestones.

2.4. A Delayed Transition Reduces Welfare

We have seen that the carbon budget + NZE scenario is the optimal policy for ensuring compliance with the carbon budget and the achievement of the NZE objective. However, this raises the question as to when it should be implemented. Indeed, according to NGFS (2022) a delayed transition is more costly. It would be possible to follow the lead of NGFS (2022) and study the consequences of complying with a carbon budget at a future date, following a certain period of inaction. This would result, to a greater or lesser extent, in the offsetting of the timing of a carbon budget that respects cumulative emissions minus the GHGs emitted during this period of inaction (Figure V). Rather than assuming zero effort until the decision is taken to comply with a carbon budget, we assume that the economy follows the NZE trajectory from 2023 and then, at a given date and until 2050, switches to a pathway compatible with compliance with a carbon budget at 1.6°C for the rest. We have selected three switchover dates: 2023, 2028, and 2033.[14] Since the cumulative emissions and therefore the damage remain the same in these different scenarios, welfare is directly comparable.

This shows that with a given level of cumulative emissions, the later the transition takes place, the more costly it is, and the less credible it is. Indeed, the later the start of the trajectory complying with a given carbon budget

14. As the NZE scenario exhausts the carbon budget corresponding to 1.6°C in 2036, it is not possible to study a subsequent switchover unless we introduce negative net emissions, which is beyond the scope of our model.

for 2023–2050, the greater the proportion of the budget that is already consumed at the time of the switchover, and the more sharply the brown capital stock needs to be reduced to emit very small amounts of GHGs during the remaining period until 2050 (Figure X). In the year in which the policy change takes place, stranding is twice as high if the change takes place in 2028

Figure X – **Carbon budget 1.6°C with different transition start dates**

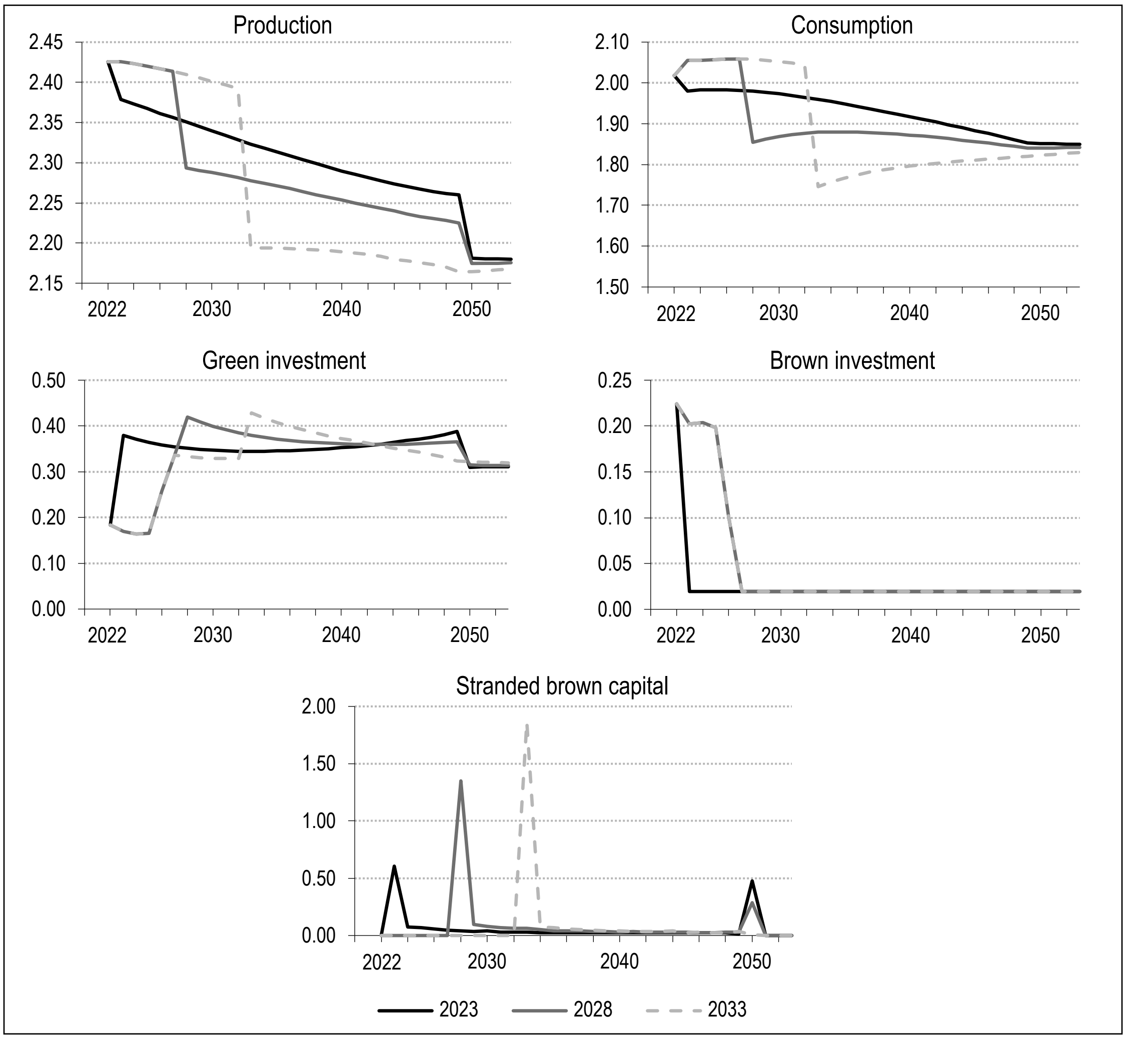


Figure XI – **Emission flows for the carbon budget 1.6°C with different transition start dates**

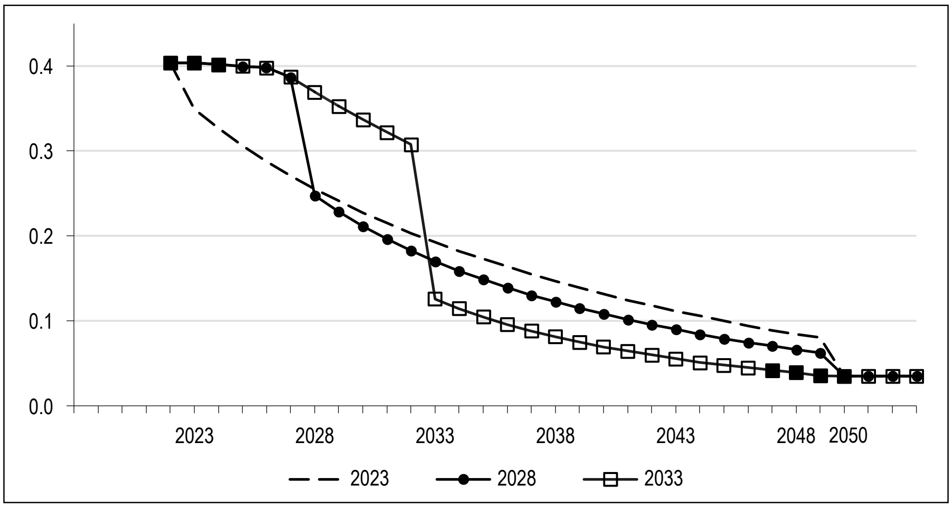
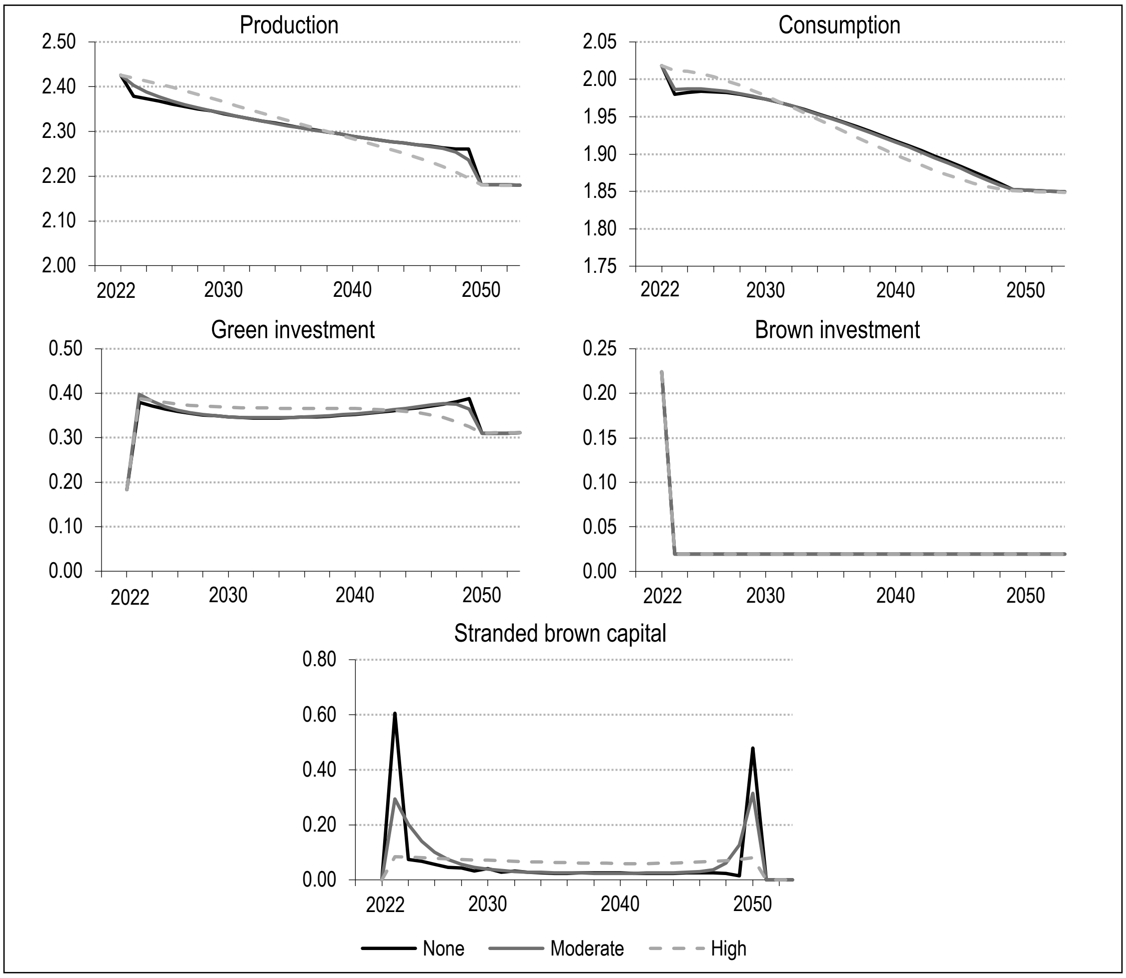


Table 5 – **A delayed transition results in increased stranding and penalises welfare**

	Carbon budget		
	2023	2028	2033
Cumulative emissions in 2050 ($GtCO_2eq$)	3.93	3.93	3.93
Difference in intertemporal utility when compared with the scenario without constraints (%)	−6.94	−8.18	−8.53
Brown capital	1,254	1,286	1,317
Green capital	5,679	5,556	5,501
Brown investment	19	34	34
Green investment	334	325	321
Total investment	354	359	355
Stranding of brown capital	36	49	46
Consumption			
Level	1,893	1,877	1,874
Difference when compared with the scenario without constraints	−126	−141	−144
Difference when compared with the scenario without constraints as a %	−6.22	−7.00	−7.15
GDP			
Level	2,227	2,217	2,210
Difference when compared with the scenario without constraints	−179	−189	−197
Difference when compared with the scenario without constraints as a %	−7.45	−7.87	−8.17

Notes: See Table 3.

Figure XII – **Different costs of stranding capital**



Notes: In 2023, the costs of stranding account for 0.1% of initial utility when they are moderate and 1.0% when they are high.

rather than in 2023, and three times higher if the change takes place in 2033 (at a level close to 2 trillion euro). If the change takes place in 2033, the carbon budget is already almost exhausted (with the NZE scenario, it is exhausted in 2036), and emissions fall by around 60% between 2032 and 2033 (Figure XI). Similarly, a delayed transition penalises consumption and welfare more: they fall by 0.9 and 1.6 points more, respectively, when the switchover takes place in 2033 rather than in 2023 when compared with a scenario without carbon constraints (Table 5). In addition, delaying the transition does not, in any way, make it any more credible: quite the opposite in fact, since any delay increases the drop in consumption that will take place when the emissions policy is finally adjusted to the target.

2.5. Adjustment Costs and Temporal Smoothing of the Stranding

The optimal trajectories complying with the various climate constraints often give rise to very significant strandings in a particular year: the year in which a one-off emissions constraint (such as NZE or Fit for 55) comes into effect or the year in which a policy complying with a given carbon budget is introduced. Such strandings, which could amount to as much as 600 billion euro during the first year in order to comply with the carbon budget at 1.6°C, or even double this if the policy is introduced five years later, seem unrealistic (Figure X). It is likely that, in order to reduce the resulting intergenerational conflicts, the effort will be smoothed over time. We therefore introduce a cost of stranding capital into the utility function, which is increasing and convex (with a quadratic form here) in relation to the quantity of stranded capital: the stranding of each additional unit of brown capital is therefore more costly than the previous unit.

The introduction of these costs results in the smoothing of the stranding, which is spread to a greater or lesser extent over time depending on the scale of the costs. In the case of a scenario with a carbon budget set at 1.6°C, with moderate stranding costs, stranding is halved in 2023 and reduced by one third in 2050 and is spread out over the years just after 2023 and before 2050 (Figure XII). Where stranding costs are high, stranding is cut to between one sixth and one seventh in 2023 and 2050 and is broadly spread over the entire period with a very gradual decline until 2050. Due to the limited reduction of brown capital at the start of the period, emissions fall more slowly than with moderate or zero costs, which means that the economy must be closer to neutrality at the end of the period in order to compensate for the increase in emissions at the beginning of the period. These capital stranding costs are realistic: in 2023, they represent 0.1% of initial utility when they are moderate and 1.0% when they are high. They make it possible to highlight more credible brown capital stranding trajectories, in terms of both their amounts and their temporal profile.

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We create an optimal investment choice model for brown capital, the use of which emits greenhouse gases (GHGs), or for green capital, which does not produce emissions, under climate constraints that may take the form of one-off GHG emissions caps (NZE or Fit for 55) or compliance with a carbon budget. We describe the optimal transitions between an initial state and carbon neutrality in a way that complies with these different types of constraints. The analysis of welfare is necessarily partial, as the damage, which differs depending on the scenario, has not been modelled. That being said, it is possible to draw more definitive conclusions by comparing the simulations that result in the same cumulative GHG emissions figures.

With optimal trajectories and using the aforementioned equivalences between emissions and global warming, the NZE scenario is compatible with global warming of 1.8°C, the Fit for 55 scenario with 1.75°C and the Fit for 55 + 90 scenario with 1.65°C. We also show that anticipatory stranding cannot take place with one-off emissions targets. In order to limit global warming to a given level, the explicit introduction of this constraint in the form of a remaining carbon budget minimizes the associated economic cost: stranding is then high during the first year with limited budgets. It is possible to come close with emissions caps spaced at regular intervals, which apply from the first year, and by limiting emissions to the emissions from this optimal trajectory. Next, at a given level of cumulative emissions, a delayed transition is more costly, leads to more stranding and is less credible. In addition, stranding costs make it possible to distribute the stranding over time. Lastly, the overall investment during the transition and in the final state is systematically lower than in the initial state.

This latter result appears to contradict the findings of the majority of studies in this area: indeed I4CE (2022) and Pisani-Ferry & Mahfouz

(2023) describe additional investment needs for the transition, which are often significant, amounting to as much as 2% of GDP each year from now until 2030. There are two directions that can be explored to reconcile these findings with those of our modelling. First, it should be noted that the projections of increased investment cover, at least partially, an additional cost of investment (in other words, an increase in the cost of the investment for the same productive capacity rather than an increase in volume). With the transition, the same service costs more with green capital than with brown capital. Second, while it is clear that the accelerated replacement of brown equipment with clean equipment (such as the replacement of gas or oil-fired boilers that are still functional with heat pumps) involves an increase in the volume of net investment in such equipment when compared with a scenario in which no transition takes place, it must nevertheless take account of the possibility of general equilibrium effects that may reduce other investments. These general equilibrium mechanisms, which are included in our models by design, are not included in estimates established by means of a bottom-up method, including supply effects resulting from the additional cost component. However, since the climate constraint is essentially an additional constraint on the production frontier, the optimal solution is to have a total capital stock that is lower after the transition. As a result, our findings, which show a fall in total investment in terms of volume in the optimal transition pathway are not necessarily incompatible with the projections of additional investment in terms of value when it comes to those investment goods most directly affected by the transition, but further analysis would be useful in order to reconcile these two sets of findings, in particular by separating the price component from the volume component in the usual projections, and by examining the consequences of the increase in the cost of investment in a general equilibrium framework.

Our quantitative findings may be sensitive to the calibration of the parameters of the model, which tells us a number of things (see Online Appendix S4):

- A rapid depreciation of capital demands further investment in order to maintain production (brown and green investments increase in line with δ), reducing the need for brown capital to be stranded as it naturally depreciates quickly. It is therefore crucial to green long-life capital.
- The transition is facilitated by strong elasticity of substitution between brown and green capital.
- The recent decline in the carbon sink complicates the transition through two mechanisms: a smaller stock of brown capital is required in order to achieve net zero emissions and the cumulative net emissions between now and 2050 will increase.
- A higher discount rate places less value on future generations. In the carbon budget scenario, this initially leads to higher consumption followed by a decline at the end of the period, as well as on average from 2023 to 2050. In the NZE and Fit for 55 scenarios, brown investment and stranding increase.

Our results describe the optimal trajectories, as determined by an omniscient, omnipotent and benevolent social planner. They can be difficult to implement in practice. The identification of these main pitfalls and the strategies for overcoming them requires further investigation. ☐

Link to the Online Appendix:
www.insee.fr/en/statistiques/fichier/8305263/ES544_Abbas-et-al_OnlineAppendix.pdf

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