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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
$\frac{K_{t_0}^b}{K_{t_0}^b + K_{t_0}^v}$	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.

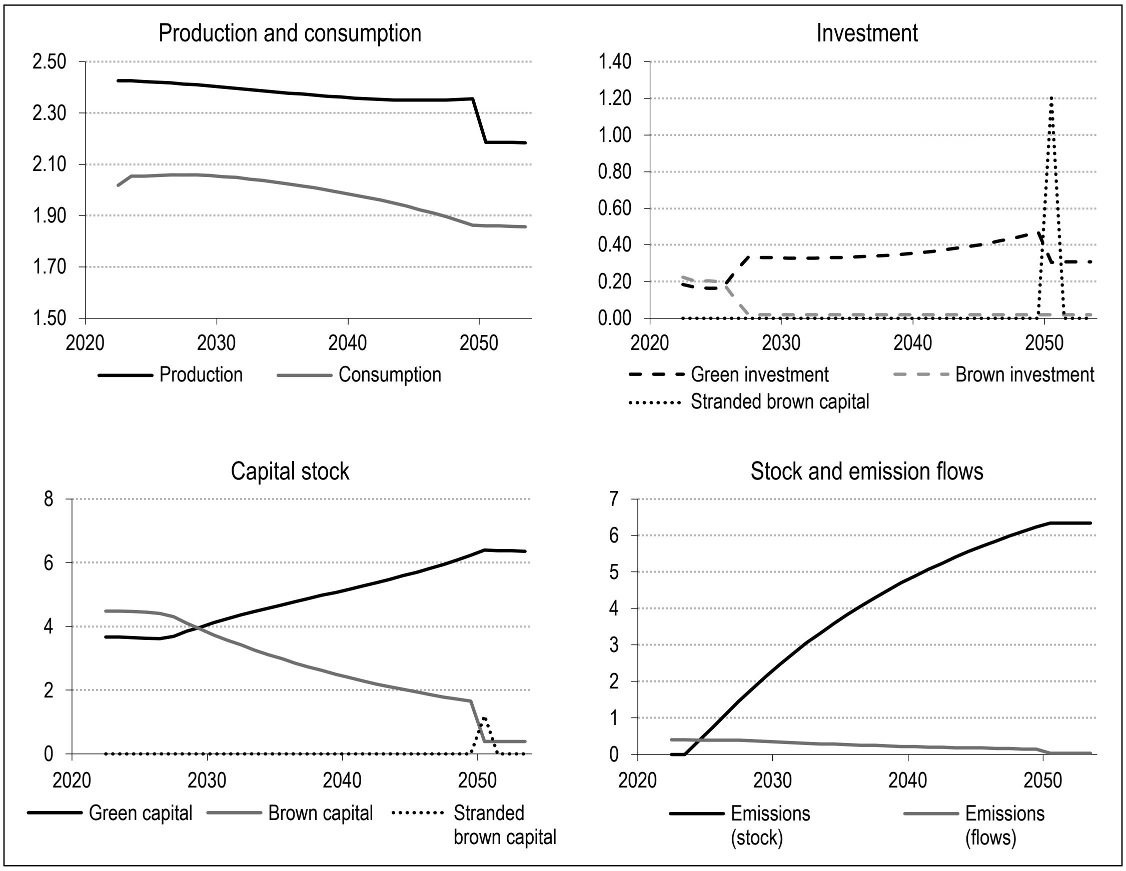
2.2. Annual Emissions Caps Versus Compliance with a Carbon Budget

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.

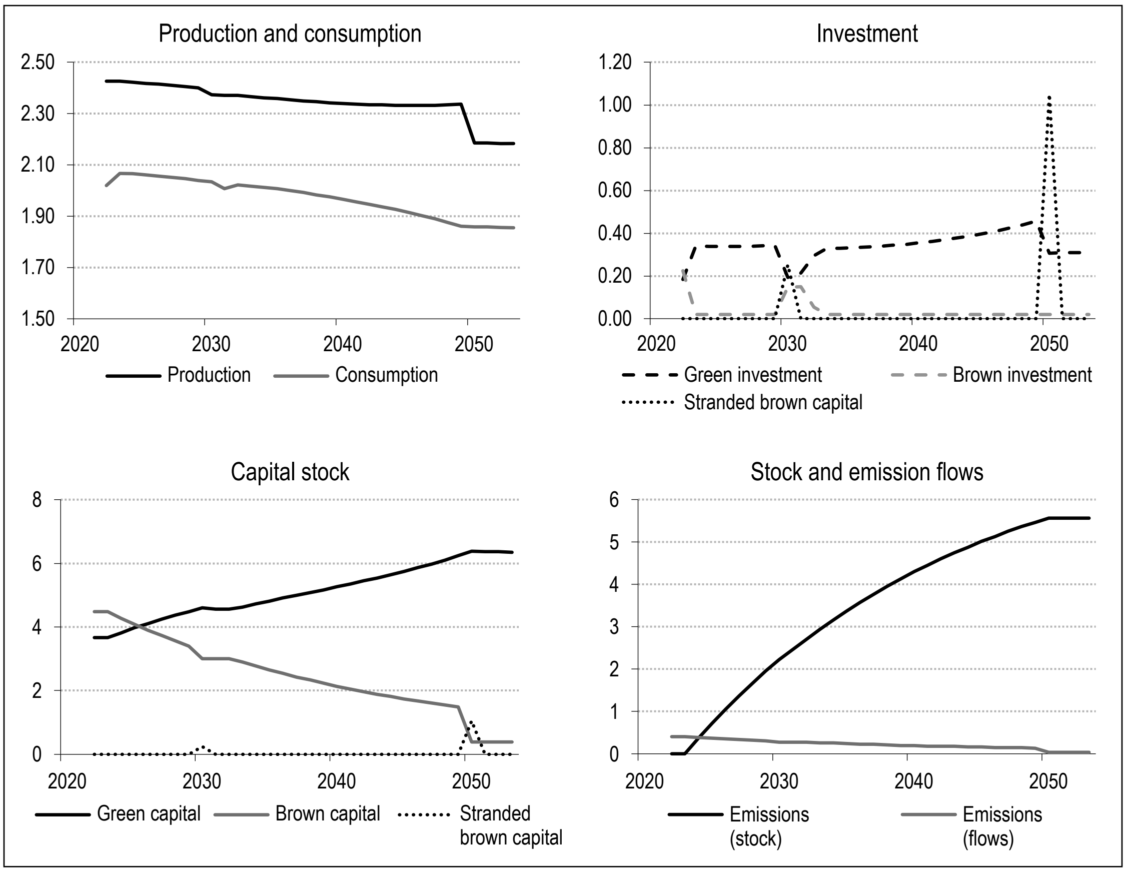
However, the fact that the emissions cap does not reduce any further after 2030 has a pernicious effect. Indeed, once the brown capital has depreciated sufficiently to meet the new constraint, it once again becomes profitable to invest in brown capital for a few more years after 2030. This results in 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.

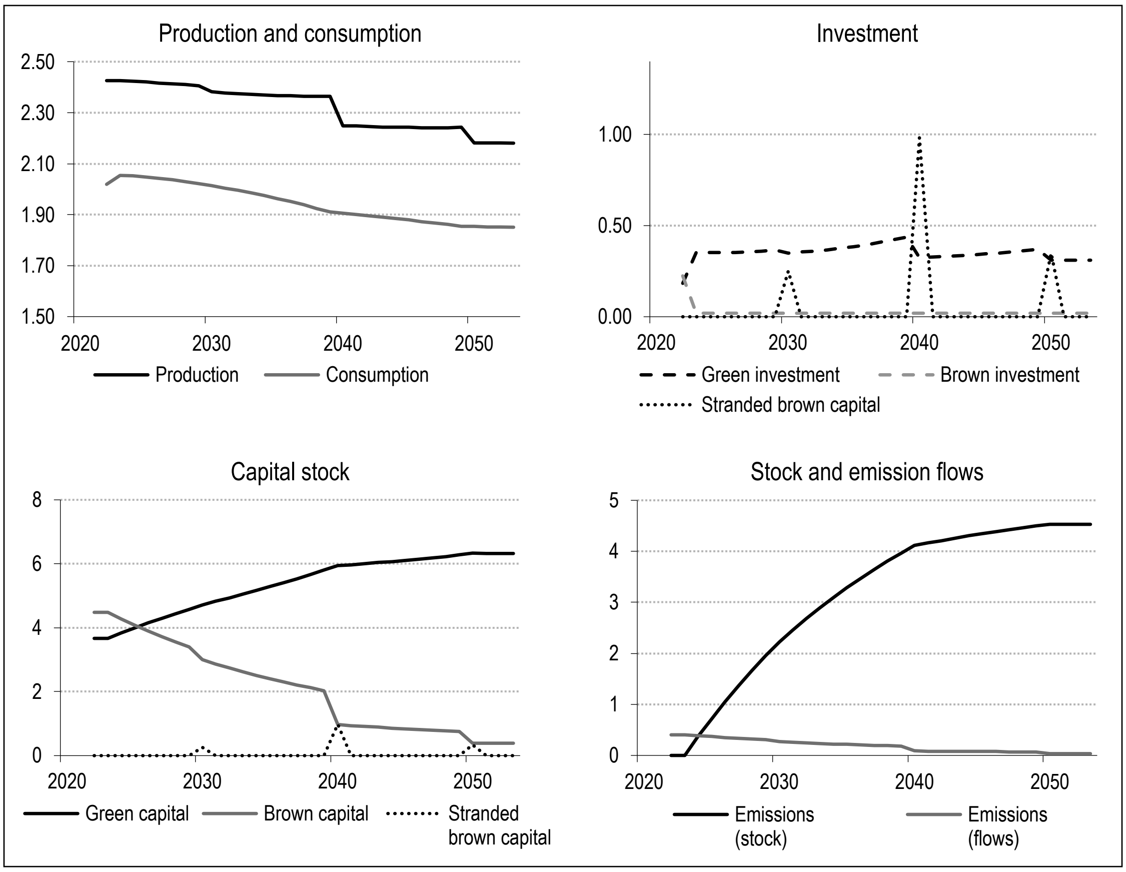
12. *In simulations not discussed here, we applied the Fit for 55 constraint in 2030 only and not in the following years, which would reflect a literal interpretation of this commitment: in 2030, green investment ceases while brown investment increases sharply; from 2032, brown investment falls once 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* $GtCO_2eq$ *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).

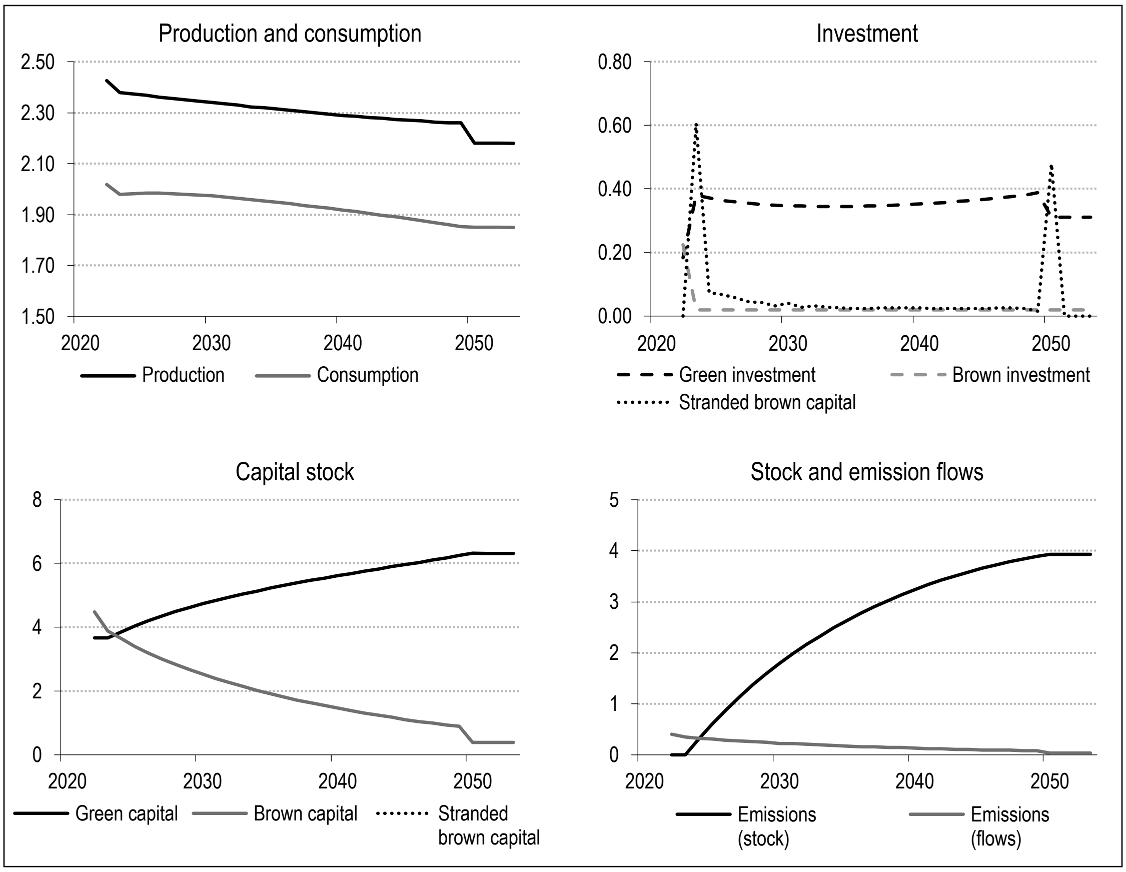
Furthermore, this disappearance of brown investment is not sufficient to adequately reduce GHG emissions. Regular stranding of capital takes place, but primarily at two points: first, on a massive scale during the first year (14% of the initial brown capital) and then again in 2050 (11% of the initial 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 $GtCO_2eq$)**

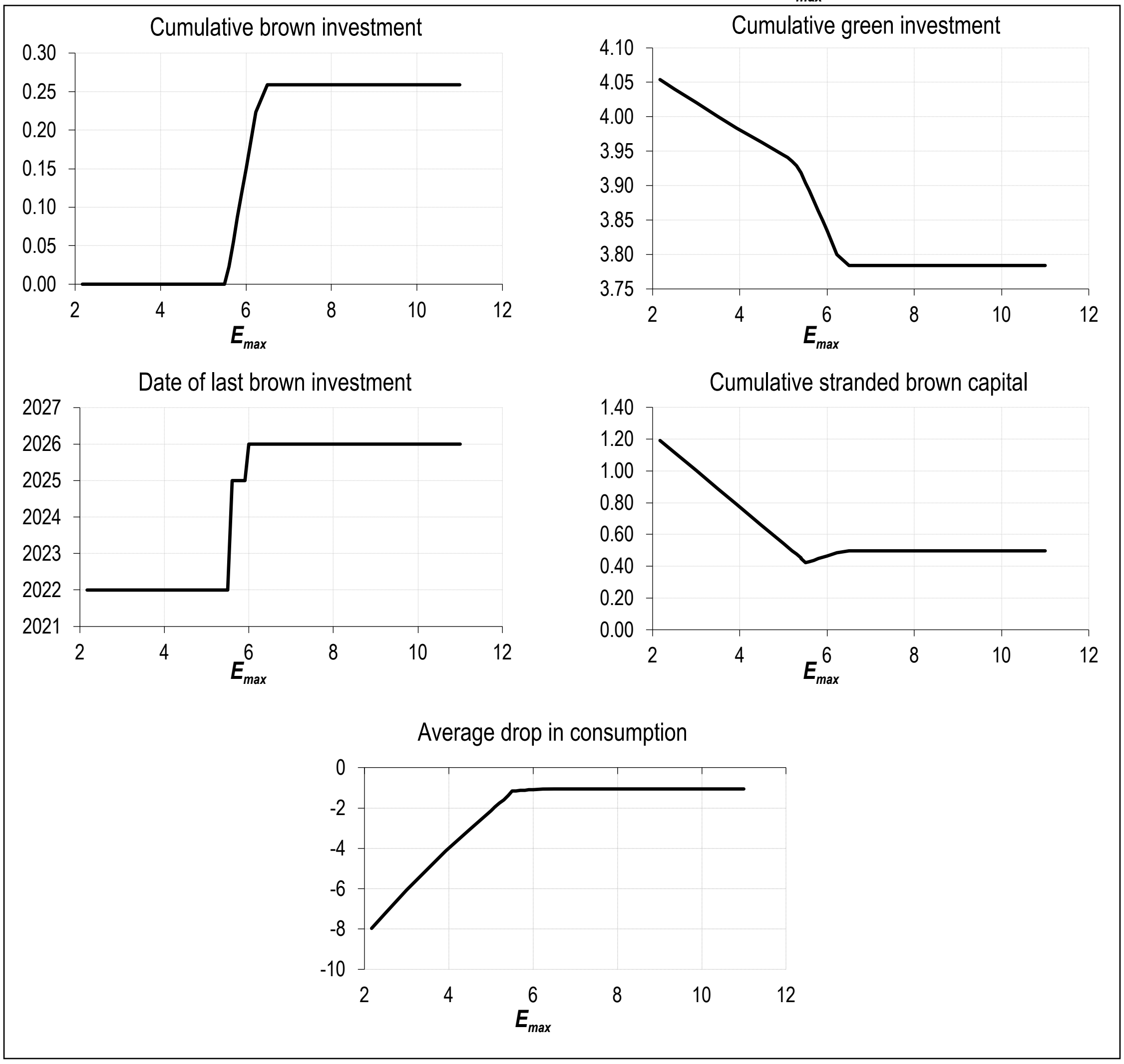


Notes: cf. Figure I.

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**

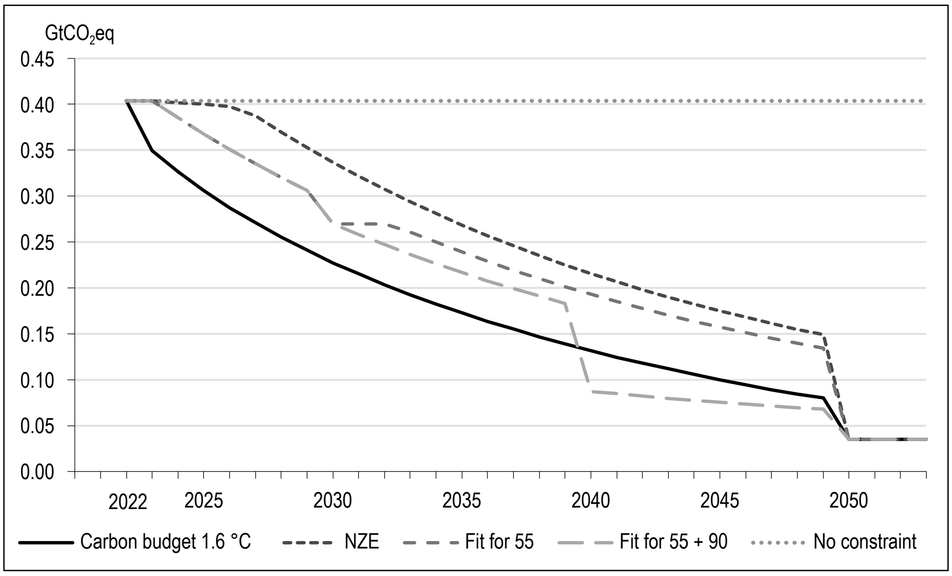
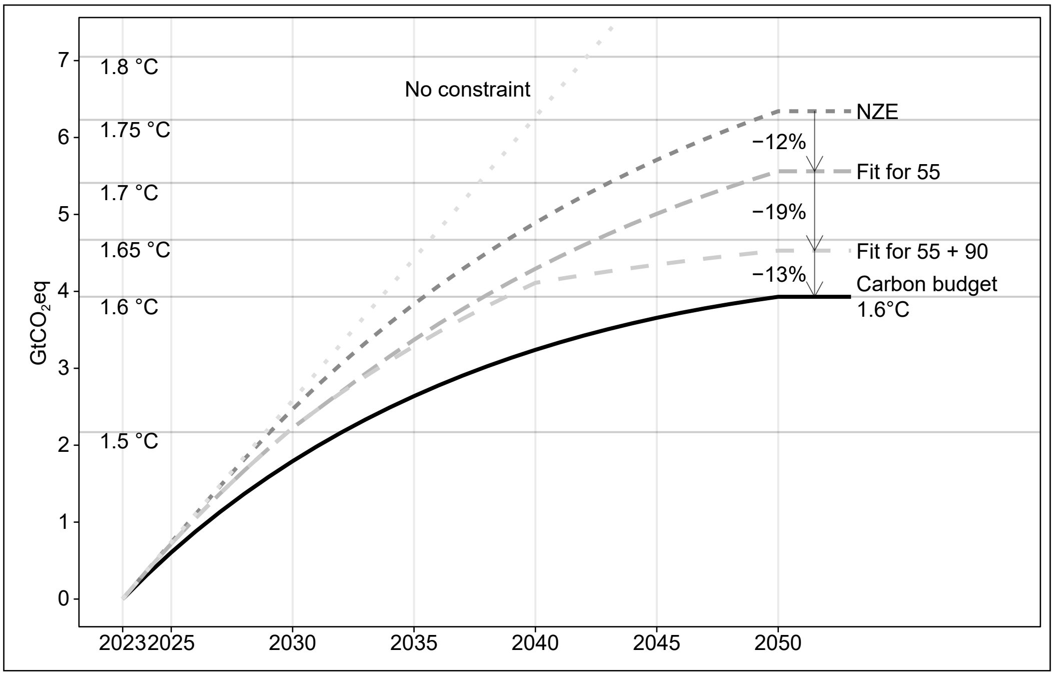


Figure VII – **Cumulative emissions for the carbon budget, NZE, Fit for 55 and Fit for 90 scenarios**



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**

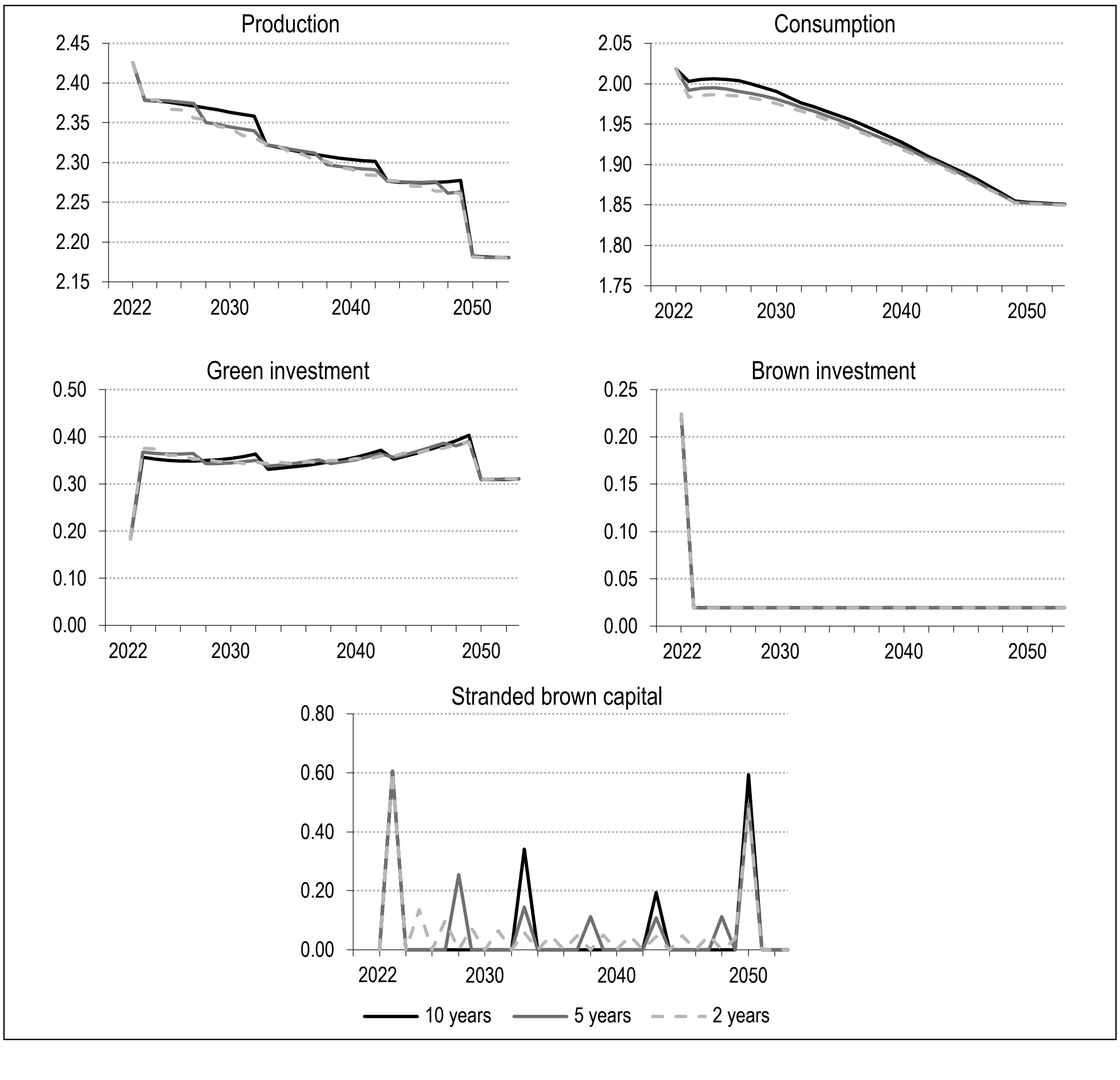


Table 4 – **More closely spaced one-off emissions targets bring the economy closer to the optimal trajectory for complying with the carbon budget at 1.6°C**

	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

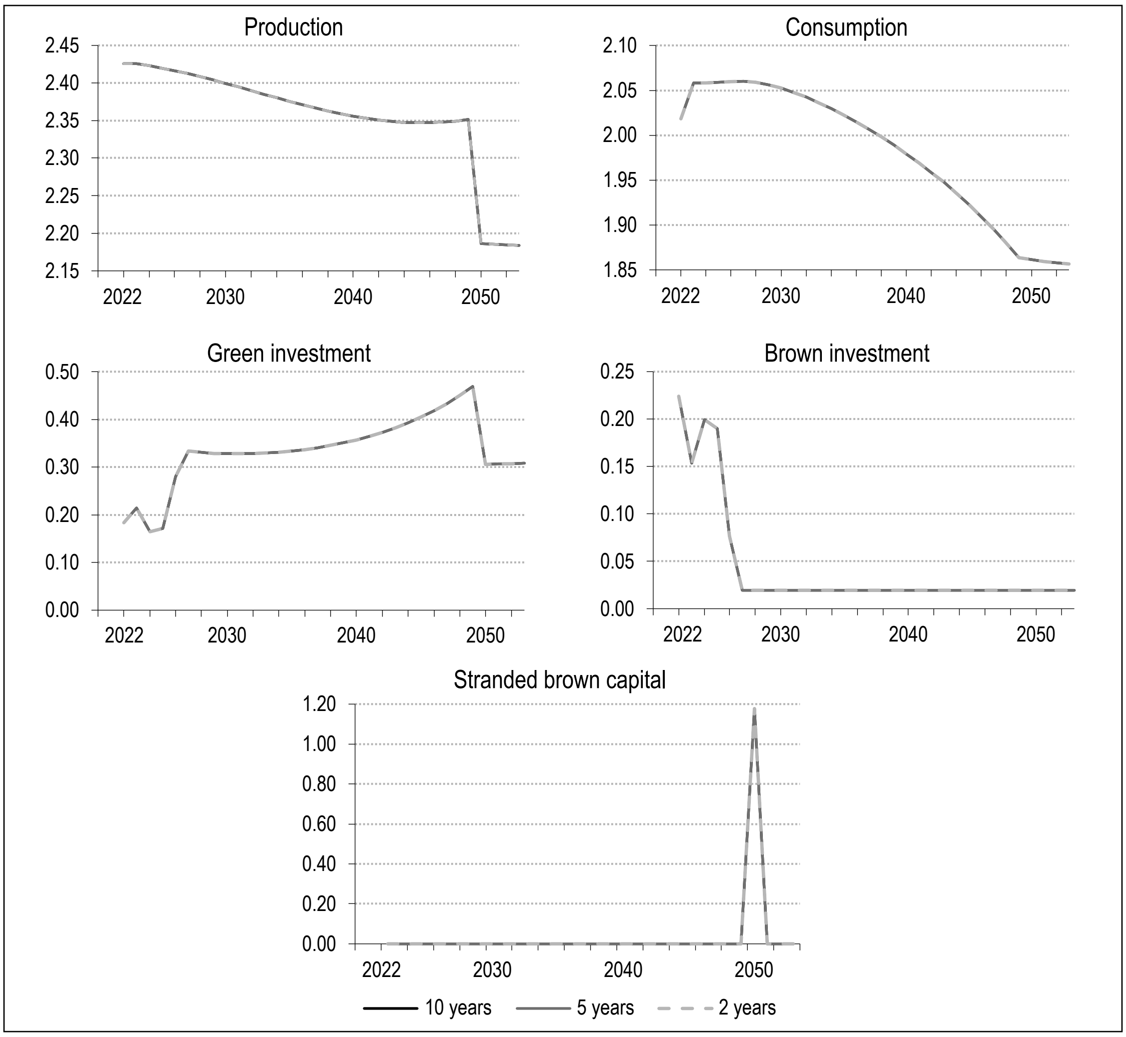
Notes: The emissions targets are also set the same as the emissions for the optimal trajectory for complying with a carbon budget of 3.93 $GtCO_2eq$, consistent with limiting global warming to 1.6°C. Annual targets result in the same solution as compliance with the carbon budget (Carbon budget 1.6°C 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**

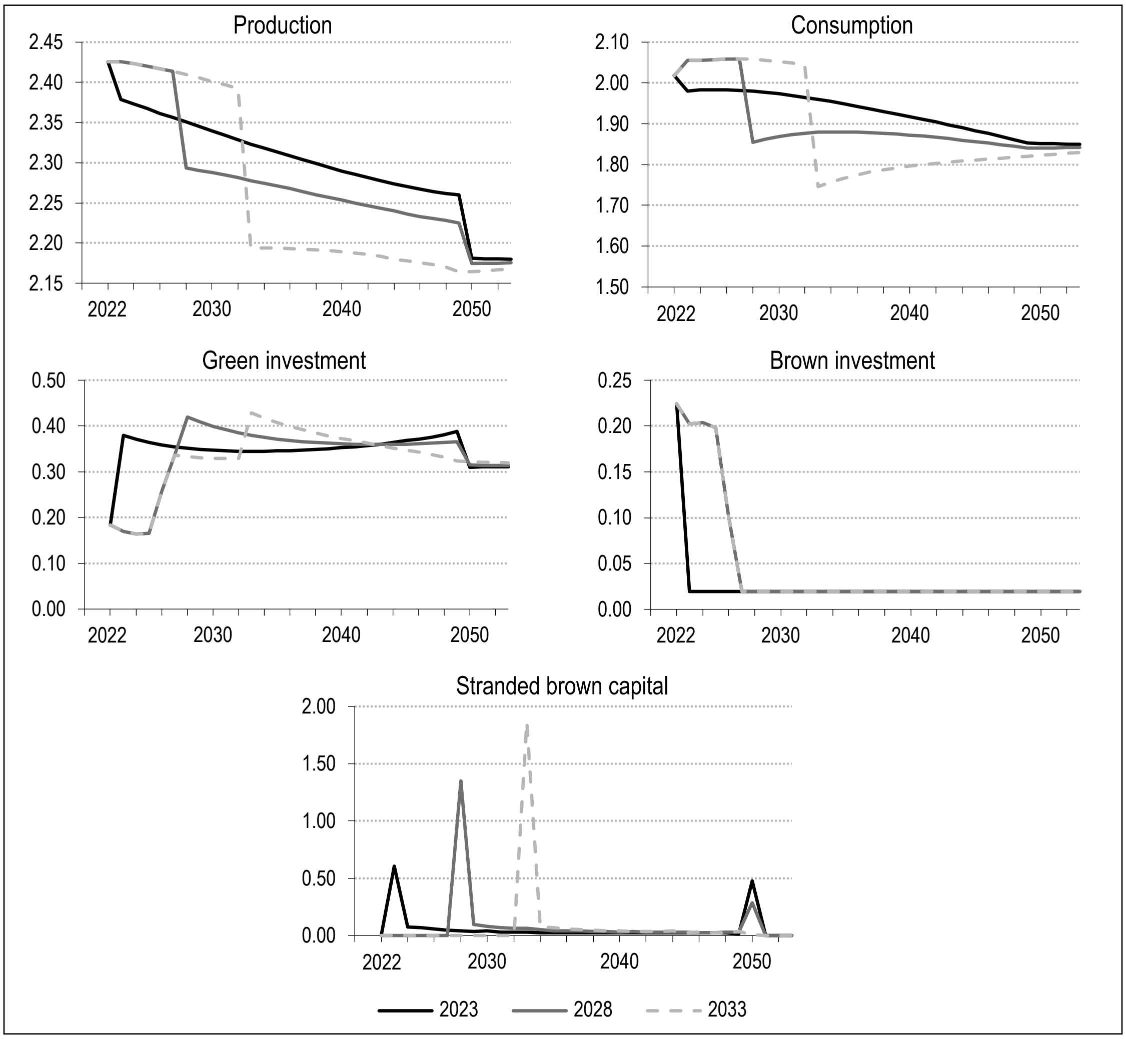


Figure XI – **Emission flows for the carbon budget 1.6°C with different transition start dates**

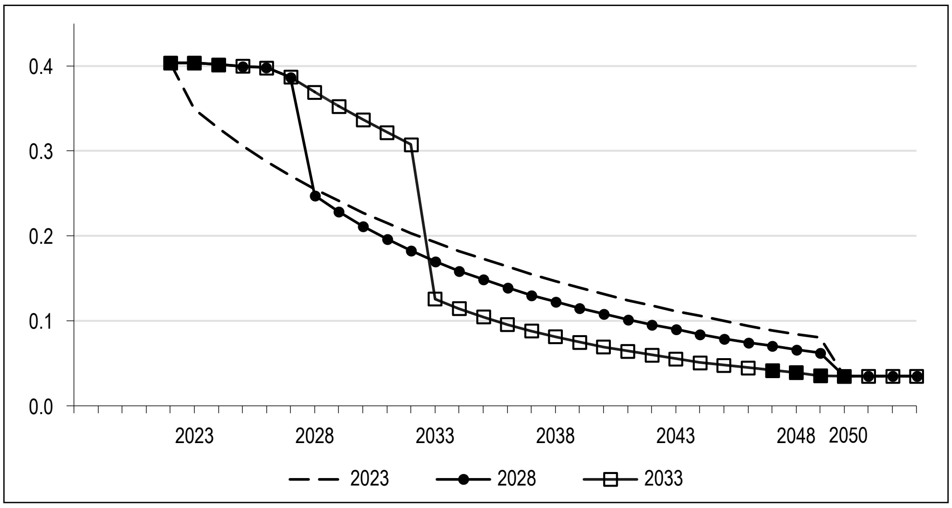
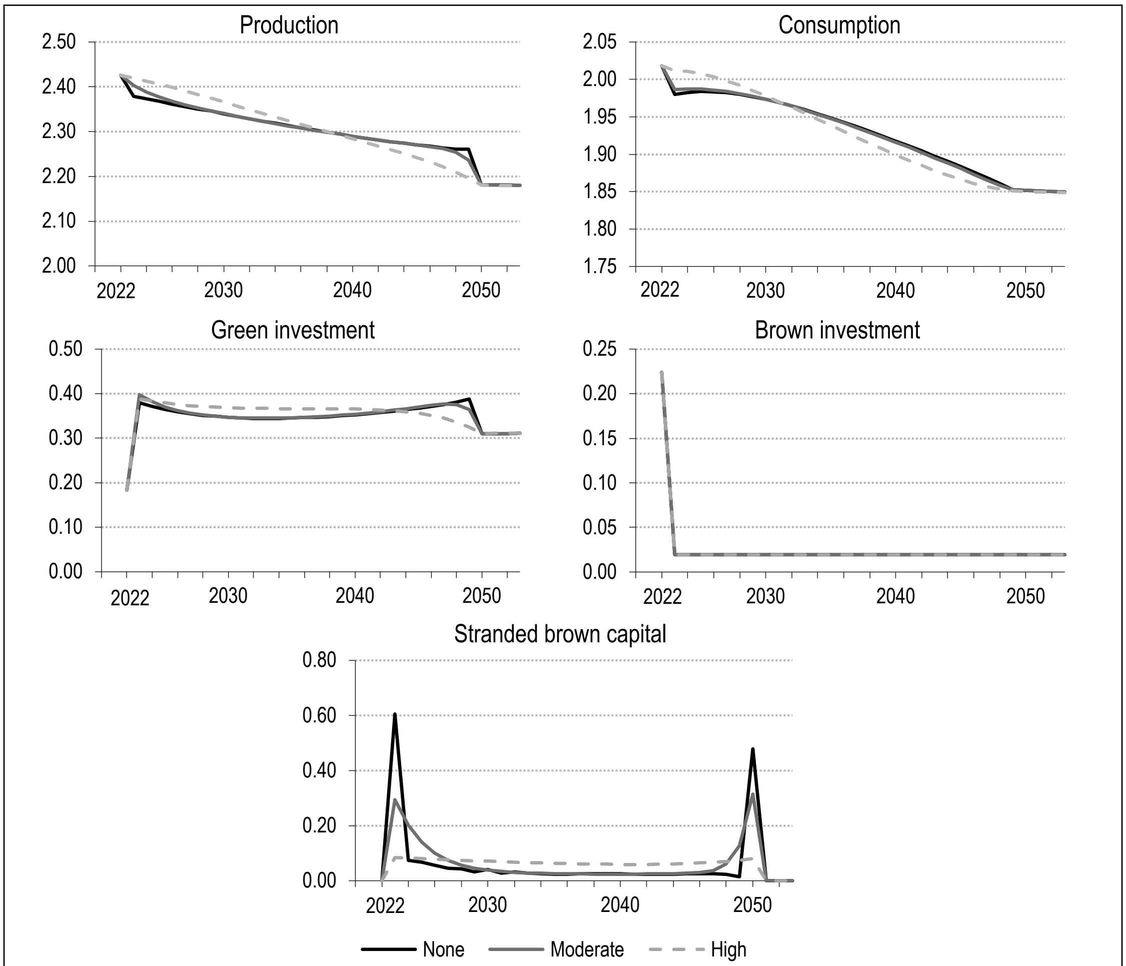


Table 5 – **A delayed transition results in increased stranding and penalises welfare**

	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.

* *
*

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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Hunting “Brown Zombies” to Reduce Industry’s Carbon Emissions

Gert Bijnens* and Carine Swartenbroekx**

Abstract – This paper provides a first estimate of the potential greenhouse gas mitigation from the intra-sector reallocation of economic activity by the European manufacturing industry away from carbon-inefficient – or “brown zombie” – firms to more carbon-efficient firms. Using techniques from the literature on productivity, we find a potential reduction of 38% of direct greenhouse gas emissions based on a limited reallocation of production, without the need for new technologies. According to our results, when designing emission reduction plans, in addition to focusing on improvements and innovation within existing firms, policymakers should also do more to encourage the reallocation of economic activity from “brown zombies” to more carbon-efficient enterprises.

JEL: D22, L23, L52, L60, O14, Q58
Keywords: climate policy, carbon emission reduction, carbon-intensive industries, reallocation, brown zombies

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The European Union's (EU) "Fit for 55" package of measures, a part of the "Green Deal" initiative,[1] contains ambitious targets for cutting greenhouse gas (GHG) emissions by 55% by 2030, compared to 1990 levels. If this reduction is not to go hand in hand with a substantial scaling down of industrial output, it implies that the carbon efficiency of European industry will have to improve drastically. Industry will have to produce the same (or higher) output with lower GHG emissions.

The debate over how to realise this ambition predominantly focuses on green innovation. The European Commission (EC) intends the new EU Industrial Strategy to lead the region's manufacturing firms towards a carbon-neutral future while making them more globally competitive. It intends to *"help industry to reduce their carbon footprint by providing affordable, clean technology solutions and by developing new business models"*.[2] The focus is clearly on developing innovative technology and processes and ensuring their adoption across Europe.[3] Although we do not question the importance of green innovation, this strategy implicitly follows the view that the necessary technology to enable Europe's manufacturing industry to start its deep decarbonisation process is not yet available.

The EU policy instrument that regulates industry emissions is the European Union Emissions Trading System (EU ETS).[4] This system forces large industrial installations to pay for at least a part of their CO_2 emissions. It not only provides a financial incentive for the adoption of renewable energy sources but also stimulates the emission-intensive manufacturing sector to reduce its carbon footprint. A complex system is used to distribute free emission rights amongst industrial installations, which is based on a benchmark set by the best-performing installations producing a similar product. This system hence acknowledges that there is a certain range of carbon performance within narrowly defined sectors. More specifically, Vieira *et al.* (2021) studied the progress of EU ETS emissions and found that manufacturing firms carrying out the same activities presented results ranging from no reduction to an abatement of more than 80% of emissions over the period 2005–2017. They therefore concluded that a lack of alternative technologies could not be the sole reason for poor mitigation results. More recently, Capelle *et al.* (2023) analysed self-reported emission data for a global sample of 4,000 large, publicly listed companies and found significant heterogeneity in environmental performance within the same industry and country.

In this paper, we therefore propose another way of improving the aggregate carbon efficiency of the manufacturing sector, in addition to pursuing innovation and other improvements within existing firms. This involves the reallocation or shift of resources between firms and industries away from carbon-inefficient companies towards more carbon-efficient ones. The importance of reallocation for aggregate productivity gains has been well established since the seminal work of Foster *et al.* (2001). They found that this mechanism of reallocating economic activity towards the most productive firms accounts for around 50% of productivity growth in US manufacturing and 90% in the retail sector. Other authors have found comparable results for Europe.[5] When resources are shifted from low- to high-productivity firms, aggregate productivity rises without an increase in the underlying productivity of individual firms.

We apply similar reasoning to gains in carbon efficiency, which we think of as "carbon productivity" or how effective companies utilise carbon emissions to produce a given level of output.[6] Existing firms can innovate, change their production techniques or invest in abatement to reduce their carbon emissions. These are the so called within firm improvements. In addition, they can reallocate resources. Reallocation refers to resources that are redistributed, within or between carbon-intensive industries, toward relatively more carbon-efficient firms, through the downsizing of the most carbon-intensive incumbents and the growth of cleaner enterprises. The concept of "zombie" firms – defined as low-productivity firms that would typically exit a competitive market – is well known in the productivity literature.[7] Due to their increasing survival rates over the past decade, they tie up scarce capital and therefore constrain the growth of more productive firms. In other words, zombie

1. *The European Green Deal is a set of policy initiatives launched by the European Commission (EC) with the aim of making Europe the first climate-neutral region in the world.*
2. *https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-an-green-deal/industry-and-green-deal_en*
3. *The recent Pisani-Ferry & Mahfouz (2023) report for France is somewhat more nuanced and states that a revolution is needed not only in production methods but also in consumption patterns. The latter also implies a reallocation of economic output between production sectors. Nevertheless, the projections of the cost of the transition for industry are based on greening existing high carbon-emitting production sites.*
4. *More information on the EU ETS can be found in Bijnens & Swartenbroekx (2022).*
5. *E.g. Gamberoni* et al. *(2016) for the Eurozone, Ben Hassine (2019) for France.*
6. *The concept of carbon productivity was firstly proposed by Kaya & Yokobori (1997) and used to describe aggregate carbon efficiency defined as GDP produced per unit of carbon emission (or vice versa).*
7. *See e.g. Adalet McGowan* et al. *(2018). Zombie firms are non-viable firms that may be increasingly kept alive by the legacy of the financial crisis, with bank forbearance, prolonged monetary stimulus, and the persistence of crisis-induced SME support policy initiatives.*

firms impede reallocation that could increase productivity. We in turn introduce here the concept of "brown zombies", or firms with the lowest "carbon productivity" within their sector.

Our analysis reveals that manufacturing industry has demonstrated negligible reductions in emission intensity over the 2013–2019 period. Even within finely defined sectors, there exists a substantial variability in emission intensity, defined as the ratio of emissions to value added. While there was a marginal decrease in emission intensity between 2013 and 2019, primarily attributed to resource reallocation, noteworthy reductions were not driven by within firm improvements, nor by firms entering or exiting the market. To reach the targets set, future emission reductions must markedly surpass historical achievements. Beyond technological advancements, there remains considerable potential for emission mitigation by transitioning production to the most carbon-efficient entities within a sector, thereby moving output away from brown zombies.

As a first contribution, we introduce decomposition methods from the productivity literature to analyse past changes in carbon emission intensity. As a second contribution, we are amongst the first to estimate the mitigation potential due to intra-sector reallocation of economic activity away from carbon-inefficient firms towards carbon-productive ones.[8] We find that a limited shift within a sector and away from the most emission-intensive firms could result in a 38% reduction in EU-ETS emissions. According to our results, when developing emission reduction plans, in addition to focusing on greening incumbent industrial firms, policymakers should also take more account of the fact that some brown zombies will have to shrink and cede the market to more carbon-efficient companies.

This paper is organised as follows: the first section summarises the data we use. Section 2 breaks down past changes in emission intensity into contributions from within firm improvements, reallocation, and market entry and exit. Section 3 quantifies the potential for future emission reductions from reallocation. Finally, we present our conclusions and highlight the need to consider the reallocation of industrial activity to meet the EU's emission reduction targets.

1. Data

1.1. GHG Emissions and Emission Intensity at the Firm-Level

The analysis in this paper is based on linking installation-level GHG emission data from the EU ETS with firm-level financial data from Bureau Van Dijk's ORBIS database. This allows us to track firm-level emission intensity, i.e. emissions relative to output. Below we further describe each data source in detail and provide summary statistics.

We start from the European Union Transaction Log (EUTL), the central reporting and monitoring system for all EU ETS transactions managed by the European Commission. The system covers some 10,000 stationary installations in the energy and industry sectors and airlines operating in the EU. All industrial installations above a certain thermal input capacity threshold are regulated by the EU ETS. Each installation must report annually on the verified amount of CO_2 emitted.[9] For each tonne emitted, the company owning the installation must surrender a right to emit (an emission allowance) to the European Commission. Companies regulated by the EU ETS must acquire these allowances either on the carbon market or through EU ETS auctions. Many manufacturing firms regulated by the EU ETS receive a significant number of allowances for free.

The boundary of the emissions regulated by the EU ETS is the installation itself. The EU ETS requires the owner of an installation to hand over emission allowances for the direct emissions of that installation (scope 1). Emissions from the suppliers to the installation (either emissions from purchased energy, scope 2, or other externally purchased products, scope 3) are therefore only covered by the EU ETS, if the supplying installation is covered by the EU ETS. If an installation or firm has its own energy generation unit, the firm also needs to surrender allowances for the emissions of its own, in-house energy generation unit. In short, an owner of an installation regulated by the EU ETS only needs emission allowances for the emissions directly originating from that installation.

The European Union Transaction Log (EUTL) includes actual yearly emissions and freely allocated emissions at the installation level. We exclude emissions from the aviation sector and only use information on stationary installations. The EUTL also provides a national company registration number and company name that

8. Capelle et al. *(2023) use information on 4,000 publicly listed firms across the world and estimate that if all these firms were to produce at the emission intensity of the 25th percentile within their country and industry, aggregate emissions would fall by 33%. Note that since the EU ETS is valid for the entire EU, in this paper we do not compare emission intensities within a country, but within the EU.*

9. *The emission unit used within the EU ETS is CO_2-eq. or CO_2-equivalent as the system also covers GHGs other than CO_2.*

links the installation to its corporate operator. The EUTL also includes an activity for each installation. The list of activities can be found in the Appendix. Each activity is either linked to a product (e.g. "processing of ferrous metals", "production of ammonia") or to "combustion". A combustion installation generally refers to an installation that uses heat to generate electricity and, consequently, companies in the power generation sector operate most of them. A combustion installation may also belong to a manufacturing company whose activity is not specifically included in the EU ETS (e.g. food processing) or a services company or organisation (e.g. hospitals, universities).

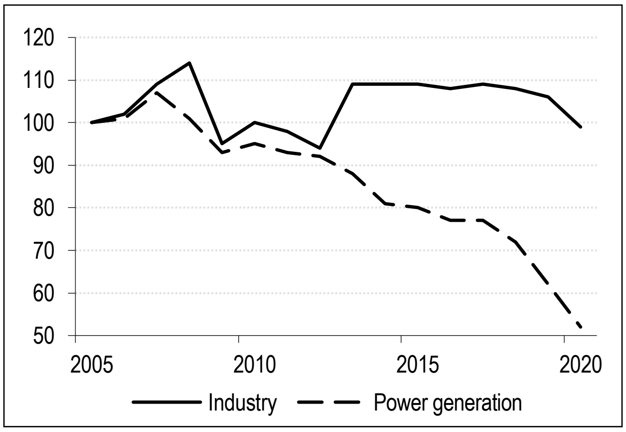
EU ETS emissions from installations operated by a power generation company declined significantly and halved over the 2005–2020 period (Figure I). Power companies reduced carbon intensity through measures such as coal-to-gas switching and increased adoption of renewable energy sources (Marcu *et al.*, 2021). However, emissions from installations outside the power generation industry remained stable over the past decade.

This trend in absolute emissions only tells part of the story. Emissions cannot be evaluated independently of the associated economic output. For industry, changes in emissions are closely linked with changes in output. However, declining activity is not the aim of the European Green Deal. The desired path toward climate neutrality for European industry leads to reductions in the emission-intensity of outputs, i.e. in the amount of CO_2 emitted per unit of output.

We use value added as a measure for firm output. To link emissions with value added, we use information on the corporate operator or owner of the installation gathered from Bureau van Dijk's ORBIS database. ORBIS is the largest cross-country, firm-level database available and accessible for economic and financial research.[10] It is a commercial database provided by the electronic publishing firm Bureau van Dijk. ORBIS collects information from administrative sources, in particular, detailed balance sheets, income statements, and the profit and loss accounts of firms. The financial accounting data is harmonised across countries and provided in a standard global format. We use unconsolidated financial information from local registry filings to ensure that only financial information from activities carried out by the specific entity are included in our analysis, as opposed to consolidated accounts that may include the activities of other companies from the same group. Our analysis makes use of the ORBIS value added (in euro[11]) and industry (2-digit NACE code) variables. When value added is not reported we take the difference between operating revenue and intermediate inputs. Value added is deflated with a corresponding deflator specific for value added at the two-digit industry-country level. The deflators are retrieved from the Structural Analysis Database of the OECD.[12] In case 2-digit deflators are not available, we use the information from higher levels of industry aggregation. Since year-on-year changes in value added can be volatile, the growth rate is winsorised at the 1st and 99th percentile.

10. See, e.g. Gal (2013) who uses ORBIS for productivity calculations, Koch & Themann (2022) who study the impact of the EU ETS on firm productivity and Pak et al. *(2019) who analyse the labour share in OECD countries.*
11. For non-euro countries, ORBIS converts value added to euro based on the average exchange rate of the relevant year.
12. The data can be retrieved from: http://www.oecd.org/sti/ind/stanstructuralanalysisdatabase.htm

Figure I – **Relative trend in emissions covered by the EU ETS, 2005 = 100**



Note: "Power generation" include emissions from all installations for which the operator has a NACE code between 35 and 39, i.e. electricity, gas, steam and air conditioning supply and water supply (sewerage, waste management and remediation activities). "Industry" includes emissions from all other stationary installations.
Source: EUTL.

We link the installation from the EUTL with its corporate owner in ORBIS. Where a direct match between the company identifiers in the EUTL and in ORBIS is not possible, we use ORBIS's fuzzy search based on the installation owner's name. In the event of multiple results, we manually select the most feasible match. We disregard installations that could not be linked with a company's financial statement in the ORBIS database. In some cases, an installation is operated by a company that is not registered in the country in which the installation is located. These observations are also disregarded.

This paper analyses changes in emission intensity (measured in tonnes of CO_2-eq emitted, divided by value added) for industrial companies – excluding the power generation and water supply sector[13] – between 2013 and 2019.[14] It therefore needs value added to be reported in both 2013 and 2019 for continuing firms. In addition, we exclude 'small' firms with value added in 2013 or 2019 below €100,000. Overall, our analysis covers approximately 75% of stationary EU ETS installations belonging to an industrial company, excluding the power generation sector. This represents approximately 70% of emissions from stationary installations (see Online Appendix, Table S1 for an overview of coverage per country – link to the Online Appendix at the end of the article). The primary reason why this rate falls noticeably below 100% is the absence of firm value added data in ORBIS for certain countries, resulting in their exclusion from the analysis. This is not due to consistently low and uniform firm coverage across all countries.

We aggregate individual installations within a country and attribute them to the company operator. The emissions of a firm are calculated as the sum of the emissions of its installations. The activity attributed to the firm is the activity from the emitting EU ETS installation(s). If a single company operates multiple installations with different activities, we take the activity which is the source of the most emissions as the activity for the whole firm. Approximately 70% of firms within our sample only operate one installation. While oil and gas are not included as an activity within the EU ETS (these installations are categorised as combustion), we assign operating companies with NACE 2-digit 06 to oil and gas.

1.2. Summary Statistics

In total we analyse approximately 2,800 firms in 2013 and 2,500 firms in 2019. The number of installations and the quantity of emissions covered by our analysis do not differ significantly from one activity to another (see Online Appendix, Table S2 for an overview of coverage per activity). Table 1 presents the summary statistics for the firms included in our sample.

Between 2013 and 2019, the total emission intensity of industries regulated by the EU ETS (total emissions divided by the total value added, i.e. the mean of emission intensities weighted by each firm's share of value added) decreased from 1,680 to 1,627 tCO_2-eq per € million value added. The mean emission intensity also decreased. Furthermore, emissions intensity shows significant heterogeneity between all firms: In 2013, 20% of companies emitted less than 280 tCO_2-eq per million euros of added value and 20% emitted more than 4,700 tCO_2 -eq per million euros of added value (330 and 4,640 respectively in 2019). Even within carbon-intensive industries there are very large differences in the carbon emissions needed to generate economic value added. E.g. the production of cement or lime needs approximately ten times more carbon to generate the same value added as the production of glass or paper. Table 2 shows that there is significant heterogeneity in emission intensity not only between activities but also within the same activity.

2. Decomposition of the Changes in Carbon Emission Intensity

2.1. Methodology

To better understand the underlying processes that drive the change in emission intensity, we use well known techniques from the productivity literature that decompose changes in aggregate productivity into the contributions from continuing, entering, and exiting firms. The decomposition technique sheds light on the relative importance of the underlying processes of advancements within firms, reallocation between firms, and net entry of firms.

We use these techniques to decompose the change in aggregate carbon efficiency or "carbon productivity". We analyse changes in emission intensity, measured as the CO_2-eq emitted per unit of value added and distinguish between the contributions from continuing, entering, and exiting EU ETS firms.

13. NACE 2-digit code equal or below 33. This means that the power generation sector (NACE 35) is excluded. Combustion installations, possibly generating electricity onsite, belonging to a company with NACE 2-digit code below 33 are included. NACE 2-digit codes below 10 predominantly include companies active in the upstream oil and gas sector that generally operate installations categorised as combustion.

14. This period is chosen as 2013 is the start of Phase 3 of the EU ETS. 2019 is preferred as a reference point as both 2020 and 2021 emissions were affected by the COVID-19 crisis (see Marcu et al., 2022) and 2021 is the start of a new phase of the EU ETS.

Table 1 – **Summary statistics of the used dataset**

	2013	2019
Firms (number)	2,807	2,479
Single installation firms	1,984	1,719
Continuing	2,343	2,343
Exiting	464	
Entering		136
Installations (number)	4,910	4,441
Installations per firm (number)		
Mean	1.75	1.79
Median	1.00	1.00
P20	1.00	1.00
P80	2.00	2.00
Emissions per firm (in tCO_2-eq)		
Mean	163,139	183,124
Median	17,469	26,871
P20	4,766	7,424
P80	86,806	112,642
Value added per firm (in million €)		
Mean	97	117
Median	20	25
P20	5	6
P80	82	94
Emission intensity per firm (in tCO_2-eq per million € value added)		
Weighted mean	1,680	1,627
Mean	4,779	4,662
Median	1,207	1,415
P20	280	330
P80	4,702	4,640

Note: Value added in € million (in 2015 prices), emissions in tCO_2-eq, emission intensity in tCO_2-eq per € million value added. P20 and P80 refer to the 20th and 80th percentile of the distribution of the variable. Weighted mean uses share of total value added as weights (see Equation 1, Section 2).
Source: Authors' calculations based on EUTL and ORBIS data.

The total emission intensity (EI_t) at time t is defined as the total emissions divided by the total value added of the industrial firms included in our dataset. This equals the weighted average of the emissions intensity ($ei_{i,t}$) of each firm i at time t:

$$EI_t = \sum_i \theta_{i,t} ei_{i,t} \qquad (1)$$

where $\theta_{i,t}$ represents the share of value added of firm i at time t in the total value added of all firms in our sample and $ei_{i,t} = \frac{emissions_{i,t}}{value\,added_{i,t}}$ or the emission of firm i at time t divided by the value added of firm i at time t.

A first method to decompose productivity was proposed by Baily *et al.* (1992). Later, to overcome some issues stemming from this method, both Griliches & Regev (1995) and Foster *et al.* (2001) proposed different methods and decomposed productivity relative to a reference productivity level. More recently, Melitz & Polanec (2015) introduced an additional method. All methods decompose changes in productivity into three components. Firstly, the "within effect" or productivity improvements within continuing firms. Secondly, the "between effect" of continuing firms, which measures the variation of productivity following a change in the market share or reallocation of activity between continuing firms. Thirdly, the "net entry effect" captures the contribution of entering and exiting firms. While other methods exist, we focus on these three commonly used methodologies[15] where we replace productivity by carbon intensity.

15. See Ben Hassine (2019) for a more detailed discussion of the three techniques.

Table 2 – **Summary statistics on heterogeneity of emission intensity within activities**

Activity	Observations (number of firms)	Emission intensity (in tCO_2-eq per million € value added)			
		Mean	Median	P20	P80
Combustion	1,680	1,719	525	85	1,960
Refining	109	18,063	6,699	1,455	14,445
Coke	11	55,023	14,296	9,581	38,306
Metal ore	25	4,338	2,431	770	6,772
Iron or steel	224	6,520	2,115	1,005	6,111
Ferrous metals	241	1,567	746	196	2,215
Primary aluminium	25	2,989	1,979	597	5,116
Secondary aluminium	33	1,060	848	403	1,500
Non-ferrous metals	104	4,146	612	159	2,323
Cement clinker	167	23,479	21,447	14,052	34,334
Lime	140	23,625	22,561	6,650	35,553
Glass	359	2,626	1,968	770	3,723
Ceramics	775	4,113	2,059	733	5,470
Mineral wool	81	1,822	1,377	578	3,087
Gypsum or plasterboard	51	1,314	854	378	1,495
Pulp	234	1,748	1,086	481	2,847
Paper or cardboard	492	2,514	1,610	430	3,456
Carbon black	15	18,908	5,761	1,888	12,953
Nitric acid	17	4,164	1,935	662	6,190
Adipic acid	2	2,019	2,019	1,309	2,729
Ammonia	20	14,190	12,376	3,537	21,142
Bulk chemicals	199	8,281	826	194	3,959
Hydrogen	26	6,173	1,151	293	10,355
Soda ash	12	8,081	7,474	1,912	13,194
Other	18	3,734	1,458	427	6,668
Oil and gas	226	5,264	1,475	307	6,866

Note: The full names of activities are listed in Appendix. Oil and gas are not an activity listed within the EU ETS. Firms with NACE 2-digit code 06 are attributed to oil and gas.
Source: Authors' calculations based on EUTL and ORBIS data.

2.1.1. GR Method – Griliches & Regev (1995)

GR uses the average aggregate emissions intensity ($\overline{EI}$) between the two periods *t* and *t-1* as a reference.

$$\Delta EI_t = \underbrace{\sum\nolimits_{i\in C}\overline{\theta}_i \Delta ei_{i,t}}_{\text{Within effect}} + \underbrace{\sum\nolimits_{i\in C}\Delta\theta_{i,t}\left(\overline{ei}_i - \overline{EI}\right)}_{\text{Between effect}} + \underbrace{\sum\nolimits_{i\in N}\theta_{i,t}\left(ei_{i,t} - \overline{EI}\right) - \sum\nolimits_{i\in X}\theta_{i,t-1}\left(ei_{i,t-1} - \overline{EI}\right)}_{\text{Net entry effect}} \quad (2)$$

ΔEI_t (or $EI_t - EI_{t-1}$) corresponds to the change in aggregate emission intensity between the period t and t-1. EU ETS firms are indexed by i and may be classified as either continuing (C), entering (N), or exiting (X). $\theta_{i,t}$ denotes the activity share (the share of value added of firm i in the total value added of the included firms) and $ei_{i,t}$ the emissions intensity attributed to an individual EU ETS firm i in time period t. Bars over variables indicate that the average has been taken over the two time periods. Emission intensity is measured relative to value added, i.e. in tonnes of CO_2-eq emitted per unit of value added.

The contribution of the within effect is negative if continuing firms reduce their carbon intensity. The between effect is negative if firms that gain market share have a lower emissions intensity compared to the reference level. Entering (exiting) firms contribute negatively if they have a lower (higher) emission intensity relative to the reference. The net entry effect will in addition also depend on the market share of entering vs. exiting firms. A drawback of the GR decomposition is that the within and between effects are interdependent given that the within effect uses average market share and the between effect uses the change in market share. The decomposition therefore does not separately take into account the reallocation of market share to companies that become more productive.

2.1.2. FHK Method – Foster, Haltiwanger & Krisan (2001)

FHK overcomes this problem by introducing a covariance term or cross effect between market share and emission intensity. The reference level is the overall emission intensity in period $t-1$ (EI_{t-1}).

$$\Delta EI_t = \underbrace{\sum_{i\in C}\theta_{i,t-1}\Delta ei_{i,t}}_{\text{Within effect}} + \underbrace{\sum_{i\in C}\Delta\theta_{i,t}\left(ei_{i,t-1}-EI_{t-1}\right)}_{\text{Between effect}} + \underbrace{\sum_{i\in C}\Delta\theta_{i,t}\Delta ei_{i,t}}_{\text{Cross effect}} + \underbrace{\sum_{i\in N}\theta_{i,t}\left(ei_{i,t}-EI_{t-1}\right)-\sum_{i\in X}\theta_{i,t-1}\left(ei_{i,t-1}-EI_{t-1}\right)}_{\text{Net entry effect}} \quad (3)$$

The covariance between productivity and firm size, represented by the cross effect, is negative when a company's emission intensity and market shares move in opposite ways. This implies that for a firm to contribute to a reduction in the cross effect, it needs to enhance its own carbon efficiency and acquire market share, even if its emission intensity is worse than the average. Essentially, this term highlights a reallocation process, though not necessarily favouring the least emitting firms. A drawback of FHK compared to GR is that it is more prone to measurement issues.[16] Furthermore, FHK might overestimate the contribution of entering firms as they are not included in the calculation of the reference emission intensity (EI_{t-1}).

2.1.3. MP Method – Melitz & Polanec (2015)

Melitz & Polanec (2015) argue that the aforementioned techniques introduce some biases in the measurement of the contributions of entry and exit. They therefore propose a dynamic composition based on Olley & Pakes (1996).

$$\Delta EI_t = \underbrace{\Delta\overline{ei_t}}_{\text{Within effect}} + \underbrace{\Delta cov\left(\theta_{i,t}, ei_{i,t}\right)}_{\text{Cross effect}} + \underbrace{\sum_{i\in N}\theta_{i,t}\left[\sum_{i\in N}\frac{\theta_{i,t}}{\sum_{i\in N}\theta_{i,t}}ei_{i,t}-\sum_{i\in C}\frac{\theta_{i,t}}{\sum_{i\in C}\theta_{i,t}}ei_{i,t}\right]}_{\text{Net entry effect}} - \underbrace{\sum_{i\in X}\theta_{i,t-1}\left[\sum_{i\in X}\frac{\theta_{i,t-1}}{\sum_{i\in N}\theta_{i,t-1}}ei_{i,t}-\sum_{i\in C}\frac{\theta_{i,t-1}}{\sum_{i\in C}\theta_{i,t-1}}ei_{i,t-1}\right]}_{\text{Net entry effect}} \quad (4)$$

where $\Delta\overline{ei_t} = \frac{1}{n}\sum_{i\in C}ei_{i,t} - \frac{1}{n}\sum_{i\in C}ei_{i,t-1}$ and $cov\left(\theta_{i,t}, ei_{i,t}\right) = \sum_{i\in C}\left(\theta_{i,t}-\overline{\theta}_t\right)\left(ei_{i,t}-\overline{ei}_t\right)$. A notable difference with the previous methods is that the within effect now measures a change in the unweighted average of the emission intensity of continuing firms. This cross term is also different than (and therefore not comparable with) the cross term from the FHK decomposition, which captures the covariance of market share and emission intensity *changes* for an *individual firm*. On the other hand, the MP covariance captures the correlation of market shares and emission intensity within a time period.

2.2. Results

Table 3 presents the change in emission intensity between 2013 and 2019. Emission intensity decreased by approximately 3% over the period studied – from 1,680 (in 2013) to 1,627 (in 2019).[17] Table 3 further decomposes the change in emission intensity according to the three methodologies described above. It breaks down the contribution of continuing firms into improvements within continuing firms (the within effect), reallocation (the sum of the between effects and the cross term), and net entry (the entry minus the exit effect). As there are no clear signs proving one method is better than the other, the range given by the different methodologies could be seen as defining the extent of each component's contribution to the overall change in emission intensity. A reduction in emission intensity is noted with a negative number.

Within effects correspond to changes in emission intensity within a firm, holding constant its market share. Within effects therefore correspond to reductions in emission intensity (i.e. producing the same output, but with lower carbon emissions) that occur within an individual firm, due to the improvements of production processes over time. These improvements can be the result of innovation, the adoption of a new technology or measures that make existing technology and/or processes more carbon efficient. The within effect is close to zero for both GR and MP methods. This means that both the value added weighted change in emission intensity (GR, Equation 2) and the unweighted change (MP, Equation 4) is limited. The positive within effect from the FHK method is linked with the fact that FHK includes a cross term. The cross term can capture the fact that a firm can increase its market share and reduce its emission intensity at the same time. The fact that the within effect is close to zero or even slightly increasing overall

16. This is due to the FHK cross term. Random measurement error in output yields a negative covariance between emission intensity changes and changes in output shares and therefore a spuriously high within effect. In contrast, the measured within effect from GR will be less sensitive to random error in output since it averages the share across time which mitigate the influence of measurement error.

17. Emission intensity in tonne CO_2-eq per € million of value added. For reasons of simplicity, we omit the unit in the text.

Table 3 – **Decomposition of the change in emission intensity between 2013 and 2019**

		2013	Within	Reallocation			Net entry			2019
				between	cross	between + cross	entry	exit	entry − exit	
GR		1,680	−1	−69		−69	−21	−38	17	1,627
	%		*−0.1*	*−4.1*		*−4.1*	*−1.3*	*−2.3*	*+1.0*	*−3.2*
FHK		1,680	56	−14	−114	−128	−22	−41	19	1,627
	%		*+3.3*	*−0.8*	*−6.8*	*−7.6*	*−1.3*	*−2.4*	*+1.1*	*−3.2*
MP		1,680	−2		−76	−76	−21	−46	25	1,627
	%		*−0.1*		*−4.5*	*−4.5*	*−1.3*	*−2.7*	*+1.5*	*−3.2*

Note: Emission intensity (2013 and 2019) in tCO_2-eq per million € value added. GR, FHK and MP refer to the used decomposition methodologies.
Source: Authors’ calculations based on EUTL and ORBIS data.

emission intensity implies that improvements within firms to reduce their carbon intensity was, at best, very modest.

The reallocation term stems from changes in emission intensity in the market shares of the EU ETS firms. The reallocation effect is negative for all three methods. This means that production capacity is being reallocated from the most emission-intensive firms toward the less emission-intensive firms. The FHK cross term is indeed negative. This means that growing firms also reduced their emission intensity (e.g. growth leads to lower emission intensity via scale effects). The negative MP cross term must be interpreted differently. The negative correlation between emission intensity and size is higher (more negative) in 2019 than in 2013. Regardless of the method used, the reallocation component is the most significant factor.

Additionally, the decomposition allows us to quantify the contribution to emission reductions due to net entry, which corresponds to the contribution of entry and exit. Entry reduces the average emission intensity if an entrant’s intensity is lower than the average. Exit reduces average emission intensity if exiting firms have a higher emission intensity compared to the average. Here, the exit of underperforming firms allows the output to be reallocated to more carbon-efficient uses. Although the three methods calculate differently how a firm entering or exiting the market compares to the average, the results are similar. The contribution of net entry is modestly positive. This implies that the process when new firms push old firms out of the market did not contribute to reducing emission intensity.

2.3. Robustness

As explained in Section 1 on data, we link installation-level emissions from the EU ETS with firm-level financial data. Not all the (carbon-emitting) installations of European manufacturing firms are included in the EU ETS: depending on the activity of the installation, there is a size threshold for inclusion in the system. In addition, if the activity of the installation is not carbon-emitting, it will not be regulated by the EU ETS. If a firm included in the EU ETS also operates installations not included in the ETS, we will potentially underestimate its total emissions and include value added generated by non-EU ETS installations. The result is that we underestimate the true emission intensity of the firm’s carbon intensive activities, and the decomposition could be biased. Given that earlier we found that growth did go hand in hand with reducing emission intensity and that a non-EU ETS carbon emitting installation is smaller than an EU ETS installation, this aspect needs further study. Table 4 shows the same decomposition as Table 3, but only for firms that operate a single EU ETS installation.[18] As the chances that a firm operates an installation not covered by the EU ETS increase with the number of those installations that are covered, these results will be less prone to underestimating emission intensity.

A first finding is that the change in emission intensity remains small, but with opposite sign. Unlike the results including all firms, firms operating only one installation did not decrease their emission intensity. Possibly this is due to the fact that these firms have less opportunities for growth and growth is an important driver for increased carbon efficiency. Another reason might be that there are no technological spillovers possible between multiple installations of the same firms. This could make it for a single installation firm more costly and hence less feasible to improve technology or production

18. Single installation firms are firms operating only one installation throughout the period.

Table 4 – **Decomposition of the change in emission intensity between 2013 and 2019 for firms with only one installation**

	2013	Within	Reallocation			Net entry			2019
			between	cross	between + cross	entry	exit	entry − exit	
GR	1,369	−5	−15		−15	−38	−87	49	1,399
	%	*−0.4*	*−1.1*		*−1.1*	*−2.8*	*−6.4*	*+3.6*	*+2.1*
FHK	1,369	41	32	−91	−59	−37	−85	48	1,399
	%	*+3.0*	*+2.3*	*−6.6*	*−4.3*	*−2.7*	*−6.2*	*+3.5*	*+2.1*
MP	1,369	461		−492	−492	−40	−101	61	1,399
	%	*+33.7*		*−35.9*	*−35.9*	*−2.9*	*−7.4*	*+4.5*	*+2.1*

Note: Emission intensity (2013 and 2019) in tCO_2-eq per million € value added. GR, FHK and MP refer to the used decomposition methodologies. Firms with a single EU ETS installation represent approximately 70% of firms and approximately 30% of emissions in our sample.
Source: Authors' calculations based on EUTL and ORBIS data.

processes with respect to carbon emissions. We should also not rule out a reverse causality mechanism. Maybe these firms remain one installation firms and smaller compared to the average EU ETS firms simply because they did not manage to reduce emissions intensity.[19] This would be a desired effect of the EU ETS.

Secondly, the GR and FHK show very similar patterns compared to the decomposition of all firms (Table 3). Only reallocation has a sizeable contribution in bringing intensity down. MP shows more extreme results with the within and reallocation component both large and compensating each other. This is likely due to the fact the MP is more prone to outliers given that the within component is calculated based on an unweighted average. The value added of smaller firms is relatively more variable between the two time periods. Excluding firms with multiple installations increases the relative number of small firms in the sample.

Another possible reason that our results do not fully capture the underlying evolution of emission intensity is the use of deflators. While we employed the most commonly used deflator for value added on the NACE 2-digit level that is available for all European countries, the average for a fairly broad sector will never be completely accurate at the firm level. We therefore also calculate emissions based on employment instead of value added. The advantage is that using employment as a proxy for output is not subject to the use of deflators. The disadvantage is that we do not correct for changes in labour productivity. Table 5 shows that the emission intensity calculated using employment increased by more than 10% between 2013 and 2019. This result is probably biased upwards since we do not consider possible increases in labour productivity.[20] Quantitatively, the results closely resemble those based on value added. The within and net entry effects are positive, and the reallocation effect is negative. A noteworthy difference between the decomposition methods is the fact that MP within component (which is unweighted) is sizably more positive than GR and FHK (which is weighted by employment share). Smaller firms therefore saw their emission intensity go up more than larger firms. The MP cross terms also shows that size became increasingly correlated with lower emission intensity. This corroborates the finding from Table 4 that single installation firms performed worse with respect to reducing emissions intensity than multiple installation firms.

3. The Untapped Potential of Reallocation to Reduce Carbon Emission

In the previous section, we quantified the contribution of improvements within continuing firms (the within effect), reallocation (the between and cross effect), and net entry (the difference between entry and exit effect) to reductions in emission intensity. In this section, we focus specifically on the potential of reallocation to drive future reduction efforts.[21] And an effort will certainly be needed: the reduction in emission intensity of 3.2% between 2013 and 2019 (Table 3) corresponds to a yearly reduction of approximately 0.5%. This is well short of the 1.74% p.a. linear reduction factor (LRF)[22] set during Phase 3 of the EU ETS (2013–2020);

19. Or other reasons correlated with emission intensity.
20. Within the EU-28, real labour productivity increased by approximately 6% between 2013 and 2019 according to Eurostat (nama_10_lp_ulc).
21. The potential for further reallocation may be limited as cost-effective options might have been implemented already. Future emission reductions may require alternative approaches besides reallocation.
22. The linear reduction factor (LRF) refers to the yearly reduction of the cap on total emissions within the EU ETS.

Table 5 – **Decomposition of the change in emission intensity between 2013 and 2019 with emission intensity calculated based on employment**

			Reallocation			Net entry			
	2013	Within	between	cross	between + cross	entry	exit	entry − exit	2019
GR	205	21	−5		−5	−4	−13	9	230
	%	*+10.2*	*−2.4*		*−2.4*	*−2.0*	*−6.3*	*+4.4*	*+11.7*
FHK	205	22	−4	−1	−5	−4	−11	7	230
	%	*+10.7*	*−2.0*	*−0.5*	*−2.4*	*−2.0*	*−5.4*	*+3.4*	*+11.7*
MP	205	35		−19	−19	−4	−13	9	230
	%	*+17.1*		*−9.3*	*−9.3*	*−2.0*	*−6.3*	*+4.4*	*+11.7*

Note: Emission intensity (2013 and 2019) is calculated as emissions (in tCO_2-eq) per employee. Firms that do not report employment or report employment at below 5 heads in 2013 or 2019 are excluded.
Source: Authors' calculations based on EUTL and ORBIS data.

even further away from the 2.2% p.a. LRF set for Phase 4 (2021–2030); and far off the latest European Commission decisions that increase the LRF to 4.3% p.a. from 2024. In addition, Pisani-Ferry & Mahfouz (2023) estimate that French industry will need to reduce their emissions by 4.3% p.a. to reach their 2030 targets. Based on these numbers, the reduction in industrial emission intensity will have to proceed at a drastically faster rate if targets are to be met *without* a substantial drop in industrial output.[23]

The within component (disappointingly) did not contribute sizably to the reduction in emission intensity between 2013 and 2019 (Table 3).[24] This could surely change in the future as many governments push for the further development and adoption of new decarbonisation technologies. The rationale is that, in many sectors (e.g. hydrogen or carbon capture), the necessary decarbonisation technology is not yet available at an industrial scale and needs a wide range of (government) support to develop further. The fact, however, that technologies that can substantially reduce emissions already exist and are currently already used is seldom mentioned. The underlying design of the EU ETS implicitly assumes wide variations in carbon efficiency across industrial installations within narrowly defined sectors. Indeed, for the free allocation of emission allowances, EU ETS industrial installations are subdivided into 54 categories[25] for which an emission benchmark is developed. This benchmark is based on the average emissions of the top 10%, by performance, of installations producing that product in the EU. It therefore acknowledges that a substantial proportion of installations that produce a similar product do not use the most carbon-efficient technology that is already available at an industrial scale. Widespread adoption of the benchmark technology within each of these 54 categories would therefore already lead to substantial emission reductions.

Indeed, we observed a significant heterogeneity in emission intensity not only within carbon-intensive industries (Table 1) but also within the narrowly defined activities under the EU ETS (Table 2).[26] This finding need not be surprising. It does not differ from the stylised fact that traditional sectoral productivity dispersion is high (and increasing) within European countries, possibly driven by slow technology diffusion (Berlingieri *et al.*, 2020; CompNet, 2023). In addition, Capelle *et al.* (2023) find that sector heterogeneity in emission intensity within a country is much larger than the heterogeneity of total factor productivity.

Despite the significant heterogeneity, reallocation only reduced emission with 4% to 8% (corresponding to 1% to 1.5% p.a.) between 2013 and 2019 (Table 3). Since reallocation plays a very strong role in increasing traditional productivity (see, e.g. Ben Hassine, 2019; CompNet, 2023), there is no reason to believe we can achieve emission intensity improvements of 4% to 5% p.a. without a sizeable contribution from reallocation. This could be from reallocation both within industry and within the different sub-segments of a (carbon-intensive)

23. The ETS reduction targets can also be met by further greening electricity production. Firstly, the drastic drop in carbon emissions stemming from electricity generation suggests that the low-hanging fruits have already been picked. Secondly, in France, given that the carbon intensity of electricity production is already low, there is limited scope to lower the carbon footprint of electricity generation.
24. This finding is in line with Probst et al. *(2021) who found that the average annual growth of climate change mitigation technologies slowed down significantly between 2013 and 2017, possibly driven by fossil fuel prices, low carbon prices, and increasing technological maturity for some technologies.*
25. 52 products and 2 so-called fallback approaches, based on heat and fuel.
26. Installations are linked to an activity within the EU Transaction Log and not to one of the 54 categories used for the calculation of free allowances. Calculating the heterogeneity of emission intensity for these 54 categories is therefore not possible.

industry. The former corresponds to the change in consumption patterns needed to reach climate neutrality (Pisani-Ferry & Mahfouz, 2023) where final consumption substitutes consumption of carbon-intensive products with that of less carbon-intensive products. The latter corresponds to moving output towards less carbon-intensive producers of a similar product.

Reallocation within a sub-segment of a carbon-intensive industry (see the list in Appendix) also brings significant potential savings based on current production technology. To quantify this potential, we conduct a basic thought experiment. We split our sample of firms into two groups: a first group comprising the 80% least carbon-intensive (i.e. most carbon-efficient) firms within an activity and a second group comprising the 20% most carbon-intensive (i.e. least carbon-efficient) firms within an activity. We refer to this latter group as brown zombies.

Our thought experiment now assumes that these brown zombies are pushed out of the market and that their output (measured in this exercise by value added) is taken over by the remaining firms with the same activity. These brown zombie firms represent less than 10% of value added in our sample, but more than 40% of emissions (see Table 6, line Total). The reallocation scenario assumes that the total output of each activity within the EU ETS remains constant, and that the output of the top 20% of firms by emission-intensity (the brown zombies) is now produced at the emissions intensity of the other 80% of firms with the same activity. The emission-saving potential of such a reallocation exercise is substantial: the reallocated output of the bottom performers would now be produced with substantially fewer emissions. We estimate that overall emissions would drop by almost 40%, whereas the total output that must be reallocated remains modest (see Table 6 for the detailed results). The risk of stranded assets therefore remains limited.[27] Furthermore, Capelle *et al.* (2023) showed that brown zombies (or "climate laggards" as they refer to them) operate older physical capital stocks which further mitigates the impact of possible stranded assets.

To what extent is the savings potential from this reallocation exercise realistic? Our estimate of the "brown zombie" emission-savings potential depends heavily, of course, on the difference in emission intensity between the bottom 20% and top 80% of performers with respect to carbon efficiency within an activity. A large part of this savings potential might stem from the fact that some activities regulated by the EU ETS (see the Table A1 in Appendix) are broadly defined and include firms producing very different products.

While there is certainly product heterogeneity within a single activity, we believe there is also substantial emission intensity heterogeneity within the production of similar products.[28] The design of the EU ETS is based on 52 benchmark technologies for products regulated under the system. Our data only allows us to split the sample in 26 activities, which implies that on average two different products[29] are produced within an activity. On the one hand, the results of our thought experiment are therefore an upper bound of the emission savings potential of reallocation. On the other hand, it remains a reallocation of 7% of output. If all firms were to be forced to operate using the EU ETS benchmark technology based on the best 10% of firms by emission intensity, 90% of firms would be affected. The Box provides further evidence that firms within the EU ETS do produce similar products with very different emission intensities.

What could drive the observed differences in emission intensity besides producing different products? Next to using different technology, an explanation is that some firms are better (i.e. in this context less carbon emitting) at using similar technologies and processes than other firms. Furthermore, some firms might have already started with (partially) electrifying[30] their production process. This would shift the firm's emissions within the EU ETS to the electricity producer (who is, if located within the EU also included within the EU ETS).[31] As such this is a desired process since electricity production

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27. Next to stranded physical assets or capital, there is also a possibility that the climate transition leads to stranded human assets. While the overall negative effects of the reallocation of labour to green activities should remain manageable (Vandeplas et al.*, 2022), this impact will be heterogeneous across geographical areas and types of workers (Bijnens* et al.*, 2022).*

28. Also, several authors have come to similar findings. As mentioned previously, Vieira et al. *(2021) found significant differences in carbon abatement results between manufacturing firms carrying out the same activities. Capelle* et al. *(2023) found significant heterogeneity in environmental performance within the same industry and country. Furthermore, it is well documented in the productivity literature that there are large and persistent productivity differences across producers, even within narrowly defined industries (e.g. Bartelsman & Doms, 2000; Syverson, 2004; and more recently for Europe Berlingieri* et al.*, 2020; and CompNet, 2023). If productivity differences between similar firms are substantial and persistent, we find it reasonable to assume emission intensity differences between similar firms are also substantial and persistent.*

29. The European commission states that the benchmarks are based on the principle of 'one product = one benchmark'. This means that the methodology does not vary according to the technology or fuel used, the size of an installation or its geographical location.

30. Electrification refers to replacing technologies or processes that use fossil fuels with electrically-powered equivalents. Electrification is an important component of most, if not all, scenarios to become net zero. E.g., the International Energy Agency's Net Zero Scenario aims in the short term to increase the share of electricity in industry's global final energy demands increases from approx. 22% (in 2022) to 30% (in 2030).

31. Note that outsourcing of emitting activities does not only reduce emissions, but also value added. Since we use value added as denominator for carbon intensity this partially covers the effect of outsourcing on emission intensity.

Box – **Similar Products Can Be Produced by Firms With Different Emission Intensities**

In this box, we provide examples of different firms regulated by the EU ETS that produce similar products but with different emission intensities. We focus on three homogeneous activities that produce commodities with limited possibilities to differentiate based on quality: manufacture of mineral wool; production or processing of gypsum or plasterboard; and production of soda ash and sodium bicarbonate.[a]

Table A presents the emission intensity for two firms undertaking each of these activities as well as their value added and number of employees. Based on the products promoted on their websites, these firms have similar product ranges.[b] To avoid results being driven by the volatility of value added in one particular year, we take an average over the 2013–2019 period. As a robustness check, we also calculate emission intensity based on number of employees instead of deflated value added. The firms are comparable in size but clearly have different emission intensities, calculated based on both deflated value added and on number of employees.

The reallocation exercise described earlier (with details in Table 6) would reduce emissions in the mineral wool, plasterboard and soda ash activities with 5%, 8% and 15% respectively for the same output.

Table A – **Comparison of emission intensity of two otherwise comparable firms within the same activity**

Firm	Country	Emission intensity (value added)	Emission intensity (employment)	Emissions	Value added (deflated)	Value added (nominal)	Employees
Mineral wool 1	Hungary	3,698	153	27,155	7	7	178
Mineral wool 2	France	1,874	117	13,556	7	7	116
Plasterboard 1	Austria	915	102	21,826	24	24	213
Plasterboard 2	Poland	2,163	136	31,206	14	15	230
Soda ash 1	Germany	3,795	520	159,563	42	42	307
Soda ash 2	Bulgaria	6,094	1,461	693,036	114	110	474

[a] Producing soda ash is the first step in the production process of sodium bicarbonate, the two products are therefore always produced in combination.
[b] The names of these companies can be provided upon request.
Note: Value added in € millions (deflated to 2015 prices), emissions in tCO_2-eq, emission intensity (value added) in tCO_2-eq per € million value added, emission intensity (employment) in tCO_2-eq per person employed. All numbers are averages taken over the 2013–2019 period.
Source: Authors' calculations based on EUTL and ORBIS data.

has become less carbon intensive and its path to net zero is well understood. Furthermore, several studies[32] found evidence of a high degree of pass-through of a carbon tax or emissions costs to wholesale electricity prices. This ensures firms also pay for indirect emissions stemming from electricity generation. An undesired possibility is so-called carbon leakage. Carbon leakage refers to the situation where businesses transfer emission intensive production to other countries with laxer emission constraints. This could lead to an increase in their total emission intensity while our measured emission intensity comes down. In the past there has been found little proof, however, of significant carbon leakage (Verde, 2020).

Our definition of brown zombies – based on emission intensity – remains arbitrary. It corresponds to a scenario where reallocation is triggered by regulation that enforces a certain maximum emission intensity per activity. We can also define brown zombies in a manner closer to that used in the productivity literature where it is based on the financial condition of a firm.[33] We therefore conduct a similar thought experiment with brown zombies defined as firms that become cash-flow[34] negative in 2019 if all emissions are to be paid at €100/tonne CO_2.[35] This corresponds to a scenario in which reallocation is triggered by market-based policies. This most optimal path to carbon neutrality is likely to be a combination of market and non-market-based policies (Acemoglu *et al.*, 2016; Anderson *et al*, 2021).

Producing the output of brown zombies at the emissions intensity of non-zombie firms would now result in a 55% emission saving (see Online Appendix, Table S3 for detailed results). This very high figure is mainly due to the absence of free allowances in this thought experiment.

32. E.g. Fabra & Reguant (2014) for Spain, Hintermann (2016) for Germany.
33. Adelat McGowan et al. *(2018) use interest coverage ratio to define zombie firms. Other definitions exist, e.g. firms with negative value added or negative profit.*
34. We use earnings before interest, taxed depreciation, and amortisation (EBITDA) to define cashflow.
35. Note that this is defined ceteris paribus as it does not take into account an endogenous response by the firm such as passing through the increased emission costs to prices, or emission mitigation efforts, etc.

Table 6 – **Reallocation exercise away from "brown zombies"**

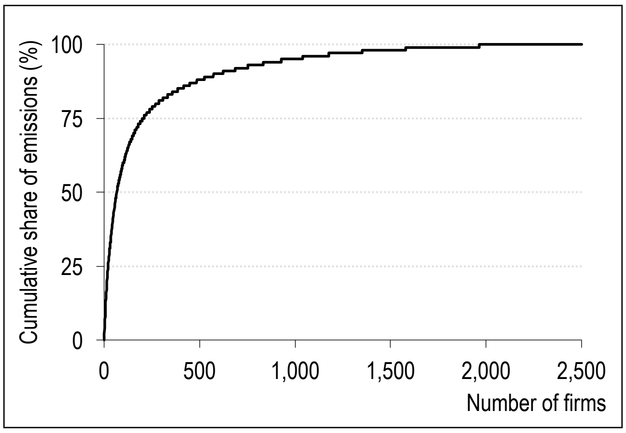
	80% least emission-intensive firms				20% most emission-intensive firms – "brown zombies"				Emission savings[1]	
	# firms	Value added	Emissions	Intensity	# firms	Value added	Emissions	Intensity	Emissions	% total
Combustion	621	165,062	17,760,229	108	159	4,449	27,136,280	6,099	26,657,580	59
Refining	40	24,166	56,603,202	2,342	10	1,148	23,755,133	20,693	21,066,212	26
Coke	4	57	1,377,279	24,163	1	1	49,870	49,870	25,707	2
Metal ore	10	899	2,420,491	2,692	2	749	5,775,289	7,711	3,758,662	46
Iron or steel	83	5,211	8,299,130	1,593	21	5,076	74,718,476	14,720	66,634,348	80
Ferrous metals	89	7,381	3,112,029	422	22	1,009	7,291,526	7,226	6,866,105	66
Primary aluminium	9	1,686	3,865509	2,293	2	123	1,047,211	8,514	765,208	16
Secondary aluminium	13	712	730,186	1,026	3	56	159,716	2,852	102,286	11
Non-ferrous metals	43	3,981	1,945,098	489	10	304	2,407,031	7,918	2,258,498	52
Cement clinker	64	4,957	69,913,969	14,104	16	367	15,243,223	41,535	10,067,022	12
Lime	52	1,441	14,975,566	10,392	13	46	2,059,478	44,771	1,581,424	9
Glass	137	6,894	10,357,700	1,502	35	853	3,985,795	4,673	2,704,229	19
Ceramics	278	5,356	7,888,791	1,473	71	291	2,058,235	7,073	1,629,624	16
Mineral wool	30	1,143	1,616,682	1,414	7	37	138,774	3,751	86,440	5
Gypsum or plasterboard	20	1,100	1,020,474	928	4	76	169,498	2,230	98,993	8
Pulp	88	7,335	4,254,649	580	22	342	1,307,165	3,822	1,108,789	20
Paper or cardboard	192	8,184	9,069,570	1,108	49	966	4,300,574	4,452	3,230,046	24
Carbon black	7	1,085	1,503,299	1,386	1	2	94,671	47,336	91,900	6
Nitric acid	7	542	1,627,898	3,004	1	1	22,488	22,488	19,484	1
Adipic acid	1	35	95,214	2,720	0					
Ammonia	8	749	10,146,416	13,547	1	16	694,956	43,435	478,210	4
Bulk chemicals	83	7,383	10,192,048	1,380	21	2,320	15,245,741	6,571	12,043,039	47
Hydrogen	11	1,507	2,405,103	1,596	2	58	1,846,508	31,836	1,753,943	41
Soda ash	4	200	1,378,128	6,891	1	95	1,008,094	10,612	353,483	15
Other	8	335	769,002	2,296	2	32	301,929	9,435	228,472	21
Oil and gas	81	13,230	11,714,743	885	20	665	8,103,617	12,186	7,514,781	38
Total	1,983	270,631	255,042,405	942	496 20%	19,082 6.6%[2]	198,921,278 43.8%[2]	10,425	171,124,485	38%

[1] Emission savings (in tCO_2-eq, % of total emissions) if the bottom 20% most emission-intensive firms would produce the same output, but with the average intensity of the 80% least intensive firms.
[2] Represents the share in the value added or emissions of the 20% most emission-intensive firms in the value added or emissions of all firms.
Notes: Figures for 2019. Value added in € millions, emissions in tCO_2-eq, emission intensity tCO_2-eq per € million value added.
Reading note: A limited reallocation from the 20% most emission-intensive firms ("brown zombies") toward the 80% least intensive firms within sectors can decrease emissions by 38%. This reallocation concerns 7% of output.
Source: Authors' calculations based on EUTL and ORBIS data.

In 2019, 70-80% of the emissions of the firms in our sample were covered by freely allocated emission allowances. Brown zombies now represent approximately 20% of value added and 70% of emissions. This market-induced reallocation has a higher savings potential but involves the reallocation of a larger share of value added.

The preceding paragraphs outline two potential strategies for reallocation reflecting EU-wide policy measures applicable to all industrial enterprises. An alternative strategy could prioritise decarbonisation initiatives on the main emitting firms. A striking feature of this data is the extreme concentration of emissions among a relatively small subset of firms (Figure II). Specifically, merely 100 companies (i.e. 4%) account for approximately 60% of the total emissions in our dataset. Additionally, these firms are predominantly situated within a handful of industrial

Figure II – **Cumulative share of total emissions of firms in the 2019 dataset**



Note: Cumulative emissions from the 2,479 firms in the 2019 dataset described in Section 1. The horizontal axis ranks the firms from most to least emitting and the vertical axis represents their cumulative emissions vis-à-vis total emissions.
Source: Authors’ calculations based on EUTL data.

sectors, with two-thirds of them active in either refining, iron and steel, or cement industries. The potential for emission reduction by targeting these 100 companies is significant. While these companies are responsible for 60% of emissions, they only contribute to 14% of the overall output in our sample. Achieving emission levels on par with the remaining 2,379 companies could result in a 38% reduction in emissions. Further details are provided in Online Appendix, Table S4.

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Based on CO_2 emissions data from the EU ETS, we find that, unlike the electricity sector, manufacturing industry has not significantly reduced its emissions over the past decade. The prevailing thought is that, while the future path for electricity generation is clear, for the manufacturing sector there is uncertainty over the technologies that should be adopted and what their actual potential is for carbon abatement. This line of thinking risks opening the door to a “wait and see approach”. However, over the next decade, if the EU’s ambitious “Fit for 55” target is to be achieved, it will not only be necessary for the energy sector to decarbonise further, but the manufacturing industry will also have to significantly reduce its carbon footprint, and quickly.

While innovation and carbon efficiency improvements within existing firms are crucial for long-term climate neutrality, we propose that medium-term emission reduction targets may also be met through the reallocation of economic activity. This approach involves shifting production from the least emission-efficient firms (brown zombies) to the most efficient ones. Reallocation, compared to the often lengthy process of developing and adopting new technologies, potentially makes it an alternative option for near-term emission reductions. However, the current discourse on industrial decarbonisation tends to prioritise the search for and adoption of new technologies, possibly overlooking the significant and more immediately accessible benefits of fully exploiting existing efficient technologies through reallocation of industrial production.

Our analysis reveals substantial variations in emission intensities within industries, with a subgroup of manufacturers contributing disproportionately to sector-wide emissions. We estimate that a significant reduction in carbon emissions -up to 38% in some cases- is possible through the reallocation of production among firms, without the need for new technology. This conclusion assumes that observed variations within narrowly specified activities are largely attributable to differences in technology or production processes rather than product distinctions. This assumption, though potentially not fully applicable to every industrial activity examined, offers an upper limit estimate for possible resource reallocation. According to our results, when designing emission reduction plans, in addition to greening incumbent industrial firms, policymakers should also take more account of the possibility that some companies may need to shrink or exit the market in favour of more carbon-efficient competitors. ☐

Link to the Online Appendix:
www.insee.fr/en/statistiques/fichier/8305256/ES544_Bijnens-Swartenbroekx_OnlineAppendix.pdf

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Table A1 – **Activities regulated under the EU ETS**

Description of the activity	Shortened notation
Aircraft operator activities	Aircraft
Combustion of fuels	Combustion
Refining of mineral oil	Refining
Production of coke	Coke
Metal ore roasting or sintering	Metal ore
Production of pig iron or steel	Iron or steel
Production or processing of ferrous metals	Ferrous metals
Production of primary aluminium	Primary aluminium
Production of secondary aluminium	Secondary aluminium
Production or processing of non-ferrous metals	Non-ferrous metals
Production of cement clinker	Cement clinker
Production of lime, or calcination of dolomite/magnesite	Lime
Manufacture of glass	Glass
Manufacture of ceramics	Ceramics
Manufacture of mineral wool	Mineral wool
Production or processing of gypsum or plasterboard	Gypsum or plasterboard
Production of pulp	Pulp
Production of paper or cardboard	Paper or cardboard
Production of carbon black	Carbon black
Production of nitric acid	Nitric acid
Production of adipic acid	Adipic acid
Production of glyoxal and glyoxylic acid	Glyoxal
Production of ammonia	Ammonia
Production of bulk chemicals	Bulk chemicals
Production of hydrogen and synthesis gas	Hydrogen
Production of soda ash and sodium bicarbonate	Soda ash
Capture of greenhouse gases under Directive 2009/31/EC	Capture GHG
Transport of greenhouse gases under Directive 2009/31/EC	Transport GHG
Storage of greenhouse gases under Directive 2009/31/EC	Storage GHG
Other activity opted-in pursuant to Article 24 of Directive 2003/87/EC	Other

Source: EUTL.

COMMENT

The Challenge of the Century and Economics

Aude Pommeret*

Abstract – The work of climate economists, on the social cost of carbon in particular, is expanding and recent academic research is being taken on board and used by government bodies. In France, for example, the Quinet Commission on the value of carbon, the Criqui Commission on the sectoral costs of cutting emissions and the Pisani-Ferry and Mahfouz Commission on the assessment of the cost of the transition were set up for use in public policy. However, interest in the challenge of the century seems to stop at economics, the recommendations from which are ultimately rarely applied. While contributing to academic research, the articles contained in this issue also contribute to ensuring that climate costs are taken into account in public policies and propose solutions to help the energy transition is achieved in the best way possible.

JEL: H23, H43, Q54
Keywords: Climate change, abatement costs, price of carbon, environmental policy

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While the importance of environmental economics as a topic for study is not fully recognised (Timbeau, 2024), it must be noted that it is not only a sub-discipline, considered to be one application among others falling within the framework of public economics, but it is also a topic that is interdisciplinary in nature, which does not simplify the task of economists who study it. For example, in order to properly model the dynamics of global warming, or to take into account the critical nature of the materials used in the construction of solar panels, wind turbines or batteries needed for the energy transition, or to evaluate the cost of thermal renovation of buildings, these economists must work closely with climatologists, geologists, thermodynamics specialists, etc. While such collaboration is already a challenge in itself, generating interdisciplinary publications that are recognised by the academic world is another.

However, economists have been studying natural resources for several decades, developing concepts that can now be used by climate economists. Moreover, the latter are currently expanding their work, notably to measure the social cost of the "greatest and largest market failure ever seen" (Stern, 2006), and there is a broad consensus appearing among economists in favour of carbon pricing, through a tax on carbon dioxide (CO_2) emissions[1] or an emission allowance system, as the best – or even the only – climate policy. For example, the European Association of Environmental and Resource Economists published a statement on carbon pricing in 2021.[2]

In practice, however, it seems that carbon pricing is popular only among economists. In France, against a backdrop of reducing the public deficit, there is no strong support for the energy transition, and the "yellow vest" movement sounded the death knell of the climate-energy contribution (the name given to the tax on carbon emissions introduced in 2014 in France), which has since been static at EUR 44.6 per tonne of CO_2. With current public debt problems preventing the funding of subsidies to support the energy transition, and standards, whether in relation to low-emission areas or agricultural standards, having proved to be unpopular, we can perhaps hope for a return to the forefront of carbon pricing, but through the back door. Carbon pricing has had more wind in its sails in recent years at European level, with initiatives such as the Carbon Border Adjustment Mechanism or the EU-ETS2.[3] However, the ecological or energy transition was not a key topic in the 2024 European elections and one can only hope that the policies that were envisaged will be maintained.

The problem, therefore, has perhaps less to do with the lack of work by economists than with the use of that work for public policy. Interest in the challenge of the century seems to stop at economics, the recommendations of which still face barriers and are not applied. The articles in this issue seek to overcome such barriers. The articles not only contribute to academic research, but also contribute to ensuring that climate costs are taken into account in public policies and propose solutions to help the energy transition.

Advances in Research on Climate Damages

There are several specific methods that can be used to assign a price to carbon. The first is to adopt a cost-benefit approach that aims to determine the social cost of carbon, in other words, the cost that allows the adoption of the socially optimal trajectory for greenhouse gas (GHG) emissions at global level, by constantly ensuring equality between the marginal abatement cost, that is, the cost of reducing GHG emissions by one tonne, and the discounted sum of the future marginal damage of one tonne of GHGs emitted today. This approach is not easy to reflect in the form of public policy; on the one hand, there is nothing to guarantee that the emission reduction trajectory entailed in the social cost of carbon is compatible with the international, European and national objectives that countries set themselves. On the other hand, this approach poses methodological problems in relation to computational complexity. In particular, the prices obtained from academic research are not yet stabilised, even though such research is extremely active.

The social cost of carbon is a good example of a topic on which climate economics research is particularly abundant… and interdisciplinary. Indeed, the work first sought to improve the

1. Climate change stems from greenhouse gas (GHG) emissions, including CO_2. However, it is possible to convert all GHGs, in accordance with their effect on global temperature for a given time horizon, into CO_2 equivalent (CO_2eq), which is often inaccurately referred to as simply CO_2. In this article, GHGs or CO_2 will generally be used indifferently.
2. See https://www.eaere.org/statement/
3. The Carbon Border Adjustment Mechanism (CBAM) aims to tax emissions from imported products at a level equivalent to that applied to domestic products subject to carbon pricing, with the primary objective of tackling carbon leakage. The EU-ETS2 is a new EU-wide emissions trading scheme, which was created to cover emissions from buildings, road transport and other sectors and will be operational in 2027. In its current form, the EU-ETS covers emissions from the electricity and heat production, industrial manufacturing and aviation sectors, which account for around 40% of total GHG emissions in the EU.

modelling of the dynamics of the terrestrial climate system (Otto *et al.*, 2013; Dietz *et al.*, 2021b; Ricke *et al.*, 2018; Hänsel *et al.*, 2020). Until now, the major economic models have largely overestimated the time between carbon emissions and warming, while ignoring the saturation of natural carbon-absorbing reservoirs (so-called carbon sinks) that occurs when the atmospheric concentration of CO_2 increases. Due to this saturation, the marginal effect of cumulative emissions on warming is constant. Assuming that damages are a convex function of warming, this implies that the optimal price of carbon increases faster than overall production.

In addition, the way in which uncertainties that affect the damage function are taken into consideration has been improved significantly. First, tipping points and uncertainties in relation to damages were incorporated into the modelling (Nordhaus, 2019; Lemoine & Traeger, 2016b; Cai *et al.*, 2015; Dietz *et al.*, 2021a) and uncertainty itself has been modelled at a more granular level by taking into account ambiguity and learning new information (Rudik, 2020; Lemoine & Traeger, 2014 and 2016a; Berger *et al.*, 2017; Lemoine & Rudik, 2017). Finally, more complex utility functions and the consideration of damages distribution have made it possible to not only identify preferences in terms of risk and time (Cai & Lontzek, 2019; Crost & Traeger, 2014; Daniel *et al.*, 2019), including a utility function in the manner of Epstein-Zin, but also to incorporate aversion to inequality (Ricke *et al.*, 2018; Moore & Diaz, 2015; Dietz & Stern, 2015; Moyer *et al.*, 2014).

Progress has also been made in taking into consideration the consequences of climate change on the economy. In some models, it is now assumed that the rate of economic growth (through investment productivity or capital depreciation) – and not just the level of production – is affected by climate damage (Ricke *et al.*, 2018; Dietz & Stern, 2015; Moyer *et al.*, 2014).

The calibration of aggregate climate damage has been improved through the use of recent economic and scientific data (Ricke *et al.*, 2018; Rudik, 2020; Moore & Diaz, 2015). Finally, advances have been made in taking into account the climate damages caused to non-commercial items, such as natural systems or cultural heritage, which cannot be identically replaced with goods traded on the market (Sterner & Persson, 2008; Bastien-Olvera & Moore, 2021; Weitzman, 2010; Drupp & Hänsel, 2021).

These advances have led to higher estimates of the social cost of carbon, frequently with values in excess of USD 100 per tonne of CO_2. Tol (2023) and Moore *et al.* (2024) perform meta-analyses on several thousand estimates of the social cost of carbon. Tol (2023) shows that over the last ten years, estimates of the social cost of carbon have increased from USD 9/tCO_2 to USD 40/tCO_2 for a high discount rate and from USD 122/tCO_2 to USD 525/tCO_2 for a low discount rate. Moore *et al.* (2024) obtain a truncated average (i.e. excluding the top and bottom 0.1% of the distribution) of USD 132/tCO_2 with a thick tail-end of distribution to the right. Most importantly, the range of estimates is wide and has remained so over the years or even widened.

To overcome the still imperfect understanding of climate damages, a second approach, which differs from the cost-benefit approach, consists in starting with a GHG emissions or concentration target, then determining the trajectory of carbon prices to reach this target at the lowest cost. This approach, known as the cost-effectiveness approach, makes it possible to avoid an exercise to determine the value and discounting of damage, in so far as the marginal damage curve is replaced by an emissions target. Its relevance is based, first, on the legitimacy of this target and, second, on a good assessment of the marginal abatement costs linked, in particular, to the portfolio of available and foreseeable technologies. The cost-effectiveness approach has been the subject of academic work in Europe in particular, initiated by Michel Moreaux.[4]

Assessments Carried Out by Government Bodies

Recent academic work is being taken on board and accepted by government bodies for use in public policy, for example by the EPA (Environmental Protection Agency) in the United States (on the basis of the cost-benefit approach), the Green Book in the UK or France Stratégie in France. In France, there is a shadow price of carbon,[5] developed in 2008 and then updated in 2019 under the name of *Valeur de l'Action pour le Climat*[6] (Value for Climate Action – VAC, the Quinet Commissions) and based on a cost-effectiveness approach, a measure of abatement costs (Criqui Commission) by major carbon emitting

4. *See, for example, Chakravorty* et al. *(2005) or van der Ploeg (2021).*
5. *The value of actions to combat climate change has historically been developed, under the name of a shadow price, for the socio-economic assessment of public investments. However, this assessment was then extended to all possible actions, to set the right priorities, encourage useful actions and schedule them over time.*
6. *The 2024 update is ongoing.*

sectors and an assessment of the cost of the transition (Pisani-Ferry and Mahfouz Commission).

The Value for Climate Action

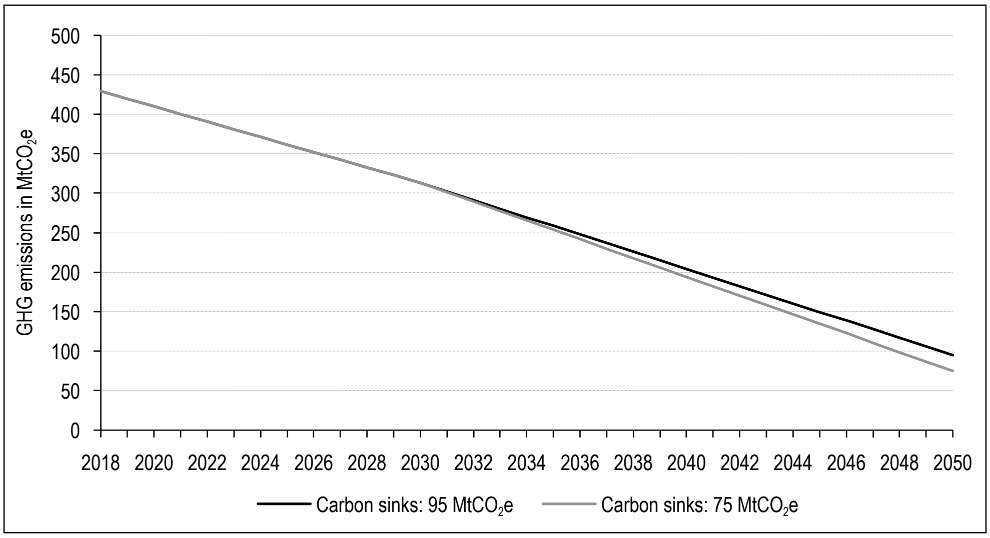
The Value for Climate Action determined by the 2019 Quinet Commission,[7] which falls under the cost-effectiveness approach, consists of setting a fictitious carbon price trajectory that triggers technological or behavioural changes compatible with a politically established gas emissions trajectory aimed at achieving net zero emissions by 2050. The relevance of this approach relies on an accurate assessment of the marginal abatement costs, that is to say the costs of reducing CO_2 emissions linked in particular to the portfolio of available and foreseeable technologies. The negative impacts of CO_2 are implicitly taken into account by the target, but climate damages ares not explicitly incorporated.

The 2019 Quinet Commission was based on a global approach incorporating, beyond the theoretical and empirical developments available, original modelling work and a prospective analysis of the available decarbonisation technologies based on the definition of an emissions trajectory. The Commission took into account a smooth emissions reduction trajectory, with an intermediate point in 2030 (−43% gross emissions compared to 1990 emissions, see Figure I), consistent with the Climate Plan of July 2017 and leading to net zero emissions (NZE) in 2050. The emissions taken into consideration concern all greenhouse gases (translated into CO_2 equivalent) and correspond to all emissions occurring on French territory, net of carbon sinks available on the national territory. The target covers all sectors, without ex-ante incorporation of sectoral targets, since one tonne of carbon (emitted or avoided) is the same regardless of the sector of origin.

Simulation and foresight exercises were carried out using both macroeconomic models and techno-economic models, which can be used to determine the temporal trajectory of the carbon price, making it possible to follow an emission reduction pathway consistent with the French NZE target. The macroeconomic models incorporate an increase in the relative price of carbon options and show how different sectors adapt to this relative price increase, invest and decarbonise. The techno-economic models use a detailed description of technologies to assess the cost of deploying the technologies necessary for decarbonisation, but are less rich in economic mechanisms. The initial simulations were supplemented with technological or techno-economic foresight exercises,[8] making it possible to assess the costs of different decarbonisation technologies – and therefore the carbon prices that trigger the abandonment of carbon solutions in favour of decarbonised solutions. Finally, the trajectory obtained was discussed with stakeholders including researchers, economists, representatives of trade unions and employers' organisations, certain professional federations and representatives of the government bodies concerned, in order to judge its relevance and the conditions for its implementation. The trade-off

7. *See also Quinet (2019b).*
8. *Such as those conducted at global level by the International Energy Agency (IEA) or at French national level as part of the preparation of the National Low Carbon Strategy (*Stratégie Nationale Bas-Carbone, *SNBC).*

Figure I – **Target trajectory for GHG emissions**



Source: Quinet (2019a).

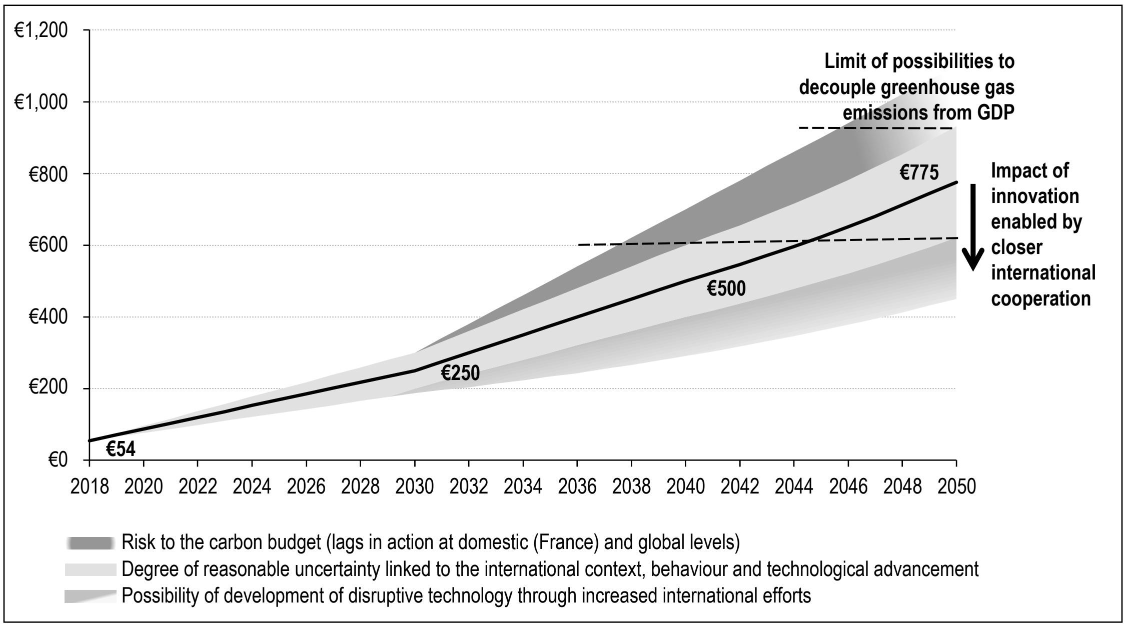
between a Value for Climate Action with an initial jump but a moderate gradient and a Value for Climate Action that is smooth at the start but with an initial steep gradient was a particular topic of debate. The gradient of the trajectory is as important a parameter as the mean value, because any assumption of growth in the Value for Climate Action implies a rate of exchange between one tonne of GHGs saved today and one tonne of GHGs saved in a year's time that measures the efforts that one wishes to put in for an early effort.

On the basis of the modelling work carried out, the Commission proposed, starting from EUR 54 in 2018,[9] setting a target Value for Climate Action of EUR 250_{2018} in 2030 (see Figure II): taking into account the changes in targets and techniques, as well as the delay in comparison with the desirable trajectory for our emissions, the trajectory defined by the Quinet Commission (2019a) therefore leads to a clear upward revision of the target shadow price, since the target set for 2030 in 2009 was EUR 100. Beyond the 2030s, the proposed price gradually aligns with a rule of growth based on the socio-economic discount rate.[10] By 2050, it is in line with the foreseeable costs of technologies allowing the recovery of CO_2 from the air – a conservative range of EUR 600 to 900_{2018}/tonne of CO_2e. In Figure II, the shaded clusters reflect uncertainties, which increase as the horizon extends beyond 2030. Greater international cooperation, allowing faster production and dissemination of innovations, while enabling groundbreaking technologies at lower cost, would achieve the same targets with a lower Value for Climate Action. In contrast, the lower availability of critical materials needed for investments or infrastructure to be built for the energy transition (solar panels, wind turbines, batteries, etc.), or a degradation of the forest carbon sink would increase the cost of technologies and imply a higher Value for Climate Action.

The Value for Climate Action is currently undergoing further revision to reflect changes in targets and context that have taken place since 2019. It consists essentially in a more precise and ambitious definition of targets, particularly at European level (−55% of emissions by 2030 compared to 1990), of technological changes, and of taking into account the unfavourable development of the forest carbon sink (the forest carbon sink in France has halved over the last ten years due to exceptional mortality in forest ecosystems and increased removals). Furthermore, the work of the Criqui Commission on sectoral abatement costs, which uses the Value for Climate Action, has made it possible to assess the practical difficulties posed by a Value for Climate Action that does not increase in line with the socio-economic discount rate over the

9. The actual value of the specific carbon pricing at that time, taking into account inflation.
10. This is Hotelling's rule, in other words, the rule for good management of an exhaustible resource in a theoretical framework (with the carbon budget then corresponding to the stock of the exhaustible resource), the value of which is intended to grow at the pace of the socio-economic discount rate.

Figure II – **The Value for Climate Action**



Source: Quinet (2019a).

whole period,[11] which does not guarantee the intertemporal neutrality of efforts.

Sectoral Abatement Costs

As recommended in the 2019 Quinet Commission's report on the Value for Climate Action, a commission on GHG emission abatement costs was established in September 2019 to identify key policy options, on a sector by sector basis, and to measure the socio-economic costs. This commission, chaired by Patrick Criqui, developed a methodology for calculating abatement costs and made estimates for five strategic sectors. The latter were chosen due to their importance in French GHG emissions, or their importance in decarbonising the energy system: transport, power grid, hydrogen production, housing and industry (see Figure III). This work, which takes on a socio-economic perspective for France, contributes to a better identification of the determining factors of abatement costs in these different sectors and makes it possible, from a planning perspective, to prioritise actions with different time horizons on the carbon neutrality trajectory.

The work of the Criqui Commission has resulted in the identification of certain specific issues regarding the assessment of abatement costs. First of all, it must be connected with the Value for Climate Action. Indeed, it is the comparison (which is less trivial than it seems, see the "Methodology" chapter of the Commission's report) of abatement costs with the Value for Climate Action that makes it possible to determine whether or not the adoption of a technology is relevant. In addition, the assessment of abatement costs is complex and shrouded in uncertainties, first, because it is necessary to take into account the evolution of the costs and performance of the different options or technologies without omitting the endogenous dimension of technical progress, notably through "learning effects". Second, the abatement is achieved through carrying out investments that are characterised by the phenomena of inertia, dynamic effects and interdependencies. It is therefore often necessary to undertake costly actions to unlock access to cheaper options. This is the case, for example, with regard to investments in transport infrastructure (for example cycle paths) that are necessary to trigger modal switches (from cars to bicycles), which will then lead to reasoning in terms of non-marginal investment: the ranking of these isolated actions in order of merit, in the manner of McKinsey's "MAC curve", which apparently responds to the concern for efficiency, therefore loses its relevance. Sometimes, it is not even possible to construct the calculation on the basis of the comparison of two isolated technologies: if we consider the complete decarbonisation of the power grid with a very high degree of penetration of renewable energies, for which the generation of electricity varies over time (it depends in particular on the weather), it is necessary to take into account the "system costs" linked to the need to constantly ensure a balance between the supply of and demand for electricity. Finally, the socio-economic approach involves taking into account external costs and benefits, the quantification of which is difficult since they do not have a market value. Valuation attempts carried out so far suggest that while these costs may be very high, they are marked by high levels of uncertainty.

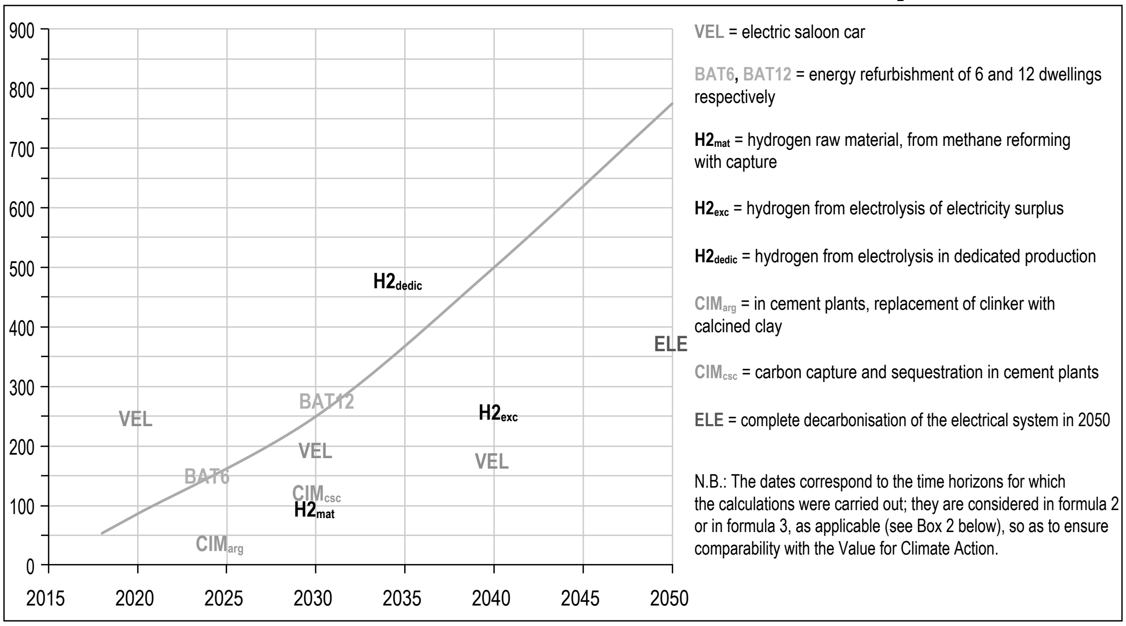
Figure III shows the abatement costs resulting from the deployment of certain technologies, which are flagship technologies for the sectors studied. They are calculated for a specific date that may differ by technology and in accordance with a fairly complex methodology that allows them to be compared directly to the Quinet (2019a) Value for Climate Action for that date. This comparison therefore makes it possible to determine, contingent upon the Quinet (2019a) Value for Climate Action trajectory, whether each of these technologies is desirable from a socio-economic point of view. The Criqui Commission finds that by 2030, the abatement costs are in the range of EUR 150/tCO_2 to EUR 250/tCO_2 for the main options in the final energy consuming sectors or for the decarbonisation of hydrogen used as raw material. As the Quinet (2019a) Value for Climate Action trajectory reaches EUR 250/tCO_2 in 2030, this graph shows that the implementation of the options studied, although costly, is therefore desirable from the point of view of the community.

The Macroeconomic Costs of the Energy Transition

Once the roadmap for the investments needed for the transition has been drawn up, questions arise about the cost of these investments, the speed of their implementation and how to cover their costs. In France, the Pisani-Ferry and Mahfouz report highlights that the climate transition is a major transformation, analogous in magnitude to the industrial revolutions of the past, which must be driven at an accelerated pace due to the delay in taking action and the new geopolitical context (Pisani-Ferry & Mahfouz, 2023).

11. See the "Methodology" chapter of the Criqui Commission's report.

Figure III – **Value for Climate Action and abatement costs (in €/tCO_2)**



Source: Criqui Commission.

This transition will be based on three main mechanisms. First of all, the replacement of fossil fuels with capital will require a substantial increase in investments for France, which will be necessary for achieving the objectives of the previous National Low Carbon Strategy (*Stratégie nationale bas-carbone*, SNBC 2), of around EUR 70 billion, at the 2021 EUR value, per year (2.5 GDP points) until 2030. Around half of this sum is expected to be covered by the public coffers, with the remainder coming from the private sector. Most of the technologies to be implemented by 2030 are already available. Second, technical progress will be redirected in an accelerated manner both towards alternatives to fossil fuels and towards improving energy efficiency. A significant role is assigned to energy sufficiency: according to this report, the main vector by 2030 will most certainly be the replacement of fossil fuels with capital, but energy sufficiency could contribute to the reduction of emissions by between 12% and 17%.

There is no guarantee, however, that the emissions trajectory chosen will ensure that the transition is achieved at minimal cost, which is precisely what the two articles in this issue call into question.

Research in Service of Public Policy

The article by Riyad Abbas, Nicolas Carnot, Matthieu Lequien, Alain Quartier-la-Tente and Sébastien Roux studies the impact on the costs of the transition of the emission reduction trajectory adopted (Abbas *et al.*, 2024). Without calling into question the cost-effectiveness approach, the article examines the way in which, the Net Zero Emissions in 2050 target should be interpreted in terms of modelling, not only to ensure compliance with the Paris Agreement, but also to minimise the costs of the transition. The assessments by the French government bodies are based on the French Energy and Climate Strategy (*Stratégie française sur l'énergie et le climat*, SFEC), which proposes a decarbonisation pathway and therefore amounts to imposing additional constraints. The article examines the consequences of these constraints on the speed of brown capital disposal and green capital investment. In the simple model proposed, these two forms of capital may have different productivity levels and are imperfectly substitutable. The investment is irreversible in the sense that turning brown capital into green capital or consumption is impossible, but brown capital can be disposed of, or "stranded", according to the applicable vocabulary. Their model can be used to examine how brown and green investments and capital stocks change over time, depending on the type and severity of the constraint specific to each decarbonisation scenario. It is calibrated to French national level: in particular, a stylised estimate is proposed of brown capital as a share of productive capital, based on the national accounts and the climate investment trajectories by I4CE (2022). The various scenarios studied, with varying levels of constraints, lead to the following conclusions. Unsurprisingly, it is in the least constrained scenario (once the scenario aimed at achieving Net Zero Emissions alone, which does not make much sense under the Paris Agreement, has been eliminated), that is to say, with intertemporal management of the carbon budget, that the disposal of brown capital and green investment are undertaken quickly, which limits the cost of the transition.

This raises the question of another type of cost: that of accepting the energy transition. If it is too high, it can simply prevent this transition. However, this article shows that the introduction of ad-hoc constraints leads to sudden disposal, which makes acceptance of the transition more difficult. The results can therefore be interpreted as a plea for management of the transition in the manner of a "carbon budget". The Hotelling's rule resulting from this also gets rid of any inconsistency in growth rate between the Value for Climate Action and the discount rate (see above). However, there is nothing preventing the imposition of an annual trajectory compatible with intertemporal management of the carbon budget. In particular, this would make it possible to verify the progress actually made in relation to that expected, on an annual basis, or even to record climate debt, a practical and convincing indicator, in these times of budgetary restrictions.

The article by Gert Bijnens and Carine Swartenbroekx also examines the issue of the transition path by looking at the disposal of brown capital: the authors seek to measure the extent of the reduction in CO_2 emissions if production were reallocated from the most polluting companies in a sector to the least polluting companies in the same sector (Bijnens & Swartenbroekx, 2024). In the background, there is the idea of a carbon price, since their "brown zombie" companies could be defined as companies that would no longer be competitive if the carbon price were imposed on them in the form of a tax (or emission permit). This concept of "brown zombies" can therefore be compared to the internal carbon prices used by some companies to verify their sustainability in anticipation of future binding climate policies: if their net result remains positive once the costs of their carbon emissions, valued at their internal price (i.e. defined by the companies themselves, but the social cost of carbon or the Value for Climate Action are good avenues), have been added to their other costs, their economic model would withstand an environmental policy for which the level of constraint would correspond to this internal price.

The authors conclude that a limited reorientation within a sector towards the least polluting companies, to the detriment of the most polluting companies, could lead to a 38% reduction in European emissions. Like those of the previous article, the authors insist on the need to pay attention to capital disposal and recommend not only focusing on green investment. Above all, this article is a genuine plea for the implementation of a carbon price rather than a subsidy for green investment: this price would spontaneously cause the "brown zombies" to disappear from the economy, in favour of less polluting companies in the same sectors.

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While economics research is largely devoted to assessing the climate cost and, to a lesser extent, the abatement costs, such as by incorporating critical materials and their recycling into renewable energy infrastructures (see Pommeret *et al.*, 2022), government bodies create carbon prices, assess abatement costs and measure the macroeconomic consequences of the transition. What's next? The articles in this issue attempt to go further, removing the barriers between recommendations and effective policies, and getting closer to practical recommendations regarding the pathway to the decarbonisation of the economy.

The two articles do not explicitly focus on the carbon price – which is unpopular with the public – but rather on green investments and the disposal of brown capital, and they arrive at similar conclusions: brown capital must be disposed of as soon as possible. While the economic effectiveness of this recommendation is unquestionable, it is difficult to envisage ways in which it would be more readily accepted, such as in the form of regulation, than as a carbon price (which could itself lead to optimal stranding).

Undoubtedly, the disciplines with which environmental economics has links should shift from hard sciences to social sciences: political science, sociology or psychology would no doubt be better able to remove the barriers and prevent interest in the challenge of the century from stopping at economics. ☐

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Recruitment Difficulties Anticipated by Companies: What Are the Explanatory Factors in France?

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Abstract – This article examines the difficulties anticipated by companies in France when it comes to recruiting staff. We match data from the 2018 and 2019 *Besoins en Main-d'Œuvre* surveys on workforce needs with company data from the FARE annual structural statistics of companies from the ESANE scheme and the DADS (*Déclaration annuelle de données sociales* – Annual Declaration of Social Data) to examine how recruitment difficulties are distributed by sector, location and size of the establishment and employment area characteristics. Together, these factors explain around 6% of the total variation in recruitment challenges, increasing to 14% when incorporating recruitment difficulties reported in the previous year. Most of the recruitment difficulties anticipated thus result from factors not observed in the data used in this article, potentially linked to the internal characteristics of each establishment, such as the quality of management and specific recruitment processes.

JEL: C01, J23, J63
Keywords: recruitment difficulties, company data, Probit

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The difficulties companies face when it comes to recruiting staff reveal frictions in how the labour market operates. Such difficulties decrease the efficiency of work allocation. Even though most job vacancies are filled (only 5% of vacancy listings were discontinued at the Pôle emploi employment agency due to a lack of qualified candidates over the last decade according to Gaumont, 2020), recruitment difficulties generate additional costs and increase the time needed to fill vacancies (Lhommeau & Rémy, 2019). According to INSEE, in July 2022, 67% of industrial companies reported experiencing recruitment difficulties, a level that was unparalleled since 1991 (INSEE, 2022). Identifying the factors that are at the root of these difficulties is therefore essential in order to guide public interventions and attempt to make the labour market more efficient.

The aim of this study is to identify the main factors that cause recruitment difficulties by focusing on the characteristics of the establishments and their environment. The data used, taken from the *Besoins en Main-d'Œuvre* (BMO) survey on workforce requirements by Pôle emploi (known as France Travail since 01/01/2024), describe the difficulties recruiters anticipate facing in the coming year. Studying anticipated rather than actual difficulties is interesting for several reasons. First, frictions, even if only anticipated but not ultimately experienced, can have actual consequences on the activity of the companies concerned. Indeed, recruiters who anticipate experiencing difficulties could reduce the number of hires or postpone them to a later date (Lhommeau & Rémy, 2020). According to the survey carried out to supplement the BMO survey by Pôle emploi, 27% of establishments that did not recruit in 2018 attributed that lack of recruitment to the anticipation of too many difficulties. Finally, anticipated difficulties reflect the point of view of recruiters. Comparing them with the actual difficulties experienced allows us to assess whether these anticipations become reality.

This study is innovative for two reasons. The first relies on the use of an original dataset combining many data sources. We first use the BMO survey from Pôle emploi. We then use the DADS social declaration data, which describe the characteristics of the workforce and wages of establishments, and the FARE tax data, as well as aggregated administrative data. This study is the first to use not only data on the establishment or company, via tax and social data, but also local geographical characteristics and granular characteristics of the occupations for which candidates are sought in recruitment processes. The second reason is that the study covers a large number of sectors and provides an establishment-level perspective, rather than using a sector- or occupation-focused approach (Niang & Vroylandt, 2020; Niang *et al.*, 2021; Arik *et al.*, 2021).

The main finding of the study is that the observed characteristics of the establishments explain only a limited part of the anticipated recruitment difficulties (approximately 3% of the total variance). Incorporating the characteristics of the occupations open for recruitment into the analysis still explains a small part of the variance (about 6% of the total variance regardless of the model and 14% if we also take into account the existence of difficulties in the past).

The rest of this article begins with a literature review concerning the factors that may explain recruitment difficulties (Section 1), then we present the data used, the sample selected and our methodology (Section 2). We set out descriptive statistics (Section 3), followed by our findings, discussing them in relation to the existing literature (Section 4). We conclude by summarising the main lessons learned from our study and suggest avenues for further exploration for researchers and policy makers.

1. Explanatory Factors Behind Recruitment Difficulties

1.1. Theoretical and Empirical References

In the economic literature, recruitment difficulties can be seen as symptomatic of a difficult match between jobseekers and companies. The theoretical framework that explains the matching mechanisms at play in the labour market was developed in the works of Diamond (1982) and Mortensen & Pissarides (1994).[1] The models introduce frictions that thus explain the coexistence of vacancies and jobseekers. This difficult matching process may be due to an excess in labour demand (excess of vacancies) or an inadequate supply of labour (few individuals looking for work). Search efforts by recruiters or jobseekers can also impact the effectiveness of finding a match. As such efforts increase, the number of matches (or the number of hires) achieved for a given number of jobseekers and job vacancies also increases (Lazear, 2014; Rémy, 2022). This study aims to

1. See Rogerson et al. (2005) for a literature review on this issue.

better understand frictions due to demand for labour by incorporating not only establishment characteristics, such as size; but also, rigidities due to the labour supply by considering variables characterising the environment, such as local population density.

Fabling & Maré (2016) use panel data on New Zealand companies to determine the factors that explain recruitment difficulties. They find a high degree of persistence across years: more than 60% of the companies that reported recruitment difficulties in 2009 were already doing so in 2008. In our study, we also find a high level of persistence. Fabling & Maré (2016) find that companies with high financial turnover report more recruitment difficulties than those with low financial turnover, even though they offer better wages on average. The authors explain this result by referring to the work of Haskel & Martin (2001), which links skills shortages with technical progress. To keep innovating and remain competitive, large companies would be those that need a more skilled workforce, which is more difficult to recruit. The findings reached in this study are different: the recruitment difficulties anticipated are lower in companies with high financial turnover and a large workforce, which is rather indicative of a learning effect over the course of recruitment campaigns, resulting in less difficulty in recruiting for large companies, which are able to establish a better quality of human resources department.

While Fabling & Maré (2016) do not find any specific effect related to local labour markets, Blanc *et al.* (2008) show that population density has an impact on recruitment difficulties. Using French data from the Midi-Pyrénées region, they find that companies recruiting in areas with low population density are likely to be more exposed to recruitment difficulties. This is due to the lack of available labour in low-density areas, and the resulting low labour supply.

Davis *et al.* (2013) look at the dynamics around the number of vacancies and the vacancy fill rate at establishment level in the United States. They find that the vacancy fill rate increases sharply with staff turnover. They explain this phenomenon by the fact that companies more accustomed to recruitment processes experience less difficulty in hiring. The authors also highlight the role of human resources structures in recruitment processes, making it easier to circulate vacancy advertisements, select candidates and negotiate wages and benefits. We also find that the higher the staff turnover rate, the fewer the recruitment difficulties, suggesting that the above-mentioned factors related to the internal organisation of companies are likely to influence the level of anticipated recruitment difficulties.

Carrillo-Tudela *et al.* (2020) show that wages at the time of hiring have an impact on the proportion of vacancies advertised by companies that are filled. Mueller *et al.* (2018) also show that job vacancies are filled quicker when the wage offered is high. We complement this earlier work and find that the establishments offering higher salaries report facing fewer recruitment difficulties.

Arik *et al.* (2021) seek to assess how, in the manufacturing sector, the characteristics of companies, their environment and the occupations for which they are recruiting affect the recruitment difficulties they face. They find that difficulties decrease with the size of the establishment and with financial turnover, suggesting that companies that have more resources and specialised recruitment departments face fewer difficulties. They also find that the higher the local unemployment rate and the local population density, the lower the anticipated difficulties, for the reasons of labour supply mentioned above. These results are very similar to those obtained in our study. The aim is to extend this work by taking into account other characteristics of companies[2] and by extending the analysis to other sectors.

1.2. Institutional Analyses of the French Labour Market

The issue of recruitment difficulties has been studied regularly by French administrative bodies such as the *Direction de l'animation de la recherche, des études et des statistiques* (DARES – the French Research, Studies and Statistics Directorate of the Ministry of Labour) or Pôle emploi (the French public employment operator). These studies aim to determine the occupations for which recruitment difficulties are the most important and why. Therefore, they focus on the characteristics of the occupations, which could explain recruitment difficulties.

The DARES studies are based on *Offre d'emploi et recrutement* (OFER) surveys on the recruitment processes of companies. Lhommeau & Rémy (2019) indicate that 17% of recruitment procedures were seen as difficult by recruiters who experienced them in 2016. Those procedures are analysed on an ex-post basis, that is

2. *The variables we incorporate are staff turnover rate, pay gap, seasonal recruitment rate and being part of a group.*

to say after the recruitment has taken place. The mismatch between the candidate profile and the company's expectations is the factor most frequently cited by companies to explain the difficulties encountered. Lhommeau & Rémy (2019) show that establishments located outside urban areas have more difficulty recruiting than others and that there are significant differences between activity sectors. This finding is also featured in the results of our study.

Lhommeau & Rémy (2020) reveal that the equipment and skills of recruiters play a role in the presence of recruitment difficulties. In particular, recruiters without a human resources department and who are less accustomed to recruiting report more difficulties. These results support the main conclusion of our study: recruitment difficulties mainly stem from the unobserved characteristics of companies, such as the quality of their human resources department.

The other main source of data on recruitment difficulties in France comes from the annual BMO survey on workforce requirements conducted by Pôle emploi. Covering all employers' establishments,[3] the BMO survey provides information on recruitment plans for the following year (ex-ante analysis) and, where appropriate, on anticipated difficulties. This survey makes it possible to monitor the way in which recruitment develops in France over the years. Together with the BMO survey, Pôle emploi also conducts an additional survey seeking to better understand past recruitment difficulties and anticipated recruitment difficulties, among other things. Just like the OFER survey, this survey highlights the unsuitability of candidate profiles for positions open for recruitment and an insufficient number of candidates as the major factors leading to recruitment difficulties. Factors related to the difficulty of the work, the image of the company or the occupation, the nature or term of the contract and the number of simultaneous recruitment processes to be carried out may also come into play (Blache & Gaumont, 2016; Gaumont *et al.*, 2020).

The surveys conducted by the Banque de France and INSEE, which are more frequent than those conducted by Pôle emploi and DARES, also measure difficulties on an ex-ante basis. The Banque de France's economic outlook update of November 2022 reveals an increase in anticipated recruitment difficulties in all sectors between May and October 2021, which can be interpreted as a symptom of the post-COVID economic recovery and a fall in the unemployment rate.

2. Data

2.1. The BMO Surveys on Workforce Needs

This study draws on the 2018 and 2019 BMO surveys on workforce needs conducted by Pôle emploi. These surveys were conducted between October and December and focused on workforce needs for the following year. The BMO surveys on workforce needs cover the private sector, including the agricultural sector, and the public sector under the jurisdiction of local authorities and publicly-owned administrative establishments. The coverage of the survey does not include administrative bodies of the state and certain publicly-owned companies, such as the Banque de France. The survey covers the 13 metropolitan regions and the five overseas regions of France. The units surveyed are establishments.

In these surveys, a recruitment plan corresponds to the desire to recruit a person for a specific position within the following year. Establishments are asked to indicate, for each category of occupations (82 categories of profession families), their total number of recruitment plans, whether or not they believe that such recruitments will be difficult and, finally, to specify the number of seasonal worker recruitments among the total number of recruitments. The study thus focuses on the anticipated difficulties related to recruitments planned.

Of the 2,410,306 establishments surveyed (i.e., establishments excluding administrative bodies of the state and publicly-owned companies), 436,608 responded to the 2018 survey (difficulties expressed at the end of 2018 for recruitments planned for 2019). In the 2019 survey (difficulties expressed at the end of 2019 for recruitments planned for 2020), 2,408,179 establishments were interviewed and 440,052 responded. We stack the 2018 and 2019 surveys and thus have 876,660 responses from establishments. We exclude establishments in the agricultural sector and those in the financial and insurance services sector, as the sources with which we will match this data do not cover those sectors. We thus start off with a sample of 760,544 observations at establishment level. Of these establishments, 26% (or 199,192 establishments) reported having recruitment plans for the following year. Our analysis focuses only on establishments that reported having recruitment plans. We use weights calculated by Pôle emploi, which ensure that the weighted sample is representative of the

3. Excluding administrative bodies of the state and publicly-owned companies.

size and activity sectors of the economic fabric at regional level. As variables of interest, we use the number of planned recruitments – including seasonal recruitments, the presence of recruitment difficulties, the activity sector (using 8 categories[4]) and the size of the establishments (using 8 categories).

2.2. Data on the Characteristics of Establishments and of their Environments

First, we supplement the BMO data with characteristics of the establishments taken from data provided by the 2015 DADS[5] annual social data declarations, in particular the number of employees by socio-professional category (we distinguish between five categories: tradespeople, merchants and entrepreneurs; executives and higher-level professions; middle-management professions; white-collar workers; blue-collar workers). This information makes it possible to calculate, for each establishment, the staff turnover rate and the pay gap between the establishment concerned and establishments of the same size in its geographical department for its structure, by socio-professional category of the recruitment. We also supplement the data with information from the 2017 FARE tax data regarding the company to which the establishment belongs: financial turnover, being part of a group and the date of creation of the company.

Next, the datasets of the *Agence Nationale de la Cohésion des Territoires* (ANCT), the French National Agency for Territorial Cohesion, provide information on the population and population density of the municipality in which the establishment is located. We also use INSEE's 2010 urban areas database (*Base des aires urbaines*) at 1st January 2018, which indicates for each municipality the urban area zoning category (large urban centre, periphery of a large urban area, etc.). Using data from the 2019 census, carried out by INSEE, we calculate unemployment rates by geographical department and socio-professional category. First, we link each recruitment plan with the geographic departmental unemployment rate for the plan's socio-professional category. We then aggregate these rates at establishment level, weighting them by the number of anticipated recruitments.[6] This variable aims to assess the level of unemployment faced by the establishment when it plans to recruit. We weight it by the structure of the recruitments planned and by socio-professional category, in order to account for the local labour supply in the labour segments in which the establishment is recruiting.

Approximately 45% of the 199,192 establishments with recruitment plans can be matched with the 2015 DADS and 2017 FARE data, resulting in a final sample of 89,139 observations. The main reason for the loss of data is the time difference between these databases and the 2018 and 2019 BMO surveys. By definition, only establishments that already existed in 2015 can be matched to 2015 DADS and 2017 FARE data, meaning they are at least three or four years old.[7] Table A1 in the Appendix shows that the unmatched establishments are mainly small establishments without employees or with fewer than five employees. Since the data on population, population density and unemployment rate are compiled at municipality or geographical department level, we do not lose any observations when they are matched with our database.

Establishments with a recruitment plan included in the final sample are therefore mainly medium or large in size and belong to a company that has already been in existence for several years. After the matching has been performed, public administrative bodies are under-represented and, conversely, establishments in the construction, industry, commerce, transport and hospitality sectors are over-represented. In our final sample, the proportion of seasonal recruitments among all recruitments is lower than in the sample of establishments planning to recruit. In contrast, the proportion of establishments anticipating recruitment difficulties for at least one recruitment plan is higher (66% compared with 52%). This difference can be explained by the over-representation of some sectors, such as construction, in which recruitment difficulties are high (see Table S1-4 of the Online Appendix – the link to the Online Appendix is at the end of the article).

4. These categories correspond to the way in which activity sectors are set out at level A10 of version 2 of the Nomenclature française d'activité *(NAF), French classification of activities, from which we remove the "Agriculture, forestry and fishing" and "financial and insurance activities" sector, as explained above.*

5. At the time of us carrying out this work, the most recent DADS data available were for 2018, but the most recent DADS data aggregated by establishment were for 2015, so the 2015 data were used in this study.

6. Appendix A2 sets out the methodology used to calculate this variable in detail.

7. Table S1-2 in the Online Appendix shows the breakdown of establishments in our final sample by the date on which their company was established. We do not observe the company creation date for establishments excluded from the final sample.

3. Descriptive Statistics

3.1. Characteristics of Establishments Anticipating Recruitment Difficulties

We begin by describing the characteristics of establishments recruiting and expressing recruitment difficulties, in terms of size, industry and length of time in existence.[8] 66% of the establishments in our sample anticipate difficulties in recruiting. Tables S1-1 to S1-10 in the Online Appendix set out the proportion of establishments with recruitment difficulties among those anticipating to recruit, broken down by the main characteristics studied in this article: size, the company's financial turnover, its length of time in existence, its staff turnover rate, etc.

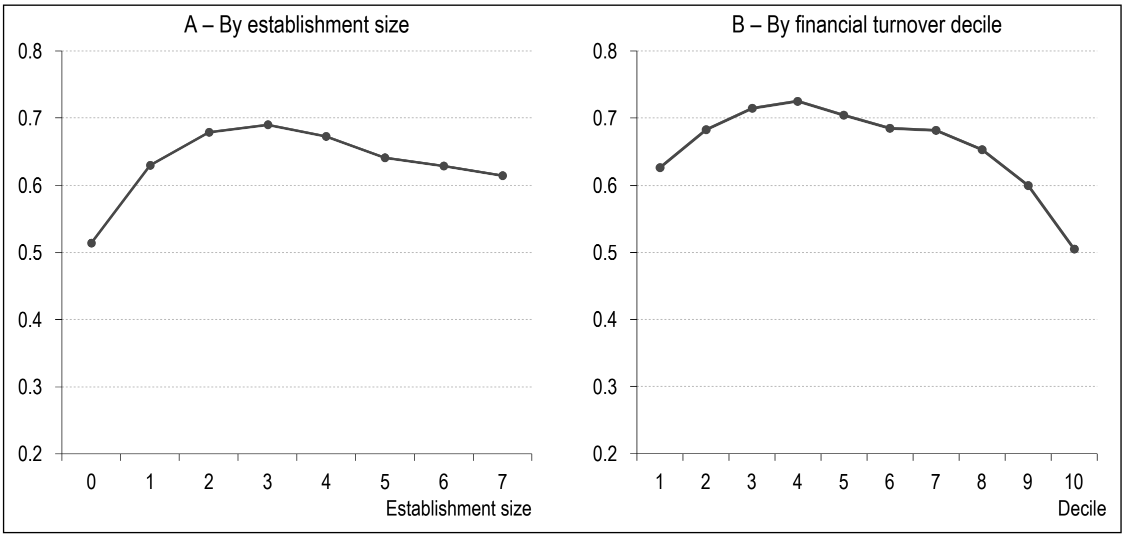
Figures I-A et I-B provide a visual representation of the results in Tables S1-1 and S1-3 in the Online Appendix. Figure I-A shows an inverted U-shaped relationship between establishment size and the proportion of recruitment plans anticipated to be difficult. The same inverted U-shaped profile is observed between deciles of financial turnover and the proportion of recruitment plans anticipated to be difficult (Figure I-B). For those with the lowest financial turnover, difficulties increase as financial turnover rises and then, beyond a certain amount, the relationship is inverted. The finding that establishments with higher financial turnover anticipate less difficulties could be explained by the fact that smaller establishments manage recruitment processes poorly, perhaps due to a lack of experience. After reaching a certain size, establishments invest in human resources departments that gain experience over time, which would decrease the rate of anticipated difficulties (Davis *et al.*, 2013). In the Online Appendix, this figure is broken down according to whether or not the establishment is part of a group (see Figure S1-I of the Online Appendix). Differences in recruitment difficulties according to financial turnover decile are largely the same, regardless of whether or not the establishments are part of a group.

Figures II et III show these analyses according to establishment size and financial turnover by activity sector. In manufacturing and construction, we observe the same inverted U-shaped curve as in the economy as a whole. However, that shape is not found in all activity sectors. For example, this is not the case in real estate activities, or in trade, transport and hospitality in relation to staffing.

Figure IV shows that there are fewer anticipated recruitment difficulties when staff turnover is high. This could be explained by the fact that establishments recruiting often and having therefore a high staff turnover rate, being thus

8. *The source of each of these variables of interest can be found in Appendix A2-1.*

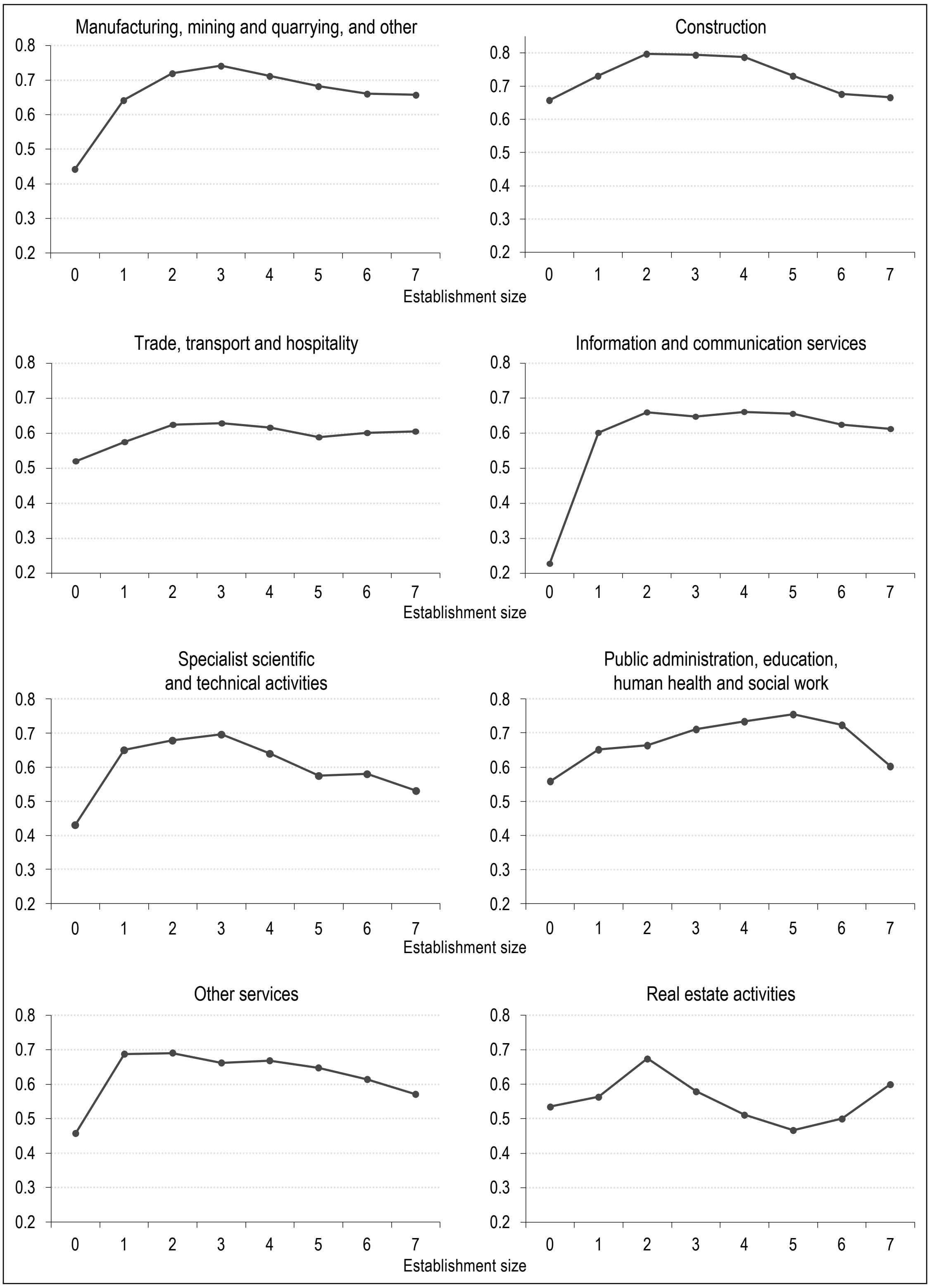
Figure I – **Anticipated recruitment difficulties by size and financial turnover**



Notes: In Figure I-A, establishment size 0 corresponds to establishments without employees, size 1 corresponds to those with 1 to 4 employees, size 2 corresponds to those with 5 to 9 employees, size 3 corresponds to those with 10 to 19 employees, size 4 corresponds to those with 20 to 49 employees, size 5 corresponds to those with 50 to 99 employees, size 6 corresponds to those with 100 to 199 employees and size 7 corresponds to those with 200 or more employees. In Figure I-B, the x-axis indicates the financial turnover decile of the company (see Table S1-3 of the Online Appendix for the amounts associated with each decile).
Reading note: Among establishments with 1 to 4 employees that anticipate recruiting, 63% anticipate at least one difficult recruitment. Among the 10% of establishments anticipating recruiting that have the lowest financial turnover, 63% anticipate at least one difficult recruitment.
Sources: BMO surveys, Pôle emploi, FARE and DADS data, INSEE.

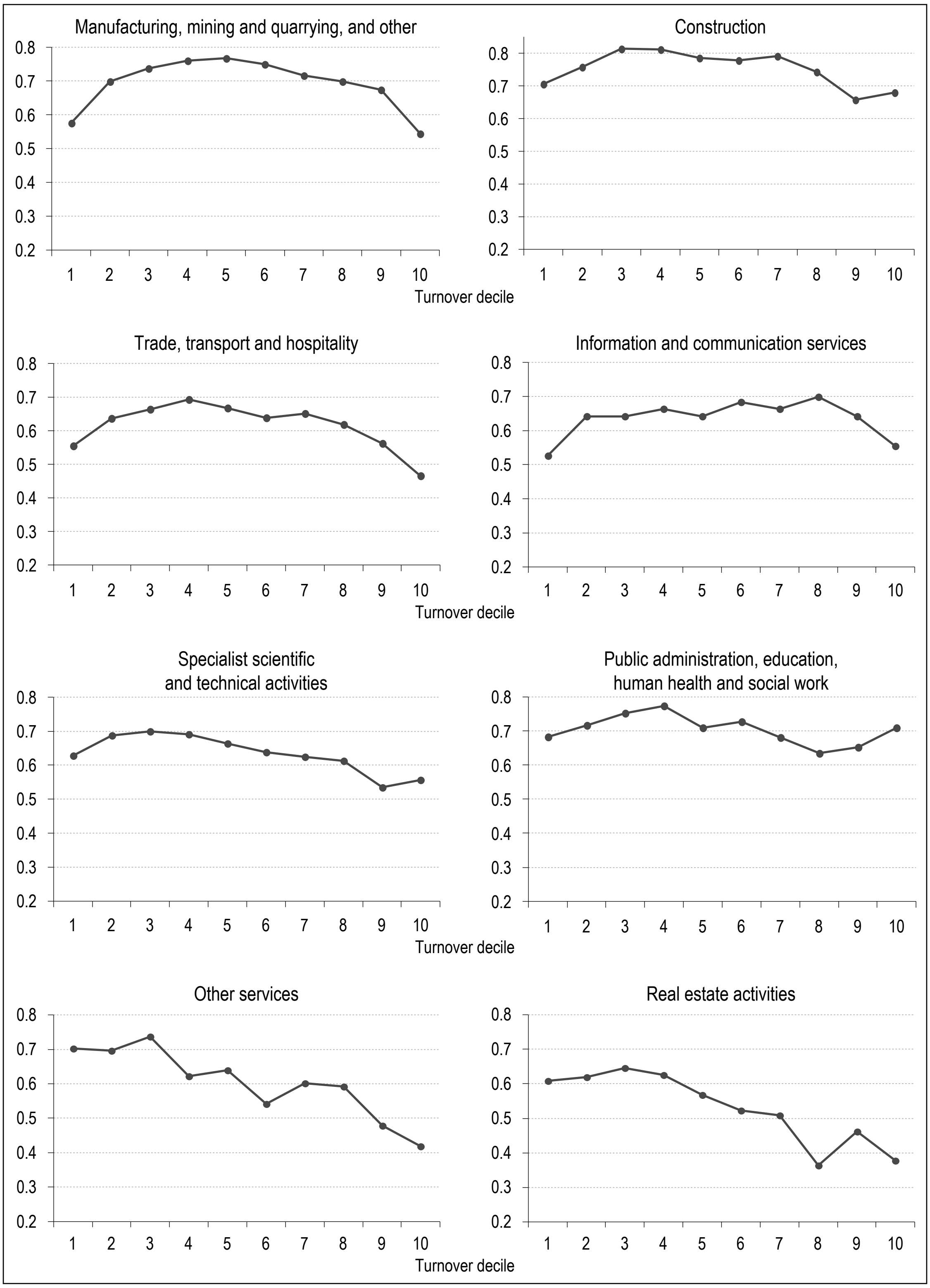
accustomed to recruiting, are also better prepared for this task, and may therefore anticipate fewer difficulties. Regarding the pay gap compared to similar establishments in the same geographical

Figure II – **Anticipated recruitment difficulties by size and activity sector**



Notes: Establishment size 0 corresponds to establishments without employees, size 1 corresponds to those with 1 to 4 employees, size 2 corresponds to those with 5 to 9 employees, size 3 corresponds to those with 10 to 19 employees, size 4 corresponds to those with 20 to 49 employees, size 5 corresponds to those with 50 to 99 employees, size 6 corresponds to those with 100 to 199 employees and size 7 corresponds to those with over 200 employees.
Reading note: In the construction sector, 72% of establishments with 1 to 4 employees anticipate at least one difficult recruitment.
Sources: BMO surveys, Pôle emploi, FARE and DADS data, INSEE.

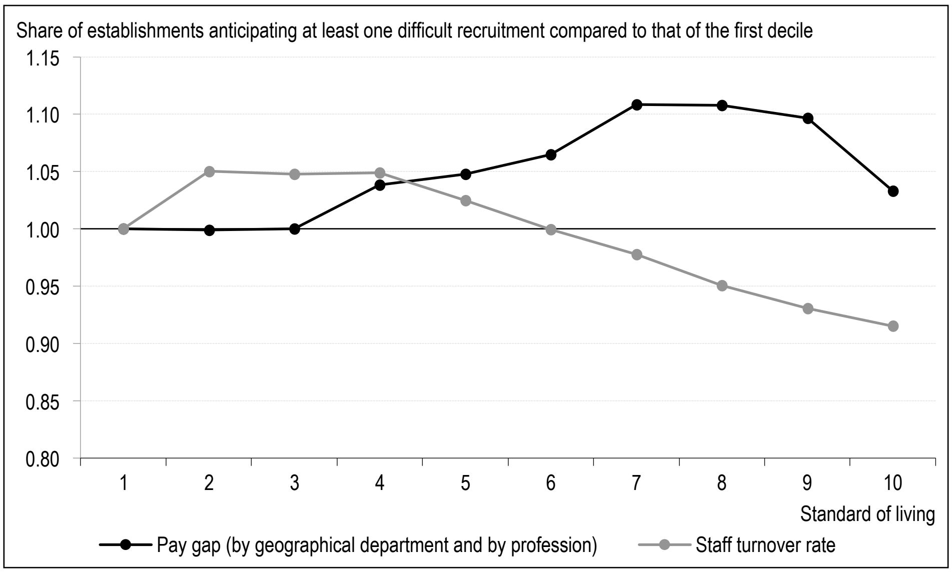
Figure III – **Anticipated recruitment difficulties by financial turnover and activity sector**



Notes: See Table S1-3 in the Online Appendix for the amounts associated with each decile.
Reading note: In the construction sector, 70% of establishments with financial turnover among the lowest 10% anticipate at least one difficult recruitment.
Sources: BMO surveys, Pôle emploi, FARE and DADS data, INSEE.

department, aside from the 10% of establishments where this gap is the highest, the higher the pay gap – i.e. the more the establishment pays relatively high wages compared to its neighbours –, the higher the anticipated recruitment difficulties. This could be explained by

Figure IV – **Anticipated recruitment difficulties by pay gap and staff turnover rate**



Notes: On the x-axis, establishments are grouped together by pay gap decile (black curve) and by staff turnover rate decile (grey curve). On the y-axis, the share of establishments anticipating at least one difficult recruitment plan is shown in the form of an index. The values are normalised so that the first decile corresponds to a base of 1.
Interpretation: The 10% of establishments with the highest staff turnover rate are 0.9 times less likely to anticipate recruitment difficulties than the 10% of establishments with the lowest staff turnover rate.
Sources: BMO surveys, Pôle emploi, FARE and DADS data, INSEE.

the fact that establishments that anticipate recruitment difficulties decide to increase their wages to make the jobs more attractive (Mueller *et al.*, 2018; Carrillo-Tudela *et al.*, 2020).

Figure S1-II of the Online Appendix shows the share of anticipated recruitment difficulties, distinguishing establishments with regard to seasonal recruitment. We observe that the proportion of establishments anticipating recruitment difficulties is lower in establishments recruiting (at least a few) seasonal workers, regardless of the total number of recruitments. This suggests that being in the habit of recruiting would help limit anticipated difficulties, as seasonal workers are often recruited on a regular basis. This may also be due to the fact that, in the case of seasonal recruitment, the same employees could be recalled from one year to the next, thereby limiting possible recruitment difficulties.[9]

Establishments that face recruitment difficulties are therefore mostly small- or medium-sized and are more often part of the manufacturing or construction sectors. Unsurprisingly, the higher the number of planned recruitments, the more frequently difficulties are anticipated for at least one recruitment: recruiting three or four people is more likely to expose the establishment to difficulties than recruiting a single employee. It is also establishments not accustomed to the process and rarely recruiting that report anticipating the most difficulties.

3.2. Geographical Disparities

Establishments in the Île-de-France region have the lowest level of recruitment difficulties in metropolitan France (60%, see Table S1-5 in the Online Appendix). The Brittany and Pays de la Loire regions have the highest proportion of establishments anticipating recruitment difficulties (71%).

Figure V shows that, regardless of the type of urban area, anticipated recruitment difficulties decrease as population density rises. The scale of the difficulties varies from one type of urban area to another, but the trend remains the same. The differences based on population density can be explained by a greater supply of labour in heavily populated municipalities and thus fewer difficulties for employers when recruiting labour. Typically, there is a low share of establishments anticipating recruitment difficulties in the city of Paris. In accordance with the findings in the literature (Blanc *et al.*, 2008), at the aggregate level, we observe that anticipated recruitment difficulties are negatively correlated

9. In addition, we observe an inverted U-shaped curve for establishments that do not recruit seasonal workers. This suggests that the more an establishment seeks to recruit individuals, the more complicated the task. However, once an establishment has completed a certain number of recruitments, fewer difficulties are anticipated. For establishments recruiting to fill more than 51 positions, the level of difficulties is the same regardless of whether or not they recruit seasonal workers. This can be explained by the fact that the large establishments that have recruitment structures and for which the process is well controlled are also those that recruit a lot.

with population, population density and unemployment rate (see Figure S1-III of the Online Appendix).[10]

4. Econometric Analysis

4.1. Presentation of the Model

The econometric analysis is based on a probit model. Unlike in linear approaches, in a probit model it is a latent – unobserved – variable Y_i^* that is specified as a linear function of the explanatory factors. The observed variable, Y_i, corresponds here to the presence of at least one recruitment plan anticipated to be difficult by the establishment. The model is written as follows, for each establishment i:

$$Y_i = \begin{cases} 1 \text{ if } i \text{ anticipates difficulties in recruiting} \\ 0 \text{ otherwise} \end{cases}$$

with the introduction of an unobservable latent variable Y_i^* (which could be the cost of recruitment difficulties in terms of time and money) such as:

$$Y_i = \begin{cases} 1 \text{ if } Y_i^* > C \\ 0 \text{ if } Y_i^* \leq C \end{cases}$$

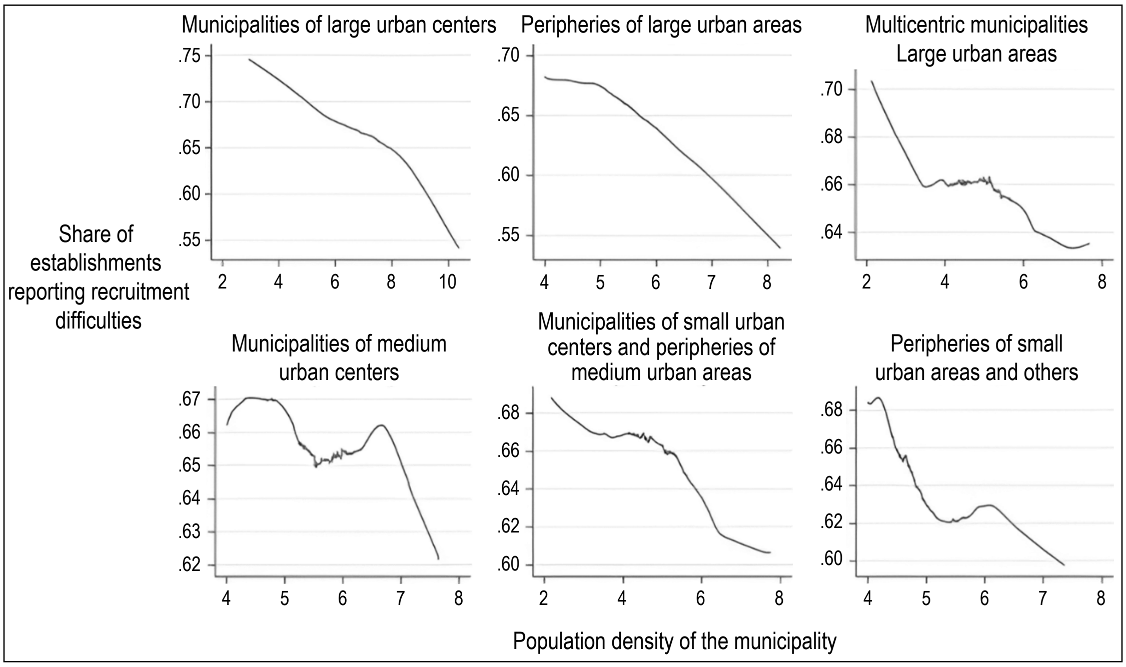
where C denotes a threshold that can be set to 0 without loss of generality.

Two groups of explanatory variables can be distinguished. The first group includes economic indicators related to characteristics of the establishment (turnover of the enterprise in log, being part of a group, staff turnover rate, proportion of seasonal workers in the establishment's recruitment and the pay gap by occupation, geographical department and size of the establishment). The second group describes the economic and geographic factors that may have an influence on the recruitment difficulties anticipated by the establishment. In particular, the population density of the municipality and the local unemployment rate are taken into account. In addition to these two groups of variables, we add dummy variables describing the occupation for which recruitment is being performed (21 categories) and the activity sector (10 categories).

Some variables could be endogenous, in particular the staff turnover rate and the pay gap. In order to take into account this potential endogeneity, the pay gap and the staff turnover rate are calculated for 2015, several years before any reported difficulties (in 2018 and 2019). As a precaution, we do not interpret the relationships between these variables and recruitment difficulties as causal.

10. Population and population density are calculated at municipality level. The unemployment rate is calculated by geographical department and occupation (see Appendix 2 for further detail).

Figure V – **Anticipated recruitment difficulties and population density by urban area type**



Notes: The figure represents the share of establishments reporting anticipating at least one difficult recruitment next year (y-axis) according to the population density of the municipality. The municipalities are divided into six categories of urban areas.
Sources: BMO surveys, Pôle emploi, FARE and DADS data, INSEE.

The latent variable Y_i^* is described by the following linear regression model:

$$Y_i^* = c + X_i^{'}\beta_1 + \sum_j S_{ij}\beta_{2j} + \sum_k \left(\frac{N_{ik}}{N_i}\right) M_{ik}\beta_{3k} + \varepsilon_i \quad (1)$$

where the vector X_i includes the two groups of characteristics mentioned above (characteristics of establishments and their environment) and S_{ij} is the dummy that has a value of 1 if the establishment is in sector j and 0 otherwise. M_{ik} is the dummy that has a value of 1 if the establishment is recruiting in occupation k and 0 otherwise. $\frac{N_{ik}}{N_i}$ is the ratio of recruitments by the establishment i in occupation k, compared with the total number of recruitments planned. This allows the dummy variables to be weighted by the number of recruitments in each occupation.

An alternative specification involves focussing on the persistence of recruitment difficulties from one year to the next. The aim is to determine whether there is inertia in the recruitment difficulties, i.e. whether establishments that reported difficulties in 2018 are more likely than others to report difficulties in 2019. Since only some of the establishments answer to the survey in two consecutive years, the sample size is reduced (18,498 observations, compared to 89,139 in the original database). In this specification, Y_i^* is a latent variable that corresponds to the anticipated difficulties reported in 2019 and takes the following form:

$$Y_i^* = c + X_i^{'}\beta_1 + \sum_j S_{ij}\beta_{2j} + \sum_k \left(\frac{N_{ik}}{N_i}\right) M_{ik}\beta_{3k} + P_i\beta_4 + \varepsilon_i \quad (2)$$

where P_i is the dummy that equals 1 if establishment i reported anticipating difficulties in 2018. β_4 here captures the *persistence* of the difficulties from one year to the next.

For each of these specifications, regressions are run with and without weighting. As explained above, only 45% of the initial sample is retained in the final sample, after matching with the DADS and FARE data, which changes the representativeness of our sample (see Table A1 in the Appendix). For this reason, in the following section and in the Online Appendix, we present the results both with and without the weights calculated by Pôle emploi.

There are three objectives behind these specifications. First, studying the signs of the coefficients makes it possible to confirm the trends observed in the descriptive statistics and compare these findings with the literature. Second, we measure what amount of the variance is explained by the selected factors. If much of the variance remains unexplained after including the characteristics of the establishments, their environment, their activity sector and the type of occupations for which they recruit, it suggests that other factors – such as the internal organisation of the establishment's activity or the mindset of the recruiters – may play a significant role in anticipating recruitment difficulties. If, on the contrary, the characteristics introduced as explanatory factors are dominant in explaining the anticipated difficulties, it will be possible to consider specific policies for establishments with the same characteristics. Third, in addition to assessing the overall amount of the explained variance, it is also interesting to compare the relative amount of the explained variance that can be attributed to the different types of explanatory factors: those that relate to the characteristics of the establishment, or its geographical or economic environment, or the occupations to which the recruitment plans relate.

4.2. Results

Table 1 presents the results of the estimation of equation (1), both unweighted (column 1) and weighted (column 2). We do not include the population of the municipality nor that of the urban area in which the municipality is located as control variables, as they are redundant with the population density variable.[11] The findings of the weighted and unweighted estimates are similar in terms of significance and sign.

The signs of the coefficients are consistent with the descriptive statistics for being part of a group, staff turnover rate, percentage of seasonal workers recruited, unemployment rate and population density: these variables are negatively correlated with anticipated recruitment difficulties. We note, however, that the coefficient associated with being part of a group is not significant, which was suggested in Figure S1-I in the Online Appendix.[12] The staff turnover rate is negatively correlated with anticipated difficulties, which can be interpreted by the fact that a high staff turnover rate probably results in a degree of familiarity with recruitment, but the coefficient is insignificant. The higher the unemployment rate and population density, the fewer recruitment difficulties there are: the greater the supply of labour, the easier

11. In Tables S2-2 and S2-3 of the Online Appendix, we set out the results with the population density replaced by the population of the municipality and the population of the urban area in which the municipality is located, yielding very similar findings.

12. The coefficient associated with being part of a group is, however, significant when the square of financial turnover is introduced into the regression (see Table S2-1 in the Online Appendix).

it is to recruit (Mortensen & Pissarides, 1994). Anticipated difficulties are positively correlated with the number of recruitments: when there are lots of positions to be filled, the task becomes more difficult for recruiters. The coefficient associated with the pay gap is insignificant.

The company's financial turnover is negatively correlated with recruitment difficulties. Table S2-1 in the Online Appendix introduces the square of financial turnover into the regression and the associated coefficient is negative. We therefore recover the convex shape shown in the descriptive statistics.

Table 2 shows the results for the estimation of equation (2). The signs of the coefficients associated with the variables already introduced in equation (1) remain unchanged for both the weighted and unweighted estimates. In all specifications, the persistence of difficulties is positive and largely significant. This suggests that there may be structural characteristics explaining recruitment difficulties, which would be unique to each establishment. For example, these could be characteristics related to the quality of the human resources department: in the absence of a sufficiently effective recruitment department, difficulties can be repeated from year to year. The persistence can also reflect the mindset of the establishment's recruiters, their optimistic or pessimistic temperament, which, if they remain in the establishment, results in the persistence of the optimistic or pessimistic nature of the anticipations. Figures S1-IV and S1-V in the Online Appendix present additional descriptive statistics on the share of establishments anticipating difficulties in 2018 and 2019 by size of establishment and activity sector.

4.3. Amount of Variance Explained and the Ways the Explanatory Factors Contribute to the Variance

The various models estimated in Tables 1 and 2 result in a relatively low value of the pseudo-R^2, whether the data are weighted or not. Together, the variables explain a maximum of around 6% of the variance in anticipated difficulties (column 2 of Table 1). This finding is consistent with previous work: for example, Fabling & Maré (2016) and Arik *et al.* (2021) find pseudo-R^2 values not exceeding 0.15.

Table 1 – **Estimation results – Existence of anticipated recruitment difficulties**

	Unweighted (1)		Weighted (2)	
Establishment characteristics				
Financial turnover (Log)	−0.0239***	(0.000955)	−0.0230***	(0.00117)
Being part of a group	−0.00194	(0.00429)	−0.00630	(0.00509)
Total number of recruitments	0.000201***	(0.000081)	0.000684***	(0.000113)
Staff turnover rate	−0.000588*	(0.000331)	−0.000342	(0.000361)
Proportion of seasonal workers in recruitments	−0.131***	(0.00477)	−0.139***	(0.00579)
Pay gap (by occupation, geographical department and establishment size)	0.000215	(0.00184)	−0.000605	(0.00255)
Size dummies	Yes		Yes	
Age dummies	Yes		Yes	
Geographical characteristics				
Population density	−0.0128***	(0.00107)	−0.0109***	(0.00130)
Unemployment rate (by geographical department and occupation)	−0.715***	(0.0337)	−0.707***	(0.0412)
Occupation characteristics				
Occupation dummies	Yes		Yes	
Activity sector dummies	Yes		Yes	
Number of observations	89,139		89,139	
Pseudo−R^2	0.0622		0.0632	

Notes: Robust standard errors are in parentheses. *** p<0.01, ** p<0.05, * p<0.10. The Probit regression covers all establishments that responded to the survey in 2018 or 2019. The explained variable is equal to 1 if the establishment reports anticipating at least one recruitment plan to be difficult, or 0 otherwise. The values shown correspond to marginal effects. Coefficients associated with establishment size and activity sector are available in Tables S2-4 and S2-5 in the Online Appendix.
Sources: BMO surveys, Pôle emploi, FARE and DADS data, INSEE.

Table 2 – **Estimation results – Persistence**

	Unweighted (1)		Weighted (2)	
Persistence effect	0.265***	(0.00745)	0.270***	(0.00924)
Establishment characteristics				
Financial turnover (Log)	−0.0309***	(0.00225)	−0.0272***	(0.00278)
Being part of a group	−0.000191	(0.00954)	−0.0154	(0.0113)
Total number of recruitments	0.000115	(0.000107)	0.000225*	(0.000122)
Staff turnover rate	−0.00099	(0.000679)	−0.00153*	(0.000964)
Proportion of seasonal workers in recruitments	−0.114***	(0.0103)	−0.115***	(0.0129)
Pay gap (by occupation, geographical department and establishment size)	−3.89e−05	(0.00292)	−0.00560	(0.00603)
Size dummies	Yes		Yes	
Age dummies	Yes		Yes	
Geographical characteristics				
Population density	−0.0170***	(0.00238)	−0.0141***	(0.00292)
Unemployment rate (by geographical department and occupation)	−0.386***	(0.0873)	−0.423***	(0.109)
Occupation characteristics				
Occupation dummies	Yes		Yes	
Activity sector dummies	Yes		Yes	
Number of observations	18,467		18,467	
Pseudo-R^2	0.140		0.145	

Notes: Robust standard errors are in parentheses. *** p<0.01, ** p<0.05, * p<0.10. The Probit regression covers the establishments that responded to the survey in both 2018 and 2019. The explained variable is equal to 1 if the establishment reports anticipating a difficult recruitment plan in 2019, or 0 otherwise. “Persistence” is a dummy variable equal to 1 if the establishment reported anticipating difficult projects in 2018, or 0 otherwise. The values shown correspond to marginal effects.
Sources: BMO surveys, Pôle emploi, FARE and DADS data, INSEE.

This is the main finding of this study. After the introduction of a large number of explanatory variables into the econometric model, which relate not only to the characteristics of the establishments, but also their environment and the occupations in which they recruit, the pseudo-R^2 value remains very low. While these observed characteristics are generally those taken into consideration to explain recruitment difficulties (de Zeeuw, 2018; Lhommeau & Rémy, 2019), our analysis suggests that the main factors are essentially unobserved. These could include, for example, organisational characteristics such as recruitment methods and the organisation of human resources departments, or idiosyncratic characteristics such as recruiters’ mindsets, which may affect their perception in terms of anticipated recruitment difficulties (Weaver, 2021).

Table 2 shows that the “persistence” of anticipated recruitment difficulties is significant. When we check using anticipated difficulties in the previous year, the predictive quality of the model is significantly improved. Compared to Table 1, the amount of variance explained increases from 6% to 14%. This persistence may be interpreted as a sign of consistency of anticipations expressed over two consecutive years. The coefficient that measures persistence varies little with the different specifications (whether or not we control for occupation, sector, size and location using dummy variables). In principle, this low level of variability reveals that these unobserved factors are independent of the observed factors. The additional variance explained by the persistence could be attributed to unobserved organisational (quality of human resources management, for example) or idiosyncratic (pessimism of the employer) factors.

4.4. Contribution of the Various Explanatory Factors

We will now examine the relative contributions of each category of variables: those that are characteristic of the establishments, those related to the establishments’ environments, and those specific to the occupation and sector for which recruitment is being conducted. Starting from the estimation of equation (1), each of the categories of variables is removed successively to compare their relative contributions.

Table 3 – **Amount of explained variance (Pseudo-R²) – Equation (1)**

	(1)	(2)	(3)	(4)	(5)
Establishment characteristics					
Financial turnover	Yes		Yes	Yes	Yes
Being part of a group	Yes		Yes	Yes	Yes
Total number of recruitments	Yes		Yes	Yes	Yes
Staff turnover rate de la main-d'œuvre	Yes		Yes	Yes	Yes
Pay gap	Yes		Yes	Yes	Yes
Proportion de saisonniers	Yes		Yes	Yes	Yes
Size dummies	Yes		Yes	Yes	Yes
Age dummies	Yes		Yes	Yes	Yes
Geographical characteristics					
Population density de population	Yes	Yes		Yes	Yes
Unemployment rate	Yes	Yes		Yes	Yes
Occupation characteristics					
Occupation dummies	Yes	Yes	Yes		Yes
Activity sector dummies	Yes	Yes	Yes	Yes	
Number of observations	89,139	89,139	89,139	89,139	89,139
Pseudo-R^2	0.0622	0.0448	0.0566	0.0394	0.0618

Notes: Probit model where the explained variable is a dummy variable equal to 1 if the establishment reports anticipating at least one recruitment plan to be difficult. "Yes" means that the variable is included in the regression as an explanatory variable (unweighted model).
Sources and coverage: BMO surveys, Pôle emploi, FARE and DADS data, INSEE. Establishments that responded to the BMO survey in 2018 or 2019.

Table 3 shows the pseudo-R^2 values for the various estimates in equation (1). The largest increase in the pseudo-R^2 comes from the inclusion of dummy variables related to occupations. It is an important conclusion: occupation-specific characteristics have the strongest explanatory power compared to the other variables, even though that power remains low. These findings are consistent with Lhommeau & Rémy (2022), who show that recruitment difficulties are very heterogeneous across occupations, distinguishing between four categories: technical, manual, personal assistance and public-facing occupations.

* *
*

The aim of this article was to study the factors traditionally raised to explain the recruitment difficulties expressed by French companies and to determine the main ones. Unlike previous studies (Lhommeau & Rémy, 2019; Gaumont *et al.,* 2020), difficulties are examined at the establishment level and not at the level of the occupation for which the establishment is seeking to recruit.

Which factors explain the difficulties expressed by recruiters? A first finding is that, together, the observed characteristics included in our models explain a maximum of 14% of the difficulties expressed by the employers surveyed. Managers of companies with similar characteristics thus have perceptions of recruitment difficulties which can vary greatly. This finding is comparable to those found in other countries (Fabling & Maré, 2016; Arik *et al*., 2021) and suggests that these difficulties are due to factors not directly observable. These can be organisational or idiosyncratic characteristics, such as the quality of human resources management and of leadership, the mindset of the company manager, the company's brand image, etc. This finding is in line with those of Algan *et al.* (2020) who show that providing support to companies to strengthen their human resources department can significantly increase the number and quality of recruitments.

The observable factors are classified by order of importance. The first category relates to the type of occupation that is sought, which contribute around one third to the explained variance. Table S1-11 in the Online Appendix lists the 10 occupations for which the proportion of employers anticipating recruitment difficulties is highest. The second type of factor is related to the characteristics of the establishment, namely its size, activity sector, the company's financial turnover and staff turnover. These factors contribute less than 30% to the explained variance. The third type of factor, contributing approximately 10% to the explained variance, concerns the geographical characteristics and the surrounding economic conditions (population density in the municipality and unemployment rate in the geographical department to which the establishment belongs).

In many activity sectors, the anticipated recruitment difficulties vary in the manner of an "inverted U-shaped curve" with the number of employees of the establishment and the company's financial turnover. The higher the staff turnover rate, the less frequently difficulties are anticipated, which is indicative of a learning effect from managing recruitment plans. The local context also has a degree of explanatory power, but it is limited: the higher the local unemployment rate and population density, the less establishments express difficulties.

In summary, these findings suggest that traditional observed characteristics provide a limited explanation for recruitment difficulties, which are explained mainly by unobserved or unobservable characteristics, such as organisational or idiosyncratic characteristics. Among observed characteristics, the occupation for which the recruitment is being carried out is the category that best accounts for the explained variance. Targeted support for occupations concerned could thus prove useful in alleviating perceived recruitment difficulties. ☐

Link to the Online Appendix:
www.insee.fr/en/statistiques/fichier/8305259/ES544_Bezy-et-al_OnlineAppendix.pdf

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APPENDIX 1

Table A1 – **Characteristics of the new sample compared to the original BMO database**

Variables	Initial database	Initial database restricted to recruitments	Final database
Percentage of establishments recruiting	26	100	100
Percentage of establishments expressing recruitment difficulties among those recruiting	52	52	66
Number of recruitments plans per establishment	1.5	5.7	7.6
Proportion of seasonal workers in recruitments	26	26	18
Breakdown by size of establishment (%)			
0 employees	11	10	1
1 to 4 employees	45	28	20
5 to 9 employees	15	16	18
10 to 19 employees	10	15	18
20 to 49 employees	12	19	23
50 to 99 employees	3	6	9
100 to 199 employees	2	4	6
200+ employees	1	2	5
Breakdown by activity sector (%)			
Manufacturing, mining and quarrying, and other	10	11	18
Construction	10	11	14
Trade, transport, hospitality	30	33	41
Information and communication services	2	3	2
Real estate activities	2	2	1
Specialist scientific and technical activities and administrative and support services	15	13	14
Public administration, education, health and social work	21	18	5
Other service activities	9	9	4
Number of observations	760,544	199,192	89,139

Notes: The “initial database” is the two stacked BMO 2018 and BMO 2019 databases. The “initial database restricted to recruitments” includes only establishments that report having at least one recruitment plan in the year they are interviewed. The “final database” is the one obtained after matching the “initial database restricted to recruitments” with the 2015 DADS and 2017 FARE data.
Due to its construction, anticipated recruitment difficulties and seasonal worker recruitment plans are calculated only for establishments with recruitment plans. The proportions of plans deemed difficult and seasonal worker plans therefore remain the same in the first and second columns. These figures vary as a result of the matching with the other databases because the characteristics of the establishments retained in the final database (size, sector) differ from the initial database. After the matching with the economic databases, the number of establishments in the agricultural and financial activities sectors was too small to be representative of the sector (fewer than 100 observations); they were therefore excluded from the analysis.
Sources: 2018 and 2019 BMO surveys (excluding establishments in the “agriculture, forestry and fisheries” and “financial and insurance activities” sectors), DADS and FARE data, INSEE.

APPENDIX 2

DESCRIPTION OF THE VARIABLES

A2-1. List of the Variables and Databases Used

Table A2 – **List of variables used in the model**

Variable	Databases used	Years selected
Establishment characteristics		
Number of recruitments	BMO surveys (Pôle emploi)	2018/2019
Size		
Sector		
Proportion of seasonal workers		
Occupation type		
Being part of a group	FARE Data (INSEE)	2017
Financial turnover*		
Total number of recruitments	DADS Data (INSEE)	2015
Pay gap		
Characteristics of their environment		
Unemployment	Population census (INSEE)	2019
Population density*	ANCT Data	2018
Population*		
Urban area category	*Base des aires urbaines* 2010 (INSEE)	2018

* Variables expressed in logarithm in the estimations.

A2-2. Calculation of the Staff Turnover Rate

We do not have data on the number of incoming and outgoing staff each year. It was therefore necessary for us to use another formula. The standard formula for the staff turnover rate is as follows:

$$Turnover = \frac{NBa + NBd}{2 \times E(01.01)}$$

where NBa is the number of incoming staff for the establishment for the year, NBd is the number of outgoing staff for the year and $E(01.01)$ is the establishment's workforce at the start of the year on 1 January. The total workforce during the year is written as $E(TOT)$ and the establishment's number of employees at the end of the year on 31 December is written as $E(31.12)$.

We can write:

$$E(TOT) = E(01.01) + NBa = E(31.12) + NBd$$

Which gives the result:

$$NBa = E(TOT) - E(01.01)$$
$$NBd = E(TOT) - E(31.12)$$

By replacing NBa and NBd in the staff rotation rate equation, we finally get:

$$Turnover = \frac{2E(TOT) - E(01.01) - E(31.12)}{2 \times E(01.01)}$$

We therefore use this formula in our study. For establishments with no staff as at 01.01, we set the staff turnover rate to 0. This implicitly means that there is no staff turnover.

A2-3. Calculation of the Unemployment Rate

The unemployment rate by geographical department is calculated using data on individuals from the 2019 Population Census (INSEE). For each geographical department, we calculate unemployment rates by socio-professional category (CS), with eight categories. These geographical departmental rates for each CS are obtained using the individual weightings provided in the census database.

Each recruitment is then assigned the unemployment rate for its socio-professional category in its geographical department.

Example: an establishment in Ain is planning to recruit for CS 1. The unemployment rate for CS 1 in Ain is 8%. We therefore assign the value of 8% to this recruitment.

We then look at all the recruitments planned by the establishment and calculate the associated average unemployment rate.

Example: an establishment in Ain is planning two recruitments in CS 1 and three in CS 2. The unemployment rate for CS 1 in Ain is 8% and for CS 2 it is 10%. The unemployment rate the establishment is facing for these recruitments is calculated as follows:

$$UnemploymentRate = 8\% \times \frac{2}{5} + 10\% \times \frac{3}{5} = 9.2\%$$

A2-4. Calculation of the Pay Gap

An average reference wage is first calculated by socio-professional category (CS with 8 categories), size of establishment and geographical department. Each recruitment is then assigned a pay gap, depending on the average wage paid by the establishment recruiting in the CS concerned, by measuring the gap with the reference wage as percentages.

Example: establishments with between three and four employees in Ain offer an average wage of €2,000 per month in CS 1. Establishment A, based in Ain and with between three and four employees is seeking to recruit in CS 1 and pays its employees in CS 1 €2,400 a month on average. The pay gap assigned to this recruitment is:

$$WageGap_{recruitment} = \frac{2{,}400 - 2{,}000}{2{,}000} = 20\%$$

Once a pay gap value has been assigned to each recruitment, it is necessary to aggregate them at establishment level. We therefore take into consideration all the recruitments carried out by each establishment and calculate the associated pay gap, weighted by the number of recruitments.

Example: establishment A hires employees in CS 1 and 2. The pay gap is 20% for CS 1 and −10% for CS 2. Establishment A hires two new employees in CS 1 and three new employees in CS 2. In this case, the formula for the pay gap is therefore:

$$WageGap = 20\% \times \frac{2}{5} + \left(-10\%\right) \times \frac{3}{5} = 2\%.$$

Sectoral Diversity and Local Employment Growth in France

Mounir Amdaoud* and Nadine Levratto*

Abstract – This article investigates the links between sectoral diversity and local employment growth in France over the period 2004-2015. Starting from the seminal contribution of Frenken *et al*. (2007), we take into account both the within and between sectoral diversities at the local level and at the neighbourhood one. Our empirical investigations confirm that within sector diversity (so called related variety) is positively associated with employment growth. Moreover, this association seems to be driven by the local related variety in growth phase and by the related variety in the neighbourhood in crisis period. We also find that the negative relationship between unrelated variety and employment growth goes only through the neighbourhood canal.

JEL: R11, O18, D62
Keywords: related variety, unrelated variety, employment growth, spatial interactions, France

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In a context of market globalisation, increasing competition, and recurrent crises, which type of economic composition matters in regional development remains strategically important information for policymakers and scholars.

The literature on innovation has long highlighted the importance of the geographical dimension in knowledge exchange among companies. A large bunch of papers shows that specialised or diversified clusters of firms can create conducive environments for the development of innovations, as knowledge flows between firms. In research on economic geography, urban economics, and regional science this discussion refers to the long-running debate between Marshall-Arrow-Romer's (MAR) approach conceptualised by Marshall (1920) and later by Arrow (1962) and Romer (1986) on the one hand and Jacobs' approach (Jacobs, 1969) on the other hand.

However, these externalities do not capture all the dimensions involved in proximity. Recent theoretical advances have highlighted the importance of considering relational proximities – cognitive, organisational, institutional, political, cultural, etc. – in modulating the benefits linked to geographical proximity (Boschma, 2005). The benefits attached to industrial diversity (Jacobs externalities) have since been broken down into related variety (between closely related industries) and unrelated variety (Frenken *et al.*, 2007). The related variety measures variety within sectors defined at an aggregated level, i.e. between industries relatively close to each other, belonging to the same aggregated industry, while the unrelated variety measures variety between industries defined at an aggregated level, i.e. between industries (broadly classified) different from one another (Mameli *et al.*, 2012). While the potential impact of related and unrelated varieties on regional growth has been widely empirically examined,[1] some open questions about the empirical application of this concept can still be identified.

This article tackles this question considering to what extent intra-industry externalities foster employment growth. It appears that most empirical analyses aiming to assess the contribution of related and unrelated variety to territorial dynamism rest upon modelling and economic techniques considering the phenomenon within each spatial unit considered. Some other, mainly case studies, interested in disentangling related and unrelated varieties focus either upon one or on a small number of territories (Brenet *et al.*, 2019; Elouaer-Mrizak & Picard, 2016) or on some specific activities (Tanner, 2014 among many others). To our knowledge, the spatial dimension of this family of externalities has not yet been explored. Indeed, the relevance of extra-regional knowledge to regional growth is largely neglected by the Glaeser-Henderson related literature, which mostly focuses on the structure of the regional industry mix (Boschma, 2005).

This article seeks thus to determine if, and to what extent, variety (related and unrelated) affects local employment growth, focusing on the local industrial structure of labour market areas (*zones d'emploi*) in France and, mostly, considering spillover effects to take into account the possible interactions and complementarity between the economic activities operating within a given labour market area and those operating in other labour market areas. It proposes to empirically distinguish between the local variety (so called direct dimension) and the variety in the neighbourhood (so called indirect dimension). Further refinement is presented, by relating local and neighbourhood varieties to the technological intensity of industries, on the one hand, and, on the other hand, by running separate analysis for the rural and the urban areas. In that respect, some investigations have stressed the relevance of sectoral specificities in examining the impact of variety on employment growth (Bishop & Gripaios, 2010; Boschma & Iammarino, 2009). Hartog *et al.* (2012), for example, introduce differences in innovation processes in high-tech and low-medium-tech sectors to explain the variation in the influence of related variety on employment. There are additional arguments supporting the idea that the mechanisms linking diversity and employment variations differ depending on geographical contexts, such as the ones between cities or between rural and urban areas (Frenken *et al.*, 2007; Duranton & Puga, 2005). According to Grabner & Modica (2022), related variety was an important driver of industrial resilience in US counties during the 2008 economic shock, and this effect was driven by intermediate and rural counties. Our approach is based on a unique dataset representative of 304 French labour market areas over the period 2004-2015. The econometric specification is inspired by those introduced by Glaeser *et al.* (1992), Henderson *et al.* (1995) and Combes (2000), but innovates by dealing with the spatial dependence serious issue. The model framework used in this study

1. Frenken et al. *(2007) for Netherlands; Boschma & Iammarino (2009) and Mameli* et al. *(2012) for Italy; Bishop & Gripaios (2010) for the UK; Hartog* et al. *(2012) for Finland; Boschma* et al. *(2012) for Spain.*

includes related and unrelated varieties as key variables and controls for density, skills and the rural or urban character of the area.

Our empirical investigations confirm that related variety is positively correlated with employment growth. Moreover, this correlation seems to be driven by the local (direct) dimension of related variety in economic growth times and by its indirect dimension in times of crisis. We also find that the negative relationship between unrelated variety and employment growth goes only through the indirect canal. Our empirical evidence also shows, that the relation between related variety and local employment is conditioned by rural-urban differences and, in some way, by the technological intensity of the local industries.

The central contribution of this article is investigating which type of variety influences employment growth and what is the origin of this influence (inside or outside the spatial unit). To the best of our knowledge, no prior studies have directly examined the link between spatial unit's dynamics and the structure of the productive fabric. Moreover, we introduce a distinction between the role played by the features of a spatial unit and the ones of the neighbouring areas. We also test the possibility of a change of regime corresponding to the financial and global crisis in 2008-2009, running estimations before, during and after the shock. Moreover, we produce new insights when considering our two forms of variety concerning the R&D intensity of sectors and territory type.

The article is organised as follows. Section 1 discusses the literature and presents the theoretical considerations for the variables of interest. The dataset and the variables are presented in Section 2. Section 3 includes results and robustness checks, then we conclude.

1. Literature Review and Theoretical Background

In the last three decades, there has been a continuous discussion on the contribution of different types of agglomeration economies to local economic development. This growing literature is not unconnected to the development of the modern economic growth theory (Romer, 1986; Lucas, 1988) that stresses the critical role of knowledge externalities in economic growth. Glaeser *et al.* (1992) initiated the research trend dedicated to the impact of the types of agglomeration economies on local economic growth. In short, the controversy centred on whether the regional specialisation of economic activities (Marshall-Arrow-Romer externalities) or regional diversity (Jacobs's externalities) is more conducive to regional solid economic performance. Yet, to date, the empirical evidence around this debate has failed to reach a consensus. Studies find as much evidence in favour of the "MAR" approach as Jacobs' hypothesis (for a recent review, see De Groot *et al.*, 2016). This ambiguity in empirical testing may be due to the theoretical concepts of specialisation and diversity[2] which are still unclear (Content & Frenken, 2016), to the level of spatial aggregation (metropolitan, local, or regional), to the type of sectors analysed (manufacturing and services) and the sector classification level (2-digit or more), to the nature of regional economic performance measure (employment, total factor productivity or labour productivity, wages, or gross domestic product), and finally to sectoral lifecycles and institutional context (O'Huallachain & Lee, 2011). Recently, a new trend of studies stemming from a conceptual renewal in institutional and evolutionary economic geography has started advocating for a more differentiated perspective on how diversification and specialisation affect regional economic growth (van Oort *et al.*, 2015; Boschma, 2005). Relying heavily on the studies that have focused on the degree of relatedness between technologies used in industries and the diffusion of knowledge and innovation (Rosenberg & Frischtak, 1983; Cohen & Levinthal, 1990; Nooteboom, 2000), scholars have integrated these concepts in the literature on agglomeration externalities and regional growth. Frenken *et al.* (2007) have stated that Jacobs' externalities cover two different forms of variety – related and unrelated varieties – that should be disentangled because they generate different economic impacts. These authors argue in line with Nooteboom (2000) that some parts of knowledge are easier to recombine and spill over across sectors when their cognitive proximity and distance are neither too small nor too big. This complementarity between sectors is captured by what Frenken *et al.* (2007) call "related variety" defined as diversity between industries that share some

2. A largest number of studies published before Frenken et al. *(2007) modelled regional diversity in terms of the inverse Hirschman-Herfindahl index (Combes* et al.*, 2004; Henderson* et al.*, 1995; Combes, 2000) without admitting diversity in related industries into the analysis. Beaudry & Schiffauerova (2009) emphasize that this can cause an underestimation of Jacobs's externalities and an overstatement of MAR externalities owing to diversity, which would be measured as simply unrelated variety. Moreover, the entropy (or the Shannon index) approach in measuring related and unrelated variety seems preferable to the Simpson/Herfindahl-Hirschman index (for a technical discussion, see Nagendra, 2002).*

complementarities in terms of knowledge bases, technologies, inputs/outputs or competences, i.e., within-industry diversity.

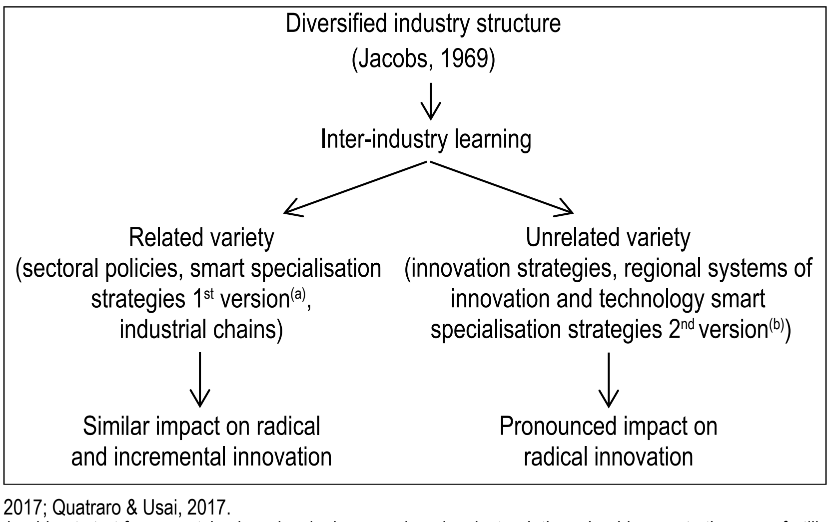
Regarding unrelated variety, between industries with no apparent or only limited linkages or complementarities (i.e., between-industry diversity), Frenken *et al.* (2007) claim that it captures a portfolio-effect. Thus, the higher the presence of unrelated sectors in a region, the higher the ability to limit sector-specific shocks (Essletzbichler, 2007) through better risk spreading. That is, the local vulnerability stabilizer function increases regional resilience and mitigates unemployment growth (Content *et al.*, 2019; Boschma & Iammarino, 2009).

Several empirical studies have been conducted over the past twenty years to investigate how the related and unrelated varieties explain regional economic development in terms of employment growth, unemployment and productivity growth, value-added growth and innovation performance or capacity (for a review and synthesis, see Content & Frenken, 2016). These investigations have found strong support for the importance of related variety for regional economic growth in the Netherlands (Frenken *et al.*, 2007), Spain (Boschma *et al.*, 2012), Great Britain (Bishop & Gripaios, 2010), Italy (Mameli *et al.*, 2012; Boschma & Iammarino, 2009) and the United States (Castaldi *et al.*, 2015).

However, this is less true of the influence of unrelated variety. While Frenken *et al.* (2007) found that Dutch Nuts 3 regions with a high level of unrelated variety between 1996-2002 dampen unemployment growth (portfolio effect), other studies show no robust correlation (Fitjar & Timmermans, 2016; van Oort *et al.*, 2015; Boschma & Iammarino, 2009).

Figure I presents the conceptual origin, the sources and ways of knowledge transfers corresponding to related and unrelated variety and how they impact local growth. Each type of variety can be linked to a particular type of territorialised public policy. Related variety, for example, inspires measures designed to boost a region's performance through greater specialisation in one or more sectors likely to share common resources, particularly technical and technological. A region could first be specialised in the automotive industry and abandon it to develop the aircraft industry and then develop train engineering. A related diversification strategy, utilising quantitative and qualitative methods, targets new activities in regions closely linked to existing local activities. The integration of relatedness metrics and qualitative analyses, inspired by entrepreneurial self-discovery, aids in identifying diversification opportunities. Advocates contend that aligning new activities with local capabilities enhances their survival rates, supported by evidence. While empirical evaluations are lacking, studies such as Balland *et al.* (2019) suggest that related diversification can effectively enhance the complexity of activities in a region, particularly in complex technologies. Rigby *et al.* (2022) further highlight the economic benefits, revealing that European regions diversifying into related and complex activities experienced higher growth from 1981 to 2015.

Figure I – **Related and unrelated variety: filiation and mechanisms**



Source: Boschma, 2017; Quatraro & Usai, 2017.
Notes: [a] Regions should not start from scratch when developing new domains; instead, they should promote the cross-fertilization of knowledge and ideas across domains (Frenken *et al.*, 2007). [b] According to this version, regional policies should rest upon unrelated rather than related diversification to avoid regional lock-in and to promote radical change in regions (Frenken, 2017; Grillitsch *et al.,* 2018; Janssen & Frenken, 2019).

The unrelated variety inspires public policies that encourage structural change in an area by developing new activities unrelated to existing industries. This would be the case when a textile region would diversify into aircraft making or pharmaceuticals. Some scholars advocate for public policies promoting unrelated diversification, departing from local capabilities but aiming to create new growth paths. This approach, proposed by Grillitsch *et al.* (2018) and Janssen & Frenken (2019), combines unrelated local capabilities to foster innovation. The focus on unrelated diversification is driven by the need to prevent regional lock-in, with proponents arguing that overcoming economic development challenges requires radical change and the development of entirely new trajectories. Additionally, the rarity and difficulty of unrelated diversification justify government support, as it involves building new capabilities and bridging cognitive distances, requiring collective action and policy intervention.

Finally, using European data from the Global Entrepreneurship Monitor on NUTS-2 and NUTS-1 regions, Content *et al.* (2019) find an empirical support for positive relationships between related and unrelated variety and regional employment growth. An important caveat resulting from this research points out that new business formation moderates the relationship between unrelated variety (but not related variety) and employment growth. This finding suggests that technological aspects are not the only elements guiding the relationship between variety and regional dynamics.

Therefore, exploring direct and neighbourhood aspects of the relatedness perspective presents opportunities for new insights into the nature of externalities of the two types of variety. Scholars' recent discussions on the function of knowledge production have suggested the importance of geographical proximity for knowledge creation and diffusion (Boschma, 2005; Buzard *et al.*, 2020; Balland & Boschma, 2021). For example, in a study on five US manufacturing sectors and 853 metropolitan counties, Kekezi *et al.* (2022) point out the role of interregional knowledge spillovers and highlight that both intra- and inter-sectoral spillovers within a county are important determinants of knowledge production. The underlying assumption is that access to extra-regional knowledge is a way of avoiding regional lock-in. Thus, complementarity or cognitive proximity between the local knowledge base and external sources of knowledge also contributes to regional innovation and economic growth.

2. Data, Variables, and Descriptive Analysis

2.1. Data and Definition of Variables

We use an original dataset depicting French "labour market areas" (*zones d'emploi* in French), the *Connaissance locale de l'appareil productif* (Local knowledge of the productive system – CLAP), provided by the French National Institute of Statistics and Economic Studies (INSEE), for the period 2004-2015. The CLAP database is an information system fed from various administrative sources (SIRENE, DADS, URSSAF and SIASP). Since 2003, it has provided localised data on paid employment and earnings at fine geographic levels (municipality). It covers the whole country and activities in both the market and non-market sectors. We use data aggregated at the labour market area level (using the 2010 division, see Aliaga (2015) for additional details) and different sectoral levels. Our study covers labour market areas from metropolitan France (labour market areas located in overseas departments are excluded from our analysis[3]), and thus include both urban and rural spaces. A labour market area is a geographical unit within which most of the labour force lives and works. Mainland France is composed of 304 labour market areas. This division is used because it is functional (see, for example, Broekel & Binder, 2007), and labour market areas are much more homogeneous than political or administrative units and make spatial analysis possible insofar as it covers the entire territory.

2.1.1. Dependent Variable

Our dependent variable is employment growth (*Growth*). It is defined as the change in the total number of employees working in area i (with i=1, …, I) over the period covered:

$$Growth_{i,t'} = \log(E_{i,t'}) - \log\left(E_{i,t}\right)$$

where E is employment, t is the beginning of the period and t' the end.

2.1.2. Independent Variables

Following Frenken *et al.* (2007) and related works later, we use two indicators of regional diversity: related variety and unrelated variety. To this end, employment data are identified at five-digit sector of the French classification of activities (NAF rev.2, 2008). Barring a few exceptions, this classification corresponds to the

3. These areas are not considered because of their geographical distance from metropolitan France (too far from the mainland and, in a few instances, geographically isolated).

NACE rev.2 (statistical classification of economic activities in the European Community), which is, in turn, derived from the International Standard Industrial Classification (ISIC) of economic activities. The indicators of related and unrelated varieties will constitute our main independent variables. They have been constructed using an entropy measure based on Shannon's function. Entropy captures economic variety of an area by measuring the uncertainty or disorder against a uniform distribution of employment across sectors. The entropy of related variety estimates variety within sectors, while the entropy of unrelated variety estimates variety between sectors.

The related variety indicator ($RelVar$) captures the diversity of related sectors. In our case related sectors are the detailed five-digit sectors belonging to the same two-digit aggregate sector. The indicator is the weighted sum of five-digit entropy within each two-digit class of French classification of activities such as:

$$RelVar_i = \sum_{g=1}^{G} P_{g,i} H_{g,i}$$

where $H_{g,i}$ is the degree of entropy (or variety) within the two-digit sector g of the labour market area i. $H_{g,i}$ is calculated as:

$$H_{g,i} = \sum_{j \in S_g \text{ with } P_{j,i} > 0} \frac{P_{j,i}}{P_{g,i}} \log_2 \left(\frac{1}{\frac{P_{j,i}}{P_{g,i}}} \right)$$

where $P_{g,i}$ is the share of employees working in two-digit sector g (NAF A88) relative to the total employment in labour market area i, and $P_{j,i}$ the ratio of the number of employees working in five-digit sector j (with $j=1,\dots,J$) within two-digit sector S_g, relative to the total employment of area i. Thus, we have:

$$P_{g,i} = \sum_{j \in S_g} P_{j,i}.$$

The related variety indicator varies between a lower bound of 0 (when employment in each two-digit sector is concentrated in only one of its five-digit sectors) to $\log_2(J) - \log_2(G)$ (if all five-digit sectors within a two-digit sector have the same employment share, for more details on calculation – see Theil, 1972) Since our study is conducted on 732 five-digit sectors (J) within 88 two-digit sectors (G), our indicator takes as the theoretical upper bound a value of 3.06.

The unrelated variety indicator ($UnrelVar$) captures diversity across two-digit sectors or inter-sector diversification. It's calculated as the entropy of the two-digit level (NAF A88):

$$UnrelVar_i = \sum_{\substack{g=1 \\ with\ P_{g,i} > 0}}^{G} P_{g,i} \log_2 \left(\frac{1}{P_{g,i}} \right).$$

It ranges from 0 (concentration of employment in just one two-digit sector) to $\log_2(G)$ (all sectors employ an equal number of employees). As our analysis distinguishes 88 two-digit sectors, the upper bound of the unrelated variety indicator is 6.46.

Subsequently, we decompose our two indicators according to the R&D intensity of the sectors (see Figure A1 in Appendix). We use the OECD taxonomy of economic activities based on R&D intensity (Galindo-Rueda & Verger, 2016) for both manufacturing and nonmanufacturing sectors.[4] We therefore distinguish, on the one hand, related variety in high-tech sectors and related variety in low- and medium-tech sectors, and on the other hand, unrelated variety in high-tech sectors and unrelated variety in low- and medium-tech sectors. It allows us to examine whether the relationship between related and unrelated varieties and employment growth varies with the technological intensity of local industries (Hartog *et al.*, 2012).

Machinery and equipment (NAF: 28) is the industry that contributes the most to related variety and unrelated variety in high-tech sectors. It's followed by industries like motor vehicles, trailers and semi-trailers (NAF: 29), chemicals and chemical products (NAF: 20), and information technology (NAF: 62) but not in the same order and same proportion. For related variety in low- and medium-tech sectors, it's industries like wholesale and retail trade (NAF: 46-47), specialised construction activities (NAF: 43) that topped the podium. For unrelated variety in low- and medium-tech sectors, it's nonmanufacturing industries like public administration and defence; compulsory social security; education; human health; residential care and social work activities (NAF: 84-88) that contribute largely.

2.2. Main Descriptive Features

The descriptive statistics of the variables used in the analysis are reported in Table 1. Our dependent variable is the employment growth rate between 2004 and 2015, a period marked by the 2008 global financial crisis. The relation

4. Based on the NAF 2 or 3-digit level, high-tech sectors comprise the following sectors in the manufacturing industry: air and spacecraft and related machinery (30.3), pharmaceuticals (21), computer, electronic and optical products (26), weapons and ammunition (25.4), motor vehicles, trailers and semi-trailers (29), chemicals and chemical products (20), electrical equipment (27), machinery and equipment (28), railroad, military vehicles and transport (30.2, 30.4 & 30.9), medical and dental instruments (32.5); and in the nonmanufacturing industry the following: scientific research and development (72), software publishing (58.2), IT and other information services (62 & 63). Remaining sectors are included in the low- and medium-tech sectors (without excluding sectors like public administration, education and human health).

between variety and employment growth may differ depending on whether one is in a period of growth or one of recession. For Bishop & Gripaios (2010), the industrial structure is more conducive to rapid change during economic slumps that may disrupt the relationship between variety and employment growth. We thus split the overall period into three sub-periods: the first one (2004-2008) precedes the 2008 global crisis, the second (2008-2012) covers the crisis phase, and the third (2011-2015) covers the post-crisis period and run the analysis separately for each sub-period.[5]

The top part of Figure II shows the employment growth in each labour market area over the three periods. Globally, for the three sub-periods, the “winning” territories are located more in the west and the south, while the territories in decline are rather in the north-east, south-west axis. The 2004-2008 period is characterized by a broader distribution of growth rates (from −0.13 to +0.48) than the 2008-2012 (from −0.13 to +0.16) and the 2011-2015 (from −0.13 to +0.11). This shrinking of the interval corresponds to the general economic slowdown in the country.

5. CLAP data is not available beyond 2015. To ensure that the three periods have the same duration (of 4 years), we have overlapped the second (2008-2012) and the third (2011-2015).

Table 1 – **Summary statistics**

Variable	Mean	Std. Dev.	Min	Max
Local employment growth 2004-2008	0.01	0.05	−0.13	0.48
Local employment growth 2008-2012	−0.02	0.04	−0.13	0.16
Local employment growth 2011-2015	−0.01	0.03	−0.13	0.11
Characteristics of the area in 2004:				
Related variety	1.87	0.27	1.09	2.37
High-tech related variety	0.06	0.05	0.00	0.26
Low- and medium-tech related variety	1.80	0.25	1.07	2.28
Unrelated variety	4.84	0.23	3.63	5.31
High-tech unrelated variety	0.36	0.20	0.00	1.06
Low- and medium-tech unrelated variety	4.46	0.21	3.44	4.84
Density	3.31	1.01	0.88	8.55
Share of highly-skilled white-collars	0.13	0.03	0.09	0.32
Characteristics of the area in 2008:				
Related variety	1.95	0.24	1.18	2.40
High-tech related variety	0.06	0.05	0.00	0.27
Low- and medium-tech related variety	1.88	0.22	1.15	2.34
Unrelated variety	4.87	0.21	3.98	5.34
High-tech unrelated variety	0.36	0.20	0.02	0.99
Low- and medium-tech unrelated variety	4.51	0.19	3.63	4.89
Density	3.32	1.01	1.03	8.58
Share of highly-skilled white-collars	0.13	0.03	0.08	0.32
Characteristics of the area in 2011:				
Related variety	1.96	0.24	1.13	2.42
High-tech related variety	0.05	0.05	0.00	0.25
Low- and medium-tech related variety	1.91	0.22	1.11	2.38
Unrelated variety	4.85	0.20	4.04	5.31
High-tech unrelated variety	0.34	0.19	0.01	0.97
Low- and medium-tech unrelated variety	4.51	0.18	3.73	4.90
Density	3.31	1.01	0.96	8.59
Share of highly-skilled white-collars	0.11	0.03	0.06	0.31
Observations	304	304	304	304

Source: INSEE, CLAP 2004-2015. Authors’ calculation.

The middle and bottom of Figure II show the distribution of related and unrelated varieties across labour market areas in 2008 and 2011 respectively. As the maps show, the two measures of variety presented as a share of total entropy[6] have different regional patterns. Related variety is higher in urban areas, whereas unrelated variety seems more equally distributed in both 2008 and 2011.[7] Many areas with a high level of total entropy show a strong resemblance with those on the map of related variety, which also have high levels; that is the case, for instance, for Lyon, Nantes, Tours and Bordeaux. When we look at the maps of unrelated variety and entropy, some differences emerge: territories with strong performances in terms of unrelated variety show an average contribution to total entropy. Some areas with relatively low levels of unrelated variety are rural (La Lozère, Pontivy and Villeneuve-sur-Lot). However, some of them are high-density zones such as Avignon, Créteil, Quimper, Lorient and Orly. An interesting fact to note is the high enough correlation (0.58) between the two types of variety. This value remains close to levels found by Aarstad *et al.* (2016) on Norwegian data and Content *et al.* (2019) on 204 European regions.

Table S1 in the Online Appendix (link to the Online Appendix at the end of the article) reports the correlation matrix of control variables used in our three-period analysis. Overall, the results of the correlation matrix revealed no serious evidence of multi-collinearity.

3. Estimation Strategy and Main Findings

3.1. Estimation Procedure

To estimate the relation of variety with regional employment growth, it is essential to consider various types of spatial interaction. Generally, three different types of interaction may explain why an observation relating to a specific location may be dependent on observations relating to neighbouring areas:

- An endogenous interaction, when the value of the dependent variable for one geographical area is jointly determined with that of its neighbours;
- An exogenous interaction, where the value of the dependent variable for one geographical area depends on the observable characteristics of its neighbours;
- An interaction effect among the error terms due to omitted variables from the model that are spatially autocorrelated.

These three types of interaction are derived from a General nesting spatial model called the Manski model (1993). The Manski model is less used in empirical works because, on the one hand, its weak identifiability leads to higher uncertainty in parameter estimates (Elhorst, 2014). On the other hand, this model is often overparameterized (Burridge *et al.*, 2016). The preferred solution in the empirical literature is to remove one of the three forms of spatial correlation, which is the solution we adopt.We apply a spatial Durbin error model (SDEM), in which the dependent variable is influenced by the independent variables, the spatial lags of the independent variables, and the spatial correlation in the error term.

$$\begin{aligned} Growth_{i,t+4} = {} & a_0 + \alpha_1 RelVar_{i,t} + \alpha_2 UnrelVar_{i,t} \\ & + \alpha_3 Control_{i,t} + \theta_1 RelVar_{w_i,t} + \theta_2 UnrelVar_{w_i,t} \\ & + \theta_3 Control_{w_i,t} + u_{i,t} \qquad (1) \\ \text{and } u_{i,t} = {} & \lambda u_{w_i,t} + \varepsilon_{i,t}, \end{aligned}$$

where $Growth_{i,t+4}$ refers to employment change in area i between year t and year t+4, $RelVar_{i,t}$ and $UnrelVar_{i,t}$ respectively refer to related variety and unrelated variety in area i in year t, w_i denotes the index of the neighbourhood of the employment area i. a_0, α_1, α_2 and α_3, θ_1, θ_2 and θ_3, the neighbourhood interaction effects, and λ, the interaction effect among the errors, are unknown parameters to be estimated, and finally ε is a vector of disturbance terms. In addition to our variables of interest, *Control* is a set of control variables selected because of their importance in the dynamics of employment. To capture urbanisation economies, we control for the employment density.[8] The underlying hypothesis is that urbanized areas promote local knowledge spillovers, linkages and imply a wide offer of local public goods (Combes, 2000; Mameli *et al.*, 2008; Paci & Usai, 2008). We expect that employment density will increase employment growth. We also control for the local level of human capital, measured by the share of highly-skilled white-collar workers in the labour force in the area.[9] The availability

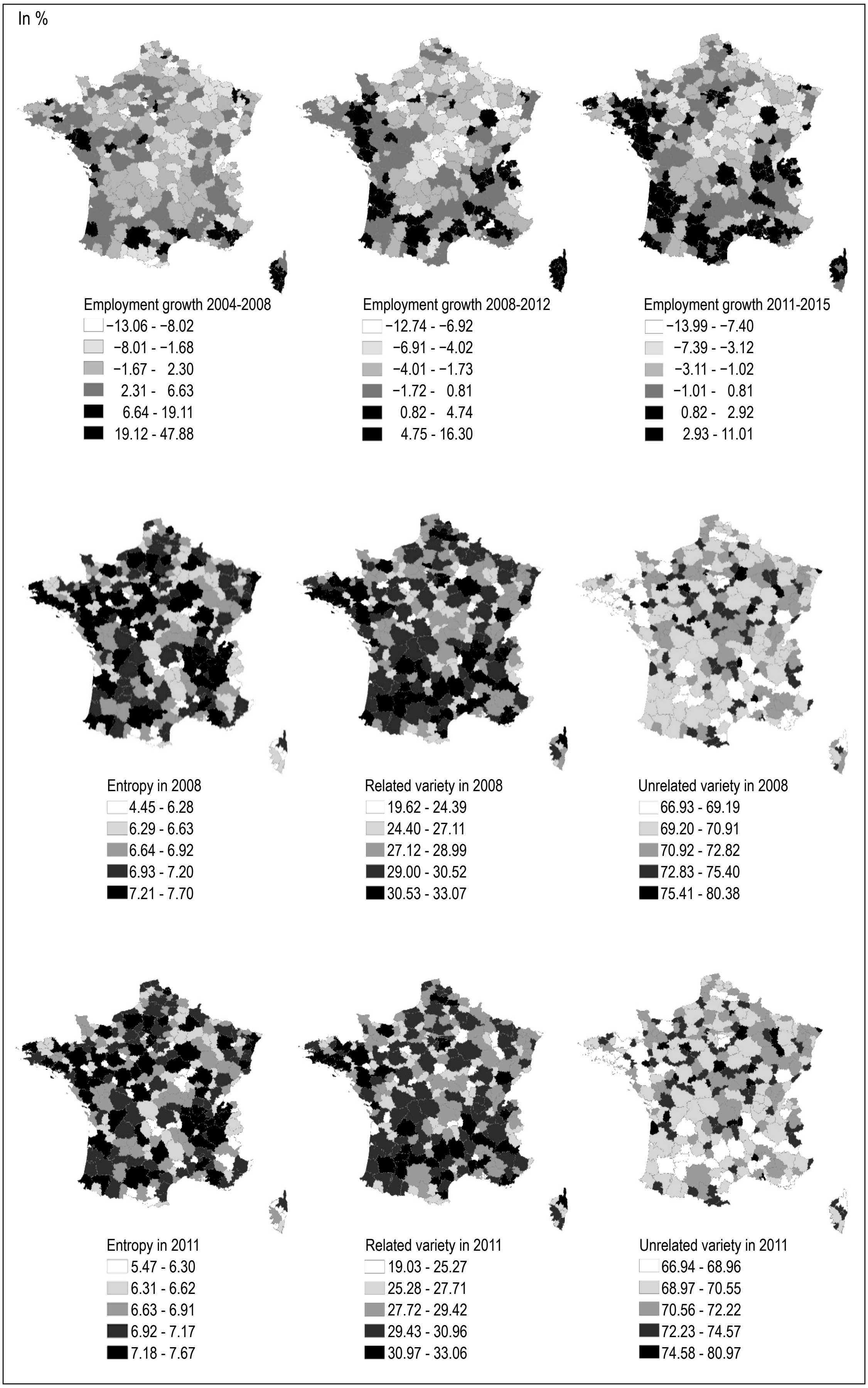
6. The decomposability of entropy measure involves that five-digit entropy is equal to the addition of related variety (weighted sum of five-digit entropy within each two-digit sector) and unrelated variety (two-digit entropy).

7. If we interpret these results with the maps of related variety and recent employment growth in mind, certain similarities can be observed for high values, especially in southeast-central France (Lyon, Issoire, Annecy and Bourg-en-Bresse) west (Nantes and Les Herbiers) and south-western regions too (Bordeaux, Bayonne, and La Teste-de-Buch).

8. Employment density is calculated as the logarithm of number of employees working in establishments located in the labour market area per square kilometre (km²).

9. This variable is measured as the percentage of upper-level employees (or highly skilled white-collars) working in establishments located in the labour market area. Upper-level employees correspond to cadres et professions intellectuelles supérieures, *the third group in the most aggregated (level 1) classification of professions and socio-professional categories (PCS). For more detail, see the composition of this group: https://www.insee.fr/fr/metadonnees/pcs2020/groupeSocioprofessionnel/1?champRecherche=true*

Figure II – **Employment growth, related variety, and unrelated variety**



Source: INSEE, CLAP 2004-2015. Authors' calculation.

of a highly skilled labour force in a region is often found to be crucial for local employment growth, as this population is expected to help innovation activities and growth (Paci & Usai, 2008; van Oort *et al.*, 2015). Recently, in a study on 204 European regions, Content *et al.* (2019) stressed that educational level captures the ability and the skills to detect and exploit potential business opportunities. The spatial weight matrix W used in the econometric estimation is the row standardized inverse spatial distance matrix (with a cut-off point).[10]

3.2. Econometric Results

This section presents the findings for our estimations over the three periods (pre-crisis, crisis and post-crisis). The diagnostics for spatial dependence obtained for the OLS version of the model are reported in the bottom portion of the result tables. Whatever the period, the Moran' I index from the regression residuals is highly significant. The spatial models were estimated using a maximum likelihood estimator with White robust standard errors. Calculating the Variance Inflation Factor (VIF) for our regressions returns a score below 2.77, which infers that multicollinearity is not a severe issue in our findings, as suggested, for instance by O'Brien (2007). The overall significance of our estimations is good, and the R-squared for spatial models ranges from 9% to 31%.

The results are presented separately for three periods: the pre-crisis period (2004-2008), the crisis period (2008-2012) and finally the post-crisis period (2011-2015). We further consider the presence of heterogeneous patterns and provide estimates separately for rural areas and urban areas.[11] We also provide estimates when labour market areas of Île-de-France (IDF) region are excluded. The IDF region is indeed very specific because of its considerable weight in employment in France (almost 23% in 2015).

The separate analysis of rural and urban areas makes sense as rural and urban areas can differ in many dimensions, such as economic production structure, human capital, institutions, history, territory, geography, etc. Some papers in the literature have dealt with this issue. For instance, Duranton & Puga (2005) stress that large cities are specialised in business services while industry takes more place in rural areas. Van Oort *et al.* (2015) investigated 205 small, medium and large European regions and only observed a positive association between related variety and employment growth in small and medium places.

3.2.1. Pre-Crisis Period Results

Table 2 reports the estimated direct and neighbourhood effects of related and unrelated variety on local employment growth. The local and to a lesser extent the neighbourhood related variety is positively correlated with employment growth during the period 2004-2008 (model 1). This is in accordance with previous studies showing a positive relation between related variety and employment dynamics (Frenken *et al.*, 2007; Wixe & Andersson, 2017; van Oort *et al.*, 2015). Firms can mediate this relation, as pointed out by Cainelli *et al.* (2016) in their micro-level analysis, higher related variety increases firm innovativeness and, consequently, productivity, resulting in higher employment growth rates. Our finding is robust to the use of another spatial weight matrix (see models 1 and 2 in Table S2 in Online Appendix). However, local unrelated variety does not seem correlated with employment growth. This last finding is also observed by Cortinovis & van Oort (2015) in their study of 260 NUTS-2 regions in Europe. The neighbourhood unrelated variety seems however to exert a negative influence on local employment dynamics.

When adding control variables (model 2), we found that the density of economic activity, as a proxy for urbanisation economies, and the level of qualification have a negative and a positive influence, respectively. These results are in line with most of those found in the literature on regional growth (Frenken *et al.*, 2007; Hartog *et al.*, 2012; Deidda *et al.*, 2006). Combes (2000) considers that this negative coefficient of the density of the local system reflects congestion effects (high land rent, congestion of infrastructures and transportation, etc.) that produce negative externalities on local employment growth. As for skilled labour, in a comprehensive analysis of 784 local labour markets in Italy, Paci & Usai (2008) stress that a higher number of educated labour forces in a region fosters innovation and knowledge spillovers and, therefore, local growth. Finally, we find that the higher the qualification of jobs in neighbouring areas the lower the employment growth.

When we decompose related and unrelated varieties following the R&D intensity of sectors,

10. We define labour market areas as neighbours when the distance between them is smaller than 67.5 km, using the inverse distance between areas as weight. This latter is inversely related to the distances between the units. If the distance between units is larger than 67.5 km, this weight is set to zero. As in most applied studies, the inverse distance matrix is row-standardized (each element in row i *is divided by the sum of row* i*'s elements) so that the impact of neighbouring areas is equalized.*

11. Labour market areas are classified as urban or rural according to their population density. Areas with a level of population density equal to or greater than the first quartile (47.91) are considered urban, the others rural.

we found that both high-tech and low- and medium-tech related varieties are positively correlated with employment growth (model 3). This finding is in some way in contrast with the result of Hartog *et al.* (2012), who show only a positive effect of related variety among high-tech sectors in Finland. Model 3 also shows that the greater the high-tech unrelated variety, the lower the employment growth.

The low- and medium-tech unrelated variety in the surrounding areas reinforces the negative effect on employment.

Table 2 – **Employment growth over 2004-2008**

Dep. Var. : Employment growth 2004-2008	Model 1	Model 2	Model 3	Model 4 (rural areas)	Model 5 (urban areas)	Model 6 (without IDF region)
Characteristics of the area in 2004:						
Related variety	0.047*** (0.013)	0.039*** (0.014)		0.078*** (0.030)	0.029** (0.014)	0.051*** (0.014)
Unrelated variety	−0.014 (0.017)	−0.017 (0.017)		−0.140*** (0.038)	0.030* (0.017)	−0.024 (0.017)
Density		−0.013** (0.005)				
Share of highly-skilled white-collars		0.714*** (0.121)				
High-tech related variety			0.213** (0.095)			
Low- and medium-tech related variety			0.044*** (0.015)			
High-tech unrelated variety			−0.065** (0.027)			
Low- and medium-tech unrelated variety			−0.017 (0.019)			
Characteristics of the neighbourhood areas in 2004:						
Related variety	0.015 (0.025)	0.010 (0.025)		−0.048 (0.060)	0.045* (0.027)	0.046 (0.029)
Unrelated variety	−0.064** (0.026)	−0.055** (0.026)		−0.031 (0.064)	−0.076*** (0.026)	−0.080*** (0.029)
Density		0.011 (0.007)				
Share of highly-skilled white-collars		−0.490** (0.202)				
High-tech related variety			0.118 (0.227)			
Low- and medium-tech related variety			0.046 (0.032)			
High-tech unrelated variety			−0.093 (0.058)			
Low- and medium-tech unrelated variety			−0.084** (0.038)			
Constant	0.269*** (0.095)	0.242** (0.107)	0.339** (0.168)	0.771*** (0.260)	0.0953 (0.121)	0.331** (0.130)
lambda	0.346*** (0.078)	0.377*** (0.075)	0.338*** (0.079)	0.645*** (0.181)	0.281** (0.110)	0.357*** (0.080)
Observations	304	304	304	76	228	285
Moran's I	6.725***	7.043***	6.706***			
R^2	0.133	0.206	0.135	0.309	0.115	0.123
Likelihood	490.660	507.180	491.993	106.285	415.011	460.255
Prob > chi2	0.000	0.000	0.000	0.000	0.000	0.000

Notes: Standard errors are shown in parentheses. ***, **, * = significance at 1%, 5% and 10%, respectively
Source: INSEE, CLAP 2004-2015. Authors' calculation.

We observe a positive association of related variety with employment growth in rural and urban areas (models 4 and 5), as well as in all areas after excluding the 19 employment areas of the IDF region, 10 of which are rural and 9 urban (model 6). Concerning neighbourhood effects, related variety is positively associated with employment growth in urban areas (model 5) and unrelated variety is negatively associated with employment growth in all models except the fourth, which focuses on rural areas.

3.2.2. Crisis Period Results

Table 3 provides the same results as Table 2 for the period 2008 to 2012, i.e. during the global crisis. The table shows that related variety in the neighbourhood is positively associated with employment growth (model 1), leading us to consider that the crisis increased interdependence between labour market areas (Cousquer, 2022). This evidence confirms that when cognitive proximity between related sectors in an area with that of its neighbourhood is not too small, it raises opportunities and interactive learning between sectors that ultimately promote employment growth. This empirical relevance is in accordance with that of Boschma & Iammarino (2009), which illustrates the importance of extra-regional knowledge on employment when it comes from industries that are related but not similar to those present in the region.

Moreover, the level of unrelated variety in the neighbourhood seems to be negatively associated with employment growth. Model 3 suggests that this association is driven by high-tech unrelated variety in neighbouring areas. Concerning other neighbourhood interactions, the level of low- and medium-tech related variety has a positive effect on employment growth.

When we distinguish between rural areas (model 4) and urban areas (model 5), we find that unrelated variety is positively associated with employment growth only in urban areas. Regarding the neighbourhoods, our results show a positive association of related variety and a negative association of unrelated variety with local employment in urban areas, and no significant association in rural areas. This last result is also verified when we exclude the IDF region from the analysis (model 6).

3.2.3. Post-Crisis Period Results and Intertemporal Comparisons

The estimations of our models for the post-crisis period (Table 4) are close to those of the pre-crisis period. Concerning direct effects, we find three similarities between the two periods: overall related variety, low- and medium-tech related variety, and the share of highly qualified jobs are positively linked with employment growth. In the case of neighbourhood effects, we found only one common feature, which is a negative association of unrelated variety with employment growth. In addition, during the post-crisis period, we found a negative association of unrelated variety in the neigbourhood and a positive association of low- and medium-tech related variety in the neigbourhood with the local employment growth. This last result is also observed during the crisis period.

Concerning urban areas, we find exactly the same results as in the pre-crisis period for the local related variety. For the neighbourhood effects, related variety plays a positive role and unrelated variety a negative one (model 5), as in the crisis. In model 6, which excludes the Île-de-France region, we obtain the same results as in model 5 for neighbourhood effect.

To sum up, concerning the direct effects over the three periods, we find that related variety is positively correlated with employment growth before the crisis, that its role becomes insignificant during the crisis period (2008-2012) but becomes significantly positive again in the post-crisis period. It seems that during the crisis, specialisation in related sectors implies less flexibility to areas to adapt their products and reconvert their economic activities. In that vein, Steijn *et al.* (2023) state in a comprehensive study on great historical depressions that crises significantly reduce the pace of diversification. The unrelated variety does not appear to play a role in our study.

When we distinguish among high-tech sectors and low- and medium-tech sectors for each type of variety, we find that both related variety in the high-tech and related variety in low- and medium-tech sectors are positively correlated with employment growth.[12] Only the unrelated variety in the high-tech sector is linked with a slowing down of employment during the period 2004-2008. This result is in contrast with that of Cortinovis & van Oort (2015), who found a negative impact of unrelated variety in low-tech regions when controlling for the regional level of technological progress. During the crisis, neither related, nor unrelated variety influence directly employment variation, a result

12. *For Hartog* et al. *(2012), the positive and significant effect of related variety among high-tech sectors in Finnish regions can be explained by the ability of high-tech sectors to produce radical innovation and thus introduce new products on the market.*

Table 3 – **Employment growth over 2008-2012**

Dep. Var. : Employment growth 2008-2012	Model 1	Model 2	Model 3	Model 4 (rural areas)	Model 5 (urban areas)	Model 6 (without IDF region)
Characteristics of the area in 2008:						
Related variety	0.012 (0.010)	0.007 (0.011)		0.000 (0.020)	0.014 (0.012)	0.013 (0.010)
Unrelated variety	0.0017 (0.012)	−0.006 (0.012)		−0.061** (0.027)	0.015 (0.013)	−0.002 (0.012)
Density		0.002 (0.003)				
Share of highly-skilled white-collars		0.134* (0.081)				
High-tech related variety			0.017 (0.067)			
Low- and medium-tech related variety			0.008 (0.012)			
High-tech unrelated variety			−0.003 (0.019)			
Low- and medium-tech unrelated variety			0.010 (0.015)			
Characteristics of the neighbourhood areas in 2008:						
Related variety	0.070*** (0.024)	0.074*** (0.026)		0.025 (0.042)	0.064** (0.025)	0.064*** (0.024)
Unrelated variety	−0.073*** (0.024)	−0.060** (0.025)		−0.049 (0.044)	−0.078*** (0.024)	−0.067*** (0.024)
Density		−0.008 (0.006)				
Share of highly-skilled white-collars		0.024 (0.192)				
High-tech related variety			0.126 (0.168)			
Low- and medium-tech related variety			0.050* (0.027)			
High-tech unrelated variety			−0.092** (0.043)			
Low- and medium-tech unrelated variety			−0.036 (0.033)			
Constant	0.168 (0.115)	0.146 (0.126)	0.018 (0.158)	0.461** (0.190)	0.134 (0.117)	0.166 (0.116)
lambda	0.515*** (0.065)	0.516*** (0.065)	0.510*** (0.066)	0.676*** (0.165)	0.470*** (0.094)	0.531*** (0.066)
Observations	304	304	304	76	228	285
Moran's I	9.500***	9.803***	9.424***			
R^2	0.099	0.118	0.106	0.253	0.086	0.096
Likelihood	620.110	623.381	620.938	144.560	478.332	586.857
Prob > chi2	0.016	0.015	0.081	0.026	0.001	0.036

Notes: Standard errors are shown in parentheses. ***, **, * = significance at 1%, 5% and 10%, respectively
Source: INSEE, CLAP 2004-2015. Authors' calculation.

maintained when we distinguish low-and-medium-tech sectors from high-tech sectors varieties.

A change occurs in the post-crisis period where we estimate a positive association of related variety in low- and medium-tech sectors and of unrelated variety in high-tech sectors with employment growth. Analysis by territory type (rural vs. urban) shows that the effect of related variety is driven by both urban and rural areas during the period 2004 to 2008. Surprisingly, there is a negative association of unrelated

Table 4 – **Employment growth over 2011-2015**

Dep. Var. : Local employment growth 2011-2015	Model 1	Model 2	Model 3	Model 4 (rural areas)	Model 5 (urban areas)	Model 6 (without IDF region)
Characteristics of the area in 2011:						
Related variety	0.018** (0.009)	0.015* (0.009)		−0.002 (0.018)	0.027*** (0.010)	0.014 (0.009)
Unrelated variety	0.009 (0.011)	−0.002 (0.011)		−0.009 (0.026)	0.008 (0.012)	0.011 (0.011)
Density		−0.000 (0.003)				
Share of highly-skilled white-collars		0.196*** (0.070)				
High-tech related variety			−0.057 (0.064)			
Low- and medium-tech related variety			0.027*** (0.010)			
High-tech unrelated variety			0.029* (0.017)			
Low- and medium-tech unrelated variety			0.002 (0.013)			
Characteristics of the neighbourhood areas in 2011:						
Related variety	0.046** (0.019)	0.037* (0.020)		0.050 (0.037)	0.047** (0.021)	0.047** (0.020)
Unrelated variety	−0.040* (0.021)	−0.039* (0.021)		−0.062 (0.040)	−0.050** (0.023)	−0.046** (0.021)
Density		−0.002 (0.005)				
Share of highly-skilled white-collars		0.178 (0.155)				
High-tech related variety			−0.009 (0.155)			
Low- and medium-tech related variety			0.045** (0.023)			
High-tech unrelated variety			−0.029 (0.036)			
Low- and medium-tech unrelated variety			−0.034 (0.029)			
Constant	0.015 (0.093)	0.057 (0.099)	0.004 (0.133)	0.233 (0.153)	0.048 (0.107)	0.035 (0.093)
lambda	0.406*** (0.073)	0.398*** (0.074)	0.407*** (0.073)	0.332 (0.208)	0.465*** (0.095)	0.402*** (0.075)
Observations	304	304	304	76	228	285
Moran's I	7.172***	6.851***	7.238***			
R^2	0.089	0.127	0.095	0.112	0.101	0.093
Likelihood	660.047	666.543	661.229	151.829	512.374	620.069
Prob > chi2	0.004	0.000	0.022	0.307	0.000	0.009

Notes: Standard errors are shown in parentheses. ***, **, * = significance at 1%, 5% and 10%, respectively
Source: INSEE, CLAP 2004-2015. Authors' calculation.

variety with employment growth in rural areas during the crisis, that is not persistent in the post-crisis period. Related variety in urban areas also seems to be positively associated with employment growth except during the crisis.[13] This result is in line with those by Cortinovis & van Oort (2015). Relatedly, Firgo & Mayerhofer

13. The bounce ability of urban counties is also verified in the study of Talandier & Calixte (2021) on the effects of the 2008 economic shock on French territories. However, in a similar study on the US case, Grabner & Modica (2022) observe effects for both rural and urban areas, with a particularly large effect for urban ones.

(2018) find in their study on Austria that employment benefits more from diversity in related fields in urban regions. However, this work, which was conducted over a large period (2000-2013), does not include the context of the crisis in the analysis.

The investigation of the neighbourhood effects tells us that, except for rural areas, related variety is positive correlated with employment growth during the crisis. However, this correlation seems less marked during the post-crisis period. Unrelated variety exerts a negative influence across the three periods studied (with a more intense influence during the crisis) both in urban areas and areas outside of the IDF region.

When considering the R&D intensity of economic activities, we find a positive association of related variety in the low- and medium-tech sector with employment growth during the crisis and post-crisis periods (the association being smaller during the post-crisis period). A negative association of unrelated variety is found in the low- and medium-tech sectors from 2004 to 2008 and in the high-tech sectors from 2008 to 2012.

The separate analysis of urban areas clearly shows positive association of neighbourhood related variety and a negative of neighbourhood unrelated variety with employment growth during the three periods. These associations are stronger during the crisis (from 2008 to 2012). This confirms the potential important role for related variety in the neighbourhood in mitigating the effects of the crisis. For the three periods, the association of related variety and unrelated variety with employment growth was only present in urban areas. It seems that when an employment area is characterised by a low intensity of forms of variety, neighbouring territories help to compensate for this deficit. This compensatory effect only applies to urban employment areas; rural employment areas do not benefit.

As a robustness check, we have estimated the same models for the three periods using a different specification of the spatial weight matrix, namely the square inverse distance neighbourhood matrix. The latter is supposed to be more robust in differentiating between neighbouring and distant areas since using square values increases the relative weights of the nearest ones. The coefficients of our key variables were found to be very similar to our main estimations in terms of significance and scale (see Tables S2 to S4 in Online Appendix).

* *
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This article aimed to investigate the relations between varieties – related and unrelated – and employment growth at the labour market area level in France mainland between 2004 and 2015. Its main contribution is to improve our understanding of how different forms of industrial variety relate to local employment growth; this is achieved, on the one hand, by developing a new perspective that considers the local and neighbourhood nature of industry relatedness, and on the other hand, by exploring crisis times and ordinary times.

While empirical results show that local industrial diversity is correlated with local employment dynamics, two questions arise, particularly for public decision-makers. The first is whether and how local industrial diversity can be increased. It seems more straightforward and less costly to support the entry of a sector related to existing activities than creating an unrelated industry. The second question concerns how public policy should deal with the interactions between territories, if local growth is influenced by industrial variety in the neighbourhood. From this perspective, various institutional frameworks could be explored. For instance, the ‘policy network’ concept, which focuses on relations between interest groups in the broad sense and evokes a form of coordination between national and sub-national levels, could find a wider field of application. Another promising development is rooted in multi-level governance as an alternative to hierarchical government, which implies a mode of negotiated relations between institutions at different institutional levels or as the interweaving of political networks within formal government institutions.

While empirical evidence suggests that the higher the industrial diversity the higher the local growth, and under the hypothesis that this relation is of cause and effect, a pivotal question for policymakers is whether diversity can be deliberately enhanced and, if so, through what means. A common assumption might be that supporting the entry and emergence of related sectors would be more straightforward and cost-effective than introducing unrelated sectors. However, empirical findings challenge this assumption, indicating that the benefits of an unrelated sectoral structure might be more economically advantageous. In addition, policymakers should also pay attention to the policies adopted in the neighbourhood to bring consistency to public action at the regional level.

To provide some answers to these questions, future research should focus on analysing how knowledge flows between related sectors on the one hand, and between unrelated sectors on the other hand, as well as on the public policies that would make it possible to increase these flows. The diversity of situations should also be addressed insofar as, since Jacobs' externalities are based on innovation, require a certain level of absorptive capacity to favour their effect on growth. The idea is that a larger regional knowledge base enhances the ability to absorb knowledge from various related and unrelated sectors, resulting in a more significant effect on employment growth (Fritsch & Kublina, 2017). Therefore, it would be essential to develop policies that not only support regional diversification but also enhance absorptive capacity to maximize the benefits of knowledge flows across sectors.

Our results suggest several avenues for future research. First, using the NAF hierarchical industry classification system, or its equivalent at the European level NACE, to calculate related and unrelated variety measures is disputable. This classification is primarily based on product relatedness, which assumes that industries belonging to a given sub-category make products that are closer to the ones made in the other sub-categoris of the same parent category than to the ones made in other sub-categories. (Hartog *et al.*, 2012). However, such categorisation may fail to account for knowledge externalities and technological proximity between industries (Boschma *et al.*, 2012). Another suggestion consists in using other sectoral taxonomies, such as the one of Pavitt (1984) which is based on technology and identifies four groups (science based industries, scale intensive industries, specialized suppliers industries, and supplier dominated industries), or Neffke & Henning's one (2008) which adopts a novel characterisation technique based on the place of manufacture of the products. The study of Wixe & Andersson (2017) stresses the importance of two other dimensions of variety resting upon the respective relatedness of education and occupation of employees, that could be taken into account in further researches. The argument is that information and knowledge transfers primarily involve individuals. Finally, a third promising research field is the investigation of the channels through which related variety leads to employment growth. In a recent study based on a novel pan-European regional survey, Content *et al.* (2019) show that entrepreneurship may be a possible transmission mechanism via which spillovers between related sectors lead to the creation of new jobs and, thus, to employment growth. ☐

Link to the Online Appendix:
www.insee.fr/en/statistiques/fichier/8305261/ES544_Amdaoud-Levratto_OnlineAppendix.pdf

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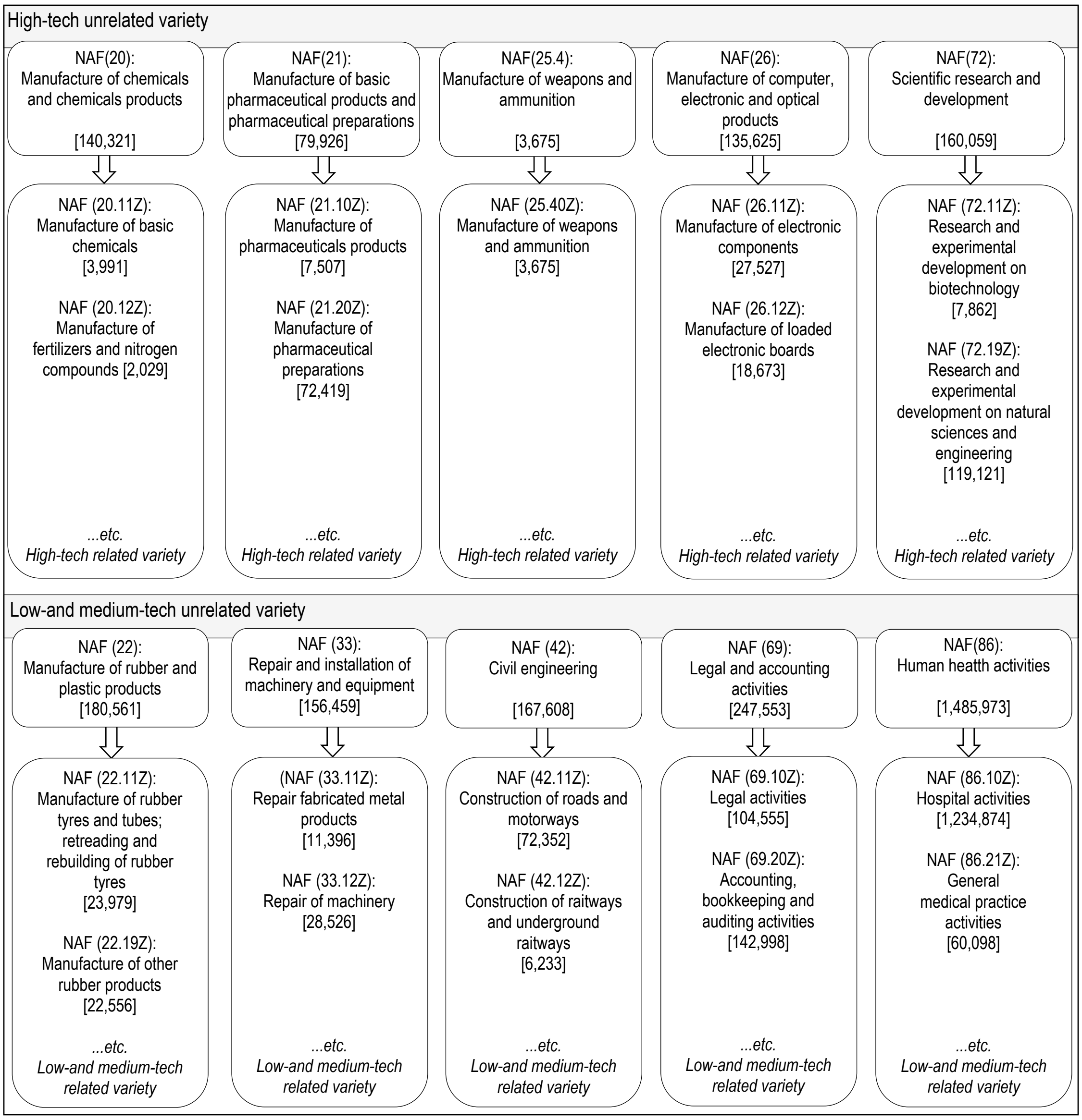
Figure A1 – **High-tech related and unrelated variety vs. low- and medium-tech related and unrelated variety**



Note: The values between brackets are employment at national level in 2011, they are obtained from CLAP information system. They are used to illustrate, on one hand, how related variety is decomposed in high-tech related variety and low- and medium-tech related variety and, on the other hand, how unrelated is decomposed high-tech related variety and low and-medium-tech unrelated variety. The figure is just an excerpt; all sectors are not represented.
Source: INSEE, CLAP 2011. Authors' calculation.

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