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Time Scales of the Low-Carbon Transition: A Data-Driven Dynamic Multi-Sector Growth Model

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Abstract: This paper employs a dynamic multi-sector growth model with changing technology to study the relevance of the price and quantity dimensions involved in the technical substitution of carbon-intensive technology, that is, the low-carbon transition. For the framing of the transition, the stylized market dynamics by Flaschel and Semmler (1987. "Classical and Neoclassical Competitive Adjustment Processes." *The Manchester School* 55 (1): 13–37) are used, who propose a cross-dual out-of-equilibrium adjustment process. The major empirical challenge to identify the adjustment speed for quantities and prices is to empirically estimate sector-specific adjustment coefficients. The transition speed is estimated for seven carbon-intensive sectors in six high-income economies (Germany, France, Italy, Netherlands, Japan, and the US) using a mixed-effects varying-slopes model on EU KLEMS data. Directed technical change is enforced by a revenue-neutral, pro-active fiscal policy of a tax–subsidy form, which has the effect to greatly accelerate the phase-out of carbon-intensive technology and the phase-in of green technology. The speed of green substitution that allows decarbonization is then evaluated analytically and computationally along four policy and time dimensions: cost advantage, a percentage tax on carbon-intensive output, a green subsidy rate, and initial investment ratios. Though the tax itself has an impact on the speed of decarbonization, it is significantly improved by green subsidies and green investments. The cost advantage of the green over the carbon technology is shown to have a negligible impact on decarbonization speed by itself. Without ambitious fiscal policy, especially in the form of green

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investment support, this substitution process appears to be too slow to reach decarbonization in a timely manner.

Keywords: low-carbon transition; complex dynamical systems; cross-dual dynamics; structural change; fiscal policy; carbon pricing

JEL Classification: C63; O25; O41; Q55

1 Introduction

According to the latest landmark reports by the UN Intergovernmental Panel on Climate Change (IPCC), global net emissions must decrease by 45 per cent by 2030, requiring a formidable structural change of the economy toward decarbonization in order to avoid climate catastrophes in the form of increasingly extreme heatwaves, wildfires, droughts, flooding, mass extinctions of species, sea-level rises, and changes in the direction of oceanic currents. Consensus among economists favors carbon pricing, either as a tax or a cap-and-trade system, as the most cost-efficient policy instrument in order to curb emissions in line with the Paris Agreement of keeping world temperature rise by 2 °C. At the current moment, very few countries are pricing carbon emissions high enough to meet climate targets (UNEP 2020). As the scale and urgency of the climate crisis intensifies and becomes more evident, its actual effectiveness to curb emissions (as well as its social regressiveness) is perceived as too low in light of the empirical evidence available (Ball 2018; Green 2021; Lilliestam, Patt, and Bersalli 2021; Narassimhan et al. 2018; Teixidó, Verde, and Nicolli 2019; Tvinnereim and Mehling 2018; Rosenbloom et al. 2020). While many countries and jurisdictions have already adopted or are in the process of introducing various schemes of carbon pricing, exponential growth of carbon emissions has steadily kept apace without substantial changes, both nationally and internationally (Narassimhan et al. 2018; Pretis 2022). Last but not least, carbon prices required to effectively decarbonize in time may be so high that are politically unfeasible, especially for low-income countries and low-income households in high-income economies.

In the face of potentially immense climate risks, the relevant policy issue may be then not so much of generic intertemporal costs versus benefits of mitigating climate change, as critically noted by Stern, Stiglitz, and others in recent contributions (Kattel et al. 2018; Stern 2022; Stern and Stiglitz 2021, 2022). Critics of the social-cost-of-carbon approach highlight that its estimates vary greatly due to a high sensitivity to model assumptions and parameters (especially concerning the discount rate and the uncertainty of future damages on the economy). Further, integrated assessment models lack transparency due to its large number of equations, uncertain parameters, and model parts. Much is still insufficiently understood (Pindyck 2013): in this context, considering the large uncertainties involved, intertemporal cost–benefit analyses may not give sufficient guidance. This paper contributes to the alternative target-consistent approach, favored by Stern and Stiglitz, to address instead the pressing issue of how much *time* the structural transition from carbon to renewable energy may take and, most importantly, whether fiscal policy should focus on the technology side of market dynamics in order to speed up this process of technological substitution to meet the Paris Agreement targets in time – in particular, whether carbon pricing is enough for speeding up such a process or green investments are further needed.

This paper also contributes to the endogenous-growth literature on directed technical change toward decarbonization where this question was also posed by Acemoglu et al. (2012, 2016), Golosov et al. (2014) and which generally supports tax–subsidy policy mixes, with subsidies targeting low-carbon R&D innovation. Instead of addressing technical change as either raising increasing the capital-to-labor ratio (i.e., capital deepening) or raising total factor productivity, our framework differs in modeling decarbonization as the dynamic substitution of carbon-intensive processes (such as fuel-based cars or fossil energy) by less carbon-intensive ones (such as electric cars or solar energy) within specific industries (such as automotive manufacturing or energy production) in an input–output setup. Our dynamical framework allows to explicitly capture the time dependency of such technical substitution on particular policy dimensions. Although some authors still consider carbon pricing as the only and most cost-efficient policy instrument available (Blum et al. 2019), others use the existing academic work and empirical evidence to call for a more diversified policy portfolio that also includes regulations, R&D subsidies, central-bank financial support, finance instruments, and public investments (Braga, Semmler, and Grass 2021; Carnevali et al. 2020; Jenkins et al. 2020; Semmler et al. 2021; Teixidó, Verde, and Nicolli 2019). While this paper finds some support for carbon pricing to accelerate the low-carbon transition in broad agreement with the literature, the effective carbon prices required to attain the Paris Agreement targets in time appear so high that they should be accompanied in particular by substantial publicly supported direct investment in green infrastructure and technology, as fiscal instruments and subsidies on the green transition show a multiplicative effect on the speed of the low-carbon transition.

For the goal of evaluating the critical role of fiscal policy in accelerating the sectoral low-carbon transition, this paper employs an original computational method that re-purposes the classic theoretical literature in micro-economic adjustment processes (Hicks 1939, 1947; Flaschel 2010; Jorgenson 1960; Mas-Colell 1986; Morishima 1981) to build data-driven dynamical input–output models of multi-sector growth with green process innovation and fossil-fuel process extinction within specific industries (Flaschel and Semmler 1987, 1992). This literature explores the *stability* of competitive economies by considering its complex price-quantity dynamics out of equilibrium through specific sector-level adjustment processes in the form of stylized facts as dynamical laws of motion. Each of such adjustment processes underlying a stylized law of motion can be characterized by its corresponding sector-specific reaction coefficient, which, resembling state-of-the-art machine-learning approaches, can be empirically calibrated using real training data to yield a data-driven dynamical system (Brunton and Kutz 2022; Vallès Codina 2023).

In contrast to existing highly aggregated approaches like integrated assessment modeling, this novel, data-driven, sector-oriented method is highly transparent in its abstract simplicity: instead of the formulation of market dynamics by excess demand functions, the baseline cross-dual dynamics in prices and quantities rely on imbalances of supply and demand moving prices (the Walrasian law of excess demand) and differences between prices and costs (deviations in profitability) driving quantities (the classical law of excess profitability). While this dynamic process can also show asymptotic convergence to equilibrium as a rest state, cross-dual dynamics in its simplest form can generate complex oscillations of prices and quantities around their long-run equilibrium values. Keynesian dual short-run dynamics, which further stabilize classical oscillations, can also be explored (Vallès Codina 2023): see Table 1 for a stylized illustration of the two types of dynamics. This paper focuses on cross-dual dynamics.

By running a large number of simulations, our stylized, data-driven approach is able to rigorously assess the sensitivity of our results to the relevant parameters at play, in contrast to other methods that only focus on a limited number of parameter variations. Our theoretical framework provides a time scale and shows how fiscal policy and instruments speed up decarbonization of the economies as required by international agreements taking advantage of the complex, self-organizing dynamics of structural change of the market system.

The paper is organized as follows. Section 2 describes the dynamical model of multi-sector growth. Section 3 analytically evaluates how fiscal policy impacts the

Table 1: Classification of micro-economic adjustment processes (Morishima 1981 and Goodwin 1983).

Cross-dual	*Walrasian Law of Excess Demand*	If demand d_i is above (below) supply x_i, price p_i rises (falls)
	Classical Law of Excess Profitability	If price p_i above (below) $cost_i$,[a] quantity x_i rises (falls)
Dual	*Oligopolistic Markup Pricing*	If price p_i above (below) $cost_i$, price p_i falls (rises)
	Inventory Adjustment	If demand d_i is above (below) supply x_i, quantity x_i rises (falls)

[a]In this literature, "costs" include capital costs in the form of normal profits.

profitability and growth differentials involved in the speed of decarbonization with respect to four relevant parameters: the carbon–green ratio in capital intensity, the carbon tax, the green subsidy, and the initial carbon–green ratio in investment. Once empirically calibrated with EU KLEMS and WIOD input–output data, Section 4 finally presents computer simulations of specific policy scenarios of the low-carbon transition, as well as a synthetic dataset of 14,250 observations for relevant ranges of the policy parameters, targeting seven specific target carbon-intensive sectors, “Electricity, gas, steam, and air conditioning supply” (D), “Manufacture of coke and refined petroleum products” (C19), and “Mining and Quarrying” (B), in five of the six high-income economies. Appendix B shows first an example for illustrative purposes of the dynamics of the model with seven-sector US 2003 input–output data and synthetic adjustment coefficients and then empirically extracts cross-dual adjustment coefficients for six high-income economies (Germany, France, Japan, Italy, Netherlands, and the US) using a mixed-effects model with varying slopes on EU KLEMS data.

2 A Multi-Sector Growth Model of the Low-Carbon Transition

2.1 Constant-Technology Cross-Dual Dynamics

The pioneering work of Morishima (1981) and Goodwin (1983) contributed an early classification of microeconomic adjustment mechanisms (Table 1) and a thorough study of their dynamics, using Lyapunov functions and gradient processes, of particular impor-tance as it highlights the complex dynamical relation between micro- and macroeconomic adjustment processes (Flaschel et al. 1997). As Flaschel notes (1997), the first two adjustment processes are a description of a proportional autocontrol mechanism through cross-effects between prices and quantities, which Morishima identified as cross-dual dynamics (Morishima 1981).

The Flaschel–Semmler cross-dual model of multi-sector growth under linear production (without fixed capital investment)[1] and constant technology describes complex price p_i and quantity x_i oscillations over time around the equilibrium values of N prices p^* (a row vector) and N quantities x (a column vector) of the Sraffa–von

1 Circulating capital on those models represents the use of intermediate goods in production. In the specific context of energy investments, the assumption of circulating capital is quite stringent; the existence of fixed capital and depreciation may impact the econometric estimation and simulations. This is addressed by works by Bródy as well as Flaschel and Semmler (Bródy 1970; Flaschel and Semmler 1986).

Table 2: Sraffa–von Neumann equilibrium (Sraffa 1960; Von Neumann 1945).

Equality of supply and demand	$Bx^* = RAx^*$
Uniform profitability	$p^*B = Rp^*A$

Neumann system (Table 2) (Sraffa 1960; Von Neumann 1945). Production is linear, with matrix A as inputs and matrix B as outputs, with positive values.[2]

By the Perron–Frobenius theorem, unique positive equilibrium values p^* and x^* solve for the positive gross rate of return or expansion rate $R > 1$. The expansion rate R is the inverse of the unique largest positive real eigenvalue of the matrix of input–output coefficients A/B, equilibrium prices p^* are its associated positive row eigenvector, and equilibrium output x^* is the associated positive column eigenvector: p^*B is the equilibrium unit revenue and Rp^*A is the equilibrium unit cost p^*A in relation to the expansion rate R (that is, costs including normal profits):[3]

$$1 + r^* = R = \frac{pBx}{pAx} \tag{1}$$

As in the Goodwin model of capital accumulation (1982), the coupled price and quantity oscillations of cross-dual dynamics are of the Lotka–Volterra predator–prey form, but in this, case profits (prices) play the role of the prey and profit-seeking investment (quantities) plays the role of the predator (Gandolfo 1971, ch. III.3). In the baseline model of cross-dual adjustment, industry market prices, relative quantities, and profitability gravitate around their equilibrium values, ultimately determined by the technological structure in line with the von Neumann–Sraffa input–output model (Sraffa 1960; Von Neumann 1945). Normal growth, around which industry growth gravitates, is zero, focusing on out-of-equilibrium dynamics of *relative* prices and quantities.

Following the *law of excess demand*, market prices p will decline (rise) if supply Bx is greater (smaller) than demand:

$$\left(\frac{\dot{p}}{p}\right)^T = -\delta_p [B - RA]x = \delta_p \left[\underbrace{RAx}_{\text{demand}} - \underbrace{Bx}_{\text{supply}}\right] \tag{2}$$

2 These matrices are "augmented" in the sense that they also incorporate labor supply and its price, the wage rate. While the general form of the matrix of outputs B captures joint production, the simpler case of single production is assumed in the remainder of this paper for convenience, so that B is the identity matrix.

3 *R*, thus, can be considered the "maximum expansion rate" (see also Shaikh (2016)), associated to equilibrium profitability r^* when wages are zero and there is no consumption from capital income, that is, all profit is re-invested.

Following the *law of excess profitability*, quantity x_i will rise (decline) if unit revenues pB are greater (smaller) than unit costs times R, RpA, since capital will flow out of the sectors with below-normal profitability into the sectors with above-normal profitability:

$$\frac{\dot{x}}{x} = +\,\delta_x\,[B - RA]^T p^T \;=\; \delta_x\,[\underbrace{B^T p^T}_{\text{revenue}} \;-\; \underbrace{RA^T p^T}_{\text{cost}}] \tag{3}$$

where $\frac{\dot{x}}{x}$ is the column vector of the growth rates in relative quantities, $\frac{\dot{p}}{p}$ is the row vector of the growth rates in relative prices, and δ_p and δ_x are diagonal matrices with N positive adjustment coefficients (so they can also be understood as vectors).

Cross-duality in its simplest form may give rise to dynamic stability, yet not necessarily the conventional "asymptotic" convergence to competitive economic equilibrium to the single-point rest state with uniform profitability across sectors of production (Flaschel and Semmler 1987). In contrast, cross-duality generally reflects the classical theme of dynamic gravitation as envisioned by the great classical economists (Adam Smith, David Ricardo, Karl Marx, and John Stuart Mill), that is, of ceaseless over- and undershooting of sectoral prices, quantities, and profitability around their long-run equilibrium "natural values" as centers of gravity determined by Leontief linear technology (Duménil and Lévy 1987; Goodwin 1983; Sraffa 1960).[4] A stylized description of the classical industry cycle is as follows: if an industry shows above (below) profitability, profit-seeking firms flow in (out), raising (lowering) supply with respect to demand until the latter is above (below) the former, triggering an increase (decrease) in prices through the Walrasian mechanism to adjust the supply–demand imbalance, but also lowering (raising) industry profitability, closing the cycle, and starting anew.

In contrast, the Keynesian tradition focuses instead on short-run dual dynamics (see Table 1), characterized by imperfect competition, oligopolistic markup price-setting, and barriers to capital entry, while investment operates within a longer time scale (Morishima 1981; Semmler 1984). In the short run, oligopolistic firms set prices as markups over costs, while varying supply through inventories in response to demand conditions. Classical cross-dual dynamics can thus be considered unsatisfactory in the short run, suggesting dynamic adjustments without cross-effects between prices and quantities where price and quantity movements may even be independent of each other for a while, what Morishima termed "dual dynamics" (Flaschel et al. 1997; Morishima 1981).

As an illustrative example of classical gravitation, constant-technology dynamics are simulated for the 2003 US direct requirements matrix with seven sectors

4 See also Foley (2003); Shaikh (2016).

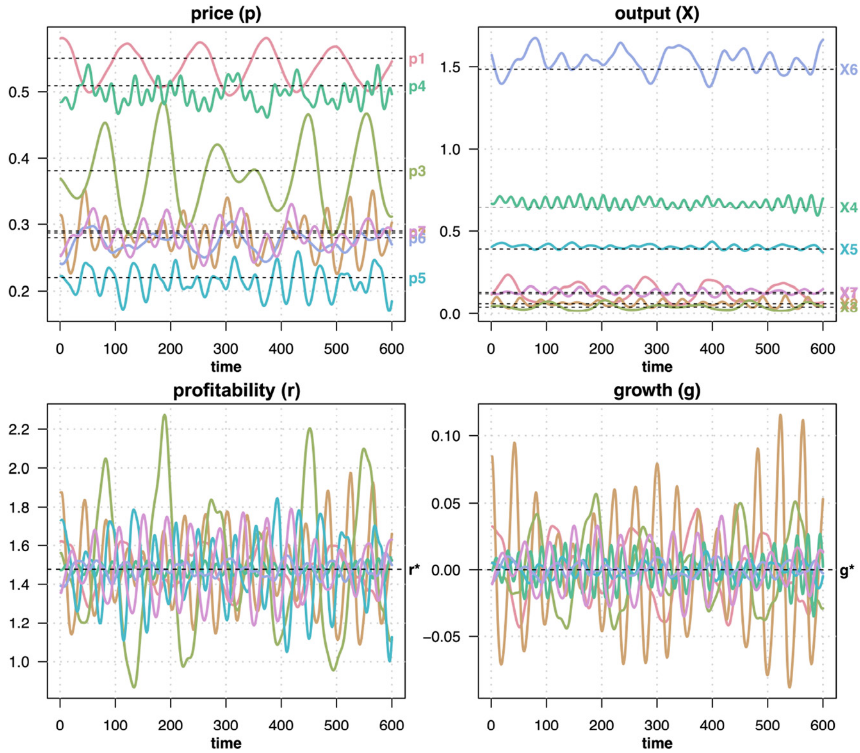

Figure 1: Constant-technology dynamics for the 2003 US direct requirements matrix, seven sectors. Dashed horizontal lines indicate equilibrium values for profitability r^*, prices p^*, quantities x^*, and aggregate growth $g^* = 0$ (as the model deals with relative prices and quantities). Each colored line refers to the time evolution of market prices, quantities, profitability, and growth for each of the seven sectors. Oscillations vary in amplitude and frequency depending on the adjustment parameters chosen.

(Figure 1).[5] The nature of the linear-response model can be appreciated in Figure 2, which shows the same stylized dynamics as a scatterplot in a two-dimensional plane. In this case, the x axis refers to the imbalance in quantities and prices (as excess unit profits), and the y axis corresponds to the change in prices and quantities, so that all observations for a specific industry will be located on a line with the slope of its corresponding adjustment coefficient.

Such general systems of micro-economic adjustment processes can be re-purposed as highly stylized dynamic macroeconomic models of multi-sector

5 Parameters for the sample simulation are given in the Appendix A: the input–output (Table 4) and the synthetic adjustment parameters that are manually selected Table 6. Equilibrium values for prices, quantities, and the expansion rate are given in Table 5 of the Appendix A.

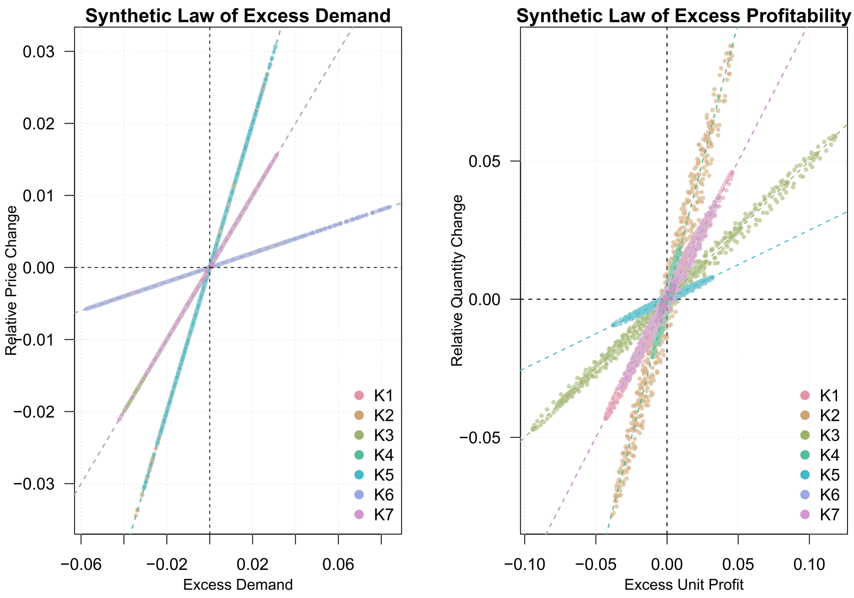

Figure 2: Relative price and quantity changes with respect to excess demand and excess unit profit. The linear slopes correspond to the manually selected adjustment parameters δ_p and δ_x. The law of excess profitability shows a slight departure from strict linearity due to the stability adjustment γ. Dashed color lines indicate the linear regressions for each sector.

growth that can be empirically calibrated without much problems using real training data, as each law of motion translates to a single reaction coefficient for each particular industry (Vallès Codina 2023). The econometric estimation of the cross-dual adjustment parameters using real training data is described in Appendix B. Once the linear adjustment coefficients are estimated for both the law of excess demand and the law of excess profitability, simulations of the dynamical process of technical substitution of specific industries can be implemented using the cross-dual model of multi-sector growth with process innovation and extinction. Keynesian dual short-run dynamics, which can further stabilize classical oscillations, can also be explored in a more general setup (Vallès Codina 2023).

2.2 Process Innovation and Extinction

In a subsequent contribution (Flaschel and Semmler 1992), Flaschel and Semmler propose an extension based on their classical competitive process of dynamical adjustment of the model of technical change presented in Silverberg (1984).[6] The Goodwin model assumes neutral, exponential, disembodied technical progress, under fixed coefficients production, with fluctuating unemployment regulating changes in the level of real wages. Instead of disembodied technical progress, the contribution by Silverberg presents an economy with a fixed production process and then proceeds by examining the stability of the resulting equilibrium state when a second production process embodied in a new capital good with different technical coefficients is introduced. For a detailed description of the dynamic process of technical substitution, we refer to the original contribution by Flaschel and Semmler (1992).

Our framework refers to a different tradition of the study of technical change based on set theory and duality theory (for an example see Morishima (1981) or Mittnik et al. (2014)). In contrast, the conventional theory on directed technical change models it as continuous increases in the capital-to-labor ratio (i.e., capital deepening) or in total factor productivity in the aggregate production function (Acemoglu et al. 2012; Golosov et al. 2014). Instead, we consider a one-off process of technical substitution in an input–output context where innovation is the result of a more efficient process taking over a less efficient one due to its cost advantage. In particular, the focus is on modeling technical change as a dynamic process of within-sector technical substitution in the form of the innovation of more cost-efficient, less carbon-intensive processes of production that explicitly takes over and extinguishes older processes, following the work of Mittnik et al. (2014).

3 Comparative-Statics Policy Analysis of the Low-Carbon Transition

In this section, the speed of the technical substitution of carbon-intensive processes by green, less carbon-intensive processes within a single industry is evaluated analytically on the dynamical model of multi-sector growth, without and with policy for carbon phase-out/green phase-in. For each of the selected policy scenarios and target industries, Figure 3 shows the time of carbon phase-out and green phase-in, i.e., the duration of the low-carbon transition when target output ratio is 1. It highlights that, although a percentage tax on carbon-intensive volumes substantially accelerates decarbonization, it should be accompanied by green investment in order

6 Silverberg's contribution (1984) is based on the Goodwin model of distributional conflict and capital accumulation (Goodwin 1982).

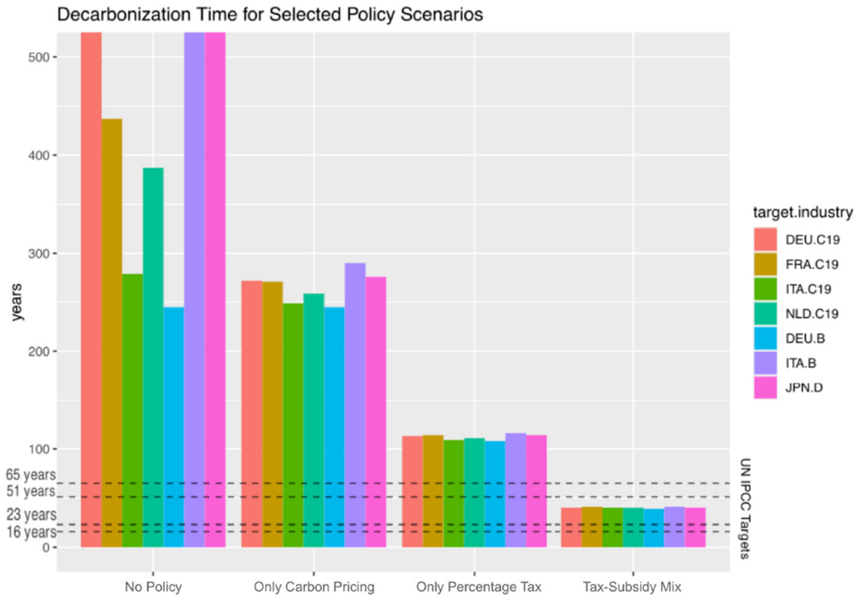

Figure 3: Decarbonization time for selected policy scenarios in seven carbon-intensive industries in five global-north economies (“manufacture of coke and refined petroleum products”; C19, “electricity, gas, steam, and air conditioning supply,” D; and “mining and quarrying,” B).

to effectively meet the 2018 UN IPCC targets, as carbon taxes alone may be too high to be politically feasible. In this model of the low-carbon transition, carbon-intensive processes c (such as fuel-based cars or fossil energy) compete with their synthetic “green” equivalents g (such as electric cars or solar energy) within a particular industry (automotive manufacturing or electricity production). Market competition between these processes works through their profitability and growth differentials, which fiscal policy can help adjust in a stylized way with respect to four impacting policy parameters: cost advantage θ, a percentage carbon tax τ on real gross output, the green subsidy ρ, and the initial investment ratio σ_0 (i.e., the initial ratio of green output over carbon output). In this setup, policies can be introduced by considering that carbon pricing impacts on the cost advantage in production θ and profitability (the price dimension), while the tax–subsidy policy operates on the volumes produced by the carbon-intensive and green processes and their growth (the quantity dimension). Although in essence a carbon price operates like a tax on carbon output, they will refer to very different (time) scales. Green bonds can be considered to impact on the initial investment ratio σ_0.[7] In our model, sector output is defined as x^j in gross quantity terms for all processes $j = 1, \ldots, N$.[8]

3.1 Carbon Phase-Out/Green Phase-In without Policy and with Carbon Pricing

In the absence of fiscal policy, technological differentials in unit costs drive profitability and growth of green innovation and carbon extinction. Unit costs are:

$$\kappa_t^j = \sum_i p_t^i a_{ij} \tag{4}$$

with corresponding market prices,

$$p_t^j = \left(1 + r_t^j\right)\kappa_t^j \tag{5}$$

profitability,

$$r_t^j = \frac{p_t^j - \kappa_t^j}{\kappa_t^j} = \frac{p_t^j}{\kappa_t^j} - 1 \tag{6}$$

and profitability deviations from equilibrium profitability r^*:

$$r_t^j - r^* = \frac{p_t^j}{\kappa_t^j} - R = \frac{p_t^j}{\kappa_t^j} - (1 + r^*) \tag{7}$$

where R is the maximum rate of expansion (equation (1)). For modeling convenience, carbon and green processes $j = c, g$ feature input–output proportional coefficients and thus constant proportional unit costs, which can be summarized by the single technical parameter θ:

$$\theta = \frac{\kappa_t^g}{\kappa_t^c} = \frac{a_{ig}}{a_{ic}} \quad \forall\, i = 1, \ldots, N \tag{8}$$

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7 Green bonds also de-risk green investment by reducing unit costs of production, although their proper study may be more relevant in a context of increasing returns to scale, in contrast to our current assumption of constant returns to scale.

8 Although substituting actual carbon sectors by synthetic green equivalents (rather than real green technologies) diminishes the realism of our framework, this modeling choice is not only explained in terms of analytical and computational convenience but also due to the current lack of empirical data available on green technologies at the necessary level of sector disaggregation. Extensions of our work to include more realistic green technologies can be computed as soon as the necessary empirical data are made available in the future.

In such situation, since green and carbon processes produce the same output and thus share a common price $p_t^c = p_t^g$ in the model, cost advantage in production θ, the ratio in unit capital costs between the green and carbon processes, is the only parameter regulating their profitability differentials,

$$\theta = \frac{p_t/\kappa_t^c}{p_t/\theta\kappa_t^c} = \frac{1+r_t^c}{1+r_t^g} \tag{9}$$

In the standard theory of capital deepening and technical change, capital deepening is separated from technical change, where the latter is measured by increasing total factor productivity. We rather follow Kaldor and Mirrlees (1962), who suggested that it is hard to distinguish between those two drivers of productivity, since capital deepening mostly brings in new technology using more productive inputs. We thus measure endogenous technical change as decreasing costs of production by the explicit introduction of newer processes of production, as indicated by the parameters κ and θ. In this model, profitability differentials, regulated by cost differences summarized by θ, drive the inflow and outflow of profit-seeking investments and corresponding variations in quantities: investments will flow into and expand green output faster only if it bears a cost advantage over the carbon process.[9]

In the context of carbon pricing, cost advantage θ is most relevant, as it is the parameter that internalizes the carbon price in the production costs of each process and will increase the profitability differential of the green process over more carbon-intensive ones. In order to see this, emission intensities of output ϵ^j can be defined in terms of CO_2 tons emitted divided by quantity produced x^j for $j = c, g$. By definition, $\epsilon^c \gg \epsilon^g$. Unit costs with carbon pricing are now

$$\sum_i p_t^i a_{ij} + \epsilon^j \pi \tag{10}$$

where π is the carbon price and $\epsilon^j\pi$ are the carbon costs faced by processes $j = c$, g where $\epsilon^c\pi \gg \epsilon^g\pi \sim 0$. The new cost advantage including carbon pricing will then be

9 The assumption of the same input–output linkages in production can be relaxed in future extensions of this work, as it is quite strong especially in the context of the low-carbon transition, where specific inputs for green technology become more and more critical over time: for instance, solar photovoltaic and wind power also require high volumes of environmentally sensitive raw materials, such as copper, silicon, aluminum, lithium, cobalt, rare earths, and silver (Dominish, Florin, and Teske 2019) – or there may be a scarcity of inputs due to specific import or export embargos. Given that there are sufficient detailed input requirements estimated for input–output tables, the price and quantity effects of an EU embargo on Russian gas and oil (or Russian export embargo for those inputs to the EU) could also be computed as in Mittnik and Semmler (2022).

$$\frac{\sum_i p_t^i a_{ig} + \epsilon^g \pi}{\sum_i p_t^i a_{ic} + \epsilon^c \pi} = \frac{\theta \kappa_t^c + \epsilon^g \pi}{\kappa_t^c + \epsilon^c \pi} = \frac{\theta + \epsilon^g \pi / \kappa_t^c}{1 + \epsilon^c \pi / \kappa_t^c} \sim \frac{\theta}{1 + \frac{\epsilon^c \pi}{\kappa_t^c}} \tag{11}$$

for $\epsilon^g \sim 0$. Internalized carbon costs $\epsilon^c \pi$ must be of the order of unit production costs κ_t^c to have a substantial impact on the profitability differential.

In order to keep track of the dynamics of the process of carbon phase-out and green phase-in, it is convenient to define the output ratio between the green and carbon processes:

$$\sigma_t = \frac{x_t^g}{x_t^c} \tag{12}$$

The growth rate differential between carbon and green processes is thus dependent on their technical parameter θ, output investment ratio σ_t, and the profitability differential ratio. Using equations (3), (7), and (12),

$$\frac{\dot{x}_t^g}{\dot{x}_t^c} = \frac{\delta_x^g}{\delta_x^c} \frac{p_t^g - R\kappa_t^g}{p_t^c - R\kappa_t^c} \frac{x_t^g}{x_t^c} = \lambda \sigma_t \frac{p^g - R\kappa^g}{p^c - R\kappa^c} = \lambda \theta \sigma_t \frac{r_t^g - r^*}{r_t^c - r^*} \tag{13}$$

as well as the λ ratio of the quantity adjustment coefficients for the carbon and green sectors, defined as

$$\lambda \equiv \frac{\delta_x^g}{\delta_x^c}$$

Using equation (13), output ratio σ_t has evolution rule (without time subscripts for simplicity):

$$\dot{\sigma} = \dot{\left(\frac{x_g}{x_c}\right)} = \frac{\dot{x}_g x_c - x_g \dot{x}_c}{x_c^2} = \frac{\dot{x}_g - \sigma \dot{x}_c}{x_c} = \frac{\frac{\dot{x}_g}{\dot{x}_c} - \sigma}{x_c / \dot{x}_c} = \frac{\dot{x}_c}{x_c} \sigma \left(\lambda \theta \frac{r_g - r^*}{r_c - r^*} - 1 \right) \tag{14}$$

Lower-cost green technology ($\theta < 1$) will thus ensure higher profitability $(r_t^g > r_t^c)$ and growth rate $(g_t^g > g_t^c)$; therefore, lower costs in production alone will eventually induce the phase-out of the carbon process. Although at the current moment green sources are increasingly outcompeting carbon ones with a cost advantage θ between 0.7 and 1.1 (IRENA 2020), there is no guarantee that profitability differentials only driven by technological differences in costs will drive the speed of decarbonization fast enough to fall within UN IPCC time targets, even if carbon pricing is considered. The point at which the low-carbon transition can be considered "successful" is the time when the green process overtakes the carbon process so that their output ratio σ_t reaches and surpasses a critical value $\hat{\sigma}$ above 1. Thus, the success of the low-carbon transition not only depends on the growth rate differentials between the carbon and green processes but also their initial output ratio σ_0 that corresponds to the initial investment in green technology.

3.2 Carbon Phase-Out/Green Phase-In with Tax–Subsidy Policy

The target-consistent path approach for carbon pricing first imposes time targets for the duration of the low-carbon transition as given, established by policy-makers following the advice of the climate science. The welfare problem of the policy maker thus consists of finding the required policy set (τ, ρ, σ_0) given carbon phase-out time target t^*, that is, a percentage carbon tax rate τ on real carbon output x^c, raising a tax revenue of τx^c[10] is that is added to green investment x^g at subsidy rate ρ, starting from initial investment ratio σ_0) to phase out carbon, $\sigma_t \rightarrow \hat{\sigma}$ at target value $\hat{\sigma}$ within duration time $t \rightarrow t^*$, with associated carbon emissions $\hat{E}$:

$$\sigma_0 + \int_0^{t^*} \dot{\sigma}_t(\tau, \rho)\mathrm{d}t = \hat{\sigma} \tag{15}$$

Taking advantage of the cross-dual adjustment dynamics, the policy maker employs the tax–subsidy mix to expand the profitability and growth differentials between the green and carbon processes. Instead of taxing carbon content as in carbon pricing, the tax levied is on the volume produced by the carbon-intensive process, as in Mittnik and Semmler (2022). Green and carbon outputs using the tax–subsidy mix (where the hat notation distinguishes the variable with and without policy) thus becomes:

$$\hat{x}_t^c = x_t^c - \tau x_t^c = x_t^c(1-\tau)$$

$$\hat{x}_t^g = x_t^g + \rho\tau x_t^c = x_t^c(\sigma_t + \tau\rho)$$

Output proportion with tax–subsidy policy τ, ρ becomes:

$$\hat{\sigma}_t = \frac{\hat{x}_t^g}{\hat{x}_t^c} = \frac{\sigma_t + \tau\rho}{1-\tau} \tag{16}$$

Profitability for the carbon and green sectors internalizes the tax–subsidy policy:

$$1 + \hat{r}_t^c = \frac{p_t^c x_t^c(1-\tau)}{\kappa_t^c x_t^c} = \left(1 + r_t^c\right)(1-\tau) \tag{17}$$

$$1 + \hat{r}_t^g = \frac{p_t^c x_t^c(\sigma_t + \tau\rho)}{\theta\kappa_t^c x_t^c \sigma_t} = \left(1 + r_t^c\right)\frac{1 + \frac{\tau\rho}{\sigma_t}}{\theta} \tag{18}$$

10 The relation between the tax on carbon output τ and carbon price π is $\tau = \frac{\varepsilon\pi}{p^c}$.

While the negative contribution of tax τ is linear on the carbon sector, its positive effects on green profitability depend on the fraction $\frac{\tau\rho}{\sigma_t}$, i.e., they are the largest when carbon output is much larger than green output ($\sigma_t \sim 0$), that is, at the beginning of the introduction of the policy, and they are multiplied by cost advantage θ.

The profitability differential once the policy is introduced can be then computed in terms of cost advantage θ, output proportion σ_t, and tax rate τ:

$$\frac{1+\widehat{r}_t^c}{1+\widehat{r}_t^g} = \frac{\sigma_t\theta(1-\tau)}{\sigma_t+\tau\rho} = \frac{\theta(1-\tau)}{1+\frac{\tau\rho}{\sigma_t}} \tag{19}$$

which shows how a tax–subsidy policy can reinforce cost-induced profitability and growth differentials (when $\theta < 1$) or even offset them (when $\theta > 1$). Growth rate differential with policy τ, ρ with and without policy can be compared:

$$\frac{1+\widehat{g}_t^g}{1+\widehat{g}_t^c} = \left[\frac{1+g_t^g}{1+g_t^c} + \frac{\tau\rho}{\sigma_t}\right]\frac{1}{1-\tau} \tag{20}$$

Once again, the additive presence of the ratio $\frac{\tau\rho}{\sigma_t}$ shows that the policy to direct technical change toward decarbonization is the most effective at the earliest stages of the phase-in (i.e., $\sigma_t \sim 0$) when the subsidy rate is nonzero. This result, confirmed by the simulations, shows the relevance of green subsidies ($\rho > 0$) in kickstarting and mobilizing private funds for decarbonizing the economy, in line with recent studies (Deleidi, Mazzucato, and Semieniuk 2020; Heine et al. 2019; Semmler et al. 2021). However, a tax rate τ on real output alone can already accelerate substantially the phase-out of the carbon sector without any green subsidies $\rho = 0$, even if green cost advantage is lower ($\theta > 1$), although there is no guarantee decarbonization may occur in time to achieve the UN IPCC targets.

4 Simulation Results

4.1 Specific Policy Scenarios of the Low-Carbon Transition

The simulations can be conceived as a computational, stylized "thought experiment" to identify what are the policy dimensions most relevant in the domain of the low-carbon transition, that is, whether carbon prices or green investment. Simulations study the phase-out of the carbon process and phase-in of the green process within particular carbon-intensive industries by time t^*, of relative capital intensities θ, under a carbon tax rate τ, a green subsidy rate ρ, and initial investment ratio σ_0. The specific carbon-intensive industries targeted for substitution are "Manufacture of coke and refined petroleum products" (C19), "Electricity, gas, steam, and air conditioning supply" (D), and "Mining and Quarrying" (B), which feature positive adjustment coefficients for seven sectors in five of the selected countries: Germany, France, Italy, Japan, and the Netherlands. Apart from this one-off process of substitution, no other forms of technological change occur as the growth model operates on constant technology.[11] At the current moment, green energy is increasingly outcompeting carbon energy: the cost of green energy can be considered to be between 0.7 and 1.1 times the cost of carbon energy – this is the range of values chosen for θ, which can also be thought to internalize a carbon price (IRENA 2020). For OECD economies, the current share of final energy consumption in renewable sources over carbon sources is around 5 % (Upadhyaya 2010), which is the benchmark value that is taken for the initial output ratio σ_0 in the simulations, which can also be increased by the issuance of green bonds. For simplicity, target carbon–green output ratio is $\widehat{\sigma} = 1$, which implies that the low-carbon transition is successfully achieved when green output is equal to carbon-intensive output. Each timestep can be considered as one year, given the time dimension included in the adjustment coefficients, which were computed from yearly data.

Specific simulations of the low-carbon transition for particular policy scenarios under different chosen parameters in order to obtain a first qualitative, stylized comparison of their impact on carbon phase-out and green phase-in. For each of the selected policy scenarios and target industries, Figure 3 shows the time of carbon phase-out and green phase-in, i.e., the duration of the low-carbon transition when target output ratio is 1, highlighting that, although a percentage tax on carbon-intensive volumes substantially accelerates decarbonization, it should be accompanied by green investment in order to effectively meet the 2018 UN IPCC targets, as carbon taxes alone may be too high to be politically feasible. While the flagship UN Emissions Gap Report of 2021 recently urged the pledging nations to halve carbon emissions in the next 8 years, the simulation results are compared with slightly less drastic duration targets for decarbonization of the 2018 UN IPCC report of 2018 (Masson-Delmotte et al. 2018):
16 years for a 66 % chance of avoiding a temperature increase of 1.5 °C,
23 years for a 50 % chance of avoiding a temperature increase of 1.5 °C,
51 years for a 66 % chance of avoiding a temperature increase of 2 °C, and
65 years for a 50 % chance of avoiding a temperature increase of 2°C

Each row of Figures 4–7 shows the simulated trajectories of prices, quantities, profitability, and growth rates for all industries (the full list of industries is given in

11 As investment has the effect of increasing labor and capital productivity over time, the constant-technology assumption is obviously very strong in the long run: in this sense, the simulation results should be understood more qualitatively than quantitatively, as they only aim to answer how policy can speed up carbon phase-out in time, in particular, whether only carbon pricing will be enough to curb emissions in time or instead more ambitious fiscal policy is required.

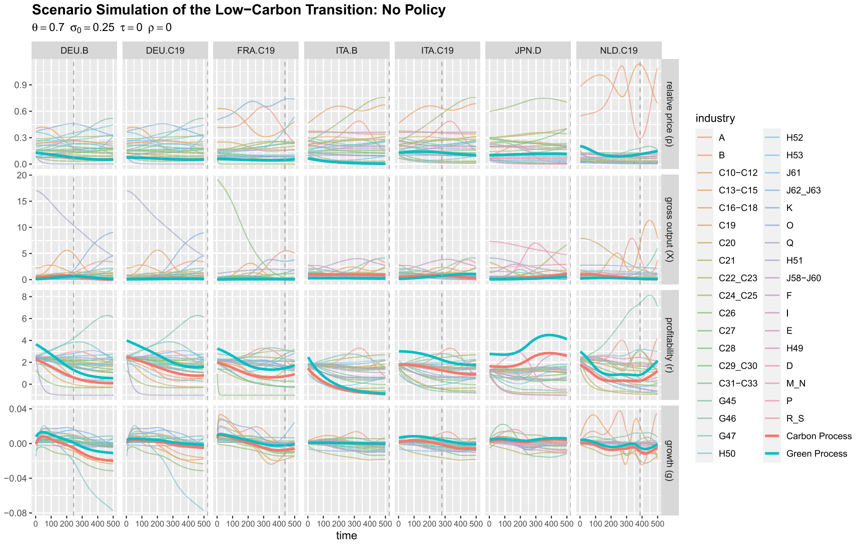

Figure 4: Scenario simulation of the low-carbon transition: no policy. Driven by lower production costs alone, profitability and growth differentials are not large enough to decarbonize in a hundred years. The vertical dashed line indicates the moment where the green process takes over the carbon process, i.e., $\hat{\sigma} = 1$.

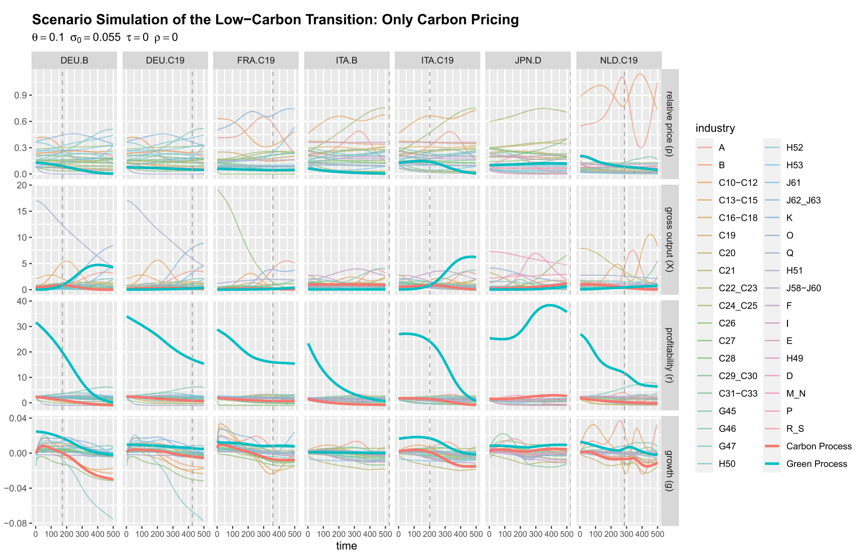

Figure 5: Scenario simulation of the low-carbon transition: only carbon pricing. Despite an extreme carbon price ($\theta = 0.1$), carbon pricing alone is not able to successfully increase the profitability differential of the green process enough to speed up the substitution process even below 150 years. The vertical dashed line indicates the moment where the green process takes over the carbon process, i.e., $\hat{\sigma} = 1$.

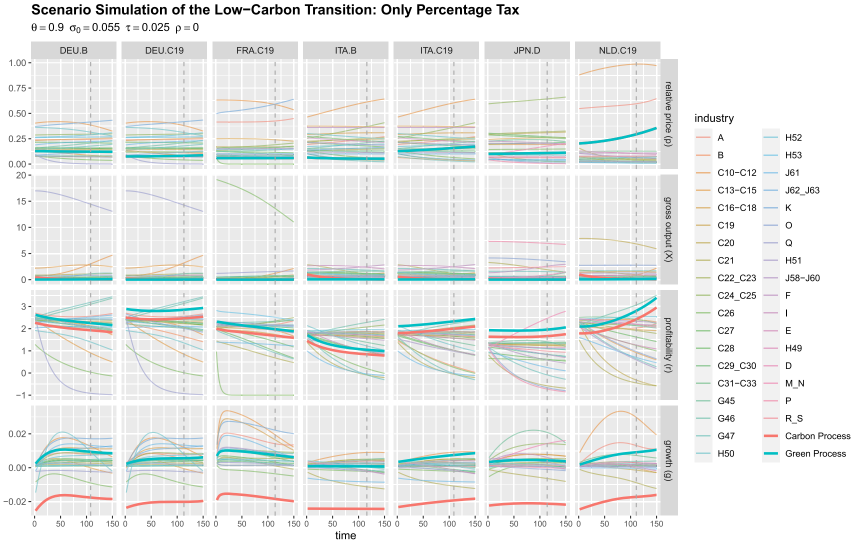

Figure 6: Scenario simulation of the low-carbon transition: only percentage carbon tax. A percentage carbon tax directly impacts growth (rather than profitability), speeding up decarbonization closer to, but still far from, UN IPCC targets. The vertical dashed line indicates the moment where the green process takes over the carbon process, i.e., $\widehat{\sigma} = 1$.

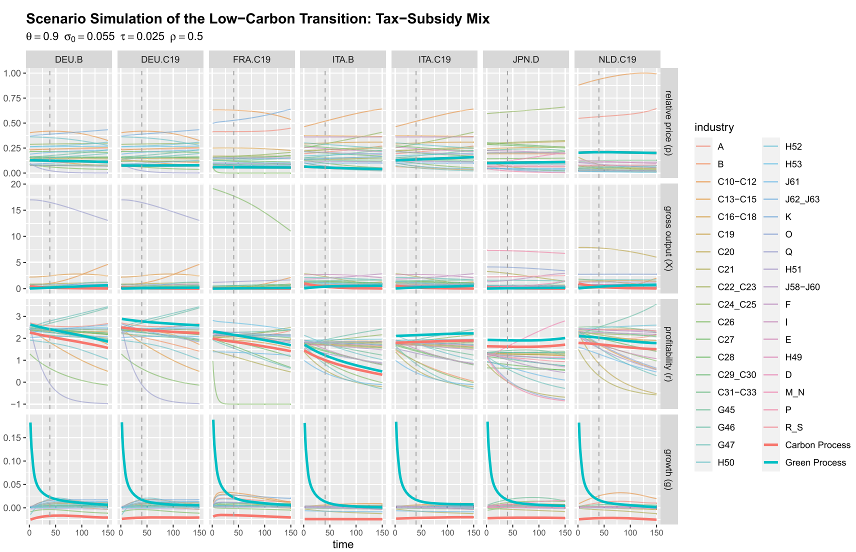

Figure 7: Scenario simulation of the low-carbon transition: tax–subsidy mix. Only a combination of carbon taxes and green subsidies can accelerate decarbonization to reach UN IPCC targets in time. The vertical dashed line indicates the moment where the green process takes over the carbon process, i.e., $\widehat{\sigma} = 1$.

Table 7 in Appendix C). Each column corresponds to a different industry under decarbonization, where the carbon-intensive and the green processes are highlighted with less alpha transparency and larger width in red and green than the other industries, respectively. The vertical dashed line indicates the moment where the output of the green process overtakes the output of the carbon-intensive process. As they share the same price, the trajectory of the price of the carbon-intensive process is identical to the green one. However, it is the two bottom rows, showing the industry trajectories of profitability and growth rates, which are the most informative, as they highlight the differentials between the carbon and green processes regulated by fiscal policy that make decarbonization feasible: while the profitability differential is regulated by the cost advantage parameter θ (on which carbon pricing operates), the tax–subsidy scheme operates over the growth rate differential, progressively increasing it from scenario 2 to scenario 4.

The specific scenarios are the following:

1. **No policy** (Figure 4), with a very high initial investment ratio of 25 % and very high cost advantage for the green process ($\theta = 0.7$). Although this is a very favorable scenario for a fast technical substitution in absence of policy, profitability and growth differentials are not large enough as induced by lower production costs alone so that the fastest green phase-in takes place in around 250 years, for German mining and quarrying. For three industries, decarbonization time exceeds the maximum time of 500 years.
2. **Only carbon pricing** (Figure 5), with carbon pricing inducing an extremely high cost advantage for the green process ($\theta = 0.1$), an initial investment ratio in line with the current empirical evidence. Even with an extreme carbon price, carbon pricing alone is not able to successfully increase the profitability differential of the green process enough to speed up the substitution process even below 150 years for any of the studied industries and below 500 years for Italian Mining and Quarrying and Japanese Electricity Production.
3. **Only percentage carbon tax** (Figure 6), with a 2.5 % percentage tax on carbon-intensive output, an initial investment ratio in line with the current empirical evidence, and similar cost advantage $\theta = 0.9$. By directly impacting growth rather than profitability, the substitution process substantially speeds up to bring decarbonization in around 100 years, which is still considerably beyond the Paris Agreement targets.
4. **Tax–subsidy mix** (Figure 7), with a 2.5 % percentage tax on carbon-intensive output and 50 % subsidy rate, an initial investment ratio in line with the current empirical evidence, and similar cost advantage $\theta = 0.9$. By using only half of the tax revenue raised from taxing carbon-intensive output ($\rho = 0.5$), decarbonization time finally falls within the 2018 UN IPCC targets, showing the multiplicative effect of green investment to accelerate decarbonization.

4.2 General Role of Fiscal Policy Parameters in Accelerating the Low-Carbon Transition

While the simulation results of the former section already highlight that it is more convenient to use fiscal policy to impact on growth directly rather than profitability, a more systematic computational analysis of the policy space can be conducted using the empirically calibrated growth model to complement the comparative-statics analysis of Section 3. In this section, 14,250 simulations are computed for specific ranges of the four policy parameters at stake in order to investigate how the duration of decarbonization t^* depends on them: the range for relative cost advantage θ is (0.7, 1.1), the range for the percentage tax rate τ is (0, 0.24) (i.e., the share of carbon-intensive volume that is taxed), the range for the green subsidy rate ρ is (0, 1), and the range for the initial output ratio is (0.1, 0.25). The industries studied are “Manufacture of coke and refined petroleum products” (C19) for Germany, France, Italy, and Netherlands, and “Electricity, gas, steam and air conditioning supply” (D) for Japan. Table 3 shows the regression results of the dependence of decarbonization speed on the four policy parameters as regressors, which is highly significant for all of them and with a very high R^2 value.

In this context, the regression slopes for each policy parameter correspond to the magnitude of their impact on decarbonization speed: the percentage tax on carbon-intensive output bears the largest impact on speed, around 10 times higher than the subsidy rate (which is expected, as ρ multiplies τ in the model) and the initial output ratio. Since the latter have very different upper thresholds, respectively, 1 and 0.25, green subsidies are thus expected to bear a four-time impact on the speed of decarbonization compared to the initial output ratio. Most strikingly,

Table 3: OLS regression results for decarbonization speed $1/t^*$ with respect to the four policy parameters: initial investment ratio σ_0, cost advantage θ, tax rate τ, and subsidy rate ρ.

Dependent variable	Independent variable				Constant
	σ_0	θ	τ	ρ	
Speed $1/t^*$	0.028***	−0.002***	0.322***	0.023***	−0.011***
	(0.001)	(0.0003)	(0.001)	(0.0001)	(0.0003)

Observations	13,341	Residual std. error	0.006 (df = 13336)
R^2	0.945	*F* statistic	57,437.620*** (df = 4; 13336)
Adjusted R^2	0.945	*Note:*	*p < 0.1; **p < 0.05; ***p < 0.01.

the impact of cost advantage θ is almost negligible, casting severe doubt on the feasibility of carbon pricing alone as an effective tool to decarbonize in time. Following these results, the most effective fiscal strategy would dispense with making firms internalize carbon prices in production and focus instead on a high percentage tax rate on real carbon-intensive output (as in sales), accompanied by substantial green investment, both in the form of a single large initial investment σ_0 and green subsidies ρ. Keynesian dual dynamics addressing mark-up pricing can be used to properly assess to what extent firms pass on the carbon tax to customers.

For the illustrative sake of clarity, Figure 8 shows the dependence of decarbonization speed $1/t^*$ (i.e., the inverse of the duration of decarbonization time) for a

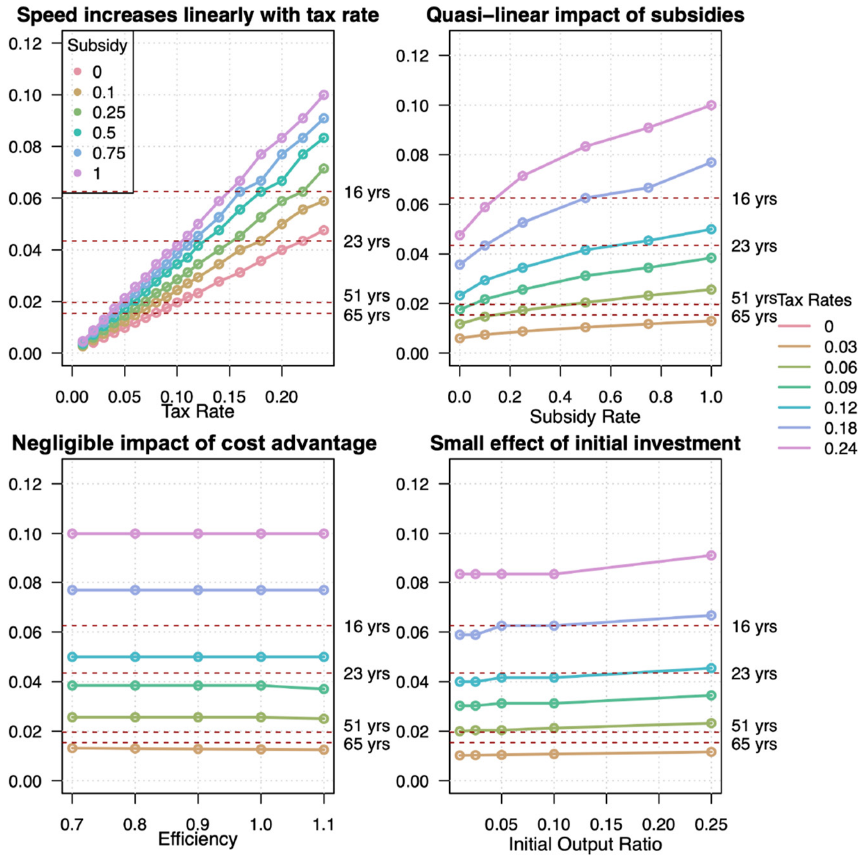

Figure 8: Impact of parameters on decarbonization speed for sector C19, Germany, for many values of the tax rate. When the tax rate is the dependent variable, the different lines correspond to different values of the subsidy rate. Horizontal dashed lines correspond to the necessary speed to meet the IPCC targets.

specific sector (C19, Germany) with respect to each parameter, for different values of the tax rate. In agreement with the regression results, the figure shows a very robust linear dependence of decarbonization speed on the tax rate τ. The relationship between speed and subsidy rate ρ is more complex, indicating a multiplicative interaction with the tax rate: linear at low tax rates and logarithmic at high tax rates, showing that green subsidies are most effective when carbon taxes are the highest. In contrast, cost advantage θ and initial investment ratios have negligible impacts on decarbonization speed within their respective domains. The impact of carbon pricing on decarbonization speed is relevant only if carbon prices are so high that θ is closer to zero.

For instance, the top-left panel shows that, for a cost advantage $\theta = 0.8$ and an initial output ratio of $\sigma_0 = 0.05$, a very high tax rate of $\tau = 0.22 = 22\,\%$ decarbonizes sector C19 within an IPCC target of 23 years for any subsidy rate, even with $\rho = 0$. If all carbon tax revenues are instead re-invested as green subsidies ($\rho = 1$), then decarbonization within the same 23 years can already be achieved with half of the tax rate, $\tau = 0.11$. For any subsidy rate from 0 to 100 %, a tax rate of $\tau = 0.05$ decarbonizes sector C19 within a substantially higher IPCC target time of 51 years. Many current state policy guidelines aim at decarbonizing by 2050; this would require a tax rate on real output (as in sales) between 0.06 and 0.16, depending on the subsidy rate.

5 Conclusions

The transition speed toward a low-carbon economy has become a critical issue due to the increase in intensity and severity of extreme weather events in the form of increasingly severe heatwaves, wildfires, droughts, flooding, mass extinctions of species, sea-level rises, or changes in the direction of oceanic currents. Current consensus among economists considers that the market failure of climate change needs to be addressed through a rigorous analysis of the costs and benefits of climate change mitigation. However, the traditional theoretical frameworks (Kattel et al. 2018; Stern 2022; Stern and Stiglitz 2022) and the associated policy of carbon pricing, either as taxation or a cap-and-trade system, need complementary measures to be able to speedily resolve the "grand challenge" of climate change society faces today in the face of the potentially immense risk of climate catastrophes: If those risks are very large due to tipping points and sudden changes, a proper cost–benefit analysis with adequate discounting of future damages is very hard to undertake. Hence, this paper follows the target-consistent price path approach, which starts first from decarbonization targets as given by climate scientists and policymakers and then proceeds to compute the appropriate set of policies to achieve them. In agreement with recent contributions (Acemoglu et al. 2016; Braga, Semmler, and Grass 2021; Deleidi, Mazzucato, and Semieniuk 2020; Heine et al. 2019; Jenkins et al. 2020; Semmler et al. 2021; Nyambuu and Semmler 2023), this paper shows how global aggregate carbon pricing alone, although cost-efficient, is not effective enough to curb emissions in time: carbon pricing urgently needs to be accompanied by a myriad other sector-oriented fiscal policies such as setting standards through regulations, R&D subsidies, central-bank financial support in the form of green finance, and, most especially, public investment on climate-oriented infrastructure and clean energy development and deployment. As to the role of the private sector, by adjusting sectoral profitability and growth differentials of carbon phase-out/green phase-in using carbon pricing and, most importantly, green investment subsidies, this paper clearly shows how fiscal policies can take advantage of the complex, self-organizing, and out-of-equilibrium dynamics of the market system: by regulating multi-sector growth in balance with the ecosystem, fiscal policy can accelerate decarbonization within specific carbon-intensive sectors to support the Paris Agreement targets.

The results of the paper highlight the feasibility of fiscal policy to accelerate structural change within specific carbon-intensive industries toward the low-carbon transition and thus stabilize economic-ecosystem interactions in a timely manner. Target-consistent fiscal policies are evaluated analytically and computationally following an original empirically calibrated macroeconomic model of multi-sector growth and technical process substitution that re-purposes the classic literature on micro-economic adjustment processes to focus on the dynamic stability of competitive economic equilibrium (Fisher 2013; Flaschel 2010; Hahn 1982; Hicks 1939, 1947; Jorgenson 1960; Mas-Colell 1986; Morishima 1981). Much of this work, based on set theory, duality, and choice of technique literature in the tradition of disequilibrium theory, is mostly forgotten in the current literature on equilibrium dynamics. In this literature, the stability of the economic system is explored by considering specific adjustment processes out of equilibrium, characterized by particular reaction coefficients in the form of stylized facts as dynamical sectoral laws of motion that can be empirically calibrated.

Furthermore, in contrast to aggregate approaches like integrated assessment modeling, our stylized methodology of market adjustment processes is highly transparent and practical for policy purposes. Resembling state-of-the-art supervised machine-learning models, the linear adjustment coefficients of the data-driven dynamical model can be empirically calibrated with real data using a hierarchical mixed-effects linear model with varying slopes on EU KLEMS datasets, although other functional forms can be attempted in more sophisticated fashion, such as the logistic function. By running a large number of simulations, our stylized, data-driven approach is able to rigorously assess the sensitivity of our results to the relevant parameters at play, in contrast to existing methods that only focus on a limited number of parameter variations. Data of higher quality and timespan may substantially improve the econometric estimation. As extreme weather events in terms of frequency and severity intensify, it becomes more evident that the actual success of fiscal policy will be critical in leading the low-carbon transition and effectively impact market-based multi-sector growth dynamics in balance with the eco-system.

Appendix A: Parameters for the Sample Simulation with Seven Sectors

Table 4: 2003 US direct requirements matrix.

	1	2	3	4	5	6	7
1. Agriculture	0.2008	0.0000	0.0011	0.0338	0.0001	0.0018	0.0009
2. Mining	0.0010	0.0658	0.0035	0.0219	0.0151	0.0001	0.0026
3. Construction	0.0034	0.0002	0.0012	0.0021	0.0035	0.0071	0.0214
4. Manufacturing	0.1247	0.0684	0.1801	0.2319	0.0339	0.0414	0.0726
5. TTU	0.0855	0.0529	0.0914	0.0952	0.0645	0.0315	0.0528
6. Services	0.0897	0.1668	0.1332	0.1255	0.1647	0.2712	0.1873
7. Other	0.0093	0.0129	0.0095	0.0197	0.0190	0.0184	0.0228

[a]TTU: Trade, Transportation, and Utilities.

Table 5: Sraffa–von Neumann equilibrium values for 2003 US 7-sector input–output data (Miller and Blair 2009, p. 29).

Natural prices	$p^* = (0.550, 0.287, 0.381, 0.509, 0.220, 0.280, 0.290)$
Equi-proportional quantities	$x^* = (0.0727, 0.0367, 0.0244, 0.3854, 0.2331, 0.8853, 0.0780)$
Uniform rate of expansion	$R = 2.477343$

Table 6: Synthetic coefficients for the 7-sector example.

Walrasian price reaction to supply–demand imbalances	$\delta_p = (0.1, 1, 0.5, 0.5, 1, 0.1, 0.5)$
Classical quantity reaction to profitability deviations	$\delta_x = (1, 2, 0.5, 2, 0.25, 1, 1)$
Derivative control parameter	$\gamma = 1$

Appendix B: Empirical Calibration of the Model

The real dataset employed to estimate the adjustment coefficients of the model covers 36 industries in six developed economies (Germany, France, Italy, Japan, Netherlands, and the US) in the EU KLEMS database for an annual interval of 23 years between 1995 and 2017 (Van Ark and Jäger 2017, https://euklems.eu/). Input–output data is extracted from the World Input–Output Database (Timmer et al. 2015, https://www.rug.nl/ggdc/valuechain/wiod/wiod-2016-release). Among many other variables, the EU KLEMS dataset features sector price indices, quantity and value measures of gross output and intermediates, and labor compensation. Growth rates relative to average of prices and quantities can be directly computed from the time series of its indices. For each country and year, the general expansion factor R is computed following its definition as the ratio between the total monetary value of gross output over the total monetary value of inputs for production (labor compensation plus intermediate goods), see equation (1). In order to extract relative imbalances from the EU KLEMS dataset (Figure 9, above), relative values are computed by dividing each yearly observation by their 23-year time average, taken as a convenient approximation of their centers of gravity. For the law of excess demand, sectoral gross output in quantity terms is employed as supply; the expansion factor times intermediates in quantity terms are employed as demand. For the law of excess profitability, unit revenue is computed as the sectoral ratio of gross output in monetary terms to gross output in quantity terms, while unit costs (i.e., production costs times the expansion factor) are computed as the sum of intermediates in monetary terms and labor compensation divided by gross output in quantity terms.

For real training data, a convenient method of estimation of the linear industry adjustment coefficients employs a mixed-effects model with varying slopes and no intercept:

$$y_i = \beta_{j[i]} x_i + \epsilon_i \tag{21}$$

where the varying slopes $\beta_{j[i]}$ correspond directly to the industry adjustment coefficients δ_j in the Flaschel–Semmler model. In this mixed-effects model, observations i are grouped by the 36 industries of each of the six countries, so that there are $36 \times 6 = 216$ groups of observations. In distribution notation,

$$y_i \sim N\left(\beta_{j[i]} x_i, \sigma_y^2\right) \qquad \beta_j \sim N\left(\mu_\beta, \sigma_\beta^2\right) \tag{22}$$

Figure 9 (below) shows the distributions of cross-dual adjustment coefficients in prices and quantities for the 36 industries of each country, respectively. Quantity adjustments are found to be generally higher than price adjustments. Out

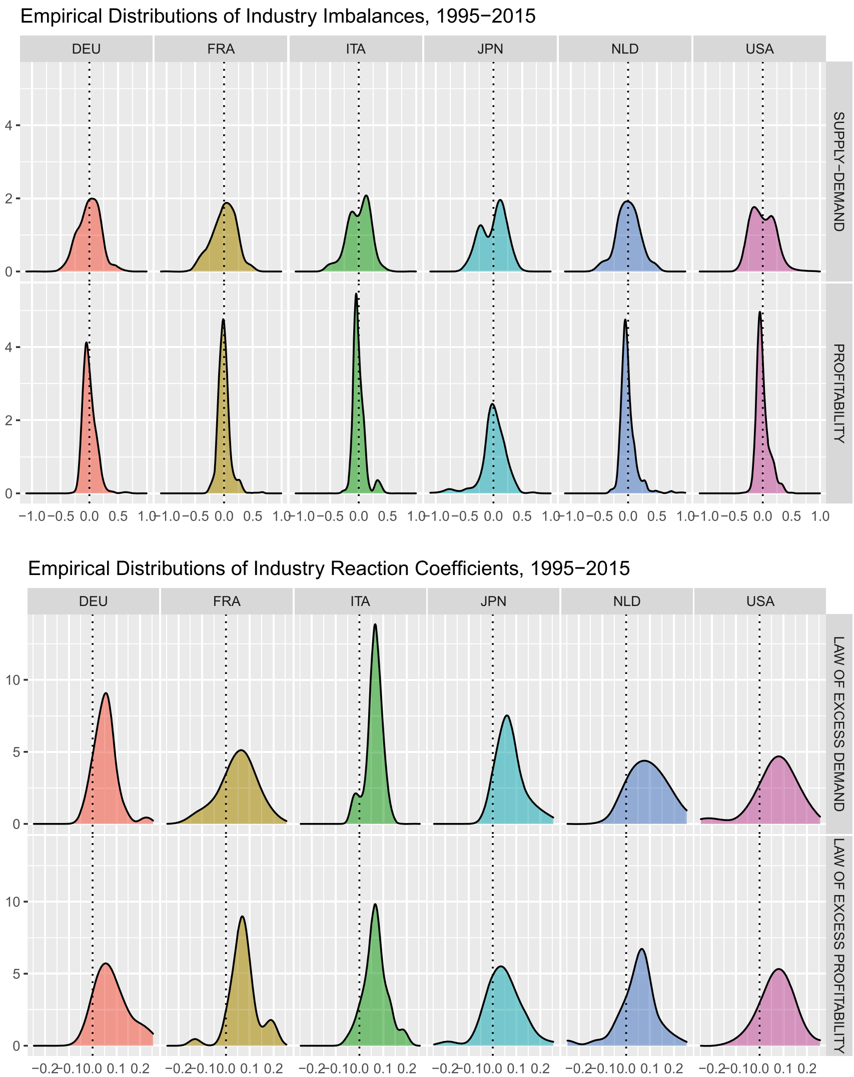

Figure 9: Empirical distributions of industry supply–demand imbalances and deviations from normal profitability (above), and industry reaction coefficients (below), for selected countries, 1995–2015.

of the 212 adjustment coefficients for prices and quantities, 22.5 % and 12.5 % are negative, which is nonsensical in the basic cross-dual framework; those sectors are disregarded in the simulations. Rather than the baseline cross-dual adjustments, these coefficients may indicate dual transmission in the Keynesian tradition.

Appendix C: Industry List

Table 7

Table 7: List of industries of the world input–output database.

Code	Description
A	Agriculture and fishing
B	Mining and quarrying
C10–C12	Manufacture of food products, beverages, and tobacco products
C13–C15	Manufacture of textiles, wearing apparel, and leather products
C16–C18	Manufacture of wood and paper products
C19	Manufacture of coke and refined petroleum products
C20	Manufacture of chemicals and chemical products
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
C22–C23	Manufacture of rubber, plastic products, and other nonmetallic mineral products
C24–C25	Manufacture of basic metals and fabricated metal products
C26	Manufacture of computer, electronic, and optical products
C27	Manufacture of electrical equipment
C28	Manufacture of machinery and equipment n.e.c.
C29–C30	Manufacture of motor vehicles and other transport equipment
C31–C33	Manufacture of furniture; other manufacturing; repair and installation of machinery and equipment
D	Electricity, gas, steam, and air conditioning supply
E	Water collection, treatment and supply; sewerage; waste collection, treatment, and disposal activities
F	Construction
G45	Wholesale and retail trade and repair of motor vehicles and motorcycles
G46	Wholesale trade, except of motor vehicles and motorcycles
G47	Retail trade, except of motor vehicles and motorcycles
H49	Land transport and transport via pipelines
H50	Water transport
H51	Air transport
H52	Warehousing and support activities for transportation
H53	Postal and courier activities
I	Accommodation and food service activities
J58	Publishing activities
J59–J60	Publishing activities, including motion picture, sound, video, and television program production

Table 7: (continued)

Code	Description
J61	Telecommunications
J62–J63	Computer programming, consultancy and related activities; information service activities
K	Financial service and insurance activities
M–N	Administrative, professional, scientific, and technical activities; legal and accounting activities
O	Public administration and defence; compulsory social security
P	Education
Q	Human health and social work activities
R–S	Other service activities

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