The Labor Market Consequences of Rapid Sectoral Shifts*

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Abstract

Sectoral shifts require costly labor reallocation, fueling concerns about how quickly they occur. We study how the pace of sectoral shifts affects the earnings distribution among workers initially attached to declining sectors. We develop a life-cycle model with skill heterogeneity, directed search and job-ladders in which labor demand gradually rises in one sector and declines in another. The model reveals three insights. First, workers' lifetime earnings are strongly non-linear and even non-monotone in the horizon over which the transition unfolds. Second, accelerating the transition creates a trade-off between benefiting more workers on the extensive margin, and thickening the tail of losses on the intensive margin. Third, labor market frictions are important to quantify these non-linearities. We apply our model to the climate transition and find substantial earnings losses from a baseline transition ending in 2060. Completing the transition in 2050 reduces average losses but has substantial distributional effects.

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1 Introduction

Secular changes in economic activity often require substantial labor reallocation from declining sectors to growing ones. These sectoral shifts are ubiquitous and include the contraction of manufacturing and the rise of services, sectoral reallocation following a trade liberalization, or transitions where a vintage technology is replaced by a newer one.[1] A particularly relevant example for today is the climate transition, during which economic activity will shift from polluting to clean industries. The labor reallocation that accompanies these sectoral shifts is often costly for workers attached to the declining sector, who forgo specific human capital and experience periods of unemployment over the transition, with lasting effects on their earnings (Jacobson et al., 1993; Davis and von Wachter, 2011). These reallocation costs fuel concern about how quickly these transitions take place. For instance, survey evidence and voting behavior suggests that labor market concerns are a significant obstacle to public support for climate action (Dechezleprêtre et al., 2025; Bombardini et al., 2025). Despite the important political economy ramifications, we know surprisingly little about how workers' outcomes depend on the timeline over which sectoral shifts unfold.

This paper studies how the *pace* at which a sectoral shift occurs affects the earnings distribution among workers initially employed in the declining sector. For instance, in the climate context, we study how completing the energy transition by 2060, 2050, 2045, etc. affects the distribution of earnings losses among workers initially attached to polluting industries, who are most at risk of displacement and most likely to oppose the transition. While much of the literature focuses on particular historical transitions, we conduct a *counterfactual* analysis asking how workers' earnings distributions would change were the government to intervene to accelerate or slow a transition.[2] Our goal is to develop general conceptual insights that are portable to a variety of sectoral shifts, and apply these insights in a particularly policy-relevant context for today: the climate transition.

We develop a model that captures the displacement and reemployment expe-

[1] Other examples include the decline of physical retail and the surge in warehousing jobs supporting online retail or situations where a burgeoning private sector takes over public activities in a formerly planned economy (Atkeson and Kehoe, 1996; Boeri, 2000).

[2] See Traiberman (2020), Caliendo et al. (2019), Dix-Carneiro (2014), and Adão et al. (2024) among others for papers who study one particular realized transition.

rience of workers initially attached to a declining industry. The model features finitely-lived workers with heterogeneous skills. As the old sector declines, workers may look for employment in this shrinking sector, transition to a new and rising sector, or claim an outside option which captures the rest of the economy or early retirement. Although our full model features a realistic frictional labor market, endogenous skill accumulation, and gross flows between sectors, we momentarily abstract from these features to develop clear conceptual insights.

Changes in preferences and technology induce a transition of economic activity away from the old sector towards the new sector. The government can accelerate or slow down this transition by implementing sector-specific subsidies financed by lump sum taxes on workers, thereby shifting the path of marginal revenue products of labor (MRPL) across sectors. These paths of MRPL are *sufficient statistics* for sectoral labor demand that entirely determine workers' labor market outcomes. We thus study how exogenous perturbations in the paths of MRPL — corresponding to more or less ambitious timelines and reflecting different government subsidies — affect the distribution of workers' present discounted value of future earnings or "lifetime earnings."[3]

Three conceptual insights emerge from our analysis. First, workers' lifetime earnings are highly *non-linear* or even *non-monotone* in the horizon of the transition. The non-linearity implies that accelerating a transition by 1, 5 or 10 years has dramatically different implications for workers. Under a status quo transition, workers experience a given shift in labor demands by the time they retire. A faster transition not only means that they will be exposed to this shift for longer; it also exposes them to a larger shift which they otherwise would not have experienced before retirement. These two effects reinforce one another and imply that a faster transition has a non-linear effect on lifetime earnings. Extrapolating from small changes around a status quo transition can thus be very misleading.

Workers' earnings changes can even be *non-monotonic* in the pace of the transition: some workers suffer at first when the transition accelerates, but may benefit from an even faster one. This non-monotonicity results from the tension between two opposing forces: a faster transition displaces workers faster from the old sec-

[3] A second, complementary question is: what is the fiscal cost of implementing a particular path for the MRPL in each sector? This question is of course essential to conduct optimal policy analysis. However, answering it requires knowledge of a number of additional parameters that are difficult to estimate and is thus outside the scope of this paper, which focuses on labor markets.

tor, worsening earnings losses early in the transition; at the same time, it creates more good, high-paying jobs in clean sectors before they retire. We show analytically that the relative importance of the second effect grows as the transition accelerates. In particular, workers generally suffer the most for *medium-speed* transitions where the transition is fast enough that the worker experiences all of the earnings drop in the declining sector, but slow enough that they retire before sufficiently benefiting from growth in the rising sector.

The second insight is that the government faces a trade-off as it accelerates the transition: on the one hand, a faster transition increases the mass of workers who gain at the *extensive margin*; on the other hand, it thickens the tail of large earnings losses at the *intensive margin*. These results have important political economy implications when it comes to the support for various transition timelines. We also find that older workers — who are more likely to participate in the political process (Census Bureau, 2025) — are *less* likely to benefit from a faster transition at the extensive margin, as they have a shorter horizon over which to recoup the short-run losses incurred after being displaced from the old sector.

We first establish these results analytically in a frictionless model where labor markets are perfectly competitive. We then develop a quantitative version of our model that nests the frictionless benchmark as a limit and takes into account important features of the data that can affect earnings losses over the transition. First, unemployment spells and job ladders are crucial to explain workers' earnings losses after separation in practice (Jacobson et al., 1993; Huckfeldt, 2022; Jarosch, 2023). We therefore allow for involuntary unemployment due to search frictions and a job ladder arising from on-the-job search (Menzio and Shi, 2011), which generates unemployment scarring as workers fall from the ladder. Second, human capital depreciation has long been recognized as another important source of unemployment scarring (Ljungqvist and Sargent, 1998). We therefore suppose that workers have multi-dimensional skills, which they accumulate on-the-job and dis-accumulate off-the-job (Guvenen et al., 2020; Lise and Postel-Vinay, 2020). Finally, there are large gross flows between industries (Pilossoph, 2014) and job-to-job switches often entail wage cuts (Sorkin, 2018). Accordingly, we assume that workers face a noisy discrete choice across labor markets so that their job search is partially directed across jobs.

Our third finding is that labor market frictions are important determinants of

the effects of a faster transition. We repeat our counterfactual analysis in the quantitative model and find workers' earnings remain highly non-linear in the transition horizon. We decompose the contribution of each additional quantitative features by adding them one-by-one to the frictionless model, until we reach the full quantitative model. We find that search frictions and on-the-job search (i.e., the job ladder) are the two key additions. Search frictions matter because filling a vacancy is costly, as it is in the data (Gavazza et al., 2018; Muehlemann and Strupler Leiser, 2018). Vacancy creation in the new sector only picks up meaningfully once the transition is rapid enough that it raises firms' productivities sufficiently to recoup this hiring cost — thereby introducing non-linearities of its own. Meanwhile, the presence of a job ladder means that workers slowly climb their way towards good and high-paying jobs in the old sector initially. As the transition accelerates, these jobs are no longer posted, resulting in large and permanent losses for workers who keep searching for jobs in the old sector because they do not have appropriate skills in the new sector. Overall, we conclude that policymakers should take labor market frictions into account when considering the effect of a faster transition.

After developing conceptual insights that apply to any shifts in economic activity where one sector expands at the expense of another one, we turn to a particular and concrete application: the climate transition. This application is especially relevant for today's policymakers: it concerns a substantial share of the workforce, i.e., 10-15 million workers, roughly the size of manufacturing employment in the early 2000s; its pace is partly under the control of the government; and most of the transition has yet to take place. Of course, the prospective nature of our analysis means that there is substantial empirical uncertainty about long-run outcomes, particularly when it comes to employment in clean and polluting sectors several decades away. We thus consider a menu of scenarios, in the range of existing predictions (Mayfield et al., 2023; Finkelstein Shapiro and Metcalf, 2023; IRENA, 2023).

Our next step is to estimate the *distribution* of these endowments in the particular context of interest. We develop a novel structural estimation strategy that leverages the block recursivity of competitive search equilibria, which allows us to solve for workers' policy functions independently from the distribution of skill endowments. The timing with which workers reallocate between dirty and clean sectors in the early part of the climate transition for which we have data allows us to trace the distribution of skill endowments non-parametrically. We also estimate

the rate at which workers accumulate specific skills by comparing the extent to which young and old workers reallocate — given that old workers had more time to accumulate specific skills in the polluting sector.

In our main scenario, we find that 80% of workers initially attached to polluting industries (or 5% of the US workforce) lose from the climate transition. These workers lose on average 5.5% in lifetime earnings, with some workers losing by more than 10%. These numbers lie in the range of estimates available in the context of trade liberalization and import competition from China (Dix-Carneiro, 2014; Traiberman, 2020; Autor et al., 2016). We then use our model to ask how changing the pace of the remaining transition affects workers' earnings. We find that a slight majority of workers would prefer to accelerate the transition so it ends in 2050 or 2040 instead of 2060. Consistent with our conceptual insights, we find that policymakers face a tradeoff when accelerating the transition: doing so creates more winners at the extensive margin; at the same time, it thickens the tail of earnings losses at the intensive margin, with some workers losing an additional 3% relative to the baseline transition ending in 2060.

Our work connects to a literature studying historical transitions associated to particular labor demand shocks. Dix-Carneiro (2014) estimates a dynamic equilibrium model with sector-specific human capital to quantify the impact of trade liberalization in Brazil. Traiberman (2020) argues that import competition led to a loss in occupation-specific human capital, which generated substantial welfare costs for workers in Denmark. Caliendo et al. (2019) study the effect of trade liberalizations in a rich setting in which workers face fixed costs of moving across sectors and regions, but without heterogeneous skill endowments or skill accumulation and without involuntary unemployment or job ladders. Braxton and Taska (2023) find that workers incur substantial earnings losses when technological changes make their skills obsolete. Adão et al. (2024) show that that the adoption of new technologies takes more time when workers do not possess the right skills to operate these technologies. In contrast to this literature, we do not study one particular historical episode. Instead, we ask a counterfactual question: how large would earnings losses be if we accelerated a given transition?

We also contribute to a literature asking whether policymakers should slow down the adoption of technologies. Guerreiro et al. (2021), Costinot and Werning (2023) and Lehr and Restrepo (2023) argue that taxing new technologies can

be optimal to mitigate the distributional consequences of automation. Beraja and Zorzi (2024) show that the pace of technological transitions is inefficiently fast when workers are unable to smooth consumption upon displacement. Braxton and Taska (2024) investigate the role of retraining subsidies to insure workers against technological change. Much of this literature focuses on the benefits of slowing transitions. Relative to this literature, we uncover strong non-linearities and non-monotonicities in earnings losses as transitions get faster and argue that there could be benefits to both accelerating and slowing transitions. We clarify the structural objects that underlie these effects, argue that the set of workers who win from a transition changes as it accelerates more and more, and that accounting for involuntary unemployment and earnings scarring is important to capture these non-linearities. We apply these lessons in the context of the climate transition.

Our climate application contributes to a growing body of work on the costs and benefits of the energy transition. A large literature documents substantial societal gains from a fast climate transition (Barrage and Nordhaus, 2023; Bilal and Känzig, 2024; Nath et al., 2024). At the same time, Bilal and Stock (2025) note that there has been comparatively little work on the labor reallocation and earnings losses associated with this transition, which motivates our application. Empirical work documents the ongoing reallocation of workers towards green industries (Curtis and Marinescu, 2023; Curtis et al., 2023). Consoli et al. (2016) and Bassanini et al. (2024) argue that green jobs require on average more education, more training, and a more intensive in cognitive skills. Walker (2011, 2013) and Känzig (2023) document substantial and long-lasting earnings losses due to environmental regulation, confirming that workers' skills are imperfectly transferable to clean industries.[4] Instead, our analysis estimates the distribution of earnings losses associated with this transition, studies how the set of winners and losers changes endogenously as the transition accelerates, and emphasizes the importance of non-linear effects.

2 Frictionless Benchmark

This section considers a frictionless benchmark economy to transparently illustrate the core economic mechanisms at play. Section 5 extends the model to allow for

[4] A complementary set of papers studies how policy can influence the speed of this transition (Acemoglu et al., 2012, Acemoglu et al., 2016, Acemoglu et al., 2023).

realistic frictional labor markets; the model studied here is nested in the full model.

Time is continuous and indexed by $t \geq 0$. There are three sectors k. With an eye to our application, we label $k = C$ for "clean" or "creating", $k = D$ for "dirty" or "destroying/declining," and $k = O$ for an "outside" option, which represents early retirement and other sectors unaffected by the transition, such as manufacturing workers seeking jobs outside of services. The transition is a scenario where, relative to trend, labor demand declines in the D sector and rises in the C sector. The outside option is unaffected by the transition.

2.1 Workers

Demographics and preferences. Workers, indexed by i, live for J periods and are replaced by new ones upon retirement. Workers supply labor and consume in ages $j \in [0, J]$. Their preferences are represented by

$$\mathbb{E}_0 \left[\int_0^J \exp\left(-\rho t\right) u\left(c_t\right) dt \right] \tag{2.1}$$

where c_t is consumption of numeraire, $u(c) \equiv c^{1-\sigma}/\left(1-\sigma\right)$ is the flow utility function, and $0 < \rho < \infty$ is the discount rate. We let τ denote a worker's birth date, or cohort, so that incumbents' age as of period 0 is $-\tau$.

Skills. Workers have heterogeneous labor productivities in each k. Let ψ denote the units of human capital that the worker supplies if employed in sector D, and $\hat{\psi}$ denote a worker's relative skill in sector C. Workers may transfer a share $b^O \geq 0$ of their skills in the declining sector to the outside option. Therefore, a worker's productivities may be summarized by

$$h\left(\psi, \hat{\psi}, k\right) = \begin{cases} \psi & \text{if } k = D \\ \psi \times \hat{\psi} & \text{if } k = C \\ \psi \times b^k & \text{if } k = O \end{cases} \tag{2.2}$$

We assume that all workers are endowed with $\psi = 1$ and draw an endowment of $\hat{\psi}$ from a distribution $G\left(\hat{\psi}\right)$. In the simple model studied here, we assume that these productivities are fixed over a worker's life, and we relax this assumption in

the quantitative model of Section 5.

2.2 Firms

All firms are owned by a continuum of infinitely-lived, risk-neutral entrepreneurs who discount at rate ρ.

Final good. A representative competitive final goods producer combines the output of the creating and destroying sectors to produce according to $Y_t = Z_t F_t \left(X_t^D, X_t^C\right)$, where Z_t is aggregate TFP, and X_t^k are intermediate goods produced in sector k. The aggregator F_t has constant returns-to-scale and is weakly concave in each argument.[5] We consider the case where the two intermediates are (not necessarily perfect) substitutes, e.g., EVs and ICEs.

Intermediates. The two intermediate goods X_t^k are produced by combining a continuum of mass 1 of varieties x_t^k using a CES aggregator with elasticity of substitution larger than one. These firms produce using labor services $x_t^k = a_t^k g^k\left(n_t^k\right)$, where a_t^k are labor productivities, $n^k = \int_{i \in k} h\left(\psi_i, \hat{\psi}_i, k\right) di$ is the amount of labor services employed in k, and $g^k(\cdot)$ is an increasing function which captures returns to scale in sector k production. Firms are price takers in the labor market but compete monopolistically in product markets, and sell their output to the final goods producer at price p_t^k in a symmetric equilibrium.

Productivities. Entrepreneurs who own the intermediate goods firms can invest resources to improve their productivity a_t^k thus increasing profits. We allow for technological spillovers across sectors and technological depreciation as in Eaton and Kortum (1999). Our specification ensures that the economy admits a long-run balanced growth path (BGP) where output of all sectors grows at rate $g^\star > 0$. As we explain in Section 3.1, our results do not depend on the exact specification for the evolution of Z_t and a_t^k.[6] We therefore relegate the exposition of these features to Appendix B.2 to economize space.

[5] We assume F_t has bounded derivatives so goods prices are finite when the transition begins. Otherwise, the marginal revenue product of labor in C would be so high the clean sector is in its infancy that workers would jump to the clean sector in $t = 0$, which is clearly counterfactual.

[6] Appendix B.2 shows that our conclusions hold if climate damages endogenously affect Z_t.

2.3 Government and Markets

Labor Markets. In this frictionless benchmark economy, labor markets are perfectly competitive. Workers may supply their labor to intermediate goods producers in sector k at a competitively determined wage per efficiency unit w_t^k. They may also take the outside option, in which case they receive a flow endowment of numeraire $h\left(\psi, \hat{\psi}, O\right)$. Workers freely choose which sector to work in at every instant.

Government. The government has two instruments to influence the transition after it begins in $t = 0$. First, the government can introduce a subsidy or tax τ_t^k on the purchase of intermediate goods, e.g., a subsidy on EV sales. Second, it can use subsidies ς_t^k on innovation (or investment) in each sector, e.g., a subsidy on R&D to develop efficient battery cells. We suppose that the government balances its budget in every period using lump sum transfers to workers.

Financial Markets. Financial markets are incomplete with respect to the aggregate shock, i.e., workers did not preemptively write contingent contracts against the path of the climate transition. Our main analysis focuses on the case with risk-neutral workers ($\sigma = 0$) as is standard in much of the labor search literature (Menzio and Shi, 2011; Bilal et al., 2022; Braxton and Taska, 2023). Our object of interest is the present discounted value of earnings.

2.4 Equilibrium

We define equilibrium formally in Appendix B.3. Appendix B.5 proves that the equilibrium admits a balanced growth path in which all worker and firm values grow at the same rate g^* and scale linearly with the reference skill ψ. A transition between the sectors may occur either due to changes in the final goods production technology $F_t(\cdot)$ (e.g. due to shifts in preferences), changes in physical productivity in the sectors a_t^k, or due to government tax and subsidy policy $\left(\tau_t^k, \varsigma_t^k\right)$. Next, we describe how the transition unfolds.

3 Status Quo and Counterfactual Transitions

The government can use its instruments to change the pace of the transition. This section describes the set of allocations that the government can implement with its policy tools, discusses the status quo transition that would prevail without further intervention, and explains the counterfactuals that we conduct.

3.1 Implementable Allocations

Our goal is to study how workers' lifetime earnings change as one changes the pace at which the transition unfolds. Doing so seems a daunting task, as it appears to require a number of difficult-to-estimate parameters, such as how preferences across the two goods $F_t(\cdot)$ change over time, the returns to scale in each sector $g^k(\cdot)$, and parameters governing innovation such as cross-sector knowledge spillovers and the innovation production function. To make progress, we leverage two convenient features of our model, which both carry over to our full model of section 5. First, define the marginal revenue product of labor (MRPL) in sector k as

$$\text{MRPL}_t^k \equiv \left(1+\tau_t^k\right) a_t^k p_t^k g^{k,\prime}\left(n_t^k\right) \tag{3.1}$$

Then the following two properties hold:

Proposition 1. *The government can implement any arbitrary path of marginal revenue products of labor $MRPL_t^k$ in each sector using its instruments. Furthermore, labor market outcomes depend exclusively on sequences of $MRPL_t^k$.*

We prove this proposition in the context of our full model, which nests the frictionless benchmark, in Appendix B.7. The first property is that the government can implement any arbitrary path of MRPLs using its subsidies on intermediates τ_t^k and subsidies on innovations ς_t^k, even if prices, innovation and spillovers respond endogenously: that is, there is a complete mapping between tax policy and MRPLs.

Second, marginal products of labor are sufficient statistics to characterize workers' labor market outcomes. Therefore, one does not need separate knowledge of the innovation process, nor the functions $F_t(\cdot)$ or $g^k(\cdot)$ to study labor outcomes. This holds trivially in the frictionless benchmark with competitive labor markets since wages in sector k are equal to marginal revenue products in equilibrium, but

it will also hold in the model with search frictions. Along a balanced growth path, these MRPLs grow at the same rate g^* as the economy at large; it is therefore sufficient to consider de-trended marginal revenue products

$$A_t^k \equiv \text{MRPL}_t^k / \exp(g^\star t). \tag{3.2}$$

These two results imply that policymakers can proceed sequentially when deciding how to manage a transition. In particular, they may separately answer two distinct questions. First: What are the distributional labor market consequences of different paths for the marginal revenue products of labor A_t^k across sectors? Then: conditional on these labor market consequences, what are the fiscal costs and benefits of implementing a particular path of A_t^k?[7]

This paper is concerned with answering the first question. This is the first step for policymakers: how expensive would it be to compensate workers who suffer from the climate transition for given paths of A_t^k? Given that the government can implement any path of A_t^k, this question is *orthogonal* to the production side of the economy and, in particular, the difficult-to-estimate parameters listed above. The paths of A_t^k are all one must know to characterize workers' outcomes.

The second question is much more difficult to answer, as doing so requires knowledge of all the parameters governing innovation, changes in preferences, and the efficacy of government policy tools. These empirical challenges deserve their own paper.

Our goal is thus a *positive* analysis: how do different paths of MRPLs associated to accelerating or slowing a sectoral shift affect its distributional consequences. To that end, we henceforth focus on the labor market block of the model and exogenously feed in paths of A_t^k. However, the innovation and production blocks provide guidance on reasonable shapes for the transition to follow, as we now discuss.

[7] We take as given that the government may have some motive to intervene in the transition. Motives for intervention could include redistribution or to correct perceived inefficiencies. For example, in the climate context, the government may wish to accelerate the transition to mitigate climate damages, while one could imagine external returns to scale in the structural change context, or terms of trade manipulation in a trade context. We are agnostic about these precise motivations; our goal is to characterize the labor market effects of managing these labor demand movements.

3.2 Model Exercises

Status Quo Transition. Consider first the status quo transition that prevails without further government intervention.[8] The period before $t = 0$ corresponds to our initial balanced-growth path in which all sectors grow at rate $g^\star$, so A_t^k is constant. We assume there is no demand for the creating sector good along this initial balanced-growth path, so its employment is zero before $t = 0$.[9] The transition is initiated in $t = 0$ by a change in F_t in favor of the good produced in the creating sector, reflecting either a change in government mandates or a change in preferences (e.g., increased awareness on climate issues). Thus, the price of the creating sector good – and thus A_t^C – becomes positive in $t = 0$. A transition then ensues during which MRPLs rise in the C sector and decline in the D sector, following sectoral innovation, labor reallocation and any further changes in preferences.[10]

An example of such a transition is depicted in the left Panel of Figure 1. The solid black line plots a path of A_t^C in the creating sector, and the dashed line shows a path for A_t^D in the declining sector. We normalize the initial value of $A_0^D = 1$ as the scale of the economy without loss of generality. The level of A_0^C in the creating sector when the transition begins is not separately identified from the mean of the distribution of skill endowments G, since workers could be productive in the clean sector on average either because A_0^C is high or because they have high skills there. Thus, we also normalize $A_0^C = 1$.

We assume that the post-transition BGP shares the same growth rate $g^\star$ as the initial BGP, as implied by our innovation block. Thus, A_t^k converge to some finite A_∞^k. We parameterize the paths of marginal revenue products of labor as

$$A_t^k = A_0^k + \bar{\Phi}^k(t) \times \left(A_\infty^k - A_0^k\right) \tag{3.3}$$

under the status quo transition, where A_0^k and A_∞^k are the start and end values of labor productivity. We assume $A_\infty^C > A_0^C$ and $A_\infty^P < A_0^P$.[11] The timing of this

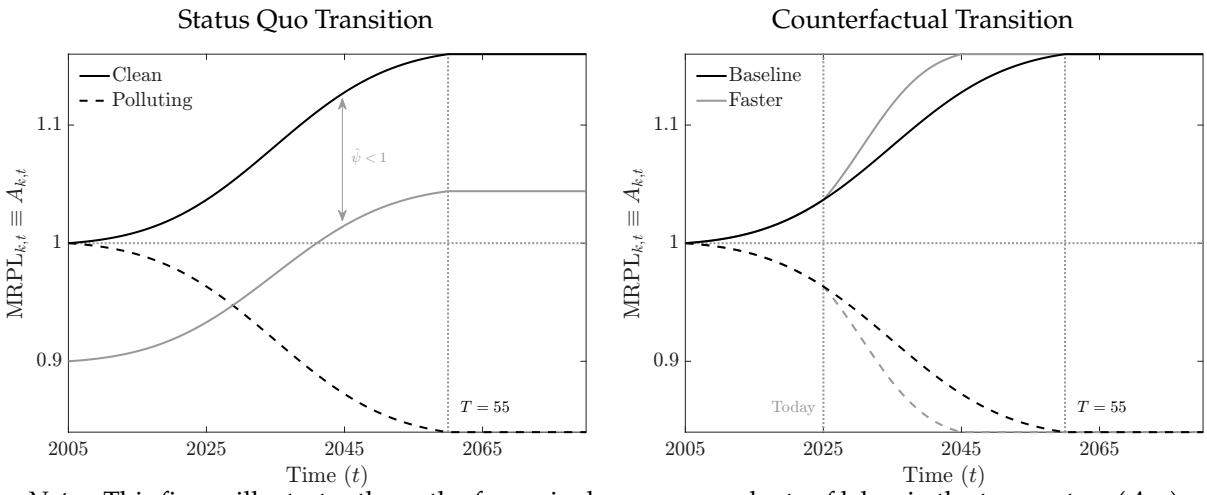
[8] The government might have *already* intervened under the current policy regime, e.g., there are subsidies to innovation and to EV adoption, etc.

[9] In effect, we focus on workers who are initially employed in the declining sector, who are most exposed to the transition. Focusing on an initial steady state where the creating sector is absent additionally eases calibration of steady state parameters, as discussed in Section 5.2.

[10] The presence of technological spillovers along the initial balanced-growth path implies that the initial physical productivity a_t^k is positive in the clean sector, despite the lack of direct innovation.

[11] That the old sector is declining relative to trend does not imply the old sector is declining in

Figure 1: Marginal revenues product of labor $A_{k,t}$



Notes: This figure illustrates the path of marginal revenue products of labor in the two sectors ($A_{k,t}$) under various transition scenarios. The black curves correspond to our baseline transition with $\eta = 1$. The solid and dashed curves indicate the creating and destroying sector, respectively. The left panel plots labor productivity of a worker with $\hat{\psi} < 1$ in the creating sector in gray. The gray curves in the right panel correspond to a faster transition $\eta > 1$.

sectoral shift is parameterized by the increasing functions $\bar{\Phi}^k : \mathbb{R} \to [0, 1]$, which represent the share of the transition that is completed as of period t. Let T_0 denote the period in which the transition completes (i.e. $\bar{\Phi}^k(T_0) = 1$ for both k); we call T_0 the "transition horizon."

A natural example to consider is that the productivities A_t^k follow S-shaped curves over the status quo transition. S-shapes are characteristic of innovation and technology adoption (Griliches, 1958), and are a good fit in the climate context (Shepherd et al., 2012). As we explain in Appendix B.6, the S-curve in the creating sector reflects higher returns to innovation in that sector early on, followed by smooth convergence to a new balanced growth path in the long run; the opposite happens in the declining sector. The S-shape is not crucial to our analytical results, but we will maintain it throughout our illustrations.

All workers have $\psi = 1$ throughout their lives, and thus produce A_t^D labor services in the D sector and $A_t^C \hat{\psi}$ labor services in the C sector. Therefore, the productivity of workers in the C sector will follow the path of A_t^C scaled down by their specific skills $\hat{\psi}$. This is depicted by the gray line in the left panel of Figure 1.

absolute terms, rather that it grows at a slower rate over the transition than previously.

Counterfactual Transitions. We consider counterfactuals in which, starting from some data t_0, A_t^k evolves according to

$$A_t^k = A_0^k + \bar{\Phi}_t^k \left(t_0 + \eta \left(t - t_0 \right) \right) \times \left(A_\infty^k - A_0^k \right), \quad \text{for } t \geq t_0,\ \eta > 0. \tag{3.4}$$

The parameter η governs the speed of transition. The paths of A_t^k align exactly with the benchmark transition when $\eta = 1$. Increasing η compresses the timeline of the transition such that future events arrive sooner: the transition accelerates. A higher η implies that the transition completes at some counterfactual horizon $T < T_0$. We have argued that the government can implement any arbitrary path of A_t^k given its instruments. A higher η therefore reflects more aggressive government intervention early during the transition; e.g., the government subsidizes EV purchases early during the transition. Our counterfactuals focus on temporary interventions which hold fixed the long-run balanced growth path and levels of A_∞^k.[12] The gray curves in the right panel of Figure 1 illustrate one such counterfactual transition associated to some $\eta > 1$ supposing intervention begins today.

For each counterfactual, we compute changes in workers' lifetime earnings as

$$d\mathcal{W}\left(j, \hat{\psi}, s; \eta = \hat{\eta}\right) \equiv \frac{W_{t_0}\left(j, \hat{\psi}, s\right)\big|_{\eta=\hat{\eta}}}{W_{t_0}\left(j, \hat{\psi}, s\right)\big|_{\eta=1}} - 1, \tag{3.5}$$

where $W_{t_0}\left(j, \hat{\psi}, s\right)\big|_{\eta=\hat{\eta}}$ corresponds to a worker's value function (Appendix B.1) evaluated in t_0 when the transition speed is $\hat{\eta}$. In other words, we compute expected earnings changes from the transition from t_0 onward, relative to the status quo transition. In Section 6.3, we additionally conduct a retrospective exercise where we compare workers' values as of t_0 under the baseline transition with $\eta = 1$ relative to no transition at all.

Climate Application. While our conceptual insights apply to multiple transitions, it is useful to specialize equations (3.3)-(3.4) to our climate application to fix ideas. The most important early climate agreement was the Kyoto Protocol, which established binding reduction targets for greenhouse gas (GHG) emissions for the

[12] For instance, suppose that the government eventually reverts to the same long-run subsidies (or taxes) that prevail at the laissez-faire. In this case, our innovation process ensures that the level of the long-run balanced-growth path is unchanged. As an extension, we also consider counterfactuals in which both η and the long-run levels A_∞^k change.

192 countries that ratified it, including the US. The Kyoto Protocol was adopted in 1997 and entered into force in 2005. We therefore choose our period $t = 0$ to be the year 2005. The most important following accord was the Paris Climate Agreement of 2015 which pushed most developed countries to target net-zero emissions by the year 2050.[13] The US, however, pulled out of the Paris Agreement and is not currently on track to meet this target by 2050. The median response in a recent survey of US energy CEOs suggest that 2060 is a more realistic timeline (Bain & Company, 2025). We therefore assume that the baseline status quo transition in our model runs from 2005 to 2060 (as depicted by $T_0 = 55$ in the left panel of Figure 1). For concreteness, we refer to these dates throughout our analysis. Our counterfactual analyses consider speeding up these transitions starting in $t_0 = 2025$: the exercise that is most relevant to policymakers today.

4 Economic Mechanisms

We first study the economic mechanisms in the frictionless benchmark. Throughout, workers are assumed to be active from 25 to 65 years of age ($J = 40$) and, unless otherwise stated, we set $b^O < A^D_\infty$ so that no worker is employed in the outside sector. The next section studies the extent to which labor market frictions quantitatively affect our core insights.

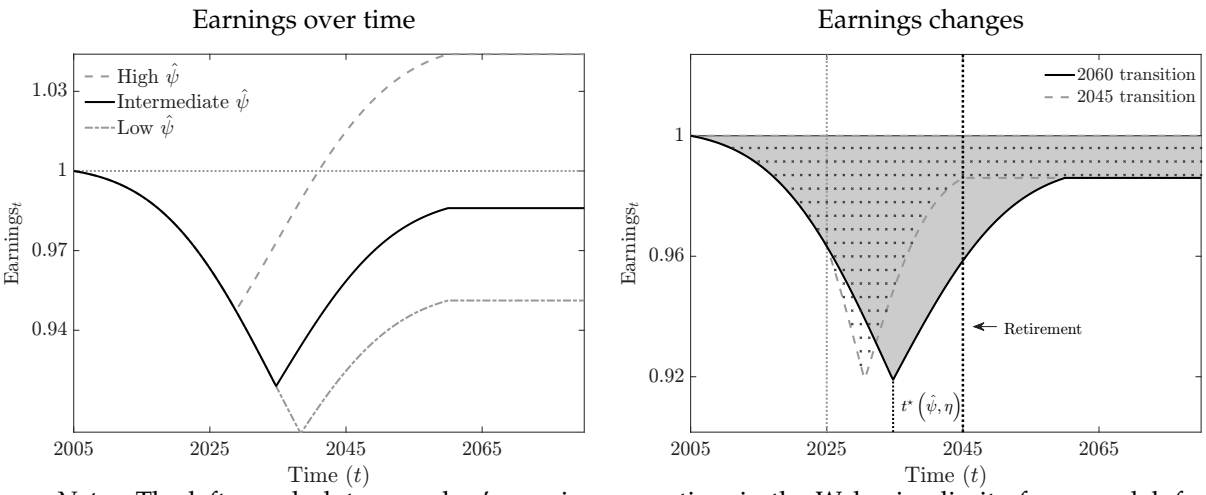
4.1 Non-Linear Effects of Transition Horizon

The left panel of Figure 2 plots the path of earnings over time for a particular worker with $\hat{\psi} < 1$ under the status uqo transition ($\eta = 1$). The worker initially supplies labor to the declining sector. At every instant, they compare their earnings in that sector A^D_t to their potential earnings in the creating sector $A^C_t\hat{\psi}$ and supply labor in the creating sector if and only if $\hat{\psi} \geq A^D_t / A^C_t$. The right-hand side of this inequality shrinks over time. Therefore, a worker remains in the declining sector until a switching time $t^\star\left(\hat{\psi}\right) \geq 0$ which depends on their relative skill $\hat{\psi}$, and switches to the creating sector thereafter.[14] A worker switches sector if their

[13] See Naser and Pearce (2022) for more on the history of international climate accords.

[14] Formally, $t^*(\hat{\psi})$ is the solution to the equation $\hat{\psi} = A^D_{t^*(\hat{\psi})} / A^C_{t^*(\hat{\psi})}$, with $t^\star\left(\hat{\psi}\right) \equiv 0$ or $t^\star\left(\hat{\psi}\right) \equiv \infty$ if no solution exists and the worker either switches immediately or never at all.

Figure 2: Lifetime Earnings Losses From Transitions of Various Speeds



Notes: The left panel plots a worker's earnings over time in the Walrasian limit of our model, for various productivities $\hat{\psi}$ in the clean sector. The right panel indicates lifetime earnings changes in the status quo transition with $\eta = 1$ and how they change as the transition accelerates to end 15 years earlier.

stopping time occurs during their life span: $t^\star\left(\hat{\psi}\right) < J + \tau$.

Workers' earnings decline following the path of A_t^D while they remain in the declining sector. Earnings rise with A_t^C after they switch sectors. Those with a higher relative skill $\hat{\psi}$ (dashed) switch earlier and benefit more in the long-run.

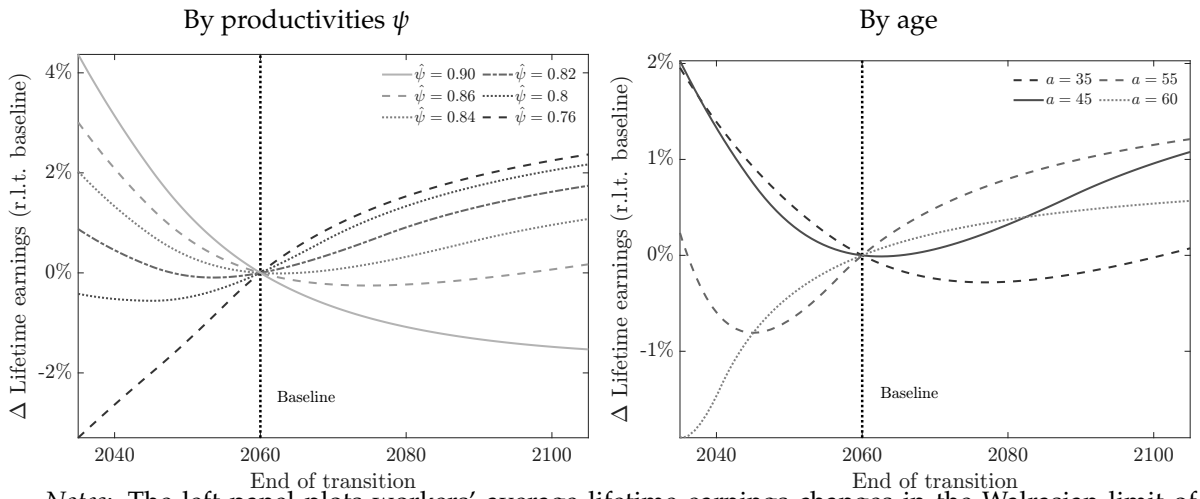
The effect of the status quo transition on workers' lifetime earnings is given by the area between their realized earnings path and $A_0^P = 1$, discounted at rate ρ until retirement. This is depicted by the gray shaded area in the right panel of Figure 1. Workers with imperfectly transferable skills ($\hat{\psi} < 1$) lose from the early phase of the transition since the productivity gap between sectors opens up slowly. Thus the gray area is likely negative for many workers.[15]

Now consider an accelerated transition, depicted by the checked region in the right panel of Figure 2. A faster transition has two opposing effects on a worker's lifetime earnings. On the one hand, it steepens the fall in income while the worker remains in the declining sector. On the other hand, the worker switches to the creating sector sooner, earnings grow faster after the worker switches and a larger share of the transition is completed before retirement.

The interplay of these two forces generates our first key insight: lifetime earnings changes are highly non-linear or even non-monotonic as a function of the

[15] Section 6.3 estimates the distribution of these gray areas in the climate context.

Figure 3: Average lifetime earnings changes



Notes: The left panel plots workers' average lifetime earnings changes in the Walrasian limit of our model as a function of the transition horizon T, for various values of the productivity $\hat{\psi}$ in the creating sector. All earnings changes are relative to the baseline transition ending in 2060, and faster transitions are parameterized as in equation (3.4). The horizontal axis corresponds to the end date of the transition considered. All workers have 20 years remaining in their careers (median age). The right panel repeats the same exercise for various ages as of 2025, when fixing the productivity $\hat{\psi} = 0.86$ in the creating sector. We suppose all workers are born at 25 years old and retire at 65.

horizon over which the transition unfolds. This is illustrated by Figure 3, which plots changes in lifetime earnings as a function of the year when the transition is complete. We scale the transition speed such that it represents the end date of the transition T, which we plot on the horizontal axis; that is, if the status quo transition ends in a period T_0, then $\eta \equiv T_0/T$. For each of these transitions, we compute the change in lifetime earnings (from 2025 onwards) relative to the baseline transition ending in 2060 – thus all lifetime earnings changes are zero for a transition ending in 2060 by construction. Moving to the right on the plot represents slowing down the transition. The left panel repeats this experiment for workers with various relative productivities $\hat{\psi}$ and who have 20 years of work remaining, while the right panel repeats the exercise for workers of different cohorts with $\hat{\psi} = 0.86$.

Non-linearities. Changes in lifetime earnings can be very *non-linear* in the speed of transition. Some workers gain from a faster transition while others lose. However, these marginal changes vary sharply as the transition accelerates. For instance, a worker with $\hat{\psi} = 0.86$ is mostly indifferent to small accelerations relative to 2060, but benefits more and more as the pace of the transition accelerates further. Accelerating the transition by 1, 5, or 10 years will therefore have vastly different

impacts on workers' lifetime earnings. Policymakers should be cautious about extrapolating from small changes around the 2060 timeline.

The non-linearity arises because changing the transition horizon non-linearly changes the area of earnings losses, as well as due to discounting. This is true even for workers who will never or always switch to the creating sector regardless of the transition speed and even if the transition $\bar{\Phi}^k(\cdot)$ were itself linear, as we prove in Appendix A. Consider, for instance, the case of the worker with $\hat{\psi} = 0$ who will never switch to the C sector regardless of the transition speed. For relatively slow transitions, worker's earnings loss is given by the discounted area of a triangle, whose base is the worker's remaining lifespan, and whose height is the total decline in A_t^D by the time of the worker's retirement.[16] Let $\bar{A}$ be the value of A_t^D at the time of the worker's retirement. An accelerated transition induces two effects on workers' earnings: not only do they reach $\bar{A}$ sooner and so spend more time at that low level of income before retirement, they are also exposed to an even larger decline in income before they retire. These effects reinforce one another and translate into non-linear lifetime earnings effects.[17]

Non-monotonicities. Our second key insight is that earnings changes can even be *non-monotonic* in the pace of transition: some workers who initially lose from a faster transition end up benefiting from an even faster one. For instance, the worker with $\hat{\psi} = 0.84$ would benefit from either a slower or a faster transition than the status quo. For this worker, a *medium-speed* transition that ends 2060 represents the worst of all worlds: it is sufficiently fast that they experience all declining sector losses, but sufficiently slow that they retire before their earnings recover from growth in the creating sector.[18]

A simple way to understand the U-shape is by considering a worker who retires at exactly the moment they would have switched to creating sector under the baseline transition ($t^*\left(\hat{\psi}\right) = J + \tau$).[19] This worker spends their whole career in the

[16] If the transition finishes before the worker's retirement, the earnings loss becomes the area of a trapezoid, yielding an additional non-linearity.

[17] These results are easiest to see with the realistic feature of finite lives, but this logic also holds if workers are infinitely lived but discount the future at a positive rate. One could also understand this result by noting that changing the transition horizon has a non-linear effect on the total decline in A_t^D by a worker's retirement.

[18] Graphically, this occurs when the area in the gray triangle in Figure 2 is maximized — this is the case when the worker's switching time $t^*(\psi)$ is close to their retirement age.

[19] The U-shape can survive with standard discounting rather than retirement; however, the model with retirement is both realistic and most transparently illustrates the economics.

declining sector and thus clearly prefers a slower transition. But they may also prefer a faster transition, as they now switch to the creating sector during their career and benefit from the productivity increases there. This gives rise to the U-shape.

Non-monotonicities occur for any worker with intermediate relative productivities $\hat{\psi}$ who would switch sectors during some period $0 < t < \infty$ under *some* transition speed, as we prove formally in Appendix A. These are exactly the workers who form the bulk of the cross-sector reallocation.[20]

Initial age also matters by affecting workers' horizon. The right panel of Figure 3 repeats the same exercise for various ages as of 2005, fixing the relative productivity $\hat{\psi} = 0.86$. The magnitude and shape of these non-monotonicities are sensitive to a workers' age because older workers have a shorter remaining horizon over which to experience earnings changes. In the example depicted here, older workers spend less time in the clean sector receiving earnings gains. As a result, they are more likely to experience a decrease in overall lifetime earnings as the transition accelerates. Therefore, both workers' skill $\hat{\psi}$ and cohort τ are crucial inputs to their earnings losses from transitions of different speeds.

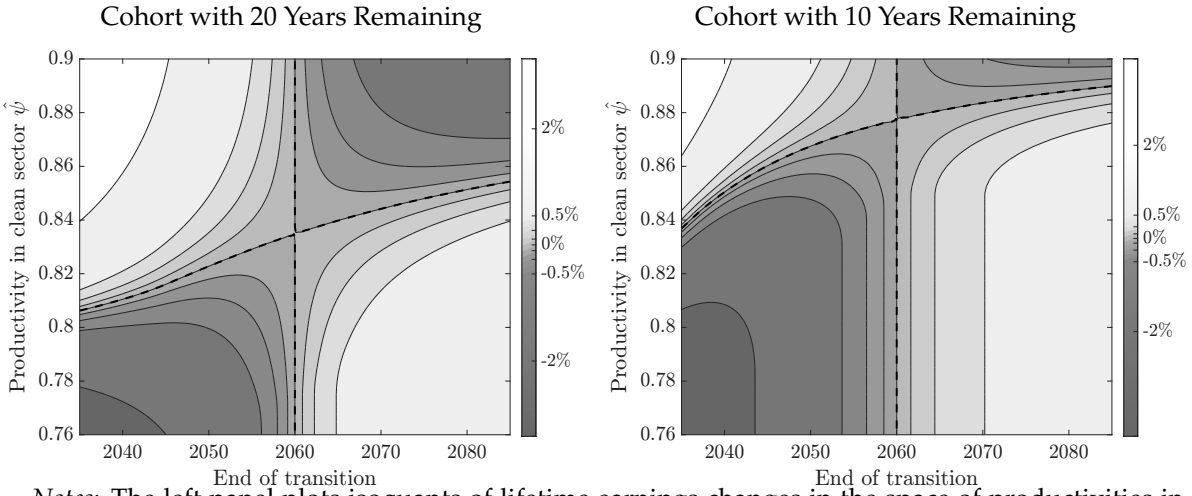
The introduction of an outside option does not change these qualitative insights. If the worker can always receive a constant b^O in the outside option, their earnings profile features a flat region at b^O whenever $A_t^D \leq b^O \leq A_t^C \hat{\psi}$. Accelerating the transition still steepens the initial earnings decline, which is still traded off against potentially larger gains after switching to the C sector. Thus the nonlinearity and non-monotonicities emphasized above survive. Of course, the earnings floor at b^O affects the model quantitatively, as explored in section 5.

4.2 Political Economy Implications

An important corollary of the non-monotonicity is that the set of workers who would prefer a faster transition changes with its speed. Figure 3 plots isoquants of lifetime earnings changes relative to the status quo transition in the space of relative productivities $\hat{\psi}$ and the end date of the transition. The region to the left

[20] Workers who either switch sectors immediately or never switch have a monotonic earnings profile over time. Therefore, they always gain or lose from a faster transition. We prove that there are two cutoffs $\underline{\psi} < \bar{\psi}$ such that all workers with $\psi < \underline{\psi}$ are strictly worse off as the transition accelerates, those with $\psi > \bar{\psi}$ are strictly better off, while all the workers with $\psi \in \left[\underline{\psi}, \bar{\psi}\right]$ workers have earnings losses which are U-shaped in the speed of transition.

Figure 4: Lifetime earnings change isoquants



Notes: The left panel plots isoquants of lifetime earnings changes in the space of productivities in the clean sector ψ and the speed of the transition η. All earnings changes are relative to a baseline transition ending in 2060, and faster transitions are parameterized as in equation (3.4). The horizontal axis corresponds to the end date of the transition considered. All workers have 20 years remaining in their careers (median age). The right panel illustrates how the distribution of earnings changes as the transition accelerates with $\eta = 1.5$ or $\eta = 2$ when assuming that ψ is distributed normally with mean 0.85 and standard deviation 0.05. Again, all earnings changes are relative to the baseline transition with $\eta = 1$.

of 2060 represents a faster transition. Darker colors indicate larger losses from the transition, while lighter colors correspond to smaller losses or even gains relative to the status quo. The left panel plots these isoquants for workers with 20 years of remaining work life, while the right panel repeats the exercise for older workers with only 10 years of working life remaining. Intuitively, high $\hat{\psi}$ workers benefit more from (or are hurt less by) a faster transition than are low $\hat{\psi}$ workers.

The figure reveals four interesting patterns. First, observe that the set of workers who would prefer a marginally faster transition as one accelerates the pace of transition – that is, any worker who crosses from a dark region to a lighter region as we move left on the plot – changes as the transition accelerates. Therefore, on the extensive margin, the set of workers who would vote for a marginally faster transition is sensitive to its pace.

Next, one can see this especially starkly by studying the dashed line on the plot, which divides the set of workers who prefer a given transition speed to the status quo transition ending in 2060. High $\hat{\psi}$ workers benefit from faster transitions while low $\hat{\psi}$ workers benefit from a slower transition. This dividing line is upward-

sloping, which means that a larger share of workers win on the extensive margin as we accelerate the transition more and more. Importantly, some workers – such as a worker with $\hat{\psi} = 0.82$ and 20 years remaining – *switch* from "losers" to "winners." The set of people who benefit from the transition depends on its speed.[21]

Third, observe that the darkest colors on the plot are in its bottom left corner: accelerating the transition creates a thicker and longer tail of earnings losses. Indeed, a faster transition presents a trade-off: while it increases the mass of workers who benefit from the transition on the extensive margin, it also generate a thicker tail among those who lose from it on the intensive margin. This trade-off has important political economy considerations if voters are strongly motivated by their anticipated labor market outcomes and presents a conundrum for policymakers.

Finally, comparing the left and right panel reveals that old and young workers are differentially affected by changing the transition speed. Accelerating a transition redistributes between workers of different skill transferabilities $\hat{\psi}$ and age. The relative voting behaviors of these groups therefore has repercussions for public support for rapid transitions. This may be particularly salient in the case of the climate transition (Dechezleprêtre et al., 2025).

4.3 Summary and Discussion

Our model reveals two novel conceptual insights. First, the labor market consequences of a technological transition are highly non-linear in the horizon over which it takes place: completing a transition by 1, 5, or 10 years will carry drastically different consequences for workers' earnings. Indeed, lifetimes earnings changes can even U-shaped in the transition horizon: some workers suffer the most from medium-speed transitions that displace them early from the declining sector without improving their prospects sufficiently in the creating sector before retirement. These non-monotonicities arise for any marginal worker who switches sectors for some $0 < t < \infty$, and their degree is determined by workers' relative skills and age. Third, a faster transition generally increases the mass of workers who benefit from the transition, but generates a thicker tail among those who lose, presenting a trade-off for policymakers. As we will soon see, labor market frictions

[21] The region to the right of 2060 represents a slower transition than baseline. Slowing down the transition also changes the share of winners and losers, as well as the degree to which they lose, reflecting that those who would prefer a faster transition are also locally harmed by a slower one.

amplify these findings.

These insights are applicable to settings in which demand falls for one set of jobs and rises for another. Our setup nests scenarios where one technology becomes obsolete and is taken over by another more productive one (Aghion and Howitt, 1992; Violante, 2002), or trade shocks that induce a reallocation of labor (Dix-Carneiro, 2014; Dix-Carneiro et al., 2023; Traiberman, 2020), and our conceptual insights appear portable to these contexts.

These conclusions are unaffected by whether workers anticipate the future path of A_t^k. In this frictionless benchmark, workers make decisions based solely on the current level of A_t^k. Thus, the non-monotonic relationship between lifetime earnings and the transition horizon will continue to hold qualitatively even if agents are uncertain about the future path of A_t^k.

While we have focused on the role of the transition horizon T, similar economics hold if government intervention also affected A_∞^k. Broadly, three objects matter for a worker's lifetime income: the scale of the earnings decline experienced in the D sector, the scale of the earnings increase in the C sector, and the timing the worker switches sectors. If intervention amplifies the difference between A_∞^D and A_∞^C, this would affect the path of A_t^k in a similar manner to increasing η in the short-run, and so generate similar effects on lifetime earnings as changing the transition horizon.

Before proceeding, it is worth discussing the interpretation of our A_t^k. The paths of A_t^k reflect firms' incentives to employ workers using the creating and declining technologies, respectively. Empirically, these two technologies might co-exist in the same industry. For instance, a manufacturer of ICE vehicles may begin producing EVs and the two technologies can co-exist within the firm. In practice, technology adoption leads to substantial worker displacement even within the same firm: the transition from ICE towards EVs requires substantial retraining among auto workers and has already resulted in layoffs at auto manufacturers.[22] Braxton and Taska (2023) find that technology adoption leads to displacement and substantial

[22] Conventional cars use many components that are not present in EVs and vice versa, such as catalytic converters, fuel tanks, engines, and batteries, which all rely on skills that are not directly portable between EVs and ICEs. See, for example, the substantial layoffs at Ford, while Volkswagen workers are being retrained to build EVs. Meanwhile, the European Association of Automotive Suppliers projects half a million jobs will be lost from an EV transition, while the the Economic Policy Institute similarly projects large layoffs in the US (accessed July 2, 2025).

earnings losses for incumbent workers who do not possess the right skills; Kogan et al. (2020) document a higher separation risk in industries that innovate more, as workers' skills become obsolete more rapidly. This dynamic also appears to play out in the climate context: climate-friendly regulations lead to layoffs (Greenstone, 2002; Walker, 2011) and green jobs tend to require more cognitive skills and experience (Consoli et al., 2016; Marin and Vona, 2019).

Overall, the evidence supports that the labor reallocation across technologies is costly as we have assumed in our setup, including for the climate transition. One can think of the A_t^k as the penetration of each technology in the economy and the incentives to hire workers to operate these technologies, and $\hat{\psi}$ as the relative ability of workers to operate these technologies. Our model captures the idea that workers with a high $\hat{\psi}$ are more likely to operate the C technology by switching employers. The same would be true if the firm could choose to reallocate workers to the C technology on-the-job.[23]

5 The Role of Labor Market Frictions

This section shows that labor market frictions quantitatively amplify the labor market effects of accelerating a transition. We therefore augment the model of section 2 with a realistic labor market block and calibrate it to match a number of steady state moments. We maintain the preferences, technologies, government, and financial market specifications of section 2; only the labor market block changes.

5.1 A Realistic Labor Market

Skill accumulation. Workers have multi-dimensional skills that accumulate endogenously. There is a general skill ψ^G, which applies to all pursuits, and specific skills ψ^D and ψ^C which apply to one sector only. Workers' overall productivities in declining and creating sectors are $\psi^G\psi^D$ and $\psi^G\psi^C$, respectively. Workers are endowed with a unit of general skill $\psi^G \equiv 1$ at birth and one unit of specific skill

[23] It is costly for the firm to familiarize the worker with the clean technology and production process regardless of whether the worker is reallocated on-the-job or is hired from outside the firm. These costs are a large component of a workers' hiring ν in practice (Muehlemann and Strupler Leiser, 2018). Whether the switch takes place within or across firms is irrelevant if reallocation within the firm requires an internal job posting with the same matching technology f.

$\psi^D \equiv 1$ in the declining sector. They are endowed with a heterogeneous C-specific skill at birth $\psi^C \sim G$. After this initial endowment, workers accumulate the general skill ψ^G at rate δ_j^+ when employed in the declining or creating sectors, δ_j^O in the outside sector, and $\delta^U < 0$ when unemployed. Specific skills ψ^D and ψ^C grow at rate $\hat{\delta}$ when employed in the corresponding sector. In the following, we will establish that we can keep track of a reference skill $\psi \equiv \psi^G \psi^D$ and a relative skill $\hat{\psi} \equiv \psi^C / \psi^D$ instead of ψ^D, ψ^G and ψ^C separately. Workers' productivity $h\left(\psi, \hat{\psi}, k\right)$ is then defined as in equation (2.2).

Labor services. A continuum of atomistic firms in each sector each hires one worker to produce labor services. They sell their labor services to intermediate goods firms at price $\mathcal{P}_t^k$ which they take as given. The labor services produced by a firm is equal to the skill of the worker that they hire $h\left(\psi, \hat{\psi}, k\right)$. The total labor units sold to sector k is given by $n_t^k = \int h\left(\psi, \hat{\psi}, k\right) d\mu_t^k\left(\psi, \hat{\psi}\right)$ where $\mu_t^k\left(\psi, \hat{\psi}\right)$ is the measure of workers employed in a sector k labor services firm in period t with skills $\left(\psi, \hat{\psi}\right)$.

Directed search. Workers and labor services firms search for each other in frictional labor markets. Search is directed, as in Menzio and Shi (2011), within and across sectors. Workers search for jobs with intensity $\lambda^U > 0$ off-the-job and $\lambda^E > 0$ on-the-job, giving rise to a job-ladder in the polluting and clean sectors. Labor markets in the declining and creating sectors are indexed by a worker's age j, their skills $\left(\psi, \hat{\psi}\right)$, the sector k, and the wage rate w that workers and firms agree on throughout the duration of the match. We abstract from renegotiation in w since wages rarely fall on-the-job in practice (Grigsby et al., 2021) and discussions about pay cut rarely take place even if they could save jobs (Davis and Krolikowski, 2025).[24] The wage rate w is paid for each unit of effective labor $h\left(\psi, \hat{\psi}, k\right)$ that they supply, and effective wages are indexed by the growth rate $g^\star$ that prevails along the balanced-growth paths. Employed workers therefore earn $wh\left(\psi, \hat{\psi}, k\right) \exp\left(g^\star t\right)$ and firms claim the rest of revenues.

To rationalize the fact that job switches often entail wage cuts (Sorkin, 2018) and there are gross flows across occupations and sectors (Moscarini and Thomsson, 2007; Pilossoph, 2014; Caliendo et al., 2019), we allow for search to be imperfectly

[24] Wage rigidities are an important feature to explain employment dynamics during sectoral reallocations (Rodriguez-Clare et al., 2025).

directed, as it is in practice (Wu, 2024). Accordingly, we suppose that a worker of type $\mathbf{x} \equiv \left(j, \psi, \hat{\psi}\right)$ in market $s \equiv (k, w)$ searches in a market s' with probability

$$p_t\left(s'; \mathbf{x}, s\right) \equiv \frac{\exp\left(f\left(\theta_t\left(\mathbf{x}, s'\right)\right)\left[W_t\left(\mathbf{x}, s'\right) - W_t\left(\mathbf{x}, s\right)\right]/\zeta\right)}{\sum_{\hat{s}} \exp\left(f\left(\theta_t\left(\mathbf{x}, \hat{s}\right)\right)\left[W_t\left(\mathbf{x}, \hat{s}\right) - W_t\left(\mathbf{x}, s\right)\right]/\zeta\right)}, \tag{5.1}$$

where the sum is over the sectors $k = D, C$ and wages $w \in \{w_1, \ldots, w_N\}$, as well as the outside sector O and unemployment U.[25] Worker are more likely to search in a given market s' if the expected improvement in its value is larger. This search behavior can be microfounded by introducing idiosyncratic amenity shocks that are distributed i.i.d. according to a Type-1 Extreme Value distribution with scale parameter ζ (Artuç et al., 2010) or by assuming that workers have to acquire costly information about the jobs that they apply to (Matêjka and McKay, 2015).[26] The parameter ζ captures the degree to which search is directed: search is purely directed as $\zeta \to 0$ as in canonical directed search, and purely random when $\zeta \to \infty$.[27] Matches are destroyed exogenously at rate $\chi > 0$.

Firm entry. A constant returns to scale matching function yields a job-finding probability for workers $f(\theta)$ within each market, where θ is market tightness defined as the ratio of vacancies to job-seekers and f is increasing and concave. The corresponding job-filling probability for firms is $q(\theta) \equiv f(\theta)/\theta$ which decreases with θ. Let $V_t\left(j, \psi, \hat{\psi}, s\right)$ denote the value to a firm employing a worker of age j and with skill in market s. Firms post vacancies for a worker with reference skill ψ at a cost $\nu\psi \exp(g^\star t) > 0$, where ν represents both a vacancy and expected hiring cost. This cost grows at rate $g^\star$ to ensure that the economy admits a balanced-growth path. There is free entry in each market s so that

$$q\left(\theta_t\left(j, \psi, \hat{\psi}, s\right)\right) V_t\left(j, \psi, \hat{\psi}, s\right) \leq \nu\psi \exp\left(g^\star t\right) \tag{5.2}$$

[25] We discretize the grid for wages, for numerical convenience. The continuous case obtains when $N \to +\infty$. We allow for a relatively fine grid for wages in our numerical implementation. We suppose that workers only search in markets with positive vacancies.

[26] The first formulation would increase workers' values by allowing them to enjoy job-specific amenities. On the contrary, the second would decrease them by assuming that workers have to acquire costly information. We follow Traiberman (2020) and do not include the amenity value or information processing cost in workers' values since we focus on earnings changes.

[27] Firms know the characteristics of the worker they are matching with, which preserves the block-recursive nature of the equilibrium (as in Menzio and Shi, 2011).

in every period t, with equality if a positive measure of vacancies are posted.

Outside sector and unemployment. The rest of the economy is unaffected by the transition. Workers receive an income of $\psi b^O \exp(g^\star t)$ of final goods in the outside option, and of $\psi b^U \exp(g^\star t)$ when they are unemployed, for $b^U \geq 0$ capturing unemployment benefits. We think of the outside option as capturing retirement and jobs that workers can find relatively easily with limited scope for professional progression. For this reason, we assume that jobs in the outside sector have an exogenous job-finding probability of f^O conditional on search and we abstract from the job-ladder in this outside option. Workers can freely transition to unemployment when given a search opportunity. New cohorts ($\tau > 0$) are born unemployed.

Recursive Formulation and Equilibrium. We state workers' and firms' values recursively in Appendix B.1. We define the equilibrium formally in Appendix B.3. The labor market block of the model satisfies a block recursive equilibrium as is standard in this class of directed search models (Menzio and Shi, 2011). Finally, we establish in Appendix B.4 that the values are linear in $\psi \exp(g^* t)$ which allows us to track *only* the relative skill $\hat{\psi} \equiv \psi^C / \psi^D$ as an explicit state variable when characterizing values, making the model and its estimation computationally manageable.[28] We continue to focus on the case with risk-neutral workers. The search decisions made by workers, and thus the total earnings impact of the transition, would be the same if workers were risk-averse ($\sigma > 0$) but faced complete markets for idiosyncratic risk: that is, they could trade contingent securities against all idiosyncratic risks of job-finding or separations. In both cases, workers value the present discounted value of earnings, which will be our main object of interest.

The frictionless economy of section 2 is obtained as a limit of this model in which search is perfectly directed ($\zeta \to 0$), vacancy posting is free ($\nu \to 0$), unemployment pays less than employment ($b^U \leq A^D_\infty$) and skills are fixed over workers' lives ($\delta^+_j = \delta^O_j = \delta^U = \hat{\delta} = 0$). Proposition 1 continues to hold in this economy, as we prove in Appendix B.7.

[28] Economizing the state variable ψ is possible because the vacancy posting costs scale with ψ.

Table 1: External calibration

Parameter	**Description**	**Value**	**Source**
J	Lifespan	40	Career length
ρ	Discount rate	0.03	3% Interest Rate
α	Elast. of matching function	1.45	Schaal (2017)
δ_j^+	General Skill Accum.	Wage Profiles	CPS ORG
δ^U	Skill Decum.: Unemployed	-0.096	Schmieder et al. (2016)
δ^O	Skill Accum.: O sector	0	Growth of Economy

5.2 Calibration

External Calibration. A unit length of time corresponds to a year. Workers live for 40 years ($J = 40$) and we set the discount rate $\rho = 0.03$. Following Den Haan et al. (2000), we parameterize the matching function so that the job-finding and job-filling rates are given by $f(\theta) = (1 + \theta^{-\alpha})^{-1/\alpha}$ and $q(\theta) = (1 + \theta^{\alpha})^{-1/\alpha}$, respectively, with $\alpha = 1.45$ as in Schaal (2017).

Turning to skill accumulation, we directly measure the rate $\delta_j^+ + \hat{\delta}$ in the CPS using on-the-job wage growth among workers attached to polluting sectors before the transition starts. Workers' in the outside income see income increases at the same rate the economy grows, so we set $\delta_j^O = 0$. Finally, we let $\delta_j^U = -0.096$, corresponding to a 0.8% loss in human capital per month of unemployment following evidence from Schmieder et al. (2016).

Internal Calibration. The search intensity for unemployed workers λ^U targets a monthly UE rate of 25% (Shimer, 2005), while the search intensity for employed workers λ^E targets a monthly EE rate of 2.5% (Fujita et al., 2024). The degree of noise in search ζ replicates the fact that 30% of job-switchers experience a wage cut (Grigsby et al., 2021).[29] We obtain a standard deviation of 0.075, which is small relative to average flow wages.

We set the vacancy posting cost ν to match an average markdown of 20%, (Berger et al., 2022). This is a natural moment to target: if vacancy posting costs are high, firm values must also be high for the free entry condition (5.2) to hold, which pushes for a higher markdown. The markdown plays a key role in the model: it

[29] Tjaden and Wellschmied (2014) and Sorkin (2018) report very similar numbers.

Table 2: Calibration

Parameter	Description	Value	Moment	Source	Target	Model
Search						
λ^U	Search intensity (U)	5.974	UE rate (M)	Shimer (2005)	25%	25%
λ^E	Search intensity (E)	1.185	EE rate (M)	Fujita et al. (2024)	2.5%	2.5%
ζ	Search Directedness	0.035	Share of wage cuts	Grigsby et al. (2021)	30%	30%
Job creation & destruction						
ν	Vacancy post. cost	0.437	Average markdown	Berger et al. (2022)	20%	20%
χ	Job destruction rate	0.07	Unemployment rate	-	5%	5%
Benefits and Skill						
b^O	Benefit in O	0.642	Wage change (EUO)	CPS ORG	-16%	-16%
b^U	Benefit in U	0.343	Average UI replac.	US UI rules	40%	40%
$\hat{\delta}$	Specific Skill Accum.	0.0012	Net Reall. $D \to C$ by age	CPS	–	–

determines the profitability of each job, and hence firms' incentives to create vacancies and fire workers along the transition. We obtain a vacancy posting cost of 16.5% of annual output, which is around the estimate of Shimer, 2005. We choose the separation rate χ to match a steady state unemployment rate of 5%.

The unemployment benefit b^U is chosen so that workers who get laid off have an average replacement rate of 50% as a share of their previous wage, reflecting a mix of home production and unemployment insurance. We obtain $b^U = 0.350$ which reflects the fact that workers' wages are less than 1 in equilibrium.

The two remaining parameters will be application-specific, and we choose them to be in line with our climate application of section 6. We choose the flow payoff of the outside option b^O by targeting the mean wage change of workers initially attached to dirty industries who undergo an E-U transition followed by a U-E transition to any outside sector in consecutive years of the CPS Outgoing Rotation Group (ORG) supplement. Workers on average experience a 10% decline in hourly wages and 22% decline of weekly earnings following such a transition; we target the midpoint of this range: -16%. This leads us to estimate $b^O = 0.538$, and motivates why we set $A^D_\infty = 0.84$ in our baseline scenarios so that workers are indifferent, on average, between the outside option and the D sector in the long-run. Finally, we

choose the rate at which workers accumulate specific skills $\hat{\delta} = 0.0012$ to match the age gradient of net reallocation of dirty-attached workers to the clean sector over time, as described in depth in section 6.2. Section 6 provides more details on the climate application, including how we define clean and dirty sectors.

5.3 The Role of Frictions

The left panel of Figure 5 recreates the analysis of Figure 3 in our full model for different levels of endowed $\hat{\psi}$.[30] One can see that the strong non-linearities and non-monotonicities emphasized in section 4 survive in the full model. Comparing the magnitudes of the earnings changes from transitions of different speeds with those in Figure 3, one can see that earnings changes are often quite different in the full model than in the frictionless limit.

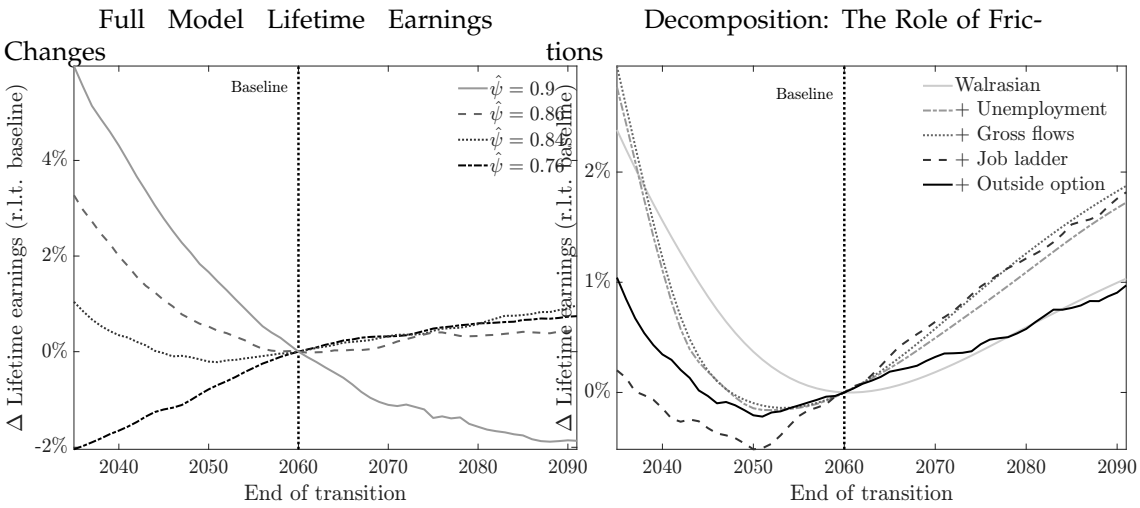
The right panel of 5 explicitly compares the earnings losses in the full model (solid black line) against a benchmark Walrasian model with skill accumulation (solid gray line) for a worker with endowed $\hat{\psi} = 0.84$ and 20 years of remaining working life. Comparing these two solid lines reveals that labor market frictions substantially reduce the gains from accelerating the transition relative to the status quo for this worker: while a transition ending in 2040 would increase this worker's lifetime earnings by around 1.5% in the frictionless model, it only marginally increases lifetime earnings in the full model. Indeed, the sign of the earnings change even flips for some transition speeds. In other words, the additional features of our full model — namely, search frictions, gross flows, job-ladders, and outside options — are important to assess the labor market implications of accelerating a technological transition.

The frictionless benchmark is nested in the full model when workers labor markets are not frictional, search is perfectly directed, there are no job-ladders, and the outside sector is not valuable. The right panel of Figure 5 decomposes the forces introduced by the full model by progressively adding these features to the model, starting from the frictionless benchmark.[31] There are four lines in addition to the

[30] Since workers of a given age and skill may be employed in multiple different markets, we must choose an initial market to construct this plot. Here we assume workers enter 2025 unemployed. We produce this plot averaging over the equilibrium distribution of employment in Appendix Figure 15, after we have estimated the distribution of skill endowments $G\left(\hat{\psi}^{\text{endow}}\right)$ for our climate application.

[31] Appendix Figure 11 repeats this decomposition for workers with $\hat{\psi} = 0.76$ and 0.86.

Figure 5: The Role of Labor Market Frictions



Notes: The left panel plots workers' average lifetime earnings changes in 2025 in our full model as a function of the transition horizon, for various values of the productivity $\hat{\psi}$ in the clean sector. All earnings changes are relative to the baseline transition ending in 2060, and faster transitions are parameterized as in equation (3.4). The horizontal axis corresponds to the end date of the transition considered. All workers have 20 years remaining in their careers. We consider workers who are unemployed as of January 2025. The right panel decomposes these earnings changes for a worker with productivity $\hat{\psi} = 0.84$ in the creating sector. The solid gray line corresponds to our frictionless benchmark from Section 2, augmented with skill accumulation. The other lines add one feature after another until we obtain our full model corresponding to the solid black line.

frictionless benchmark, reflecting the four reasons why the full model may differ.

First, the model with labor market frictions introduces the possibility of structural unemployment. This is isolated by the gray dash-dot line, which adds a simple frictional labor market: search is perfectly directed by unemployed workers, but there is no outside option or on-the-job search (i.e. $\lambda^U > 0$, but $\zeta \to 0, \lambda^E = 0, b^O = 0$). Firms only post vacancies if they expect to recoup the costs of doing so. Therefore, job-finding rates gradually fall in the D sector, and fall faster if the transition accelerates. This decline is offset by increases in vacancy posting in the creating sector. However, vacancies are only posted in the C sector for those with the skills to work in that sector. Therefore, low-$\hat{\psi}$ workers face an unpleasant choice: they may either search for a shrinking set of jobs in the declining sector, or they can seek a near-unattainable job in the growing sector. These workers may thus experience long-term structural unemployment and large lifetime earnings losses, which are compounded by loss of general human capital while unemployed. On the other hand, high $\hat{\psi}$ workers see ever-growing job finding rates in the clean sec-

tor, and thus spend less and less time unemployed as the transition continues. Accelerating the transition thus generates different effects on high and low $\hat{\psi}$ workers through this unemployment margin, which introduces its own non-linearities.

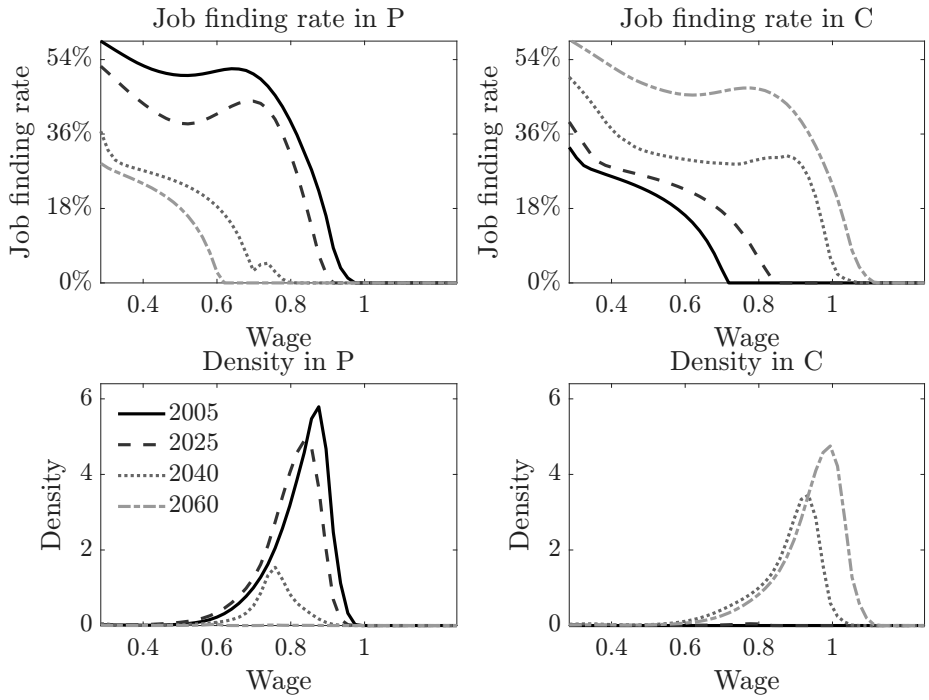
Second, workers' search behavior differs in the full model due to partially directed search and gross flows. Comparing the dash-dot to the dotted line, which adds partially directed search and thus gross flows ($\zeta > 0$), isolates the role of gross flows and finds it to be minimal. Although gross flows are substantially larger than net flows in both model and data, the effects of accelerating the transition are not strongly impacted by gross flows.

Third, labor market frictions generate endogenous movements in the wages of employed workers due to workers' ability to climb the job-ladder. The dashed line adds on-the-job search to the model ($\lambda^E > 0$), giving rise to a job-ladder. As the transition unfolds, not only do firms post fewer vacancies in D in total, but they particularly post fewer vacancies at high wages. As a result, it becomes increasingly difficult to find high-wage jobs in the declining sector. On the other hand, firms become gradually more willing to post high wage jobs in the creating sector, at least for workers with high $\hat{\psi}$. These dynamics endogenously determine the ease with which workers can climb the job-ladder in each sector. The more rapid the transition, the more rapidly will the job-ladder collapse in the declining sector and expand in the creating sector, which amplifies the losses for low $\hat{\psi}$ workers and gains for high $\hat{\psi}$ workers. This force appears quantitatively important in Figure 5.

To visualize these job-ladder effects, the top row of Figure 6 plots the job-finding rate across the wage distribution in the declining (left column) and creating (right column) sectors in the full model for a worker with 20 years of working life remaining and $\hat{\psi} = 0.84$. The four lines indicate the job finding rates in different years over the course of the status quo transition, beginning from the beginning of the transition in 2005 (solid black line) to the year of government's first intervention in 2025 (dashed line), a later year in the transition 2040 (dotted line) and in the final steady state of 2060 (dash-dotted line). The figure shows that the job-finding rate falls in the declining sector at every wage level. But the decline is most pronounced in high wage markets, with the top markets closing entirely. The opposite occurs in the creating sector, with expanding vacancy posting at every wage, especially at the top.

Movements in these job-finding rates and workers' optimal search behavior

Figure 6: Job finding rates and the wage distribution



Notes: The first row plots the job finding rate as a function of the wage posted by firms in various periods, for workers born with relative productivity $\hat{\psi} = 0.84$. The second row plots the equilibrium distribution over such wages, for the same periods and the same relative productivity. The first column corresponds to the dirty sector, and the second to the clean sector.

yield the wage distributions plotted in the bottom row of Figure 6. Over time, the wage distribution shifts left in the declining sector, and right in the creating sector. Furthermore, workers gradually leave the D sector to join the C sector, as can be seen by the declining mass of workers in D and rising mass in C.

Accelerating the transition causes these shifts to occur faster, both because A_t^k shifts faster, and through anticipation effects as workers and firms anticipate future job search, vacancy posting, and human capital accumulation.[32] Whether these effects lead to larger or smaller costs of accelerating the transition depends on a worker's skill $\hat{\psi}$ and the amount of time left to climb the ladder before retirement.

The final force in the full model is the presence of an outside option. Moving from the dashed to the solid line in the right panel of Figure 5 shows that the outside option ($b^O > 0$) mitigates the losses associated with a rapid transition. This is because the outside option is unaffected by the transition. Thus, as good jobs be-

[32] The strength of this anticipation effect would be muted if there was uncertainty about the future path of A_t^k. However, the forces arising from the level of A_t^k apply regardless of uncertainty.

come harder to find in the declining sector, more workers take the outside option which remains steadily available, mitigating the prevalence of structural unemployment. Although this outside option sector itself brings potentially substantial losses, it is better than the alternative of prolonged structural unemployment, and so mitigates the costs of accelerating the transition. Indeed, the lowest $\hat{\psi}$ workers eventually become relatively insensitive to the transition speed, as they will seek employment in the outside option immediately irrespective of marginal changes in the transition horizon.

Overall, our full model offers an additional conceptual takeaway relative to the frictionless benchmark: labor market frictions are a key determinant of the earnings effects of the transition. Since firms only post vacancies in the clean sector if workers are sufficiently productive to help them recoup their hiring and operating costs, workers with low skill in the clean sector will experience larger earnings losses than predicted by the frictionless model both due to structural unemployment and a declining job ladder. Along with the conceptual insights established in section 4, the takeaways of this section appear portable to a variety of transitions.

6 Application to the Climate Transition

Studying how the pace of the transition affects workers is especially important in the context of the climate transition. A faster transition carries direct environmental benefits which increase the incentives to accelerate it, and our paper studies on the labor market implications of doing so. The transition will also be sizable, affecting 10-15 million workers in dirty industries, and quick relative to other transitions such as the structural transformation from manufacturing to services, as it is expected to unfold over 35 years or so.

6.1 Sector Definitions and Path of MRPLs

Sector Definitions. We follow the 2024 OECD employment report (Bassanini et al., 2024) in defining "Dirty" industries as 6-digit NAICS industries in the top decile of emissions intensities. Examples of industries classified as dirty include "Petroleum refineries" and "Industrial gas manufacturing." Using this definitions, 11.4 million workers were employed in the dirty sector as of 2004Q4, according to the Quarterly

Census of Employment and Wages (QCEW). We define dirty-attached workers as those employed in the Dirty sector for the entirety of their first 4-month wave in the Current Population Survey (CPS).

We define clean sectors as those that produce green goods following Bontadini and Vona (2023). This approach only permits goods-producing sectors to be clean. Therefore, we supplement this output-based approach with the task-based approach employed by the US Energy Employment Report (Granholm, 2024) and additionally consider sectors to be clean if a majority of its workers are engaged in green tasks according to the BLS' Green Goods and Services (GGS) survey. Examples of clean industries are "Materials recovery facilities" (i.e. recycling) and "Primary battery manufacturing." Appendix D provides more information on all aspects of our sector definitions.[33]

Paths of A_t^k. We parameterize the transition function $\bar{\Phi}^k(t)$ as truncated normal CDFs with mean μ and standard deviation σ. We fit μ and σ to match data and forecasts from the U.S. Energy Information Administration (EIA) on the share of power generated by fossil fuels and renewable sources between 2005 and 2050. As Appendix Figure 10 shows, the estimated curve fits the raw data well.

It is worth reiterating that our analysis is *prospective*. There is thus uncertainty regarding long-run changes that have yet to occur. We test the sensitivity of our results under a menu of scenarios for long-run labor demands A_∞^k; no individual estimate should thus be taken as definitive. Our baseline scenario assumes symmetric 16% changes in productivity, such that workers are indifferent between the outside sector and the dirty sector in the long run: $A_\infty^C = 1.16$ and $A_\infty^D = 0.84$.

6.2 Estimating the Skill Distribution

Applying our framework to a particular episode requires one additional input relative to the steady state calibration of Section 5.2: the distribution of skill endowments $G\left(\psi^C\right)$.[34] We now estimate the set of skills that best matches realized reallo-

[33] In the CPS, we attribute a share of dirty manufacturing to clean over time in proportion to the share of cars sold which use alternative fuels. We do this both to capture technology adoption over time, and because the CPS has less granular industry codes than 6-digit NAICS.

[34] Since all workers are endowed with one unit of general and polluting sector skill, one can equivalently conceptualize $G(\cdot)$ as the distribution of relative skill $\hat{\psi}$ at birth, which we term $\hat{\psi}^{\text{endow}}$.

cation of workers in the early phase of the transition, conditional on the assumed scenario for labor demands $A_{k,t}$. More details are provided in Appendix D.

Identification. We identify the distribution of skill endowments non-parametrically by matching the observed labor reallocation between the dirty and clean sectors over the period 2005–2025. The idea is best understood by inspecting the left panel of Figure 2. In the frictionless benchmark of Section 4, workers reallocate only if $\hat{\psi} \geq A_t^D / A_t^C$, so the share of workers who have already switched by period t is $1 - G\left(A_t^D / A_t^C\right)$. Labor reallocation over time therefore allows us to trace the distribution $G\left(\hat{\psi}\right)$ non-parametrically given the paths for A_t^k.[35] Of course, the process of labor reallocation is richer in our full model: workers differ in their employment statuses and skill accumulation histories, reallocation is frictional and search is imperfectly directed.[36] However, the same principle applies in our model, allowing us to estimate the endowment distribution G.

To disentangle the distribution of endowments $G(\cdot)$ from skill accumulation $\hat{\delta}$, we compare two cohorts born in different periods. The older cohort has spent more time in the dirty sector by 2005, and thus will have accumulated more skills specific to D. As a result, they have lower $\hat{\psi}$'s and reallocate to the clean sector slower, as in the data.

Threats to Identification. In our model, workers reallocate on the basis of their relative productivity $\hat{\psi}$ and the sectoral productivities A_t^k. One possible concern is that workers could also reallocate for amenity reasons: they enjoy supplying labor to the clean sector. We argue that this distinction is unimportant in our context. To understand why, consider the frictionless model of section 4, augmented to allow for amenities. Specifically, suppose that the flow payoffs from working in the clean sector are $A_t^C \Lambda_t \hat{\psi} \xi$, where ξ is an idiosyncratic component of the relative amenity and Λ_t is an aggregate component of the relative amenity. Workers supply labor to

[35] We consider a menu of terminal values A_∞^k in our analysis. Different terminal values generate different paths for relative productivities A_t^P / A_t^C, which in turn changes the estimated distribution $G\left(\hat{\psi}\right)$ in order to match the data. However, we only match reallocation patterns from 2005-2025 for estimation of $G(\cdot)$. The long-run behavior of reallocation will still depend on the exact choice of A_∞^k given our time-invariant estimated distribution of skill endowments.

[36] Absent noisy search, workers with skill $\hat{\psi}$ below a certain cutoff do not reallocate by 2025; as a result, the distribution would not be identified below this cutoff. The presence of amenity shocks circumvents this issue by assuming that all workers have a positive probability to reallocate.

the clean sector if and only if the product of their idiosyncratic productivity $\hat{\psi}$ and their relative amenity ξ in the clean sector are sufficiently large relative to the relative sectoral productivities and the aggregate amenity, i.e., $\hat{\psi}\xi \geq A_{P,t}/\left(\Lambda_t A_{C,t}\right)$. This condition is isomorphic to the one in Section 4, when setting

$$\hat{\psi}' \equiv \hat{\psi}\xi \quad \text{and} \quad A_t^{C\prime} \equiv \Lambda_t A_t^C$$

Accordingly, the paths of A_t^k also reflect the relative amenity value of supplying labor in the clean sector. Given this path, our estimation backs out the distribution of $\hat{\psi}\xi$ which determines workers' incentives to reallocate and values.

The dynamic is more complicated in the full model, where agents are forward-looking and labor markets are frictional, but the same economics hold: if workers prefer to work in the clean sector, they accept lower wage payments. This leads to higher firm values, exactly as if they were more skilled in that sector. Thus the distinction between amenities and productivity is not crucial for understanding the labor market effects of the climate transition in our context, so long as one is willing to interpret our estimates as a broader measure of worker well-being which includes amenities. Besides amenities, our estimates of $\hat{\psi}$ also capture other forms of reallocation costs, e.g., due to geographic mobility between employers.

Estimation. The estimation problem is to choose a distribution G and rate of specific skill accumulation $\hat{\delta}$ to solve

$$\min_{G,\hat{\delta}} \sum_{\tau} \int_{2005}^{2025} \left(z_{\tau,t}^{\text{data}} - \int_0^1 z_{\tau,t}^{\text{model}} \left(\hat{\psi}^{\text{endow}}; \hat{\delta} \right) G \left(\mathrm{d}\hat{\psi}^{\text{endow}} \right) \right)^2 dt, \tag{6.1}$$

where $z_{\tau,t}^{\text{data}}$ indicates the empirical share of workers in cohort τ that have reallocated between period 0 and t and $z_{\tau,t}^{\text{model}}\left(\hat{\psi}^{\text{endow}}; \hat{\delta}\right)$ is the share of workers in the same cohort and endowed with skill $\hat{\psi}^{\text{endow}}$ that have reallocated over the same period in the model.[37] The latter is a function of specific skill accumulation $\hat{\delta}$. We measure $z_{\tau,t}^{\text{data}}$ as the share of workers initially attached to dirty industries that reallocated to the clean sector in the CPS, relative to the share of employment in clean

[37] Comparing wages in the model and in the data would necessitate tracking workers' absolute advantage ψ, since wages in the data are subject to composition effects. Studying wages would thus necessitate estimating a joint distribution of ψ^P and ψ^C, drastically complicating the estimation.

or dirty in 2005.[38]

We leverage the block recursivity of our directed search model (Menzio and Shi, 2011) to solve problem (6.1) efficiently. This property allows us to solve workers' reallocation shares $z^{\text{model}}_{\tau,t}\left(\hat{\psi}^{\text{endow}};\hat{\delta}\right)$ *independently* from the distribution G.[39] Problem (6.1) thus amounts to solving for the distribution G given these optimal policies and a guess of $\hat{\delta}$, then updating our guess of $\hat{\delta}$ until convergence. We provide more details in Appendix C.

The distribution of skills $G\left(\hat{\psi}\right)$ is chosen to match the average reallocation of workers who were between the age of 25 and 40 years old when the transition began in 2005. The approach is illustrated by the left panel of Figure 7. The empirical reallocation of workers attached to dirty sectors is depicted by the solid black line. Roughly 10% of these workers had reallocated to clean industries by 2025. Each of the dotted lines correspond to model-implied net reallocations of workers with a different endowment of $\hat{\psi}$, fixing a value of $\hat{\delta}$. Block recursivity implies that the reallocations of each $\hat{\psi}$ can be solved for independently. The reallocation patterns of workers with different $\hat{\psi}$ have different shapes and do not overlap; thus one can identify the share of workers within each bin. The estimation problem then consists of choosing the weights on the dotted lines in order to best match, which can be done efficiently by projecting the model reallocations onto the data with an OLS regression that constrains the sum of coefficients to 1.

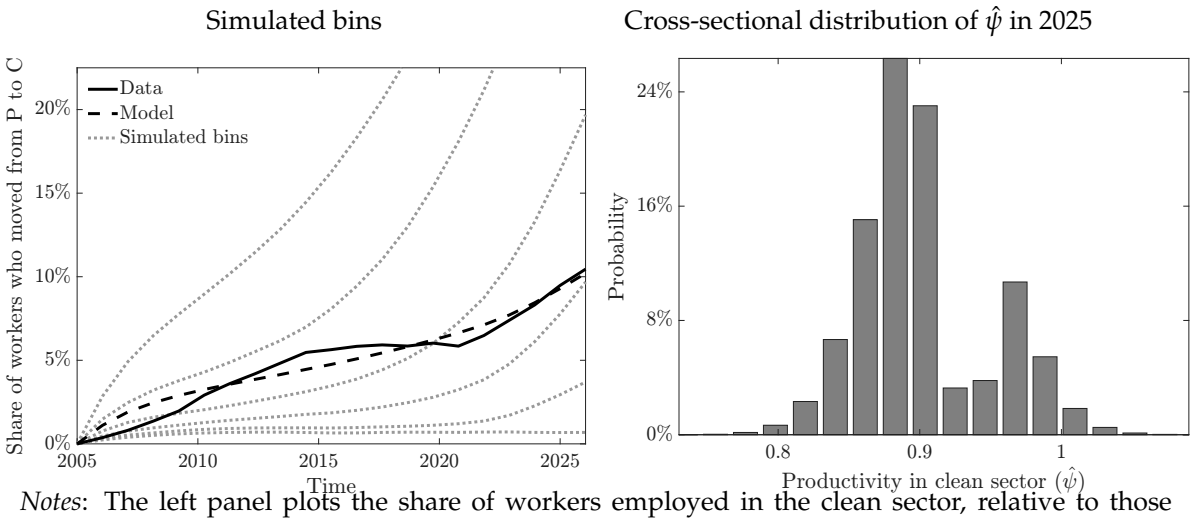
Note that workers with extremely low $\hat{\psi}$ will never reallocate. All such workers have identical earnings losses from the transition regardless of its speed. We thus normalize the level of $\hat{\psi}$ for these never switchers to 0 and choose the mass of these "never-switchers" such that employment in C is twice that in D in the long-run steady state, which is in line with the wide range of estimates in the literature, and test sensitivity to this choice.[40]

[38] The CPS does not allow us to track workers over long periods. We therefore weight individuals in later waves of the CPS by the probability that they would have been attached to the polluting sector in the pre-2005 period according to their observables. Appendix D provides more details.

[39] Recall that general equilibrium effects on, say, innovation rates or the relative price of clean sector goods are accounted for by the path of A^k_t and can be freely counteracted by appropriate government policy (Proposition 1).

[40] In brief, IRENA (2023) estimates that, by 2050, between 27.9% and 85.8% of energy sector will be "clean" depending on what one assumes about the other transition-related sectors such as grid improvement. Other studies by McKinsey & Company (2022) and Mayfield et al. (2023) estimate numbers within this range. Most studies find only small impacts on the total level of employment in the economy (Finkelstein Shapiro and Metcalf, 2023; Borgonovi et al., 2023)

Figure 7: Estimation of the skill distribution



Notes: The left panel plots the share of workers employed in the clean sector, relative to those employed either in the clean or polluting sectors. Workers are weighted by the probability that they are attached to the polluting sector, based on their observables and pre-2005 relationship between those observables and the likelihood of being attached to the polluting sector. We pool the two cohorts used for the estimation (born in 1960 and 1975) for legibility. The solid curve is the data from the CPS. The dotted curves correspond to simulated bins associated to various values of $\hat{\psi}^{\text{endow}}$ under the estimated $\hat{\delta}$. The dashed curve corresponds to the model-generated reallocation when using the estimated distribution of $\hat{\psi}^{\text{endow}}$. The right panel plots the cross-sectional distribution of relative productivity $\hat{\psi}$ in the population in 2025.

We repeat this exercise for a variety of values for $\hat{\delta}$ and choose the value that best matches the reallocation patterns of the workers aged 25-30 years old versus 35-40 years old as of 2005, which we plot in Appendix Figure 13. Model-implied reallocation under the estimated distribution matches the data well, as can be seen by the dashed line in the left panel of Figure 7.

The right panel of Figure 7 plots the cross-sectional distribution of relative skills $\hat{\psi}$ as of 2025 induced by our estimates of G and $\hat{\delta}$, conditional on $\hat{\psi} > 0$. The distribution generally shows two types of workers. First, there is a mass of workers who have relatively high skill in the clean sector (above 0.95). These are the workers who reallocate quite quickly in the data. There is also a mass of workers with substantially lower skill in the clean sector who are much less likely to reallocate given the productivity gap across sectors. The estimation requires a mix between these two types to rationalize the slow start in labor reallocation and its recent uptick. Roughly 55% of workers are never-switchers.

Aside from the many steady state moments discussed in section 5.2, the model

replicates a number of features of labor markets specific to the climate application. The model is able to reproduce the reallocation to C of workers attached to the dirty sector, both overall and by cohort. It additionally replicates flows of these workers to the O sector: net flows to the C sector are much smaller (less than 1% per year) than gross flows between sectors (around 2.5% per month) in both data and model. In the model, the probability of experiencing an E-E switch from the dirty to the outside sector is 0.3% per month in steady state and 0.5% in 2025. In the data, those numbers are 0.4% before 2005 (specifically 1996-2005) and 0.5% in 2025. Thus our model matches flows between C, D and O well.

6.3 Earnings Losses from the Climate Transition

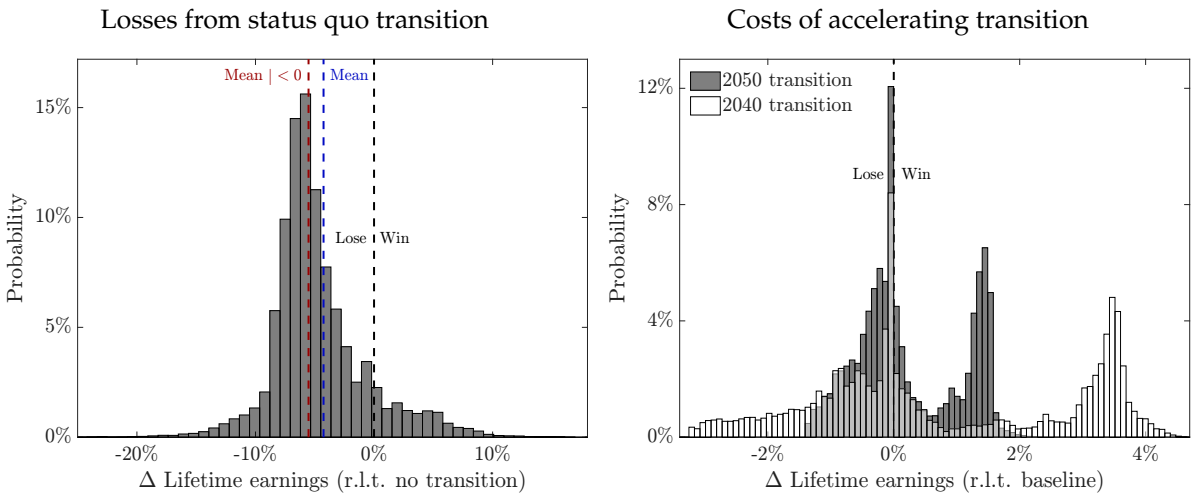
Losses under status quo transition. We first compute the distribution of lifetime earnings changes, starting from 2025, arising from a baseline climate transition ending in 2060 relative to a no-transition scenario (i.e. $A_{k,t} = 1$ forever in both sectors).[41] The left panel of Figure 8 plots this distribution for incumbent workers who were alive in 2025. Most workers initially attached to dirty industries lose from the status quo transition, i.e., the gray area in Figure 2 is negative for them. Our estimates unsurprisingly suggest that most workers initially attached to dirty industries have relative productivity $\hat{\psi} < 1$ in the clean sector, while only a few workers accumulate sufficient skills in the clean sector to benefit from the transition.

The average worker loses 4.3% of lifetime earnings as a result of the status quo transition unconditionally, and 5.5% of lifetime earnings conditional on being hurt by the transition. However, some workers experience substantially larger losses, on the order or $10 - 20\%$ of remaining lifetime income. Importantly, these figures correspond to *ex ante* changes in expected lifetime earnings, i.e., the change in workers' values. Some workers will experience even larger earnings changes *ex post* if they are displaced. These large labor market costs rationalize the opposition to the climate transition in some quarters (Dechezleprêtre et al., 2025).

As a point of comparison, the earnings losses that we estimate over the early phase of the transition are of a similar order of magnitude to those documented in the influential literature on import competition from China. Autor et al. (2016)

[41] This distribution is computed by simulating the model forward from 2005 to 2025 to estimate the distribution of employment, age and skills as of 2025.

Figure 8: Changes in expected lifetime earnings under the baseline transition



Notes: This figure plots the cross-sectional distribution of changes in lifetime earnings from climate transitions of different horizons. The left panel reports changes associated to the status quo transition that ends in 2060, relative to no transition at all. We report *ex ante* expected earnings changes as of 2025. The right panel reports changes associated to transitions ending in 2050 (in gray) or 2040 (in white) relative to the status quo transition.

estimate that workers' earnings fall by around 3.9% if exposed to a $3,000 increase in imports per worker.[42] Traiberman (2020) and Dix-Carneiro (2014) document similar costs following trade liberalization in Denmark and Brazil, respectively.[43]

For additional context, Davis and von Wachter (2011) estimate that workers see lifetime earnings declines on the order of 18.6% if they experience job loss during an economic downturn, which matches our setting in which the sector employing a worker disappears. Given this number, roughly one-in-four workers would need to be displaced by the transition in order to rationalize an average loss of 4.3% if each displacement led to an 18.6% earnings loss.

Compensating workers who lose from the transition would be relatively expensive. Given that average annual earnings in dirty industries is $39,000 in the QCEW in 2004, the average dirty-sector worker loses $24,474 in present value earnings as a result of the status quo transition.[44] Multiplying this figure by 11.4 mil-

[42] The discussion in section 4.4 of Autor et al. (2016) suggests workers lose $515 of earnings against a base of $40,000 from a $1,000 increase in imports per worker.

[43] Dix-Carneiro (2014) finds that intersectoral mobility costs are between 1.4 and 2.7 times annual average wages. This translates to roughly $3.5\% - 6.75\%$ when spread over a 40-year career.

[44] These numbers account for workers' remaining life by multiplying each worker's remaining lifetime earnings by their earnings loss to calculate a dollar-weighted average earnings loss. Ap-

lion — the number of workers attached to these industries in 2004 — implies compensating these workers would cost more than $279 billion in present discounted terms, or $13.1 billion per year in our model. For comparison, the U.S. Congress budgets roughly half a billion per year for the Trade Adjustment Assistance for Workers (TAA), a program that assists workers who lost their job to foreign competition. While expensive, these numbers appear small relative to the larger estimates of the social cost of carbon in the literature (Bilal and Känzig, 2024).

Counterfactual Transitions Speeds. We now turn to our counterfactual analysis. The right panel of Figure 8 plots the distributions of earnings losses from accelerating the transition such that it ends in 2050 (in gray) or 2040 (in white), relative to maintaining the status quo transition. Two main features stand out. First, earnings changes are indeed non-linear in the speed of the transition: the distribution associated to the 2040 transition is not simply a linearly "stretched" version of the 2050 transition. In particular, the left tail gets thicker as the transition accelerates: a transition ending in 2040 leads some to lose an additional 2.5% of lifetime earnings relative to the baseline transition ending in 2060. It is worth reiterating that these numbers reflect earnings changes *in expectation*. Some workers can experience much larger changes *ex post* if they get displaced.

Second, 45% of workers would prefer the transition to end in 2050 rather than 2060, but this share increases as the transition accelerates. This echoes the insight of section 4.2: policy makers face a tradeoff between having more winners on the extensive margin and a thicker tail of losers on the intensive margin. Workers on average gain around 0.3% of lifetime earnings as from the 2050 transition, and 0.8% from the 2050 transition. It may thus be feasible to compensate workers who lose from a faster transition, but distributional effects remain a concern.

Appendix E conducts a number of additional analyses of the quantitative model. First, Figure 15 reports average changes in lifetime earnings by age, which do indeed increase non-linearly as the transition is accelerated. Next, Figure 16 presents the share of workers who experience a U-shape in lifetime earnings as one accelerates the transition from 2060; that is, what share workers whose lifetime earnings initially fall as the transition accelerates from 2060 begin to prefer faster transitions at each transition horizon. When the transition is accelerated to end in 2050,

pendix Figure 14 reports the distribution of losses for young and old workers separately.

around 16% of workers who initially preferred a slower transition will have experienced the trough in their earnings and would prefer an even faster transition, while 9% of workers have more than overcome that initial decline in lifetime earnings; these numbers grow as the transition is accelerated further. Finally, Figure 17 reproduces Figure 6 for the quantitative model, integrating over the estimated distribution of $\hat{\psi}$. Overall, we find that accelerating the climate transition to end in 2050 has modest effects on worker incomes on average but significant distributional consequences, and many workers have U-shaped lifetime earnings profiles.

Sensitivity. As discussed above, we conduct a prospective analysis which comes with a substantial empirical uncertainty. We therefore explore the sensitivity of our results in Appendix Figure 18. Specifically, we consider a variety of alternative values for A^k_∞ and a range of targets for long-run employment shares. The distribution of losses from both status quo and counterfactual transitions are largely unchanged, reflecting the fact that changing A^k_∞ leads to different estimates for $\hat{\psi}$ to rationalize realized net reallocation.

7 Conclusion

This paper studies the labor market consequences of changing the pace of a sectoral shift. We develop a life-cycle model in which workers with heterogeneous skills direct their job search across a sector whose labor demand declines and a sector that grows over time. The speed of these labor demand movements generally has non-linear or even non-monotonic effects on workers' lifetime earnings. Policymakers face a trade-off between increasing the share of workers who benefit from the transition and thickening that tail of workers who lose from it. Labor market frictions amplify both the level and non-linearity of earnings losses of accelerating a transition, due to the response of structural unemployment and the job-ladder. These findings apply to general settings in which labor demand gradually declines for one set of jobs and rises for another.

We apply the model to study the labor market consequences of accelerating the climate transition. We estimate the joint distribution of skill and age using a novel estimation technique leveraging the block recursivity of directed search models, and find that workers attached to polluting sectors lose about 5% of life-

time earnings on average from a baseline climate transition ending in 2060 with substantial heterogeneity. Accelerating the transition to complete by 2050 will lead many workers to be better off, but exacerbate the losses suffered by those with the least transferable skills. Compensating workers who lose from a faster transition would cost in the hundreds of billions of dollars. Future work should study optimal policy taking into account these labor market costs when the transition speed is endogenously determined by market forces and fiscal policy, and to explore the quantitative role of uncertainty for these transitions.

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A Frictionless Benchmark

In this appendix, we establish formally that workers' earnings change non-linearly and potentially non-monotonically as a function of the horizon over which the transition unfolds. In other words, completing the transition 5 or 10 years earlier has a very different effect on workers; and some workers who lose at first from a faster transition may benefit from an even faster one. We show that these results hold for a wider class of transitions than the ones considered in Section 4.

In the following, we index workers by their relative skill $\hat{\psi}$ in the new sector and their birth date τ. We denote today's period by $t_0 \geq 0$. We let $t^\star\left(\hat{\psi}, \tau; \eta\right)$ denote the optimal time at which a worker switches to the new sector, where η parametrizes how quickly sectoral MRPLs change. Finally, we define $\hat{A}\left(t, \eta\right) \equiv A_C\left(t, \eta\right) / A_D\left(t, \eta\right)$ as the relative MRPL between the new and old sectors, where we have made the dependence on calendar time t and η explicit. We impose minimal regularity assumptions on $\hat{A}\left(t, \eta\right)$ at this point: the function is continuous in both arguments; it increases with time t and the pace η; and it converges to its long-run level $\hat{A}\left(t, \eta\right) \to \hat{A}_\infty$ for all t as the transition becomes infinitely fast $\eta \to +\infty$. We let $\hat{A}_{t_0} \equiv \hat{A}\left(t_0, \eta\right)$ for any η denote the relative MRPL that prevails today in period t_0, i.e., the comparative statics starts at a fixed level in period t_0 as we did in Section 4. Similarly, we let $\hat{A}_\infty \equiv \lim_{t \to \infty} \hat{A}\left(t, \eta\right)$ for any η denote the final relative MRPL.

A.1 Always, Never and Occasional Switchers

Before explaining why workers' earnings are non-linear and even non-monotonic in the transition horizon, it is useful to first partition the set of workers into three groups based on their reallocation pattern: always switchers reallocate immediately to the new sector, regardless of how early the transition ends; never switchers never reallocate to the new sector; and occasional switchers reallocate during their lifetime only when the transition is sufficiently fast relative to their remaining lifespan.

Lemma 1. *The set of workers $\left(\tau, \hat{\psi}\right)$ can be partitioned into:*

1. ***Always switchers** with $\hat{\psi} \geq \hat{A}_{t_0}^{-1}$ who move immediately to the clean sector so*

$t^\star\left(\hat{\psi}, \tau; \eta\right) = t_0$ *irrespective of* τ *and* η.

2. ***Never switchers*** *with* $\hat{\psi} \leq \hat{A}_\infty^{-1}$ *who never move to the clean sector so* $t^\star\left(\hat{\psi}; \eta\right) = \infty$ *irrespective of* τ *and* η.

3. ***Occasional switchers*** *with* $\hat{\psi} \in \left(\hat{A}_\infty^{-1}, \hat{A}_{t_0}^{-1}\right)$ *who potentially move to the clean sector if they are sufficiently young and the transition is sufficiently short. For these workers,*

$$t^\star\left(\hat{\psi}, \tau; \eta\right) = \min\left\{\max\left\{\bar{t}\left(\hat{\psi}; \eta\right), t_0\right\}, J + \tau\right\} \tag{A.1}$$

where the cutoff $\bar{t}\left(\hat{\psi}; \eta\right)$ *satisfies*

$$\hat{\psi} = \hat{A}\left(\bar{t}\left(\hat{\psi}; \eta\right), \eta\right)^{-1} \tag{A.2}$$

and is therefore strictly decreasing in $\hat{\psi}$*, strictly decreasing in* η*, and satisfies* $\bar{t}\left(\hat{\psi}; \eta\right) \to 0$ *as* $\eta \to +\infty$.

Proof. A worker supplies labor to the new sector if and only if

$$\hat{\psi} A_C\left(t, \eta\right) \geq A_D\left(t, \eta\right) \quad \text{or} \quad \hat{\psi} \geq \hat{A}\left(t, \eta\right)^{-1} \tag{A.3}$$

during their lifetime. Note that the relative MRPL $\hat{A}\left(t, \eta\right)^{-1}$ decreases over time since the MRPL increases over time in the new sector and decreases in the old sector. Workers with $\hat{\psi} \geq \hat{A}_{t_0}$ always supply labor to the new sector for any $t \geq t_0$. On the contrary, those with $\hat{\psi} \leq \hat{A}_\infty^{-1}$ never supply labor to the new sector. For any intermediate value $\hat{\psi} \in \left(\hat{A}_\infty^{-1}, \hat{A}_{t_0}^{-1}\right)$, there exists a cutoff $\bar{t}\left(\hat{\psi}; \eta\right)$ that satisfies (A.1) since $\hat{A}\left(t, \eta\right)$ is a continuous function of t. Workers supply labor to the old sector until $\bar{t}\left(\hat{\psi}; \eta\right)$ and then supply labor to the new sector. The higher the relative productivity $\hat{\psi}$, the smaller the cutoff since $\hat{A}\left(t, \eta\right)^{-1}$ decreases over time. In turn, a faster transition implies a smaller cutoff since $\hat{A}\left(t, \eta\right)^{-1}$ decreases with the pace of the transition. Furthermore, the cutoff $\bar{t}\left(\hat{\psi}; \eta\right) \to 0$ as $\eta \to +\infty$ since $\hat{\psi} > \hat{A}_\infty^{-1}$ and $\hat{A}\left(t, \eta\right)^{-1} \to \hat{A}_\infty^{-1}$ for all t as $\eta \to +\infty$. Finally, a worker only switches in their lifetime if the cutoff $\bar{t}\left(\hat{\psi}; \eta\right)$ occurs before they retire in period $J + \tau$, which yields the switching time (A.2).[45] □

[45] Since we work in continuous time, it is without loss of generality to assume that a worker who never switchers does, in fact, switch at the exact time of their retirement $J + \tau$.

A.2 Non-Linearity of Lifetime Earnings

We now establish that earnings changes are non-linear for always and never switchers as a function of the horizon over which the transition is completed. In other words, workers are affected non-linearly as the transition ends 5, 10 or 15 years earlier, and extrapolating from small changes can be misleading. We will turn our attention to occasional switchers later in this appendix.

A worker's lifetime earnings starting from today's period t_0 are given by

$$\begin{aligned}\mathcal{W}\left(\hat{\psi},\tau;\eta\right) = &\int_{t^+(\tau)}^{t^\star\left(\hat{\psi},\tau;\eta\right)} e^{-\rho\left(t-t^+(\tau)\right)} A_P\left(t,\eta\right) dt \\ &+ \hat{\psi}\int_{t^\star\left(\hat{\psi},\tau;\eta\right)}^{J+\tau} e^{-\rho\left(t-t^+(\tau)\right)} A_C\left(t,\eta\right) dt, \end{aligned} \tag{A.4}$$

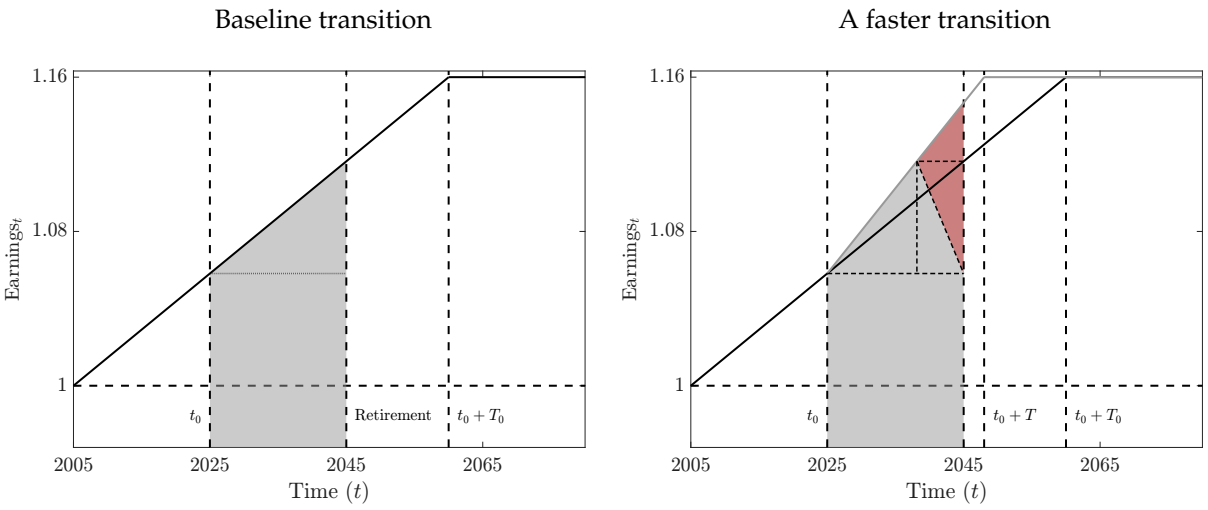
where $t^+\left(\tau\right) \equiv \max\left\{\tau, t_0\right\}$ is the first period where worker is present after today and $t^\star\left(\hat{\psi},\tau;\eta\right)$ still denotes the period when the worker switches to the clean sector. We focus on incumbent workers so $\tau \in \left(t_0 - J, t_0\right]$. We start by inspecting always switchers. In this case, lifetime earnings become

$$\mathcal{W}\left(\hat{\psi},\tau;\eta\right) = \hat{\psi}\int_{t_0}^{J+\tau} e^{-\rho(t-t_0)} A_C\left(t,\eta\right) dt \tag{A.5}$$

Starting from a baseline horizon that ends T_0 periods from today, we are interested in characterizing changes in lifetime earnings as a function of the horizon T over which the transition is completed. As in Section 4, we therefore set $\eta = T_0/T$. Figure 9 illustrates the path of earnings for an always switcher worker with $\hat{\psi} = 1$. The left panel corresponds to the baseline transition. With our climate application in mind, we suppose that the first period $t = 0$ corresponds to 2005 and today's period t_0 corresponds to 2025. The baseline transition ends in 2060. As a convenient benchmark, we suppose that the transition is linear over time and we relax this assumption later. The shaded gray area corresponds to workers' lifetime earnings (A.5) in the case where there is no discounting, i.e., $\rho = 0$.[46] The right panel of Figure 9 considers a faster transition starting from today's period t_0. This transition is completed $T < T_0$ periods from today. In the following, we let $\Delta T \equiv T_0 - T$. The

[46] The gray area extends down all the way to zero. We truncated the plot to improve readability.

Figure 9: Non-linear earnings changes



Notes: This figure plots the path of earnings over a time for an always switcher worker with $\hat{\psi} = 1$. The left panel illustrates a baseline transition ending in $t_0 + T_0$ or T_0 periods from today. The shaded gray area corresponds to lifetime earnings when there is no discounting, i.e., $\rho = 0$. The right panel illustrates a faster transition ending in $t_0 + T$ with $T < T_0$. The shaded gray and red areas correspond to lifetime earnings in this case.

sum of the shaded gray and red areas correspond to lifetime earnings in this case.

Lifetime earnings can be expressed as

$$\mathcal{W}(\cdot) = \overline{\mathcal{W}} + \hat{\psi} \times \frac{1}{2} \times (J + \tau - t_0) \times \Omega \times \frac{T_0}{T_0 - \Delta T}, \tag{A.6}$$

for two constants $\overline{\mathcal{W}}$ and Ω. The term $\overline{\mathcal{W}} \equiv (J + \tau - t_0) \times A_C(t_0, 1)$ corresponds to the shaded gray area that appears in both panels of Figure 9. In turn, $(J + \tau - t_0)$ is the basis of the triangle on top of this rectangle, while the term $\Omega \equiv (J + \tau - t_0) \times [A_C(J + \tau, 1) - A_C(t_0, 1)]$ corresponds to its height under the baseline transition when $T = T_0$ or $\Delta T = 0$. Finally, the term $T_0/(T_0 - \Delta T)$ stretches the height of this triangle as the transition is completed earlier.

The expression (A.6) is convex in ΔT, i.e., workers are affected non-linearly as the transition is completed 5, 10 or 15 years earlier. This result is intuitive: completing the transition one year earlier only means accelerating it by a fraction $1/T_0$ at first; as the transition accelerates and ends earlier, every additional $\Delta T = 1$ year represents a larger and larger share $1/T$ of the remaining horizon $T < T_0$; eventu-

ally, the line in Figure 9 becomes *extremely* steep as ΔT shrinks towards T_0.[47] This result can also be understood geometrically: lifetime earnings increase by the two shaded red triangles on the right panel of Figure 9 as the transition accelerates.[48] The area of the bottom triangle scales linearly with ΔT. On the contrary, the area of the top triangle grows non-linearly with ΔT since its base is linear and ΔT but its height increases too.

The case where the worker is a never switcher is symmetric so we omit it. Finally, it is worth noting that the transition above made two assumptions to convey the insights transparently. First, we abstracted from discounting. Of course, exponentially discounting can reinforce the non-linearities documented above. Second, we consider a linear transition. Naturally, non-linearities in the functions $\bar{\Phi}_t^k$ themselves in expression (3.4) , e.g., coming from *S*-curves, can further strengthen the non-linearities in earnings.

A.3 Non-Monotonicity of Lifetime Earnings

We now establish that earnings changes are non-linear for occasional switchers as a function of the horizon over which the transition is completed. This result can be shown quite generally, with weak restrictions on the paths of MRPLs.

Assumption 1. *Let marginal revenue products of labor across sectors satisfy:*

1. $A_k(t,\eta)$ *and* $\hat{A}_t(\eta) \equiv A_C(t,\eta) / A_P(t,\eta)$ *are twice differentiable in* t *and* η *almost everywhere,*
2. $\partial_t A_{P,t}(\eta) \leq 0 \leq \partial_t A_{C,t}(\eta)$, $\partial_\eta \partial_t A_{C,t}(\eta) \geq 0$, $\partial_\eta \partial_t A_{P,t}(\eta) \leq 0$ *for all* t *and* η,
3. $\lim_{\eta\to\infty} \hat{A}(t,\eta) = \lim_{t\to\infty} A_C(t) / A_P(t)$ *for all* t, *and*
4. $\partial_t A_{P,t}(0) = \partial_t A_{C,t}(0) = 0$

The first assumption means that the transition is smooth almost everywhere. The second assumption defines the kinds of transitions that we consider, i.e., the old sector declines (relative to trend) while the new sector grows. A larger η speeds up the transition in that it implies a faster MRPL growth in the new sector and a

[47] Of course, workers' earnings are bounded by the flat region in Figure 9, which might itself introduce additional non-linearities.

[48] By construction, the shaded gray areas are the same in the two panels of Figure 9.

faster decline in the old sector. The third assumption states that, in the limit as η goes to infinity, the relative MRPL instantly jumps to its long run level. On the contrary, there is no transition at all if $\eta = 0$.Overall, this set of assumptions is strictly weaker than those imposed in Section B.4, i.e., the non-monotonicity property does not dependent on the particular transition that we assumed in that section.

Proposition 2. *Suppose that Assumption 1 holds, then lifetime earnings $\mathcal{W}\left(\hat{\psi}, \tau; \eta\right)$ are*

1. ***Increasing** in η for the always switchers with $\hat{\psi} \geq \hat{A}_0^{-1}$,*
2. ***Decreasing** in η for the never switchers with $\hat{\psi} \leq \hat{A}_\infty^{-1}$,*
3. ***U-shaped** in η for the occasional switchers with $\hat{\psi} \in \left(\hat{A}_\infty^{-1}, \hat{A}_{t_0}^{-1}\right)$. Formally, for each relative productivity $\hat{\psi}$ and birth date τ, there exist critical speeds $0 < \eta_l\left(\hat{\psi}, \tau\right) < \eta_h\left(\hat{\psi}, \tau\right) < \infty$ such that $\mathcal{W}\left(\hat{\psi}, \tau; \eta\right)$ is decreasing in η for $\eta < \eta_l\left(\hat{\psi}, \tau\right)$ and increasing in η for $\eta > \eta_h\left(\hat{\psi}, \tau\right)$.*

Proof. First, consider the always switchers. These workers switch immediately to the clean sector, regardless of how when the transition is completed, i.e., $t^\star\left(\hat{\psi}; \eta\right) = t_0$ for any η. Their earnings increase over time, so they are trivially made better off when the transition is completed faster. On the contrary, never-switchers stay put in the polluting sector, i.e., $t^\star(\hat{\psi}; \eta) = \infty$ for all η. Their earnings decrease over time, so they are made worse off by a faster transition.

Consider now an occasional switcher with $\hat{\psi} \in \left(\hat{A}_\infty^{-1}, \hat{A}_{t_0}^{-1}\right)$. For these workers, we claim that there exists some η_h such that $\partial_\eta \mathcal{W}\left(\tau, \hat{\psi}; \eta\right) > 0$ for all $\eta \geq \eta_h$ and some $\eta_l < \eta_h$ such that $\partial_\eta \mathcal{W}\left(\tau, \hat{\psi}; \eta\right) < 0$ for all $\eta \leq \eta_l$. That is, these worker's welfare decreases at first as the transition is completed earlier, and eventually increases.

We first consider an incumbent worker born in $\tau \in (t_0 - J, t_0]$. Note that $t^\star(\hat{\psi}; \eta)$ is continuous and decreasing in η since $\hat{A}_t\left(t, \eta\right)$ is continuous and increasing in η. Under Assumption 1 and by the intermediate value theorem, there exists some η_l for which $t^\star\left(\hat{\psi}; \eta_l\right) = J + \tau$ so the worker switches to the new sector exactly at retirement. That is, the worker never switcher in their lifetime if the transition is slow enough that $\eta < \eta_l$ and the worker is made worse off in this region

as the transition accelerates. Now, consider a pace η with $0 \leq t^{\star}\left(\hat{\psi};\eta\right) \leq J+\tau$, i.e., the worker switches at some point before retirement. In this case, the change in lifetime earnings is

$$\frac{d\mathcal{W}(\tau,\hat{\psi};\eta)}{d\eta} = \int_0^{t^{\star}(\hat{\psi};\eta)} e^{-\rho t}\frac{\partial A^P\left(t,\eta\right)}{\partial \eta}dt + \hat{\psi}\int_{t^{\star}(\hat{\psi};\eta)}^{J+\tau} e^{-\rho t}\frac{\partial A^C\left(t,\eta\right)}{\partial \eta}dt \tag{A.7}$$

We will show that there exists some $\eta_h > \eta_l$ such that this expression is positive for all $\eta > \eta_h$.

First, note that the second term of the right-hand side of (A.7) is positive since $A^C\left(t,\eta\right)$ increases with η. So it suffices to show that

$$\lim_{\eta\to\infty}\int_0^{t^{\star}(\hat{\psi};\eta)} e^{-\rho t}\frac{\partial A^P\left(t,\eta\right)}{\partial \eta}dt = 0 \tag{A.8}$$

Then, note that

$$\int_0^{t^{\star}(\hat{\psi};\eta)} e^{-\rho t}\frac{\partial A_t^P(\eta)}{\partial \eta}dt > \int_0^{t^{\star}(\hat{\psi};\eta)} \frac{\partial A_t^P(\eta)}{\partial \eta}dt \tag{A.9}$$

since $A^P\left(t,\eta\right)$ decreases with η. Furthermore,

$$\int_0^{t^{\star}(\hat{\psi};\eta)} \frac{\partial A_t^P(\eta)}{\partial \eta}dt > \frac{\partial}{\partial \eta}\int_0^{t^{\star}(\hat{\psi};\eta)} A_t^P(\eta)dt \tag{A.10}$$

since $t^{\star}(\hat{\psi};\eta)$ decreases with η. Then, note that

$$\frac{\partial}{\partial \eta}\int_0^{t^{\star}(\hat{\psi};\eta)} A_t^P(\eta)dt < 0 \tag{A.11}$$

both because $t^{\star}\left(\hat{\psi},\eta\right)$ and $A^P\left(t,\eta\right)$ decrease with η. However, it must be that

$$\lim_{\eta\to\infty}\frac{\partial}{\partial \eta}\int_0^{t^{\star}(\hat{\psi};\eta)} A_t^P(\eta)dt = 0 \tag{A.12}$$

Suppose by contradiction that expression (A.12) does not hold. Then, for each $\bar{\eta}$, there exists an $\epsilon < 0$ and an infinite number of subsets with positive measure in

$(\bar{\eta}, \infty)$ such that

$$\frac{\partial}{\partial \eta} \int_0^{t^\star(\hat{\psi};\eta)} A_t^P(\eta) dt < \epsilon \tag{A.13}$$

for each η in these subsets. Then

$$\begin{aligned} 0 &= \int_0^{t^\star(\hat{\psi};\eta)} A_t^P(\eta) dt \Big|_{\eta=\infty} \\ &= \int_0^{t^\star(\hat{\psi};\eta)} A_t^P(\eta) dt \Big|_{\eta=\bar{\eta}} + \int_{\bar{\eta}}^{+\infty} \left\{ \frac{\partial}{\partial \tilde{\eta}} \int_0^{t^\star(\hat{\psi};\tilde{\eta})} A_t^P(\tilde{\eta}) dt \right\} d\eta \qquad \text{(A.14)} \\ &= -\infty \qquad \text{(A.15)} \end{aligned}$$

which yields the desired contraction. Therefore, expression (A.12) holds.

Combining expressions (A.7), (A.9)–(A.10) and (A.12),

$$\lim_{\eta \to \infty} \frac{d\mathcal{W}(\tau, \hat{\psi}; \eta)}{d\eta} > \lim_{\eta \to \infty} \hat{\psi} \int_{t^\star(\hat{\psi};\eta)}^{J+\tau} e^{-\rho t} \frac{\partial A_t^C(\eta)}{\partial \eta} dt > 0, \tag{A.16}$$

which show that there exists indeed a pace $\eta_h > \eta_l$ above which these workers benefit from a transition that ends sooner. Thus, welfare is non-monotone in the transition horizon for these incumbent workers.

Having established the desired result for incumbent cohorts, we now consider a future cohort who is born in $\tau \in (t_0, +\infty)$. Proceeding as above, there exists some other η_l for which $t^\star\left(\hat{\psi}; \eta_l\right) = J + \tau$ so the worker switches to the new sector exactly at retirement. For these new cohorts, there exists some other η_h for which $t^\star\left(\hat{\psi}; \eta_h\right) = \tau$ so the worker switches to the new sector at birth. That is, the worker never switches to the new sector during their lifetime if the transition is slow enough that $\eta < \eta_l$ and the worker is made worse off in this region as the transition ends sooner. On the contrary, the work switches immediately to the new sector if the transition is rapid enough that $\eta > \eta_h$ and the worker is made better off in this region as the transition ends even sooner. Then, for all $\eta < \eta_l$, the worker remains in the old sector for their whole career and are made worse off by a faster transition, while for all $\eta > \eta_h$ they remain in the new sector their whole career and are made better off by a fast transition. Thus, welfare is also non-monotone in the transition horizon for these new cohorts. □

B Full Model

This appendix provides additional derivations and proofs for our full model introduced in Sections 2 and 5. Section B.1 states workers' and firms' values recursively. Section B.2 characterizes firms' optimal choices of production and innovation. Section B.3 defines the equilibrium formally. Section B.4 shows that values satisfy some homogeneity property that allows us to characterize these values in terms of de-trended marginal revenue products of labor A_t^k, and not to keep track of a worker's overall skill ψ in our state space. Section B.5 characterizes the balanced-growth path of the economy before the transition begins. Section B.6 shows that the sectoral marginal revenues of product tend to be S-shaped along the status quo transition. Section B.7 proves the implementability result (Proposition 1) in our full model. Finally, Section B.8 extends our model to allow for climate damages.

B.1 Workers' and Firms' Values

Skill accumulation. Before stating workers' and firms' values, it is useful to perform a change of variable and define the "reference" skill $\psi \equiv \psi^G \psi^P$ and the "relative" skill $\hat{\psi} \equiv \psi^C / \psi^P$. Using the laws of motions that we described in Section 5, the reference skill ψ grows at rate

$$\delta_j^\star(k) \equiv \begin{cases} \delta_j^+ + \hat{\delta}_j & \text{if } k = D \\ \delta_j^+ & \text{if } k = C \\ \delta_j^k & \text{if } k = O, U \end{cases} \tag{B.1}$$

depending on the worker's employment status. In turn, the relative skill grows at rate

$$\hat{\delta}_j^\star(k) \equiv \begin{cases} -\hat{\delta}_j & \text{if } k = D \\ \hat{\delta}_j & \text{if } k = C \\ 0 & \text{if } k = O, U \end{cases} \tag{B.2}$$

In the following, we let

$$h\left(\psi,\hat{\psi},k\right)=\begin{cases}\psi & \text{if } k=D\\ \psi\times\hat{\psi} & \text{if } k=C\\ \psi\times b^{k} & \text{if } k=O,U\end{cases} \tag{B.3}$$

denote a workers' total productivity across sectors. After this change of variable, workers are indexed by five states: their age j; their reference skill ψ; their relative skill in the clean sector $\hat{\psi}$; their employment status $e=E,O,U$; and, if employed, their sector k and their wage w. The last three states can be combined into a single state s which corresponds to a market (k,w) when the worker is employed, or to O or U when the worker claims the outside option or is unemployed.

Worker values. The value of an employed worker of age j with skills ψ and $\hat{\psi}$ that is currently in submarket s satisfies

$$\begin{aligned}\rho W_{t}\left(j,\psi,\hat{\psi},s\right)&=w\left(s\right)h\left(\psi,\hat{\psi},k\left(s\right)\right)\exp\left(gt\right)\\&+\lambda^{E}\sum_{s'}p_{t}\left(s';j,\psi,\hat{\psi},s\right)f\left(\theta_{t}\left(j,\psi,\hat{\psi},s'\right)\right)\left[W_{t}\left(j,\psi,\hat{\psi},s'\right)-W_{t}\left(j,\psi,\hat{\psi},s\right)\right]\\&+\chi_{0}\left[W_{t}\left(j,\psi,\hat{\psi},U\right)-W_{t}\left(j,\psi,\hat{\psi},s\right)\right]\\&+\frac{d}{d\epsilon}W_{t+\epsilon}\left(j+\epsilon,\psi\exp\left(\delta_{j}^{\star}\left(k\left(s\right)\right)\epsilon\right),\hat{\psi}\exp\left(\hat{\delta}_{j}^{\star}\left(k\right)\epsilon\right),s\right)\Big|_{\epsilon=0}\end{aligned} \tag{B.4}$$

for each age $j\in[0,J)$, where $W_{t}\left(j,\psi,\hat{\psi},U\right)$ is the value of being unemployed, which is defined below. Workers discount flows at rate ρ. When employed, they earn $w\left(s\right)$ for each productive unit of labor $h\left(\psi,\hat{\psi},k\left(s\right)\right)\exp\left(gt\right)$ that they provide, with $h\left(\cdot\right)$ given by expression (B.3).[49] Workers have the opportunity to search for another job at rate λ^{E}. They search in submarket s' with probability $p_{t}\left(s';j,\psi,\hat{\psi},s\right)$ given by expression (5.1). The match is dissolved exogenously at rate χ_{0}. Finally, there is a drift in the reference and relative skills ψ and $\hat{\psi}$ at rates (B.1)–(B.2, in age, and over time.[50] The boundary condition is $W_{t}\left(J,\psi,\hat{\psi},s\right)=0$ upon retirement at age $j=J$. The terminal conditions are similar for the the val-

[49] As discussed in Section 5.1, workers' wage compensation grows at rate g on-the-job to ensure that wages w admit a stationary distribution along a balanced-growth path.

[50] These drifts are characterized by the single index ϵ.

ues below so we omit them for concision. It is worth noting that workers might receive transfers for the government. These lump sum transfers do not distort workers' labor supply decisions when workers are risk-neutral (or have access to perfect borrowing), as we assume in this paper. Therefore, we exclude these transfers from workers' values, allowing us to interpret them as the present discounted value of future earnings — the object of interest in this paper.

In turn, the value of the outside option satisfies

$$\begin{aligned}\rho W_t\left(j,\psi,\hat{\psi},O\right) &= h\left(\psi,\hat{\psi},O\right)\exp\left(gt\right) \\ &+ \lambda^E\sum_s p_t\left(s;j,\psi,\hat{\psi},O\right) f\left(\theta_t\left(j,\psi,\hat{\psi},s\right)\right)\left[W_t\left(j,\psi,\hat{\psi},s\right)-W_t\left(j,\psi,\hat{\psi},O\right)\right] \\ &+ \chi_0\left[W_t\left(j,\psi,\hat{\psi},U\right)-W_t\left(j,\psi,\hat{\psi},O\right)\right] \\ &+ \frac{d}{d\epsilon}W_{t+\epsilon}\left(j+\epsilon,\psi\exp\left(\delta_j^\star\left(O\right)\epsilon\right),\hat{\psi},O\right)\Big|_{\epsilon=0}\end{aligned} \tag{B.5}$$

for $j < J$, since they receive benefits $h\left(\psi,\hat{\psi},O\right)\exp\left(gt\right)$, and search for jobs with intensity λ^E. Workers separate from the outside option exogenously at rate χ_0. There is a drift in the general and hence reference skill, in age, and over time. Similarly, the value of an unemployed worker satisfies

$$\begin{aligned}\rho W_t\left(j,\psi,\hat{\psi},U\right) &= h\left(\psi,\hat{\psi},U\right)\exp\left(gt\right) \\ &+ \lambda^U\sum_s p_t\left(s;j,\psi,\hat{\psi},U\right) f\left(\theta_t\left(j,\psi,\hat{\psi},s\right)\right)\left[W_t\left(j,\psi,\hat{\psi},s\right)-W_t\left(j,\psi,\hat{\psi},U\right)\right] \\ &+ \frac{d}{d\epsilon}W_{t+\epsilon}\left(j+\epsilon,\psi\exp\left(\delta^\star\left(U\right)\epsilon\right),\hat{\psi},s\right)\Big|_{\epsilon=0}\end{aligned} \tag{B.6}$$

for each age $j \in [0, J)$, since they receive benefits $h\left(\psi,\hat{\psi},U\right)\exp\left(gt\right)$ and search for jobs with intensity λ^U. There also is a drift in the general and hence reference skill, in age, and over time. Given these values, workers' search probabilities are given by

$$p_t\left(s';\mathbf{x},s\right) \equiv \frac{\exp\left(f\left(\theta_t\left(\mathbf{x},s'\right)\right)\left[W_t\left(\mathbf{x},s'\right)-W_t\left(\mathbf{x},s\right)\right]/\zeta\right)}{\sum_{\hat{s}}\exp\left(f\left(\theta_t\left(\mathbf{x},\hat{s}\right)\right)\left[W_t\left(\mathbf{x},\hat{s}\right)-W_t\left(\mathbf{x},s\right)\right]/\zeta\right)}, \tag{B.7}$$

where $\mathbf{x} \equiv \left(j,\psi,\hat{\psi}\right)$ denotes a worker's state excluding its current market s.

Firm values. The value of a filled job in submarket s is given by

$$\begin{aligned}\rho V_t\left(j,\psi,\hat{\psi},s\right) = & \left(\mathcal{P}_t^{k(s)} - w\left(s\right)\right) h\left(\psi,\hat{\psi},k\left(s\right)\right)\exp\left(gt\right) \\ & - \chi_0 V_t\left(j,\psi,\hat{\psi},s\right) \\ & - \lambda^E \sum_{s'} f\left(\theta_t\left(j,\psi,\hat{\psi},s'\right)\right) p_t\left(s';j,\psi,\hat{\psi},s\right) V_t\left(j,\psi,\hat{\psi},s\right) \\ & + \frac{d}{d\epsilon} V_{t+\epsilon}\left(j+\epsilon,\psi\exp\left(\delta_j^\star\left(k\left(s\right)\right)\epsilon\right),\hat{\psi}\exp\left(\hat{\delta}_j^\star\left(k\right)\epsilon\right),s\right)\Big|_{\epsilon=0}\end{aligned} \tag{B.8}$$

for each age $j \in [0, J)$, where $\mathcal{P}_t^k$ denotes the de-trended prices of labor services provided in the polluting or clean sectors given by the equilibrium conditions (B.15) below. The boundary condition is $V_t\left(J,\psi,\hat{\psi},s\right) = 0$ when the worker retires at age $j = J$. Firms discount flows using the equilibrium interest rate $r \equiv \rho$.[51] The match is dissolved either exogenously at rate χ_0, or because workers voluntarily quit due to on-the-job search. The opportunity for on-the-job search arrives at rate λ^E and the probability of separating conditional on searching is given by $f\left(\theta_t(\cdot)\right)$ in each market s', weighted by the probability that the individual searches there $p_t\left(s';j,\psi,\hat{\psi},s\right)$. The firm's value also features a drift in workers' skills, in their age, and over time.

Tightnesses. There is free entry in each market so equilibrium tightnesses $\theta_t\left(j,\psi,\hat{\psi},s\right)$ satisfy

$$q\left(\theta_t\left(j,\psi,\hat{\psi},s\right)\right) V_t\left(j,\psi,\hat{\psi},s\right) \leq \nu\psi\exp\left(gt\right) \tag{B.9}$$

in every period t and market s, with equality if a positive measure of vacancies are posted. Firms post vacancies for a worker with reference skill ψ at a cost $\nu\psi\exp\left(gt\right) > 0$, where ν captures both the cost of posting the vacancy and hiring the worker. This cost grows at rate g to ensure that the economy admits a balanced-growth path.

[51] The equilibrium interest rate is $r = \rho$ since entrepreneurs have linear utility.

B.2 Production, Innovation and Government

Production. The representative final good producer combines the goods produced by the declining and the increasing one using the technology

$$Y_t = F_t\left(X_t^D, X_t^C\right) \tag{B.10}$$

As usual, the technology (B.10) can alternatively be interpreted as workers' preferences over these two goods.

Innovation. Entrepreneurs who own the firms producing intermediate goods can invest resources to improve their productivity a_t^k, thus increasing profits. Their productivity evolves according to $da_t^k = \left(z_t^k - \delta_a^k a_t^k\right) dt$, where z_t^k is gross investment and δ_a^k is the rate at which a firm's technology becomes obsolete relative to newer ideas (Caballero and Jaffe, 1993; Akcigit et al., 2022). Following Eaton and Kortum (1999), we allow for technological spillovers

$$z_t^k = \sum_{k'} \beta_{k'}^k \times \left[\int_{-\infty}^{t} \exp\left(-\beta_{k'}^k (t-s)\right) \times \iota\left(I_s^{k'}\right) ds\right] \times a_t^{k'} dt, \tag{B.11}$$

where ι reflects decreasing returns to innovation.[52] We use I_t^k to denote the investment rate on each technology, so the level of investment is $I_t^k a_t^k$; this investment is expressed in terms of a bundle of intermediates with constant-returns-to-scale. In turn, the coefficients $\beta_{k'}^k > 0$ capture the innovation spillovers across sectors, and v reflects decreasing returns in R&D investment. We suppose that the spillover coefficients are positive, symmetric and satisfy $\sum_{k'} \beta_{k'}^k = 1$. As we show in Appendix B.5, this specification ensures there exists a balanced-growth path where output in the clean and polluting sectors grow at the same rate $g > 0$. In this initial balanced-growth path, there is little demand for the good eventually produced in the new sector; the price of this good is therefore very low, and so is its productivity since there are no incentives to innovate. We model sectoral shifts as transitions that affects the *level* of economic activity and its allocation across sectors, but not

[52] Alternative and multiplicative formulations are sometimes used in the literature, e.g., Acemoglu (2002). In our context, these formulations have the disadvantage that they allow laggard sectors to bring down the rest of the economy; this feature is particularly problematic since we consider an initial balanced-growth path where the climate sector is not active yet (Section 3).

the long-term growth rate of the economy. We place appropriate restrictions on the innovation technology ι and $\beta^k_{k'}$ to ensure that the economy converges to a new balanced-growth path that grows at the same rate g as the initial one.[53]

Equilibrium prices and innovations. The final good producer chooses its demand for intermediates so that

$$P^k_t = \frac{d}{dX^k_t} F_t \left(X^P_t, X^C_t \right), \tag{B.12}$$

for each sector $k = D, C$, where P^k_t is the purchase price of intermediates. In turn, the supply of intermediates is

$$X^k_t = a^k_t y^k \left(n^k_t \right), \tag{B.13}$$

where

$$n^{k'}_t = \int \mathbf{1}_{\{k(s)=k'\}} h \left(\psi, \hat{\psi}, k\left(s\right) \right) d\mu \left(j, \psi, \hat{\psi}, s \right) \tag{B.14}$$

is the labor supply in a sector k', with $k\left(s\right)$ denoting the sector that a given worker in market s is employed in. The previous expression uses the fact that there is a continuum of monopolistic firms of mass 1 which produce each type of intermediate. In turn, the optimal demand for labor services coming from these monopolistic firms implies that

$$\left(1 + \tau^k_t\right) a^k_t P^k_t y^{k,\prime} \left(n^k_t \right) = \frac{\epsilon^k}{\epsilon^k - 1} \mathcal{P}^k_t \exp\left(gt\right) \tag{B.15}$$

A firm which uses more labor services raises its output by an amount which depends on the sectoral TFP a^k_t and the marginal product $y^{k,\prime}\left(n^k_t\right)$, sells these units at price P^k_t, and also earns a subsidy τ^k_t from the government. At the same time, using more labor services comes at a cost $\mathcal{P}^k_t$. At optimum, firms equalize these quantities up to a constant markup. The prices $\mathcal{P}^k_t$ are de-trended using the growth rate g. As we show in Appendix B.5, this normalization ensures that the prices $\mathcal{P}^k_t$ are stationary along a balanced-growth path.

[53] While we interpret the stock as a^k_t as intangible capital, it could alternatively be interpreted as tangible (or physical) in the case with no technological spillovers. The initial and final growth rates are $g = 0$ in this case.

Turning to the innovation problem, entrepreneurs solve

$$\begin{aligned}\max_{\left\{I_t^k, a_t^k\right\}} & \int_0^{+\infty} \exp\left(-rt\right) \left[\left(1+\tau_t^k\right) P_t^k a_t^k y^k\left(n_t^k\right) - \left(1-\varsigma_t^k\right) \mathcal{C}\left(P_t^D, P_t^C\right) I_t^k a_t^k\right] \\ \text{s.t. } & da_t^k = \left(z_t^k - \delta_a^k a_t^k\right) dt, \\ & z_t^k = \sum_{k'} \beta_{k'}^k \times \left[\int_{-\infty}^t \exp\left(-\beta_{k'}^k \left(t-s\right)\right) \times \iota\left(I_s^{k'}\right) ds\right] \times a_t^{k'} dt\end{aligned} \tag{B.16}$$

in each sector $k = D, C$, given some initial condition for a_0^k and taking innovations $I_t^{k'}$ and technologies $a_t^{k'}$ as given in the other sector $k' \neq k$. The unit cost function $\mathcal{C}\left(P_t^D, P_t^C\right)$ is homogeneous of degree 1 and reflects the constant-returns-to-scale bundle that firms use to innovate (Section 2.2). By the Principle of Optimality, entrepreneurs can choose their investment rate I_t^k and stock a_t^k, keeping fixed their optimal labor demands n_t^k. In equilibrium, these labor demands coincide with aggregate sectoral labor supplies.

Investing resources I_t^k allows firms to improve their productivity a_t^k and hence their revenues, but is comes at a cost. At optimum, the marginal benefit of investing equals the marginal cost

$$\iota'\left(I_t^k\right) \int_0^{+\infty} \mu\left(t+s\right) \beta_k^k \times \exp\left(-\beta_k^k s\right) \times a_{t+s}^k ds = \left(1-\varsigma_t^k\right) \mathcal{C}\left(P_t^D, P_t^C\right) a_t^k, \tag{B.17}$$

where $\mu\left(t\right)$ is the multiplier on the law of motion for a_t^k, and the marginal benefits reflect changes in revenues

$$\begin{aligned}&\left(1+\tau_t^h\right) P_t^k y^k\left(n_t^k\right) - \left(1-\varsigma_t^k\right) \mathcal{C}\left(P_t^D, P_t^C\right) I_t^k \\ &+ \left(\beta_k^k \times \int_{-\infty}^t \exp\left(-\beta_k^k \left(t-s\right)\right) \times \iota\left(I_s^k\right) ds - \delta_a^k\right) \mu\left(t\right) = r\mu\left(t\right) - \dot{\mu}\left(t\right)\end{aligned} \tag{B.18}$$

This system characterizes the optimal solution to the problem (B.16), together with the law of motion

$$da_t^k = \left(z_t^k - \delta_a^k a_t^k\right) dt \tag{B.19}$$

with

$$z_t^k = \sum_{k'} \beta_{k'}^k \times \left[\int_{-\infty}^t \exp\left(-\beta_{k'}^k \left(t-s\right)\right) \times \iota\left(I_s^{k'}\right) ds\right] \times a_t^{k'} dt \tag{B.20}$$

and the initial condition for a_0^k.

Government. The government chooses a path of subsidies $\{\tau_t^k, \varsigma_t^k\}$ and sets lump sum taxes to balance its flow budget

$$T_t = \sum_k \left(\tau_t^k X_t^k + \varsigma_t^k I_t^k a_t^k \right) \tag{B.21}$$

B.3 Equilibrium Definition and Block-Recursivity

In this appendix, we define an equilibrium formally.

Definition 1. Given a path of government subsidies $\{\tau_t^k, \varsigma_t^k\}$, an equilibrium consists of sequences of workers' and firms' values $W_t\left(j, \psi, \hat{\psi}, s\right)$ and $V_t\left(j, \psi, \hat{\psi}, s\right)$, search probabilities $p_t\left(s'; j, \psi, \hat{\psi}, s\right)$, tightnesses $\theta_t\left(j, \psi, \hat{\psi}, s\right)$, a distribution $\boldsymbol{\mu}_t\left(j, \psi, \hat{\psi}, s\right)$, sectoral outputs X_t^k, sectoral labor supplies n_t^k, prices of intermediates P_t^k, prices of labor services $\mathcal{P}_t^k$, sectoral TFPs a_t^k, and lump sum taxes T_t such that:

1. Workers' values satisfy (B.4)–(B.6) in Appendix B.1
2. Firms' values satisfy (B.8) in Appendix B.1
3. The search probabilities satisfy (B.7) in Appendix B.1
4. The tightnesses satisfy (B.9) in Appendix B.1
5. The distribution is consistent with the flows implied by workers' and firms' values (see Appendix C.3)
6. Sectoral outputs are given by (B.13) in Appendix B.12
7. Sectoral labor supplies are given by (B.14) in Appendix B.12
8. The price of intermediaries satisfies (B.12) in Appendix B.12
9. Sectoral TFPs satisfy (B.17)–(B.20) in Appendix B.12
10. Lump sum taxes balance the government's flow budget (B.21) in Appendix B.12

Our equilibrium satisfies two obvious properties. First, workers' labor market outcomes are entirely pinned down by the paths of de-trended MRPLs A_t^k given by (3.2) in the text. Second, given these MRPLs, the labor market satisfies the usual block-recursivity property of directed search models (Menzio and Shi, 2011).[54]

Lemma 2. *Workers' labor market outcomes — i.e., the probability that they are employed in a given sector, their position in the job ladder — depend on endogenous prices and government subsidies exclusively through the sequences of de-trended marginal revenue products of labor A_t^k. Furthermore, the labor market equilibrium is block-recursive given paths for A_t^k, i.e., the values $W_t\left(j,\psi,\hat{\psi},s\right)$ and $V_t\left(j,\psi,\hat{\psi},s\right)$, search probabilities $p_t\left(s';j,\psi,\hat{\psi},s\right)$ and tightnesses $\theta_t\left(j,\psi,\hat{\psi},s\right)$ can be characterized independently from the evolution of the distribution $\boldsymbol{\mu}_t\left(j,\psi,\hat{\psi},s\right)$.*

Proof. It is clear from the equilibrium definition that workers' and firms' values are entirely determined by a closed system that is parametrized exclusively by the normalized prices of labor services $\mathcal{P}_t^k$. In particular, this closed system does not depend on the distribution $\boldsymbol{\mu}_t\left(j,\psi,\hat{\psi},s\right)$. Using the definition of marginal revenue products of labor (3.1)–(3.2) and the equilibrium condition (B.15), we have

$$\mathcal{P}_t^k = \left(1+\tau_t^k\right) a_t^k P_t^k / \exp\left(gt\right) \equiv A_t^k \tag{B.22}$$

Therefore, workers' outcomes can be expressed exclusively as a function of the marginal revenue products of labor A_t^k. □

Finally, we show in Appendix B.4 that the equilibrium can be characterized without keeping track of the state ψ which allows us to solve for it more efficiently.

B.4 Normalized and De-Trended Values

This appendix establishes that workers' and firms' are linearly homogenous in $\psi \exp\left(gt\right)$, where g still denotes the rate at which output grows in the polluting

[54] Of course, these MRPLs might themselves depend on workers' labor supplies (due to decreasing returns, innovation, etc.) which could affect the baseline transition that the economy starts from. See Section 3 for an explanation of the counterfactual exercises that we conduct.

and clean sectors in the long-run. This homogeneity property offers two benefits. First, it allows us to characterize de-trended values that are constant over a balanced-growth path, which is required for our numerical implementation. Second, it allows us not keep track of the overall skill ψ in our state space, making our analysis computationally feasible. Formally, we will show that workers' and firms' values satisfy

$$W_t\left(j,\psi,\hat{\psi},s\right) = \psi \exp\left(gt\right) W_t^{\star}\left(j,\hat{\psi},s\right) \tag{B.23}$$

$$V_t\left(j,\psi,\hat{\psi},s\right) = \psi \exp\left(gt\right) V_t^{\star}\left(j,\hat{\psi},s\right), \tag{B.24}$$

for some $W_t^{\star}$ and $V_t^{\star}$ that do not depend on workers' overall skill ψ and depend on time only through the price of labor services $\mathcal{P}_t^k$, which are constant along a balanced-growth path (B.5). While establishing this property, we will also show that

$$\theta_t\left(j,\psi,\hat{\psi},s\right) = \theta_t^{\star}\left(j,\hat{\psi},s\right) \quad , \quad p_t\left(s';j,\psi,\hat{\psi},s\right) = p_t^{\star}\left(s';j,\hat{\psi},s\right) \tag{B.25}$$

for some $\theta_t^{\star}$ and $p_t^{\star}$ that do not depend on workers' overall skill ψ and whose dependence on time is only due to changes in prices over the transition. In the following, we use the fact that $h\left(\psi,\hat{\psi},k\right) \equiv \psi h^{\star}\left(\hat{\psi},k\right)$ with $h^{\star}\left(\hat{\psi},k\right) \equiv h\left(1,\hat{\psi},k\right)$ using the definition (B.3).

Note that workers' and firms' are interdependent. We will therefore guess and verify that the properties (B.23)–(B.25) hold jointly. First, consider the value of a worker employed in market s. Using the definition (B.4), the law of motion of ψ, the two properties above and expanding the time derivative with respect to ϵ, we

obtain

$$\begin{aligned}\rho\frac{W_t\left(j,\psi,\hat{\psi},s\right)}{\psi\exp\left(gt\right)} &= w\left(s\right)h^{\star}\left(\hat{\psi},k\left(s\right)\right)\\ &+\lambda^{E}\sum_{s'}p_t^{\star}\left(s';j,\hat{\psi},s\right)f\left(\theta_t^{\star}\left(j,\hat{\psi},s'\right)\right)\left[W_t^{\star}\left(j,\hat{\psi},s'\right)-W_t^{\star}\left(j,\hat{\psi},s\right)\right]\\ &+\chi_0\left[W_t^{\star}\left(j,\hat{\psi},U\right)-W_t^{\star}\left(j,\hat{\psi},s\right)\right]\\ &+\left(g+\delta^{\star}\left(k\left(s\right)\right)\right)W_t^{\star}\left(j,\hat{\psi},s\right)+\hat{\psi}\hat{\delta}_j^{\star}\left(k\left(s\right)\right)\frac{\partial}{\partial\hat{\psi}}W_t^{\star}\left(j,\hat{\psi},s\right)\\ &+\frac{\partial}{\partial j}W_t^{\star}\left(j,\hat{\psi},s\right)+\frac{\partial}{\partial t}W_t^{\star}\left(j,\hat{\psi},s\right),\end{aligned}\tag{B.26}$$

which confirms that $W_t\left(j,\psi,\hat{\psi},s\right)$ indeed scales with $\psi\exp\left(gt\right)$, and hence satisfies expression (B.23). Therefore, the normalized and de-trended value evolves as

$$\begin{aligned}\rho^{\star}W_t^{\star}\left(j,\hat{\psi},s\right) &= w\left(s\right)h^{\star}\left(\hat{\psi},k\left(s\right)\right)\\ &+\lambda^{E}\sum_{s'}p_t^{\star}\left(s';j,\hat{\psi},s\right)f\left(\theta_t^{\star}\left(j,\hat{\psi},s'\right)\right)\left[W_t^{\star}\left(j,\hat{\psi},s'\right)-W_t^{\star}\left(j,\hat{\psi},s\right)\right]\\ &+\chi_0\left[W_t^{\star}\left(j,\hat{\psi},U\right)-W_t^{\star}\left(j,\hat{\psi},s\right)\right]\\ &+\delta^{\star}\left(k\left(s\right)\right)W_t^{\star}\left(j,\hat{\psi},s\right)+\hat{\psi}\hat{\delta}_j^{\star}\left(k\left(s\right)\right)\frac{\partial}{\partial\hat{\psi}}W_t^{\star}\left(j,\hat{\psi},s\right)\\ &+\frac{\partial}{\partial j}W_t^{\star}\left(j,\hat{\psi},s\right)+\frac{\partial}{\partial t}W_t^{\star}\left(j,\hat{\psi},s\right)\end{aligned}\tag{B.27}$$

where $\rho^{\star}\equiv\rho-g$. Proceeding similarly for the values (B.5)–(B.6) also confirms that $W_t\left(j,\psi,\hat{\psi},O\right)$ and $W_t\left(j,\psi,\hat{\psi},U\right)$ scale with $\psi\exp\left(gt\right)$ and yields the law of motions for the normalized values, which we spell out explicitly in Appendix C.1.

Turning to firm's values (B.8), following the steps above confirms our guess.

The normalized and de-trended value evolves as

$$\begin{aligned} r^{\star} V_t^{\star}\left(j, \hat{\psi}, s\right) = & \left(\mathcal{P}_t^{k(s)} - w\left(s\right)\right) h^{\star}\left(\hat{\psi}, k\left(s\right)\right) \\ & - \chi_0 V_t^{\star}\left(j, \hat{\psi}, s\right) \\ & - \lambda^E \sum_{s'} f\left(\theta_t^{\star}\left(j, \hat{\psi}, s'\right)\right) p_t^{\star}\left(s'; j, \hat{\psi}, s\right) V_t^{\star}\left(j, \hat{\psi}, s\right) \\ & + \delta^{\star}\left(k\left(s\right)\right) V_t^{\star}\left(j, \hat{\psi}, s\right) + \hat{\psi} \hat{\delta}_j^{\star}\left(k\right) \frac{\partial}{\partial \hat{\psi}} V_t^{\star}\left(j, \hat{\psi}, s\right) \\ & + \frac{\partial}{\partial j} V_t^{\star}\left(j, \hat{\psi}, s\right) + \frac{\partial}{\partial t} V_t^{\star}\left(j, \hat{\psi}, s\right), \end{aligned} \tag{B.28}$$

where $r^{\star} \equiv r - g$ with $r = \rho$ in equilibrium. We will establish in Appendix B.5 that the price of labor services $\mathcal{P}_t^k$ given by (B.15) is constant along a balanced-growth path.

Having verified the properties (B.23), we now show that the properties (B.25)–(B.25) also hold. Using the free entry condition (5.2) and the fact that the vacancy posting costs scale with ψ in Section 5,

$$q\left(\theta_t^{\star}\left(j, \hat{\psi}, s\right)\right) V_t^{\star}\left(j, \hat{\psi}, s\right) \leq \nu h^{\star}\left(\hat{\psi}, k\left(s\right)\right) \tag{B.29}$$

with the usual complementary slackness condition, which confirms that $\theta_t^{\star}\left(j, \hat{\psi}, s\right)$ depends neither on the overall skill ψ nor the growth rate g. Proceeding similarly, the search decisions

$$p_t\left(s'; \tilde{\mathbf{x}}, s\right) \equiv \frac{\exp\left(f\left(\theta_t\left(\tilde{\mathbf{x}}, s'\right)\right)\left[W_t\left(\tilde{\mathbf{x}}, s'\right) - W_t\left(\tilde{\mathbf{x}}, s\right)\right]/\zeta\right)}{\sum_{\hat{s}} \exp\left(f\left(\theta_t\left(\tilde{\mathbf{x}}, \hat{s}\right)\right)\left[W_t\left(\tilde{\mathbf{x}}, \hat{s}\right) - W_t\left(\tilde{\mathbf{x}}, s\right)\right]/\zeta\right)} \tag{B.30}$$

do not depend on these objects either, with $\tilde{\mathbf{x}} \equiv \left(j, \hat{\psi}\right)$.

The homogeneity property (B.23) implies that we can economize one state variable when computing workers' and firms' values or iterating on the distribution of workers' states (Appendix C). In particular, none of the moments that we target in Section 5.2 depend on the level of the overall skill ψ. In Section 6.3, we compute workers' earnings losses in 2025 under the baseline transition (Figure 8). In this case, the level of ψ and its evolution are relevant; we use stochastic simulations to track the workers' states over time.

B.5 Balanced-Growth Path

In this appendix, we establish the growth rates at which various quantities and prices must grow along a balanced-growth path. We are interested in characterizing workers' outcomes as the economy transitions from one balanced-growth path to another after the clean sector effectively emerges (Section 3).

Lemma 3. *Consider a balanced-growth path where government subsidies τ_t^k and ς_t^k are constant over time. Then, the amount of intermediates X_t^P and X_t^C produced in the polluting and clean sectors and aggregate output Y_t grow at the same rate $g > 0$. The normalized prices of labor services $\mathcal{P}_t^k$ defined in Appendix B.2 are constant.*

Proof. We guess and verify that, along a balanced-growth path, the productivities a_t^k and the outputs of intermediaries X_t^k and aggregate output Y_t grow at rate g, while the normalized prices of labor services $\mathcal{P}_t^k$ and sectoral labor supplies n_t^k are constant.

Starting with the firms' vacancy posting and workers' labor supplies, note that workers' equilibrium labor supplies are entirely determined by the coupled system of partial differential equations that define workers' and firms' values (B.27)–(B.28), together with the free entry condition (B.29), and the search probabilities (B.30). This is a closed system: it does not depend on the rest of the economy, except for the prices of labor services $\mathcal{P}_t^k$. If prices are constant along a balanced-growth path, then sectoral labor supplies n_t^k are as well.

Turning to the production of intermediates, if technologies a_t^k grow at rate g and sectoral labor supplies n_t^k are constant, then the technology (B.13) implies that the outputs of intermediaries X_t^k indeed grow at rate g. Furthermore, if productivities a_t^k grow at rate g, then the labor demands (B.15) imply that the normalized prices of labor services $\mathcal{P}_t^k$ are indeed constant.

Considering final good production, if the output of intermediaries X_t^k grow at rate g, then the technology (B.10) implies that aggregate output Y_t indeed grows at rate g. Similarly, the demand for intermediaries (B.12) implies that the price of intermediaries P_t^k indeed grows at rate $-z\bar{g}$, since the first derivatives of F_t are homogeneous of degree 0 by Euler's theorem, and Z_t is homogeneous of degree $-z$.

Finally, we turn to the innovation choices. Suppose that the prices of the final goods P_t^P and P_t^C grow at rate $-z\bar{g}$, that sectoral labor supplies n_t^k are constant,

and that $I_t^{k'}$ is constant and $a_t^{k'}$ grows at rate $\bar{g}$ in the other sector $k' \neq k$. Then, we can guess and verify that I_t^k is constant and a_t^k is constant using the optimality conditions (B.17)–(B.20).

In summary, we have established what rate quantities and prices must grow at along any balanced-growth path. We do not establish formally the existence and stability of a balanced-growth path since this is not the goal of our paper. However, it is worth noting that spillovers in the innovation process (B.11) ensures that the asymptotic growth rate of productivities a_t^k must be the same across sectors. To see that, suppose by contradiction that the polluting sector grows faster asymptotically than the clean sector, i.e., $\bar{g}^P > \bar{g}^C$. Then, $a_t^C / \exp\left(\bar{g}^P t\right) \to 0$ as $t \to +\infty$, so that

$$\frac{z_t^C}{\exp\left(\bar{g}^P t\right)} \to \beta_P^C \times \left[\int_{-\infty}^{t} \exp\left(-\beta_P^C \left(t-s\right)\right) \times \iota\left(I_s^P\right) ds\right] \times a_t^P dt$$

using the innovation process (B.11). Therefore, productivity in the clean sector must grow at the same rate as in the polluting sector, which yields the desired contraction. The argument is symmetric if the clean sector were to grow faster. □

B.6 S-Shaped Transitions

Our model naturally generates S-shaped transitions for the marginal revenue products of labor A_t^k. This type of S-curves are characteristic of innovation and technology adoption (Griliches, 1958; Shepherd et al., 2012).

Accordingly, we will show below that the paths for A_t^C is S-shaped and the path of A_t^P is inverse S-shaped when the intermediates are sufficiently substitutable, and technological spillovers, climate damages and government subsidies are not too large.[55] To do so, we proceed in several steps. First, we consider a limit economy where intermediates are perfectly substitutable, and there are no technological spillovers, climate damages or government subsidies. Using this economy, we show that the levels of A_t^C and A_t^P are higher and lower, respectively, along the final balanced-growth path compared to the initial one. We argue that the transition between these stationary levels is indeed S-shaped or inverse S-shaped. The final step appeals to the continuity of the equilibrium with respect to its parameters to show that the S-curves are preserved away from the limiting economy, i.e., when

[55] These conditions ensure that the MRPL in the two sectors do not co-move too strongly.

allowing for imperfect substitutes, some spillovers, climate damages, etc.

Limiting economy. We momentarily consider the limit where the intermediates are perfect substitutes in the technology (B.10), there are no technological spillovers $\beta^k_{k'} \to 0$ for $k' \neq k$, there are no climate damages so $Z_t \to 1$ and $z \to 0$ in expression (B.33), and there are no policy interventions $\tau^k_t = \varsigma^k_t = 0$ for each $k = P, C$ and all t.[56] In the following, we will use the fact that $g^\star \equiv (1-z)\,\bar{g} = \bar{g}$ in this limit.

Step 1 (long-run levels). We have shown in Appendix B.5 that A^k_t is constant along a balanced-growth path. Starting with the initial balanced-growth path, there is no demand for the intermediate produced by the clean, so the demand for intermediates (B.12) implies that $P^C_t = P^C = 0$. The innovation choice (B.17)–(B.20) implies that there is no investment in the clean sector, so $a^C_t / \exp(\bar{g}t) \to 0$. Therefore, $A^C_t \equiv a^C_t P^C / \exp(\bar{g}t) \to 0$. Furthermore, $P^P_t = P^P > 0$ in the polluting sector so firms innovate and $A^P_t > 0$ along the initial balanced-growth path.

The transition starts with a change in F_t in favor of the good produced in the clean sector. The demand for intermediates (B.12) implies that $P^C_t = P^C > 0$, where the equality holds in the limit where the intermediates are perfect substitutes and there are no climate damages (by assumption). There are thus incentives to invest in both sectors. The innovation choice (B.17)–(B.20) implies that $a^c_t / \exp(\bar{g}t) > 0$ along the final balanced-growth path. Therefore, $A^C_t \equiv a^C_t P^C / \exp(\bar{g}t) > 0$.

As shown at the beginning of this section, the A^k_t terms determines workers' incentives to supply labor across sectors. At least *some* workers will supply labor to the clean sector since $A^C_t > 0$ and G has full support. Therefore, $n^C_t > 0$ along the final balanced-growth path, and n^P_t is lower in the polluting sector than it used to be along the initial balanced-growth path. Furthermore, the demand for intermediates (B.12) implies that $P^P_t = P^P$ is unchanged in the limit where the intermediates are perfect substitutes. The innovation choice (B.17)–(B.20) implies that $a^P_t / \exp(\bar{g}t) > 0$ must be lower than along the initial balanced-growth path since the number of employed workers n^P_t is lower. Therefore, $A^P_t \equiv a^P_t P^P / \exp(\bar{g}t) > 0$ decreases between the initial and final balanced-growth paths.

[56] Spillovers remain positive as we take this limit, so the economy still admits balanced-growth paths where the two sectors grow at the same rate (Appendix B.5). Of course, the level and transition between these balanced-growth depend on the strength of these spillovers.

In summary, the levels of A_t^C and A_t^P are higher and lower, respectively, along the final balanced-growth path compared to the initial one.

Step 2 (transitions). The only way for $A_t^C \equiv a_t^C P_t^C / \exp(gt)$ to reach its higher level is for a_t^C to rise at a rate *higher* than g initially and then a *lower* rate. After *de-trending* at rate g, the path of A_t^C must therefore be S-shaped in the clean sector. The opposite happens in the polluting sector and the path of A_t^P is inverse S-shaped.

Step 3 (continuity). By continuity of the equilibrium with respect to its parameters, the paths of A_t^k are still S-shaped or inverse S-shaped away from the limit that we took above, i.e., even if we allow for imperfect substitutability, some spillovers, etc.

B.7 Proof of Proposition 1 in the Full Model

We start by showing that sectoral productivities a_t^k and the price of intermediates P_t^k can be expressed exclusively in terms of marginal revenue products of labor A_t^k and innovation subsidies ς_t^k.

Lemma 4. *Productivities a_t^k and intermediate prices P_t^k can be expressed exclusively in terms of marginal revenue products of labor A_t^k and innovation subsidies ς_t^k.*

Proof. The inventors' optimal innovation choice (B.17)–(B.20) that determines productivities a_t^k depends on four objects: the marginal revenues products of labor $A_t^k \equiv \left(1+\tau_t^k\right) P_t^k a_t^k / \exp(gt)$; sectoral labor demands n_t^k; the subsidies ς_t^k; and the unit cost $\mathcal{C}\left(P_t^P, P_t^C\right)$ of innovation. By Lemma 4, sectoral labor demands n_t^k are entirely determined by the sequence of A_t^k. Furthermore, the demand for intermediaries (B.12) imply that the prices of intermediates P_t^k can also be expressed in terms of the outputs of intermediates X_t^k, which themselves depend only on a_t^k and n_t^k using the technology (B.13). Putting all these elements together, productivities a_t^k can be expressed solely as a function of the marginal revenues products of labor A_t^k and the subsidies ς_t^k. The same is true for the intermediate prices P_t^k. □

Combining Lemmas 2–4, we now show that the government can choose appropriate subsidies to implement any arbitrary paths of A_t^k.

Proof of Proposition 1. Suppose that the government seeks to implement arbitrary paths of marginal revenue products of labor $\mathbf{A} \equiv \left\{A_t^k\right\}$ and subsidies on innovation $\boldsymbol{\varsigma} \equiv \left\{\varsigma_t^k\right\}$. By Lemma 4, sectoral productivities a_t^k and P_t^k can be expressed directly as a function of these two sequences $\mathbf{A}$ and $\boldsymbol{\varsigma}$. By definition (3.1)–(3.2), the sequence of distortionary subsidies on purchases of intermediates

$$\tau_t^k = \frac{A_t^k \exp\left((1+z)\,\bar{g}t\right)}{a_t^k\left(\mathbf{A},\boldsymbol{\varsigma}\right) P_t^k\left(\mathbf{A},\boldsymbol{\varsigma}\right)} - 1 \tag{B.31}$$

implement the path in equilibrium $\mathbf{A}$, where we have made the dependence of the numerator on $\mathbf{A}$ and $\boldsymbol{\varsigma}$ explicit. Therefore, the government can indeed implement any path of marginal revenue products it desires. Finally, the government chooses lump sum taxes to balance its budget. As discussed in Appendix B.2, these taxes are non-distortionary and do not affect workers' labor supplies or equilibrium quantities or prices. □

B.8 An Extension With Climate Damages

The full model that we presented in Sections 2 and 5 is purposefully general so it can be applied to various sectoral shifts, e.g., structural transformation from manufacturing to services, the transition from retail to warehousing, etc. In Section 6, we apply our model to the climate transition. One feature that sets this transition apart from other sectoral shifts is the presence of climate damages. In this appendix, we show how such damages can be incorporated in our analysis and we establish that our implementability result (Proposition 1) carries through in this case.

Climate damages. The representative final good producer uses the technology

$$Y_t = Z_t F_t\left(X_t^P, X_t^C\right), \tag{B.32}$$

taking the climate damages

$$Z_t = Z^\star\left(\left\{X_{t'}^D, X_{t'}^C\right\}_{t'\leq t}\right) \tag{B.33}$$

as given. The function $Z^\star$ is allowed to depend on the entire history of sectoral

productions (possibly with some decay) and decreases in its arguments. To ensure that the economy admits a balanced-growth path despite these climate damages, we suppose that $Z^\star$ is homogenous of degree $-z$ where $z \in (0,1)$ controls the extent to which climate damages reduce long-term growth.

Implementability result. ...

C Computational Appendix

C.1 Workers' and Firm's Values

In this appendix, we formulate workers' and firms' values recursively.

States. Workers are indexed by their age j; their relative skill $\hat{\psi}$ in the clean sector; and their employment state s (Section B.1). As shown in Appendix B.4, we do not need to include workers' overall skill ψ in our state space. To save on notation, we let $W_t\left(j,\hat{\psi},s\right) \equiv W_t^\star\left(j,\hat{\psi},s\right)$ denote workers' normalized values defined in Appendix B.4. We define the functions V_t, $\mathcal{O}_t$, θ_t, $p_t$and h and the constants δ_j^+, $\hat{\delta}_j$ and ρ similarly, dropping the $\star$ superscript relative to Appendices B.1 and B.4.

Workers. The value of an employed worker satisfies

$$\begin{aligned}\rho W_t\left(j,\hat{\psi},s\right) = {} & w\left(s\right)h\left(\hat{\psi},k\left(s\right)\right)\\ & + \lambda^E \sum_{s'} p_t\left(s';j,\hat{\psi},s\right) f\left(\theta_t\left(j,\hat{\psi},s'\right)\right)\left[W_t\left(j,\hat{\psi},s'\right) - W_t\left(j,\hat{\psi},s\right)\right]\\ & + \chi_0\left[W_t\left(j,\hat{\psi},U\right) - W_t\left(j,\hat{\psi},s\right)\right]\\ & + \delta_j\left(k\left(s\right)\right)W_t\left(j,\hat{\psi},s\right) + \hat{\psi}\hat{\delta}_j\left(k\left(s\right)\right)\frac{\partial}{\partial\hat{\psi}}W_t\left(j,\hat{\psi},s\right)\\ & + \frac{\partial}{\partial j}W_t\left(j,\hat{\psi},s\right) + \frac{\partial}{\partial t}W_t\left(j,\hat{\psi},s\right) \qquad \text{(C.1)}\end{aligned}$$

for all ages before retirement $j \in [0,J)$, relative productivity $\hat{\psi}$ in the clean sector, and markets $s \equiv (k,w)$. The probability that a worker searches in market s' when

they receive a search opportunity and are employed in sector s is

$$p_t\left(s';j,\hat{\psi},s\right)\equiv\frac{\exp\left(f\left(\theta_t\left(j,\hat{\psi},s'\right)\right)\left[W_t\left(j,\hat{\psi},s'\right)-W_t\left(j,\hat{\psi},s\right)\right]/\zeta\right)}{\sum_{\hat{s}}\exp\left(f\left(\theta_t\left(j,\hat{\psi},\hat{s}\right)\right)\left[W_t\left(j,\hat{\psi},\hat{s}\right)-W_t\left(j,\hat{\psi},s\right)\right]/\zeta\right)} \tag{C.2}$$

In turn, the value of a worker employed in the outside sector is

$$\begin{aligned}\rho W_t\left(j,\hat{\psi},O\right)=&\,h\left(\hat{\psi},O\right)\\&+\lambda^E\sum_s p_t\left(s;j,\hat{\psi},O\right)f\left(\theta_t\left(j,\hat{\psi},s\right)\right)\left[W_t\left(j,\hat{\psi},s\right)-W_t\left(j,\hat{\psi},O\right)\right]\\&+\chi_0\left[W_t\left(j,\hat{\psi},U\right)-W_t\left(j,\hat{\psi},O\right)\right]\\&+\delta_j\left(O\right)W_t\left(j,\hat{\psi},O\right)+\frac{\partial}{\partial j}W_t\left(j,\hat{\psi},O\right)+\frac{\partial}{\partial t}W_t\left(j,\hat{\psi},O\right),\end{aligned} \tag{C.3}$$

Finally, the value of an unemployed worker satisfies

$$\begin{aligned}\rho W_t\left(j,\hat{\psi},U\right)=&\,h\left(\hat{\psi},U\right)\\&+\lambda^U\sum_s p_t\left(s;j,\hat{\psi},U\right)f\left(\theta_t\left(j,\hat{\psi},s\right)\right)\left[W_t\left(j,\hat{\psi},s\right)-W_t\left(j,\hat{\psi},U\right)\right]\\&+\delta_j\left(U\right)W_t\left(j,\hat{\psi},U\right)+\frac{\partial}{\partial j}W_t\left(j,\hat{\psi},U\right)+\frac{\partial}{\partial t}W_t\left(j,\hat{\psi},U\right)\end{aligned} \tag{C.4}$$

The boundary conditions associated to the workers' values are

$$W_t\left(J,\hat{\psi},s\right)=W_t\left(J,\hat{\psi},O\right)=W_t\left(J,\hat{\psi},U\right)=0 \tag{C.5}$$

for all workers $\left(\hat{\psi},s\right)$ when they retire at age $j=J$.

Firms. The value of a firm $V_t\left(j,\hat{\psi},s\right)$ determines the equilibrium tightnesses $\theta_t\left(j,\hat{\psi},s\right)$. The value of a firm, excluding vacancy-posting and current operating costs, satis-

fies

$$
\begin{aligned}
rV_t\left(j,\hat{\psi},s\right) = & \left(A_t^{k(s)} - w\left(s\right)\right) h\left(\hat{\psi},k\right) \\
& - \chi_0 V_t\left(j,\hat{\psi},s\right) \\
& - \lambda^E \sum_{s'} f\left(\theta_t\left(j,\hat{\psi},s'\right)\right) p_t\left(s';j,\hat{\psi},s\right) V_t\left(j,\hat{\psi},s\right) \\
& + \delta_j\left(k\left(s\right)\right) V_t\left(j,\hat{\psi},s\right) + \hat{\psi}\hat{\delta}_j\left(k\left(s\right)\right) \frac{\partial}{\partial\hat{\psi}} V_t\left(j,\hat{\psi},s\right) \\
& + \frac{\partial}{\partial j} V_t\left(j,\hat{\psi},s\right) + \frac{\partial}{\partial t} V_t\left(j,\hat{\psi},s\right), \qquad \text{(C.6)}
\end{aligned}
$$

for all ages before retirement $j \in [0, J)$, relative productivity $\hat{\psi}$ in the clean sector, and markets $s \equiv (k, w)$, where $r \equiv \rho$ is the interest rate. The expression above uses the fact that $\mathcal{P}_t^k = A_t^k$, as we have shown in Appendix B.3. The boundary condition associated with (C.6) is

$$V_t\left(J,\hat{\psi},s\right) = 0 \qquad \text{(C.7)}$$

for all workers $\left(\hat{\psi},s\right)$ when they retire at age $j = J$.

Free entry. The equilibrium tightnesses $\theta\left(j,\hat{\psi},s\right)$ are pinned down by the firms' free entry condition

$$q\left(\theta_t\left(j,\hat{\psi},s\right)\right) V_t\left(j,\hat{\psi},s\right) = \nu \qquad \text{(C.8)}$$

if this equation has a solution, and $\theta_t\left(j,\hat{\psi},s\right) = 0$ otherwise.

C.2 Solving for Workers' and Firms' Values

Discretized system. We start by discretizing the differential equations of Appendix C.1. We let Δ denote the time step between periods t and ages j, and $\hat{\Delta}$ denote the distance between grid points for the relative skill $\hat{\psi}$. We let $\Delta \equiv 1/4$ so each period corresponds to a quarter. Our finite difference scheme is implicit in markets s, i.e., we evaluate the continuation values associated to changes in s in period t. As usual, the coefficients in front of these continuation values are evaluated in $t + \Delta$ to obtain a linear system in the current values. On the contrary, our scheme is explicit in the relative skills $\hat{\psi}$, which allows us to parallelize computation over $\hat{\psi}$ to speed up our code. As usual, the scheme is explicit in age j and time t, i.e., we evaluate

the continuation values associated to aging or the passing of time.

After discretization, the value of being employed becomes

$$\begin{aligned}\rho W_{t+\Delta}\left(j,\hat{\psi},s\right) = & \, w\left(s\right) h\left(\hat{\psi},k\left(s\right)\right) \\ & + \lambda^{E} \sum_{s'} p_{t+\Delta}\left(s';j+\Delta,\hat{\psi},s\right) f\left(\theta_{t+\Delta}\left(j+\Delta,\hat{\psi},s'\right)\right) \\ & \qquad \times \left[W_{t}\left(j,\hat{\psi},s'\right) - W_{t}\left(j,\hat{\psi},s\right)\right] \\ & + \chi_{0}\left[W_{t}\left(j,\hat{\psi},U\right) - W_{t}\left(j,\hat{\psi},s\right)\right] \\ & + \delta_{j}\left(k\left(s\right)\right) W_{t}\left(j,\hat{\psi},s\right) \\ & + \hat{\psi}\hat{\delta}_{j}\left(k\left(s\right)\right) \frac{W_{t+\Delta}\left(j+\Delta,\hat{\psi}+\hat{\Delta}\left(k\left(s\right)\right),s\right) - W_{t+\Delta}\left(j+\Delta,\hat{\psi},s\right)}{\hat{\Delta}\left(k\left(s\right)\right)} \\ & + \frac{W_{t+\Delta}\left(j+\Delta,\hat{\psi},s\right) - W_{t}\left(j,\hat{\psi},s\right)}{\Delta} \end{aligned} \tag{C.9}$$

for all markets $s \equiv (k, w)$ excluding the outside sector and unemployment, where $\Delta > 0$ denotes the time step. In turn, the step $\hat{\Delta}$ for the relative skill $\hat{\psi}$ depends on which sector the worker is employed. With an abuse of notation, we let $\hat{\Delta}\left(k\left(s\right)\right) \equiv \hat{\Delta}$ when $k\left(s\right) = C$ and $\hat{\psi}$ increases and $\hat{\Delta}\left(k\left(s\right)\right) \equiv -\hat{\Delta}$ when $k\left(s\right) = P$ and $\hat{\psi}$ decreases.

In turn, value of being employed in the outside sector O satisfies

$$\begin{aligned}\rho W_{t+\Delta}\left(j,\hat{\psi},O\right) = & \, h\left(\hat{\psi},O\right) \\ & + \lambda^{E} \sum_{s} p_{t+\Delta}\left(s;j+\Delta,\hat{\psi},O\right) f\left(\theta_{t+\Delta}\left(j+\Delta,\hat{\psi},s\right)\right) \\ & \qquad \times \left[W_{t}\left(j,\hat{\psi},s\right) - W_{t}\left(j,\hat{\psi},O\right)\right] \\ & + \chi_{0}\left[W_{t}\left(j,\hat{\psi},U\right) - W_{t}\left(j,\hat{\psi},O\right)\right] \\ & + \delta_{j}\left(O\right) W_{t}\left(j,\hat{\psi},O\right) + \frac{W_{t+\Delta}\left(j+\Delta,\hat{\psi},O\right) - W_{t}\left(j,\hat{\psi},O\right)}{\Delta} \end{aligned} \tag{C.10}$$

and the value of being unemployed satisfies

$$\begin{aligned}\rho W_{t+\Delta}\left(j,\hat{\psi},U\right) = & \, b^{U} \\ & + \lambda^{U}\sum_{s} p_{t+\Delta}\left(s;j+\Delta,\hat{\psi},U\right) f\left(\theta_{t+\Delta}\left(j+\Delta,\hat{\psi},s\right)\right) \\ & \qquad \times\left[W_{t}\left(j,\hat{\psi},s\right)-W_{t}\left(j,\hat{\psi},U\right)\right] \\ & + \delta_{j}\left(U\right) W_{t}\left(j,\hat{\psi},U\right) + \frac{W_{t+\Delta}\left(j+\Delta,\hat{\psi},U\right)-W_{t}\left(j,\hat{\psi},U\right)}{\Delta}\end{aligned} \tag{C.11}$$

Finally, the value of a firm becomes

$$\begin{aligned}rV_{t+\Delta}\left(j,\hat{\psi},s\right) = & \left(A_{t}^{k(s)}-w\left(s\right)\right) h\left(\hat{\psi},k\left(s\right)\right) \\ & - \chi_{0} V_{t}\left(j,\hat{\psi},s\right) \\ & - \lambda^{E}\sum_{s'} f\left(\theta_{t+\Delta}\left(j+\Delta,\hat{\psi},s'\right)\right) p_{t+\Delta}\left(s';j+\Delta,\hat{\psi},s\right) V_{t}\left(j,\hat{\psi},s\right) \\ & + \delta_{j}\left(k\left(s\right)\right) V_{t}\left(j,\hat{\psi},s\right) \\ & + \hat{\psi}\hat{\delta}_{j}\left(k\left(s\right)\right)\frac{V_{t+\Delta}\left(j+\Delta,\hat{\psi}+\hat{\Delta}\left(k\left(s\right)\right),s\right)-V_{t+\Delta}\left(j+\Delta,\hat{\psi},s\right)}{\hat{\Delta}\left(k\left(s\right)\right)} \\ & + \frac{V_{t+\Delta}\left(j+\Delta,\hat{\psi},s\right)-V_{t}\left(j,\hat{\psi},s\right)}{\Delta},\end{aligned} \tag{C.12}$$

for all markets $s \equiv (k, w)$.

Workers' and firms' values are characterized by the system (C.9)–(C.12) together with the boundary conditions (C.5) and (C.7), the search probabilities (C.2), and the free entry condition (C.8) that pins down θ_t. Note that this system is independent of the distribution of workers' states — this is the block-recursive property of directed search model (Menzio and Shi, 2011).

Numerical solution. We explain below how we solve for workers' and firms' values.

Algorithm. Solve for workers' and firms' values.

Step 0. Let the terminal values for workers $W_T\left(J,\hat{\psi},s\right)$, $W_T\left(J,\hat{\psi},O\right)$ and $W_T\left(J,\hat{\psi},U\right)$ and firms $V_T\left(J,\hat{\psi},s\right)$ satisfy the boundary conditions (C.5) and (C.7) at retirement at age J. Initiate the recursion by setting the time index to $t = T - \Delta$ and the age index to $j = J - \Delta$.

Step 1. Compute the search probabilities $p_{t+\Delta}\left(s';j+\Delta,\hat{\psi},s\right)$ using (C.2), and the

tightnesses $\theta_{t+\Delta}\left(j+\Delta,\hat{\psi},s\right)$ using (C.8).

Step 2. Solve for workers' values:

Solve for the values

$$\mathbf{W}_t\left(j,\hat{\psi}\right)=\Delta\left\{\mathbf{B}_t\left(j,\hat{\psi}\right)+\left[\mathbf{M}_{t+\Delta}\left(j+\Delta,\hat{\psi}\right)+\mathbf{\Lambda}\right]\mathbf{W}_{t+\Delta}\left(j,\hat{\psi}\right)\right\}, \tag{C.13}$$

where the vector $\mathbf{W}_t\left(j,\hat{\psi}\right)$ contains workers' values, the matrix $\mathbf{M}_{t+\Delta}\left(j+\Delta,\hat{\psi}\right)$ captures workers' transitions across states that are part of the implicit scheme, the vector $\mathbf{B}_t\left(j,\hat{\psi}\right)$ contains workers' flow earnings and the transitions that are part of the explicit scheme, and the matrix $\mathbf{\Lambda}$ captures discounting and the evolution of the overall skill ψ which we do need keep track of in our state space. Formally, workers' values are

$$\mathbf{W}_t\left(j,\hat{\psi}\right)_{[s,1]}\equiv W_t\left(j,\hat{\psi},s\right), \tag{C.14}$$

the transition matrix is

$$\mathbf{M}_t\left(j,\hat{\psi}\right)\equiv\begin{bmatrix}\mathbf{M}_{1,1,t}\left(j,\hat{\psi}\right) & \mathbf{M}_{1,2,t}\left(j,\hat{\psi}\right) & \mathbf{M}_{1,3,t}\left(j,\hat{\psi}\right)\\ \mathbf{M}_{2,1,t}\left(j,\hat{\psi}\right) & M_{2,2,t}\left(j,\hat{\psi}\right) & M_{2,3,t}\left(j,\hat{\psi}\right)\\ \mathbf{M}_{3,1,t}\left(j,\hat{\psi}\right) & M_{3,2,t}\left(j,\hat{\psi}\right) & M_{3,3,t}\left(j,\hat{\psi}\right)\end{bmatrix}, \tag{C.15}$$

and the flows and discounting are

$$\mathbf{B}_t\left(j,\hat{\psi}\right)\equiv\begin{bmatrix}\mathbf{B}_{1,t}\left(j,\hat{\psi}\right)\\ B_{2,t}\left(j,\hat{\psi}\right)\\ B_{3,t}\left(j,\hat{\psi}\right)\end{bmatrix}\quad,\quad\mathbf{\Lambda}\equiv\begin{bmatrix}\mathbf{A}_1 & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & A_2 & 0\\ \mathbf{0} & 0 & A_3\end{bmatrix} \tag{C.16}$$

We start by describing the terms involving workers employed in the polluting or clean sectors, i.e., $s\neq O,U$. We define the square matrix

$$\begin{aligned}\mathbf{M}_{1,1,t}\left(j,\hat{\psi}\right)_{[s,s']}\equiv{}&\lambda^E p_{t+\Delta}\left(s';j+\Delta,\hat{\psi},s\right)f\left(\theta_{t+\Delta}\left(j+\Delta,\hat{\psi},s'\right)\right)\\&+\mathbf{N}_t\left(j,\hat{\psi}\right)_{[s,s']}\end{aligned} \tag{C.17}$$

with

$$\mathbf{N}_t\left(j,\hat{\psi}\right)_{[s,s']} \equiv \begin{cases} -\lambda^E \sum_{\hat{s}} p_{t+\Delta}\left(\hat{s}; j+\Delta, \hat{\psi}, s\right) f\left(\theta_{t+\Delta}\left(j+\Delta,\hat{\psi},\hat{s}\right)\right) & \text{if } s'=s \\ -\chi_0 \mathcal{F}^{k(s)}\left(V_{t+\Delta}\left(j+\Delta,\hat{\psi},s\right)\right) & \\ 0 & \text{otherwise} \end{cases},$$

and the column vectors

$$\mathbf{M}_{1,2,t}\left(j,\hat{\psi}\right)_{[s,1]} = \lambda^E p_{t+\Delta}\left(O; j+\Delta,\hat{\psi},s\right) \tag{C.18}$$

$$\begin{aligned}\mathbf{M}_{1,3,t}\left(j,\hat{\psi}\right)_{[s,1]} =& \lambda^E p_{t+\Delta}\left(U; j+\Delta,\hat{\psi},s\right) \\ &+ \chi_0 \mathcal{F}^{k(s)}\left(V_{t+\Delta}\left(j+\Delta,\hat{\psi},s\right)\right)\end{aligned} \tag{C.19}$$

where we have used the fact that workers can transition instantaneously to the outside sector or unemployment if they are given the opportunity to search. We also define the column vectors

$$\begin{aligned}\mathbf{B}_{1,t}\left(j,\hat{\psi}\right)_{[s,1]} \equiv & w(s)\, h\left(\hat{\psi}, k(s)\right) \\ &+ \hat{\psi}\hat{\delta}\left(k(s)\right) \frac{W_{t+\Delta}\left(j+\Delta,\hat{\psi}+\hat{\Delta}\left(k(s)\right),s\right) - W_{t+\Delta}\left(j+\Delta,\hat{\psi},s\right)}{\hat{\Delta}\left(k(s)\right)},\end{aligned} \tag{C.20}$$

and the diagonal matrix

$$\mathbf{\Lambda}_{1[s,s']} = \begin{cases} \frac{1}{\Delta} + \delta_j\left(k(s)\right) - \rho & \text{if } s'=s \\ 0 & \text{otherwise} \end{cases} \tag{C.21}$$

We now turn to workers employed in the outside sector, i.e., $s = O$. We define the row vector

$$\mathbf{M}_{2,1,t}\left(j,\hat{\psi}\right)_{[1,s]} \equiv \lambda^E p_{t+\Delta}\left(s; j+\Delta,\hat{\psi},O\right) f\left(\theta_{t+\Delta}\left(j+\Delta,\hat{\psi},s\right)\right), \tag{C.22}$$

the scalar

$$\begin{aligned} M_{2,2,t}\left(j,\hat{\psi}\right) = & \lambda^{E} p_{t+\Delta}\left(O; j+\Delta, \hat{\psi}, O\right) \\ & - \lambda^{E} \sum_{s} p_{t+\Delta}\left(s; j+\Delta, \hat{\psi}, O\right) f\left(\theta_{t+\Delta}\left(j+\Delta, \hat{\psi}, s\right)\right) \\ & - \chi_0 \bar{\mathcal{F}} \end{aligned} \tag{C.23}$$

with $\bar{\mathcal{F}}$ denoting the exogenous separation hazard in $s = O$, and the scalar

$$M_{2,3,t}\left(j,\hat{\psi}\right) \equiv \lambda^{E} p_{t+\Delta}\left(U; j+\Delta, \hat{\psi}, O\right) + \chi_0 \bar{\mathcal{F}}. \tag{C.24}$$

We also define the scalars

$$B_{2,t}\left(j,\hat{\psi}\right) \equiv h\left(\hat{\psi}, O\right) \tag{C.25}$$

and

$$\Lambda_2 \equiv \frac{1}{\Delta} + \delta_j\left(O\right) - \rho \tag{C.26}$$

Finally, we consider unemployment workers, i.e., $s = U$. We define the row vector

$$\mathbf{M}_{3,1,t}\left(j,\hat{\psi}\right)_{[1,s]} \equiv \lambda^{U} p_{t+\Delta}\left(s; j+\Delta, \hat{\psi}, U\right) f\left(\theta_{t+\Delta}\left(j+\Delta, \hat{\psi}, s\right)\right), \tag{C.27}$$

the scalar

$$M_{3,2,t}\left(j,\hat{\psi}\right) = \lambda^{U} p_{t+\Delta}\left(O; j+\Delta, \hat{\psi}, U\right), \tag{C.28}$$

and the scalar

$$\begin{aligned} M_{3,3,t}\left(j,\hat{\psi}\right) \equiv & \lambda^{U} p_{t+\Delta}\left(U; j+\Delta, \hat{\psi}, U\right) \\ & - \lambda^{U} \sum_{s} p_{t+\Delta}\left(s; j+\Delta, \hat{\psi}, U\right) f\left(\theta_{t+\Delta}\left(j+\Delta, \hat{\psi}, s\right)\right). \end{aligned} \tag{C.29}$$

We also define the scalars

$$B_{3,t}\left(j,\hat{\psi}\right) \equiv b^{U} \tag{C.30}$$

and

$$\Lambda_3 \equiv \frac{1}{\Delta} + \delta_j(U) - \rho. \tag{C.31}$$

Step 3. Solve for the firms' values:

Solve for the values by inverting the system

$$\mathbf{V}_t\left(j,\hat{\psi}\right) = \Delta\left\{\mathbf{D}_t\left(j,\hat{\psi}\right) + \left[\mathbf{P}_{t+\Delta}\left(j+\Delta,\hat{\psi}\right) + C\right]\mathbf{V}_{t+\Delta}\left(j,\hat{\psi}\right)\right\}, \tag{C.32}$$

where the vector $\mathbf{V}_t\left(j,\hat{\psi}\right)$ contains firms' values, the matrix $\mathbf{P}_{t+\Delta}\left(j+\Delta,\hat{\psi}\right)$ captures workers' transitions across states that are part of the implicit scheme, the vector $\mathbf{D}_t\left(j,\hat{\psi}\right)$ contains firms' flow profits and the transitions that are part of the explicit scheme, and the scalar C captures discounting and the evolution of the overall skill ψ which we do need keep track of in our state space. Formally, the firms' values are

$$\mathbf{V}_t\left(j,\hat{\psi}\right)_{[s,1]} \equiv V_t\left(j,\hat{\psi},s\right), \tag{C.33}$$

with the square matrix

$$\mathbf{P}_t\left(j,\hat{\psi}\right)_{[s,s']} \equiv \begin{cases} -\lambda^E \sum_{\hat{s}} f\left(\theta_{t+\Delta}\left(j+\Delta,\hat{\psi},\hat{s}\right)\right) p_{t+\Delta}\left(\hat{s};j+\Delta,\hat{\psi},s\right) & \text{if } s'=s \\ -\chi_0 \mathcal{F}\left(V_{t+\Delta}\left(j+\Delta,\hat{\psi},s\right)\right) & \\ 0 & \text{otherwise} \end{cases},$$

the column vector

$$\begin{aligned} \mathbf{D}_t\left(j,\hat{\psi}\right)_{[s,1]} = & \left(A_t^{k(s)} - w(s)\right) h\left(\hat{\psi},k(s)\right) - \chi_0 \mathcal{O}_{t+\Delta}\left(j+\Delta,\hat{\psi},s\right) \\ & + \hat{\psi}\hat{\delta}\left(k(s)\right) \frac{V_{t+\Delta}\left(j,\hat{\psi}+\hat{\Delta}\left(k(s)\right),s\right) - V_{t+\Delta}\left(j,\hat{\psi},s\right)}{\hat{\Delta}\left(k(s)\right)}, \end{aligned} \tag{C.34}$$

and the scalar

$$C_{[s,s']} = \begin{cases} \frac{1}{\Delta} + \delta_j\left(k(s)\right) - r & \text{if } s'=s \\ 0 & \text{otherwise} \end{cases}. \tag{C.35}$$

Step 4. Set the age $j' = j - \Delta$, repeat Steps 1–3, and continue until $j = 0$.

Step 5. When solving for transitions, set $t' = t - \Delta$, repeat Steps 1–4 in that period, and continue until $t = 0$. This last step is redundant when solving for steady state values.

In principle, the finite difference scheme described above could become unstable if the diagonal elements of $\Delta \times \mathbf{M}_{t+\Delta}\left(j+\Delta, \hat{\psi}\right)$ and $\Delta \times \mathbf{P}_{t+\Delta}\left(j+\Delta, \hat{\psi}\right)$ exceed 1 in absolute value. This occurs, for instance, if the worker is fired with probability 1 but can also perform a job-to-job transition. To address this issue, we truncate the diagonal elements to ensure that they are bounded by 1 and re-scale the off-diagonal elements proportionately to make sure that the rows sum up to 0.

C.3 Distribution of Workers' States

We denote the density of workers' states by $\mu_t(\mathbf{x})$. This density is a continuous function of age j and the relative productivity in the clean sector $\hat{\psi}$, and a discrete function of the sector k. While the wage w is a continuous variable, only a subset of markets are active in equilibrium. Therefore, the distribution admits mass points along this continuous dimension. Accordingly, we define an integral of the form $\int f(s, \mathbf{x}_{-1})\, \mu_t(ds, \mathbf{x}_{-1})$ as a discrete sum over markets $s \equiv (k, w)$ with positive mass, where $\mathbf{x}_{-1}$ denotes the other states. As in Appendix C.1, we do not keep track of a worker's overall skill ψ when iterating over the distribution.

As usual, the law of motion of the distribution is closely related to the recursive formulation of workers' values (Appendix C.2). In fact, the matrix $\mathbf{M}_t(j, \omega)$ encodes the information required to iterate on the distribution. This is intuitive: this matrix captures the outflows from the current state and the inflows into subsequent ones. The only flows that are not captured by $\mathbf{M}_t(j, \omega)$ are the changes in the relative productivity in the clean sector $\hat{\psi}$ that are included in $\mathbf{B}_t\left(j, \hat{\psi}\right)$ as part of the explicit scheme.

Abstracting momentarily from changes in $\hat{\psi}$, the law of motion for the distribution is

$$\frac{d}{dt}\boldsymbol{\mu}_t\left(j, \hat{\psi}\right) = \mathbf{M}_t(j, \omega)'\, \boldsymbol{\mu}_t\left(j, \hat{\psi}\right) \tag{C.36}$$

for all ages $j \in [0, J-\Delta)$, where

$$\begin{gathered}\boldsymbol{\mu}_t\left(j,\hat{\psi}\right)_{[s,1]} \equiv \mu_t\left(j,\hat{\psi},s\right) \quad \boldsymbol{\mu}_t\left(j,\hat{\psi}\right)_{[\text{end-1},1]} \equiv \mu_t\left(j,\hat{\psi},O\right) \\ \boldsymbol{\mu}_t\left(j,\hat{\psi}\right)_{[\text{end},1]} \equiv \mu_t\left(j,\hat{\psi},U\right)\end{gathered} \tag{C.37}$$

Integrating (C.36) over a short time interval Δ,

$$\boldsymbol{\mu}_{t+\Delta}\left(j,\hat{\psi}\right) = \boldsymbol{\mu}_t\left(j-\Delta,\hat{\psi}\right)\exp\left(\mathbf{M}_t\left(j,\hat{\psi}\right)'\Delta\right), \tag{C.38}$$

where $\exp(X) \equiv \sum_{k=0}^{\infty} 1/k!X^k$ is the matrix exponential. We iterate on (C.38) separately over consecutive intervals of length Δ over which the transition matrices are kept constant. The non-linear formulation (C.38) is computationally more intensive compared to a simple linear approximation of expression (C.36). However, it allows us to compute workers' values over relative long time intervals, e.g., quarterly $\Delta \equiv 1/4$, while still accounting for multiple, high-frequency changes in employment status that occur over these intervals or shorter ones. Doing so is important to ensure that our model-simulated moments (such as monthly job flows) are consistent with their empirical counterparts measured in the CPS (Appendix C.4).

As mentioned, the law of motion above does not account for changes in the relative productivity $\hat{\psi}$ in our explicit scheme. We adopt a simple approach to account for these transitions. We let

$$\boldsymbol{\mu}_{t+\Delta}\left(j,\hat{\psi}\right) = \sum_{\tilde{\psi}} \mathbf{Q}\left(\hat{\psi},\tilde{\psi}\right)\boldsymbol{\mu}_t\left(j-\Delta,\tilde{\psi}\right)\exp\left(\mathbf{M}_t\left(j,\tilde{\psi}\right)'\Delta\right), \tag{C.39}$$

where the sum is over the initial relative productivities $\tilde{\psi}$. The matrices $\mathbf{Q}\left(\hat{\psi},\tilde{\psi}\right)$ are diagonal and the elements $[s,s]$ indicate whether $\hat{\psi}$ changes or not depending on workers' current employment status s. If the worker is employed in the clean or polluting sectors, i.e., $k(s) = P, C$, then the relative productivity evolves deterministically by $\hat{\delta}\left(k(s)\right)\Delta$ after a time step Δ. When this new value does not fall on a grid point for $\hat{\psi}$, we allocate the corresponding mass to the neighboring points following the non-stochastic simulation method of Young (2010). Accordingly, we

set the diagonal elements to

$$\mathbf{Q}_t\left(\hat{\psi},\tilde{\psi}\right)_{[s,s]} \equiv \begin{cases} 1-q\left(\hat{\psi},\tilde{\psi},s\right) & \text{if } \hat{\psi}=\hat{\psi}_0\left(\tilde{\psi},s\right) \\ q\left(\hat{\psi},\tilde{\psi},s\right) & \text{if } \hat{\psi}=\hat{\psi}_1\left(\tilde{\psi},s\right), \\ 0 & \text{otherwise} \end{cases} \tag{C.40}$$

where $\hat{\psi}_0\left(\tilde{\psi},s\right)$ is the largest point on the grid for relative productivities that is smaller or equal to $\tilde{\psi}+\hat{\delta}\left(k\left(s\right)\right)\Delta$ and $\hat{\psi}_1\left(\hat{\psi},\tilde{\psi},s\right) \equiv \hat{\psi}_0\left(\tilde{\psi},s\right)+\hat{\Delta}$ is the smaller point that is strictly larger than it, and $q\left(\hat{\psi},\tilde{\psi},s\right) \equiv \left(\hat{\psi}-\tilde{\psi}-\hat{\delta}\left(k\left(s\right)\right)\right)/\hat{\Delta}$ assigns masses in inverse proportion to the distance between $\tilde{\psi}+\hat{\delta}\left(k\left(s\right)\right)\Delta$ and the closest grid points. All the off-diagonal elements are zero.

An alternative approach would be to extend the law of motion (C.38) by stacking the vectors $\boldsymbol{\mu}_{t+\Delta}\left(j,\hat{\psi}\right)$ for all values of $\hat{\psi}$, and define a larger transition matrix that also accounts for flows between values of $\hat{\psi}$. This approach turns out to be computationally demanding since this new transition matrix is very large and the formulation prevents numerical parallelization. The only difference between our approach (C.39) and this alternative one is that we suppose that the state $\hat{\psi}$ evolves only once at the end of the time interval Δ, whereas the alternative approach accounts for its evolution over this interval.

Finally, the law of motion (C.39) has a boundary at age $j=J$ when workers retire. The flow of retirees, and hence newborns, is

$$\mu_t^R = \int\int \mu_{t-\Delta}\left(J,d\hat{\psi},ds\right) \tag{C.41}$$

Newborn workers are endowed with an overall skill $\psi=1$ and a relative skill $\hat{\psi}\sim G$. Accordingly, the distribution of workers' states among newborn workers is

$$\mu_t\left(0,\hat{\psi},s\right) = \begin{cases} \mu_t^R \times G\left(d\hat{\psi}\right) & \text{if } s=U \\ 0 & \text{otherwise} \end{cases} \tag{C.42}$$

Stationary distribution and transition. The economy starts from a stationary distribution where the clean sector is absent, i.e., $A^C \equiv 0$. We normalize the stationary distribution so it has a unit mass.

C.4 Calibration

We discretize our continuous time model into short periods corresponding to a quarter, i.e., $\Delta \equiv 1/4$. We explain below how we compute the moments that we use in our steady state calibration (Section 5.2).

State space reduction in initial steady state. First off, it is useful to note that our initial steady state does not depend on the distribution G of relative skill $\hat{\psi}$ in the clean sector, since that sector is effectively absent with $A^C = 0$ (Section 3.2). This property can easily be shown by guessing and verifying that $W_t\left(j, \hat{\psi}, s\right) = W_t\left(j, s\right)$ and $V_t\left(j, \hat{\psi}, s\right) = V_t\left(j, s\right)$ for any $\hat{\psi}$ and employment state s at the initial state, since the worker never supplies labor in the clean sector.[57] The derivation is similar to Appendix B.4, so we omit it here. Furthermore, the initial steady state does not depend on $\hat{\delta}_j$ directly, only on $\delta_j^+ + \hat{\delta}_j$ which we directly measure in the data (Section 5.2). When it comes to our steady state calibration, we can therefore normalize $\hat{\psi} = 1$ and set $\hat{\delta} = 0$, without loss of generality, as we discipline ten parameters internally. Once these parameters are calibrated, we can structurally estimate the distribution G and the rate $\hat{\delta}$ using reallocation flows over the transition. As we explain in Section 6.2, this structural estimation involves simulating the initial steady state, accounting for the endogenous evolution of $\hat{\psi}$ which is relevant for the subsequent transition, and then simulating workers forward over this transition.

Employment flows. We compute the EE, EU and UE probabilities over one month, i.e., $T \equiv 1/12$. When doing so, we account for the possibility that workers might experience multiple job transitions within the same month. For instance, a worker who first experiences an EU transition followed by an UE one during the same month will be counted in the EE probability, which ensures that our moment is comparable to the EE probability as measured in the CPS.

To compute the EU probability, we use the law of motion (C.38) since we do not account for changes in $\hat{\psi}$ within a month. We make two changes compared to this law of motion. First, we initialize it using the distribution of states conditional

[57] When doing so, we use the fact that: $h\left(\hat{\psi}, s\right) = h\left(s\right)$ does not depend on $\hat{\psi}$ whenever the worker is employed in the polluting sector or the outside sector, or is unemployed; $\frac{\partial}{\partial \hat{\psi}} W_t\left(j, \hat{\psi}, s\right) = 0$ for all employment states since $W_t\left(j, \hat{\psi}, s\right) = W_t\left(j, s\right)$ under our guess; and $\theta_t\left(j, s\right) = 0$ and hence $f\left(\theta_t\left(j, s\right)\right) = 0$ in the clean sector since $A^C = 0$.

on employment $\boldsymbol{\mu}_t^E$ instead of the unconditional distribution $\boldsymbol{\mu}_t$. Second, we set the time step to $T = 1/12$ instead of $\Delta = 1/4$. We use this new law of motion for all ages j and productivities $\hat{\psi}$. The EU probability corresponds to the mass of workers with state $s = U$ after a month. We proceed analogously to compute the UE probability.

Similarly, we combine two moments to compute the EE probability over a month: the probability that an employed worker is again employed in a month in *any* market (computed in a way that is similar to the one described above); and the probability that the worker stays in their current job.[58] The EE probability is the difference between the these two quantities. To compute the second moment, we use the same law of motion as before, except with an alternative matrix $\widetilde{\mathbf{M}}_t\left(j, \hat{\psi}\right)$ in which all the *inflows*, i.e., the negative terms, are all zero. This matrix lets workers "flow out" of the system as they move out of their current job. The mass of workers who remain after a month is the probability that a worker stays in the current job.

Elasticity of the separation probability w.r.t. output change. We compute the elasticity of the separation probability following an idiosyncratic, permanent and unanticipated decrease $\alpha \in (0, 1)$ in a firm's output. We compute this elasticity over the year following the shock to be consistent with our empirical target (Chan et al., 2023). This is a partial equilibrium exercise that only affects one firm and its worker. All aggregate quantities remain unchanged and so are workers' outside options. We then compute the average response across workers whose firms is subject to this change.

The first step consists of computing alternative values for the workers $\widehat{W}_t\left(j, \hat{\psi}, s\right)$ and firms $\widehat{V}_t\left(j, \hat{\psi}, s\right)$ that are subject to this shock. These new values satisfy recursions similar to the ones of Appendix C.2 with a few differences. First, output is now $(1-\alpha) A_t^{k(s)} h\left(\hat{\psi}, k\left(s\right)\right)$. Second, the continuation values $W_t\left(j, \hat{\psi}, s\right)$ in *other markets* (or employment states) are treated as exogenous in expression (C.9) and evaluated at steady state since the outside options are unchanged.[59] The worker's job finding probabilities $f\left(\theta_t\left(j, \hat{\psi}, s\right)\right)$ are also exogenous. In contrast,

[58] A worker who leaves their current job for unemployment and then moves back to the same market (but a different job) is still counted in the EE probability to be consistent with the data.

[59] However, the continuation values associated to changes in $\hat{\psi}$ are endogenous.

Table 3: Internal calibration

Parameter	Description	Walras	+ Unempl	+ Gross	+ OJS	+ Outside
Search						
λ^U	Search intensity (U)	—	9.332	8.492	8.280	5.973
λ^E	Search intensity (E)	—	0	0	1.569	1.185
ζ	Search Directedness	—	0	0.023	0.023	0.035
Job creation & destruction						
ν	Vacancy post. cost	—	0.932	0.879	0.382	0.437
ϕ	Job destruction rate	—	0.072	0.073	0.071	0.070
Benefits						
b^O	Benefit in O	—	0	0	0	0.642
b^U	Benefit in U	—	0.354	0.354	0.351	0.343

the search behavior of employed workers and $\hat{p}_t\left(s';j,\hat{\psi},s\right)$ and firms' firing decisions $\mathcal{F}\left(\hat{V}_t\left(j,\hat{\psi},s\right)\right)$ are endogenous. In our comparative statics, we consider a permanent productivity change of $\alpha = 0.1$.

The second step consists of computing the average separation probability at the annual level ($T \equiv 1$) associated to these values. This moment captures *any* separation that occurs during the year — either when a firm lays off a worker, or when a worker moves to another employer. This probability is given by one minus the probability that a worker stays in their current job. This moment is computed as we described above, except that account for changes in the relative skill $\hat{\psi}$ over this longer period by using the law of motion (C.39). Finally, we compare this new separation probability to the one that prevails in steady state and we express this change as an elasticity in terms of $1-\alpha$.

Calibrated parameters. Table 3 describes the calibration across models.

D Details on Climate Application

D.1 Sector Definitions

As discussed in the main text, there have been many attempts to define clean and polluting industries. Our baseline sector definitions use data from the US Environmental Protection Agency (EPA), Bureau of Labor Statistics (BLS) and the OECD's list of green goods and services. To define dirty industries, we use data on emissions intensity – measured as the kilograms of CO2-equivalent gas emissions per dollar of output – by 6-digit NAICS industry codes from the Supply Chain Greenhouse Gas Emission Factors published by the Environmental Protection Agency (EPA), which accounts for emissions produced throughout the supply chain of production of each commodity. An industry is deemed to be dirty if it is in the top decile of emissions intensities, weighted by employment. Employment information comes from the Quarterly Census of Employment and Wages (QCEW), which is a quarterly census of the total total employment and average wages of all establishments in the United States.

These emissions data do not provide information on emissions in the energy sector and are missing for some other key sectors. Some sectors are not polluting themselves, but produce polluting output. We therefore handcode some additional sectors as polluting. These sectors are: "Fossil fuel electric power generation," "Crude Oil & Natural Gas Extraction," various coal mining sectors (NAICS 212114, 212115, 213111, 213112), "Manufacturing of oil and gas field machinery," "Pipelines for oil and gas," "Petroleum product manufacturing," "Petroleum merchant wholesalers," "Construction of oil and gas pipelines," "Pipelines for oil and gas," and "Coal and other mineral merchant wholesalers."

To define "clean" sectors, we combine two approaches as described in the main text. First, we follow the output based approach of Bontadini and Vona (2023), who find that 95% of the production of "green goods"[60] is concentrated in just 13 out of 119 4-digit European NACE industries and that green and polluting production does not occur in the same sector. We classify these 13 European sectors – Bicycle

[60] The list of green goods employed by Bontadini and Vona (2023) is based on the Combined List of Environmental Goods (CLEG) of the OECD and considers goods which are useful for the green transition. For instance, solar panels and wind turbines are classified as "green goods" even if their production is emission-intensive, since the goods themselves are green by nature.

manufacturing, manufacture of railway locomotives, manufacture of steam generators, shaping and processing of flat glass (which is used for solar panels), manufacture of electricity distribution and control apparatus, manufacture of instruments and appliances for measuring/testing, manufacture of cooling/ventilation equipment, manufacture of engine and turbines excluding aircraft and gasoline engines, manufacture of electronic components, manufacture of electric lighting equipment, manufacture of non-electric domestic appliances and installation of industrial machinery and equipment – as clean. Examples of the 54 NAICS sectors that are green by this definition include "Automatic environmental control manufacturing," "Electric power and specialty transformer manufacturing," and "Turbine and turbine generator set units manufacturing."

We supplement this output-based approach with the task-based approach employed by the US Energy Employment Report (Granholm (2024)). We use data from the 2012 Green Goods and Services (GGS) survey produced by US Bureau of Labor Statistics (BLS) to study the share of workers employed in each industry that are engaged in green tasks and define a sector as clean if at least 50% of their employees work on green tasks. The BLS GGS surveys workers in 325 6-digit NAICS industries and encodes green activities as either 1) producing energy from renewable sources (60 sectors), 2) energy efficiency (132 sectors), 3) pollution reduction and removal, greenhouse gas reduction, and recycling and reuse (122 sectors), 4) natural resource conservation (74 sectors), or 5) environmental compliance, education and training, and public awareness (45 sectors; sectors can belong to more than one category). Finally, we handcode battery manufacturing as green, since this is a crucial input to electrification of transport, and is not included in these other definitions.

Table 4 reports the 5 largest polluting and clean sectors according to 2019 employment. The largest polluting sectors are gas stations, sectors related to delivery, air travel and plastic product manufacturing. The largest clean sectors are semiconductor manufacturing (a key input to solar panels), other motor vehicle parts manufacturing (which includes car batteries), and recyclable material merchant wholesalers. Around 12 million jobs remain in the polluting sectors as of 2019, suggesting substantial scope for job displacement still to come.

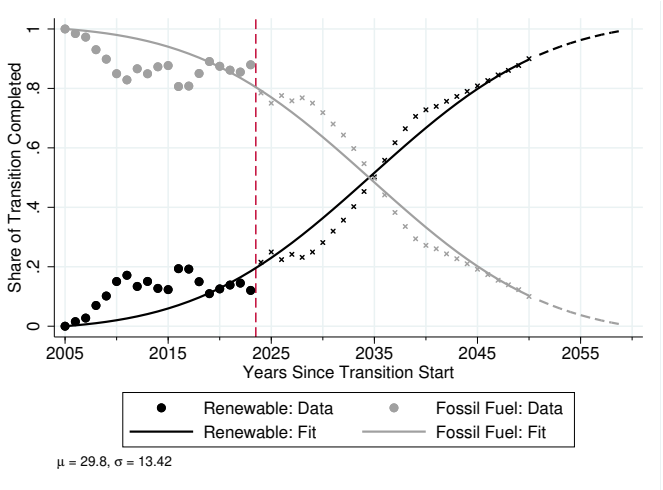
To calibrate the shape of the S-curve for productivity $\bar{\Phi}(t)$, we use data from the US Energy Information Authority (US EIA), who provide information and pro-

Table 4: Largest Polluting and Clean Industries

Industry	2019 Employment (000s)
Polluting	
Gasoline stations with convenience stores	840.4
Couriers and express delivery services	707.0
General freight trucking, long-distance	524.2
Scheduled passenger air transportation	447.5
Plastics product manufacturing (other)	306.8
TOTAL	11,945
Clean	
Semiconductors and related device mfg.	184.6
Other motor vehicle parts mfg.	156.1
Search, detection, and navigation instruments	133.9
Recyclable material merchant wholesalers	103.1
Remediation services	91.7
TOTAL	2,280

jections on energy production by type from 2005 to 2050. We assume $\bar{\Phi}^D(t) = 1 - \bar{\Phi}^C(t)$ so the transition is symmetric. We calculate the share of energy produced by fossil fuels and renewable sources in every year. We then normalize the share of the transition that is complete as of 2005 to be 0, and then assume that the projected shares in 2050 constitute 90% of the transition being completed. This yields the data points in Figure 10. We then fit a normal CDF, truncated between 2005 (year 0) and 2060 (year 55). We estimate that the mean of the underlying normal distribution is 29.8 (i.e. half of the transition will be completed by the year 2035) and the standard deviation is 13.42.

Figure 10: Estimated S-curve of energy generation transmission



Notes: This figure plots the estimated $\Phi^k(t)$ in equation (3.3), which is assumed to take truncated normal CDF. Data come from the US Energy Information Administration (EIA)'s. Dashed lines indicate projections through 2060.

D.2 Current Population Survey – Cleaning and Targets

The source of many of the moments used in our calibration is the Current Population Survey (CPS), which is a large, nationally-representative survey of U.S. households. The CPS has a rotating panel structure whereby households enter the sample for a four-month rotation, before leaving for 8 months and returning for a subsequent four months. All individuals within a household are surveyed, and one can link individuals through time so long as they remain at the same address throughout the sample period. In addition, respondents are asked additional questions about their usual weekly earnings and hourly wage in the final month of each rotation (month 4 and 8 in the sample). We use the IPUMS sample produced by Flood et al. (2024). We restrict attention to those aged 25 to 65 in surveys years 2000 through 2025, and use the survey to measure employment in clean and polluting sectors, as well as wage changes as one switches from polluting to other sectors.

To construct these moments, we must merge our sector definitions with the industries in the CPS. The CPS uses Census industry codings, which are generally at a coarser level of granularity than 6-digit NAICS codes. We use Census industry to NAICS crosswalks provided by the Census, available here. We assign CPS indus-

try codes a polluting versus clean status iteratively. We first merge our CPS data, which now include NAICS codings, with our classifications at the 6-digit level. Of the 10,949 unique industry x year codings present in the CPS, 901 merge at the 6 digit level. We then progressively merge at coarser levels. At each coarser level, we assign clean vs polluting vs other status according to the classification of the majority employment at the 6-digit NAICS within the coarser level. For instance, suppose there is a 5-digit NAICS code which contains two 6-digit NAICS codes, one of which is clean and the other of which is polluting. If the 6-digit NAICS code associated with the clean sector is larger (smaller) than the 6-digit NAICS associated with polluting, then the 5-digit NAICS code will be coded as clean (polluting). Employment data from this procedure come from the QCEW. Proceeding in this way merges 2,016 industry-years at the 5-digit level, 6,691 industry-years at the four-digit level, 1,329 at the 3-digit level, and 307 at the 2-digit level. The remaining unmerged industries are all in the public sector and dropped from the analysis.

At this stage, there remain a couple of industries that remain uncoded, because it does not have a majority of employment in either clean, polluting or other (e.g. 1/3 of the broader sector is in each of the three categories). These we handcode as follows. We define the industry "Cycles and misc. transportation equipment" as clean, supposing that a climate transition may involve more clean commuting.[61] We define the "Sanitary Services" industry as clean, since it includes some recycling and sanitation services and does not have polluting subindustries.

Given the industry groupings, we must then define polluting-attached workers. In the 1995 through 2004 period – the pre-transition period – we call an individual "attached to the dirty sector" if they are employed in the polluting sector for four consecutive months during the first rotation. By this metric, 4.4% of workers qualify as attached to D before 2005. To calculate the moment used in our calibration of b^O – the average wage change of an individual going from polluting to unemployed to outside – we first measure the real wage of such workers in the final month of their first rotation. We then condition on individuals appearing as unemployed at some point in their second rotation, before being employed in

[61] Indeed, the largest subindustry of this industry group is bicycle manufacturing, but this is offset by a variety of military industries such as tank manufacturing, which are likely not subject to the climate transition.

an outside sector in the final month of the second rotation, when we measure their real wage again.[62] All wages are deflated by the CPI-U. By focusing on individuals who have at least one spell of unemployment before joining the outside sector, we remove individuals who might switch to the outside sector due to an unmodeled career opportunity in that sector.

Of course, focusing solely on individuals who remain employed in the polluting sector for the first rotation would introduce substantial composition bias as the transition gets underway. We therefore instead weight individuals by the likelihood that they are polluting-attached based on their observables. To do so, we first recode the provided education, race and marital status variables so that the education groupings are High School or Less, Some College, Bachelor's Degree, and Master's Degree or Higher, the race groupings are White, Black, or Other, and the marital status variable is an indicator for being married. We additionally use geographic information, which the CPS partially provides down to the county level. The Census Bureau has changed confidentiality rules regarding individuals living in small geographic areas over time. As a result, some counties and metro areas appear in some waves of the CPS but not others. In order to have a consistent probability of being polluting-attached, we require consistent geographic codings over time. To harmonize geographic codings, we therefore focus on county and metropolitan statistical area (MSA) codes that are present no fewer than all but one in every year from 2000 through 2025.[63] This yields 194 counties and 209 metro areas. State information is included for all years. We then compute the probability of an individual i being polluting-attached given a vector of observables (education $\times$ race $\times$ marital status $\times$ sex $\times$ geography) X as $Pr_i = \mathbb{E}\left[1\left\{i \text{ is polluting-attached}\right\}|X\right]$ in the pre-transition period. We apply this same probability to all individuals with the same vector of observables X during the early transition years (2005-2025). In effect, we study the effect of the transition on people who, based on observable characteristics, are likely to have been working in the polluting sector were the transition not to have occurred. Since

[62] We target a wage cut of 24%, consistent with the behavior of hourly wages. Weekly earnings fall an average of 35.5%. Targeting a smaller wage cut makes the outside sector more attractive in the calibration and thus provides a conservative of the cost of the transition.

[63] Many counties appear only in 2004 when a recode in the CPS occurred. We continue to include these counties since we can use information aggregated from the full pre-transition sample to construct polluting-attached probabilities.

Table 5: Characteristics of Workers Holding Clean and Polluting Sector Jobs

	Polluting		Clean	
	2006	2024	2006	2024
% $\leq$ High School	64.4	58.1	49.4	42.2
% Some College	24.3	26.3	31.2	29.2
% Bachelor's	9.4	14.1	16.6	22.7
% $>$ Bachelor's	1.9	1.5	2.8	5.9
% Age: 45+	49.3	51.0	47.7	49.9
% White	86.2	94.5	85.8	82.8

some combinations of observables do not exist in all years, we begin by calculating Pr_i using the most granular geographic level to the coarsest (county $\rightarrow$ MSA $\rightarrow$ state $\rightarrow$ national). While the unconditional probability that a worker is polluting-attached is 3.9%, some individuals having a 100% probability of being polluting-attached given their observables. These individuals are located in traditional mining communities (parts of Texas and West Virginia), are lower education and male. The median observation in our sample has a 1.8% chance of being old-attached, while 25% of individuals are assigned a zero likelihood of being old attached and are thus dropped from our analysis.

Table 5 reports the characteristics of probabilistically D-attached workers who hold jobs in polluting sectors and clean sectors as of 2006 and 2024. The workers holding polluting jobs are substantially less educated than those holding clean jobs in both periods, suggesting that high human capital workers join the clean sector. In addition, those working in clean sectors are younger than those in polluting sectors.

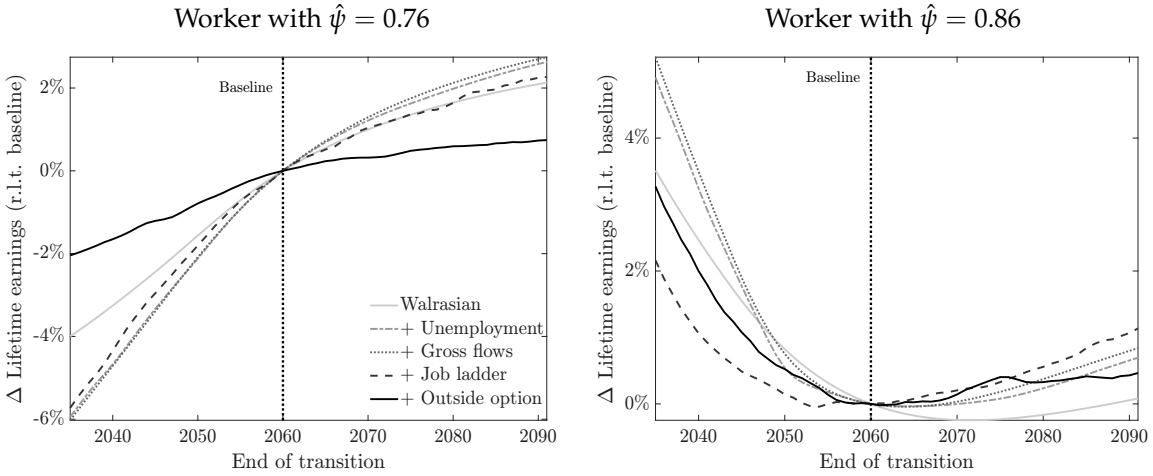
We then calculate the share of individuals are employed in the clean or the polluting sector at every point in time, weighting by the product of their survey weight and probability of being attached to the dirty sector. To correct for misspecification from overly coarse industry classifications and within-industry shifts in technology, we ascribe a fraction of polluting manufacturing employment to clean and polluting sectors.[64] We do so based on the share of cars sold that run on alter-

[64] We maintain the following four manufacturing sectors as polluting over the full transition: Petroleum products (NAICS 3241), Petrochemical manufacturing (NAICS 3251), Oil and gas field machinery and equipment (NAICS 333132) and Motor vehicle gasoline engine and parts mfg (NAICS 336310).

native fuel (hybrid, plug-in hybrid, electric, or biofuel).[65] This correction has the added benefit of partially accounting for within-industry transition: the industry classifications associated with motor vehicle manufacturing do not distinguish between internal combustion engine and EV vehicles, despite the fact that the skills needed to produce those two types of cars may be quite different and those two subindustries will be subject to very different paths of labor demand. Finally, we extract the trend component of employment shares by taking the moving average over 12 quarters before and after a target date. We then target the share of employment in either clean or polluting sectors that is in clean sectors as part of our estimation in Section 6.2.

E Additional Quantitative Results

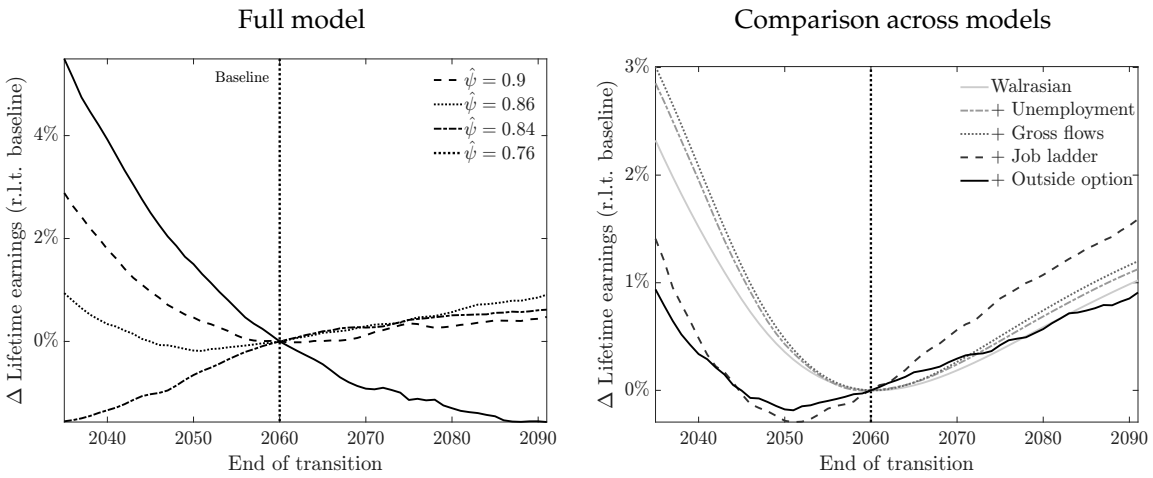
Figure 11: Counterfactual earnings changes



Notes: This figure plots workers' lifetime earnings changes in 2025 across models as a function of the transition horizon. All changes are relative to the baseline transition ending in 2060, and faster transitions are parameterized as in equation (3.4). The horizontal axis corresponds to the end date of the transition considered. All workers have 20 years remaining in their careers (median age). The left panel corresponds to a worker with $\hat{\psi} = 0.76$ and the right panel to a worker with $\hat{\psi} = 0.86$.

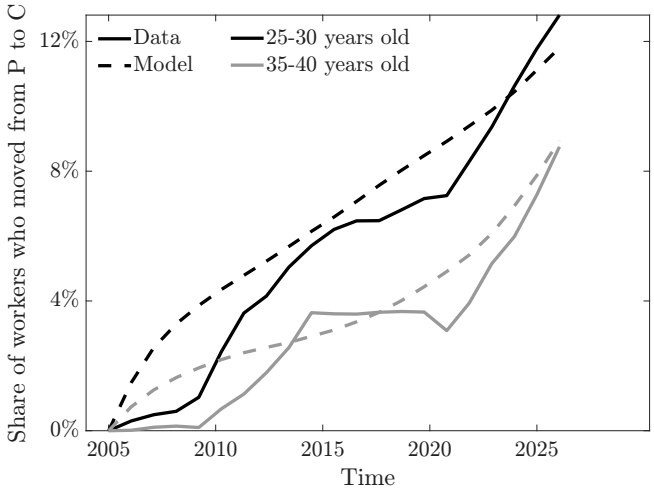
[65] To calculate these shares, we use data from the US Bureau of Transportation on total car sales by year, available from here, and on alternative energy vehicle sales, available here (both accessed June 3, 2025). Total car sales data go through 2021 while alternative-fuel sales go to 2024. We therefore extrapolate total car sales assuming a constant log-linear trend.

Figure 12: Counterfactual earnings changes



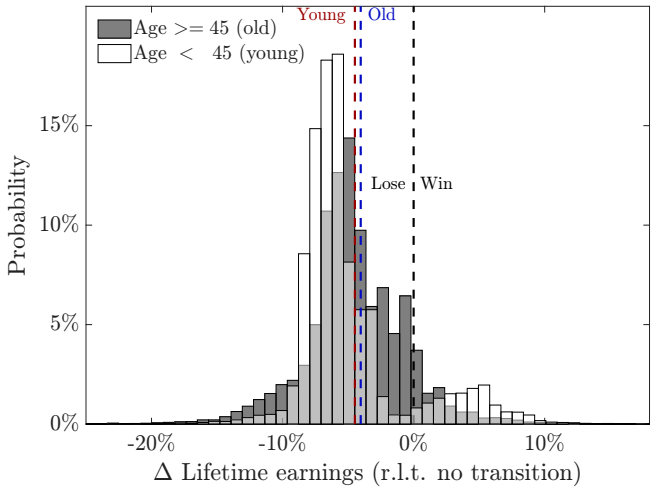
Notes: This plot reproduces Figure 5 in the main text, this time averaging across employment states using the distribution that prevails in 2025 under the baseline transition. The left panel plots workers' average lifetime earnings changes in 2025 in our full model as a function of the transition horizon, for various values of the productivity $\hat{\psi}$ in the clean sector. All earnings changes are relative to the baseline transition ending in 2060, and faster transitions are parameterized as in equation (3.4). The horizontal axis corresponds to the end date of the transition considered. All workers have 20 years remaining in their careers (median age). The right panel decomposes these earnings changes for a worker with productivity $\hat{\psi} = 0.84$ in the clean sector. The solid grey line corresponds to our frictionless benchmark from Section 2, augmented with skill accumulation. The other lines add one feature after another until we obtain our full model corresponding to the solid black line.

Figure 13: Labor reallocation by cohort



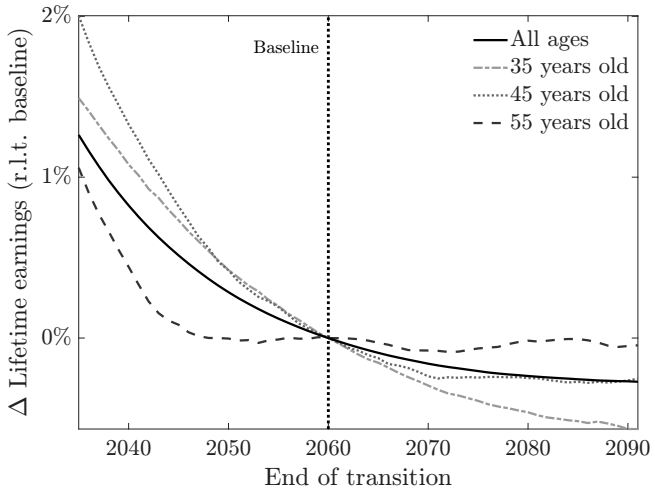
Notes: This figure plots the share of workers employed in the clean sector, expressed as a share of workers initially employed in the dirty sector. Workers are weighted by the probability that they are attached to the polluting sector, based on their observables and pre-2005 relationship between those observables and the likelihood of being attached to the polluting sector. The solid curves are the data from the CPS. The dashed curves correspond to our model, given the estimated rate of specific skill accumulation $\hat{\delta}$.

Figure 14: Lifetime earnings change by age



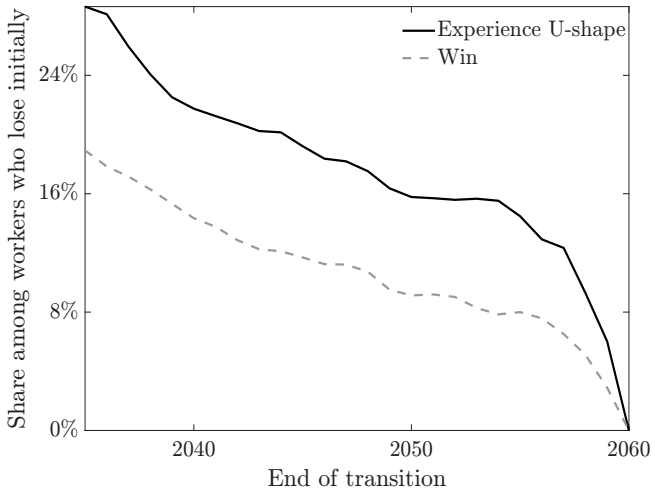
Notes: This figure plots the distribution of earnings losses in 2025 for young and old workers. Young workers are defined as those who are less than 45 years old (i.e., $j < 20$) in 2025, while old workers are the rest.

Figure 15: Counterfactual lifetime earnings change by age



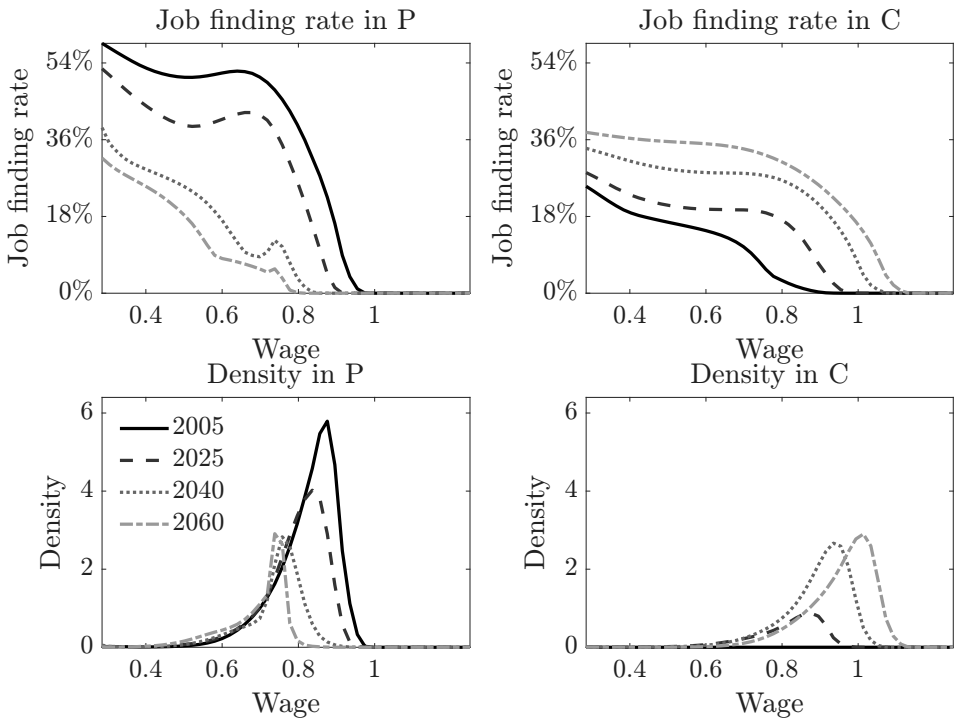
Notes: This figure plots average lifetime earnings changes in 2025 in our full model as a function of the transition horizon, for various ages. All earnings changes are relative to the baseline transition ending in 2060, and faster transitions are parameterized as in equation (3.4). The horizontal axis corresponds to the end date of the transition considered. We average workers within each age using the distribution that prevails in 2025 under the baseline transition.

Figure 16: Share of workers who experience non-monotonicities



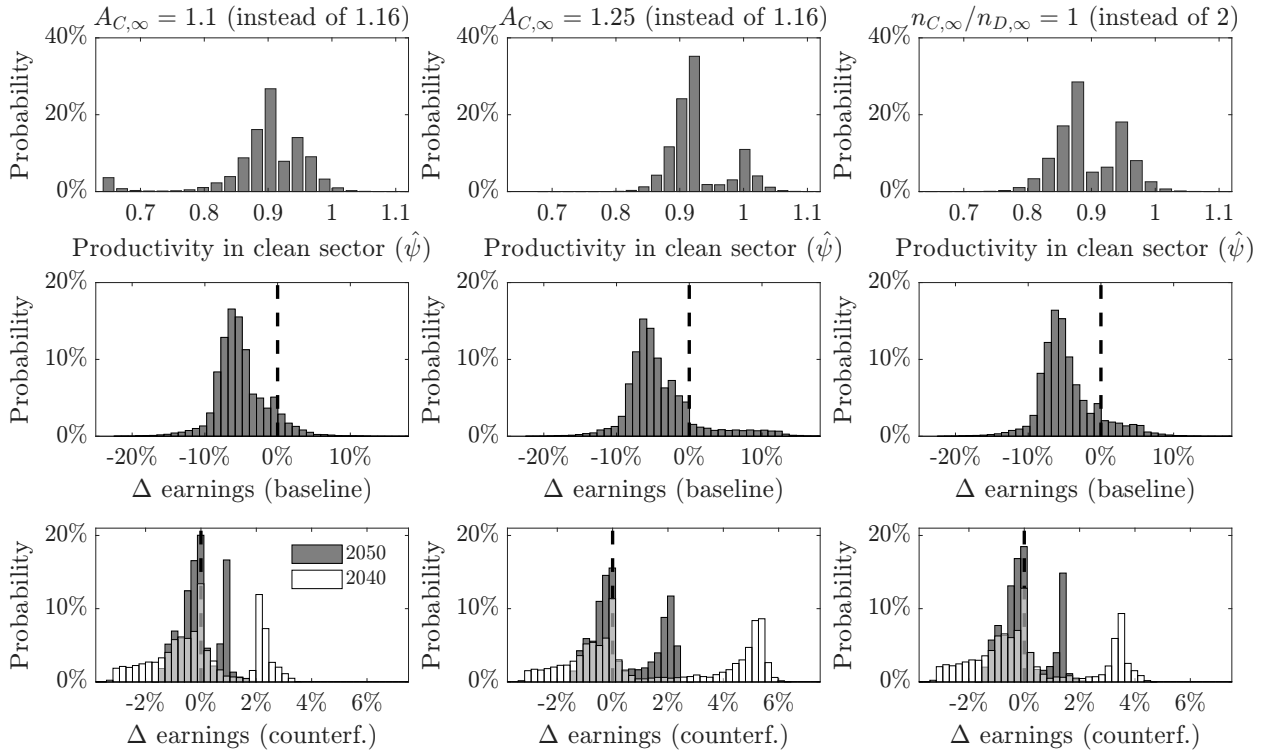
Notes: This figure plots the share of workers who experience non-monotonic changes in lifetime earnings in 2025 as a function of the transition horizon. This share is expressed relative to workers who lose at first when accelerating the transition, starting from the baseline one ending in 2060. The solid black curve indicates the share of workers who experience a *U*-shape as the transition accelerates, i.e., those who gain *at the margin* relative to their trough, and the dashed grey curve indicates the share of workers who gain relative to the baseline transition, i.e., those who gain *in level* compared to the 2060 transition.

Figure 17: Job finding rates and the wage distribution



Notes: This plot reproduces Figure 6 in the main text, this time averaging across relative productivities $\hat{\psi}$ at birth using the distribution G estimated in our application (Section 6). The first row plots the job finding rate as a function of the wage posted by firms. The second row plots the distribution of workers over such wages. The first column corresponds to the dirty sector, and the second to the clean sector.

Figure 18: Sensitivity analyses



Notes: This figure corresponds to three sensitivity analysis. The first column corresponds to the case where the final productivity in the clean sector is $A_{C,\infty} = 1.1$ instead of 1.6 in our baseline scenario. The second column corresponds to the case where $A_{C,\infty} = 1.25$. And the third column corresponds to the case where we target a 1:1 ratio of labor supplies in the clean sector relative to the polluting sector, instead of 2:1 in our baseline scenario. In turn, the first row plots to the distribution of workers' relative productivities in the clean sector in 2025. The second row plots to the distribution of earnings losses in 2025 from the baseline transition ending in 2060. The third row plots the distribution of counterfactual earnings changes from transitions ending in 2050 and 2040.