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# Firm Productivity and the Composition of Jobs in the Green Economy

## FACTOR REALLOCATION WITH HETEROGENEOUS CLEAN DESTINATIONS



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### Abstract

We study the macroeconomic consequences of emissions reductions in a model with heterogeneous firms, search-and-matching frictions, endogenous technology adoption, and sector-specific capital adjustment costs. Extending the framework of Finkelstein Shapiro and Metcalf (2023) and calibrating to Finland, we distinguish between high- and low-productivity clean technologies within a three-sector framework. Our results show that an emission reduction policy implemented via a carbon tax induces modest losses in output and consumption, as part of the reallocation away from emissions-intensive sector is absorbed by lower-productivity clean sector. By contrast, the standard two-sector model with a single clean technology shows slightly positive output effects due to a greater increase in average firm productivity. These findings highlight that the macroeconomic costs of climate policies depend on the productivity composition of the expanding clean sector. Within the emissions-intensive sector, emissions are mainly reduced through abatement activities, but the degree of factor reallocation is still substantial: under the baseline calibration, employment in the emissions-intensive sector declines by nearly one-quarter in response to a 40% emissions reduction target. Lower abatement costs reduce the extent of factor reallocation required to achieve a given emissions reduction target.

# Tiivistelmä

## Yritysten tuottavuus ja työpaikkojen rakennemuutos puhtaassa siirtymässä

Tutkimme päästövähennysten makrotaloudellisia seurauksia mallissa, jossa yritykset ovat heterogeenisia, työmarkkinoilla esiintyy etsintäkitkoja, teknologian käyttöönotto määräytyy endogeenisesti ja pääomakannan sopeuttamiseen liittyy toimialakohtaisia kustannuksia. Laajennamme Finkelstein Shapiron ja Metcalfin (2023) mallikehikkoa ja kalibroimme sen Suomen talouteen. Kolmen sektorin mallissa erotamme toisistaan korkean ja matalan tuottavuuden puhtaat teknologiat. Tulostemme mukaan hiiliverolla toteutettu päästövähennyspolitiikka pienentää jonkin verran tuotantoa ja kulutusta, koska osa päästöintensiiviseltä sektorilta pois siirtyvistä tuotannontekijöistä ohjautuu matalan tuottavuuden puhtaalle sektorille. Sen sijaan tavanomaisessa kahden sektorin mallissa, jossa on vain yksi puhdas teknologia, tuotantovaikutukset ovat lievästi myönteisiä yritysten keskimääräisen tuottavuuden suuremman kasvun ansiosta. Tulokset osoittavat, että ilmastopolitiikan makrotaloudelliset kustannukset riippuvat laajenevan puhtaan sektorin tuottavuusrakenteesta. Päästöintensiivisellä sektorilla päästöjä vähennetään pääasiassa päästövähennystoimilla, mutta myös tuotannontekijöiden uudelleenkohdentuminen on huomattavaa: peruskalibroinnissa päästöintensiivisen sektorin työllisyys vähenee lähes neljänneksen, kun päästöjä vähennetään 40 prosenttia. Alhaisemmat päästövähennyskustannukset vähentävät tietyn päästövähennystavoitteen saavuttamiseksi tarvittavaa tuotannontekijöiden uudelleenkohdentumista.

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# 1 Introduction

Achieving the climate targets set in the Paris Agreement requires deep emissions cuts, particularly among wealthier countries and those that have contributed most to cumulative global emissions. In this context, EU member states have adopted ambitious emissions reduction targets, both in terms of the pace and magnitude of the required reductions. A major concern associated with the transition to a cleaner economy is its potential impact on labor markets and productivity (Albrizio et al., 2017; Marin and Vona, 2019). In particular, which types of jobs will expand or contract, and how will capital adjust as environmental policies alter relative prices and profitability? A growing empirical literature highlights substantial heterogeneity in green employment, particularly in terms of occupational characteristics and skill requirements (Consoli et al., 2016; Vona et al., 2018; Bowen et al., 2018; Bontadini and Vona, 2023). The green transition is therefore not simply a shift toward a homogeneous clean sector: clean activities can differ in their productivity, capital intensity, and skill requirements.

This paper studies these issues in a general-equilibrium environment with heterogeneous firms, frictional labour markets, endogenous firm entry, endogenous technology choice, and costly capital reallocation. Our starting point is the framework in Finkelstein Shapiro and Metcalf (2023), which embeds carbon taxation in a model with search-and-matching frictions, endogenous labour-force participation, firm creation, and a choice between emissions-intensive and green production technologies. That framework provides a natural benchmark for our analysis because it captures two margins that are central for the green transition: workers reallocate across production activities through a frictional labour market, and firms respond to carbon taxation through entry and technology adoption.

Our contribution is to ask how the implications of this benchmark change once the sectoral structure of the green transition and the adjustment of capital are modelled in greater detail. We disaggregate the clean side of the economy into two non-polluting technologies: a high-productivity clean sector and a low-productivity clean sector. This extension is motivated by the fact that the green transition is not simply a movement from emissions-intensive production to a homogeneous clean sector. In practice, non-polluting or low-emission activities are highly heterogeneous. Some clean activities are relatively productive, capital intensive, and skill intensive. Others are labour-intensive service activities with lower measured productivity, even though they generate relatively low emissions.

A two-sector clean-versus-dirty structure presented in Finkelstein Shapiro and Metcalf (2023) collapses these destinations into a single clean aggregate. As a result, it may implicitly associate the green transition with a movement toward a relatively productive clean technology. This is useful for isolating the technology-adoption mechanism, but it may understate the possibility that part of the transition is absorbed by lower-productivity clean activities.

This distinction matters for aggregate outcomes. A reallocation away from emissions-intensive production can reduce emissions even when it does not raise aggregate productivity. If displaced labour and capital move primarily toward high-productivity clean activities, the transition may generate a productivity dividend that offsets some of the costs of carbon taxation. If, instead, a substantial part of the reallocation is absorbed by lower-productivity clean services, the same emissions reduction can be associated with weaker output growth and lower wages.

The paper also relates to a broader debate on the productivity consequences of environmental policy. The Porter hypothesis argues that well-designed environmental regu-

lation can induce innovation and partly offset compliance costs through improved efficiency (Porter and van der Linde, 1995; Ambec et al., 2013). Empirical evidence, however, suggests that the productivity effects of environmental policy are heterogeneous across firms, sectors, and time horizons, and should not be interpreted as an automatic aggregate productivity gain (Albrizio et al., 2017). Our approach is complementary to this literature. Instead of modelling research and development directly, we study how climate policy changes the sectoral and technological composition of production in a macroeconomic model with labour-market frictions and firm entry. The results show that even if environmental policy induces cleaner production and technology adoption, the aggregate productivity effect depends on which clean activities expand.

Our work is also connected to the quantitative literature on climate policy in dynamic general equilibrium models. Early contributions examine environmental policy in business-cycle models with pollution externalities and alternative policy rules (Fischer and Springborn, 2011; Heutel, 2012). Another strand emphasizes directed technical change and endogenous innovation in clean and dirty technologies (Acemoglu et al., 2012; Fried, 2018), while models incorporating labor-market frictions examine how carbon policy reallocates employment across emissions-intensive and clean sectors (Hafstead and Williams, 2018). More recent empirical macroeconomic evidence suggests that carbon pricing can entail short-run output and employment costs (Känzig, 2023), although aggregate economic effects appear relatively modest (Metcalf and Stock, 2020).

Relative to these contributions, our focus is on the composition of the clean economy itself: the transition may be green in emissions terms, but its macroeconomic effect depends on whether expanding clean sectors are high- or low-productivity destinations for labour and capital. The key gap in this literature is that it treats the clean sector as a homogeneous destination; this paper fills that gap by showing that the productivity

composition of the clean expansion is the primary determinant of the macroeconomic cost of the transition.

Our quantitative calibration focuses on Finland. The country has adopted ambitious national climate targets and is also subject to the EU's emissions-reduction framework. At the same time, a substantial share of economic activity remains concentrated in emissions-intensive industries. To study the effects of emissions reductions through carbon pricing, we calibrate the model to Finnish data and compare two alternative sectoral structures. The two-sector model follows the standard distinction between clean and emissions-intensive production, while the three-sector model further separates clean production into high- and low-productivity activities.

Given the 40 percent emissions reduction target, the carbon tax achieves the targeted reduction in emissions in both model versions. However, the macroeconomic consequences differ across specifications. In the two-sector model, the reallocation toward the clean sector generates relatively benign aggregate outcomes, which is more or less aligned with the findings in Finkelstein Shapiro and Metcalf (2023) using the US data. In the three-sector model, part of the reallocation is absorbed by the low-productivity clean sector, which weakens the productivity gains from the transition and leads to less favourable output and consumption effects. Those workers that leave the emissions-intensive sector flow mainly down the productivity ladder. Still, the emission reduction target itself is mainly attained through abatement activities in the emissions-intensive sector.

The remainder of the paper is organized as follows. Section 2 sets out the empirical context. Section 3 presents the model. Section 4 describes the calibration and reports the comparison between the two- and three-sector models, in the steady state and along the transition. Section 5 develops further extensions of the model: the role of sector-specific

capital adjustment costs, and an abatement-technology sensitivity analysis. Section 6 discusses the findings and the final section concludes.

## 2 Context: The three sectors in the case of Finland

To motivate the structure of the macroeconomic model we build in the next section, we characterize emissions intensity and labor productivity across industries in Finland. Rather than grouping industries into only two sectors, emissions-intensive and clean, we specifically examine heterogeneity within the clean sector. First, we consider emissions. To this end, we use observed fossil (Scope 1) $CO_2$ emissions per worker rather than a predefined classification of industries as "green". Emissions per worker allow us to separate an emissions-intensive group from the rest. Second, using the net value added per worker as an indicator for productivity, we split the remainder into high-productivity and low-productivity clean groups. We label the three groups $r$, $n$, and $s$, respectively, and use that notation throughout. Table 1 summarizes key differences across the three sectors, and Appendix B lists the industries assigned to each group.[1]

Three features stand out in Table 1. First, carbon intensity is highly asymmetric across sectors. Sector $r$ emits roughly 39 tonnes of fossil $CO_2$ per worker, compared with about one tonne in each clean sector. This is nearly 40 times the intensity of sector $n$ and more than 60 times that of sector $s$. Sector $r$ accounts for 95% of production-based fossil $CO_2$ emissions while employing 28% of workers. A carbon tax therefore falls, to

[1]Employment is from Statistics Finland table 13aq (employed persons aged 15–74) and value added from table 123h (net value added at basic prices, current prices), both grouped as described. Emissions are production-based fossil $CO_2$ from table 11ig. The published emissions data do not separate durable from non-durable manufacturing, which together account for 0.7% of national fossil $CO_2$; the resulting ambiguity shifts $r$'s emissions intensity by at most 0.3 tonnes per worker and is immaterial for the comparisons below.

Table 1: The three sectors in Finnish data, 2023.

| | $n$ (high-clean) | $r$ (emissions-intensive) | $s$ (low-clean) |
|---|---|---|---|
| Employment (1,000 persons) | 726 | 740 | 1,141 |
| Employment share (%) | 27.9 | 28.4 | 43.8 |
| Net value added per worker (€1,000) | 85.9 | 75.3 | 57.3 |
| Fossil $CO_2$ per worker (tonnes) | 1.0 | 39.2 | 0.6 |
| Share of fossil $CO_2$ (%) | 2.5 | 95.2 | 2.4 |

Notes: Authors' calculations from Statistics Finland data; see footnote for tables and groupings. Value added is net value added at basic prices in current prices, divided by employed persons.

a first approximation, primarily on one sector that employs slightly more than a quarter of Finnish workers.

Second, the clean side is not homogeneous. Net value added per worker is roughly €86,000 in sector $n$, compared with €57,000 in sector $s$, a gap of about 50%. This difference is larger than the productivity gap between either clean sector and the emissions-intensive sector: 31% between $r$ and $s$, and 14% between $n$ and $r$. Treating the clean sector as a single destination therefore masks substantial heterogeneity across activities that differ more from each other than from the emissions-intensive sector. Third, and most important for what follows, the emissions-intensive sector lies between the two clean sectors in terms of productivity, at roughly €75,000 per worker. Resources leaving sector $r$ can therefore move either up or down the productivity distribution.

It is also instructive to examine how these sectoral patterns have evolved over time. Between 2008 and 2023, employment in the emissions-intensive sector fell by roughly 13%, while its employment share declined by about 7 percentage points. In contrast, the employment share of the low-productivity clean sector rose by roughly 6 percentage points, while the share of the high-productivity clean sector remained broadly un-

changed. Over the same period, aggregate fossil $CO_2$ emissions per worker fell by about half.[2]

# 3 The model

The model is a macro-climate framework with endogenous firm entry and technology choice, search-and-matching labour markets in each production category, and Jermann (1998)-style capital adjustment costs. The setup extends the two-sector model of Finkelstein Shapiro and Metcalf (2023) (henceforth FSM) along three dimensions: $(i)$ firms can adopt one of three production technologies rather than two, which yields two endogenous productivity cutoffs and three categories of active firms; $(ii)$ each sector has its own physical-capital stock that is subject to quadratic adjustment costs; and $(iii)$ the domestic economy is calibrated to Finland and is small relative to the global pollution stock, so the emissions externality on output is generated by a global pollution accumulation that includes an exogenous flow from the rest of the world. Apart from these three extensions the description below follows closely the setup in FSM.

The economy has two layers of production. A continuum of perfectly competitive intermediate-goods producers in each category ($n$, $r$, $s$) uses sector-specific labor and capital to produce differentiated intermediate inputs, which are then purchased by final-goods firms that transform them into a single variety of the consumption good. Final-goods firms are monopolistically competitive, differ in idiosyncratic productivity, and choose which production technology to operate. Entry is subject to a sunk resource cost, and the productivity of a new entrant is drawn from a Pareto distribution. Sorting into the

[2]Computed from Statistics Finland table 11ws, which is on a national accounts basis and therefore differs in level from the figures in Table 1. Food, beverage and textile manufacturing are assigned to $r$ in the time-series calculations because the published series do not report them separately; reassigning them to $s$ does not materially affect the results.

three technologies is therefore endogenous, governed by two productivity cutoffs that the carbon tax shifts. The labor market in each sector is governed by a separate search-and-matching technology, a separate vacancy-posting margin, and Nash bargaining. The full set of equilibrium conditions is collected in Appendix A. The remainder of this section presents the main building blocks and key optimality conditions.

## 3.1 Firms

### 3.1.1 Production structure, technology choice, and market demand

There is an unbounded measure of monopolistically competitive final-goods firms whose entry is subject to a sunk resource cost $f_e$. After paying the entry cost, a new firm draws its idiosyncratic productivity $a$ from a Pareto distribution $G(a) = 1 - (a_{\min}/a)^{k_p}$ with shape parameter $k_p$ and lower bound $a_{\min}$. The realized productivity remains fixed until the firm exits with exogenous probability $\delta_f \in (0, 1)$. Each firm produces a single output variety, so we refer to a firm with productivity $a$ simply as "firm $a$."

Three production technologies are available. The regular ($r$) technology generates carbon-dioxide emissions; emissions are subject to a carbon tax $\tau_t$ and can be partially mitigated through abatement spending. The high-clean ($n$) technology does not generate emissions but requires a per-period fixed operating cost $f_n$. The low-clean ($s$) technology also does not generate emissions; operating it does not entail any fixed cost beyond the entry cost $f_e$. As in FSM, sorting is endogenous: there are two threshold productivity levels $a_{r,t} < a_{n,t}$ such that, in equilibrium, firms with $a \in [a_{\min}, a_{r,t})$ adopt the $s$-technology, firms with $a \in [a_{r,t}, a_{n,t})$ adopt the $r$-technology, and firms with $a \geq a_{n,t}$ adopt the $n$-technology. The three categories of active firms therefore have a strict or-

dering in idiosyncratic productivity, and the most productive firms endogenously bear the fixed cost of operating the high-clean technology.

Both clean technologies and the emissions-intensive technology rely on sector-specific labour (subject to search-and-matching frictions) and sector-specific physical capital as inputs. Emissions from the emissions-intensive sector contribute to a global pollution stock $x_t$ that, in turn, reduces output for all firms through a damages function $D(x_t)$.[3]

Total output aggregates output across firms with a constant-elasticity-of-substitution (CES) aggregator. Following Ghironi and Melitz (2005), if $X$ denotes the potential measure of firms in the economy and $\varepsilon > 1$ the elasticity of substitution across varieties, the aggregate output and price index are

$$Y_t = \left( \int_{x \in X} y_t(x)^{\frac{\varepsilon-1}{\varepsilon}} \, dx \right)^{\frac{\varepsilon}{\varepsilon-1}}, \qquad P_t = \left( \int_{x \in X} p_t(x)^{1-\varepsilon} \, dx \right)^{\frac{1}{1-\varepsilon}}. \tag{1}$$

With three categories of active firms and the Pareto-and-cutoff sorting described above, the consumption-based price index can be written compactly in terms of average prices and the measures of firms in each category,

$$1 = \left[ N_{n,t} \, \tilde{\rho}_{n,t}^{1-\varepsilon} + N_{r,t} \, \tilde{\rho}_{r,t}^{1-\varepsilon} + N_{s,t} \, \tilde{\rho}_{s,t}^{1-\varepsilon} \right]^{\frac{1}{1-\varepsilon}}, \tag{2}$$

where $N_{j,t}$ is the measure of firms operating with technology $j \in \{n, r, s\}$ and $\tilde{\rho}_{j,t}$ is the average real price charged by firms in category $j$. The corresponding demand function faced by the average firm in category $j$ is $\tilde{y}_{j,t} = \tilde{\rho}_{j,t}^{-\varepsilon} Y_t$. Following FSM, real

[3] Climate damages could also have sector-specific impacts; however, to keep the model comparable to the original FSM setup, we assume that the productivity losses induced by climate change are uniform across sectors.

model variables are mapped to data-consistent counterparts by multiplying by $N_t^{1/(1-\varepsilon)}$ (Ghironi and Melitz, 2005).

**Optimal pricing.** Given the demand function for firm $a$'s output, each active firm sets its price as a constant markup over its real marginal cost. With idiosyncratic productivity $a$ and category-$j$ marginal cost $mc_{j,t}$, the optimal real price is

$$\rho_{j,t}(a) \;=\; \frac{\varepsilon}{\varepsilon-1}\,\frac{mc_{j,t}}{a}, \qquad j \in \{n,r,s\}, \tag{3}$$

which, evaluated at the category-specific average idiosyncratic productivity $\tilde{a}_{j,t}$, delivers the average price $\tilde{\rho}_{j,t} = \frac{\varepsilon}{\varepsilon-1}\, mc_{j,t}/\tilde{a}_{j,t}$.

**Productivity cutoffs and technology choice.** The threshold productivity levels $a_{r,t}$ and $a_{n,t}$ are pinned down by indifference conditions for the marginal firm. A firm with productivity $a_{n,t}$ must be indifferent between operating with the $r$-technology (paying the per-period fixed cost $f_r$ but no fixed cost of high-clean adoption) and adopting the $n$-technology (paying $f_n$); a firm with productivity $a_{r,t}$ must be indifferent between operating with the $s$-technology (no fixed cost) and switching to the $r$-technology and paying $f_r$:

$$\pi^y_{n,t}(a_{n,t}) \;=\; \pi^y_{r,t}(a_{n,t}), \qquad \pi^y_{r,t}(a_{r,t}) \;=\; \pi^y_{s,t}(a_{r,t}). \tag{4}$$

The two cutoffs sort firms into the three sectoral categories, with strictly increasing average idiosyncratic productivity from $s$ to $r$ to $n$. The firm selection into each sector takes place as follows (see Figure 1). The $s$-technology has no fixed operating cost, so at $a_{min}$ it has the highest net profit. A firm with sufficiently high productivity $a \geq a_{r,t}$ can cover the additional fixed cost $f_r > 0$ of the emissions-intensive technology. It therefore

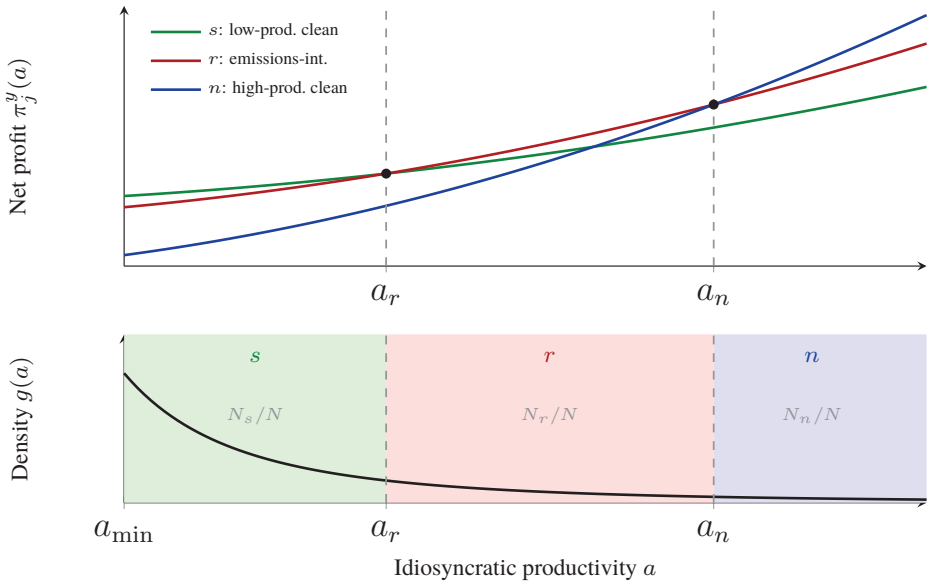



Figure 1: Technology selection

switches from $s$ to $r$ since the net profit from $r$-technology is greater than from the other two technologies for firms which have a productivity draw such that $a_{r,t} \leq a < a_{n,t}$. A firm with even higher productivity $a \geq a_{n,t}$ can additionally cover the fixed cost $f_n > f_r$ of the high-clean technology. It therefore switches to $n$-technology since the net profit from that technology exceeds the net profits from the other two technologies for those firms. The carbon tax $\tau_t$ enters (4) through the emissions-intensive sector marginal cost $mc_{r,t}$ (see Section 3.1.2 below) and therefore shifts both cutoffs simultaneously: the tax makes the $r$-technology less attractive relative to both $s$ and $n$, so $a_{r,t}$ rises and $a_{n,t}$ falls.

**Evolution of firms and category measures.** Let $N_t$ denote the total measure of active firms at time $t$ and $N_{e,t}$ the measure of new entrants. The sum of those firms survive to the next period with probability $1 - \delta_f$ next period, so

$$N_{t+1} \;=\; (1 - \delta_f)\big(N_t + N_{e,t}\big). \tag{5}$$

Given the Pareto distribution of idiosyncratic productivity, the measures of firms in each category are simply the corresponding Pareto tail and interval probabilities times $N_t$,

$$\frac{N_{n,t}}{N_t} = \left(\frac{a_{\min}}{a_{n,t}}\right)^{k_p}, \quad \frac{N_{r,t}}{N_t} = \left(\frac{a_{\min}}{a_{r,t}}\right)^{k_p} - \left(\frac{a_{\min}}{a_{n,t}}\right)^{k_p}, \quad \frac{N_{s,t}}{N_t} = 1 - \frac{N_{n,t}}{N_t} - \frac{N_{r,t}}{N_t}, \tag{6}$$

so that an equilibrium movement in either cutoff translates one-to-one into an endogenous reallocation of firms across the three technology categories.

**Firm averages.** Conditional on the cutoffs, the *average* idiosyncratic productivity in each category is the $(\varepsilon - 1)$-th moment of the truncated Pareto distribution,

$$\tilde{a}_{j,t} = \left[\frac{1}{N_{j,t}/N_t} \int_{a \in \mathcal{A}_{j,t}} a^{\varepsilon-1}\, dG(a)\right]^{\frac{1}{\varepsilon-1}}, \qquad j \in \{n, r, s\}, \tag{7}$$

with the integration ranges $\mathcal{A}_{s,t} = [a_{\min}, a_{r,t})$, $\mathcal{A}_{r,t} = [a_{r,t}, a_{n,t})$, and $\mathcal{A}_{n,t} = [a_{n,t}, \infty)$. Closed-form expressions for $\tilde{a}_{n,t}$, $\tilde{a}_{r,t}$, and $\tilde{a}_{s,t}$ are:[4]

$$\tilde{a}_{n,t} = \zeta\, a_{n,t}, \tag{8}$$

$$\tilde{a}_{r,t} = a_{r,t}\, \tilde{a}_{n,t} \left[\frac{a_{n,t}^{k_p-(\varepsilon-1)} - a_{r,t}^{k_p-(\varepsilon-1)}}{a_{n,t}^{k_p} - a_{r,t}^{k_p}}\right]^{1/(\varepsilon-1)}, \tag{9}$$

$$\tilde{a}_{s,t} = (\zeta\, a_{r,t})\, a_{\min} \left[\frac{a_{r,t}^{k_p-(\varepsilon-1)} - a_{\min}^{k_p-(\varepsilon-1)}}{a_{r,t}^{k_p} - a_{\min}^{k_p}}\right]^{1/(\varepsilon-1)}, \tag{10}$$

where $\zeta \equiv [k_p/(k_p - (\varepsilon - 1))]^{1/(\varepsilon-1)}$ is the standard Ghironi–Melitz constant. Given category-specific average profits $\tilde{\pi}^y_{j,t}$, the average profit across all active firms is the share-weighted sum $\tilde{\pi}^y_t = \sum_{j \in \{n,r,s\}} (N_{j,t}/N_t)\, \tilde{\pi}^y_{j,t}$.

[4] These expressions correspond to the averages used in a different setting by Finkelstein Shapiro et al. (2025) and Finkelstein Shapiro and Kuusela (2026).

**Free entry.** As in FSM, prospective entrants pay the sunk entry cost $f_e$ today and, with probability $1 - \delta_f$, obtain a perpetual stream of expected average profits starting next period. Free entry equates the entry cost to the discounted expected continuation value of an active firm,

$$f_e \;=\; \mathbb{E}_t\, \Xi_{t+1|t}(1-\delta_f)\big[\tilde{\pi}^{y}_{t+1} + f_e\big], \tag{11}$$

where $\Xi_{t+1|t}$ is the household stochastic discount factor (see Section 3.2 below).

### 3.1.2 Intermediate goods, emissions, and capital

There is a measure-one continuum of perfectly competitive producers of intermediate goods for each of the three categories. These producers use category-specific labour $n_{j,t}$, which is subject to search-and-matching frictions, and category-specific physical capital $k_{j,t}$, which is subject to quadratic adjustment costs. The technologies are

$$F^j(n_{j,t}, k_{j,t}) \;=\; z_{j,t}\, n_{j,t}^{1-\alpha_j}\, k_{j,t}^{\alpha_j}, \qquad j \in \{n, r, s\}, \tag{12}$$

where $z_{j,t}$ is a sector-specific productivity factor. Output of category-$j$ intermediate goods is sold competitively to final-goods firms in category $j$ at the marginal-cost price $mc_{j,t}$. Climate damages are embedded in production through the damage function impacting the productivity in all sectors, $D(x_t)F^j$.

**Emissions, abatement, and the emissions-intensive wedge.** The production of intermediate goods for $r$-firms generates emissions $e_t$ that add to the global pollution stock $x_t$. As in Heutel (2012), emissions are a fraction $1 - \mu_t$ of unabated emissions, where

the unabated flow is a power function of emissions-intensive output:

$$e_t = (1-\mu_t)\,\mu_e\left(D(x_t)\,F^r(n_{r,t},k_{r,t})\right)^{1-\nu}, \qquad \Gamma_t = \gamma\,\mu_t^{\eta}\,D(x_t)\,F^r(n_{r,t},k_{r,t}), \quad (13)$$

with $\mu_e$ the emissions intensity and $\Gamma_t$ the resource cost of abatement at effort level $\mu_t$. Effectively, producers in the emissions-intensive sector choose $\mu_t$ to equate the marginal cost of abatement to the marginal benefit of avoiding the carbon tax. The carbon tax and the abatement cost together create a emissions-intensive sector wedge,

$$\Omega_{r,t} \;\equiv\; 1 - \frac{(1-\nu)\,\tau_t\,(1-\mu_t)\,\mu_e\,(D(x_t)\,F^r)^{-\nu}}{mc_{r,t}} - \frac{\gamma\,\mu_t^{\eta}}{mc_{r,t}}, \quad (14)$$

which scales the marginal value of an additional worker and the marginal product of capital in the $r$-sector. When $\tau_t > 0$ and the tax induces positive abatement effort ($\mu_t > 0$), the wedge satisfies $\Omega_{r,t} < 1$, reducing the effective marginal revenue products of labour and capital in the emissions-intensive sector. In the absence of a carbon tax and abatement ($\tau_t = \mu_t = 0$), the wedge equals unity, and the sector faces no additional distortion beyond the market-structure terms already embedded in $mc_{r,t}$. The $n$- and $s$-sectors are affected by the carbon tax only indirectly through general equilibrium effects.

**Capital with Jermann-style adjustment costs.** The sector-specific capital stocks evolve according to $k_{j,t+1} = (1-\delta)k_{j,t} + i_{j,t}$ for $j \in \{n, r, s\}$, where $i_{j,t}$ denotes sector specific investments and $\delta$ is the depreciation rate. We follow Jermann (1998) and assume that resources $\frac{\phi_j}{2}\,(i_{j,t}/k_{j,t} - \delta)^2 k_{j,t}$ are lost when investment deviates from steady-state replacement, where $\phi_j > 0$ is the curvature of the adjustment-cost function. The quadratic specification yields a closed-form Tobin's $q$ and an investment-Euler equation that converge to the frictionless neoclassical first-order condition as $\phi_j \to 0$. The shadow value

of installed capital and the investment-Euler equation are

$$\lambda_{j,t} = 1 + \phi_j\left(\tfrac{i_{j,t}}{k_{j,t}} - \delta\right), \tag{15}$$

$$\lambda_{j,t} = \mathbb{E}_t\, \Xi_{t+1|t}\left[r^k_{j,t+1} + \tfrac{\phi_j}{2}\left(\tfrac{i_{j,t+1}}{k_{j,t+1}} - \delta\right)\left(\tfrac{i_{j,t+1}}{k_{j,t+1}} + \delta\right) + (1-\delta)\lambda_{j,t+1}\right], \tag{16}$$

for $j \in \{n, r, s\}$. The capital rental rate $r^k_{j,t}$ equals the marginal product of sector-$j$ capital, scaled in the emissions-intensive sector by $\Omega_{r,t}$. The case $\phi_j = 0$ collapses these expressions to the standard frictionless capital Euler equation studied in FSM.

**Sectoral market clearing.** Sectoral market clearing equates damages-adjusted production to the demand for intermediate inputs by category-$j$ final-goods firms,

$$D(x_t)\, F^j(n_{j,t}, k_{j,t}) \;=\; N_{j,t}\, \frac{\tilde{y}_{j,t}}{\tilde{a}_{j,t}}, \qquad j \in \{n, r, s\}. \tag{17}$$

The condition in (17) stems from equating the revenue from producing the category-$j$ intermediate good with the average cost of the final-good producer buying the intermediate good.

## 3.2 Households

There is a representative household with a measure-one continuum of members who can be employed in one of the three sectors, unemployed and searching in one of the three sectors, or out of the labour force. The household owns all firms and provides the sunk entry cost; it also receives lump-sum rebates of carbon-tax revenue. Letting $lfp_{j,t} \equiv n_{j,t} + (1 - p_{\theta_j,t})s_{j,t}$ denote sectoral labour-force participation (with $n_{j,t}$ the measure of employed workers and $s_{j,t}$ the measure of searchers in sector $j$, and $p_{\theta_j,t}$ the

job-finding probability), the household maximizes

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[ u(c_t) - h\big(lfp_{n,t}, lfp_{r,t}, lfp_{s,t}\big) \right] \tag{18}$$

subject to a flow budget constraint, the sectoral employment laws of motion $n_{j,t} = (1 - \rho_n)n_{j,t-1} + s_{j,t}p_{\theta_j,t}$, and the firm-mass law of motion (5). The term $1 - \rho_n$ denotes the exogenous probability of continuing in the current employment relationship.

In the calibrated quantitative model, we use a CRRA utility $u(c_t) = c_t^{1-\sigma_c}/(1 - \sigma_c)$ and a participation disutility aggregator that is symmetric across sectors but allows for sector-specific weights:

$$h(\,\cdot\,) \;=\; \tfrac{\chi_r}{1+\chi_r} \Big[ \sum_{j \in \{n,r,s\}} \kappa_j \big(n_{j,t} + (1 - p_{\theta_j,t}) s_{j,t}\big) \Big]^{1+\frac{1}{\chi_r}}, \tag{19}$$

with $\chi_r$ the elasticity of participation and $\kappa_j$ sector-specific scale parameters.

**Firm-creation Euler.** The household's first-order condition for new entrants $N_{e,t}$ is the free-entry condition (11): the household creates new firms up to the point where the sunk cost equals the discounted continuation value of an additional active firm next period. Combined with the indifference conditions for the two productivity cutoffs, this condition closes the firm side of the model and makes the technological composition of production (the shares $N_{j,t}/N_t$) endogenous to the carbon tax.

**Search optimality across three sectors.** The first-order condition for searchers in sector $j$ equates the marginal disutility of being in the labour force, net of forgone unem-

ployment benefits $b_{ss}$, to the expected return from searching,

$$\frac{h'_{j,t} - b_{ss}\, c_t^{-\sigma_c}}{p_{\theta_j,t}\, c_t^{-\sigma_c}} \;=\; w_{j,t} - b_{ss} + \mathbb{E}_t\, \Xi_{t+1|t}(1-\rho_n)\big(1 - p_{\theta_j,t+1}\big)\frac{h'_{j,t+1} - b_{ss}\, c_{t+1}^{-\sigma_c}}{p_{\theta_j,t+1}\, c_{t+1}^{-\sigma_c}}, \quad (20)$$

for each $j \in \{n, r, s\}$. The left-hand side is the worker surplus $\mathcal{W}_{j,t}$.

## 3.3 Equilibrium

**Labour market: matching and wage bargaining.** Each sector has its own matching technology and own labour-market tightness. The number of new matches in sector $j$ is given by a CES matching function in sector-specific searchers $s_{j,t}$ and vacancies $v_{j,t}$,

$$m_{j,t} \;=\; \frac{s_{j,t}\, v_{j,t}}{\big(s_{j,t}^{\xi} + v_{j,t}^{\xi}\big)^{1/\xi}}, \qquad j \in \{n, r, s\}, \quad (21)$$

with $\xi$ the (common) matching elasticity. The sector-specific job-finding and vacancy-filling probabilities are $p_{\theta_j,t} = m_{j,t}/s_{j,t}$ and $q_{\theta_j,t} = m_{j,t}/v_{j,t}$, and sectoral employment evolves according to $n_{j,t} = (1-\rho_n)n_{j,t-1} + m_{j,t}$ with $\rho_n$ the (common) job separation rate.

The value of an active match in sector $j \in \{n, s\}$ to the firm is the marginal revenue product of an additional worker net of the wage, plus the discounted continuation value of the match,

$$\mathcal{J}_{j,t} \;=\; D(x_t)\, mc_{j,t}\, F^j_{n_j}(n_{j,t}, k_{j,t}) - w_{j,t} + \mathbb{E}_t\, \Xi_{t+1|t}(1-\rho_n)\, \mathcal{J}_{j,t+1}, \qquad j \in \{n, s\}, \quad (22)$$

and an analogous expression with the additional emissions-intensive sector wedge $\Omega_{r,t}$ for $j = r$. The free-entry condition for vacancies equates the marginal cost of posting

a vacancy, $\psi_j/q_{\theta_j,t}$, to the value of a filled job. Wages are set sector-by-sector by Nash bargaining with worker bargaining weight $\nu_n$, which equates a constant proportional share of match surpluses,

$$\mathcal{W}_{j,t} \;=\; \frac{\nu_n}{1-\nu_n}\,\mathcal{J}_{j,t}, \qquad j \in \{n, r, s\}, \tag{23}$$

yielding the standard wage rule that splits the joint surplus between worker and firm. The carbon tax affects $w_{r,t}$ directly through $\Omega_{r,t}$ in $\mathcal{J}_{r,t}$ and indirectly through general equilibrium for $w_{n,t}$ and $w_{s,t}$. Summing across sectors yields aggregate participation and the unemployment rate,

$$lfp_t \;=\; \sum_{j\in\{n,r,s\}} \big[n_{j,t} + (1-p_{\theta_j,t})s_{j,t}\big], \qquad ur_t \;=\; \frac{\sum_j (1-p_{\theta_j,t})s_{j,t}}{lfp_t}. \tag{24}$$

**Pollution dynamics.** Domestic emissions $e_t$ are generated by the emissions-intensive sector according to (13) and they add to a global pollution stock $x_t$ that also receives an exogenous flow $\bar{e}^{ROW}$ from the rest of the world,

$$x_t \;=\; \rho_x\, x_{t-1} + e_t + \bar{e}^{ROW}, \qquad 0 < \rho_x < 1. \tag{25}$$

Because $\bar{e}^{ROW}$ is taken as a parameter, the domestic carbon tax has only a marginal direct effect on the global pollution stock; the bulk of the response of $x_t$ to domestic policy operates through the persistence parameter $\rho_x$ and the new steady-state level of $e_t$.

**Resource constraint and symmetric equilibrium.** Following FSM, a symmetric equilibrium is defined in Appendix A.1 as a sequence of allocations and prices that, taking

the carbon-tax sequence $\{\tau_t\}$ and the rest-of-the-world emissions flow $\bar{e}^{ROW}$ as given, satisfies all household, firm, and market-clearing conditions. The aggregate resource constraint allocates output across consumption, vacancy posting, fixed entry and operating costs, abatement spending, gross sectoral investment, and the quadratic capital-adjustment frictions:

$$\begin{aligned} Y_t \;=\; c_t \;+\; \sum_{j\in\{n,r,s\}} \psi_j v_{j,t} \;+\; \Gamma_t \;+\; f_e N_{e,t} + f_n N_{n,t} + f_r N_{r,t} \\ +\; \sum_{j\in\{n,r,s\}} i_{j,t} \;+\; \sum_{j\in\{n,r,s\}} \tfrac{\phi_j}{2}\left(\tfrac{i_{j,t}}{k_{j,t}} - \delta\right)^2 k_{j,t}. \end{aligned} \tag{26}$$

The two new terms relative to FSM are the third summation block ($s$-sector vacancy and investment costs) and the quadratic adjustment-cost terms in the bottom row, which enter the resource constraint as a deadweight loss whenever sectoral investment deviates from its steady-state replacement level.

# 4 Quantitative analysis

## 4.1 Parameters, calibration

We calibrate the model to Finnish data from 2023. One model period is one quarter. Parameters are set in two groups: a first group taken directly from the literature, and a second group calibrated to match specific features of the Finnish economy. Parameters drawn from the literature are listed in Table 2 and they are the same as in Finkelstein Shapiro and Metcalf (2023). We retain these literature-based values to discipline the calibration and to keep the Finnish exercise comparable with the benchmark model and the existing literature. The capital share $\alpha_j$ is set to the same value in all sectors;

the discount factor $\beta$, the CRRA curvature $\sigma_c$, and the capital depreciation rate $\delta$ take standard values. The firm-heterogeneity parameters follow Ghironi and Melitz (2005). Labor-market frictions follow the search literature. The participation-elasticity parameter $\chi_r$ is from Chetty et al. (2011) and Chetty et al. (2013). The emissions-and-damages parameters follow Heutel (2012), Hafstead and Williams (2018), Nordhaus (2008), and Annicchiarico et al. (2018). The quarterly job separation rate $\rho = 0.10$ is taken from the macro-search literature (den Haan et al., 2000); it exceeds Finnish administrative separation rates of roughly 3–5% per quarter because the model's separation concept encompasses job-to-job transitions alongside layoffs and quits, producing a composite turnover rate consistent with the calibrated unemployment rate.

Table 2: Parameter values, description, and sources.

*Parameters from Literature*

| Parameter | Value | Description | Source |
|---|---|---|---|
| $\alpha_n, \alpha_r, \alpha_s$ | 0.32 | Capital share (all sectors) | Standard value in lit. |
| $\beta$ | 0.985 | Discount factor | Standard value in lit. |
| $\sigma_c$ | 2 | CRRA parameter | Standard value in lit. |
| $\chi_r$ | 0.26 | Elasticity of LFP | Chetty et al. (2011, 2013) |
| $\varepsilon$ | 3.8 | Elast. substit. firm output | Ghironi and Melitz (2005) |
| $k_p$ | 4.2 | Pareto shape parameter | Finkelstein Shapiro and Metcalf (2023) |
| $a_{\min}$ | 1 | Min. idiosyncratic productivity | Normalization |
| $\rho$ | 0.1 | Job separation probability | Search lit. |
| $\mu_n$ | 0.5 | Worker bargaining power | Search lit. |
| $\delta$ | 0.025 | Capital depreciation rate | Standard value in lit. |
| $D_1$ | 0.69825 | Damages parameter | Annicchiarico et al. (2018) |
| $\eta$ | 2.8 | Elast. of abatement rate | Nordhaus (2008) |
| $\gamma$ | 1 | Weight, abate. cost function | Hafstead and Williams III (2018) |
| $1-\nu$ | 0.696 | Elast. parameter, emissions | Heutel (2012) |
| $\rho_x$ | 0.9979 | Persistence of pollution | Heutel (2012) |
| $\phi$ | 0.1 | Capital adjustment cost | Baseline; $\phi = 1, 2$ also reported |

The remaining parameters are calibrated jointly to match a set of Finnish steady-state moments. On the labor-market side, the calibration targets an unemployment rate

Table 3: Parameter values, description, and targets in the two- and three-sector models.

*Calibrated Parameters: two-sector model*

| Parameter | Value | Description | Target |
|---|---|---|---|
| $D_0$ | 4.7856e-08 | Damages parameter | Pollution damages/GDP $= 0.0069$ |
| $\psi_r$ | 1.6562 | Vacancy posting cost (emissions-intensive) | Vac. costs/GDP $= 0.028\, w_r$ |
| $\psi_n$ | 1.6562 | Vacancy posting cost (high-clean) | $\psi_n = \psi_r$ |
| $e_{row}$ | 999.00 | Emissions rest of world | $e_{row}/(e + e_{row}) = 0.999$ |
| $\kappa_r$ | 0.6520 | $r$ LFP disutility param. | $n_r = 0.1844$ |
| $\kappa_n$ | 0.5801 | $n$ LFP disutility param. | $lfp = 0.70$ |
| $b$ | 32.6736 | Unemployment benefits | $b = 0.6\, \bar{w}$ |
| $f_e$ | 0.75814 | Sunk entry cost | $f_e/Y = 0.01$ |
| $f_i$ | 0.0062131 | Fixed cost (high-clean tech) | Endogenous; matches cutoff $z_i$ |
| $\xi$ | 0.4714 | Matching elasticity param. | Unempl. rate $= 7.2\%$ |
| $\mu_e$ | 0.74672 | Weight of $r$ output on emissions | Normalization $e = 1$ |
| $\bar{x}$ | 332502.08 | Baseline pollution in $D(x)$ | $\bar{x} = D_1\, x_{ss}$ |

*Calibrated Parameters: three-sector model*

| Parameter | Value | Description | Target |
|---|---|---|---|
| $D_0$ | 4.786e-08 | Damages parameter | Pollution damages/GDP $= 0.0069$ |
| $\psi_r$ | 12.847 | Vacancy posting cost (emissions-intensive) | Vac. costs/GDP $= 0.028\, w_r$ |
| $\psi_n$ | 12.847 | Vacancy posting cost (high-clean) | $\psi_n = \psi_r$ |
| $\psi_s$ | 12.847 | Vacancy posting cost (low-clean) | $\psi_s = \psi_r$ |
| $e_{row}$ | 999.00 | Emissions rest of world | $e_{row}/(e + e_{row}) = 0.999$ |
| $\kappa_r$ | 0.4270 | $r$ LFP disutility param. | $n_r = 0.1844$ |
| $\kappa_n$ | 0.4378 | $n$ LFP disutility param. | $lfp = 0.70$ |
| $\kappa_s$ | 0.3434 | $s$ LFP disutility param. | $n_s/(n_n + n_r + n_s) = 0.4377$ |
| $b$ | 253.49 | Unemployment benefits | $b = 0.6\, \bar{w}$ |
| $f_e$ | 0.1763 | Sunk entry cost | $f_e/Y = 0.0003$ |
| $f_i$ | 0.0026 | Fixed cost (high-clean tech) | Endogenous; matches cutoff $z_i$ |
| $f_r$ | 6.707e-04 | Fixed cost (emissions-intensive tech) | Endogenous; matches cutoff $z_r$ |
| $\xi$ | 0.4773 | Matching elasticity param. | Unempl. rate $= 7.2\%$ |
| $\mu_e$ | 0.4133 | Weight of $r$ output on emissions | Normalization $e = 1$ |
| $\bar{x}$ | 332502.08 | Baseline pollution in $D(x)$ | $\bar{x} = D_1\, x_{ss}$ |
| $z_n$ | 1.265 | Productivity shifter, high-clean | $w_s/w_n = 0.783$ |
| $z_r$ | 1.215 | Productivity shifter, emissions-intensive | Midpoint of admissible range $[1.175, 1.255]$ |
| $z_s$ | 1.000 | Productivity shifter, low-clean | Normalization ($z_s = 1$) |

of 7.2%, an unemployment-benefit replacement rate of 60% of the average wage, and sectoral employment shares consistent with Finnish data.[5]

The environmental block follows FSM. The damage function, $D(x_t) = \exp\big[-d_0(x_t - \bar{x})\big]$, affects production symmetrically across all three sectors through (17). Note that these damage channels, however, play only a minor role in the unilateral policy experiment we present in this section. This is a feature of the Finnish small-country experiment rather than a general property of the damage channel: Finland's calibrated share of the global emissions flow is very small, so reductions in Finnish emissions have little effect on the global pollution stock that enters the common damage function. With that in mind, the reference pollution level is parameterized by $D_1 = \bar{x}/x_{ss}$ and set equal to the ratio of pre-industrial to 2015 atmospheric $CO_2$ concentrations, $280/401$, following Annicchiarico et al. (2018). We then calibrate $d_0$ so that steady-state damages, $1 - D(x_{ss})$, equal 0.69% of output, which is the same as in FSM. Finally, $\bar{e}^{ROW}$ is chosen so that the domestic share of global emissions is consistent with Finland's small contribution to the global emissions flow.

Two versions of the model are calibrated to the same data. The two-sector version follows FSM and partitions the economy into a clean and a emissions-intensive sector. The three-sector version disaggregates the clean aggregate into a high-productivity clean technology and a low-productivity clean technology. This disaggregation introduces three sector-specific productivity shifters. One ($z_s$) is a normalisation; one ($z_n$) is identified by the targeted wage ratio $w_s/w_n$; and the third ($z_r$) is not identified by any moment in the calibration. The existing moments therefore pin down the relative pro-

[5]The sectoral partition is the one set out in Section 2: the emissions-intensive sector ($r$) comprises primary production, energy-intensive manufacturing, energy and utilities, water and waste, construction, and transport; the high-productivity clean sector ($n$) comprises services to industry, other business services, and education; and the low-productivity clean sector ($s$) comprises other manufacturing, trade, and services to households.

ductivity of the two clean sectors but do not provide an additional independent target for $z_r$. We set $z_r$ at the midpoint of the range over which the model admits an economically meaningful steady state as a neutral working value within that admissible range. Similarly, when setting the target that defines the sunk firm entry cost, we set it in such a way to ensure a well-defined steady state.[6]

Because within-sector abatement absorbs a substantial part of the emissions adjustment, the results also depend on the assumed abatement-cost schedule. We retain the benchmark literature values for the abatement block to preserve comparability, while calibrating the emissions-intensity scale to the Finnish baseline. We examine the sensitivity of the results with respect to the assumed abatement cost schedule in Section 5.2.

Finally, we set the emission reduction target. Finland's Climate Act commits the country to carbon neutrality by 2035 and sets statutory emissions-reduction targets of 60% by 2030, 80% by 2040, and at least 90% by 2050 relative to 1990. These targets provide a useful benchmark for the policy experiment that we conduct in this section. Throughout the paper, we study a carbon tax calibrated to reduce domestic emissions by 40% relative to the 2023 baseline. This corresponds to a long-run emissions level of roughly 24.7 Mt $CO_2$e and places the experiment between Finland's statutory 2030 and 2040 targets. The experiment is also close in magnitude to the 35% reduction studied by Finkelstein Shapiro and Metcalf (2023).

[6] Although the targeted $f_e/Y$ ratios differ across the two calibrations (because solution stability requires different scales of $f_e$ in the two models), the implied per-period aggregate entry resource cost $f_e N_e/Y$ is almost identical at $\approx 16\%$ in both calibrations. In this sense, the two models allocate equivalent fractions of output to firm creation, and the cross-model differences reported in Tables 4 and 5 are driven by the sectoral structure rather than by a calibration discrepancy on the entry margin. A similar re-scaling applies to the vacancy-posting cost parameters: $\psi_j = 12.847$ in the three-sector model compared to $\psi_j = 1.656$ in the two-sector model (a factor of roughly eight). The difference reflects the proportionally larger steady-state output and employment base in the three-sector calibration; the targeted ratio of vacancy costs to output, $0.028\, w_r$, is identical across both models, so the two calibrations impose equivalent vacancy-cost burdens on the labour market.

## 4.2 Steady-state effects

Tables 4 and 5 report the steady-state effects of a carbon tax that delivers a 40% long-run reduction in Finnish emissions. Table 6 provides a comparison of the main changes. In the two-sector model, total output rises slightly by 0.05% and consumption decreases by 0.05% (Table 4). Total employment, unemployment and labor force participation all increase slightly. The emission-intensive sector abates its emissions by 29.6%, and the rest of the emissions reductions come from sectoral reallocation of production. Here the changes are more substantial in magnitude. Emissions-intensive sector employment falls by 20.3%, emissions-intensive sector capital by 21.1%, and the number of emissions-intensive firms by 11.8%. The clean sector absorbs these resources: employment rises by 9.0%, capital by 7.9%, and the number of clean firms by 26.0%. The share of clean-firm output rises from 69% to 75%. This produces a technology-composition effect: overall average firm productivity rises by 0.73%, even though the average productivity of firms within each category declines as the cutoff moves and the composition within categories changes.

A striking difference emerges once the clean sector is divided into high- and low-productivity activities: the sign of the aggregate output response changes relative to the two-sector benchmark. In the three-sector model, total output falls by 0.33% and consumption by 0.24% (Table 5). Abatement now reaches a lower level of 27.8% of the emissions reduction target, meaning more of the emissions reduction happens through sectoral reallocation than in the two-sector model. Moreover, the reallocation away from emissions-intensive production is no longer absorbed by one clean sector. Instead, it is divided between high-productivity clean activities and low-productivity clean activities. Employment in the high-clean sector rises by 9.9%, and employment in the low-clean

Table 4: Steady-state changes in response to a carbon tax that delivers a 40% reduction in emissions, two-sector model (n = clean, r = emissions-intensive).

| Variable | Before Tax (Baseline) | After Tax | Change Rel. to Baseline |
|---|---|---|---|
| *Levels (% change)* | | | |
| Total Output | 7.6883 | 7.6922 | 0.050 |
| Consumption | 5.0336 | 5.0313 | -0.048 |
| $n$ Employment | 0.4652 | 0.5071 | 9.017 |
| $r$ Employment | 0.1844 | 0.1470 | -20.278 |
| Total Employment | 0.6496 | 0.6542 | 0.701 |
| $n$ Real Wage | 5.3337 | 5.3217 | -0.226 |
| $r$ Real Wage | 5.9986 | 5.9854 | -0.220 |
| $n$ Capital | 306.611 | 330.804 | 7.890 |
| $r$ Capital | 137.753 | 108.704 | -21.087 |
| Firms ($N$) | 606.682 | 594.208 | -2.056 |
| $n$ Firms ($N_n$) | 156.692 | 197.355 | 25.952 |
| $r$ Firms ($N_r$) | 449.991 | 396.853 | -11.809 |
| $n$ Avg. Idiosync. Prod. ($\tilde{a}_n$) | 2.0435 | 1.9247 | -5.812 |
| $r$ Avg. Idiosync. Prod. ($\tilde{a}_r$) | 1.1472 | 1.1222 | -2.175 |
| Overall Avg. Firm Prod. | 1.3787 | 1.3888 | 0.731 |
| *Rates and shares (percentage-point change)* | | | |
| Unemployment Rate | 7.200% | 7.357% | 0.157 |
| LFP Rate | 70.000% | 70.611% | 0.611 |
| Abatement Rate | 0.000% | 29.590% | 29.590 |
| Share of $n$-Firm Output | 69.000% | 74.961% | 5.961 |
| Share of $r$-Firm Output | 31.000% | 25.039% | -5.961 |
| Share of $n$ Firms ($N_n/N$) | 25.828% | 33.213% | 7.386 |
| Share of $r$ Firms ($N_r/N$) | 74.172% | 66.787% | -7.386 |
| Tax Rev./Output | 0.000% | 0.354% | 0.354 |
| *Welfare* | | | |
| Welfare gain (CEV, % of $c$) | — | — | -0.905 |

Notes: Overall Avg. Firm Prod. is defined as $(N_n/N)\,\tilde{a}_n + (N_r/N)\,\tilde{a}_r$. All real variables are expressed in data-consistent terms. Welfare is the consumption-equivalent variation that makes the household indifferent between the baseline and post-tax steady states.

Table 5: Steady-state changes in response to a carbon tax that delivers a 40% reduction in emissions, three-sector model (n = high-productivity clean, r = emissions-intensive, s = low-productivity clean).

| Variable | Before Tax (Baseline) | After Tax | Change Rel. to Baseline |
|---|---|---|---|
| *Levels (% change)* | | | |
| Total Output | 16.882 | 16.826 | -0.329 |
| Consumption | 11.100 | 11.073 | -0.242 |
| $n$ Employment | 0.1809 | 0.1988 | 9.888 |
| $r$ Employment | 0.1844 | 0.1414 | -23.300 |
| $s$ Employment | 0.2843 | 0.3145 | 10.613 |
| Total Employment | 0.6496 | 0.6547 | 0.784 |
| $n$ Real Wage | 13.517 | 13.479 | -0.280 |
| $r$ Real Wage | 13.183 | 13.146 | -0.280 |
| $s$ Real Wage | 10.584 | 10.554 | -0.285 |
| $n$ Capital | 1075.32 | 1177.02 | 9.458 |
| $r$ Capital | 1067.61 | 815.64 | -23.601 |
| $s$ Capital | 1300.97 | 1433.18 | 10.162 |
| Firms ($N$) | 20730.32 | 20678.11 | -0.252 |
| $n$ Firms ($N_n$) | 493.64 | 644.25 | 30.511 |
| $r$ Firms ($N_r$) | 3801.10 | 2809.36 | -26.091 |
| $s$ Firms ($N_s$) | 16435.58 | 17224.50 | 4.800 |
| $n$ Avg. Idiosync. Prod. ($\tilde{a}_n$) | 3.605 | 3.381 | -6.200 |
| $r$ Avg. Idiosync. Prod. ($\tilde{a}_r$) | 1.773 | 1.803 | 1.684 |
| $s$ Avg. Idiosync. Prod. ($\tilde{a}_s$) | 1.168 | 1.188 | 1.667 |
| Overall Avg. Firm Prod. | 1.337 | 1.340 | 0.183 |
| *Rates and shares (percentage-point change)* | | | |
| Unemployment Rate | 7.200% | 7.334% | 0.134 |
| LFP Rate | 70.000% | 70.651% | 0.651 |
| Abatement Rate | 0.000% | 27.771% | 27.771 |
| Share of $n$-Firm Output | 31.224% | 34.321% | 3.097 |
| Share of $r$-Firm Output | 31.000% | 23.889% | -7.111 |
| Share of $s$-Firm Output | 37.776% | 41.790% | 4.014 |
| Share of $n$ Firms ($N_n/N$) | 2.381% | 3.116% | 0.734 |
| Share of $r$ Firms ($N_r/N$) | 18.336% | 13.586% | -4.750 |
| Share of $s$ Firms ($N_s/N$) | 79.283% | 83.298% | 4.015 |
| Tax Rev./Output | 0.000% | 0.094% | 0.094 |
| *Welfare* | | | |
| Welfare gain (CEV, % of $c$) | — | — | -0.388 |

Notes: Overall Avg. Firm Prod. is defined as $(N_n/N)\,\tilde{a}_n + (N_r/N)\,\tilde{a}_r + (N_s/N)\,\tilde{a}_s$. All real variables are expressed in data-consistent terms. Welfare is the consumption-equivalent variation that makes the household indifferent between the baseline and post-tax steady states.

Table 6: Long-run comparison of the two- and three-sector models.

| Description | Two-sector model | Three-sector model |
|---|---|---|
| *Aggregate outcomes (% change unless otherwise noted)* | | |
| Emissions target | -40.000 | -40.000 |
| Total output | 0.050 | -0.329 |
| Consumption | -0.048 | -0.242 |
| Total employment | 0.701 | 0.784 |
| Overall average firm productivity | 0.731 | 0.183 |
| Output per worker | -0.647 | -1.104 |
| Capital per worker | -1.781 | -1.298 |
| Welfare gain, CEV (% of baseline $c$) | -0.905 | -0.388 |
| *Sectoral employment and capital* | | |
| $n$ employment: clean / high-clean | 9.017 | 9.888 |
| $r$ employment: emissions-intensive | -20.278 | -23.300 |
| $s$ employment: low-clean | — | 10.613 |
| $n$ capital: clean / high-clean | 7.890 | 9.458 |
| $r$ capital: emissions-intensive | -21.087 | -23.601 |
| $s$ capital: low-clean | — | 10.162 |
| *Technology composition and abatement* | | |
| $n$ firms: clean / high-clean | 25.952 | 30.511 |
| $r$ firms: emissions-intensive | -11.809 | -26.091 |
| $s$ firms: low-clean | — | 4.800 |
| Share of $n$-firm output (pp) | 5.961 | 3.097 |
| Share of $r$-firm output (pp) | -5.961 | -7.111 |
| Share of $s$-firm output (pp) | — | 4.014 |
| Abatement rate (pp) | 29.590 | 27.771 |
| Tax revenue/output (pp) | 0.354 | 0.094 |

Notes: This table collects the "Change relative to baseline" columns from Tables 4 and 5. Level variables are percentage changes; rates and shares are percentage-point changes.

sector rises by slightly more, 10.6%. Capital follows the same pattern, increasing by 9.5% in the high-clean sector and 10.2% in the low-clean sector. The output share of high-clean firms rises from 31.2% to 34.3%, while the output share of low-clean firms rises from 37.8% to 41.8%. Because the low-clean sector is the larger of the two in levels, these similar growth rates imply that roughly three-fifths of the net increase in clean employment is absorbed by low-productivity activities.

To summarize, the changes in the aggregate outcomes are small in both models (Table 6). However, in the three-sector model, aggregate output effect turns negative. The composition effect explains the mechanism. Moving resources from emissions-intensive production to high-clean production raises the productivity composition of the economy, while moving resources from emissions-intensive production to low-clean production lowers it. Since a substantial part of the reallocation is absorbed by the low-clean sector, the aggregate productivity gain is much weaker than in the two-sector model. Overall, average firm productivity rises by only 0.18%, roughly a quarter of the 0.73% obtained in the two-sector model. Additionally, slightly more of the emissions reduction comes from sectoral reallocation rather than from within-sector abatement investments in the three-sector model. Consequently, carbon tax revenue relative to GDP is also smaller. Interestingly, the welfare loss, as measured by the CEV, is smaller in the three-sector model. This is explained by the calibrated utility function parameters (Table 3). The calibrated LFP disutilities differ between sectors and those differences influence the CEV measures. Although distinguishing the two clean destinations changes the sign of the aggregate output effect, the long-run output and consumption responses remain modest in magnitude. The main contribution of the three-sector structure is to reveal how the destination of reallocated resources changes the composition and productivity consequences of decarbonisation.

### 4.3 Dynamic transition to a new steady state

The steady-state comparison describes the initial and final allocations. We next examine how the economy moves between them. The dynamic adjustment is obtained by solving the non-linear deterministic transition.[7] The economy is given a pre-announced, linearly increasing emissions tax that reaches its new steady-state level after 40 quarters and remains there thereafter.

Figure 2 shows the transition paths in the two- and three-sector models. In both cases the carbon tax follows the same 40-quarter ramp and emissions decline gradually toward the long-run target. Note that these dynamic solutions have been solved using $\phi = 0.1$ as the capital adjustment cost parameter. This represents a nearly frictionless case. There are two notable differences in the transition paths. First, output in the two-sector model peaks after 40 quarters and then starts gliding towards the new steady state. In the three-sector model, output starts decreasing immediately towards the lower steady state. Second, consumption also follows the same dynamic pattern as the output. The transition paths show a more pronounced difference than the steady-state comparison alone: around the end of the 40-quarter tax phase-in, the gap between the two GDP responses is roughly half a percentage point.

## 5 Extensions

In this section, we maintain the three-sector structure while examining the implications of changes in two key model features: capital adjustment costs and the cost of emissions abatement. As described in Section 3.1.2, capital adjustment costs influence the transition dynamics, with higher costs slowing the reallocation of capital across sectors

[7] We use Dynare in Matlab to solve the transition path.

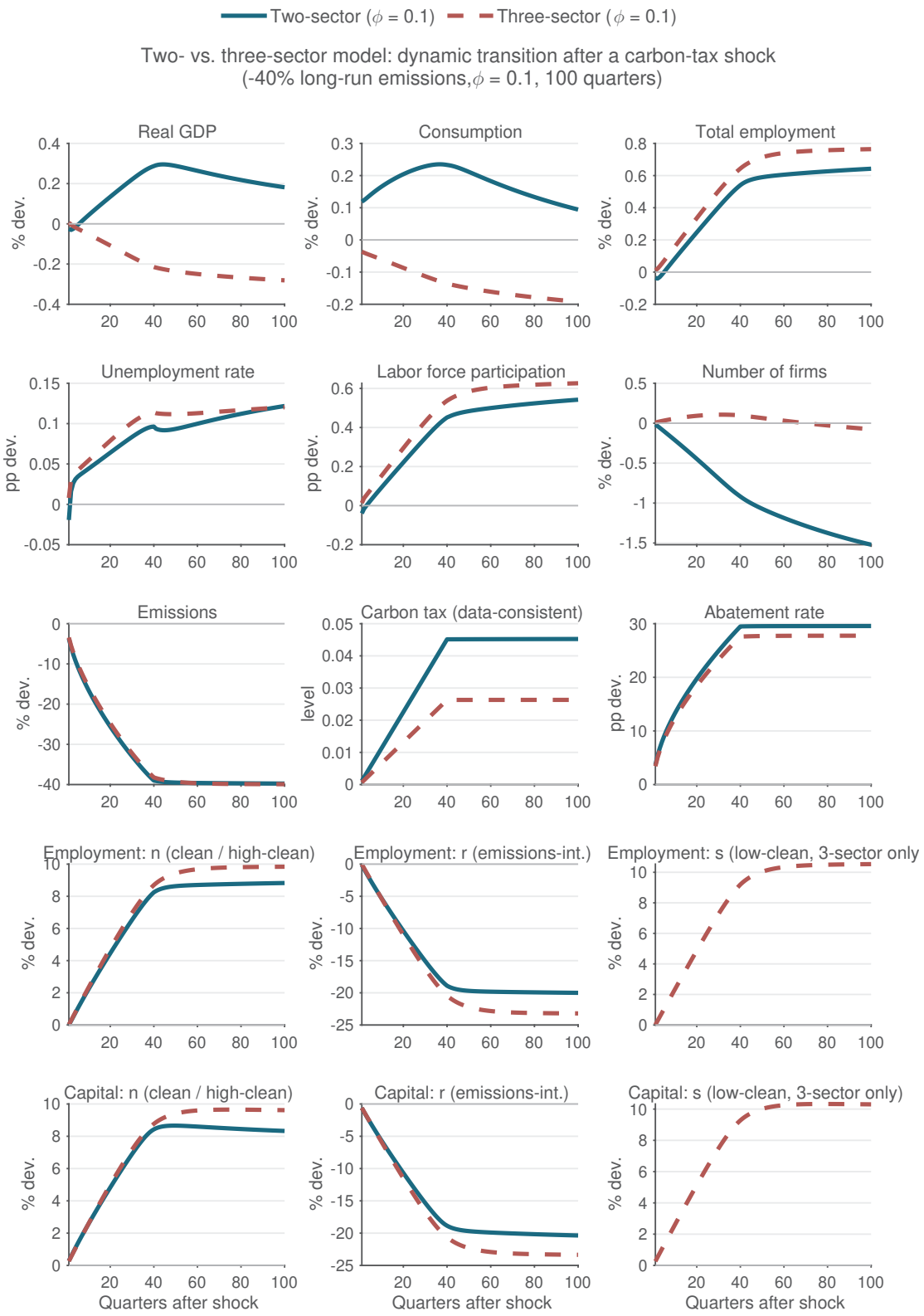



Figure 2: Two-sector vs. three-sector model: dynamic transition after the 40-quarter carbon-tax ramp, capital adjustment cost $\phi = 0.1$. Each panel plots the percent (or percentage-point) deviation from the pre-shock steady state over the first 100 quarters. Solid lines: three-sector model. Dashed lines: two-sector model.

without affecting the long-run equilibrium. Abatement costs, in contrast, influence the long-run allocation of resources across sectors. Lower abatement costs reduce the extent of sectoral reallocation required to achieve a given emissions reduction target by allowing the emissions-intensive sector to adjust through greater abatement rather than reductions in production.

## 5.1 Capital adjustment costs

We begin by comparing three values of the capital adjustment cost parameter, $\phi \in \{0.1, 1, 2\}$, in the three-sector model. The parameter is assumed to be identical across all sectors. Because capital is sector specific, higher adjustment costs slow the reallocation of capital from emissions-intensive production toward the two clean sectors. While the long-run steady state remains unchanged, the transition dynamics depend on the magnitude of these adjustment costs.

Figure 3 shows that higher adjustment costs flatten and lengthen the sectoral capital responses. With low adjustment costs, emissions-intensive capital declines more rapidly and clean-sector capital rises more quickly. With high adjustment costs, capital remains closer to its initial allocation for longer. This also slows the decline in output, since the three-sector model is not simply moving capital toward a uniformly better clean destination. Part of the reallocation is toward the low-productivity clean sector. Slower capital adjustment can therefore cushion the short-run output loss by delaying the movement toward the lower-productivity part of the clean economy. However, attaining the emissions reduction target gets pushed further down the horizon as adjustment costs increase.

Table 7 presents welfare measures of the transition path. Note that the full-path CEV also becomes less negative as $\phi$ rises. This is explained by the fact the attainment of

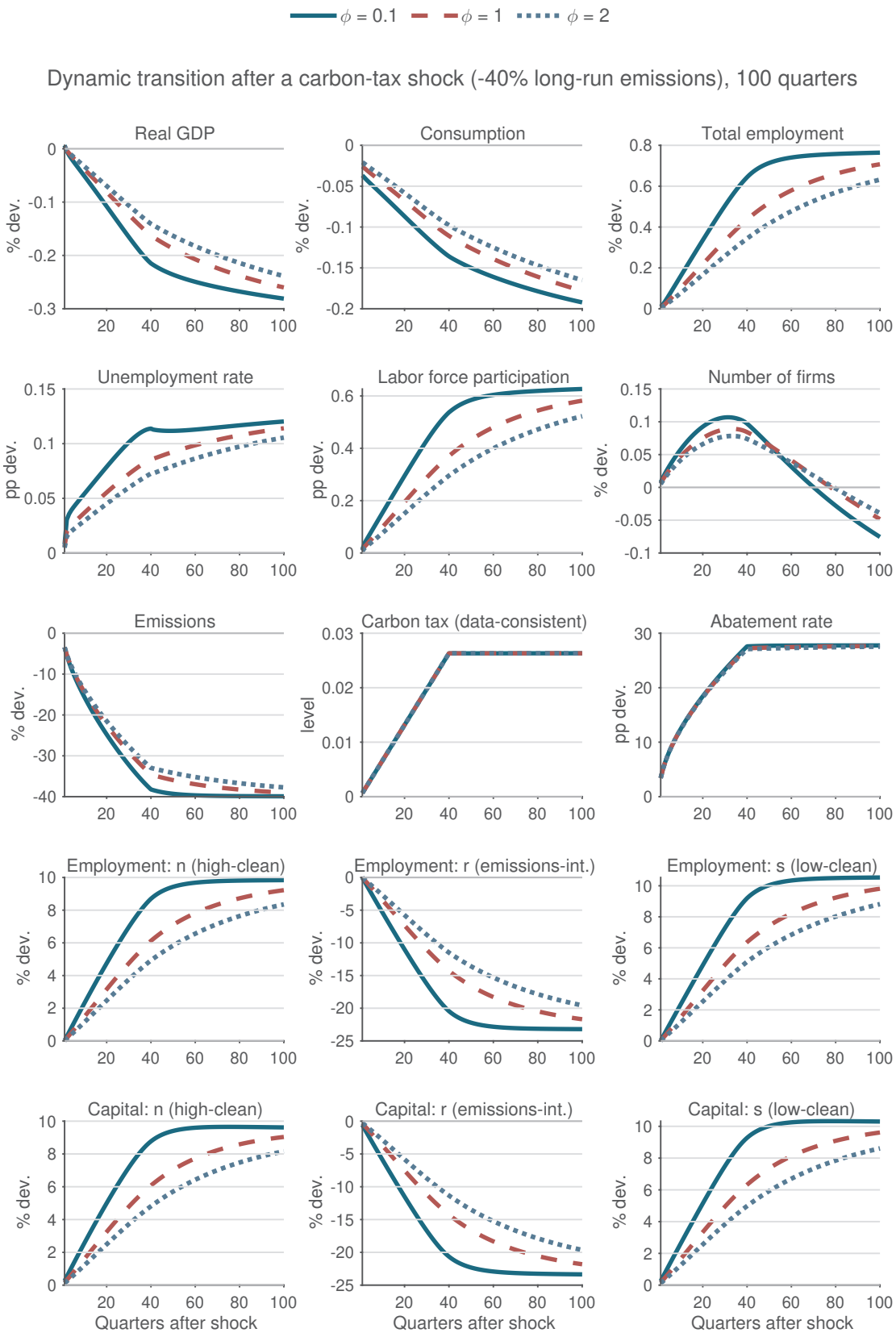



Figure 3: Three-sector model: dynamic transition after the 40-quarter carbon-tax ramp under three capital-adjustment-cost scenarios ($\phi \in \{0.1, 1, 2\}$). Each panel plots the percent (or percentage-point) deviation from the pre-shock steady state over the first 100 quarters of the transition.

the new steady state is delayed and the household benefits from that delay. However, this welfare comparison should be interpreted with caution because higher adjustment costs also delay emissions reductions. The less negative full-path CEV therefore reflects both adjustment frictions and differences in transition timing, rather than a pure welfare benefit of costly capital reallocation.

Table 7: Welfare cost of the transition to a –40% emissions steady state, for three capital adjustment cost scenarios.

| Metric | $\phi = 0.1$ | $\phi = 1$ | $\phi = 2$ |
|---|---|---|---|
| *Welfare (consumption-equivalent variation, % of baseline c)* | | | |
| CEV, full transition path | -0.160 | -0.137 | -0.124 |
| CEV, new steady state only | -0.388 | -0.388 | -0.388 |
| CEV, transition component | 0.228 | 0.251 | 0.264 |

Notes: Computations use the household quarterly discount factor $\beta = 0.9850$. Welfare CEV is computed over the full transition path (plus an infinite continuation at the new steady state); positive values are welfare gains and negative values are losses. The "new SS only" row is the counterfactual CEV if the household jumped instantaneously to the new steady state, and is identical across scenarios by construction. The "transition component" is the full-path CEV minus the SS-only CEV and isolates the welfare cost of the dynamic adjustment itself.

## 5.2 Exogenous abatement-technology progress

The baseline model assumes that the cost of emissions abatement remains constant throughout the transition. In practice, however, abatement costs may decline over time as firms adopt cleaner production technologies and environmental policies encourage directed technical change (Acemoglu et al., 2012, 2016). Although we do not model directed technological change endogenously, we examine the sensitivity of our quantitative results in Section 4 to an exogenous decline in abatement costs as the carbon tax is gradually introduced.

To this end, we introduce a multiplicative wedge $\exp(-\psi_t)$ on the abatement-cost parameter $\gamma$, such that the emissions-intensive firm's cost of abating a fraction $\mu_t$ of its emissions becomes $\gamma \exp(-\psi_t)\, \mu_t^{\eta}\, Y_{r,t}$. We assume that $\psi_t$ increases linearly from zero to a permanent long-run level $\psi^*$ over the same 40-quarter horizon as the carbon-tax phase-in. Setting $\psi^* = 0$ recovers the baseline scenario of Section 4, while $\psi^* = \log 2$ corresponds to a halving of abatement costs. We consider three scenarios: $\psi^* \in \{0, 0.3, \log 2\}$. The carbon-tax target (a 40% long-run emissions reduction) and the capital adjustment cost parameter ($\phi = 0.1$) are held fixed at their baseline values across all three scenarios.

Table 8 reports the new steady-state outcomes. The carbon tax required to achieve the targeted 40% emissions reduction falls from $0.0263$ at $\psi^* = 0$ to $0.0182$ at $\psi^* = \log 2$, representing a 31% reduction. Cheaper abatement also reduces the extent of factor reallocation: employment in the emissions-intensive sector declines by 15.2%, compared with 23.3% in the baseline scenario, while the corresponding capital contraction falls from 23.6% to 15.4%. At the same time, the abatement rate $\mu$ increases from 27.8% to 32.7%. These changes translate into smaller aggregate economic losses. Output declines by 0.21% rather than 0.33%, consumption by 0.16% rather than 0.24%, and the welfare loss measured by the consumption-equivalent variation (CEV) falls from 0.388% to 0.249% of baseline consumption.

Table 8 further shows that cheaper abatement affects the scale of labor reallocation but has little effect on its composition. The share of the net increase in clean employment absorbed by the low-productivity sector declines only marginally, from $62.8\%$ at $\psi^* = 0$ to $62.6\%$ at $\psi^* = 0.3$ and $62.3\%$ at $\psi^* = \log 2$, even as the overall magnitude of reallocation falls by approximately one-third. Cheaper abatement therefore reduces the extent of reallocation required to achieve a given emissions target without substantially shift-

Table 8: Steady-state effects of the carbon tax under three abatement-technology scenarios, three-sector model. The columns under each $\psi^*$ report the post-tax steady state and the percent or percentage-point change relative to the (common) baseline.

| | Baseline | $\psi^* = 0$ | $\psi^* = 0.3$ | $\psi^* = \log 2$ |
|---|---|---|---|---|
| *Levels (% change relative to baseline)* | | | | |
| Total Output | 16.882 | −0.329 | −0.277 | −0.213 |
| Consumption | 11.100 | −0.242 | −0.205 | −0.158 |
| $n$ Employment | 0.1809 | +9.89 | +8.41 | +6.56 |
| $r$ Employment | 0.1844 | −23.30 | −19.67 | −15.21 |
| $s$ Employment | 0.2843 | +10.61 | +8.91 | +6.84 |
| $n$ Real Wage | 13.517 | −0.280 | −0.240 | −0.188 |
| $r$ Real Wage | 13.183 | −0.280 | −0.240 | −0.188 |
| $s$ Real Wage | 10.584 | −0.285 | −0.244 | −0.192 |
| $n$ Capital | 1075.32 | +9.46 | +8.05 | +6.28 |
| $r$ Capital | 1067.61 | −23.60 | −19.94 | −15.42 |
| $s$ Capital | 1300.97 | +10.16 | +8.54 | +6.55 |
| $n$ Firms ($N_n$) | 493.64 | +30.51 | +25.60 | +19.62 |
| $r$ Firms ($N_r$) | 3801.10 | −26.09 | −22.10 | −17.14 |
| $s$ Firms ($N_s$) | 16435.58 | +4.80 | +4.08 | +3.18 |
| *Rates, shares, and policy (pp change relative to baseline, except $\tau$ in level)* | | | | |
| Unemployment Rate | 7.200% | +0.134 | +0.112 | +0.086 |
| LFP Rate | 70.000% | +0.651 | +0.545 | +0.417 |
| Abatement Rate | 0.000% | +27.77 | +30.07 | +32.66 |
| Tax Revenue / GDP | 0.000% | +0.094 | +0.081 | +0.065 |
| Carbon tax rate $\tau_{\text{data}}$ (level) | 0 | 0.0263 | 0.0228 | 0.0182 |
| *Welfare* | | | | |
| Welfare gain (CEV, % of $c$) | — | −0.388 | −0.325 | −0.249 |

Notes: All scenarios target a 40% long-run emission reduction and use $\phi = 0.1$. $\psi^* = 0$ reproduces the baseline of Table 5. The carbon-tax rate and tax revenue / GDP are reported on the same data-consistent basis as in Section 4. Welfare is the consumption-equivalent variation that makes the household indifferent between the baseline and the post-tax steady state.

ing its composition toward the high-productivity clean sector. These results suggest that policies aimed at lowering the barriers to adopting high-productivity clean technologies and policies that reduce abatement costs within the emissions-intensive sector address distinct margins of adjustment.

# 6 Discussion

The two-sector model in Section 4 replicates the Finkelstein Shapiro and Metcalf (2023) finding that a carbon tax is broadly compatible with small positive aggregate effects, given the technology-adoption channel. Although our two-sector model is calibrated to Finland rather than the United States, resulting in different magnitudes, the qualitative findings are consistent with theirs. The three-sector model places the same policy in a setting that is structurally richer. As a point in contrast, the output effect turns negative. Moreover, the increase in the average productivity is smaller than in the two-sector model results.

Our findings can also be situated within the broader literature on the macroeconomic effects of carbon taxation. Studies of carbon taxes in models with frictional labor markets and a single emissions-intensive sector that competes with an exogenously specified non-polluting sector generally find that aggregate output and consumption fall after a carbon tax, even when revenue recycling and abatement margins are present (Hafstead and Williams, 2018; Heutel, 2012; Annicchiarico and Diluiso, 2019). Models with directed technical change and clean-versus-dirty research portfolios deliver more nuanced predictions but typically find that the short-run cost of decarbonization is non-negligible (Acemoglu et al., 2016). The two-sector framework of Finkelstein Shapiro and Metcalf (2023), with endogenous technology adoption, sits at the optimistic end of this spec-

trum. Our three-sector extension lies closer to the middle. It preserves the endogenous technology-adoption channel that distinguishes their model but adds the realistic feature that the cleanest technology is costly to adopt and that there is a less productive alternative available to firms that cannot pay the high-clean fixed cost.

In terms of policy design, the model provides several insights. While the carbon tax $\tau_t$ influences the size of the emissions-intensive sector, the fixed costs $f_n$ and $f_r$ determine how much of the resulting reallocation is directed toward the high-clean technology. From a policy-design perspective the most useful summary statistic is therefore the position of the endogenous cutoffs $(a_r, a_n)$. Any complementary policy that makes high-clean adoption cheaper moves $a_n$ down and shifts the technology-composition channel back toward the optimistic two-sector reading. Such policies include direct subsidies to $f_n$, de-risking instruments for green capital, or workforce investments that raise the average productivity in $n$.

Our analysis has four main limitations that warrant further consideration. First, the representative-household structure abstracts from worker heterogeneity, preventing us from examining how the effects of environmental policy on wages and employment vary across workers with different productivity levels. Second, the closed-economy framework excludes international trade and the associated competitiveness and carbon-leakage channels. This is a particularly strong assumption for a small open economy such as Finland. Allowing for international trade could alter the magnitude of sectoral adjustment through changes in competitiveness, import substitution, and carbon leakage.

Third, the climate damage function $D(x_t)$ enters all three sectoral production functions symmetrically. In reality, however, sectors differ in their vulnerability to the physical impacts of climate change, potentially affecting the incentives for sectoral reallocation. However, in our calibration, emissions from the rest of the world are held fixed, and

Finland's relatively small contribution to global emissions implies that the domestic carbon tax has a negligible effect on climate damages. Consequently, the climate-damage channel plays only a minor role in our quantitative results.

Fourth, technology adoption follows a mechanical Pareto-based sorting mechanism, whereby firms with productivity above $a_n$ adopt the high-productivity clean technology, while those between $a_r$ and $a_n$ operate in the emissions-intensive sector. This framework captures differences in fixed technology adoption costs but abstracts from additional frictions, such as learning costs and technological irreversibility. Moreover, although capital stocks and adjustment costs are sector specific, the model does not explicitly account for technology-specific capital installed at the firm level. Consequently, firms switching technologies do not incur additional costs associated with scrapping existing assets or stranded capital. Introducing such frictions, including capital irreversibility and scrapping costs, could slow clean-technology adoption and increase the associated adjustment costs.

Future research could address several of these limitations. Introducing worker heterogeneity would allow the model to examine the distributional consequences of environmental policy. Incorporating international trade would capture competitiveness and carbon-leakage channels that are particularly relevant to European climate policy. Finally, endogenizing technological innovation would allow the model to jointly determine the evolution of abatement costs and sectoral reallocation, rather than treating technological progress as an exogenous process.

# 7 Conclusions

This paper has studied the macroeconomic and labour-market consequences of reducing emissions in an economy with heterogeneous firms, search-and-matching frictions, endogenous technology adoption, and sector-specific capital adjustment costs. We have extended the framework of Finkelstein Shapiro and Metcalf (2023) by distinguishing three technologies and by introducing Jermann-style capital adjustment costs within each sector. Both extensions are calibrated to Finnish data.

The central finding is that the composition of the clean expansion is a first-order determinant of the macroeconomic cost of climate policy. In a two-sector model, a carbon tax that delivers a 40% emissions reduction generates mildly positive aggregate output and productivity effects because the only destination for displaced resources is the clean sector. In the three-sector model, the same policy generates minor aggregate output and consumption losses, because a substantial fraction of the reallocation flows to the low-productivity clean sector rather than to the high-productivity clean sector. Average firm productivity rises by only 0.18% in the three-sector model, roughly a quarter of the 0.73% obtained in the two-sector benchmark.

Several important qualifications apply to our analysis. First, the representative household structure abstracts from worker heterogeneity, limiting our ability to examine the distributional consequences of environmental policy. Second, the closed-economy framework excludes international competitiveness and trade-related adjustment channels that are particularly relevant for a small open economy such as Finland. Third, the assumption of symmetric climate damages across sectors abstracts from potentially important differences in sectoral vulnerability to climate change and their implications for resource allocation. Finally, the Pareto-based technology-sorting mechanism abstracts from addi-

tional frictions, such as learning costs and capital stranding, that could slow the expansion of clean production and amplify short-run adjustment costs. Incorporating these mechanisms would be a useful direction for future research.

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# A Equilibrium conditions: three-sector model

## A.1 Definition of equilibrium

Taking the exogenous tax sequence $\{\tau_t\}$ and the rest-of-the-world emission flow $\bar{e}^{ROW}$ as given, the allocations and prices

$$\Big\{\tilde{\pi}^y_{n,t},\ \tilde{\pi}^y_{r,t},\ \tilde{\pi}^y_{s,t},\ \tilde{\rho}_{n,t},\ \tilde{\rho}_{r,t},\ \tilde{\rho}_{s,t},\ mc_{n,t},\ mc_{r,t},\ mc_{s,t},\ \tilde{a}_{n,t},\ \tilde{a}_{r,t},\ \tilde{a}_{s,t},\ a_{n,t},\ a_{r,t},\ \tilde{\pi}^y_t,$$

$$N_t,\ N_{n,t},\ N_{r,t},\ N_{s,t},\ N_{e,t},\ \Gamma_t,\ e_t,\ \mu_t,\ \tilde{y}_{n,t},\ \tilde{y}_{r,t},\ \tilde{y}_{s,t},$$

$$v_{n,t},\ v_{r,t},\ v_{s,t},\ s_{n,t},\ s_{r,t},\ s_{s,t},\ m_{n,t},\ m_{r,t},\ m_{s,t},\ p_{\theta_n,t},\ p_{\theta_r,t},\ p_{\theta_s,t},\ q_{\theta_n,t},\ q_{\theta_r,t},\ q_{\theta_s,t},$$

$$n_{n,t},\ n_{r,t},\ n_{s,t},\ w_{n,t},\ w_{r,t},\ w_{s,t},\ \mathcal{W}_{n,t},\ \mathcal{W}_{r,t},\ \mathcal{W}_{s,t},\ \mathcal{J}_{n,t},\ \mathcal{J}_{r,t},\ \mathcal{J}_{s,t},\ h'_{n,t},\ h'_{r,t},\ h'_{s,t},\ lfp_t,\ ur_t,$$

$$k_{n,t},\ k_{r,t},\ k_{s,t},\ i_{n,t},\ i_{r,t},\ i_{s,t},\ \lambda_{n,t},\ \lambda_{r,t},\ \lambda_{s,t},\ r^k_{n,t},\ r^k_{r,t},\ r^k_{s,t},$$

$$x_t,\ c_t,\ Y_t,\ \Omega_{r,t}\Big\}$$

satisfy:

$$1 = \left[N_{r,t}\,\tilde{\rho}_{r,t}^{1-\varepsilon} + N_{n,t}\,\tilde{\rho}_{n,t}^{1-\varepsilon} + N_{s,t}\,\tilde{\rho}_{s,t}^{1-\varepsilon}\right]^{\frac{1}{1-\varepsilon}}, \tag{27}$$

$$\tilde{\pi}_{n,t}^{y} = \left[\tilde{\rho}_{n,t} - \tfrac{mc_{n,t}}{\tilde{a}_{n,t}}\right]\tilde{y}_{n,t} - f_n, \tag{28}$$

$$\tilde{\pi}_{r,t}^{y} = \left[\tilde{\rho}_{r,t} - \tfrac{mc_{r,t}}{\tilde{a}_{r,t}}\right]\tilde{y}_{r,t} - f_r, \tag{29}$$

$$\tilde{\pi}_{s,t}^{y} = \left[\tilde{\rho}_{s,t} - \tfrac{mc_{s,t}}{\tilde{a}_{s,t}}\right]\tilde{y}_{s,t}, \tag{30}$$

$$\tilde{\rho}_{j,t} = \frac{\varepsilon}{\varepsilon - 1}\,\frac{mc_{j,t}}{\tilde{a}_{j,t}}, \qquad j \in \{n, r, s\}, \tag{31}$$

$$\tilde{y}_{j,t} = \tilde{\rho}_{j,t}^{-\varepsilon}\,Y_t, \qquad j \in \{n, r, s\}, \tag{32}$$

$$\left[\tfrac{\varepsilon}{\varepsilon-1}\tfrac{mc_{n,t}}{a_{n,t}} - \tfrac{mc_{n,t}}{a_{n,t}}\right]\left(\tfrac{\varepsilon}{\varepsilon-1}\tfrac{mc_{n,t}}{a_{n,t}}\right)^{-\varepsilon} Y_t - f_n = \left[\tfrac{\varepsilon}{\varepsilon-1}\tfrac{mc_{r,t}}{a_{n,t}} - \tfrac{mc_{r,t}}{a_{n,t}}\right]\left(\tfrac{\varepsilon}{\varepsilon-1}\tfrac{mc_{r,t}}{a_{n,t}}\right)^{-\varepsilon} Y_t - f_r, \tag{33}$$

$$\left[\tfrac{\varepsilon}{\varepsilon-1}\tfrac{mc_{r,t}}{a_{r,t}} - \tfrac{mc_{r,t}}{a_{r,t}}\right]\left(\tfrac{\varepsilon}{\varepsilon-1}\tfrac{mc_{r,t}}{a_{r,t}}\right)^{-\varepsilon} Y_t - f_r = \left[\tfrac{\varepsilon}{\varepsilon-1}\tfrac{mc_{s,t}}{a_{r,t}} - \tfrac{mc_{s,t}}{a_{r,t}}\right]\left(\tfrac{\varepsilon}{\varepsilon-1}\tfrac{mc_{s,t}}{a_{r,t}}\right)^{-\varepsilon} Y_t, \tag{34}$$

$$N_{n,t} = \left(\tfrac{a_{\min}}{a_{n,t}}\right)^{k_p} N_t, \tag{35}$$

$$N_{r,t} = \left[\left(\tfrac{a_{\min}}{a_{r,t}}\right)^{k_p} - \left(\tfrac{a_{\min}}{a_{n,t}}\right)^{k_p}\right] N_t, \tag{36}$$

$$N_{s,t} = N_t - N_{n,t} - N_{r,t}, \tag{37}$$

$$\tilde{a}_{n,t} = \zeta\, a_{n,t}, \tag{38}$$

$$\tilde{a}_{r,t} = a_{r,t}\,\tilde{a}_{n,t}\left[\frac{a_{n,t}^{k_p-(\varepsilon-1)} - a_{r,t}^{k_p-(\varepsilon-1)}}{a_{n,t}^{k_p} - a_{r,t}^{k_p}}\right]^{1/(\varepsilon-1)}, \tag{39}$$

$$\tilde{a}_{s,t} = (\zeta\, a_{r,t})\, a_{\min}\left[\frac{a_{r,t}^{k_p-(\varepsilon-1)} - a_{\min}^{k_p-(\varepsilon-1)}}{a_{r,t}^{k_p} - a_{\min}^{k_p}}\right]^{1/(\varepsilon-1)}, \tag{40}$$

$$\tilde{\pi}_{t}^{y} = \tfrac{N_{n,t}}{N_t}\,\tilde{\pi}_{n,t}^{y} + \tfrac{N_{r,t}}{N_t}\,\tilde{\pi}_{r,t}^{y} + \tfrac{N_{s,t}}{N_t}\,\tilde{\pi}_{s,t}^{y}, \tag{41}$$

$$f_e = \mathbb{E}_t\,\Xi_{t+1|t}\,(1-\delta_f)\big[\tilde{\pi}_{t+1}^{y} + f_e\big], \tag{42}$$

$$N_{t+1} = (1-\delta_f)\big(N_t + N_{e,t}\big), \tag{43}$$

$$D(x_t)\, F^j(n_{j,t}, k_{j,t}) = N_{j,t}\, \frac{\tilde{y}_{j,t}}{\tilde{a}_{j,t}}, \qquad j \in \{n, r, s\}, \tag{44}$$

$$m_{j,t} = \frac{s_{j,t}\, v_{j,t}}{\left(s_{j,t}^{\xi} + v_{j,t}^{\xi}\right)^{1/\xi}}, \qquad j \in \{n, r, s\}, \tag{45}$$

$$n_{j,t} = (1 - \rho_n)\, n_{j,t-1} + m_{j,t}, \qquad j \in \{n, r, s\}, \tag{46}$$

$$p_{\theta_j,t} = \tfrac{m_{j,t}}{s_{j,t}}, \qquad q_{\theta_j,t} = \tfrac{m_{j,t}}{v_{j,t}}, \qquad j \in \{n, r, s\}, \tag{47}$$

$$h'_{j,t} = \kappa_j\, \mathcal{A}_t^{1/\chi_r}, \qquad j \in \{n, r, s\}, \tag{48}$$

$$\mathcal{A}_t \equiv \sum_{i \in \{n,r,s\}} \kappa_i \left[ n_{i,t} + (1 - p_{\theta_i,t}) s_{i,t} \right], \tag{49}$$

$$lfp_t = \sum_{j \in \{n,r,s\}} \left[ n_{j,t} + (1 - p_{\theta_j,t})\, s_{j,t} \right], \tag{50}$$

$$ur_t = \frac{\sum_{j \in \{n,r,s\}} (1 - p_{\theta_j,t})\, s_{j,t}}{lfp_t}, \tag{51}$$

$$\mathcal{W}_{j,t} = \frac{h'_{j,t} - b_{ss}\, c_t^{-\sigma_c}}{p_{\theta_j,t}\, c_t^{-\sigma_c}}, \qquad j \in \{n, r, s\}, \tag{52}$$

$$\mathcal{W}_{j,t} = w_{j,t} - b_{ss} + \mathbb{E}_t\, \Xi_{t+1|t} (1 - \rho_n) \left(1 - p_{\theta_j,t+1}\right) \mathcal{W}_{j,t+1}, \qquad j \in \{n, r, s\}, \tag{53}$$

$$\mathcal{J}_{j,t} = D(x_t)\, mc_{j,t}\, F^j_{n_j}(n_{j,t}, k_{j,t}) - w_{j,t} + \mathbb{E}_t\, \Xi_{t+1|t} (1 - \rho_n)\, \mathcal{J}_{j,t+1}, \qquad j \in \{n, s\}, \tag{54}$$

$$\mathcal{J}_{r,t} = D(x_t)\, mc_{r,t}\, F^r_{n_r}(n_{r,t}, k_{r,t})\, \Omega_{r,t} - w_{r,t} + \mathbb{E}_t\, \Xi_{t+1|t} (1 - \rho_n)\, \mathcal{J}_{r,t+1}, \tag{55}$$

$$\Omega_{r,t} = 1 - \frac{(1 - \nu)\, \tau_t\, (1 - \mu_t)\, \mu_e \left(D(x_t)\, F^r(n_{r,t}, k_{r,t})\right)^{-\nu}}{mc_{r,t}} - \frac{\gamma\, \mu_t^{\eta}}{mc_{r,t}}, \tag{56}$$

$$\mathcal{W}_{j,t} = \tfrac{\nu_n}{1 - \nu_n}\, \mathcal{J}_{j,t}, \qquad j \in \{n, r, s\}, \tag{57}$$

$$\frac{\psi_r}{q_{\theta_r,t}} = \mathcal{J}_{r,t}, \tag{58}$$

$$\frac{\psi_n}{q_{\theta_n,t}} = D(x_t)\, mc_{n,t}\, F^n_{n_n}(n_{n,t}, k_{n,t}) - w_{n,t} + \mathbb{E}_t\, \Xi_{t+1|t}(1-\rho_n)\, \frac{\psi_n}{q_{\theta_n,t+1}}, \tag{59}$$

$$\frac{\psi_s}{q_{\theta_s,t}} = D(x_t)\, mc_{s,t}\, F^s_{n_s}(n_{s,t}, k_{s,t}) - w_{s,t} + \mathbb{E}_t\, \Xi_{t+1|t}(1-\rho_n)\, \frac{\psi_s}{q_{\theta_s,t+1}}, \tag{60}$$

$$k_{j,t+1} = (1-\delta)\, k_{j,t} + i_{j,t}, \qquad j \in \{n, r, s\}, \tag{61}$$

$$\lambda_{n,t} = 1 + \phi\left(\frac{i_{n,t}}{k_{n,t}} - \delta\right), \tag{62}$$

$$\lambda_{r,t} = 1 + \phi_r\left(\frac{i_{r,t}}{k_{r,t}} - \delta\right), \tag{63}$$

$$\lambda_{s,t} = 1 + \phi\left(\frac{i_{s,t}}{k_{s,t}} - \delta\right), \tag{64}$$

$$\lambda_{n,t} = \mathbb{E}_t\, \Xi_{t+1|t}\left[ r^k_{n,t+1} + \frac{\phi}{2}\left(\frac{i_{n,t+1}}{k_{n,t+1}} - \delta\right)\left(\frac{i_{n,t+1}}{k_{n,t+1}} + \delta\right) + (1-\delta)\, \lambda_{n,t+1}\right], \tag{65}$$

$$\lambda_{r,t} = \mathbb{E}_t\, \Xi_{t+1|t}\left[ r^k_{r,t+1} + \frac{\phi_r}{2}\left(\frac{i_{r,t+1}}{k_{r,t+1}} - \delta\right)\left(\frac{i_{r,t+1}}{k_{r,t+1}} + \delta\right) + (1-\delta)\, \lambda_{r,t+1}\right], \tag{66}$$

$$\lambda_{s,t} = \mathbb{E}_t\, \Xi_{t+1|t}\left[ r^k_{s,t+1} + \frac{\phi}{2}\left(\frac{i_{s,t+1}}{k_{s,t+1}} - \delta\right)\left(\frac{i_{s,t+1}}{k_{s,t+1}} + \delta\right) + (1-\delta)\, \lambda_{s,t+1}\right], \tag{67}$$

$$r^k_{j,t} = D(x_t)\, \alpha_j\, mc_{j,t}\, \frac{F^j(n_{j,t}, k_{j,t})}{k_{j,t}}, \qquad j \in \{n, s\}, \tag{68}$$

$$r^k_{r,t} = D(x_t)\, \alpha_r\, mc_{r,t}\, \frac{F^r(n_{r,t}, k_{r,t})}{k_{r,t}}\, \Omega_{r,t}, \tag{69}$$

$$e_t = (1-\mu_t)\, \mu_e \left(D(x_t)\, F^r(n_{r,t}, k_{r,t})\right)^{1-\nu}, \tag{70}$$

$$\Gamma_t = \gamma\, \mu_t^{\eta}\, D(x_t)\, F^r(n_{r,t}, k_{r,t}), \tag{71}$$

$$\tau_t\, \mu_e \left(D(x_t)\, F^r(n_{r,t}, k_{r,t})\right)^{1-\nu} = \gamma\, \eta\, \mu_t^{\eta-1}\, D(x_t)\, F^r(n_{r,t}, k_{r,t}), \tag{72}$$

$$x_t = \rho_x\, x_{t-1} + e_t + \bar{e}^{ROW}, \tag{73}$$

$$\begin{aligned} Y_t \;=\; & c_t + \sum_{j\in\{n,r,s\}} \psi_j\, v_{j,t} + f_e\, N_{e,t} + f_n\, N_{n,t} + f_r\, N_{r,t} + \Gamma_t \\ & + i_{n,t} + i_{r,t} + i_{s,t} + \frac{\phi}{2}\left(\frac{i_{n,t}}{k_{n,t}} - \delta\right)^2 k_{n,t} + \frac{\phi_r}{2}\left(\frac{i_{r,t}}{k_{r,t}} - \delta\right)^2 k_{r,t} + \frac{\phi}{2}\left(\frac{i_{s,t}}{k_{s,t}} - \delta\right)^2 k_{s,t}, \end{aligned} \tag{74}$$

where the sectoral production functions $F^j$ and their marginal products $F^j_{n_j}$, $F^j_{k_j}$, the damage function $D(x_t)$, the household stochastic discount factor $\Xi_{t+1|t}$, the labor-disutility aggregator $\mathcal{A}_t$, the Pareto-shape constant $\zeta$, and all other parameters are defined in the main text. Real model variables are mapped to data-consistent counterparts following Ghironi and Melitz (2005) by multiplying by $N_t^{1/(1-\varepsilon)}$.

# B Industry classification

Table 9 lists the NACE Rev. 2 industries assigned to each of the three groups used in Section 2. The assignment rule is applied in two steps. Direct fossil $CO_2$ emissions per worker separate the emissions-intensive group from the rest; net value added per worker then splits the remainder into the high- and low-productivity clean groups. Manufacturing (Section C) is the only Section split across groups: divisions 10–15 (food, beverages, textiles) have emissions intensities comparable to services and are assigned to $s$, while divisions 16–33 are assigned to $r$.

Table 9: NACE Rev. 2 industries by model sector.

| NACE code | Industry |
|---|---|
| *Panel A. $r$ — emissions-intensive* | |
| A, B | Agriculture, forestry and fishing; mining and quarrying |
| 16–18 | Wood and paper products; printing |
| 19–23 | Coke and refined petroleum; chemicals and pharmaceuticals; rubber, plastics and other non-metallic mineral products |
| 24–33 | Basic metals and metal products; electronics; electrical equipment; machinery; motor vehicles and other transport equipment; furniture |
| D, E | Electricity, gas, steam and air conditioning; water supply, sewerage and waste |
| F | Construction |
| H | Transportation and storage |
| *Panel B. $n$ — high-productivity clean* | |
| J | Information and communication |
| K, L | Financial and insurance activities; real estate activities |
| M | Professional, scientific and technical activities |
| O | Public administration and defence; compulsory social security |
| P | Education |
| *Panel C. $s$ — low-productivity clean* | |
| 10–15 | Food products, beverages and tobacco; textiles, apparel and leather |
| G | Wholesale and retail trade; repair of motor vehicles |
| I | Accommodation and food service activities |
| N | Administrative and support service activities |
| Q | Human health and social work activities |
| R | Arts, entertainment and recreation |
| S–U | Other service activities; activities of households as employers; extraterritorial organisations |

Notes: Employment is from Statistics Finland table 13aq (employed persons aged 15–74), net value added from table 123h, and production-based fossil $CO_2$ from table 11ig. Sections T and U are negligible in employment and are grouped with S. Administrative and support services (N) and public administration (O) fall on opposite sides of the productivity split despite both being commonly described as business or public services; this is the main reason the two clean groups cannot be read as a private/public distinction.

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