Labor Mobility with Environmental Regulation

Jonathan Leisner*

June 3, 2022

Abstract

Changelog:

- Version 1: Only age in state space. No stochasticity.
- Version 2: Added stochasticity in the form of Type I extreme value sector-specific preference shocks. This implies that the model must be solved in expected value function space.
- Version 3: Implemented switching costs directly into utility. A worker's previously chosen sector enters her state space because switching costs vary across sector-pairs.
- Version 4: Added firms and their production functions which take four inputs: human capital, physical capital, clean energy and dirty energy. Dirty energy generates emissions. I have closed the model by assuming Cobb-Douglas utility from consumption and by specifying the supply of physical capital. Some products are tradeables and which case their output price is exogenous (small country assumption). Other products are non-tradeables and their price is determined endogenously.
- Version 5: In terms of additional sections, I have added the following:
  Brief introduction including literature review and contribution (section 1), description of estimation method (section 3) including an estimation routine in appendix G and finally I reordered and rewrote the model section (section 2) and added a description of the human capital equilibrium (section 2.2.7).

*University of Copenhagen. Oster Farimagsgade 5, 1353 Copenhagen K, Denmark. E-mail: jl@econ.ku.dk.

- **Version 6:** Added tenure (i.e. accumulation effects) and education to human capital (section 2.2.1), and hence also to the state space. Education can take multiple fixed values: low-skill, high-skill non-technical and high-skill technical. I also rewrote the introduction to include: better motivation in the form of inequality/yellow vests + more arguments for why a structural approach is necessary.

1 Introduction

With climate scientists repeatedly calling for action to mitigate climate change, politicians and governments around the world have committed themselves to reduce the amount of green house gasses emitted into the atmosphere. To reach the stated goals, significant regulatory action is necessary. However, politicians often hesitate with imposing environmental reforms due to fear of job loss or widening inequality. For example, the EU's European Green Deal explicitly states that the plan must "leave no person behind"[1].No politician wants to see a Yellow Vests Movement in their country.

The economist's preferred tool of a market-based regulation such as a carbon tax has been unpopular in many countries for similar reasons. Moreover, knowledge about how carbon taxes or environmental regulation more generally affect the labor market in the short and medium run is scant. Which workers are affected by stricter environmental regulation and what will it require to compensate their welfare loss? What are the benefits of announcing policies in advance, phasing taxes in gradually as opposed to immediate implementation and what are the consequent trade-offs in terms of additional emissions?

In this paper, I set up and estimate a structural model of the labor market to subsequently perform counterfactual simulations to answer these questions. The structural approach, while relying on more assumptions, has a number of advantages relative to reduced-form studies. First and most importantly, the reforms that we wish to analyze are counterfactual in nature and very few appropriate natural experiments exist. Second, the structural approach circumvents some of the identification issues of existing reduced-form studies such as handling general equilibrium effects and the lack of proper control groups.

The model I propose builds on an existing dynamic discrete choice framework used extensively in the labor literature (Dix-Carneiro 2014; Ashournia 2018; Traiberman 2019). overvej at være eksplicit om forskelle I extend the model to include emissions and labor market frictions relevant to capture the main features of the data on workers, industries and emissions. Similar to the existing literature, the model features workers that are heterogeneous along several dimensions such as educational attainment, age and tenure. Each worker solves a dynamic discrete choice problem to decide which sector to supply their human capital to. Firms demand this hu-

[1] See `https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en`. Visited on April 8 2022.

man capital and emit carbon dioxide when producing. The labor market is characterized by multiple barriers to mobility, including the accumulation of sector-specific knowledge and direct utility costs of switching sectors. The model is estimated using Danish linked worker-firm data. With the estimated model in hand, counterfactual simulations show if particular individuals are hit harder than other from carbon taxes and quantifies the
individuals of particular ages, initial sectors.
overall costs of an environmental regulation for workers.

The results have policy implications. By estimating the size of the losses for workers, politicians can make a more informed decision about whether and how to enact e.g. carbon taxes. For example, if a government wishes to compensate the losers from a carbon tax, the model can help identify who loses and quantify by how much. The model can also shed light on the importance of the timing of policy implementations e.g. the benefits of announcing taxes in advance or gradual phase ins.

My paper relates to three strands of literature. First, researchers have produced reduced form evidence of how environmental regulation affects labor markets. Walker (2013) used a difference-in-differences strategy to estimate the employment and earning loss effects of the 1990 Clean Air Act Amendments (CAAA) in the U.S. Although related, the CAAA was a non-market based regulation designed to reduce emissions of non-green house gas emissions such as sulfur dioxide (SO_2). While he controls for various worker characteristics, the differential effects across workers are not a particular focus.

Yip (2018) performs a reduced form study of the carbon tax enacted in British Columbia in Canada also using a difference-in-differences identification strategy. In terms of research question, his study is the one that comes the closest to mine. The estimations show that especially low-educated workers are hit the hardest by the carbon tax. As he himself notes, one might worry that the results are driven by an adverse labor market shock hitting the same province as the carbon tax was enacted in. Corroborating this, the implementation of the carbon tax overlaps quite closely with the beginning of the financial crisis.

The second strand of literature tries to answer the same questions about carbon taxes and employment effects using structural models. Structural approaches to these questions are complementary to the reduced-form studies by explicitly taking care of the existence of spillover effects through the labor market. The fact that in reduced-form studies, the control group used for identification is often indirectly affected by general equilibrium effects such as price or wage changes means the external validity of a result is less clear (Hafstead and Williams 2018). The model of Hafstead and Williams (2018) is a search-and-matching model used to analyze the unemployment impact of carbon taxes. Their model does not allow sector-to-sector switches, has only two productive sectors, relies on calibration rather than estimation and most importantly, workers are assumed homogeneous. The computable general equilibrium (CGE) model of Goulder et al. (2019) links two different CGE models to analyze the question of how carbon taxes affect the five different income quintiles. Their model features many sectors and detailed accounts of the US tax system and heterogenous households in terms of preferences for consumption and leisure, it does not however include any labor market frictions. Furthermore, as is customary for most CGE models, parameters are calibrated rather than estimated. By modeling multiple dimensions of heterogeneity across individuals in a model framework ideal for analyzing labor supply decisions, I add to this strand of the literature.

Thirdly, the dynamic discrete choice model framework that I employ has been used in multiple earlier papers to analyze the labor market effects of e.g. international trade (Dix-Carneiro 2014; Ashournia 2018; Traiberman 2019) and automation Humlum (2019). The methodology builds on early papers such as Rust (1987) and Keane and Wolpin (1997). To the best of my knowledge, I am the first to apply the framework for studying environmental regulation.

2 Model

In each year, a firm representing each sector produces using four inputs: human capital, physical capital, clean energy and dirty energy. Dirty energy represents the firm's use of fossil fuels and generates carbon dioxide emissions. Human capital is supplied by workers of age 30 to 65 after which they retire. In each period, each worker receives a wage offer from each sector that depends on the amount of human capital that she can supply to that sector. With these offers, she chooses the sector which maximizes her expected discounted lifetime utility. Switching sectors has a direct utility cost as well as a wage cost since she loses some of her accumulated human capital by switching. The model equilibrium is found by solving for the values of skill prices that clear the market for human capital.

2.1 Firms and emissions

The set of sectors, denoted $\mathcal{S}$, contains S sectors indexed by s. The discrete time dimension spans T periods indexed by $t = 0, 1, \ldots, T-1$. In each sector s, a representative firm produces its output using four inputs: human capital, H_{st}, physical capital, K_{st}, clean energy E_{st} and fossil fuel based energy, O_{st}. The production technology is given by the Cobb-Douglas function

$$Y_{st} = A_{st} H_{st}^{\alpha_{st}^1} K_{st}^{\alpha_{st}^2} \left(E_{st}^{\theta_s} + O_{st}^{\theta_s} \right)^{\frac{1-\alpha_{st}^1-\alpha_{st}^2}{\theta_s}}. \tag{1}$$

where A_{st} represents TFP and $\left(E_{st}^{\theta_s} + O_{st}^{\theta_s} \right)^{\frac{1}{\theta_s}}$ is a CES aggregate governing the firm's use of energy. The use of fossil fuels generates carbon dioxide emissions Z_{st} with a fixed coefficient η_s,

$$Z_{st} = \eta_s O_{st}. \tag{2}$$

Notice that η_s varies across sectors. This reflects that the mix of dirty energy inputs such as oil, coal and natural gas varies across sectors. Since η_s does not vary across time, I implicitly assume that the optimal mix of dirty inputs is fixed throughout for a given sector. The firm maximizes profits under perfect competition taking input and output prices and the emission tax τ_s as given.[2]

[2] The firm's first order conditions are stated in appendix A.

We denote sector $s = 0$ as the "unemployment sector". This sector has no production function but simply offers a fixed "wage" corresponding to some relevant average of Danish welfare transfers.

2.2 Workers indexed by i

In each year, workers active on the labor market choose a sector s to work in to receive the wage w_{ist}. There is no saving or borrowing, and the number of hours worked is fixed, making the choice a discrete one. A worker is active as long as her age a_{it} is between 30 and 65, after which she leaves the labor market. Each worker is characterized by set of state variables collected in Ω_{it}. vector

The instantaneous utility function for the worker is the sum of wages w, switching costs M and unobserved (to the econometrician) sector-specific preference shocks ε. Each of these elements will be elaborated on below.

Denote by $d_{ist} \in \{0, 1\}$ a dummy variable equal to one when the chosen sector is s in year t for worker i. With this notation the value function at time ι, i.e. the expected present value of the maximum attainable utility, is the solution to the utility maximization problem,

$$V_\iota(\Omega_{i\iota}) = \max_{\{d_{ist}\}_{s\in S, t=\iota,\dots,T-1}} E_\varepsilon \left[\sum_{t=\iota}^{T-1} \rho^t \sum_{s\in S} d_{ist} \left(w_{ist} - M(s, s_{t-1}, \Omega_{it}) + \varepsilon_{ist} \right) \right] \tag{3}$$

where ρ denotes the discount factor and the subscript on the expectations operator reflects that the expectation is with respect to the preference shock ε that is unobserved also to the worker in each future period.

The maximization of expected utility obeys the Bellman equation

$$V_t(\Omega_{it}) = \max_s V_{st}\left(\Omega_{it}\right). \tag{4}$$

where each of the alternative-specific value functions are given by

$$V_{st}(\Omega_{it}) = \begin{cases} w_{ist} - M(s, s_{it-1}, \Omega_{it}) + \varepsilon_{ist} + \rho E_\varepsilon \left[V_{t+1}\left(\Omega_{it+1}\right) | d_{ist} \right] & \text{for } a_{it} < 65 \\ w_{ist} - M(s, s_{it-1}, \Omega_{it}) + \varepsilon_{ist} & \text{for } a_{it} = 65 \end{cases} \tag{5}$$

for each s and where continuation values are zero when the worker is of age 65 since she will retire in the end of the year. The conditioning of $V_{t+1}(\Omega_{it+1})$ on d_{ist} reflects that current choices has implications for next year's state space and therefore continuation values. The state space includes a worker's age, previous sector, educational attainment, tenure and her expectation of current and future skill prices:

definition af tenure nævnes her

$$\Omega_{it} = \left\{a_{it}, s_{it-1}, \text{educ}_i, \text{ten}_{it}, \{r_{st+\iota}\}_{\iota=0}^{65-a_{it}}\right\}. \tag{6}$$

Strictly speaking, the vector of unobserved preference shocks across sectors $\boldsymbol{\varepsilon}_{it}$ also enters the worker's state space, since she uses the realization of the shock to make her decision.

2.2.1 Wages and human capital accumulation

At the beginning of each period, the worker receives a wage offer from each sector. The wage offer $w_{ist}(\Omega_{it})$ is the product of two parts, the amount of effective human capital that she can supply to sector s, $H_s(\Omega_{it})$, and the unit skill price r_{st} which she takes as given. For effective human capital, the relevant variables of the state space are a_{it}, educ_i, ten_{it} and s_{it-1} and her wage offer is therefore given by

$$w_{ist} = H_s(a_{it}, \text{educ}_i, \text{ten}_{it}, s_{it-1})r_{st}. \tag{7}$$

The effective human capital function H_s is given by

$$\begin{aligned} H_s(a_{it}, \text{educ}_i, \text{ten}_{it}, s_{it-1}) \equiv \exp\Big(&\beta_s^0 a_{it} + \beta_s^1 (a_{it})^2 + \\ &\beta_s^2 \mathbf{1}(\text{educ}_i = \text{low-skill}) + \\ &\beta_s^3 \mathbf{1}(\text{educ}_i = \text{high-skill tech.}) + \\ &\beta_s^4 \mathbf{1}(\text{educ}_i = \text{high-skill non-tech.}) + \\ &\beta_s^5 \text{ten}_{it} \mathbf{1}(s = s_{it-1})\Big) \end{aligned} \tag{8}$$

capturing that wages depend on age, which proxies for general experience, educational attainment and tenure. The dummy variable interaction with tenure captures that sector-specific knowledge, by definition, is only valuable in the sector it was accumulated.

A worker's tenure captures sector-specific knowledge and is accumulated with each consecutive year that she works in the same sector. Following Humlum (2019), tenure evolves according to

$$\text{ten}_{it+1} = \begin{cases} \text{ten}_{it} + 1 & \text{if} \quad s_{it} = s_{it-1} \\ 1 & \text{if} \quad s_{it} \neq s_{it-1} \end{cases} \tag{9}$$

2.2.2 Switching costs

The worker incurs direct utility costs when switching sectors. These costs could represent searching costs or simply a preference for not moving sector (Ashournia 2018). I parametrize these switching costs, denoted $M(s_t, s_{t-1}, \Omega_{it})$, in the following way[3]:

$$M(s_t, s_{t-1}, \Omega_{it}) = \begin{cases} m_1(s_t, s_{t-1}) m_2(\Omega_{it}) & \text{if } s_t \neq s_{t-1} \\ 0 & \text{if } s_t = s_{t-1} \end{cases} \tag{10}$$

where

$$m_1(s_t, s_{t-1}) = \exp\left(\xi^{out}_{s_{t-1}} + \xi^{in}_{s_t}\right). \tag{11}$$

$$m_2(a_{it}, \text{educ}_i) = \exp\Big(\kappa_0 a_{it} + \kappa_1 (a_{it})^2 + \kappa_2 \mathbf{1}(\text{educ}_i = \text{low-skill}) + \kappa_3 \mathbf{1}(\text{educ}_i = \text{high-skill tech.}) + \kappa_4 \mathbf{1}(\text{educ}_i = \text{high-skill non-tech.})\Big) \tag{12}$$

This structure implies that staying in the same sector does not involve switching costs and that conditional on switching sectors, the direct utility cost is the product of two terms. The first one, m_1, only depends on the sector switched to and from. The second, m_2 is a shifter which depends on individual characteristics.

Ashournia and Dix-Carneiro normalize one of these to zero. I dont see why this is necessary, they should be identified without.

2.2.3 Skill price expectations

A worker's optimal choice today depends on her expectation of future skill prices, $\{r_{st+\iota}\}_{\iota=0}^{65-a_{it}}$. To make this forecast, I follow Lee (2005) and assume that workers have perfect foresight over future unit prices. Since the model terminates in period $T-1$ and workers aged $a < 65$ would take wages in period $t \geq T$ into account, I assume that they act as if skill prices stay fixed for the rest of their time on the labor market, following Ashournia (2018). Essentially, the assumption is that workers have static expectations in

[3]The parameterization uses elements from both Traiberman (2019) and Ashournia (2018).

period $T-1$, i.e. they expect future ($t > T-1$) skill prices to equal current skill prices:

$$\{r_{sT-1+t}\}_{t=1}^{65-a_{iT-1}} = \{r_{sT-1}\}_{t=1}^{65-a_{iT-1}}, \tag{13}$$

where the lack of i subscript on r reflects that all workers have the same expectation about future prices. To summarize, workers always predict skill prices correctly, but when they forecast skill prices that ~~do not exist in the model~~ because they lie later than $T-1$, they simply predict the skill prices observed in $T-1$. Man forstår det ikke

I simply want to say that the last period price is "duplicated" $65 - a_{it}$ times. How can I write that?

2.2.4 Unobserved types

2.2.5 The unemployment sector

2.2.6 Solving the worker's dynamic program

To solve the worker's problem, distributional assumptions on the idiosyncratic preference shocks must be made. I assume that these are independent across sectors and time, and follow the Gumbel, or Type I extreme value, distribution,

$$\varepsilon_{ist} \sim \text{Gumbel}(-0.57721\sigma, \sigma) \tag{14}$$

where 0.57721 is Euler's constant.[4] As explained e.g. in Traiberman (2019), the scale parameter σ determines the worker's sensitivity to wage differentials. When σ is larger, extreme draws are more likely which leaves wage differentials with less influence on the optimal choice. As is well known, this particular distributional assumption is computationally convenient because it produces closed-form solutions for continuation values and conditional choice probabilities.

The expected value function, also called the EMAX function or the integrated value function, has the closed form (see e.g. Aguirregabiria 2021):

$$E_\varepsilon\left[V_t(\Omega_{it})\right] = \sigma \log\left(\sum_s \exp\left(\frac{w_{ist} - M(s, s_{it-1}, \Omega_{it}) + \rho E_\varepsilon\left[V_{t+1}(\Omega_{it+1})|d_{ist}\right]}{\sigma}\right)\right). \tag{15}$$

The corresponding conditional (on the state space) choice probabilities also take the

[4] The recentering of the distribution implies that shocks have a mean of zero.

common logit-form:

$$P(d_{ist}=1|\Omega_{it})=\frac{\exp\left(\frac{w_{ist}-M(s,s_{it-1},\Omega_{it})+\rho E_{\varepsilon}[V_{t+1}(\Omega_{it+1})|d_{ist}]}{\sigma}\right)}{\sum_j \exp\left(\frac{w_{ijt}-M(j,s_{it-1},\Omega_{it})+\rho E_{\varepsilon}[V_{t+1}(\Omega_{it+1})|d_{ijt}]}{\sigma}\right)}. \tag{16}$$

These probabilities make up the policy function, i.e. the policy function at a particular point in the state space and in time is a vector (bold notation) of probabilities P,

$$\boldsymbol{P}\left(\Omega_{it}\right)=\Big(P(d_{i0t}=1|\Omega_{it}),\ldots,P(d_{iS-1t}=1|\Omega_{it})\Big). \tag{17}$$

Skift exp operator fra E, da det er det samme som clean

The full solution procedure for the worker's problem is stated in appendix B.

2.2.7 Equilibrium on the market for human capital

The unit price of human capital is determined in equilibrium. It is the sequence of skill prices that, in each year and in each sector, equates human capital demand and human capital supply. To measure human capital supply, I introduce a few definitions. MASS_t is the number of individuals in the economy at time t. $\widetilde{\Omega}$ is the collection of all possible points in the state space, excluding skill prices, and I index each point by ω. $D_t(\omega)$ measures the share of individuals in the population characterized by the point ω at time t such that $\sum_{\omega\in\widetilde{\Omega}} D_t(\omega)=1$. Finally, define by $P\left(d_{\omega st}=1|\,\omega,\{\boldsymbol{r}_{t+\iota}\}_{\iota=0}^{65-30}\right)$ the probability that an individual, defined by the state space point ω (in the beginning of period t) as well as the expectation of future skill prices, chooses to work in sector s in period t. The bold notation $\boldsymbol{r}_t$ refers to the vector of skill prices across sectors $s\in\mathcal{S}$ at time t.

With these definitions, total supply of human capital to sector s is given by

$$H_{st}^{supply}(\{\boldsymbol{r}_{t+\iota}\}_{\iota=0}^{65-30})=\text{MASS}_t\sum_{\omega\in\widetilde{\Omega}} D_t(\omega)P\left(d_{\omega st}=1|\,\omega,\{\boldsymbol{r}_{t+\iota}\}_{\iota=0}^{65-30}\right) \qquad \forall s,t. \tag{18}$$

With human capital demand in sector s given by

$$H_{st}^{demand}(r_{st})=\alpha_{st}^{1}p_{st}^{Y}\frac{Y_{st}}{r_{st}} \tag{19}$$

from (24) in appendix A, the equilibrium conditions which implicitly define the sequence of skill prices are

$$
\begin{aligned}
H_{st}^{supply}(\{\boldsymbol{r}_{t+\iota}\}_{\iota=0}^{65-30}) &= H_{st}^{demand}(r_{st}) \\
\text{MASS}_t \sum_{\omega \in \widetilde{\Omega}_t} D_t(\omega) P\left(d_{\omega st} = 1 \middle|\, \omega, \{\boldsymbol{r}_{t+\iota}\}_{\iota=0}^{65-30}\right) &= \alpha_{st}^1 p_{st}^Y \frac{Y_{st}}{r_{st}} \qquad \forall s, t.
\end{aligned} \tag{20}
$$

This concludes the model parts sufficient for estimation.

2.3 Closing the model

To close the model for counterfactual simulations, additional structure and assumptions are necessary. I invoke the small country assumption and assume that the output prices of tradeable sectors are exogenous. Closing the model means endogenizing the output prices in the non-tradeable sectors, p_s^Y for $s \in \mathcal{S}^{NT}$, as well as specifying physical capital supply.

To determine the equilibrium price of non-tradeables, I must specify the, necessarily domestic, demand for these products. To do so, I follow the previous literature (Dix-Carneiro 2014; Ashournia 2018) and assume that consumers' utility over consumption C_{st} is Cobb-Douglas in the $S-1$ consumable products (sector 0 does not produce anything since it represents unemployment):

$$
u(C_{1t}, \dots, C_{st}, \dots, C_{S-1t}) = \prod_{s=1}^{S-1} C_{st}^{\mu_s} \tag{21}
$$

implying that the fraction μ_s of income is spent on the good from sector s. I assume that all factors (including energy) being paid consume only in Denmark and that the proceeds from carbon taxes are paid back to consumers lump-sum. I also assume that unemployment is financed via lump-sum transfers from employed workers and the other factors. This implies that total income for consumers is given by $\sum_{s=1}^{S-1} p_s^Y Y_s$ (note how the unemployment sector is left out since it represents no net-gain to income in the aggregate).

By definition for nontradeables, what is produced domestically must all be consumed domestically. Therefore, the equilibrium condition in nominal terms is

$$
p_s^Y Y_s = p_s^Y C_s = \mu_s \sum_{j=1}^{S-1} p_j^Y Y_j \tag{22}
$$

which must hold for all $s \in \mathcal{S}^{NT}$. This equation system of S^{NT} equations and unknowns can be solved to yield the prices p_s^Y.

To fully close the model, assumptions on physical capital supply are necessary. I will experiment with two different assumptions:

- Assume that physical capital is sector-specific and fixed. This means the return to physical capital varies in simulations, or måske ligegyldigt scenarie
- Assume that the return to physical capital is fixed but still sector specific. In the model, the quantity of physical capital in each sector is residually determined to ensure the sector-specific returns are kept fixed. This assumption was made in Ashournia (2018).

3 Estimation

Estimation proceeds in three steps. First, calibration of a number of parameters including the discount factor. Second, a reduced-form estimation of the elasticity governing energy use, θ. Third, a structural estimation of the remaining model parameters.

3.1 Calibration

The calibrated parameters are: αs and the discount factor ρ and the emission intensity η_s. I also calibrate the consumption share parameters μ.

3.2 Estimation of the energy elasticity

The energy elasticity is estimated by relying on two model assumptions. First, the functional form of the production function and second, the assumption of exogenous energy prices. Dividing the firm's first order condition for clean energy by the one for dirty energy, taking logs and rearranging gives

$$\log\left(\frac{E_{st}}{O_{st}}\right) = \frac{1}{\theta_s - 1}\log\left(\frac{p_t^E}{\eta_s\tau_{st} + p_s^O}\right) + \epsilon_t \qquad \forall t \tag{23}$$

This equation will not hold exactly in the data e.g. due to measurement error. Therefore, we can add an error term and run the equivalent regression once for each sector to recover an estimate of θ_s for each sector.

3.3 Estimation of the remaining model parameters

The remaining parameters are estimated by maximum likelihood. The initial period is 1996 and the terminal period is $T-1 = 2016$. Throughout the estimation, we fix nominal value added (deflated to 2016) $p_{st}^Y Y_{st}$ to equal its data counterpart $\overline{p_{st}^Y Y_{st}}$ for each s and t. The value of A_{st} is determined residually to make sure (1) is always upheld. Fixing value added eases estimation considerably, because the equilibrium human capital skill price can be found without regard to the remaining three inputs.

During estimation, I must simulate the economy forward. Rather than simulating distinct individuals, I measure the share of sector employment accounted for by individuals at each point in the state space. Building on the the definitions from section 2.2.7, define

type of individuals given point in state space bla bla

$D_{st}(\omega) = D_t(\omega)P\left(d_{\omega st} = 1 | \, \omega, \{\boldsymbol{r}_{t+\iota}\}_{\iota=0}^{65-30}\right)$ as the share of total employment in year t that is accounted for by employment in sector s of individuals with state space vector ω.[5] This implies that $\sum_{\omega \in \widetilde{\Omega}} D_{st}(\omega)$ is the actual employment share of sector s in year t.

By using the policy function, I can measure the share of individuals at each point represented by the share $D_{st}(\omega)$ who move to each of the sectors simply by calculating the vector $D_{st}(\omega)\boldsymbol{P}(\Gamma(\omega, s))$ where Γ is the transformation function which updates the state space in year $t+1$ for an individual who is characterized by ω and the choice of sector s in year t.[6] Using this methodology, we can measure employment shares in all years. To convert this into employment in levels, we simply multiply by MASS_t.

gamma beskriver også dem som bliver i sektoren.

The methodology of calculating employment shares over time sidesteps the need to draw Gumbel shocks, saving computational time when simulating. This methodology was also employed in Humlum (2019). The full estimation procedure is outlined as a step-wise procedure in appendix G.

3.4 Estimation results

[5] For example, one of these would measure "the share of total employment accounted for by 37-year old workers, who worked in sector 2 in the previous period, have 3 years of tenure, are highly educated non-technical workers and choose sector $s = 3$ now."

[6] For example, the transformation function adds 1 to age, inserts the choice of sector in year t as next period's lagged sector choice and updates tenure according to equation (9).

4 Counterfactual simulations

When solving the model for counterfactual simulation purposes, the terminal period can be set to be sufficiently into the future, e.g. $T - 1 = 2100$.

4.1 Simulating from the model

4.2 Scenario 1: A gradually increasing carbon tax

A The firm's first order conditions

Denoting the output price p^Y_{st}, the rental price of physical capital r^K_{st}, the skill price of human capital r^H_{st}, the price of clean energy p^E_{st} and the price of dirty energy p^O_{st}, the problem has the four first order conditions

$$\begin{aligned} r^H_{st} &= p^Y_{st} A_{st} \alpha^1_{st} H_{st}^{\alpha^1_{st}-1} K^{\alpha^2_{st}} \left(E^{\theta_s}_{st} + O^{\theta_s}_{st}\right)^{\frac{1-\alpha^1_{st}-\alpha^2_{st}}{\theta}} \\ &= \alpha^1_{st} p^Y_{st} \frac{Y_{st}}{H_{st}} \end{aligned} \tag{24}$$

$$\begin{aligned} r^K_{st} &= p^Y_{st} A_{st} \alpha^2_{st} K_{st}^{\alpha^2_{st}-1} H^{\alpha^1_{st}} \left(E^{\theta_s}_{st} + O^{\theta_s}_{st}\right)^{\frac{1-\alpha^1_{st}-\alpha^2_{st}}{\theta}} \\ &= \alpha^2_{st} p^Y_{st} \frac{Y_{st}}{K_{st}} \end{aligned} \tag{25}$$

$$\begin{aligned} p^E_{st} &= p^Y_{st} A_{st} \left(1-\alpha^1_{st}-\alpha^2_{st}\right) \left(E^{\theta_s}_{st} + O^{\theta_s}_{st}\right)^{\frac{1-\alpha^1_{st}-\alpha^2_{st}}{\theta}-1} E^{\theta-1} K_{st}^{\alpha^2_{st}} H^{\alpha^1_{st}} \\ &= \left(1-\alpha^1_{st}-\alpha^2_{st}\right) p^Y_{st} \frac{E^{\theta_s}}{E^{\theta_s}+O^{\theta_s}} \frac{Y_{st}}{E_{st}} \end{aligned} \tag{26}$$

$$\begin{aligned} \eta_s \tau_{st} + p^O_{st} &= p^Y_{st} A_{st} \left(1-\alpha^1_{st}-\alpha^2_{st}\right) \left(E^{\theta_s}_{st} + O^{\theta_s}_{st}\right)^{\frac{1-\alpha^1_{st}-\alpha^2_{st}}{\theta}-1} O^{\theta-1} K_{st}^{\alpha^2_{st}} H^{\alpha^1_{st}} \\ &= \left(1-\alpha^1_{st}-\alpha^2_{st}\right) p^Y_{st} \frac{O^{\theta_s}}{E^{\theta_s}+O^{\theta_s}} \frac{Y_{st}}{O_{st}}. \end{aligned} \tag{27}$$

B Solution procedure for the worker's problem

Update this with new M and bigger state space

The full solution to the problem entails finding all expected value functions, $E_\varepsilon V_t(\Omega_{it})$. In the following I will be explicit about the content of Ω_{it} while suppressing skill prices since they stay fixed throughout.

Solving the model proceeds in two steps. As explained in the main text, workers have static expectations about future skill prices in the terminal period $T-1$. Since the model is solved with backwards recursion, this is the period where the algorithm starts. What we calculate are the continuation values when the skill prices are constant and equal to $\boldsymbol{r}_{T-1}$ for all the periods that a worker has left on the labor market. To calculate these expected value functions, we perform the following steps:

1. Set skill prices equal to $\boldsymbol{r}_{T-1}$ throughout the following steps 2-4.

2. Start at age $a_i = 65$. Calculate the expected value function, i.e. calculate $E_\varepsilon V_{T-1}(a_i, s_{iT-2})$ using the closed-form expression in (15) with the continuation

values equal to zero:

$$E_\varepsilon V_{T-1}(a_i, s_{iT-2}) = \sigma \log \left(\sum_s \exp \left(\frac{w_{ist} - M(s, s_{iT-2}, \Omega_{iT-1})}{\sigma} \right) \right). \quad (28)$$

3. Move to age $a_i = 64$. Calculate $E_\varepsilon V_{T-1}(a_i, s_{iT-2})$ using the continuation value found in the previous step. The closed-form solution is

$$E_\varepsilon \left[V_{T-1}(a_i, s_{iT-2}) \right]$$
$$= \sigma \log \left(\sum_s \exp \left(\frac{w_{isT-1} - M(s, s_{iT-1}, \Omega_{iT}) + \rho E_\varepsilon \left[V_{T-1}(a_i + 1, s) \right]}{\sigma} \right) \right). \quad (29)$$

   The continuation value $\rho E_\varepsilon \left[V_{T-1}(a_i + 1, s) \right]$ reflects the expected value of having one year on the labor market when the skill prices equal $\boldsymbol{r}_{T-1}$.

4. Perform the previous step for ages $a_i = 63$ through 30, each time using the continuation value found in the previous step.

This procedure yields $E_\varepsilon V_{T-1}(a_i, s_{iT-2})$ for $a_i = 30, \ldots, 65$, i.e. the values when skill prices are constant for $35, \ldots, 0$ future periods. These, together with corresponding policy functions, represent the solution to the model in period $T - 1$.

Having calculated period $T-1$ expected value functions, we can calculate the expected value functions of the remaining periods using backwards recursion. Skill prices across sectors and time $\boldsymbol{r}$ are taken as given throughout and suppressed from the notation. The remaining procedure runs as follows:

1. Start from period $T - 2$.

   (a) Start from age $a_i = 65$. Calculate the value function $E_\varepsilon V_{T-2}(a_i, s_{iT-3})$, which has no continuation value, using the closed-form expression (15).

   (b) Set $a_i = 64$. Calculate $E_\varepsilon V_{T-2}(a_i, s_{iT-3})$ by using the continuation value $E_\varepsilon V_{T-1}(a_i + 1, s_{iT-2})$, i.e. the value function in the next period when the worker is also one additional year older. The calculation is given by

$$E_\varepsilon \left[V_{T-2}(a_i, s_{iT-3}) \right]$$

$$= \sigma \log \left(\sum_s \exp \left(\frac{w_{isT-2} - M(s, s_{iT-3}, \Omega_{iT-2}) + \rho E_\varepsilon \left[V_{T-1}(a_i + 1, s) \right]}{\sigma} \right) \right). \tag{30}$$

(c) Repeat the previous step recursively for ages $a_i = 63, \dots, 30$.

2. Perform steps (a) - (c) recursively for periods $t = T - 3, \dots, 0$.

The procedure gives all expected value functions. One can also retrieve the policy function by applying (16).

C Simulating forward

When simulating individuals forward, I treat the initial composition of the state space as exogenous. I also treat the initial composition of entering cohorts as exogenous. When simulating for estimation, these compositions are year-specific and given from the data. As mentioned in the main text, workers have static expectations about skill prices from the terminal period $T - 1$ onward.

C.1 Counterfactual simulations

When performing simulations, I wish to produce counterfactual simulations for periods $t > 2016$. To be able to do this, I must solve the model iterating backwards from a future period $t > T - 1$, sufficiently into the future, say, year 2100. I still assume that workers with active labor market years left in year 2100 have static expectations over future skill prices r_{st}.

Describe simulation method

C.2 Initial conditions, Retiring and entering cohorts

With each t, I must initialize a new cohort, i.e. a new set of workers of age 30 who enter the model. With an estimation sample spanning years $1996, \dots, 2016$, for these years I have data on all workers of age 30 and use these data directly when simulating. Since the previous sector choice s_{t-1} enters a worker's state space, I use the worker's employment when she was age 29. I treat her sector choice at age 29 as exogenous.

I initialize the simulation with the actual composition of workers as of 1996 and in each consecutive year up until and including 2016, I add a new cohort of age 30 with a composition equal to that observed in the data. For years after 2016, I must make an assumption about the composition of the entering cohort. I assume that the cohort of each year $t > 2016$ has a composition equal to that of year 2016.[7] For example, this means I impose that a certain fraction of the entering 30-year olds worked in sectors 0 to $S-1$ since that information enters their state space.

With these assumptions I can simulate employment from the model in all years 1996 until 2016. It does however require treating the state space of the workers that are in the middle of their careers when I observe them for the first time as exogenous. This might not be ideal, and Wooldridge (2005) has suggested a solution that I might employ later on.

D Solving for the human capital equilibrium

Finding the equilibrium skill prices entails solving for the human capital equilibrium. The routine runs in the following steps:

1. Using some vector of initial values for skill prices $\boldsymbol{r}^0$, solve for the worker's expected value functions and policy function. With these, simulate choices forward and calculate H_{st}^{supply} for each s and t.

2. Set $H_{st}^{demand} = H_{st}^{supply}$ and calculate the skill prices r_{st} consistent with the first order conditions from (24). Name the vector of these skill prices $\boldsymbol{r}^1$.

3. Check if all elements of $\boldsymbol{r}^1 - \boldsymbol{r}^0$ are sufficiently close to zero. If not, update to a new proposed skill price vector,

$$\boldsymbol{r}^2 = 0.1\boldsymbol{r}^1 + 0.9\boldsymbol{r}^0. \tag{31}$$

   $\boldsymbol{r}^2$ becomes the next iteration's $\boldsymbol{r}^0$.

4. Repeat the previous three steps until convergence in skill prices is obtained and the equilibrium is found.

[7] I could easily make a different assumption, but this one is simple and transparent.

E Solving for equilibrium output prices of nontradables

The output prices of nontradables are endogenized in counterfactual simulations. At the same time, Y is endogenized, so the firm's first order conditions must be solved too.

The routine runs in the following steps:

1. From a given set of skill prices,

hvordan løser vi for E, O og K når Y ikke længere er eksogen?

F Counterfactual simulation routine

The counterfactual simulation routine runs in the following steps:

1. Counterfactual simulations are initialized in the final sample year, 2016. Following Dix-Carneiro (2014), I fix the sector TFP measure A_{st} to its 2016 value for all $t >= 2016$. Correspondingly, the factor shares α^1_{st} and α^2_{st} are fixed to their 2016 values for all $t >= 2016$. The output prices of all tradables are normalized to 1 throughout.

2. Entering generations have the same composition as the last entering generation of the estimation sample, i.e. in 2016.

3. The terminal period for the counterfactual simulations is placed sufficiently into the future, in 2060.

4. Solve for the human capital equilibrium following appendix D. Simultaneously, solve for the equilibrium output prices by following appendix E.

5.

G Estimation routine

The estimation routine runs in the following steps:

1. Measure value added in real monetary terms, $\overline{p^Y_{st} Y_{st}}$. Set $p^Y_{st} Y_{st} = \overline{p^Y_{st} Y_{st}}$ throughout the estimation routine (similarly to Dix-Carneiro 2014). Previously calibrated and estimated parameters are also held fixed.

2. Using some vector of initial parameter values and initial values for skill prices $\boldsymbol{r}^0$, solve for the worker's expected value functions and policy function. With these, simulate choices forward.

3. Calculate H_{st}^{supply} for each s and t. Set $H_{st}^{demand} = H_{st}^{supply}$ and calculate the skill prices r_{st} consistent with the first order conditions from (24). Name the vector of these skill prices $\boldsymbol{r}^1$.

4. Check if all elements of $\boldsymbol{r}^1 - \boldsymbol{r}^0$ are sufficiently close to zero. If not, update to a new proposed skill price vector,

$$\boldsymbol{r}^2 = 0.1\boldsymbol{r}^1 + 0.9\boldsymbol{r}^0. \tag{32}$$

   $\boldsymbol{r}^2$ becomes the next iteration's $\boldsymbol{r}^0$.

5. Repeat the previous three steps until convergence in skill prices is obtained.

6. Calculate the log-likelihood value for the current set of parameters. Using an optimization algorithm, guess a new set of parameters.

7. Repeat the previous 5 steps until the optimizer converges on a set of parameter values.

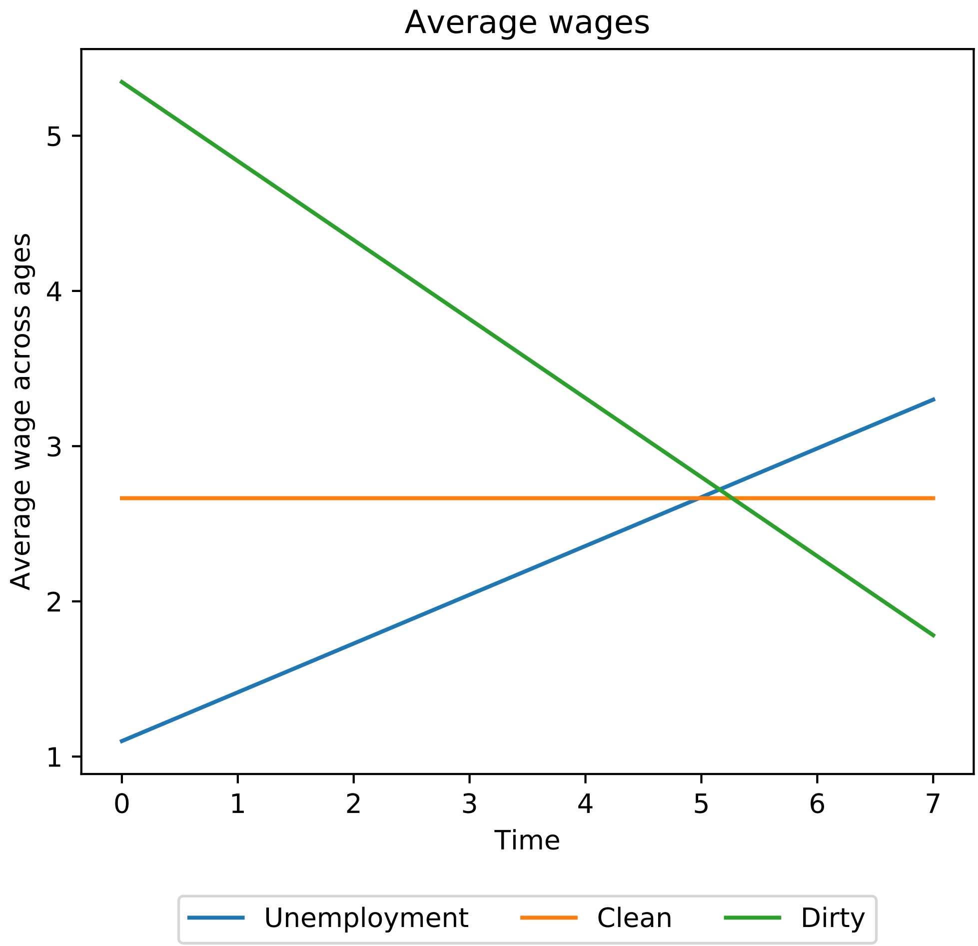
8. Calculate K_{st}, E_{st} and O_{st} from their respective first order conditions (25), (26) and (27). Then, calculate A_{st} residually by

$$A_{st} = \frac{\overline{p_{st}^Y Y_{st}}}{H_{st}^{\alpha_{st}^1} K_{st}^{\alpha_{st}^2} \left(E_{st}^{\theta_s} + O_{st}^{\theta_s}\right)^{\frac{1-\alpha_{st}^1-\alpha_{st}^2}{\theta_s}}}. \tag{33}$$

   where we have normalized the output price of each sector to 1 without loss of generality since each price ever only enters as a product with A_{st}.

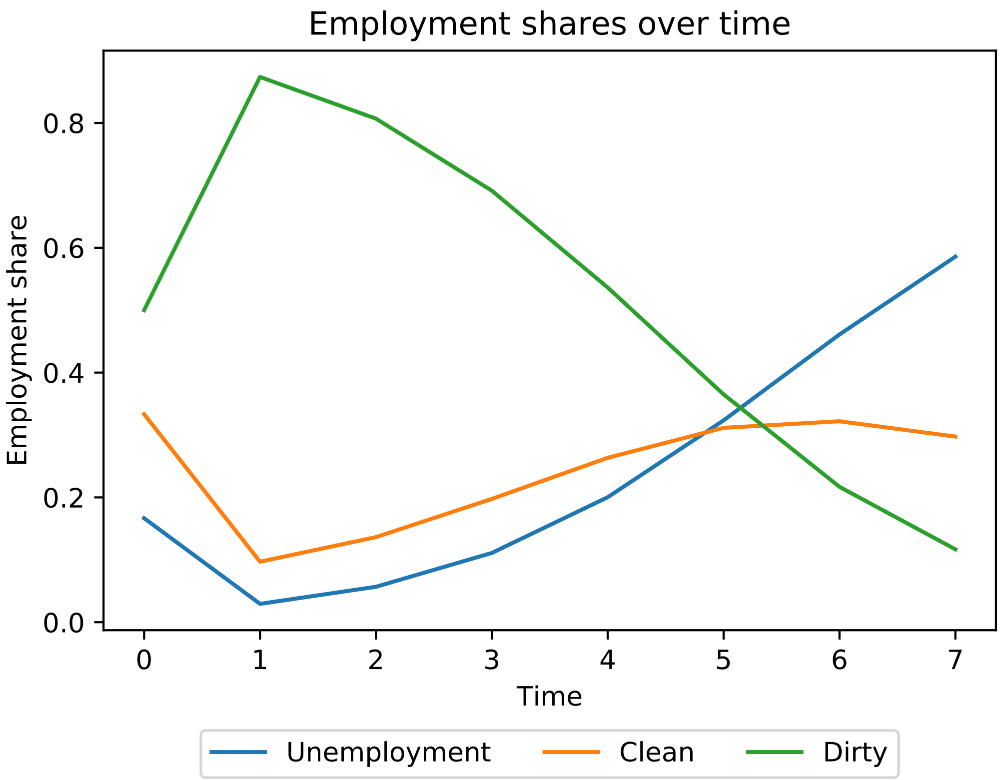
H Results

Figure 1: Average wages.



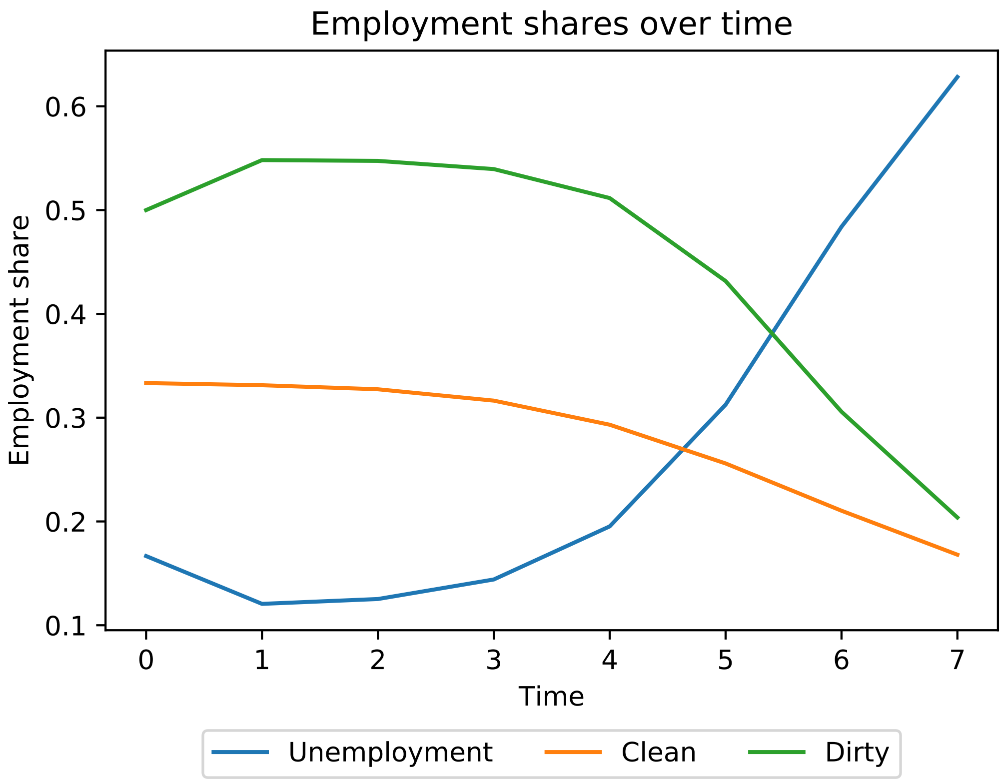
Note: Average wages across ages for each sector over time. At the moment these are completely exogenous.

Figure 2: Employment shares.



Note: Employment shares for each sector over time.

Figure 3: Employment shares, high switching costs.



Note: Employment shares for each sector over time. This simulation has higher switching costs.

Table A1: Unconditional switching probabilities

From ↓ / To →	Unemployment	Clean	Dirty
Unemployment	0.279573	0.240375	0.480052
Clean	0.255692	0.265419	0.478889
Dirty	0.243142	0.221388	0.535470

Note:

Table A2: Unconditional switching probabilities, high switching costs

From ↓ / To →	Unemployment	Clean	Dirty
Unemployment	0.957522	0.002832	0.039646
Clean	0.091361	0.907167	0.001472
Dirty	0.114501	0.000036	0.885463

Note:

Todo list

References

Aguirregabiria, Victor (2021). "Empirical Industrial Organization: Models, Methods, and Applications". *University of Toronto.*

Ashournia, Damoun (2018). "Labour market effects of international trade when mobility is costly". *The Economic Journal* 128.616, pp. 3008–3038.

Dix-Carneiro, Rafael (2014). "Trade liberalization and labor market dynamics". *Econometrica* 82.3, pp. 825–885.

Goulder, Lawrence H, Marc AC Hafstead, GyuRim Kim, and Xianling Long (2019). "Impacts of a carbon tax across US household income groups: What are the equity-efficiency trade-offs?" *Journal of Public Economics* 175, pp. 44–64.

Hafstead, Marc A.C. and Roberton C. Williams (2018). "Unemployment and environmental regulation in general equilibrium". *Journal of Public Economics* 160, pp. 50–65. ISSN: 0047-2727.

Humlum, Anders (2019). "Robot adoption and labor market dynamics". *Princeton University.*

Keane, Michael P and Kenneth I Wolpin (1997). "The career decisions of young men". *Journal of political Economy* 105.3, pp. 473–522.

Lee, Donghoon (2005). "An estimable dynamic general equilibrium model of work, schooling, and occupational choice". *International Economic Review* 46.1, pp. 1–34.

Rust, John (1987). "Optimal replacement of GMC bus engines: An empirical model of Harold Zurcher". *Econometrica: Journal of the Econometric Society*, pp. 999–1033.

Traiberman, Sharon (2019). "Occupations and import competition: Evidence from Denmark". *American Economic Review* 109.12, pp. 4260–4301.

Walker, W Reed (2013). "The transitional costs of sectoral reallocation: Evidence from the clean air act and the workforce". *The Quarterly journal of economics* 128.4, pp. 1787–1835.

Wooldridge, Jeffrey M (2005). "Simple solutions to the initial conditions problem in dynamic, nonlinear panel data models with unobserved heterogeneity". *Journal of applied econometrics* 20.1, pp. 39–54.

Yip, Chi Man (2018). "On the labor market consequences of environmental taxes". *Journal of Environmental Economics and Management* 89, pp. 136–152.

Non-cited sources

Känzig, Diego (2021). "The unequal economic consequences of carbon pricing". *London Business School mimeo.*