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Workers' Earnings Losses Due to the Low-Carbon Transition. Theory and Application in a CGE Model

Abstract

Designing a just transition that leaves no one behind necessitates an understanding of the potential economic costs of this transition for particularly vulnerable individuals. In this article, we analyse the costs of transitioning from high-carbon to less-carbon-intensive sectors for workers. First, we discuss potential reasons for such costs. Second, we employ a microeconomic model to demonstrate that information on the magnitude of these costs can be derived from the empirically observed sectoral labour supply curves. We then illustrate how the system of supply curves can be integrated into a standard Computable General Equilibrium framework. We calculate the potential earnings losses incurred by workers during the transition and compare them to the size of the Just Transition Fund by the European Commission. Finally, we employ the model to estimate the transition costs for Poland. In 2040, the loss for workers due to climate policy is approximately \$1 billion, equivalent to 0.5% of total labour compensation. The state could use a Just Transition Fund or allocate a portion of its carbon tax revenue to compensate for these losses, thus reducing the resistance of the most affected workers to more ambitious climate policies.

Keywords

Just transition | Computable General Equilibrium | Climate Change Mitigation | mining phase-out

JEL Codes

Q43, Q52, E24, J24

1. Introduction

A transition to a low-carbon economy will be a boon for workers who find work in green industries and could be a major challenge for those in 'dirty industries' who cannot move easily to other sectors. Limiting the temperature rise to 1.5°C by the end of the century would require a drop of up to 75% in global consumption of coal between 2010 and 2030, according to the projections of integrated assessment models (Riahi et al., 2017). Given little change in coal consumption between 2010 and 2020, the preponderance of the reduction must be scheduled for the coming decade. Such a massive drop in a short period of time implies that workers in the mining sector will lose jobs and have a need to search for other employment.

We argue that workers in carbon-intensive sectors who are forced to move to other sectors will receive lower wages than they receive currently. Those workers possess specific skills shaped by their experience, education and personal traits. The returns for those skills differ among economic sectors. According to microeconomic theory, the ranking of those returns across sectors is revealed by workers' current choices: if they decide to stay in mining, it must be that, considering their skills, it offers the highest possible return. Moving to the sector of second choice involves lower returns and hence lower wages.

The losses endured by mining workers attracted considerable attention among policy makers. The 'Just Transition Declaration' signed by negotiators during the United Nations Climate Change Conference (COP24)

in Katowice recognises the need for ‘social security programmes for workers whose jobs will be lost or transformed’. In Germany, the commission named ‘Growth, Structural Change and Employment’ was set to propose ways to support formerly coal dependent regions (Bauers et al., 2018). The European Commission introduced the ‘Just Transition Fund’ to support affected workers (European Commission, 2020). The compensation would be justified from the perspective of political economy since it could be necessary to win sufficient support for the climate policy.

The purpose of this paper is to support the debate on the design of just transition for workers by developing a methodology for computing what compensation would be required to balance the earnings loss for workers in the carbon-intensive sectors, which are being phased out due to climate policy. We show how the size of this loss can be inferred from the parameters of labour supply curve at the sectoral level. Next, we propose a framework that allows one to quantify the loss under climate policy scenarios using the large-scale multisector numerical general equilibrium models. Finally, we perform simulations to project the size of the potential earnings loss for workers due to climate policy. The calibrations and estimations will be performed for the Polish economy, which has the largest coal-mining sector in the EU¹. This strategy will allow us to estimate the size of the compensation required to balance the adverse effects of climate policy on the labour market.

The social issues associated with a fast transition are recognised in the emerging academic literature on just transition (Spencer et al., 2018; Sartor, 2018). This literature is complemented by numerous case studies by country on coal-sector phase-outs; for the German study, see, e.g., Brauers et al. (2018); and for the Polish study, see, e.g., Skoczkowski et al. (2019). These descriptive studies explain challenges for workers along the transition, but they do not explore how the challenges translate into quantified earnings losses for workers. On the other hand, numerous studies that utilise the Computable General Equilibrium (CGE) framework, such as Pradhan and Ghosh (2022) for India, Nong (2020) for South Africa, Fragkos and Paroussos (2018) for EU, Kiula (2018) and Antosiewicz et al. (2020) for Poland, quantify macroeconomic impacts, including effects on employment, of green reforms, but they do not explicitly explore the the loss

of labour compensation associated with the imperfect flow of labour across sectors.

Our study aims to contribute to an emerging strand of literature that attempts to bridge the two approaches by quantifying the costs due to obstacles signalled in the descriptive literature using tools provided by the CGE literature, and by incorporating these costs in the macroeconomic analysis of green reforms. We summarise the findings of this literature and position our contribution in greater detail in the section below.

2. Why We Can Expect Costs of Low-Carbon Transition for Workers – CGE Perspective

The CGE literature offers several explanations regarding the losses that workers might suffer when their original sector is phased out. The first explanation is that some workers are forced out of the labour market into unemployment or inactivity due to the presence of labour market failures such as rigid wages (Devarajan et al., 2011; Törmä et al., 2015; Hafstead and Williams, 2020, Baran et al., 2020) or search frictions (Fæhn et al., 2009; Hafstead and Williams, 2020). When the market fails to balance demand with supply, a reduction in the demand for workers in the dirty sector due to climate policy leads to an increase in involuntary unemployment and loss of labour income for those workers who lost jobs. In addition, Hafstead and Williams (2018, 2020) postulate that searching for a new job is more difficult for workers who must switch sectors than for those who move between jobs within the same sector, and they thus suffer income loss for a longer period. On the other hand, in countries with a high rate of unemployment before the energy transition, the development of a low-carbon economy can increase demand for labour, leading to a drop in unemployment (Karapinar et al., 2019, Pollitt et al., 2015).

A second explanation is offered by studies that consider the possibility that low-skilled workers could move to another sector only if firms in that sector have a demand for these types of workers (Chateau et al., 2018; Perrier and Quirion 2018). In those models, low-skilled workers in all sectors receive lower wages if a reform leads to a drop in demand for low-skilled labour.

¹ According to Eurostat (2024), the coal and lignite sector in Poland employed 84,000 workers in 2020, which constituted 74% of EU employment in that sector.

The third explanation is suggested by the model of wage differentials (Hsieh 2019). The model assumes that each worker draws her potential productivity in each sector from the Frechet distribution. The worker then compares her payoff for working in one sector with her payoff for working in other sectors. Her current choice is the sector with the highest payoff.

According to this framework, forcing a worker to move from her current sector will lead to a loss of productivity. The second largest payoff the worker could receive outside her current sector is the worker's outside option. For some workers in dirty sectors, the outside option could be very close to the value of their current job; perhaps such a worker has skills that allow a smooth transition to well-paid jobs in other sectors. For others, the outside option could be much lower than the value of their current job. This could be the case for workers with skills that are very specific to the sector in which they are employed. They currently receive a high salary but would receive a low salary if they were to change sector. For these workers, the cost of leaving their current sector could be significant.

Our study is similar to the wage differentials approach, although we do not explicitly model the distribution of worker productivity. We assume that average productivity in a sector is not constant, but depends on the number of workers in that sector. This dependence takes into account the fact that the workers are heterogeneous: a worker entering the sector may have different productivity than those who were there before.

3. Supply Curves Reflect Costs of Transition for Workers

In order to quantify the loss of productivity for a given size of structural change, one could use information contained in empirically observed sectoral labour supply curves. Under the assumption that workers are rational actors who choose their sector in order to maximise their payoff, the supply curve reflects the distribution of outside options of workers in a given sector. When a reduction in wage from w' to w'' motivates a fraction ϕ of workers to move, it follows that for the remaining $(1 - \phi)$ workers the highest payoff from work in another sector (the outside option) must be lower than w'' . For the ϕ workers who moved, the outside option must be somewhere between w' and w'' . In the next subsection, we demonstrate how

information contained in a supply curve can be used to recover the outside option of marginal workers at any given wage level. Subsequently, we show how one could use this information to compute the total costs when dirty sectors are phased out.

3.1. Efficiency Units in Each Sector

Consider a worker who must decide between allocating his or her labour across K different sectors. That worker's productivity could differ between sectors. More specifically, following Hsieh et al. (2019), we assume that the worker possesses some amount of efficiency units² in one sector and a potentially different amount of efficiency units in another sector. In addition, we allow workers to be heterogeneous; that is, within one sector two workers might have different productivities. We assume that wage per efficiency unit in sector k , w_k , is the same for all workers in that sector. Let $\mathbf{w} = (w_1, \dots, w_K)$ denote the vector of wages per amount of efficiency units for sectors $1, \dots, K$. The compensation a worker receives from working in sector k is w_k times the amount of efficiency unit the worker possesses in sector k . The worker simply chooses the sector which offers the highest compensation.

Throughout the paper we assume that changes in wages do not alter the total supply of labour and that the supply of labour is always equal to the demand by firms; that is, there is no unemployment. Furthermore, we do not distinguish between cohorts of workers – in each period all workers can make a decision about where to work and this decision has no consequences for their opportunities or payoffs in the future. These assumptions are made to simplify the presentation of the main argument. We briefly discuss the potential bias in our results caused by these assumptions in Section 4.

Let $n_j(\mathbf{w})$ be the share of workers who wish to work in sector j and let $N_j(\mathbf{w})$ be the sum of their efficiency units. Before specifying the relationship between N and n , consider the following experiment: if we start with $w_j = 0$ and then gradually increase it, n_k increases. We would expect that the first workers who join sector j are those with the highest amount of efficiency units

² Labour in efficiency units represents the quantity of labour adjusted for productivity. For instance, if Worker A is twice as productive as Worker B in a specific production process, Worker A is considered to have twice as many efficiency units of labour.

in that sector. As we continue to increase w_j , the sector is approached by other workers with a lower amount of efficiency units. The last workers to join are those for whom the sector is a particularly unfavourable match. This means that as n_j increases, the average productivity of workers decreases. To reflect this logic, we assume that the average amount of efficiency units in a sector is described by equation (1):

$$\frac{N_j}{n_j} = a_j n_j^\gamma \mu \quad (1)$$

where a_j and $\gamma < 0$ are parameters (which we will soon determine using the parameters of the supply curve) and μ is the parameter we will use to reflect productivity growth due to exogenous technological progress³. The parameter a_j represents the average productivity in the sector in a hypothetical situation if all workers are employed in sector j (i.e. if $n_j = 1$) and $\mu = 1$. The parameter γ can be interpreted as the elasticity of average labour productivity in the sector with respect to changes in the share of workers employed in the sector.

Next, we specify the shape of the supply curve, $n_j(w)$. Since n_j represents the share of workers, we must choose a function that satisfies $\sum_j n_j(w) = 1$. Ideally, we would also choose a function that permits constant elasticity of the labour supply, $d \log n_j / d \log w_j$. Satisfying both conditions at the same time is not possible. However, we can choose a functional form that uses an elasticity that is nearly constant, providing that the number of sectors is large and no sector has very large n_j (conditions which are usually satisfied in CGE models):

$$n_j = \frac{(s_j w_j)^\alpha}{\sum_k (s_k w_k)^\alpha} \quad (2)$$

where s_j and α are the parameters determining the shape of the supply curve. The parameter α governs the response of labour supply to a change in wages. The parameters s_j is a share parameter: $(s_j)^\alpha$ represents the share of workers willing to work in sector j in the

base year, when all wages per efficiency unit, w_j , are normalised to unity.

If supply is given by equation 2, elasticity of supply is given by

$$\begin{aligned} \frac{\partial n_j}{\partial w_j} \frac{w_j}{n_j} &= \alpha \frac{(s_j)^\alpha (w_j)^{\alpha-1} w_j}{\sum_k (s_k w_k)^\alpha} \frac{w_j}{n_j} - \alpha \frac{(s_j w_j)^\alpha (s_j)^\alpha (w_j)^{\alpha-1} w_j}{(\sum_k (s_k w_k)^\alpha)^2} \frac{w_j}{n_j} \\ &= \alpha \frac{(s_j w_j)^\alpha}{\sum_k (s_k w_k)^\alpha} \frac{1}{n_j} - \alpha \left(\frac{(s_j w_j)^\alpha}{\sum_k (s_k w_k)^\alpha} \right)^2 \frac{1}{n_j} = \alpha (1 - n_j), \end{aligned} \quad (3)$$

which approaches α as n_j approaches zero. In fact identical functional form was derived from a micro-founded model with heterogeneous workers by Witajewski-Baltvilks and Boratyński (2021) for the case of two-sector economy.

Now consider two sectors, j and k . After a decline in w_j , n_j drops and n_k increases. This indicates that before the change in sector j , there was a marginal worker who was indifferent about staying in sector j or moving to sector k . For that worker, the payoff in the two sectors must be equal. To compute that payoff, we must first compute the amount of efficiency units of the marginal worker in both sectors. According to (1), that worker leaving sector j causes the total amount of efficiency units in that sector to drop by

$$\frac{dN_j}{dn_j} = \frac{d(a_j n_j^{\gamma+1} \mu)}{dn_j} = a_j (\gamma + 1) n_j^\gamma \mu \quad (4a)$$

When that worker enters sector k , the total amount of efficiency units in k increases by

$$\frac{dN_k}{dn_k} = a_k (\gamma + 1) n_k^\gamma \mu \quad (4b)$$

If workers maximise their compensation, for workers at the margin compensation must be equal in both sectors:

$$\frac{dN_j}{dn_j} w_j = \frac{dN_k}{dn_k} w_k \quad (4c)$$

which implies that:

$$\frac{a_j}{a_k} \left(\frac{n_j}{n_k} \right)^\gamma = \left(\frac{w_j}{w_k} \right)^{-1} \quad (4d)$$

³ In the quantitative part of our study (described in section 4) we assume that the productivity of labour grows at the growth rate equal to GDP growth projections from the EU Reference Scenario 2020 (European Commission 2021). In Poland, the average annual growth rate is 2.9% in the 2020s and 1.8% in the 2030s.

However, this last result depends on an additional assumption – that workers' preferences are homogeneous and that workers are indifferent between jobs offering the same remuneration. To understand the importance of this assumption, consider the alternative setup where all workers have exactly the same productivity, but their preferences are heterogeneous: some workers are highly satisfied with working in a particular sector, while others are not. Suppose also that wages are initially equal in all sectors. A fall in the wage in one sector will give some workers an incentive to leave. All those who stay will be those who find their current job more satisfying than other jobs. This will also be true for the marginal worker: she is indifferent between her current job and the outside option because, on the one hand, her current job gives her more satisfaction, and on the other hand, it gives her lower compensation. However, if the marginal worker's compensation differs between her current and potential sectors, the condition necessary to derive equation (4c) is not satisfied.

Assuming homogeneous preferences, we can combine (2) and (4d) to understand how the elasticity of labour supply (α) could be translated into the elasticity of average productivity with respect to a change in labour supply (parameter γ). In order to do this, we can derive the labour supply in sector j relative to the labour supply in sector k by using the equation (2):

$$\frac{n_j}{n_k} = \frac{(s_j w_j)^\alpha}{(s_k w_k)^\alpha} \quad (5)$$

Since we assume that a_j and a_k are constant (independent of $\mathbf{w}$), then $\gamma = -1/\alpha$ and $a_j/a_k = s_j/s_k$. Since s_j can be normalised, then $a_j = s_j$.

Finally, we can express the sum of efficiency units of all workers in the sector:

$$N_j = a_j n_j^{\gamma+1} \mu = s_j \left(\frac{(s_j w_j)^\alpha}{\sum_k (s_k w_k)^\alpha} \right)^{\frac{\alpha-1}{\alpha}} \mu \quad (6)$$

3.2. Recovering Costs of Phase-out from Supply Curve

Next we demonstrate how the information contained in the labour supply curves could be used to recover the costs of phasing out a given sector.

A sectoral phase-out implies that all workers are forced to leave the sector. In our setup, forcing each worker to leave a sector is equivalent to lowering that worker's wage per efficiency units below the point at which she or he is indifferent to staying in or leaving the sector. We will consider an exercise in which we lower wage in sector j forcing consecutive workers to leave, starting with the workers for whom the costs of leaving the sector are the smallest. For now, we will assume that all other wages are held constant – an assumption we will relax in the general equilibrium setup of Section 4. Each time, the reduction in employment requires lowering wages by dw_j/dn_j . At every point during this process, the reduction in wages does not actually affect workers who are leaving the sector. These workers reached the minimal compensation that they were willing to accept, and when their wages drop, they immediately jump to a new sector, receiving the same compensation that they had previously. However, the drop in wages affects all workers who remain in the sector. Every time the wage drops by one unit, these workers lose the compensation equal to N_j efficiency units. Thus, the total loss of earnings for workers due to a complete sector j phase-out is equal to

$$\int_{\bar{n}_j}^0 N_j \frac{dw_j}{dn_j} dn_j \quad (7)$$

We will use $\bar{n}_j$ and $\bar{w}_j$ to denote initial labour supply and initial wage, respectively.

Using the expression for N_j derived earlier, this integral can be evaluated as:

$$\int_{\bar{n}_j}^0 N_j \frac{dw_j}{dn_j} dn_j = (\sum_k (s_k w_k)^\alpha)^{\frac{1}{\alpha} \mu} - (\sum_{k \neq j} (s_k w_k)^\alpha)^{\frac{1}{\alpha} \mu} \quad (8)$$

3.3. CET Supply System in CGE Framework

The equations describing the system of supply curves in Section 3.2 can be incorporated directly into the CGE framework. An alternative approach is to specify an optimisation problem with representative workers that gives exactly the same predictions as those described in Sections 3.2 and 3.3. This second approach is more useful in cases where models consist of a set of objective functions and constraints for various actors. In this subsection, we show that the supply system presented in Section 3.2 can easily be

incorporated into the CGE framework by assuming the existence of a representative worker with Constant Elasticity of Transformation (CET) constraints on the distribution of labour across sectors.

Consider a representative worker who receives an endowment of labour L from households. The worker can transform this labour into productive units of labour dedicated to each sector i , according to the following transformation possibility frontier:

$$\sum_j \left(\frac{N_j}{s_j} \right)^\rho = \mu^\rho \quad (9)$$

where s_j is the share parameter, and the parameter ρ determines the ease with which units of labour across sectors are transformed (the higher the value of ρ , the more difficult the transformation).

Note that in this setup labour is sector-specific in the sense that one unit of labour cannot be freely moved between sectors without a change in productivity. When the representative worker transforms a unit of efficient labour from one sector to fit another sector, the amount of efficiency units that is now available for the new sector is given by:

$$\frac{dN_k}{dN_j} = - \left(\frac{N_j}{N_k} \right)^{\rho-1} \left(\frac{s_j}{s_k} \right)^{-\rho} \quad (10)$$

The objective of the representative worker is to choose the allocation of efficient labour, N_j , that maximises the total return to labour. Formally, the optimisation problem reads

$$\max_{\{N_j\}_{j=1}^K} \sum_j w_j N_j \quad (11)$$

subject to constraint (9)

The optimal allocation satisfies the first order conditions, given by:

$$w_j - \lambda \rho s_j^{-\rho} N_j^{\rho-1} = 0 \quad (12a)$$

where λ is the shadow value of a marginal unit of endowment. Using the constraint (9) we find that

$$\lambda \rho = \left(\sum_j (s_j w_j)^{\frac{\rho}{\rho-1}} \right)^{\frac{\rho-1}{\rho}} \mu^{\frac{-1}{\rho-1}} \quad (12b)$$

and

$$\frac{s_j^{\frac{\rho}{\rho-1}} w_j^{\frac{1}{\rho-1}} \mu}{\left(\sum_k s_k^{\frac{\rho}{\rho-1}} w_k^{\frac{\rho}{\rho-1}} \right)^{\frac{1}{\rho}}} = N_j \quad (12c)$$

The total return to labour for all workers in the economy is given by

$$\sum_j N_j w_j = \left(\sum_j s_j^{\frac{\rho}{\rho-1}} w_j^{\frac{\rho}{\rho-1}} \right)^{\frac{\rho-1}{\rho}} \mu \quad (13)$$

and the total loss due to phase-out of sector j is given by

$$\left(\sum_k s_k^{\frac{\rho}{\rho-1}} w_k^{\frac{\rho}{\rho-1}} \right)^{\frac{\rho-1}{\rho}} \mu - \left(\sum_{k \neq j} s_k^{\frac{\rho}{\rho-1}} w_k^{\frac{\rho}{\rho-1}} \right)^{\frac{\rho-1}{\rho}} \mu \quad (14)$$

Note that these predictions are exactly the same as in Sections 3.1 and 3.2, as long as $\alpha = \rho/(\rho-1)$.

We can also compute the loss of workers for any change in the vector of wages. If $\bar{w}$ is the vector of initial wages and w is the vector of new wages, the total loss for workers in the economy is given by:

$$\sum_k N_k(\bar{w}) \bar{w}_k - \sum_k N_k(w) w_k = \left(\sum_k s_k^{\frac{\rho}{\rho-1}} \bar{w}_k^{\frac{\rho}{\rho-1}} \right)^{\frac{\rho-1}{\rho}} \mu - \left(\sum_k s_k^{\frac{\rho}{\rho-1}} w_k^{\frac{\rho}{\rho-1}} \right)^{\frac{\rho-1}{\rho}} \mu \quad (15)$$

3.4. Tracing Workers and Computing Earnings Loss by Sector

In Section 3.3 we demonstrated how one could use information on the system of supply curves to compute the total loss for all workers in the economy. Policy makers and public opinion might also be interested in tracing the wages (and losses) of particular groups of workers, e.g., workers who were originally employed in mining. In this section, we demonstrate a strategy for estimating such loss.

We start by noting that estimating the loss of workers employed in sector j after phase-out of this sector is trivial if there is no change in the wages of

other sectors. In such a case, workers employed in other sectors suffer no loss; none of them suffer any productivity loss since none of them moves. Hence the total loss could be attributed only to workers from the phased-out sector.

If the transition involves changes in the general equilibrium level of wages in several sectors, movement of labour is more complex. There could be several sectors that experience outflow of labour. Below, we provide a strategy for estimation of the loss of a group of workers who are originally employed in a sector that is being phased out. This group could be defined, e.g., as a pool of workers who would be employed in mining, during a given year, in a reference scenario with no climate policy. Alternatively, it could be a pool of workers employed in mining during the reference year, e.g., at the beginning of the analysed period. The choice of reference does not affect the main steps of the derivations. We will focus on the comparison between compensation of workers employed in mining in the reference scenario and compensation of the same group of workers in a policy scenario.

In the reference scenario at time t , the total compensation of workers employed in sector j can be expressed using (6) by

$$N_j(\bar{\mathbf{w}})\bar{w}_j = s_j \bar{w}_j \left(\frac{s_j \bar{w}_j}{(\sum_k (s_k \bar{w}_k)^\alpha)^{\frac{1}{\alpha}}} \right)^{\alpha-1} \mu \quad (16)$$

In the policy scenario, this group of workers is split into two groups. We will trace the compensation and productivity of each group.

The first group consists of workers who are still in the sector within the policy scenario. Their total productivity (sum of efficiency units of all workers) is given by $N_j(\mathbf{w})$, and their compensation is

$$N_j(\mathbf{w})w_j = s_j w_j \left(\frac{s_j w_j}{(\sum_k (s_k w_k)^\alpha)^{\frac{1}{\alpha}}} \right)^{\alpha-1} \mu \quad (17)$$

The second group consists of workers who left for another sector due to the change in wages that is induced by the policy. The amount of efficiency units that belongs to workers from that group and that are now employed in sector l can be approximated as the difference between total amount of efficiency units in sector l within the policy scenario and that number in the counterfactual. Here, the counterfactual assumes that the wage in sector j was the same as in the reference scenario:

$$s_l \mu \left(\frac{s_l w_l}{(\sum_k (s_k w_k)^\alpha)^{\frac{1}{\alpha}}} \right)^{\alpha-1} - s_l \mu \left(\frac{s_l \bar{w}_l}{(\sum_{k \neq j} (s_k \bar{w}_k)^\alpha + (s_j \bar{w}_j)^\alpha)^{\frac{1}{\alpha}}} \right)^{\alpha-1} \quad (18)$$

Detailed derivations and the discussion of the assumptions behind this approximation is presented in the Appendix A1.

The total compensation for workers who were originally employed in sector j is the sum of the compensation of the two groups. Using the equation (6), it can be expressed as:

$$N_j w_j + \left[1 - \left(\sum_{k \neq j} \frac{N_k w_k}{\sum_m N_m w_m} + \frac{\bar{N}_j \bar{w}_j}{\sum_m N_m \bar{w}_m} \left(\frac{\sum_m N_m \bar{w}_m}{\sum_m N_m w_m} \right)^\alpha \right)^{\frac{1-\alpha}{\alpha}} \right] \sum_{l \neq j} N_l w_l \quad (19)$$

The total cost for workers who were originally employed in sector j is the difference between their current compensation, stated above, and the compensation in the reference point, $\bar{N}_j \bar{w}_j$.

4. Quantitative Results

The first step in quantifying the predictions of the model and the loss of earnings for workers is the calibration of the parameters in the system of supply curves. We outline the details of our calibration strategy in Section 4.1. In the second step, the supply curves must be integrated into a larger general equilibrium framework that is able to project changes in demand for labour upon transition. From a mathematical point of view, integrating upward-sloping labour supply curves with the system of downward-sloping demand curves, which results from optimisation problems involving firms and consumers captured by the CGE model, allows the endogenisation of wage vectors that until now remained exogenous in our analysis. In Section 4.2, we provide quantitative predictions on the costs of transition generated with the CGE model with integrated sectoral labour supply curves. In the supplementary material to this paper⁴ we provide some details on the dPLACE model – a large CGE modelling framework that we utilised for our simulations and details on the decarbonisation scenario analysed to quantify workers' losses.

⁴ The supplementary material is available at <https://zenodo.org/communities/econjusttransition/>

4.1. Calibration of Labour Module Parameters

The supply system has $K+1$ parameters: K share parameters (s_j 's) and the parameter α . We calibrate share parameters by matching the model's predictions of labour compensation at the sectoral level with the compensations observed in the data. To calibrate α , we use elasticity of labour supply at the sectoral level. Below, we provide details of our estimation strategy.

4.1.1. Calibration of Share Parameters

In order to evaluate labour compensation by sector as a function of parameters, we can use equation (6):

$$N_j w_j = \left(\frac{(s_j w_j)^\alpha}{(\sum_k (s_k w_k)^\alpha)^{\frac{\alpha-1}{\alpha}}} \right) \quad (20)$$

Note that the calibration is performed for the base year and in that year $\mu=1$. The total compensation can then immediately be evaluated as:

$$\sum_j N_j w_j = (\sum_k (w_k s_k)^\alpha)^{1/\alpha} \quad (21)$$

Using these two expressions as well as information on labour compensation in each sector j , $w_j N_j$, we can uniquely determine $s_j w_j$

$$\left(\frac{N_j w_j}{\sum_j N_j w_j} \right)^{1/\alpha} \sum_j N_j w_j = s_j w_j \quad (22)$$

Note that in the model we can normalise every sectoral wage at the base year to unity by choosing appropriate values for s_j .

4.1.2. The Calibration of Elasticity Parameter

We calibrate the parameter α by using the elasticity of labour at the sectoral level. Before we proceed with mapping the predictions of the model with observed empirical results, we must highlight two important distinctions. First, note that the theoretical framework in Section 3 distinguishes between two supply curves: the relation between wages and supply of labour expressed in physical units (equation 2),

and the relation between wages and supply of labour expressed in efficiency units (equation 6). In the CGE framework, the production choices of firms depend only on the amount of available efficiency units. Thus, it is most convenient to express quantity of labour in the CGE model using efficiency units and integrate the model with the efficiency unit supply curves. However, for calibration purposes, we need to use the physical labour supply curve since employment in terms of efficiency units is not observable. The mathematical derivations in Section 3.1 show that the slopes of the two curves are different, but the relation between the two can easily be determined.

The second distinction concerns the interpretation of variable w_j . In our model, w_j represents the wage per efficiency unit in sector j . In the model, we assume that every worker can offer a constant amount of efficiency units in sector j (but for a given worker, the potential amount of efficiency units could differ between sectors, and in a given sector different workers can have different amounts of efficiency units). This implies that the change in wage w_j is proportional to the observed change in wage received by a worker in sector j . Note that this change will be different from the change in observed average wage in the sector since after the change in w_j , the composition of workers changes – those with the lowest amounts of efficiency units are leaving the sector. We need to keep this distinction in mind when calibrating the parameter α . In particular, we need to use empirical supply curves obtained from analysing the response of number of workers to exogenous wage shocks; that is, that which is observed in survey data that trace the wage and sector of employment of the same individual over time. The supply curve obtained from estimating a simple relationship between labour supply and average wage observed in the sector is not appropriate for our calibration.

The elasticity parameter α in equation 2 can be approximated with empirically observed elasticity of labour supply as long as each sector is relatively small. When this condition is satisfied, a change in sectoral wage has only a small impact on the aggregate wage index (the denominator on the right-hand side of equation 2) and therefore elasticity of labour supply predicted by equation 2 is close to α . For instance, in the case of mining sector, which employs 0.4% of workers in the Polish economy, according to equation 2, elasticity of labour would be equal to 2.489 when $\alpha = 2.5$.

We obtain the value of the elasticity of labour supply at the sectoral level from literature that estimates the elasticity of separation rate⁵ with respect to wages at the firm level. Manning (2003) shows that the long-run elasticity of labour supply should be exactly twice the elasticity of separation rate. The empirical literature was reviewed by Ashenfelter (2010), who finds the values of elasticity of labour supply in the range 1.5–4. However, there is also evidence in the literature of much lower values: the elasticity for monopsonies was estimated using survey data by Booth and Katic (2011) who obtained estimates in the range 0.71–0.75.

The choice of the value of the elasticity is further complicated for three reasons. First, our application requires the use of the elasticity of labour at the sectoral level, whereas the available literature provides evidence on the elasticity at the firm level. Since switching between firms is likely to be easier than switching between sectors, the elasticity at the sectoral level should be smaller than at the firm level. Second, in our framework, any resistance by workers to leaving their current job is attributed to the expected loss in productivity. In reality, however, this resistance could be at least partly due to other factors, such as workers' preferences (if they dislike other jobs). Third, the empirical studies do not take into account natural attrition: in the very long time horizon we consider in our simulations, the older cohorts of workers retire and are replaced by younger cohorts who have few constraints on their choice of sector. For the latter two reasons, the elasticity relevant to our study should be larger than the one reported in the previous paragraph.

For our study we chose a value of 2.5 for the elasticity of labour in our base simulation. We also ran sensitivities for values of 1.2, 1.5, 2.0, 3.0 and 5.0. We have also attempted to run the simulations for the values lower than 1.2, but in these cases the numerical model was not able to find a solution, which may indicate that ambitious emission reductions are not feasible when the elasticity of transformation is very low.

4.2. Numerical Results

In this section we present the numerical predictions of the model for the decarbonisation scenario, which assumes 76% reduction in GHG emissions by 2040

(relative to 1990). We estimate the resulting costs of the structural change for workers by comparing the macroeconomic outputs of the model in the simulations with and without frictional transition of labour across sectors. In the supplementary material to this paper (see footnote 4), we also present the main projections on structural change, fuel demand and detailed results for output and employment by sector in the simulation with labour market frictions.

In order to compute the loss of earnings for workers due to frictional transition between sectors, we compare two simulations. In the first simulation, we assume that the flow of workers is smooth; all workers in all sectors have exactly the same wage. Sectoral employment is determined by the intersection of horizontal labour supply and downward-sloping labour demand in each sector. Every worker who leaves, for instance, the mining sector and moves to another sector receives exactly the same payoff as in the old sector. Thus, the shift leaves productivity of the workers unaffected. This simulation is intended to provide a projection for a hypothetical scenario in which there were no transition costs for workers. We call this scenario the 'no frictions scenario'. In the second simulation we take into account the loss of productivity due to the effects described in Section 3. This simulation represents a scenario with frictions.

Inspection of the results under the two simulations suggest that the structural changes in both are almost identical. We observe very similar changes in output, in demand for electricity and fuels. Therefore, we will focus on the comparison of the key macroeconomic variables: GDP and compensation of labour.

The differences in compensation of employees and the GDP are depicted in Figure 1. In 2030, accounting for the loss of labour productivity due to frictional transition reduces the total compensation of labour by 0.38% relative to the case when the loss is ignored. In 2040, the loss increases to 0.44%. The decline of productivity due to frictional transition also implies a reduction of GDP. In 2030, this reduction is rather small (0.16%). By 2040, however, the difference in GDP between the two simulations attains 0.41%.

The monetary value of the potential loss for workers due to frictional transition is presented in Figure 2. The potential loss of earnings is computed as a difference in total labour compensation between the two simulations. In 2020, the loss is US\$0.24 billion (at 2011 prices) per annum. In 2030, the annual loss is at the level of \$0.69 billion, and in 2040 it reaches \$0.97 billion.

⁵ The separation rate is the proportion of workers who leave their current employment within a given period.

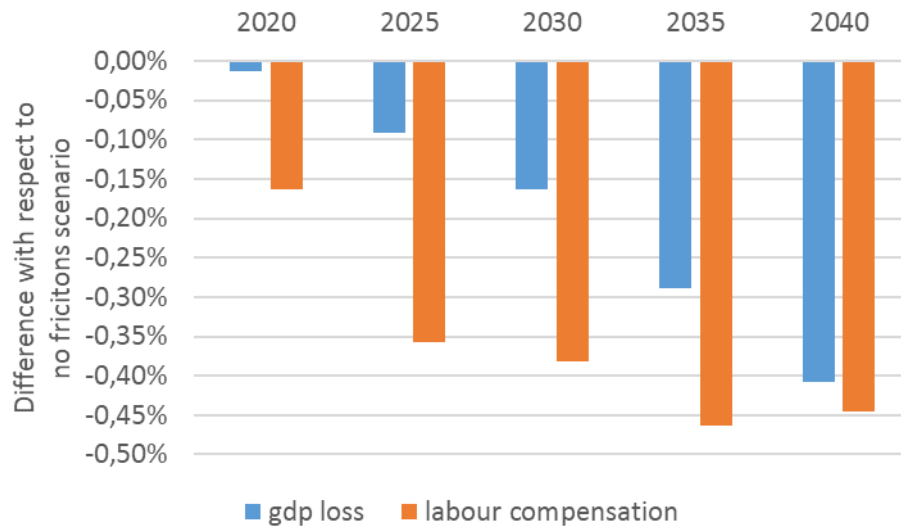


Figure 1. GDP and labour compensation loss in Poland due to frictional transition of labour between sectors (percentage difference between the frictionless decarbonisation simulation and the simulation with frictions throughout the transition)

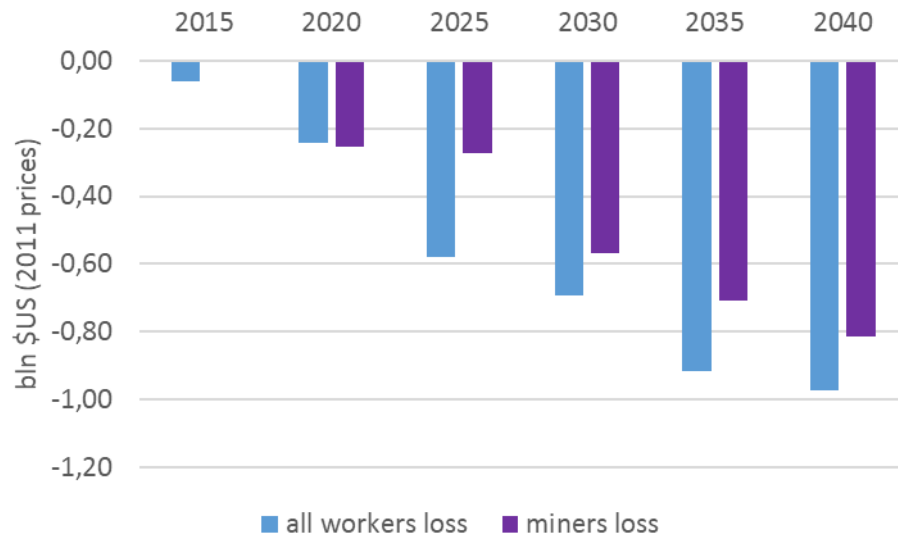


Figure 2. Labour compensation loss for all workers and for miners in Poland due to frictional transition of labour between sectors (absolute difference between frictionless decarbonisation simulation and the simulation with frictions throughout the transition)

We have also performed a sensitivity analysis by running the simulations under the alternative values of three parameters: (i) elasticity of transformation of labour (parameter α in the framework in Section 3), which governs how easy it is for workers to switch between sectors, (ii) elasticity of substitution between electricity and fossil fuels, which governs how easy it is for firms to replace use of fossils with electrified production, and (iii) elasticity of substitution between

capital-labour composite and energy, which governs how easy it is for firms to switch to more energy-saving (but more capital-intensive) production.

Figure 3 compares the results for the cases where the elasticity of labour supply at sectoral level is 1.2, 1.5, 2.0, 2.5, 3.0 and 5.0. We have also tried to run the simulations for elasticities equal to and lower than 1.1, but for this case the model is not able to find a numerical solution, suggesting that either ambitious

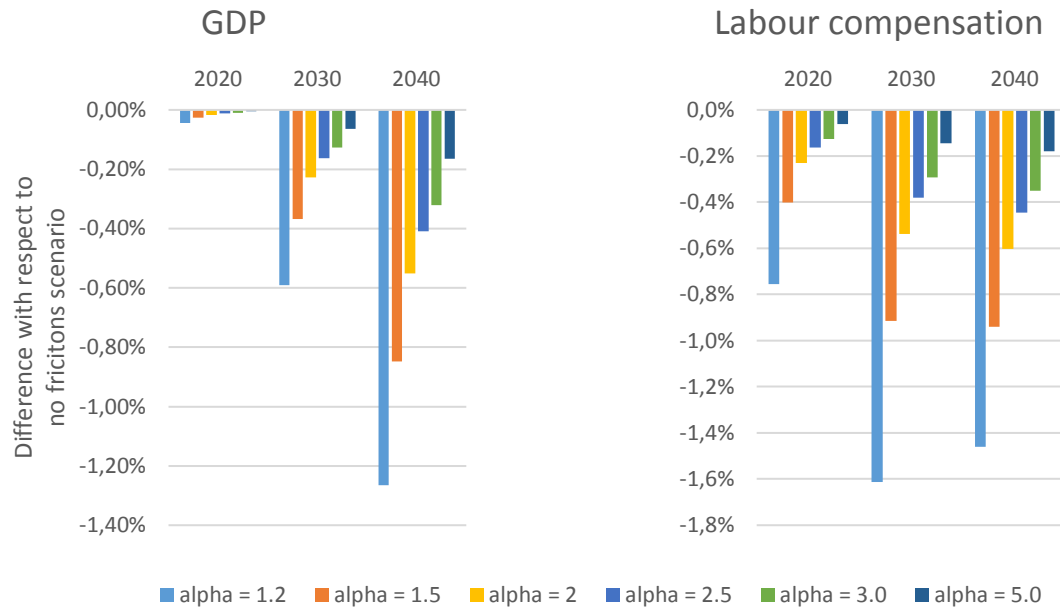


Figure 3. GDP (left panel) and labour compensation (right panel) loss in Poland due to frictional transition of labour between sectors (percentage difference between the frictionless decarbonisation simulation and the simulation with frictions throughout the transition) for the alternative assumptions regarding elasticity of labour supply at the sectoral level

emission reductions are not feasible when the elasticity of transformation is very low, or that our numerical tool is not suitable for analysing transformation when switching sectors is extremely costly for some workers. The results in Figure 3 show that a higher elasticity of transformation is associated with lower transition costs for workers, which is consistent with the predictions of the theory presented in Section 4: a high elasticity of transformation corresponds to a high elasticity of labour supply at the sectoral level, indicating that a small increase in wages leads to a large inflow of workers into a sector. According to the theory presented in 3.1, this implies that the worker who switches experiences only a small drop in productivity. Conversely, a small elasticity of transformation and a small elasticity of labour supply are associated with a large drop in productivity. In the context of our simulation, the switching workers are workers leaving the phasing-out sectors, such as mining. Forcing them to switch is associated with a large loss of productivity and hence wages for these workers when the elasticity is low.

Figures 4 and 5 show the results for the alternative values of the elasticities of substitution between electricity and fossil fuels, and between the energy composite and other inputs. For the former, changing the elasticities clearly does not affect our results much. In the latter case, GDP results are identical for all

values of elasticities considered. Labour compensation in a high elasticity (we consider the value of 1.5) is associated with a 0.04 percentage point higher loss in 2035, compared to the low elasticity case (the value of 0.5). This is because the ease of substituting energy with capital leads to a greater reduction in the consumption of fuels, which in turn leads to a greater reduction in demand for the sectors producing these fuels, necessitating a greater movement of workers between sectors. However, the results clearly show that the effect is temporary and its magnitude is small.

We also estimate the financial loss of income for miners using the methodology developed in Section 3.4. We trace the labour compensation for a group of workers who were employed in the mining sector in 2015. This includes workers who left the sector after 2015 and those who decided to stay. The loss is computed as a difference between labour compensation for that group in a given year and the compensation that group received in 2015. In 2030, the loss of those workers is \$0.57 billion (Figure 2) and in 2040 that loss grows to \$0.81 billion.

The estimates of losses of earnings produced by our model are likely to be biased upwards due to the imperfect treatment of dynamics in our setup. In particular, in our derivations we have assumed that all workers belong to one cohort. In reality, there are different cohorts with different transition costs. For

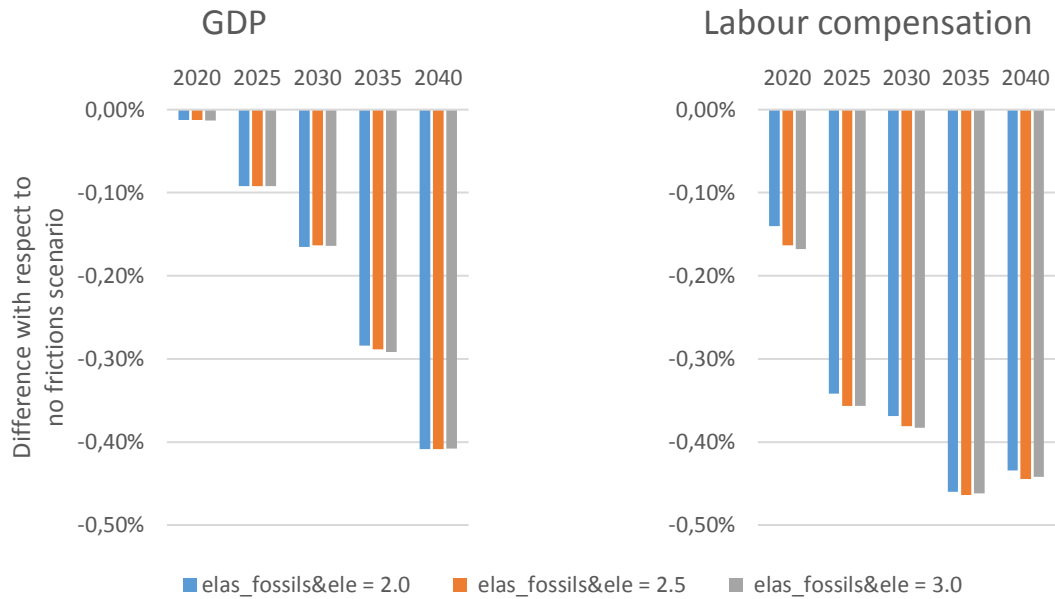


Figure 4. GDP (left panel) and labour compensation (right panel) loss in Poland due to frictional transition of labour between sectors (percentage difference between the frictionless decarbonisation simulation and the simulation with frictions throughout the transition) for the alternative assumptions regarding elasticity of substitution between fossils and electricity

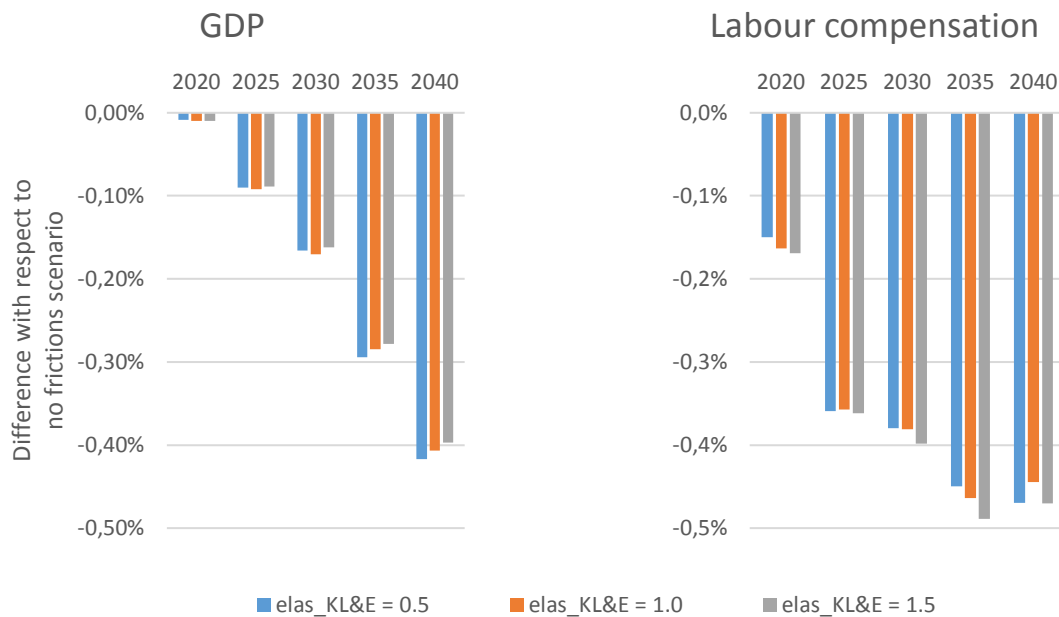


Figure 5. GDP (left panel) and labour compensation (right panel) loss in Poland due to frictional transition of labour between sectors (percentage difference between the frictionless decarbonisation simulation and the simulation with frictions throughout the transition) for the alternative assumptions regarding elasticity of substitution between energy composite and the capital-labour composite

example, workers who belong to cohorts that enter the labour market after the announcement of climate policy will avoid investing in skills that are only relevant for dirty sectors, so their transition costs

will be very low. If the climate policy is announced in the first year, the number of cohorts entering the labour market after the announcement of the climate policy will continue to increase over time. Therefore,

for years in the distant horizon, especially for 2040, the average transition costs are likely to be lower than those reported by our model.

5. Conclusions and Policy Discussion

Limiting climate change requires urgent and global action: a fundamental restructuring of production, changes in consumption patterns and wide adoption of new carbon-neutral technologies. All these changes imply a large number of new jobs, but also a loss of jobs related to production and use of fossil fuels. A number of workers will need to flow between sectors, especially in countries with large mining sectors.

In this paper we argued that the movement of labour induced by climate policy can be associated with substantial economic costs. We showed how the size of this cost is related to the slope of the labour supply curves at the sectoral level. Deriving this relationship allows us to model workers' costs of transition in a CGE framework by incorporating a system of sectoral labour supply curves. Subsequently, we calibrated the parameters of that system using elasticities of labour supply available in the literature and sectoral labour shares available in the national statistics. Finally, we used the model to estimate the workers' transition costs in Poland, which is the largest producer of coal in the European Union.

Our results suggest that the costs of transition in Poland will be increasing over time and reach 0.44% of labour compensation in 2040. While this figure appears manageable at the country level, it might be large enough to pose a significant political threat to the implementation of climate policy. Some workers would suffer much larger losses than others. The annual cost associated with the lost earnings for workers who were previously employed in the mining sector would amount to more than US\$0.8 billion (close to 0.4% of total labour compensation) in Poland in 2040. If these workers are not compensated, they will likely form a force opposing implementation of an ambitious climate policy. The simplest solution to this problem would be the establishment of a fund that would compensate the most affected workers and hence spread the costs of the transition more equally.

The European Union has identified the challenges associated with transitioning to a low-carbon economy

and has established the Just Transition Fund (JTF) to support regions most impacted by this transition. With a budget of €19.7 billion allocated for the 2021–2027 period, the JTF is intended to mitigate the socioeconomic effects of the transition by facilitating the development of regional economies. Specific measures include upskilling and reskilling of workers, investments in small and medium-sized enterprises, and initiatives to promote clean energy development. Poland, given its significant reliance on coal, is the largest recipient of these funds, with an allocation exceeding €3.85 billion to support its coal-dependent regions (European Commission, 2022) for the period 2021–2027, which implies an average annual budget of €0.55 billion (\$0.61 billion). During this period, the fund would be sufficient to compensate workers for lost earnings. If the fund remains at a similar level after 2027, it will enable compensating a significant part of the workers' losses.

In addition to the JTF, the EU has introduced complementary funding mechanisms aimed at advancing just transition objectives. The Modernisation Fund, for example, emphasises the modernisation of energy systems and the enhancement of energy efficiency in lower-income EU Member States. Furthermore, the Just Transition Mechanism comprises two additional components: InvestEU, which is designed to promote sustainable investment, innovation, and job creation; and the Public Sector Loan Facility, which seeks to stimulate public investment in relevant areas.

It is noteworthy that these EU policy instruments do not include direct financial compensation for workers. Instead, their primary focus is on building a conducive economic environment to deliver long-term benefits for affected regions. Among these policies, addressing skills deficits is particularly relevant for workers, as it aims to improve their employment prospects through targeted training and educational initiatives. The OECD's 2024 Employment Outlook (OECD, 2024) emphasises the necessity of equipping workers with skills aligned with the demands of emerging green sectors. Workers in carbon-intensive industries, who tend to have lower participation rates in training programs, require targeted interventions to improve their employability. On the other hand, the transferability of specific skills, such as those in electrical, mechanical, and safety compliance areas, from coal-based employment to roles in the solar and wind energy sectors further underscores the potential for such transitions (Alves Dias et al., 2018). EU funding

instruments can be utilised to support upskilling and reskilling initiatives. These instruments include the Education Guarantee Pilot, the Recovery and Resilience Facility, REACT-EU, and the European Social Fund Plus (European Commission, 2024).

While active labour market policies may not produce immediate outcomes, empirical evidence indicates that they can generate favourable employment effects over the longer term, particularly during periods of economic recession (Card et al., 2017). Additionally, research highlights the efficacy of wage insurance schemes – temporary subsidies to supplement earnings of displaced workers – in facilitating transitions to new employment (Cahuc, 2018). Finally, social dialogue mechanisms play a crucial role in achieving a just transition. By fostering collaboration among governments, labour unions, and employers, these mechanisms promote inclusive decision-making, address workers' concerns, and balance economic, social, and environmental priorities (Galgóczi, 2020).

In addition, transition costs could be reduced by reducing the uncertainty associated with their job search. This could be achieved, for example, by encouraging the mobility of whole groups of workers (e.g., entire branches of companies) from mining activities to carbon-neutral activities. This would ensure that the transition is managed by managers and not individual workers who might not have sufficient knowledge regarding anticipated structural change and the prospects of various career options.

The design and evaluation of particular policy instruments would require detailed analysis that goes beyond the scope of this paper. Our goal in this study was to provide a quantitative analysis of the costs of the transition to a carbon-neutral future as perceived by workers as well as a theoretical basis for future work in this field. The preliminary quantitative evidence suggests that the size of the cost could be substantial indeed, and the topic deserves further attention from the research community.

The theoretical setup in this study was derived under several assumptions that are unlikely to hold in real life: inelastic aggregate labour supply, no unemployment and no intertemporal optimisation by workers. Lifting these assumptions could potentially alter some of the predictions and will certainly affect the quantitative results. Extending the framework to include a larger number of key features of the labour market would be an interesting area for future research.

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Appendix A1. Detailed Derivations for Section 3.4

The purpose of this appendix is to provide detailed derivations of the amount of efficiency units that belongs to workers from who would be employed in sector j in the reference scenario and who are employed in sector l in the policy scenario. To simplify exposition, in the derivations we will assume $\mu=1$.

Consider the amount of efficiency unit in sector l . The total change in efficiency units for this sector is

$$s_l \left(\frac{s_l \bar{w}_l}{\left(\sum_k (\bar{w}_k s_k)^\alpha \right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} - s_l \left(\frac{s_l w_l}{\left(\sum_k (w_k s_k)^\alpha \right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} \quad (\text{A1})$$

This must be decomposed into: (i) inflow of workers from sector j due to changes in wage, w_j , (ii) inflow/outflow of workers from/to other sectors due to changes in other wages, (iii) correction of (i) due to changes in other wages, (iv) correction of (ii) due to changes in mining wages.

(i) If only mining wage change, the change in efficient labour in Sector j would be

$$s_l \left(\frac{s_l \bar{w}_l}{\left(\sum_{k \neq j} (\bar{w}_k s_k)^\alpha + (w_j s_j)^\alpha \right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} - s_l \left(\frac{s_l \bar{w}_l}{\left(\sum_k (\bar{w}_k s_k)^\alpha \right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} \quad (\text{A2})$$

(ii) If only other wages change, the amount of efficient labour in Sector l would be

$$s_l \left(\frac{s_l w_l}{\left(\sum_{k \neq j} (w_k s_k)^\alpha + (\bar{w}_j s_j)^\alpha \right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} - s_l \left(\frac{s_l \bar{w}_l}{\left(\sum_k (\bar{w}_k s_k)^\alpha \right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} \quad (\text{A3})$$

The residual change constitutes (iii) and (iv). However, one would expect (iv) to be small in size as long as sector j is relatively small: among those who leave sector l to enter other sectors, few would consider moving to j (even if wages in sector j were constant) and therefore few are affected by changes in w_j . Hence, we ignore this effect, and we attribute the residual to (iii).

The total efficiency units in sector j that previously belonged to workers employed in mining is the total change less the effect in (ii):

$$\begin{aligned} & s_l \left(\frac{s_l w_l}{\left(\sum_k (w_k s_k)^\alpha \right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} - s_l \left(\frac{s_l \bar{w}_l}{\left(\sum_k (\bar{w}_k s_k)^\alpha \right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} \\ & - \left(s_l \left(\frac{s_l w_l}{\left(\sum_{k \neq j} (w_k s_k)^\alpha + (\bar{w}_j s_j)^\alpha \right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} - s_l \left(\frac{s_l \bar{w}_l}{\left(\sum_k (\bar{w}_k s_k)^\alpha \right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} \right) = \\ & s_l \left(\frac{s_l w_l}{\left(\sum_k (w_k s_k)^\alpha \right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} - s_l \left(\frac{s_l w_l}{\left(\sum_{k \neq j} (w_k s_k)^\alpha + (\bar{w}_j s_j)^\alpha \right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} \end{aligned} \quad (\text{A4})$$

Therefore, the total compensation for workers who were employed in the mining sector before the change is:

$$\begin{aligned}
 & w_j s_j \left(\frac{s_j w_j}{\left(\sum_k (w_k s_k)^\alpha \right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} \\
 & + \sum w_l s_l \left[\left(\frac{s_l w_l}{\left(\sum_k (w_k s_k)^\alpha \right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} - \left(\frac{s_l w_l}{\left(\sum_{k \neq j} (w_k s_k)^\alpha + (\bar{w}_j s_j)^\alpha \right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} \right] \quad (A5) \\
 & = N_j w_j + \left[1 - \left(\sum_{k \neq j} \frac{N_k w_k}{\sum_m N_m w_m} + \frac{\bar{N}_j \bar{w}_j}{\sum_m \bar{N}_m \bar{w}_m} \left(\frac{\sum_m \bar{N}_m \bar{w}_m}{\sum_m N_m w_m} \right)^\alpha \right)^{\frac{1}{\alpha}-1} \right] \sum_{l \neq j} N_l w_l
 \end{aligned}$$