Centre for Climate and Energy Analyses

How To Compute the Cost for Workers within the "Just Transition" to a Low-Carbon Future?

Working paper

Authors:

Jan Witajewski-Baltvilks, Jakub Boratyński, Robert Jeszke, Maciej Pyrka

LIFEClimateCAKEPL

KOBiZE

Warsaw, April 2022

IOŚ-PIB

AUTHORS AND COPYRIGHT

Jan Witajewski-Baltvilks, Jakub Boratyński, Robert Jeszke, Maciej Pyrka

This document was prepared in the Centre for Climate and Energy Analyses (CAKE) established in the National Centre for Emissions Management (KOBiZE), part of the Institute of Environmental Protection - National Research Institute (IOŚ-PIB).

This document was prepared within the scope of the project: "The system of providing and disseminating information in order to support the strategic implementation of the climate policy (LIFE Climate CAKE PL)" - LIFE16 GIC/PL/000031 – LIFE Climate CAKE PL.

If you have any comments or questions regarding this document, please contact: cake@kobize.pl.

The document was completed in March 2022.

Disclaimer: The findings, interpretations, and conclusions expressed in this document are those of the authors, and not necessarily of the organisation with which the authors are affiliated. This document is distributed in the hope that it will be useful, but the IOŚ-PIB shall not be held liable for any damage caused as a consequence of the use of its content.

This cover has been designed using resources from Freepik.com (ph.vector)

Contact:

Address:	Chmielna 132/134, 00-805 Warszawa
WWW:	www.climatecake.pl
E-mail:	cake@kobize.pl
Tel.:	+48 22 56 96 570
Twitter:	@climate_cake

The project "The system of providing and disseminating information in order to support the strategic implementation of climate policy (LIFE Climate CAKE PL)" is co-financed from the EU LIFE programme and the resources of the National Fund for Environmental Protection and Water Management.

Table of contents

List of abbreviations

AEA	Annual Emission Allocation
CAKE	Centre for Climate and Energy Analyses
CET	Constant Elasticity of Transformation
CGE	Computable general equilibrium model
COP	Conference of the Parties
CO_2 eq.	Carbon dioxide equivalent
EU	European Union
EU ETS	EU Emission Trading System
EUA	European Union Allowances allocated to the operators of stationary installations and used to account for emissions in the EU Emissions Trading System (EU ETS); 1 EUA = 1 t CO_2 eq.
GDP	Gross Domestic Product
GECO	Global Energy and Climate Outlook
GHG	Greenhouse gases
GTAP	Global Trade Analysis Project
KOBiZE	National Centre for Emissions Management
LULUCF	Land Use, Land Use Change and Forestry
OECD	Organisation for Economic Co-operation and Development
NDCs	Nationally Determined Contributions
Non-ETS	Sectors which are not covered by the EU Emissions Trading System (EU ETS)

Main conclusions

- **Low carbon transition requires a radical drop in production of coal and employment in the mining sector.**
- **We expect that workers in mining who are forced to move to other sectors will receive lower wages than they receive currently.**
- **First workers who leave mining are those who are indifferent between jobs in mining and jobs in the other sectors. Those who wait are those who expect that their future payoff in the other sectors is significantly lower than their current payoff in mining.**
- **We use the shape of sectoral labour supply curves to compute the loss of workers throughout the transition.**
- **The costs of transition in Poland will be increasing over time and reach 1% of total labour compensation in 2040.**
- **The cost associated with the loss of workers who were previously employed in the mining sector would amount to 0.5% of total labour compensation in Poland in 2040.**

Summary

1. In the paper we propose a novel methodology that allows to compute the loss of workers throughout the low-carbon transition. We use microeconomic theory supported with empirical evidence to argue that for many workers in mining sector their current payoff in mining is significantly larger than their potential payoff in other sectors. Next, we incorporate our framework in a numerical economic model to compute the loss of workers throughout the low-carbon transition in Poland. We find that the costs of transition in Poland will be increasing over time and reach 1% of labour compensation in 2040. The cost associated with the loss of workers who were previously employed in the mining sector would amount to more than US$1.1B, close to 0.5% of total labour compensation in Poland in 2040.
2. Computable General Equilibrium (CGE) models predict that the transition to a low-carbon future generates economic costs because low-carbon inputs cannot substitute for their carbon-intensive counterparts without loss of productivity. We argue that there is an additional cost of transition associated with the movement of labour across sectors. The cost arises whenever sectoral labour supply curves are not perfectly elastic and is substantial when curves are inelastic (which is suggested by the empirical literature). When supply is inelastic, i.e. does not respond greatly to changes in wages, it is likely because, for many workers, the opportunity costs of moving to a new sector are lower than their current wage. Hence, when workers are forced to move, they suffer loss. In this paper, we provide a formal framework linking loss of workers due to the transition to a low-carbon economy with the slope of the sectoral labour supply curve. We show how one can incorporate the system of supply curves into a standard CGE framework and use it to compute the loss of workers throughout the transition in climate policy scenarios.

1. Introduction

3. A transition to a low-carbon economy will be a boon for workers who find work in green industries and could be a disaster 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.
4. Workers in mining 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 to 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 that sector, 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.
5. 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 recognizes 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 plans to introduce the ‘Just Transition Fund’ to support affected workers (European Commission, 2020a). The compensation would be justified from the perspective of political economy since it could be necessary to win sufficient support for the climate policy.
6. The purpose of this paper is to support the debate on the design of just transition for workers by (i) explaining why workers from the phased-out sector can expect a reduction in wages according to economic theory and (ii) developing a methodology for computing what compensation would be required to balance the loss for workers in the mining sector, which is being phased-out due to climate policy. We propose a novel microfounded theoretical model that is able to account for sector-specific human capital of workers in the general equilibrium setting. In order to quantify the loss, we incorporate the structure of the theoretical model in the large-scale multisector numerical general equilibrium model. Finally, we perform simulations to project the size of the loss for workers due to climate policy. The calibrations and estimations will be performed for the Polish economy, which has the largest mining sector in the EU. 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.

7. The costs of transition for workers are recognized in descriptive studies; however, it was not yet studied extensively using formal economic modelling. The social issues associated with a fast transition are recognized 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 must be complemented by research that examines the key determinants of losses for workers using formal models grounded in microeconomic theory and that quantifies the losses using numerical macroeconomic models.

2. Why we can expect costs of transformation for workers

8. Empirical evidence suggests that workers cannot flow between sectors during major structural changes at no cost. Autor et al. (2016) examine the consequences of labour shifts across U.S. industries due to changes in the trade pattern. They found that it involved adjustment costs and had significant distributional effects. Baran et al. (2020) analyse the decline of the mining industry in Poland using microdata on employment. The study shows that only 35% of workers who left mining before retirement age found employment in another sector; the remaining part became unemployed or inactive. There is also empirical evidence suggesting that for a large share of workers, the value of a job in an alternative sector or location is low compared to the value of their current job. Booth and Katic (2011) examine the response of the labour supply in Australian firms after a change in wages. The evidence suggests that the number of workers scarcely changes (elasticity of supply at the level of 0.75). Similar value was found by Manning (2003) for the UK. If workers were not to face any cost, the elasticity would be infinite: a small drop in wages would cause a massive outflow to other sectors.
9. 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 (Fæhn et al., 2009; Devarajan et al., 2011; Baran et al., 2020). When wages are rigid, 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.
10. 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 (Devarajan et al., 2011; Chateau et al., 2018; OECD, 2018). In those models, low-skilled workers in all sectors receive lower wages if the carbon tax leads to a drop in demand for low-skilled labour. This approach, however, maintains the assumption that workers are homogeneous within an educational group. For instance, it does not consider

that miners with vocational education and long experience in mining will be less productive in other sectors (for example, transportation services) due to their sector-specific experience being rendered ‘useless’.

11. The third explanation is suggested by the theory of wage differentials, frequently used in models of international trade (see e.g. Jones (1971)). Those models assume that a worker who wishes to move to another sector must pay a cost, possibly fixed, which could be interpreted, for example, as a loss of productivity. These models assume, however, that the cost is the same for every worker.

12. Our analysis resembles the approach suggested in the theory of wage differentials. However, it takes it a step further by allowing the cost to depend on the size of the flow induced by the policy. When the policy induces a small flow of workers, only workers with small costs of transition will move. Conversely, when the policy induces a large flow, even workers with large costs must move. This novel setup allows for a more realistic modelling of labour market flows.

13. The argument underlying our approach is built upon the notion of opportunity cost and its variation among workers. Every worker compares his or her payoff for working in one sector versus that for working in other sectors. This payoff is determined by workers’ individual skills. Skills are formed by that workers’ education, on-the-job and outside job experience, personal traits and innate abilities. Importantly, skills can vary between workers. As a result, different workers could have different payoffs in the same sector. Also, since the payoffs are sector-specific, one worker could have different payoffs in different sectors.

14. The largest payoff the worker could obtain outside his or her current sector is the opportunity cost of the worker’s current choice. Since the payoffs vary across workers and sectors, the opportunity costs will likewise vary. For some workers, the opportunity cost could be very close to the value of the job in mining; perhaps such a worker detests working under difficult conditions or has qualifications allowing for a smooth transition to well-paid jobs in other sectors. For others, the opportunity cost could be much lower than the value of their current job. This could be the case for workers who believe that working in mining raises their social status in the local community (this case was considered in Baran et al. (2020)). They could also have qualifications that are very specific to the sector in which they are employed. They currently receive a high salary but would earn a very low salary if they were to change the sector in which they work.

15. For each worker, the difference between payoffs from working in mining and the opportunity cost constitutes the surplus that that worker receives from the possibility of working in mining. Since opportunity costs differ across miners, as noted above, the surplus will likewise differ. For some workers, the surplus is close to zero even before any climate policy is introduced. These workers could move smoothly to other industries with little or no cost. For others, the surplus is large. The sum of surpluses for all workers yields the total loss for workers due to mining sector phase-out. In the following section, we frame this argument in

a simple theoretical model and develop a methodology that facilitates the computation of the loss for workers due to transition.

3. Supply curves reflect costs of transition for workers

16. The costs of transition for workers can be computed using information contained in the system of labour supply curves at the sectoral level. Three features of the system will be particularly useful for us:

    - Supply curves are upward sloping.
    - Average efficiency of workers in a sector depends on the number of workers in that sector.
    - The parameters of the curves can be estimated using empirical data.

17. We discuss the role of these features in Section 3.1. Subsequently, in Section 3.2, we mathematically describe the simplest supply system that has all the features listed above, and in Section 3.3 we analyse its predictions regarding loss of welfare for workers after transition. In Section 3.4 we show that exactly the same system and exactly the same predictions can be obtained in CGE models by assuming a representative worker with a Constant Elasticity of Transformation (CET) constraint on distribution of labour across sectors.

3.1. System of labour supply curves at the sectoral level

18. Introducing the upward-sloping relationship between the supply of labour and wages in every sector in a model allows to differentiate, between sectors, the responses of wages to climate policies. Due to climate policy, carbon-intensive sectors will face larger cuts in demand than other sectors. To ensure that enough workers switch to other sectors, wages in their sectors must be low relative to wages in other sectors. This implies, however, that workers who stay in the carbon-intensive sector will face welfare loss.

19. Reductions in the wages of carbon-intensive sectors also have implications for the projected effectiveness of climate policy. Lower wages in these sectors imply lower costs of production and therefore a drop in output for any negative demand shock. For example, a carbon tax that reduces demand for coal will lead to lower wages for miners, lower mining costs, and therefore lower prices for coal. Although the tax eventually reduces demand for coal, the size of this reduction is lower than if we assume that wages in mining are constant.

20. CGE models that assume the same wage in every sector implicitly assume that supply of labour would drop to zero for sectors in which wages are lower than average even by a small

margin. This assumption contrasts with the results of empirical studies which suggest that only a small fraction of labour decides to leave sectors that experience wage cuts (see Section 4.1.2). This signifies that CGE, assuming a uniform wage, underestimates costs of climate policy and overestimates its effectiveness.

21. Another important feature of the supply system is that the relation between efficiency units of labour leaving one sector and entering another sector *is not* one-to-one and depends on the size of a structural change. For instance, miners who believe that their payoff in other sectors is similar to the one they currently have are indifferent about staying in or leaving the sector, and they move immediately after a small change in wages. We would anticipate that these workers would experience little change in their productivity since productivity is proportional to payoffs. In contrast, miners who move only when they experience a deep cut in wages are likely to believe that their payoff in other sectors is low. In this case, we would expect that their new productivity would be much lower than it was in mining. Furthermore, we would expect this outcome to be linked to the shape of the labour supply curve.

22. Finally, in order to quantify the loss of productivity for a given size of structural change, one would ideally 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 maximize their payoff, the supply curve reflects the distribution of opportunity costs of working in a given sector. When a reduction in wage from w' to w'' motivates a fraction s of workers to move, it follows that for the remaining $(1 - s)$ workers the highest payoff from work in another sector (the opportunity cost) must be lower than w''. For the s workers who moved, the opportunity cost 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 opportunity costs of marginal workers at any given wage level. Subsequently, we show how one could use this information to compute the total costs when one sector is phased out.

3.2. Efficiency units in each sector

23. Consider a worker who must decide between allocating his labour across K different sectors. His or her productivity could differ between sectors. More specifically, we assume that the worker possesses some amount of efficiency units in one sector and a potentially different amount of efficiency units in another sector. In addition, we allow workers to be heterogeneous; that is, in a given sector there could be workers with a different amount of efficiency units. We assume that wage per efficiency unit in sector k , w_k, is the same for all workers in that sector. Let $\mathrm{w} = (w_1, \dots, w_K)$ denote the vector of wages per amount of efficiency units for sectors $1, \dots, K$.

24. Let $n_j(\mathrm{w})$ be the share of workers who decide to work in sector j and let $N_j(\mathrm{w})$ be the sum of 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 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. To reflect this logic, we assume that the average amount of efficiency units in a sector, $\frac{N_j(\mathrm{w})}{n_j(\mathrm{w})}$, is given by $\frac{N_j}{n_j} = a_j n_j^{\gamma}$, where a_j and $\gamma < 0$ are parameters (which we will soon determine using the parameters of the supply curve).

25. Next, we specify the shape of the supply curve, $n_j(\mathrm{w})$. Since n_j represents the share of workers, we must choose a function that satisfies $\sum_j n_j(\mathrm{w}) = 1$. Ideally, we would also choose a function that permits constant elasticity of the labour supply, $\frac{d \ln n_j}{d \ln w_j}$. 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 no sector dominates (a condition which is usually satisfied in any CGE model):

$$n_j = \frac{(s_j w_j)^{\alpha}}{\sum_k (s_k w_k)^{\alpha}} \tag{1}$$

where s_j is a parameter.

26. Now two sectors, j and k, are considered. After a small 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 compensation in the two sectors must be equal. To compute that compensation, we must first compute the amount of efficiency units of the marginal worker in both sectors. That worker leaving sector j causes the total amount of efficiency units in that sector to drop by $\frac{dN_j}{dn_j} = a_j(1+\gamma)n_j^{\gamma}$. When that worker enters sector k, the total amount of efficiency units in k increases by $\frac{dN_k}{dn_k} = a_k(1+\gamma)n_k^{\gamma}$. Equating that worker's compensation in both sectors:

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

At the same time, comparing the supply curves for j and k results in:

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

27. Since we assume that a_j and a_k are constant (independent of w), then it is necessary that $\gamma = -\frac{1}{\alpha}$ and $\frac{a_j}{a_k} = \frac{s_j}{s_k}$. Since s_j can be normalized, then $a_j = s_j$.

Clearly, $\gamma < 0$ for any upward-sloping supply curve.

28. The resulting system of supply curves expressed in terms of efficiency units is given by

$$N_j = a_j n_j^{\gamma+1} = s_j \left(\frac{(s_j w_j)^{\alpha}}{\sum_k (s_k w_k)^{\alpha}} \right)^{\frac{\alpha-1}{\alpha}} \quad (2)$$

3.3. Recovering costs of phase-out from supply curve

29. Forcing each worker to leave a sector is equivalent to lowering her or his 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 force consecutive workers to leave, starting with the workers for whom the costs of leaving the sector are the smallest. Each time, the reduction in employment requires lowering wages by $\frac{dw_j}{dn_j}$. 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 for workers due to sector j phase-out is equal to

$$\int_{\bar{n}_j}^{0} N_j \frac{dw_j}{dn_j} dn_j$$

where $\bar{n}$ is initial labour supply.

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

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

3.4. CET supply system in CGE framework

31. 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 optimization 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 CET constraints on the distribution of labour across sectors.

32. 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:

$$\sum_j \left(\frac{N_j}{s_j}\right)^{\rho} = L \tag{3}$$

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).

33. 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:

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

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

$$\max_{\{N_j\}_{j=1}^{k}} \sum_j N_j w_j \tag{4}$$

subject to equation (3).

35. The optimal allocation satisfies the first order conditions for (4), given by

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

where λ is the shadow value of a marginal unit of endowment. Using the constraint, (3) we find that

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

and

$$N_j = s_j \overline{w}_j \left(\frac{(s_j)^{\frac{\rho}{\rho-1}}(w_j)^{\frac{1}{\rho-1}}}{\left(\sum_k (s_k w_k)^{\frac{\rho}{\rho-1}}\right)^{\frac{1}{\rho}}}\right)^{\frac{1}{\rho-1}} \tag{5}$$

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

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

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

$$\left(\sum_k (s_k \overline{w}_k)^{\frac{\rho}{\rho-1}}\right)^{\frac{\rho-1}{\rho}} - \left(\sum_{k\neq j} (s_k w_k)^{\frac{\rho}{\rho-1}}\right)^{\frac{\rho-1}{\rho}}$$

37. Note that these predictions are exactly the same as in Section 3.3, as long as $\alpha = \frac{\rho}{\rho-1}$.

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

$$\sum_k N_k(\overline{\mathrm{w}})\overline{w}_k - \sum_k N_k(\overline{\mathrm{w}}) w_k = \left(\sum_k (s_k \overline{w}_k)^{\frac{\rho}{\rho-1}}\right)^{\frac{\rho-1}{\rho}} - \left(\sum_k (s_k w_k)^{\frac{\rho}{\rho-1}}\right)^{\frac{\rho-1}{\rho}}$$

3.5. Tracing workers and computing loss by sector

39. In Section 3.3 we demonstrated how one could use information on the system of supply curves to compute the 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.

40. 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.

41. 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.

42. In the reference scenario at time t, the total compensation of workers employed in sector j can be expressed using (5) by

$$N_j(\overline{\mathrm{w}})\overline{w}_j = s_j\overline{w}_j\left(\frac{\left(s_j\overline{w}_j\right)^{\alpha}}{\left(\sum_k (s_k w_k)^{\alpha}\right)^{\frac{1}{\alpha}}}\right)^{\alpha-1}$$

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

44. 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 $N_j(\mathrm{w})$, and their compensation is

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

45. 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:

$$s_l\left(\frac{s_l w_l}{\left(\sum_k (s_k w_k)^{\alpha}\right)^{\frac{1}{\alpha}}}\right)^{\alpha-1} - s_l\left(\frac{s_l w_l}{\left(\sum_{k\neq j}(s_k w_k)^{\alpha} + \sum_k \left(s_j\overline{w}_j\right)^{\alpha}\right)^{\frac{1}{\alpha}}}\right)^{\alpha-1}$$

46. This approximation is built on the assumption that there are few workers who move to or away from sector l due to changes in wages within sector j. In theory, when relative wages in the two sectors change and workers flow between them, the size of the flow can be determined in two steps: first, by checking the change in relative size of the two sectors and, second, by applying the new ratio to the new absolute size of one of the sectors. The relative size is determined only by relative wages in the two sectors, but the absolute size is determined by the entire vector w, including the wage in sector j. In practice, however, the impact of w_j on the size of other sectors and, through this channel, on the movement of labour between them will be negligible if sector j is small relative to the total economy. We provide a more detailed derivation and discussion of this approximation in the appendix.

4. Quantitative results

47. The first step in quantifying the predictions of the model and the loss 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 optimization problems involving firms and consumers captured by the CGE model, allows the endogenization of wage vectors that until now remained exogenous in our analysis. In Section 4.2 we provide some details on the large CGE modelling framework that we will utilize for these purposes. Subsequently, in Section 4.3, we present the set of policy scenarios analysed to quantify workers' losses. Finally, in Section 4.4, we provide quantitative predictions for our study.

4.1. Calibration of labour module parameters

48. The supply system has $K+1$ parameters: K share parameters (s'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

49. In order to evaluate labour compensation by sector as a function of parameters, we can use equation (2):

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

50. The total compensation can then immediately be evaluated as:

$$\sum_j N_j w_j = \left(\sum_k (s_k w_k)^{\alpha}\right)^{\frac{1}{\alpha}}$$

51. Using these two expressions as well as information on labour compensation, we can uniquely determine $s_j w_j$:

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

52. Note that in the model we can normalize every sectoral wage to unity by choosing appropriate values for s_j.

4.1.2. The calibration of elasticity parameter

53. 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 (1)) and the relation between wages and supply of labour expressed in efficiency units (equation (2)). 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 3.2 show that the slopes of the two curves are different, but the relation between the two can easily be determined.

54. 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 in mind this distinction when calibrating the parameter α. In particular, we need to use empirical supply curves obtained from analysing the response of labour supply to wage shocks for workers, e.g. 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.

55. The elasticity parameter α in equation (1) 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 (1)) and therefore elasticity of labour supply predicted by equation (1) is equal to α.

56. We can obtain the value of the elasticity of labour supply at the sectoral level from two strands of literature: one that estimates the elasticity for monopsonies and one that estimates the elasticity of separation rate with respect to wages at the firm level. The elasticity for monopsonies was estimated using survey data by Booth and Katic (2011) who obtained estimates in the range 0.71–0.75. These could be treated as short-run elasticity, not taking into account natural attrition, and thus can be treated as a lower bound. The long-run elasticity of supply can be computed from the elasticities of separation rate. Specifically, Manning (2003) argues that the long-run elasticity should be exactly twice the elasticity of separation rate. The empirical literature estimating the elasticity of separation at the firm level was reviewed by Shenfelter (2010), who finds the values in the range 1.5–4, which implies that the elasticity of supply at the firm level is in the range 3–8. Since the elasticity is likely to be larger at the firm level than at the sectoral level, these values can be treated as an upper bound. The most likely value is therefore in the range 0.7–8. We selected the value 2 as a compromise.

4.2. Computable General Equilibrium Model

4.2.1. Key model features

57. The d-PLACE model is a recursive dynamic, global CGE model. It has been developed at the Centre for Climate and Energy Analyses (CAKE in its Polish acronym) installed in The National Centre for Emissions Management (KOBiZE), which is a part of the Institute of Environmental Protection – National Research Institute (IOŚ - PIB). The d-PLACE model is based on the static CGE model known as PLACE, which was created by the Centre for Climate Policy Analysis in 2013–2016.

58. The d-PLACE model was developed to examine the impact of energy and climate policy on the economy up to the year 2050. The global dimension of the model enables the analysis of emission abatement by distinguishing states and regions. For EU member states, the model includes emission reduction targets in the EU ETS (European Union Emissions Trading Scheme) and non-ETS sectors. The model also includes emission reduction measures for regions outside the EU, which have been derived from the NDCs (Nationally Determined Contributions) submitted under the Paris Agreement. The d-PLACE model makes it possible to analyse relative emission abatement potentials across regions, as it takes into account region-specific production technologies and consumption patterns. It gives a cost-minimization perspective on environmental and climate policy objectives as well as a comparison of burdens between regions.

59. The model also allows for a detailed modelling of greenhouse gas emissions (GHG). Emissions from the combustion of fuels and process emissions are modelled explicitly. Similarly, the use and supply of fossil fuels such as coal, gas and oil are explicitly modelled. Industries and representative consumers adjust their energy mix in response to changes in relative prices of different fuels (including the cost of emissions) and electricity. Additionally, producers may substitute energy for capital (equipment). The production process is modelled using nested constant elasticity of substitution and Leontief production functions.

60. To investigate the impact of energy and climate policy on the economy up to 2050, the model distinguishes 20 sectors/commodities including energy intensive industries such as electricity and heat generation, refined oil, chemicals, non-metallic minerals (e.g. cement-lime-gypsum, glass), paper–pulp, iron and steel, and aluminium and mining.

4.2.2. Calibration of sectoral structure

61. The d-PLACE model is solved in a recursive-dynamic manner, in 5-year steps, until 2050 (with the exception of the first step which is one year from 2014 to 2015). GTAP-10 (Global Trade Analysis Project) data have been used for benchmark calibration, i.e. they represent the initial state of the world economy in 2014. The decarbonization scenario (until 2050) conforms with external projections of GDP growth rates by country, fossil fuel prices at world-region level, and the emission limits for the EU and regions in the rest of the world.

4.3. Scenario description

62. In the decarbonization scenario, we assume implementation of the EU’s climate policy targets for GHG emission reductions by 20% in 2020 and by 40% in 2030 relative to 1990. These targets concern emissions from all sectors. Additionally, we define long-term targets to place the EU on the path toward achieving a low-carbon economy in the future. Our proposal for EU progress in cutting emissions is in line with the 2050 EU long-term strategy (EC, 2018). We assumed GHG emission reductions by 60% in 2040 and by 80% in 2050 relative to 1990.

63. Total GHG emission reductions are allocated among sectors covered by EU ETS and non-ETS. Emissions in the EU ETS are to be reduced by 21% in 2020, 43% in 2030, 65% in 2040 and 85% in 2050 relative to 2005. The non-ETS sectors would need to cut emissions by 10% in 2020, 30% in 2030, 50% in 2040 and 75% in 2050 relative to 2005.

Table 1: Total GHG emissions reduction with separate targets for EU ETS and non-ETS for EU-28 in the decarbonization scenario

Year	Total GHG emissions reduction	Emission reduction target in EU ETS	Emission reduction target in non-ETS
	compared to 1990	compared to 2005	compared to 2005
2030	53%	60%	40%
2040	76%	83%	67%

Source: CAKE/KOBiZE

64. The implemented climate policy scenario and the assumed GHG reductions targets are the same as for 'Neutrality scenario (NEU)' from the CAKE/KOBiZE study 'Poland net-zero 2050, the roadmap toward achievement of the EU climate policy goals in Poland by 2050', Warsaw, June 2021. In the climate policy scenario, the total reduction of GHG emissions results from the amended EU climate policy (European Commission, 2020b) assuming an increase in the net reduction target for 2030 to 55% as compared to 1990 emissions and maintaining efforts to achieve net zero emissions by 2050, i.e. considering removals from the LULUCF sector. This level of GHG emission reductions contributes to the EU's goal in the Paris Agreement to strive to limit global temperature change by 1.5°C (European Commission, 2018a, 2020c). Without including removals, the assumed implementation of the EU's climate policy targets for GHG emission reductions is estimated to be 53% in 2030 and 76% in 2040 relative to 1990. These targets concern emissions from all sectors. We define a long-term 2040 target to put the EU on the path toward achieving climate neutrality by 2050. Our proposal for EU progress in cutting emissions is in line with the 2050 EU long-term strategy (European Commission, 2018a).

65. Total GHG emission reductions are allocated among sectors covered by EU ETS and non-ETS. In the climate policy scenario, the distribution of reduction targets between the EU ETS and non-ETS sectors for 2030 was largely based on the impact assessment presented in September 2020 for the EC communication: 'Stepping up Europe's 2030 climate ambition' (European Commission, 2020d) and emission reduction path in the EC GECO2020 projection for the 1.5°C scenario (European Commission, 2020c). We calculated that emissions in the EU ETS are to be reduced by 60% in 2030 and 83% in 2040. The non-ETS sectors would need to cut emissions by 40% in 2030 and 67% in 2050 relative to 2005.

66. The model contains information on the supply of emission allowances on the EU ETS market. In the EU ETS, one EU-wide emission limit is set. The solutions adopted in the EU ETS enable free flow of emission allowances between sectors as well as between the EU member states. In the d-PLACE model, sectors included in the EU ETS are not allowed to emit more CO2 equivalents than the total number of emission allowances in each year. The total number of emission allowances results from the imposed reduction targets.

67. In non-ETS sectors, according to the Effort Sharing Regulation (European Parliament, 2018b), the overall EU’s emission reduction is converted into national emission reduction targets in 2030 and for member states in 2040. For member states, the redistribution of the reduction effort in non-ETS was based on the GDP per capita following the Effort Sharing Regulation (European Parliament, 2018b). Less wealthy states were assigned less ambitious targets due to potentially higher economic growth in the future and their lower investment capacity today. It was assumed that the national targets for the EU member states are ranging from 10% to 50% for the year 2030 and from 35% to 75% for the year 2040 compared to 2005 emissions. For Poland, the reduction target in the non-ETS is assumed to be -18% and 46% compared to 2005 emissions for the years 2030 and 2040, respectively. The paths toward reaching the proposed reduction targets are defined by emission limits in AEA (Annual Emission Allocation) - units used for the accounting of national annual emission limits from non-ETS sectors (1 AEA = 1 t CO2 eq.). These AEA limits are set individually for each member state and results from adopted national reduction targets. Under the Effort Sharing Regulation (European Parliament, 2018b), EU member states are required to reduce their GHG emissions and meet binding annual emission limits. Emission limits for member states were aggregated to the EU regions analysed in the scenario.
68. We assume that regions outside the EU considered in the modelling scenario will adopt binding emission limits/reduction targets included in the NDCs submitted under the Paris Agreement. GHG reduction targets for regions outside the EU were estimated based on the GHG emission projection in 2030 and 2040 from the EC GECO2020 (European Commission, 2020c) projection for the ‘New Normal’ scenario.

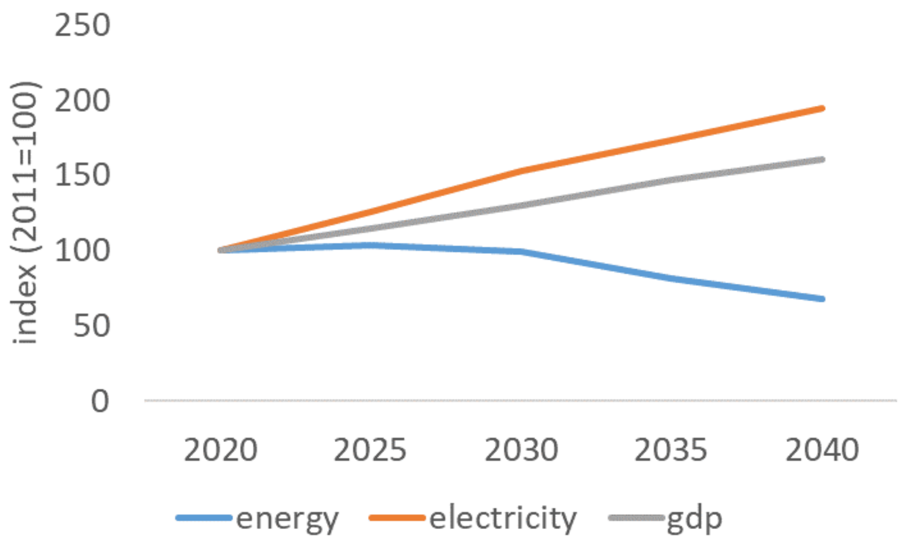
4.4. Numerical results

69. In this section we present the numerical predictions of the model for the decarbonization policy simulation. In Section 4.4.1, we present the key predictions on structural change, fuel demand and the main macroeconomic indicators in Poland in the simulation with labour market frictions. In Section 4.4.2, we compare the outputs of the model in the simulations with and without frictions.

4.4.1. Structural change due to climate policy

70. The reduction of emissions in European Union will be accompanied by a substantial structural change in the Polish economy. The first key change is a substantial increase in energy efficiency. Throughout the period 2020-2040, energy consumption will drop by 32%, while GDP will increase by 68% during the same period (see Figure 1). The reduction in energy use will be mostly driven by a drop in the use of fossil fuels. Demand for electricity will double by 2040 due to electrification of transport and industry.

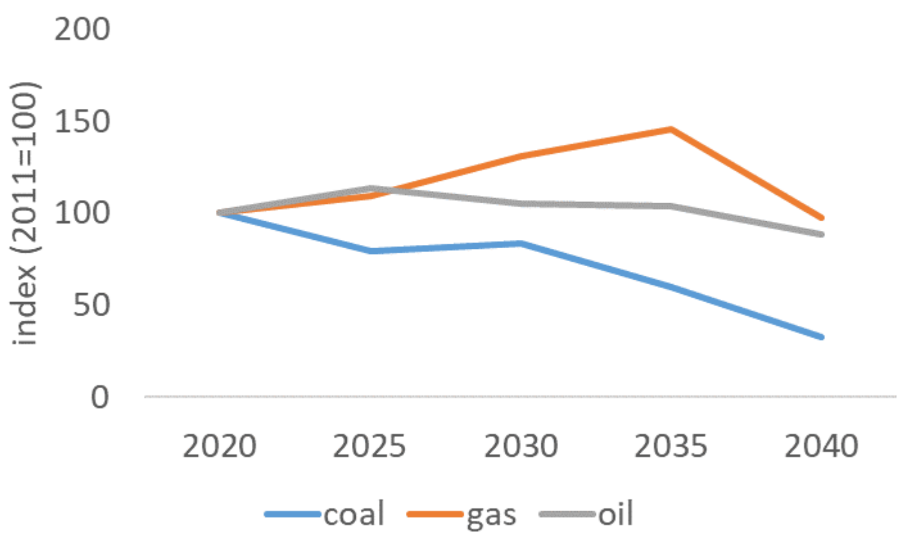
Figure 1: GDP, energy supply and electricity dynamics in the decarbonization simulation with labour market frictions in Poland



Source: CAKE/KOBiZE

71. The second major change in the economy is the change in the fuel mix in the Total Primary Energy Supply. The projections suggest a moderate drop in use of oil (by 12% between 2020 and 2040), which is driven primarily by the falling demand from the transport sector. Gas will play the role of a transitory fuel with an increase in use by 2035 and a subsequent decline. By 2040, demand for gas will be comparable to the demand in 2020. The most fundamental change for the Polish economy will be a drop in the consumption of coal. Relative to the level in 2020, the decline in coal consumption will be 17% by 2030, 40% by 2035, and by 2040 it will be 68% (see Figure 2).

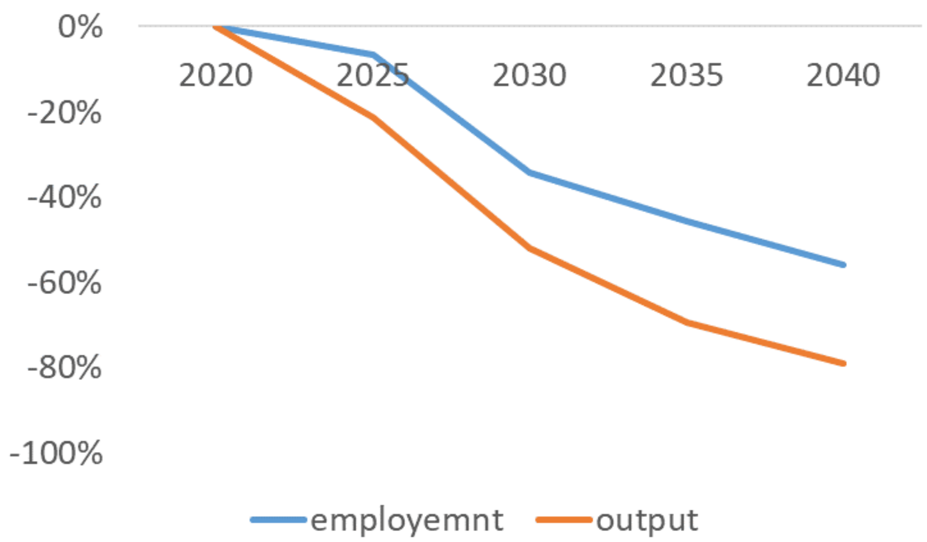
Figure 2: Dynamics of fuel consumption in the decarbonization simulation with labour market frictions in Poland



Source: CAKE/KOBiZE

72. A drop in demand for coal translates to a significant drop in the production of coal by domestic producers and in employment in that sector. Relative to the 2020 level, the output from the mining sector will fall 53% by 2030 and 80% by 2040 (see Figure 3). Because labour substitutes capital, the drop in employment in the sector is slower: it will fall by 38% in 2030 and by 62% in 2040. As explained in Sections 2 and 3, such a dramatic drop in employment in the mining sector implies a drop in productivity and the wages of workers who are forced to move to other sectors. In the next section, we quantify this loss.

Figure 3: Dynamics of output and employment in the mining sector in Poland in the decarbonization simulation with labour market frictions



Source: CAKE/KOBiZE

4.4.2. Loss due to frictional transition

73. In order to compute the loss 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; that is, every worker who leaves 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 and the transition has no cost for workers. In the second simulation, we take into account the loss of productivity due to the effects that are described in Sections 2 and 3.

74. Inspection of the results under the two simulations suggest that the structural changes in both are almost identical. We observe the same changes in output, in demand for electricity and fuels, and in employment in the mining sector. However, the results of the two simulations differ in the projections of macroeconomic variables, i.e. GDP and compensation of labour.

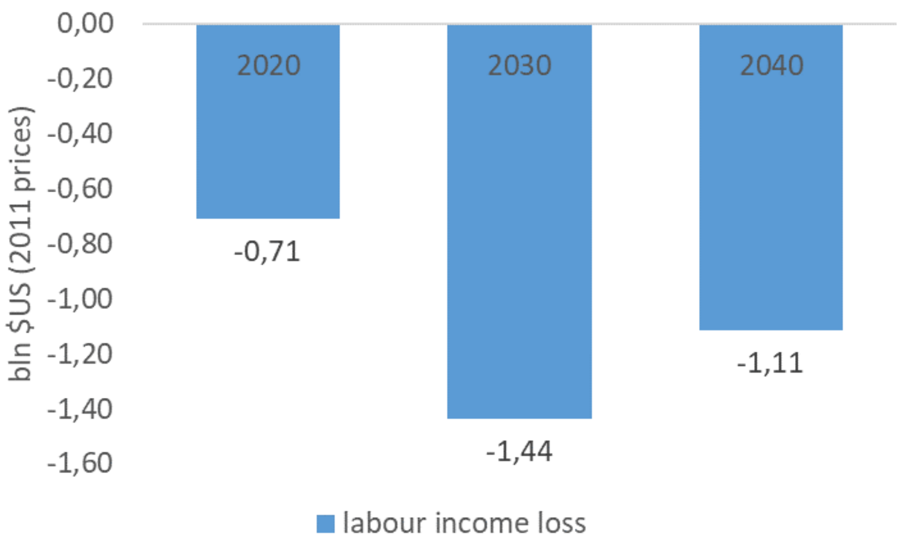
75. The differences in compensation of employees and the GDP are depicted in Figure 4. In 2030, accounting for the loss of labour productivity due to frictional transition reduces the total compensation of labour by 0.76% relative to the case when the loss is ignored. In 2040, the loss increases to 1.05%. 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 0.46%.

Figure 4: GDP and labour income loss in Poland due to frictional transition of labour between sectors (percentage difference between the frictionless decarbonization simulation and the simulation with frictions throughout the transition)

Source: CAKE/KOBiZE

76. The monetary value of the loss for workers due to frictional transition is presented in Figure 5. As explained in Section 3, the loss is computed as a difference in total labour compensation between the two simulations. In the years 2015–2020, the loss is approximately US$1B (at 2011 prices) per annum. In 2030, the annual loss is at the level of $1.44B, and in 2040 it reaches $1.11B. In 2030, the loss of workers who would be employed in mining within the scenario of no climate policy is $0.15B. In 2040 that loss grows to $0.54B. This figure is the sum of the loss of workers who left the sector and those who decided to stay.

Figure 5: Income loss for workers in Poland due to frictional transition of labour between sectors (absolute difference between frictionless decarbonization simulation and the simulation with frictions throughout the transition)



Source: CAKE/KOBiZE

5. Conclusions and policy recommendations

77. 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.

78. 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.

79. Our results suggest that the costs of transition in Poland will be increasing over time and reach 1% 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 cost associated with the loss of workers who were previously employed in the mining sector would amount to more than US$1.1B (close to 0.5% 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.

80. In addition, the costs of transition could be reduced by improving flexibility for workers and reducing the uncertainty related to their job search. Flexibility could be improved by access to job advisors and training as well as investments in public transportation, which would facilitate the mobility of workers. The uncertainty could be reduced by encouraging the movement of entire 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.

81. 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 low-carbon 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.

References

1. Autor, D.H., Dorn, D., Hanson, G.H., 2016. The China shock: Learning from labor30 market adjustment to large changes in trade. Annual Review of Economics Volume: 8(1), Pages 205–240, October
2. Baran, J., Szpor, A. and Witajewski-Baltvilks, J., 2020. Low-carbon transition in a coal-producing Country: A labour market perspective. Energy Policy, 147, 111878. https://doi.org/10.1016/j.enpol.2020.111878
3. Booth, A. L. and Katic, P., 2011. Estimating the wage elasticity of labour supply to a firm: What evidence is there for monopsony? Economic Record, Volume 87(278), Pages 359–369. https://doi.org/10.1111/j.1475-4932.2011.00728.x
4. Brauers, H., Herpich, P., Oei, P.-Y., 2018. The transformation of the german coal sector from 1950 to 2017: An historical overview. In: Gerbaulet, C., Kemfert, C., Lorenz, C., Oei, P.-Y. (Eds.), Energiewende Made in Germany Electricity Sector Reform in the European Context. Springer International Publishing AG, Berlin, Germany.
5. Chateau, J., R. Bibas and E. Lanzi, 2018. Impacts of Green Growth Policies on Labour Markets and Wage Income Distribution: A General Equilibrium Application to Climate and Energy Policies. OECD Environment Working Papers, No. 137, OECD Publishing, Paris
6. Devarajan, S., Go, D.S., Robinson, S., Thierfelder, K., 2011. Tax policy to reduce carbon emissions in a distorted economy: illustrations from a south africa cge model. The B.E. Journal of Economic Analysis and Policy, Volume: 11(1), Pages1–28, October
7. European Commission 2018a, In-depth analysis in support of the Commission Communication, European Commission, Brussels, 28 November 2018 COM(2018) 773
8. European Commission 2020b, Proposal for a Regulation of the European Parliament and of the Council establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law), European Commission, Brussels, 4.3.2020 COM(2020) 80 final.
9. European Commission 2020d, Impact Assessments accompanying the document "Stepping up Europe's 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people ", European Commission, Brussels, 2020, SWD (2020) 176 final.
10. European Commission, 2020a. Commission Welcomes the Political Agreement on the Just Transition Fund. Press Release, December 2020. https://ec.europa.eu/commission/presscorner/detail/en/ip_20_2354 [Accessed 31 January 2022].
11. European Commissiont, 2020c - Global Energy and Climate Outlook 2020 Energy, Greenhouse gas and Air pollutant emissions balances. European Commission, Joint Research Centre (JRC) [Dataset] PID: http://data.europa.eu/89h/1750427d-afd9-4a10-8c54-440e764499e4, European Commission, Joint Research Centre, 2020.
12. European Parliament, 2018b. Regulation (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (EU) No 525/2013
13. Fæhn, T., Gomez-Plana, A.G., Kverndokk, S., 2009. Can a carbon permit system reduce spanish unemployment?. Energy Economics. Elsevier, Volume 31(4), 595–604, July.
14. Jones, Ronald W., 1971. Distortions in Factor Markets and the General Equilibrium Model of Production. Journal of Political Economy, Vol. 79, No. 3 (May - Jun., 1971), Pages 437-459
15. Manning, A., 2003. Monopsony in motion: Imperfect competition in labor markets. New Jersey: Princeton University Press.

16. Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O’Neill, B. C., Fujimori, S., ... & Sartor, O. (2018). Implementing coal transitions. Insights from case studies of major coal-consuming economies. IDDRI and Climate Strategies.
17. Sartor, O., 2018. Implementing Coal Transitions: Insights from Case Studies of Major Coal-Consuming Economies. IDDRI and Climate Strategies.
18. Skoczkowski, T., S. Bielecki, M. Kochański, K. Korczak, 2020. Climate-change induced uncertainties, risks and opportunities for the coal-based region of Silesia: Stakeholders' perspectives. Environmental Innovation and Societal Transitions, Elsevier, Volume 35, 2020, Pages 460-481, ISSN 2210-4224,
19. Spencer, T., Colombier, M., Sartor, O., Garg, A., Tiwari, V., Burton, J., Caetano, T., Green, F., Teng, F., Wiseman, J., 2018. The 1.5◦C target and coal sector transition: At the limits of societal feasibility. Climate Policy, Volume 18(3), Pages 335–351.

Appendix: Detailed derivations of compensation for workers who were previously employed in mining

Total change in efficiency units for this sector is

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

This must be decomposed into: (i) inflow of workers from mining due to changes in mining wages, (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 i would be

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

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

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

The residual change constitutes (iii) and (iv). However, one would expect (iv) to be small in size: among those who leave sector *j* to enter other sectors, few would consider moving to mining (even if wages in mining were constant) and therefore few are affected by changes in mining wages. 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):

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

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

$$s_l\left(\frac{s_l w_l}{\left(\sum_k (w_k s_k)^\alpha\right)^{\frac{1}{\alpha}}}\right)^{\alpha-1} - s_l\left(\frac{s_l w_l}{\left(\sum_{k\neq j} (w_k s_k)^\alpha + (\overline{w}_j s_j)^\alpha\right)^{\frac{1}{\alpha}}}\right)^{\alpha-1}$$

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

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

$$+\sum w_l s_l\left[\left(\frac{s_l w_l}{\left(\sum_k (w_k s_k)^\alpha\right)^{\frac{1}{\alpha}}}\right)^{\alpha-1} - \left(\frac{s_l w_l}{\left(\sum_{k\neq j} (w_k s_k)^\alpha + (\overline{w}_j s_j)^\alpha\right)^{\frac{1}{\alpha}}}\right)^{\alpha-1}\right] =$$

$$= N_j w_j + \left[1 - \left(\sum_{k\neq j}\frac{N_k w_k}{\sum_m N_m w_m} + \frac{\overline{N}_k \overline{w}_k}{\sum_m \overline{N}_m \overline{w}_m}\left(\frac{\sum_m \overline{N}_m \overline{w}_m}{\sum_m N_m w_m}\right)^\alpha\right)^{\frac{1}{\alpha}-1}\right]\sum N_l w_l$$