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Distributional effects of emission pricing in a carbon-intensive economy: The case of Poland[☆,☆☆]

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ABSTRACT

We assess the distributional impact of introducing a carbon tax in a small open economy, using the case of Poland. We use a dynamic general equilibrium model with a search mechanism in the labour market, soft-linked to a microsimulation model based on household budget survey data. We evaluate the impact on various income groups and on inequality. We account for four key channels: the direct (energy) and indirect (other goods) price effects, behavioural adjustment of consumption, and changes in labour income. We consider three of ways to recycle the carbon tax revenue: lump-sum transfer, energy price subsidies, and labour tax reduction. We find that the distributional effects depend on the recycling of revenues. Using them to reduce labor taxation attenuates the negative effect of carbon tax on GDP and employment but increases inequality compared to a lump-sum transfer to households. This finding highlights the trade-off between efficiency and equity. Our results could be relevant for other countries producing fossil fuels, such as South Africa, Germany, or Australia.

1. Introduction

The avoidance of potentially catastrophic consequences of climate change requires a substantial reduction in global CO_2 emissions. Pricing carbon emissions is one of the policy measures seen as essential for mitigating climate change. Several countries have implemented carbon pricing, either through a carbon tax or through a cap-and-trade system. While there are some differences between the two approaches (Goulder and Schein, 2013), economists have argued that such market-based measures are economically efficient since they incentivise limiting emissions in sectors in which the cost of doing so is the lowest. However, governments might be hesitant to implement such policies due to public acceptability issues and concerns about the social equity of carbon pricing (Sovacool et al., 2015). Distributional economic impacts - unequal effect on households with different levels of income - and consequences for income and social inequality are at the centre of such concerns.

The literature on the aggregate economic effects of carbon pricing is vast and shows that the potential net costs of carbon pricing are moderate (see IPCC, 2014), section 6.3.6.2). By contrast, the distributional effects of carbon pricing are still under-researched. However, their relevance for understanding and managing the economic and social challenges related to the transition to a carbon-neutral economy is growing.

In this paper, we study how labour market adjustments, price responses, and the behavioural reactions of households shape the distributional consequences of emission pricing in a carbon-intensive economy, using the case of Poland. We account for four redistributive channels. We pay particular attention to job loss and labour market adjustments in sectors with different carbon-intensiveness which is a key concern in countries with noticeable shares of jobs in coal producing or coal-intensive sectors.

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The first redistributive channel is the direct price effect. Since low-income households usually spend a larger share of their income on essential goods such as electricity and heating, a tax on emissions might disproportionately affect these families. The evidence in support for this view has been found among others in Brazil (da Silva Freitas et al., 2016), South Africa (Van Heerden et al., 2006), and France (Bureau, 2011).

The second redistributive channel is the indirect price effect: a price on emissions may increase the cost of energy-intensive goods. However, the indirect effect may affect more strongly the poorer households (Jiang and Shao, 2014) or the wealthier households (Goulder et al., 2019), depending on the consumption patterns of energy-intensive goods.

The third redistributive channel is the behavioural channel, driven by the households' consumption response to price changes. Price increases may hit low-income households harder than wealthier households if the former cannot reduce their energy consumption.[1] There are several ways to quantify this effect. Some researchers assume a uniform change in energy goods consumption across various types of households (Buchs et al., 2011). Other use more sophisticated methods that account for household heterogeneity by estimating an Almost Ideal Demand System (Labandeira and Labeaga, 1999), or by estimating the price elasticity of demand for different subpopulations (Johnstone and Serret, 2006). Carbon pricing often appears less regressive if behavioural effects are taken into account since high-income households are usually less sensitive to changes in the price of energy or energy-intensive goods. However, adopting such a perspective ignores fairness considerations.

Our first contribution to the literature is to refine the fourth, key redistributive channel related to labour market responses to a carbon tax. The more carbon-intensive sectors, such as energy generation, mining, transport, or manufacturing, are more likely to reduce output and labour demand in response to a carbon tax than less carbon-intensive sectors, such as services. At the same time, these sectors differ in their demand for skills, labour productivity, and wages. As a result, the sector-specific responses to a carbon tax, in terms of job loss and wage adjustment, differ. This can affect the incomes of various groups of workers to varying degrees. To study this channel we use a multi-sector Dynamic Stochastic General Equilibrium (DSGE) model with search-and-matching on the labour market, soft-linked with a microsimulation model. Our approach is similar to Hafstead and Williams (2019), who used a general equilibrium model with labour market frictions to study the effects of mitigation policies on employment in carbon-related industries and other sectors. However, Hafstead and Williams (2019) did not translate employment adjustments into effects on personal income distribution as we do in this paper.[2]

We find that the labour market channel has a crucial contribution to the overall redistributive effect of a carbon tax. It is qualitatively different from price effects, as workers in carbon-intensive sectors (in which employment tends to decrease after introducing a carbon tax) are more likely to earn above-median wages. It is also quantitatively substantial.

Our second contribution is to use our framework to assess the trade-offs between efficiency and equity in climate policy. To this end, we compare the effects of three alternative ways of spending the carbon tax revenue under the condition of an identical emissions reduction path (reduction gradually growing from 0% in 2020 to 95% in 2050).

First, we consider transferring income from a carbon tax to household members in the form of lump-sum benefits.

Second, we analyze a price subsidy – i.e., compensation for the increase in expenditures on energy resulting from higher energy prices – to all households.[3]

Third, we consider utilising carbon tax revenue to reduce labour taxation, in line with the double dividend hypothesis (Takeda, 2007; Faehn et al. 2009; Antosiewicz et al., 2016b; Aubert and Chiroleu-Assouline, 2019; Kirchner et al., 2019). That hypothesis states that replacing highly distortionary taxes (e.g., labour tax) with environmental taxes (e.g. carbon tax) may reduce GHG emissions and increase income.

We find that introducing a carbon tax is associated with a moderate reduction in GDP. The largest decline occurs in the price subsidy scenario (1.5% after ten years) and the smallest reduction occurs in the double dividend scenario (0.9%). Crucially, we find that these scenarios differ starkly in their distributional consequences. Transferring the carbon tax revenue to households as lump-sum transfers reduces income inequality and increases the incomes of below-median households. This is because the below-median households receive more funds from lump-sum transfers than they spend on higher energy costs. Moreover, spending the revenue on lump-sum transfers appears to be a better option than subsidizing energy prices, as the macroeconomic effects are only slightly worse but inequality is noticeably larger in the price subsidy scenario than in the lump-sum scenario. However, spending the revenue on reducing labour taxation increases income inequality, as it mainly benefits high-income households.[4]

Our third contribution is to quantify the distributional effects of carbon pricing in Poland, which is a particularly interesting case study for several reasons. First, Poland is the largest producer of coal in Europe, and it consumes most of its coal domestically — coal generates more than 80% of electricity and heat in Poland. Second, since Poland transitioned from a centrally-planned to a market economy, levels of income inequality have increased substantially. Indeed, according to Eurostat data, Poland has the highest levels of wage inequality in the EU. Moreover, the share of income spent on energy and fuel is substantially higher for the poorest than for the wealthiest households. Third, carbon-intensive sectors employ a substantial share of the Polish workforce. In 2018, coal mining and related industries employed about 1%, while manufacturing employed further 21% of all workers (Kiewra et al., 2019). Therefore, introducing a carbon tax and moving away from coal in Poland may affect households through rising energy prices and the labour market channel: households in which some members work in the coal industry may be the most affected. While we calibrate our model to Poland, our methodology and findings may be relevant for other

[1] For instance, because they are credit-constrained and cannot invest in a more energy-efficient infrastructure, or because the reduction of energy use would be detrimental for health.

[2] Hafstead and Williams (2018) noticed the importance of general equilibrium with the possibility of unemployment. They develop a two-sector CGE model with search frictions to understand the effects of employment flows between the sector affected by CO2 regulation and the unregulated one. This approach allows for correcting the partial equilibrium setting used in the empirical literature, which overestimates the employment effect of environmental policies. For a complete and up-to-date critical review of the issues in the literature, see Hafstead and Williams (2020). Our approach is more nuanced because we model several sectors (as in Hafstead and Williams, 2019) and intermediate inputs in a dynamic setting in which carbon taxation impact all sectors, depending on their emission intensity (see Appendix). Also, we account for price and consumption responses which were the primary focus of other previous studies.

[3] At the time of writing, the Polish government is considering such a subsidy in response to energy price hikes introduced in early 2020.

[4] The interest of our paper is similar to Aubert and Chiroleu-Assouline (2019), but the double-dividend scenario is different. Aubert and Chiroleu-Assouline (2019) studied a change in the progressive tax system that involved modifying a tax structure to improve efficiency. In that study, the final effect depended on the labour supply elasticity of high- and low-skilled workers and the propensity to consume goods affected by the carbon tax. Here, we pay more attention to the labour demand side, which is the critical force behind employment adjustments to emission pricing (Curtis, 2018). In our paper, the double dividend results from a labor tax reduction that increases aggregate labor supply and pushes up employment in various sectors, affecting inequality.

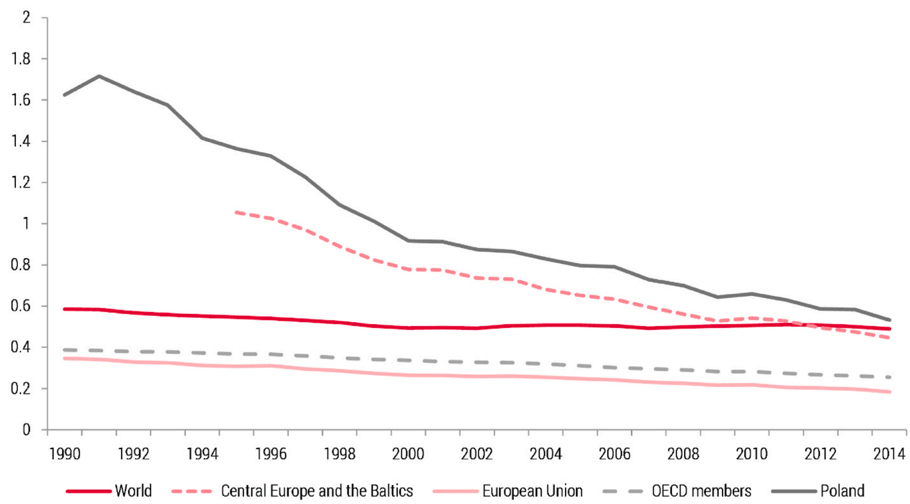

Fig. 1. Trends in carbon-intensity in Poland against regional averages.
Source: Own elaboration based on World Bank data.

countries which are still dependent on coal and have high levels of income inequality, such as Australia, South Africa, or Ukraine. Thus, understanding the distributional implications of carbon pricing in such economies may help manage the transition away from coal.

We use a macroeconomic model and a microsimulation model and use the output of the former in the latter. Various authors follow a similar approach. For instance, Rausch et al. (2011) used a static general equilibrium model with a large number of household agents to study distributional effects of a carbon tax. While they focused on wage fluctuations and did not account for job flows, we model wages and job loss and job finding responses.[5] Our macroeconomic model is a multi-sector DSGE model based on an Input-Output (IO) structure. Models with an underlying IO structure are a standard tool in environmental analysis, e.g., Computable General Equilibrium models (Hamilton and Cameron, 1994; Liang and Wei, 2012) or static IO models (Feng et al., 2010).

Our microsimulation model uses household budget survey data. It allows us to transmit the macroeconomic impulses to employment outcomes, incomes, and consumption of households, depending on their sector of employment and initial position in the income distribution. Callan et al. (2009), Rausch et al. (2011), and Alton et al. (2014) used a similar hybrid approach.[6]

2. The context of climate policy and inequality in Poland

2.1. Carbon intensity and energy mix in Poland

Among the developed economies, the Polish economy is one of the most carbon-intensive. Until the late 1980s, industrialisation in Poland's centrally planned economy was almost entirely fuelled by the extensive use of coal: in 1990, the share of coal in the energy mix was 76%. Since the early 1990s, the relative importance of fossil fuels in the energy mix has changed: the shares of natural gas and oil have increased, but the share of renewables has remained low (9% of the total primary energy supply in 2017). However, the process of industrial modernisation led to rapid improvements in energy efficiency and a decoupling of emissions from economic growth: between 1990 and 2014, the emission intensity of the Polish economy declined from 1.6 to 0.5 kg CO2 per $US (in 2010 prices; see Fig. 1). Nevertheless, the carbon-intensity of Poland remains significantly above the OECD average (0.25 kg CO2 per $US), the EU average (0.18), and the average across Central European and Baltic countries (0.44).

To achieve the targets set by the EU climate policy, the Polish energy mix will have to change quickly. Most importantly, this will require the complete elimination of coal. Coal consumption would have to be cut by 20% between 2015 and 2030 to put Poland on the path to meeting the target of emitting three tonnes of CO2 per person by 2050 (Witajewski-Baltvilks et al., 2018). The governmental Energy Policy of Poland (2019) assumes that between 2015 and 2040, the use of coal will decline by 49% (see Fig. 2). However, significantly larger changes are necessary to achieve the "2050 net zero" target set by the European Commission.[7]

The decarbonisation of the Polish economy would involve a phase-out of the mining sector and a reallocation of mining workers to other sectors. In 2020, Poland was the largest producer of coal in the EU. Most of the coal produced (83% in 2017) was consumed domestically. The amount of coal that is exported is unlikely to increase in the future because the high costs of coal extraction in Poland reduce its competitiveness on international market. Thus, a decline in consumption induced by an ambitious climate policy has to involve cuts in production, and corresponding reductions in mining employment. In 2018, coal mining employed 82,000 workers, and it is estimated (Kiewra et al., 2019) that an additional 60,000 workers were employed in sectors dependent on coal mining, which jointly constituted 1% of total employment.[8] Moreover, in Poland, large shares of employment are in energy/carbon-intensive sectors, such as manufacturing (21.2% in 2018) or transportation and storage (6.3%), relative to the EU average

[5] However, solving a dynamic DSGE model with the same level of agent heterogeneity as used by Rausch et al. (2011) would be an extremely difficult computational task. Hence, we opt for a soft-linking approach and take advantage of the rich household data in the microsimulation model.

[6] Some recent studies use micro simulations to study how carbon tax and compensation schemes affect the welfare and income distribution across households (Berry, 2019; Renner et al., 2018), based on households characteristics. See, for example, Eisner et al. (2021) for a recent application of this methodology to Austria, emphasizing transfer schemes as a function of household heterogeneity.

[7] The net zero target is motivated by the commitment to limit the temperature increase to below 1.5° by the end of century. It assumes a complete decarbonisation of the EU economies by 2050. While Poland has not yet committed to this target, it is under pressure to raise its level of ambition in the near future.

[8] Hard coal mining in Poland is concentrated in the Silesia region, where it provides a larger share of jobs (5% overall, and up to 8% among males, in 2018).

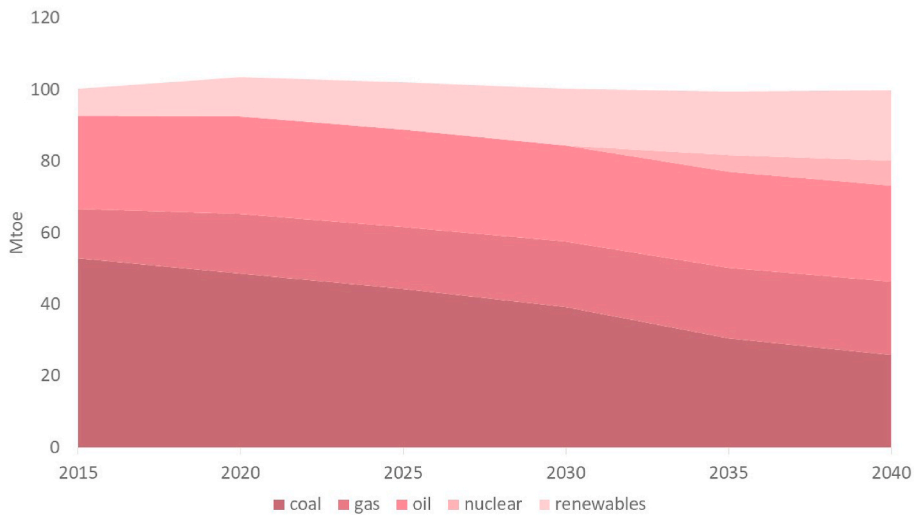

Fig. 2. Projections of the energy mix according to the Energy Policy of Poland.
Source: Own elaboration based on the Energy Policy of Poland (2019).

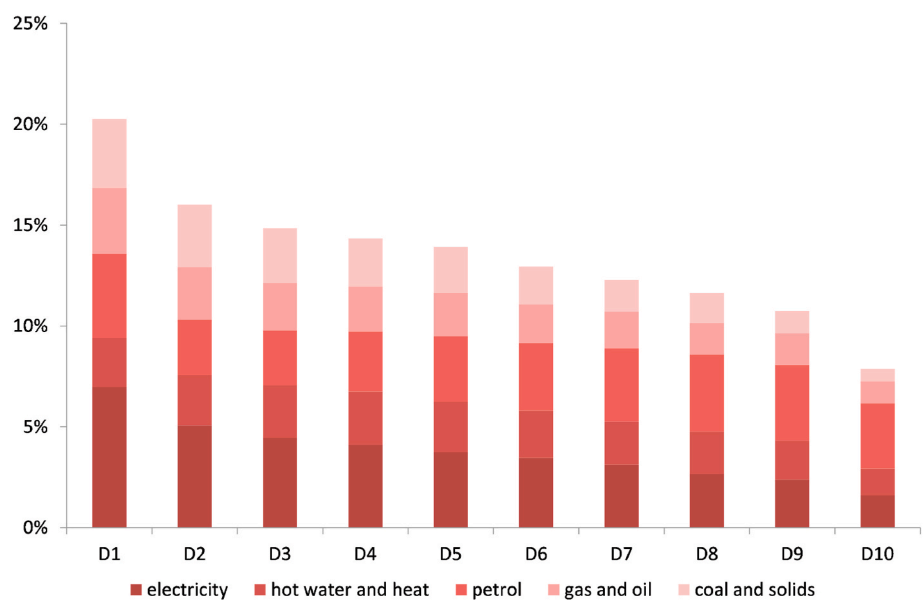

Fig. 3. Share of expenditures on energy and fuel in household income in Poland, by equivalised income deciles (2018).
Source: Own calculations based on Household Budget Survey data.

shares (15.5% and 5.3%, respectively). Therefore, the expected employment effects of decarbonisation are likely to be more far-reaching in Poland than in other EU countries.

2.2. Inequality and living standards in Poland

In Poland, income inequality increased substantially between 1989 and 2007. Although it has remained at a stable level since 2007, Poland became one of the countries with the highest levels of income inequality in the EU (Brzeziński, 2017). The increases in the top income shares and above-median inequality have been particularly pronounced in Poland (Bukowski and Novokmet, 2021). Earnings inequality has also been greater in Poland than it is in most EU countries, with the top 10% of workers earning 4.6 times more than the bottom 10% in 2014, the most recent year for which data on this issue are available (Lewandowski and Magda, 2018). Considerable wage dispersion is a key factor behind high level of income inequality, especially given that the Polish tax and benefit system reduces income inequality only slightly (Goraus and Inchauste, 2016; Brzeziński et al., 2021). As a consequence, shocks that affect employment and wage distribution have a rather strong effect on income inequality in Poland (Brzeziński, 2017).

Distributional concerns of carbon taxation in Poland are also fuelled by the fact that the share of spending on electricity, gas, and other fuels in the total consumption expenditures of Polish households is relatively high. According to the Eurostat data, in 2015 (the most recent data available), this share equalled 11.7%, and was considerably higher than the EU average of 7.3%. Moreover, lower-income households in Poland spend a much larger share of their income on energy and fuel than higher-income households do (Fig. 3). In 2018, this share was twice as large among the bottom 20% of the population as it was among the top 20% of the population. Almost 3/4 of the differences in the share of income spent on energy and fuels across different income groups can be attributed to differences in the share of income spent on electricity, coal, and solid fuels (used mainly for heating). As a consequence, 10% of households in Poland suffer from multidimensional energy poverty resulting from objective (monetary) energy deprivation and subjective deprivation (Sokołowski et al., 2020). The combination of high levels of wage and income inequality and the vulnerability of low-income households to high energy costs means that the distributional effects of climate policy in Poland are of particular importance (Żuk and Szulecki, 2020).

3. Methods and data

To assess the distributional effect of the carbon tax, we use a macroeconomic model soft-linked with a microsimulation model. In the first step, we apply a macroeconomic multi-sector dynamic stochastic general equilibrium (DSGE) model of the Polish economy named MEMO (MacroEconomic Mitigations Options). We use this model to simulate the changes in employment, wages, private consumption and prices of goods at the sector level in response to the introduction of a carbon tax. In the second step, we map the results of the macroeconomic model to a microsimulation model based on household budget data to evaluate the effects of the carbon tax on household incomes and inequality. Here, we present the two models, data sources, and the policy scenarios.

3.1. MEMO - macroeconomic DSGE model

MEMO combines two strands of economic modelling: it is an Input-Output (IO) model embedded in a dynamic stochastic general equilibrium framework. The advantages of using such a framework over a static IO model are that it enables us to account for a variety of dynamic economic adjustment mechanisms. In the context of our study, the most important features of MEMO are: open economy and search and matching mechanism on the labour market.[9] Appendix shows the main equations of the model and calibration strategy.

The main agents of the model are: a) households, which maximise utility from consumption; b) firms, which maximise profits; c) the government, which collects taxes and spends the revenue on public consumption; and d) the foreign trade sector.

The firm's production side is divided into several sectors and calibrated to the NACE Rev. 2 symmetric Input-Output table for Poland in 2015 (provided by Statistics Poland). In each sector, a representative firm operates a nested constant elasticity of substitution (CES) production function. In the first stage, the firm combines capital and energy, which it then combines with labour, and, finally, with materials (intermediate use). Materials are composed of the products of all sectors, which are further disaggregated into imported and domestically produced materials. The output of each sector is used by the household and government for consumption, invested or put to intermediate use by firms, or exported. We set the parameters controlling the shares of each flow in the production and use structure according to the data in the IO matrix.

We pay particular attention to distinguishing between sectors related to the energy system. We identify 11 sectors, as well as three types of fossil fuel products. The set of sectors $\mathcal{S}$ contains agriculture, mining (which distinguishes between specific fossil fuel products: coal, oil, and gas), light industry, energy-intensive industry, advanced industry, coke and refined petroleum products, electricity generation (separated into renewable and fossil fuel generation), construction, transport, market services, and non-market services. We model emissions as linear functions of the intermediate use of fossil fuel products: coal, oil, gas, and refined petroleum products. Table 1 specifies the sector aggregation under the column *NACE*.

Table 1
Sector aggregation from NACE and input for microsimulation model for reference scenario for 2025 (in).

Sector $s \in \mathcal{S}$	NACE	emp - Δ_s^E	wage - Δ_s^W	price - Δ_s^P	vol - Δ_s^V
AGR	A	−0.1	−1.4	0.0	−0.7
MIN	B	−6.6	−2.1	–	–
MIN-coal	B05	–	–	28.8	−4.5
MIN-oil	B06	–	–	−0.9	0.4
MIN-gas	B06	–	–	36.2	−5.7
LIND	C10-16	0.0	−1.4	−0.2	−0.7
EIIND	C17-18,20-24	−0.5	−1.5	0.2	−0.7
AIND	C25–C33	−0.1	−1.4	−0.3	−0.7
RPP	C19	−6.6	−2.1	−0.9	0.0
ENE	D-E	0.5	−0.1	7.7	−0.7
CON	F	−1.0	−1.5	−0.6	−0.7
TRA	H	−0.2	−1.4	0.5	−0.7
PRV	G,I–N,R–U	−0.1	−1.4	−0.4	−0.7
PBL	O-Q	0.6	−1.4	−0.7	−0.7

Note: Sectors are as follows: AGR - agriculture, MIN: mining, LIND: light industry, EIIND: energy intensive industry, AIND: advanced industry, RPP: refined petroleum product industry, ENE: electricity generation, CON: construction, TRA: transport, PRV: market services, PBL: public services.

We show the output for MEMO for one of the simulations (reference lump sum simulation for the year 2025) in our study in Table 1 and the full set of scenarios in subsection 3.3.

3.2. Microsimulation model soft-linked with the macroeconomic model

We use the microsimulation model to calculate the distribution of household income conditional on the output of the macroeconomic model. It is based on the household budget survey (HBS) data, collected by Statistics Poland. We use the 2016 HBS data which contain information on a sample of 36,886 households and 99,230 household members. Each household is surveyed for a full month. The HBS data include detailed information on individual incomes by type and labour market participation in the given month (131,947 observations), household expenditures by type of goods in the given month (2.6 million observations), socio-economic characteristics of individuals and characteristics of households (e.g. dwelling). Table 2 contains a summary of all used variables and symbols.

The microsimulation procedure consists of four main steps:

- Calculation of individuals' labour income and their position in the sector-specific wage distribution;
- Calculation of equivalised household income, and consumption;
- Soft-linking of outputs from the macroeconomic model for a given policy scenario (introduced in subsection 3.3) to recalculate employment, wages, transfer incomes, consumption of energy and other goods;
- Simulation runs and calculation of summary statistics pertaining to incomes by deciles, and inequality: Gini coefficient, $D9/D1$ ratio.

In the exposition, h is used to index households, i is used to index individual household members, and s is used to index economic sectors.

3.2.1. Microsimulation model on the household budget survey data

At the individual level, we take the following steps:

- We define labour income W as the sum of monthly wages earned by individuals in main and additional jobs, and monthly income from self-employment.

[9] As is the case in a recent article by Hafstead et al. (2021), the inclusion of a search mechanism in a general equilibrium setting is critical to estimating the employment effect of the carbon tax. According to them, a full-employment model overestimates the job losses from a carbon tax by about 2.5 times. The results for employment which we show in the next section are closer to their search and matching model than the full-employment CGE. However, their model includes both the extensive and intensive (hours worked) margin, and the lower response of employment is mainly due to the changes in the intensive margin.

Table 2
Key variables and symbols used in the microsimulation model.

Symbol	description
Δ_s^E	percent change in employment in sector s from MEMO
Δ_s^W	percent change in wage in sector s from MEMO
Δ_s^P	percent change in price of good in sector s from MEMO
Δ_s^V	percent change in volume of goods purchased by household in sector s from MEMO
T	per capita lump sum transfer from MEMO
SEC	sector of occupation consistent with MEMO
W	total labour income of individual
D	decile in labour income distribution of individual
$EQWH$	equivalised household size
EXP_s	total household expenditures on goods of sector s
EXP_{sEQ}	equivalised household expenditures on goods of sector s
INC	total household income
INC_{EQ}	equivalised household income
DE	direct consumption effect (energy)
IE	indirect consumption effect (other goods)
TE	lump-sum transfer effect
W'	total labour income of individual in a given scenario/simulation
EE	employment effect
S	set of sectors of MEMO and microsimulation model
S^E	set of energy sectors
S^{NE}	set of non-energy sectors

- We create variable *SEC* which codes the sector of occupation of the individual. The coding is consistent with sectors of the MEMO model shown in Table 1.
- We define deciles *D* of sector-specific labour income distribution to which a given individual belongs. For each sector *s*:

$$D = ecdf^{-1}(W_s) \tag{1}$$

where W_s is labour income truncated to sector *s*, and $ecdf^{-1}$ is the inverse of the empirical cumulative distribution function.

At the household level, we take the following steps:

- We define household income as the sum of all types of household income, including labour, pensions, benefits, financial, capital, and transfers (variable *DOCH* in the HBS).
- We map each consumption good for which expenditure data are available in the HBS (variable *R*5: about 500 different goods) to particular sectors $s \in S$ present in MEMO model. For each sector *s* we create a variable EXP_s as the sum of household's expenditures on goods produced by this sector:

$$EXP_s = \sum_{j \in s} R5_j \tag{2}$$

- We calculate equivalised household size, *EQWH*, using the widely adopted, modified OECD equivalence scale: the first adult is assigned a weight of one, each next person aged 14 or older is assigned a weight of 0.5, and each child under age 14 is assigned a weight of 0.3.
- We calculate equivalised household income, INC_{EQ}, and equivalised household expenditure on goods of particular sectors, EXP_{sEQ}.
- We assign households to one of 10 bins defined as deciles of individual equivalised household income.[10]

There are important differences between households positioned across the equivalised income distribution in Poland which has consequences for our results. The share of labour income in total household income is larger for households with higher total income: it ranges from 30% among the poorest households to 72% among the households in the top income decile (Table 3). The share of labour income among the poorer households is smaller because a larger share of the people in these households are unemployed, students, or individuals whose main sources of income are pensions or benefits. Importantly, the share of people who are employed in mining is noticeably larger among households with equivalised income above the median, and especially in the top 30%, than it is among households with below-median income.

[10] Each bin contains an equal number of individuals, but not necessarily the same number of households.

3.2.2. Soft-linking of macro- and micro-models

The following results of the MEMO model, expressed as percent deviations from the no-intervention scenario, are used as inputs in the microsimulation model:

- Δ_s^E - employment in sectors
- Δ_s^W - wages in sectors
- Δ_s^P - price of sector goods/products
- Δ_s^V - volume of household purchases of sector goods

The first two variables, Δ_s^E and Δ_s^W, are used to update the wage *W* of individuals. The remaining two variables, Δ_s^E and Δ_s^W, are used to update the expenditures EXP_s of the household on sector goods.

The soft-linking of models is enabled by the high degree of consistency between the sector wage levels in the macroeconomic and microsimulation models.[11] The sectors with above-mean wages are the same for both models, with the exception of the construction sector, and the mean income in the mining sector is one of the highest in both models (Table 4).

3.2.3. Simulation procedure

The simulation consists of calculating changes in equivalised: (i) labour income, (ii) lump-sum transfer income, and (iii) expenditures on energy and other goods, all conditional on the output of the macroeconomic model (MEMO).

To calculate the labour income effect, we account for changes in expected wage and employment probability. The employment effect results from adjusting sector-specific employment probabilities according to the output of the macroeconomic model.

- For each sector *s* for which MEMO predicts a decrease in employment in comparison to the baseline ($\Delta_s^E < 0$), each individual working in this sector loses their job with probability equal to $-\Delta_s^E$. Formally, for each individual we draw a random number ***r*** from the uniform distribution $\mathcal{U}(0, 1)$, we reclassify these individuals as unemployed and set the wage to zero for those who lose their job:

$$W' = \begin{cases} 0 & \text{if} \quad r < \Delta_s^E \\ W & \text{if} \quad r \geq \Delta_s^E \end{cases} \tag{3}$$

- For each sector *s* for which the MEMO model predicts an increase in employment in comparison to the baseline ($\Delta_s^E > 0$), we randomly select $N_s \Delta_s^E$ individuals from the pool of unemployed, where N_s is the number of people employed in sector *s*. These individuals become employed in sector *s* and we sample their wage from the sector-specific wage distribution.[12]

[11] We rescale the labour income from the macroeconomic model to the mean obtained from the HBS.

[12] More specifically, we assume that new hires sample their wage from the sector wage distribution which is truncated to the decile of their previous position in the income distribution. Adopting such a mechanism implicitly assumes that richer, and therefore high-skilled individuals take high skilled and better paid jobs.

Table 3
Basic household statistics by income decile.

decile	1	2	3	4	5	6	7	8	9	10
mean size	2.69	2.71	2.81	2.83	2.82	2.89	2.91	2.84	2.76	2.75
labour income PLN	233	400	561	699	901	1076	1311	1642	2202	3907
all income PLN	781	1240	1520	1735	1944	2170	2438	2774	3340	5454
labour income share %	30	32	37	40	46	50	54	59	66	72
employed %	27	26	30	33	37	40	44	49	55	59
unemployed %	14	8	5	5	3	2	2	1	1	1
pensioners %	19	26	26	26	25	25	24	22	17	10
students %	11	10	9	9	9	7	6	6	5	5
employed in mining %	0.5	0.9	1.0	1.7	1.5	1.8	1.6	1.7	1.9	1.6

Note: Unemployment share counted as share of total population of given decile, not as share of active on the labour market. Pensioners include those who are retired and those who receive some form of disability benefits. Employed in mining is the share of those employed in this sector out of all persons employed.
Source: Own calculations based on household budget survey data.

Table 4
Wages in microsimulation model based on household budget survey data and rescaled wages for macroeconomic MEMO model.

	AGR	MIN	LIND	EIIND	AIND	RPP	ENE	CON	TRA	PRV	PBL	mean
HBS	247	3347	1935	2414	2416	4203	3282	2117	2611	2477	2649	2169
MEMO	542	2669	1846	2393	2307	5216	3605	2390	2603	2423	2330	2169

Note: Sectors are as follows: AGR - agriculture, MIN: mining, LIND: light industry, EIIND: energy intensive industry, AIND: advanced industry, RPP: refined petroleum product industry, ENE: electricity generation, CON: construction, TRA: transport, PRV: market services, PBL: public services.
Source: Own calculations based on household budget survey data for microsimulation model and on Eurostat data for macroeconomic MEMO model.

The wage effect results from adjusting sector-specific wages according to the output of macroeconomic model:

$$W' = W'*(1+\Delta_s^W) \tag{4}$$

In order to calculate the labour effect, *LE*, we compute the sum of changes in equivalised labour income of all household members after adjusting for employment and wage effects explained above, and we express it relatively to the baseline labour income:

$$LE_h = \left(\sum_{i=1}^{LOS_h}(W'_{ih} - W_{ih})\right) \Big/ EQWH \tag{5}$$

The transfer effect, *TE*, is defined as the total equivalised income from lump-sum transfers received by a household in a given scenario, *TE*[13]

$$TE = LOS*T/EQWH, \tag{6}$$

where *LOS* is the number of household members. We also calculate the direct and indirect effects resulting from changes in prices and consumption volume of particular goods:

- Direct effect: the effect of changes in the price and consumption of energy goods. The set of energy goods is as follows: $S^E = \{coal, oil, gas, petroleum\ products, electricity\}$. We calculate the direct price effect across energy goods, *DE*, using the formula:

$$DE = \sum_{s \in S^E} EXP_s*(\Delta_s^P + \Delta_s^V + \Delta_s^P\Delta_s^V) \Big/ EQWH \tag{7}$$

- Indirect effect: the effect of changes in the price and consumption of goods produced by all sectors other than energy. The set of consumption goods is as follows: $S^{NE} = SS^E$. We calculate the indirect price effect across consumption goods, *IE*, using the formula:

$$IE = \left(\sum_{s \in S^{NE}} EXP_s*(\Delta_s^P + \Delta_s^V + \Delta_s^P\Delta_s^V)\right) \Big/ EQWH \tag{8}$$

All effects - labour, transfer, direct and indirect consumption effects - are then averaged for each income decile, and reweighted using household weights provided in the HBS data.

Since the adjustment of employment is stochastic, we repeat each simulation 100 times. Then, we average results across simulations.

3.3. Policy scenarios

Here, we describe the assumptions that underlie the three alternative scenarios of carbon taxation and recycling of revenue that we consider. In all three scenarios, we assume that the carbon tax is introduced in a way which ensures a gradual reduction in emissions from 0% in 2020 to 95% by 2050 relative to the baseline scenario without a carbon tax. This translates to a reduction of emissions by 13% in 2025 and 28% in 2030 (we assume the reduction path is the same in all three scenarios). Across all scenarios, the carbon tax rate is calculated endogenously to meet the emissions target (Table 5). For each scenario, we use the results from MEMO for 2025 and 2030. Thus, we simulate the distributional effects of the carbon tax 5 and 10 years after its introduction.

The three scenarios differ with respect to how the carbon tax revenue is spent. They are as follows:

- The lump-sum (reference) scenario. The revenue from the carbon tax is distributed as a lump-sum transfer to each individual. The tax is at the level of 126 PLN (29.4 EUR) per ton of CO2 in 2025 and 355 PLN (82.5 EUR) in 2030. The transfer amount is 36.0 PLN and 62.5 PLN per person in 2025 and 2030, respectively.
- The price subsidy scenario. The revenue from the carbon tax is used to subsidise the increases in the prices of energy and fuels for households. The carbon tax rate is the same as it is in the lump-sum scenario. The remaining part of revenue, equal to 12.2 PLN and 12.4 PLN for 2025 and 2030, is distributed as an equal lump-sum transfer to household members. Because of the price subsidy, the prices of energy and fuels faced by households in this scenario are essentially the same as they are in the baseline scenario with no carbon tax.
- The double dividend scenario. The entire revenue from the carbon tax is used to reduce the labour tax. As a lower labour tax increases the supply of labour, which is endogenous in our model, it increases GDP. As a result, the level of carbon tax required to achieve the same reduction in emissions is higher (by 3–8 PLN).

[13] Note that lump-sum transfers are not paid in the baseline scenario.

Table 5
CO2 emissions reduction and the required carbon tax level.

	2025			2030		
	lump-sum	price subsidy	double div.	lump-sum	price subsidy	double div.
CO2 reduction in %	13.2	13.2	13.2	28.2	28.2	28.2
CO2 tax rate in EUR/t	29.4	29.6	30.0	82.5	82.7	84.6
CO2 tax rate in PLN/t	126	127	129	355	356	364

Source: Own calculations based on the DSGE model.

4. Results and discussion

In the first subsection, we discuss the macroeconomic effects of introducing a carbon tax in Poland; and in the second subsection, we present the distributional effects.

4.1. The aggregate effects of carbon tax

The macroeconomic effects of introducing a carbon tax differ depending on how the revenue is used. This is due to the varying economic incentives created by the revenue recycling schemes.[14] In each scenario, GDP, investment, and consumption are lower than they are in the baseline scenario of no carbon tax (Table 6).[15] However, the decline is smaller in the double dividend scenario (0.4% in 2025 and 0.8% in 2030) than in the lump-sum and price subsidy scenario (0.6% in 2025 and 1.4–1.5% in 2030).

In the double dividend scenario, the reduction in the labour tax raises the supply of labour. This increases the marginal productivity of capital and leads to higher levels of employment and investment than in the other two scenarios. As a consequence, labour income (after tax) is noticeably higher in the double dividend scenario than it is in the other scenarios (see Table 6). Moreover, employment and labour income in the double dividend scenario are even slightly higher than they are in the baseline scenario of no carbon tax.

At the same time, the carbon tax rate necessary to achieve the target GHG reduction is higher in the double dividend scenario than in the remaining scenarios (Table 5). This is the result of a higher level of economic activity and private benefits from GHG emissions.

Table 6
Effects of carbon tax on selected macroeconomic variables in 2025 and 2030 for three recycling scenarios - deviations from the baseline (no carbon tax), in %.

	2025			2030		
	lump-sum	price subsidy	double div.	lump-sum	price subsidy	double div.
GDP	−0.6	−0.6	−0.4	−1.4	−1.5	−0.8
Investment	−2.1	−2.4	−1.5	−4.1	−4.8	−2.9
Employment	−0.1	−0.1	0.3	−0.4	−0.4	0.6
Consumption	−0.7	−0.7	−0.5	−1.9	−1.9	−1.1
Labour income after tax	−1.6	−1.6	2.5	−3.7	−3.9	5.0
Price of energy	7.67	7.73	7.84	16.17	16.26	16.57

Source: Own calculations based on the DSGE model.

If we use the carbon tax revenue to subsidise the energy consumption of households (compensating for the increase in energy prices due to the carbon tax), its distortionary effects on firms are the strongest. Thus, the declines in GDP, investment, and employment are largest in this scenario (Table 6). In comparison to the lump-sum scenario, the price subsidy scenario increases the consumption of fuels and decreases the consumption of other goods. Moreover, higher demand for energy and fuels increases the market (pre-subsidised) prices of those goods, and thus increases the costs of production for firms (which do not receive any subsidies). As a result, demand, investment, and output decline more in the price subsidy than they do in the lump-sum scenario. However, the differences with respect to the lump-sum scenario are minuscule, at least in the 10-year horizon that we study (1.5% vs. 1.4% decline in GDP by 2030).

4.2. The effects of carbon tax on various income groups and inequality

Next, we discuss the effects of a carbon tax on household incomes, distinguishing 10 groups based on the deciles of equivalised household income, and on overall income inequality, as measured by the Gini coefficient and the ratio between the ninth and the first decile of the income distribution (D9/D1 ratio).

We find that the **overall distributional effect** of a carbon tax is largely driven by how the revenue is spent. Distributing the carbon tax revenues as a lump-sum transfers to households reduces income inequality, while spending the revenues on a reduction of labour taxation increases inequality. In the lump-sum transfer scenario, the total income of households with (initially) below-median incomes increases in comparison to the baseline, because the gains from the lump-sum transfer more than compensate for the losses resulting from the higher prices of energy and other goods (Fig. 4). In the double dividend scenario, the income gains from higher employment and lower labour taxation are larger for higher decile groups, which means that inequality widens. In the price subsidy scenario, inequality shrinks, but to a much lesser extent than it does in the lump-sum scenario (Table 7).

In the lump-sum scenario, the **direct effects** of a carbon tax are clearly regressive in relative terms. Among the poorest 20% of households, the direct effect amounts to a 2.1% income loss in 2025 and a 4.1% income loss in 2030. Among the richest 20% of households, the effects are about half as large. In absolute terms, the higher-income households are affected to a greater extent because their energy consumption is higher. At the same time, the **indirect effects** are positive. This means, however, that households reduce consumption of goods other than energy in order to compensate for the higher costs of energy goods. Although in absolute terms the size of this effect increases with income, in relative terms it decreases with income. Importantly, the total effect related to price changes is clearly regressive. Among the poorest 20% of households, these effects amount to an income loss of about 0.9% in 2025 and of 2.0% in 2030, while among the richest 10% of households, the direct and indirect effects almost cancel each other out (Fig. 4).

In the lump-sum scenario, the employment effect reduces incomes across the income distribution. However, it affects the richer households to a greater extent in both absolute and relative terms. This outcome is attributable to two labour market features. First, lower demand for carbon-intensive sector goods (energy, mining and manufacturing) translates into lower wages in these sectors. This effect results in a drop in inequality, because workers in carbon-intensive sectors belong to high-income households. Carbon-intensive sectors, in which labour demand tends to decrease after the introduction of a carbon tax, offer higher wages than sectors that are more resilient to the introduction of a carbon tax, such as public services, hospitality, and retail. Second, the poorest households are more likely to be jobless and to live off of pensions and other benefits (which we assume are unaffected by the carbon tax). As a result, among the bottom 20% of households, the income

[14] In each scenario, we assume the same path of GHG emission reductions – i.e., a 13% reduction by 2025 and a 28% reduction by 2030 – which is consistent with a 95% reduction in GHG emissions by 2050 (relative to the baseline scenario of no carbon tax).

[15] We observe a decline in consumption even for the lump-sum scenario. However, the transfer to households helps to mitigate this drop, which is mainly due to the decline in GDP.

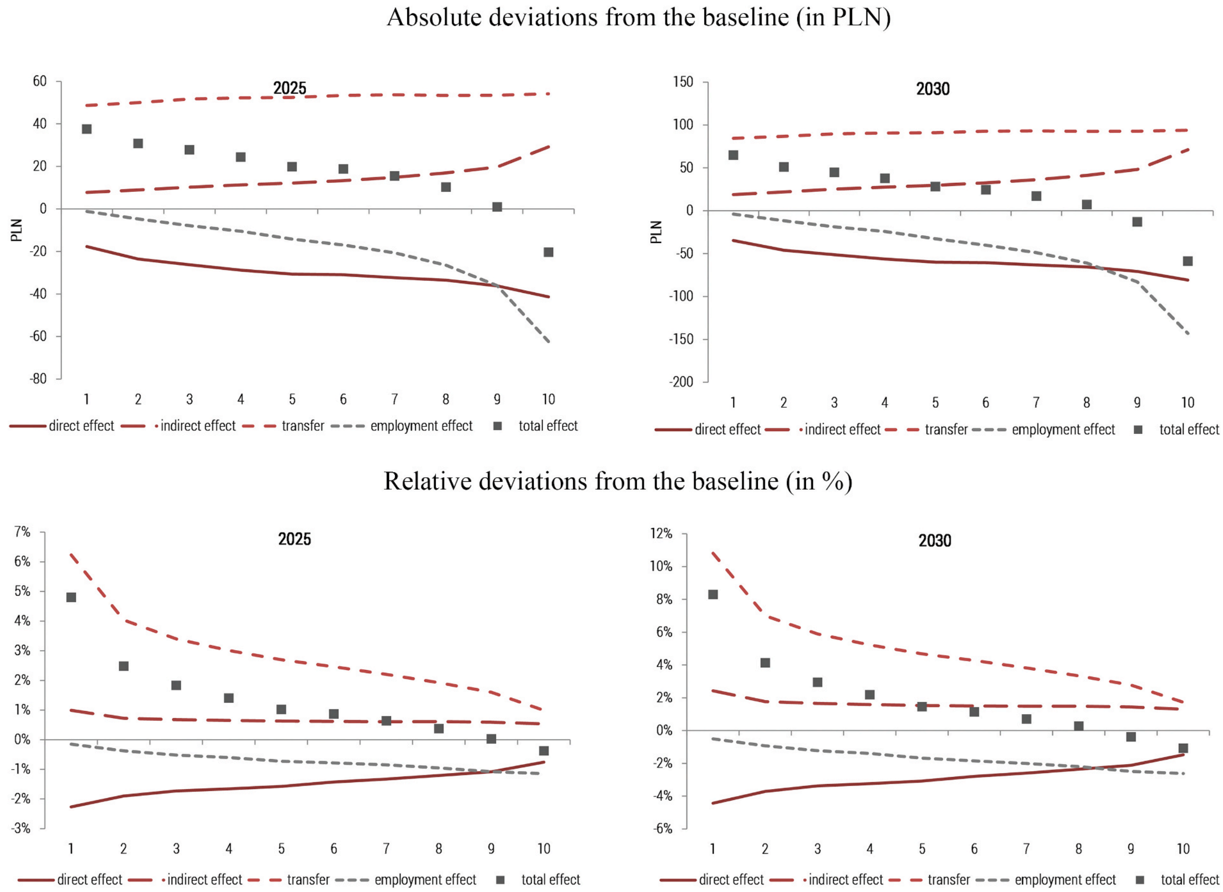

Fig. 4. The effects of the lump-sum transfer scenario of carbon tax introduction on income by decile income groups in Poland, in absolute (top panel) and relative (bottom panel) terms.
Source: Own simulations based on the DSGE model and the microsimulation model.

Table 7
Results for selected inequality statistics for scenarios.

	data	2025			2030		
		lump-sum	price subsidy	double div.	lump-sum	price subsidy	double div.
Gini coeff.	27.92	27.47	27.60	28.20	27.17	27.41	28.67
D9/D1 ratio	3.36	3.29	3.30	3.43	3.24	3.28	3.52

Source: Own calculations based on the DSGE model and the Polish HBS data.

decline driven by the employment effect is only 0.2% in 2025 and 0.5% in 2030. The respective figures for the top 20% of households are 1.2% in 2025 and 2.7% in 2030. Overall, the market mechanisms (direct and indirect consumption effects and the employment effect) reduce the disposable income of all of the household income groups, but to the greatest extent among households that have above-median incomes, but that do not belong to the top 10%.

Importantly, if the revenue is distributed as a lump-sum transfer, 80% of households benefit from higher incomes, and only the households in the top 20% record an income decline. The overall impact of the carbon tax is to reduce inequality: the Gini coefficient, as well as the D9/D1 ratio, are lower than they are in the baseline scenario of no carbon tax (Table 7).

In the price subsidy scenario, the revenue from the carbon tax is first distributed according to the household spending on energy goods, and the remaining funds are distributed as a lump-sum transfer. Thus, the **direct effect** is close to zero (Fig. 5). The direct effect comes only from the reduction in consumption of energy and fuels, and is small (from 0.1% among the top 10% of households to 0.3% among the bottom 10% of households). As the energy and fuel prices paid by firms are not subsidised, the changes in the prices of other goods and the **indirect effect** are virtually the same in this scenario as they are in the lump-sum scenario. The lump-sum transfers are positive, but are substantially lower than they are in the lump-sum scenario because 66% and 80% of the carbon tax revenues are spent on price subsidies in 2025 and 2030, respectively. As a consequence, the lump-sum transfers play a much

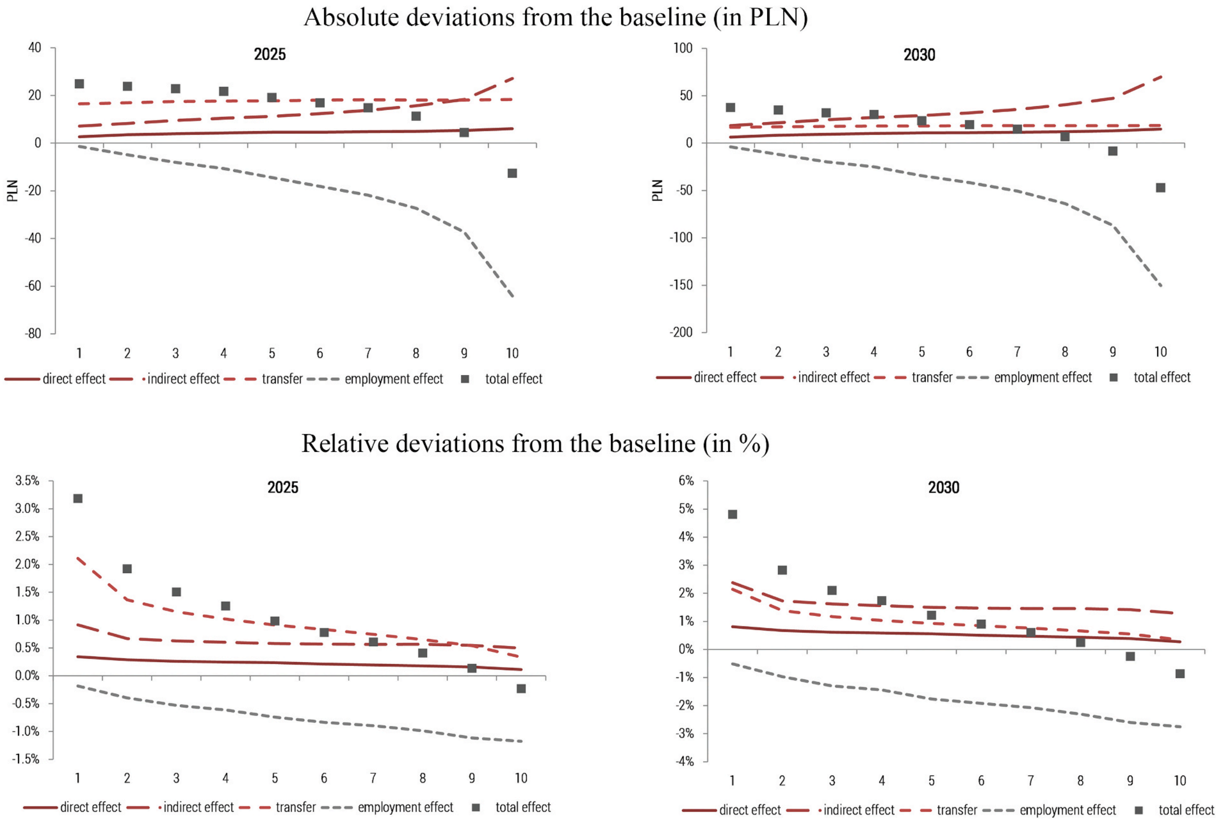

Fig. 5. The effects of the price subsidy scenario of carbon tax introduction on income by decile income groups in Poland, in absolute (top panel) and relative (bottom panel) terms.
Source: Own simulations based on the DSGE model and the microsimulation model.

smaller role in the final outcome.

The incomes of the below-median households increase more than in the reference scenario, but less than in the lump-sum scenario. The difference is the most pronounced for the first decile. At the same time, the incomes of the above-median households are higher in this scenario than they are in the lump-sum scenario, as these households benefit more from energy price subsidies than the below-median households. The **overall level of income inequality** is lower than in the baseline scenario (no carbon tax), but is higher than in the lump-sum scenario (Table 7).

In the double dividend scenario, the revenue from the carbon tax is used to finance a reduction of the labour tax. As there is no price subsidy in this scenario, the **direct and indirect effects** are virtually identical to those in the lump-sum scenario. They are marginally lower (by 0.2 pp. on average) because using the revenue from the carbon tax on an equivalent reduction in the labour tax leads to higher GDP, and, in turn, to higher disposable incomes than in the lump-sum scenario. However, the main difference between these scenarios is in the **employment effect** (Fig. 6). A lower labour tax tends to increase employment, and the resulting gain in labour income rises in line with the household's position in the income distribution (especially in absolute terms). As a result, the incomes of households that had below-median incomes before the introduction of the carbon tax remain virtually the same as in the baseline scenario of no carbon tax. However, the incomes of households that had above-median incomes increase in comparison to the baseline scenario. Moreover, the size of this income gain increases with income in both absolute and relative terms. Thus, compared to the other scenarios, the double dividend scenario is characterised by both the highest GDP and employment levels, as well as by the highest income inequality levels (Table 7).

5. Conclusions and policy implications

Implementing climate change mitigation policies poses many challenges for policymakers wishing to reduce carbon emissions. This is especially true for Poland, a major producer of fossil fuels used in its carbon-intensive energy generation. In this context, understanding the overall impact of energy and climate policies requires looking beyond changes in fuel and energy expenditures. In particular, labour market considerations such as job losses, wage adjustments, and worker reallocation across sectors are critical. Policymakers aiming to strike the right balance between aggregate macroeconomic efficiency and welfare outcomes should consider these impacts to ensure a smooth and fair decarbonisation.

Our key contribution is to develop a framework to incorporate the heterogenous employment effects in a study of distributional consequences of a carbon tax. We have used a macroeconomic model of the Polish economy with labour market frictions, which we have soft-linked with a microsimulation model detailing the financial situation of households. We have gauged how changes in the prices of energy goods,

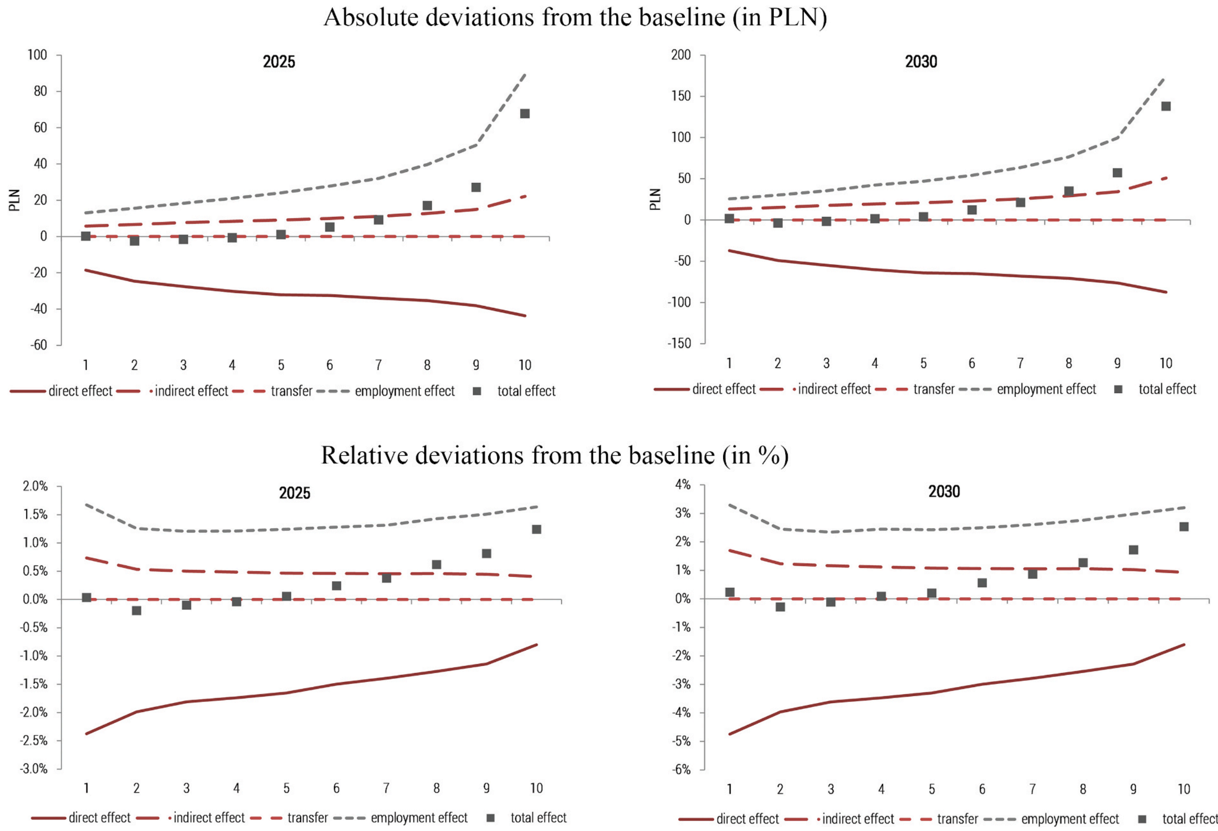

Fig. 6. The effects of the double-dividend scenario of carbon tax introduction on income by decile income groups in Poland, in absolute (top panel) and relative (bottom panel) terms.
Source: Own simulations based on the DSGE model and the microsimulation model.

changes in consumption patterns, and shifts in the labour market affect the income of households. We have shown that the employment channel is quantitatively relevant and qualitatively different from the price and behavioural channels that affect consumption. The employment effect tends to reduce inequality, while the price and behavioural effects tend to widen it. Moreover, we have shown that the overall distributional impact of carbon tax depends on another critical feature of its design, namely on how the revenue from it is recycled. We have studied three scenarios of revenue recycling and highlighted fundamental differences between them in aggregate and distributional outcomes. We have identified a trade-off between aggregate economic efficiency and inequality, which can aid policymakers in choosing the design of the carbon tax policy that meets their desired objective.

Policymakers focused primarily on the level of aggregate economic activity should opt for spending the carbon tax revenue on reducing other distortionary taxes, such as the tax on labour. Our results show that such a scheme would mitigate the drop in GDP brought about by the carbon tax and would increase total employment. However, lower labour taxation would mainly benefit households with higher incomes - in our simulations, the top 10% experience the largest income gain from such policy package. As a result, such scenario would widen income inequality and exacerbate the disparities in living standards.

Policymakers concerned with inequality or energy poverty should favour spending the carbon tax revenue on a lump-sum transfer to all households. Such a scheme would result in the poorest households receiving the largest income gains. While rising energy prices would widen income inequality, the lump-sum transfer would outweigh this effect, and, as a result, inequality would decline. This would come at the expense of aggregate outcomes. The drop in average wages, total employment, and GDP would be more pronounced than in the scenario of lowering the labour tax.

We have also considered spending the carbon tax revenue on subsidizing the increase in energy expenditures for households.[16] We have found that such a policy design is inferior to a lump sum transfer; i.e., it would lead to a slightly larger drop in GDP and employment, and to higher inequality. The policy makers opting for an energy price subsidy rather than a lump-sum transfer should, therefore, justify it on grounds other than income equality or fairness (understood as supporting the poorest households).

Our study has limitations warranting future research. We have discussed which groups of workers (by deciles of the income distribution) face lower labour incomes after introducing a carbon tax. However, we did not quantify potential welfare loss due to the reallocation costs affecting workers who would lose a job. Neither have we considered welfare effects of involuntary unemployment which go beyond income loss, for instance those related to increased stress. Moreover, we did not consider social transfers targeted to specific sub-populations. Such transfers may be considered by governments with a high institutional capacity to identify groups in need, and to target social policies to them. Finally, we did not study how externalities from the carbon tax (such as lower congestion or pollution levels) would benefit different income groups and whether these outcomes would magnify or attenuate income distributional effects. Neither did we account for regional disparities nor the spatial distribution of gains and losses resulting from the introduction of a carbon tax.

[16] Such energy price subsidies have been discussed in Poland and other countries.

CRediT authorship contribution statement

Marek Antosiewicz: Software, Data curation, Formal analysis, Writing – original draft, Visualization. **J. Rodrigo Fuentes:** Conceptualization, Writing – review & editing, Supervision. **Piotr Lewandowski:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Project administration. **Jan Witajewski-Baltvilks:** Methodology, Investigation, Writing – original draft, Visualization, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Description of DSGE model used to simulate the macroeconomic effects of the carbon tax

The main goal of the appendix is to sketch the DSGE model which we use to obtain the macroeconomic results that are used as input for the microsimulation model. We used a simplified version of the model developed by Antosiewicz and Kowal (2016). The structure of the model relies on the sectors' relationship derived from the input-output matrix. We highlight the main features needed for our microeconomic simulations.

Model structure

The model assumes a small open economy with four agents: (a) households, (b) firms, (c) government, and (d) the foreign demand sector. These agents interact in three markets: (1) labor (2) capital, and (3) goods market.

Households

There are many identical households in this economy that form a representative household that chooses consumption from maximizing an intertemporal CRRA utility function. There is no leisure in the utility function.

The usual budget constraint applies. The household uses labor income, firms' profits, the return from previous savings to pay for consumption, value added and income taxes, quadratic search costs in the labor market expressed in terms of consumption good. The working age population is divided between employed and unemployed workers.

Firms

The model is composed of 11 sectors: (1) agriculture, (2) mining which produces three distinct products: coal, oil, and gas, (3) light manufacturing industry, (4) manufacturing of coke and refined petroleum products, (5) energy-intensive manufacturing, (6) advanced manufacturing (7) energy production, (8) construction services, (9) transport services (10) market services, and (11) public services. It must include raw materials and energy sectors, given the nature of our problem (the macroeconomic effects of a carbon tax). The calibration of the production function and the relations across sectors comes directly form the input-output matrix.

Firms produce a basic sector good under monopolistic competition, employing capital, labor, materials and energy as production factors. There are trading firms that purchase this good and sell it to domestic and foreign sector markets. The agents that buy this good are: (i) (as intermediate demand) producers of basic goods (in each sector); (ii) (sector) export firms, which distribute domestic production in foreign markets; and (iii) three types of domestic final goods producers, providing investment, government, and private consumption goods. Final production is traded on the goods market with households, basic producers and government in accordance with the flows established from the input-output matrix.

$$\begin{aligned} KLEM_t^s &= \left[\left(1-\theta_{M,t}^s\right)^{\frac{1}{\varepsilon_M^S}}\left(KLE_t^s\right)^{\frac{\varepsilon_M^s-1}{\varepsilon_M^s}}+\left(\theta_{M,t}^s\right)^{\frac{1}{\varepsilon_M^s}}\left(M_t^s\right)^{\frac{\varepsilon_M^s-1}{\varepsilon_M^s}}\right]^{\frac{\varepsilon_M^s}{\varepsilon_M^s-1}} \\ Y_t^s &= e^{\xi_t^Y}\times KLEM_t^s \end{aligned} \tag{9}$$

where *KLEM* is an aggregate production factor that uses capital (*K*), labor (*L*), electricity (*E*) and materials (*M*). This is constructed using CES aggregator between *K* and *E*, then we add *L*, and finally *M*. Y_t^s represents output of sector *s* at time *t*, $\theta_{M,t}^s$ represents the share of materials in the production process of the basic good and ε_M^s is the elasticity of substitution between materials and the capital-labor-electricity (*KLE*) composite production factor. ξ_t^Y is an economy-wide productivity shock that we use to calibrate the dynamics properties of the model.

Materials play a key role in the model to estimate the CO2 emissions. Intermediate material used in sector *s*, M_t^s is obtained from a composite of fuels ($FUELS_t^s$) and a composite of all other intermediate inputs.

$$M_t^s=\left[\left(\theta_{FLS,t}^s\right)^{\frac{1}{\varepsilon_{MF}}}\left(FUELS_t^s\right)^{\frac{\varepsilon_{MF}-1}{\varepsilon_{MF}}}+\left(\theta_{MO,t}^s\right)^{\frac{1}{\varepsilon_{MF}}}\left(MO_t^s\right)^{\frac{\varepsilon_{MF}-1}{\varepsilon_{MF}}}\right]^{\frac{\varepsilon_{MF}}{\varepsilon_{MF}-1}} \tag{10}$$

where $\theta_{FLS,t}^s$ and $\theta_{MO,t}^s$ denote the share of fuels and other material in the intermediate input, with $\theta_{FLS,t}^s+\theta_{MO,t}^s=1$, while ε_{MF} represents the elasticity of substitution between inputs. In turn, combining materials $M_{i,t}^s$ in a Leontief production function generates the composite MO_t^s, used from all the basic goods sectors: $M_{i,t}^s=\theta_{i,t}^s MO_t^s$

where $\theta_{i,t}^s$ (with $\sum_{i\in S}\theta_{i,t}^s=1$) denotes the shares of intermediate good *i* in overall material consumption in sector *s*. Note that this specification allows for the introduction of energy material input into the composite *MO* For the purpose of calibration, energy only enters in the production of electricity and raw materials, to replicate the high volatility of these two energy inputs observed in the data.

Raw materials intermediate goods (different from fuels, e.g. coal, oil gas, etc.), use raw materials in a Leontief production function. In the case of fuels, a CES aggregator combines all the relevant types of fuels needed for their production.

$$FUELS_t^s = \left[\sum_{k \in FLS} \left(\theta_{k,t}^s \right)^{\frac{1}{\varepsilon_{FLS}^s}} \left(M_{k,t}^s \right)^{\frac{\varepsilon_{FLS}^s - 1}{\varepsilon_{FLS}^s}} \right]^{\frac{\varepsilon_{FLS}^s}{\varepsilon_{FLS}^s - 1}} \tag{11}$$

where $\{FLS\}$ is the set of fuels, $M_{k,t}^s$ denotes input of k-th type of fuel, $\theta_{k,t}^s$ is the share of k-th fuel type in fuels intermediate input composite, and ε_{FLS}^s denotes the elasticity of substitution between different fuels in sector s. Since, this is a small open economy, $M_{i,t}^s$ is also a composite good produced with inputs made at home ($M_{i,H,t}^s$) and abroad ($M_{i,F,t}^s$), combined according to the Armington aggregator.

The final basic good in sector s, $\overline{Y}_t^s$ is a composite made of intermediate goods produced in the way just described. The final firm produces the final good using the Dixit-Stiglitz aggregator and selling it in a perfectly competitive market.

$$\overline{Y}_t^s = \left(\int_0^1 \left(Y_t^s(i) \right)^{\frac{\rho^s - 1}{\rho^s}} di \right)^{\frac{\rho^s}{\rho^s - 1}} \tag{12}$$

where parameter ρ^s sets the markup.

Investment decisions

Firms make capital accumulation decisions in a way which maximizes the profit.

Government

The government collects value added tax, corporate income tax, labor income tax, other taxes and carbon emission tax. The revenue is spent on public goods, transfers to households and interest on public debt.

External sector

Given the small open economy assumption, the economy is a price taker in international markets for exports and imports. There is open capital account, which defines external assets (debt) accumulation.

Crucial aspects of the model

We must highlight two relevant features of the model: the modelling of the CO2 emissions and the labor market frictions.

CO2 emissions

Firms and households produce CO_2. Firms in sector s produce CO_2^s as a byproduct while using intermediate goods. Formally:

$$CO2_t^s = \theta_{H,CO2,t}^s \times Y_t^s + \sum_{j \in T} \theta_{j,CO2,t}^s \times \left(M_{j,H,t}^s + M_{j,F,t}^s \right) \tag{13}$$

where $\theta_{H,CO2,t}^s$ defines the amount of CO_2 in sector s by using j-type material produced in home (H) or foreign country (F). The main assumption is that only fuels consumption generates CO_2, in other words $\theta_{H,CO2,t}^s \neq 0$ for $j \in \{FLS\}$. Moreover, chemical processes other than fuel combustion can also produce CO_2. We assume that such CO_2 emission is proportional to the amount of goods and services produced in a given sector and is controlled by the parameter $\theta_{H,CO2,t}^s$ Similarly, the amount of CO2 emitted by households is equal to:

$$CO2_t^{CNS} = \sum_{j \in T} \theta_{j,CO2,t}^{CNS} \times M_{j,t}^{CNS} \tag{14}$$

Labor market

Wages in the model are sector specific. They are determined in general equilibrium, and hence they react to changes in sector demand induced by climate policy. The sector demand for labour is determined in the optimization of representative firms in all sectors. To model labour supply curves at sector level we assume the existence of an intermediary between representative worker and sector firms that allocates workers to different sectors using constant elasticity of substitution technology. In addition, we let the intermediary decide on the total number of vacancies in the economy, which we use to determine the unemployment rate.

The intermediary optimization problem is given by:

$$\max_{\{N_t, n_t, Vac_t\}_{t=0}^{\infty}} V_t^L = \pi_t^L + \lambda_{t+1} V_{t+1}^L$$

subject to:

$$\pi_t^L = \sum_s w_t^s n_t^s - w_t N_t - v_{Vac} Vac_t$$

$$N_t = \omega_N \left(\sum_s \omega_N^s \left(n_t^s\right)^{\frac{\varepsilon_L - 1}{\varepsilon_L}} \right)^{\frac{\varepsilon_L}{\varepsilon_L - 1}} \tag{15}$$

$$N_t = (1 - \delta_L)N_{t-1} + \Phi_t Vac_t$$

where V_t^L is the discounted sum of profits, π_t^L is the profit in period t, λ_{t+1} is the discount factor (determined endogenously based on the interest rate), w_t^s is wage in sector s, n_t^s is the supply of workers in sector s, w_t is the aggregate wage (received by representative worker) and N_t is the total demand for labour, ν_{Vac} is the cost of having an open vacancy (which could be interpreted as a search cost), Vac_t is the number of open vacancies, ω_N and ω_N^s are parameters calibrated to ensure that number of workers in each sector and total number of workers are the same as in input-output matrices for Poland, ε_L is the elasticity of transformation between sectors, δ_L is a job destruction rate (exogenous in the model) and Φ_t is the probability of filling the vacancy.

The intermediary takes aggregate wage (w_t), sector wages (w_t^s) and probability of filling the vacancy (Φ_t) as given and decides on total demand for labour (N_t), its allocation across sectors (i.e. supply of labour at a sector level, n_t^s) and total number of vacancies (Vac_t). Sector wages are set by equating sector labour supply with labour demand generated in each sector.

Matches

Given unemployment rate in the last period and number of vacancies opened by the intermediary, we determine number of matches, J_t. We assume a standard, log-linear matching function (see e.g. Mortensen and Pissarides (1994):

$$J_t = \varphi Vac_t^{1-\varepsilon_J} U_{t-1}^{\varepsilon_J} \tag{16}$$

where φ and ε_J are parameters and U_{t-1} is the number of unemployed in period $t-1$.

Given the number of matches we determine the probability of filling the vacancy:

$$\Phi_t = \frac{J_t}{Vac_t} \tag{17}$$

and the probability of finding a job:

$$\Psi_t = \frac{J_t}{U_{t-1}}$$

Here, we assume that worker who was unemployed at time $t-1$ has a chance to become employed at the beginning of period t.

Wage setting

Wage is set in the wage bargaining process. To describe the negotiations between workers and firms, we first specify the value of being unemployed:

$$V_t^U = b + \lambda_{t+1}\left(\Psi_{t+1} V_{t+t}^N + (1 - \Psi_{t+1}) V_{t+1}^U\right) \tag{18}$$

where b is the value of home production (which enters utility function) expressed in monetary terms.

We also specify value of being employed

$$V_t^N = (1 - \tau)w_t + \lambda_{t+1}(1 - \delta_L)V_{t+1}^N + \delta_L \lambda_{t+1} V_{t+1}^U \tag{19}$$

where τ is a tax on labour. We assume that the destruction of job could happen at the end of period t.

Finally, we define value of filling the vacancy for the intermediary:

$$V_t^F = m_t - w_t + (1 - \delta_L)\lambda_{t+1} V_{t+1}^F \tag{20}$$

where m_t is the marginal productivity of labour in period t, which is determined using the shadow price of N associated with the constraint (15) (the shadow price is determined in the solution of the model).

We assume that the total surplus from a match is split between workers and firms and that the share of the surplus that goes to the intermediary is constant and given by parameter α^B. This means that the ratio of the surplus for the intermediary to the surplus for the worker is constant and given by:

$$\frac{V_t^F}{V_t^N - V_t^U} = \frac{\alpha^B}{1 - \alpha_B} \tag{21}$$

Equations 18–21 determine wage as a function of last period unemployment.

Unemployment rate

Current period unemployment is determined using the dynamic equation:

$$U_t = ActivePop_t - N_t$$

where $ActivePop_t$ is the active workforce (sum of unemployed and employed workers), which we assume to be constant.

Calibration

Parameters ω_N^s are calibrated using the sector shares in total employment. ω_N is calibrated by setting the sum of sector shares equal to the total employment in the steady state. We set high elasticity of transformation between labour in different sectors ($\varepsilon_L = 1.1$). In other words, we assume that it will be easy for workers to change sector of employment. In the context of our study this will be the case if climate policy is supplemented by reskilling policies assisting the workers in carbon-intensive industries to find jobs in other sectors.

We use equations (17) and (16) to link φ and probability of filling the vacancy (Φ_t). Next, we fix probability of filling the vacancy in the steady state and use the link to calibrate φ. We assume that in the steady state the probability of filling the vacancy is equal to 0.9, as suggested by Andolfatto (1996). We also assume that job destruction rate is 3%.

We set cost of posting vacancies (ν_{Vac}) to 0.3% of GDP and firms bargaining power to 0.4. These values are comparable to the values chosen by Cheron and Langot, 2004 (0.5% and 0.6 respectively). The elasticity of the matching rate with respect to number of vacancies (ε_J) is set to 0.7. This value was chosen in order to obtain realistic reactions of unemployment to productivity shocks. It is comparable to the estimates by Blanchard and Diamond (1989) who suggested the value of 0.5.

Share of active population (*ActivePop*) in the model is fixed and computed by deducting share of inactive population from unity. According to national statistics the average share in the period 2009–2018 was 45.1%.

The parameter b determining value of being unemployed (relative to value of consumption) in the utility function is calibrated using share of unemployed workers in the steady state.

One period in the model is one quarter. The discount factor used to discount future utility and profits (λ) for all firms and consumers is set to 0.99, which is consistent with a steady-state real interest rate of 1 percent (per quarter).

Demand and productivity parameters are calibrated to ensure that sector output and use of inputs in each sector in the steady state of the economy is matched exactly to the statistical data for Poland. The primary source of these data is the input-output table from year 2015.

We set elasticity of substitution between electricity and capital to 0.24 and between fossil fuels and other materials to 0.11. Okagawa and Ban (2008) and Kuper and Van Soest, 2003 suggest that the elasticity of substitution between energy and capital is not significantly different from zero. On the other hand, studies that focus on the long-run reactions of the economy suggest that the value of this elasticity is close to unity (Hassler et al., 2012). Since our study concentrates on short- and medium-run, we decided to choose a value which is closer to zero. For the same reason we also assume low intra-fuel substitutability (elasticity equal to 0.21).

Most share parameters (productivity, demand parameters, unemployment) are calibrated to statistical data for Poland. Elasticity parameters (e.g. elasticity of substitution between capital and energy) are taken from international literature (see the paragraph above). We decided to use these estimates for the Polish model because they comes from recognized publications and because they reflect the potential of technologies (e.g. the possibility to substitute energy with capital), which is global in nature. Finally, in some cases (e.g. cost of vacancies as a fraction of GDP) we use the estimates from international literature because, to our knowledge, estimates for Poland are not available.

References

Alton, T., Arndt, C., Davies, R., Hartley, F., Makrelov, K., Thurlow, J., Ubogu, D., 2014. Introducing carbon taxes in South Africa. Appl. Energy 116, 344–354.

Andolfatto, D., 1996. Business cycles and labor-market search. Am. Econ. Rev. 86 (1), 112–132.

Antosiewicz, M., Kowal, P., 2016. MEMO III - A Large Scale Multi-Sector DSGE Model. IBS Research Report 02/2016. Available online. http://ibs.org.pl/en/publications/memo-iii-a-large-scale-dsge-model/.

Antosiewicz, M., Lewandowski, P., Witajewski-Baltvilks, J., 2016. Input vs. Output taxation—a DSGE approach to modelling resource decoupling. Sustainability 8 (4), 1–17 (April).

Aubert, D., Chiroleu-Assouline, M., 2019. Environmental tax reform and income distribution with imperfect heterogeneous labour markets. Eur. Econ. Rev. 116, 60–82.

Berry, A., 2019. Compensating households from carbon tax regressivity and fuel poverty: a microsimulation study. Energy Pol. 124, 81–94. https://doi.org/10.1016/j.enpol.2018.09.021.

Blanchard, O.J., Diamond, P.A., 1989. The Aggregate Matching Function. NBER working paper, p. w3175.

Brzeziński, M., 2017. Is High Inequality an Issue in Poland? IBS Policy Paper No. 01/2017.

Brzeziński, M., Myck, M., Najsztub, M., . Sharing the gains of transition: evaluating changes in income inequality and redistribution in Poland using combined survey and tax return data. Eur. J. Polit. Econ. 102121.

Buchs, M., Bardsley, N., Duwe, S., 2011. Who bears the brunt? Distributional effects of climate change mitigation policies. Crit. Soc. Pol. 31 (2), 285–307.

Bukowski, P., Novokmet, F., 2021. Between communism and capitalism: long-term inequality in Poland, 1892–2015. J. Econ. Growth 26, 187–239.

Bureau, B., 2011. Distributional effects of a carbon tax on car fuels in France. Energy Econ. 33 (1), 121–130.

Callan, T., Lyons, S., Scott, S., Tol, R.S., Verde, S., 2009. The distributional implications of a carbon tax in Ireland. Energy Pol. 37 (2), 407–412.

Cheron, A., Langot, F., 2004. Labor market search and real business cycles: reconciling Nash bargaining with the real wage dynamics. Rev. Econ. Dynam. 7 (2), 476–493.

Curtis, E.M., 2018. Who loses under cap-and-trade programs? The labor market effects of the NOx budget trading program. Rev. Econ. Stat. 100 (1), 151–166.

da Silva Freitas, L.F., de Santana Ribeiro, L.C., de Souza, K.B., Hewings, G.J.D., 2016. The distributional effects of emissions taxation in Brazil and their implications for climate policy. Energy Econ. 59, 37–44.

Eisner, A., Kulmer, V., Kortschak, D., 2021. Distributional effects of carbon pricing when considering household heterogeneity: an EASI application for Austria. Energy Pol. 156 https://doi.org/10.1016/j.enpol.2021.112478.

Energy Policy of Poland, 2019. Ministry of Energy. Available online at. https://www.gov.pl/web/aktywa-panstwowe/polityka-energetyczna-polski-do-2040-r-zaproszenie-do-konsultacji1 (accessed on 7th March 2020).

Fæhn, T., Gómez-Plana, A.G., Kverndokk, S., 2009. Can a carbon permit system reduce Spanish unemployment? Energy Econ. 31 (4), 595–604.

Feng, K., Hubacek, K., Guan, D., Contestabile, M., Minx, J., Barrett, J., 2010. Distributional effects of climate change taxation: the case of the UK. Environ. Sci. Technol. 44 (10), 3670–3676.

Goraus, K.M., Inchauste, M.G., 2016. The Distributional Impact of Taxes and Transfers in Poland. Policy Research Working Paper; no. WPS 7787. World Bank Group, Washington, D.C.

Goulder, L.H., Schein, A.R., 2013. Carbon taxes versus cap and trade: a critical review. Clim. Change Econ. 4, 1350010, 03.

Goulder, L.H., Hafstead, M.A., Kim, G., Long, X., 2019. Impacts of a carbon tax across US household income groups: what are the equity-efficiency trade-offs? J. Publ. Econ. 175, 44–64.

Hafstead, M.A.C., Williams, R.C., 2018. Unemployment and environmental regulation in general equilibrium. J. Publ. Econ. 160, 50–65.

Hafstead, M.A.C., Williams, R.C., 2019. Distributional Effects of Environmental Policy across Workers: A General-Equilibrium Analysis. Tech. rept. Resources for the Future, Washington, DC.

Hafstead, M.A.C., Williams, R.C., 2020. Jobs and environmental regulation. Environ. Energy Pol. Econ. 1, 192–240.

Hafstead, M.A.C., Williams, R.C., Chen, Y., 2021. Environmental Policy, Full-Employment Models, and Employment: A Critical Analysis. Journal of the Association of Environmental and Resource Economists, forthcoming.

Hamilton, K., Cameron, G., 1994. Simulating the Distributional Effects of a Canadian Carbon Tax. Canadian Public Policy/Analyse de Politiques, pp. 385–399.

Hassler, J., Krusell, P., Olovsson, C., 2012. Energy-saving Technical Change. National Bureau of Economic Research. No. w18456.

IPCC, Change [Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C.T., 2014. Zwickel. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jiang, Z., Shao, S., 2014. Distributional effects of a carbon tax on Chinese households: a case of Shanghai. Energy Pol. 73, 269–277.

Johnstone, N., Serret, Y., 2006. 1. Distributional effects of environmental policy: introduction. In: The Distributional Effects of Environmental Policy, 614, p. 1.

Kiewra, D., Szpor, A., Witajewski-Baltvilks, J., 2019. Sprawiedliwa Transformacja Węglowa W Regionie śląskim. Implikacje Dla Rynku Pracy. IBS Research Report 02/2019, May 2019.
Kirchner, M., Sommer, M., Kratena, K., Kletzan-Slamanig, D., Kettner-Marx, C., 2019. Co2 taxes, equity and the double dividend–macroeconomic model simulations for Austria. Energy Pol. 126, 295–314.
Kuper, G.H., Van Soest, D.P., 2003. Path-dependency and input substitution: implications for energy policy modelling. Energy Econ. 25 (4), 397–407.
Labandeira, X., Labeaga, J., 1999. Combining input-output analysis and micro-simulation to assess the effects of carbon taxation on Spanish households. Fisc. Stud. 20 (3), 305–320.
Lewandowski, P., Magda, I., 2018. The Labor Market in Poland, 2000-2016. IZA World of Labor 2018, p. 426. https://doi.org/10.15185/izawol.426.
Liang, Q.M., Wei, Y.M., 2012. Distributional impacts of taxing carbon in China: results from the CEEPA model. Appl. Energy 92, 545–551.
Mortensen, D.T., Pissarides, C.A., 1994. Job creation and job destruction in the theory of unemployment. Rev. Econ. Stud. 61, *3* 397–415.
Okagawa, A., Ban, K., 2008. Estimation of substitution elasticities for CGE models. In: Discussion Papers in Economics and Business, 16.
Rausch, S., Metcalf, G.E., Reilly, J.M., 2011. Distributional impacts of carbon pricing: a general equilibrium approach with micro-data for households. Energy Econ. 33, 20–33.
Renner, S., Lay, J., Greve, H., 2018. Household welfare and co2 emission impacts of energy and carbon taxes in Mexico. Energy Econ. 72, 222–235.
Sokołowski, J., Lewandowski, P., Kiełczewska, A., Bouzarovski, S., 2020. A multidimensional index to measure energy poverty: the Polish case. Energy Sources B Energy Econ. Plann. 1–21.
Sovacool, B.K., Ryan, S.E., Stern, P.C., Janda, K., Rochlin, G., Spreng, D., et al., 2015. Integrating social science in energy research. Energy Res. Soc. Sci. 6, 95–99.
Takeda, S., 2007. The double dividend from carbon regulations in Japan. The Jpn. Int Econ. 21, 336–364.
Van Heerden, J., Gerlagh, R., Blignaut, J., Horridge, M., Hess, S., Mabugu, R., Mabugu, M., 2006. Searching for Triple Dividends in South Africa: fighting CO2 pollution and poverty while promoting growth. Energy J. 113–141.
Witajewski-Baltvilks, J.I., Lewandowski, P., Szpor, A., Baran, J., Antosiewicz, M., 2018. Managing Coal Sector Transition under the Ambitious Emission Reduction Scenario in Poland. Focus on Labour. IBS Research Reports 04/2018. Instytut Badan Strukturalnych.
Żuk, P., Szulecki, K., 2020. Unpacking the right-populist threat to climate action: Poland's pro-governmental media on energy transition and climate change. Energy Res. Soc. Sci. 66, 101485.