Central European Economic Journal

sciendo

ISSN: 2543-6821 (online)

Journal homepage: http://ceej.wne.uw.edu.pl

Jan Witajewski-Baltvilks,
Jakub Boratyński

Workers or Consumers: Who Pays for Low-Carbon Transition – Theoretical Analysis of Welfare Change in General Equilibrium Setting

To cite this article

Witajewski-Baltvilks, J., Boratyński, J. (2021). Workers or Consumers: Who Pays for Low-Carbon Transition – Theoretical Analysis of Welfare Change in General Equilibrium Setting. Central European Economic Journal, 8(55), 231-245.

DOI: 10.2478/ceej-2021-0017

To link to this article: https://doi.org/10.2478/ceej-2021-0017

This article was edited by Guest Editor:

Mikołaj Czajkowski
University of Warsaw, Poland

as part of the Special Call to mark the 70th Birthday of Prof. Tomasz Żylicz

Central European Economic Journal

Jan Witajewski-Baltvilks
University of Warsaw, Poland
corresponding author: jwitajewski@wne.uw.edu.pl

Jakub Boratyński
University of Lodz, Poland

Workers or Consumers: Who Pays for Low-Carbon Transition – Theoretical Analysis of Welfare Change in General Equilibrium Setting

Abstract

Policies that are introduced to mitigate adverse consequences of climate change involve economic costs. For some households, these costs will materialise in the form of an increase in prices of consumption goods, whereas for others they will materialise in the form of falling productivity and wages. Disentangling these two effects is important in the light of the design of funds that aim to support the households that are negatively affected by climate policy. In this article, we study the effect of carbon tax on welfare through changes of consumer prices and wages in a general equilibrium setting. In the first step, we review the literature on 'top-down' models, which are used to evaluate the macroeconomic cost of climate policy. We find that these models usually do not account for loss of productivity of workers who must change their sector due to climate policy. In the second step, we develop a theoretical, micro-founded, two-sector model that explicitly accounts for the loss of productivity of workers. The compensation of climate-change mitigation costs would require allocation of separate funds for the affected consumers and workers.

Keywords

computable general equilibrium models | integrated assessment models | just transition | macroeconomic costs of transition | welfare compensation

JEL Codes

Q52

1. Introduction

Limiting an increase in global temperatures requires deep changes to be made to the structure of the economy. Attaining the RCP 1.9 target[1], which corresponds to approximately a 1.5 °C increase in temperature above its pre-industrial level (Rogelj et al., 2018), requires 41% reduction in global CO_2 emissions between 2010 and 2030 and 91% reduction between 2010 and 2050 (Riahi et al., 2017). These projections had profound consequences for planned policies: decision makers declared that their goal was to reach net-zero emissions by 2050[2] in the EU and by 2060 in China. Achieving such substantial reduction in emissions implies the need for a large change in production methods, particularly in the sectors of energy, transport and agriculture (IPCC, 2014).

At the same time, models that link the size of the greenhouse effect to the structure of the economy (known as integrated assessment models (IAMs)) predict that change of this structure will be associated with economic cost. IAMs (including computable general equilibrium (CGE) models) are designed to describe the structure of global or regional economy

1 Representative Concentration Pathway with radiative forcing of 1.9 W/m^2 in 2100

2 Total CO_2 emissions under the 'intermediate challenges' Shared Socioeconomic Pathway (SSP2) scenario (the structure may be constituted by the following elements, among others: use of resources, production technologies, expected innovations, consumption and trade patterns) and simulate its change under low-carbon pathways. The models used in the IPCC 5th Assessment Report suggest that the global cost of an ambitious mitigation scenario (limiting greenhouse gas stock to 430–480 ppm CO_2 eq) would be in the range of 2–4% of annual GDP in 2050 (IPCC, 2014). Mitigation costs in terms of reduced consumption were also found in regional studies (see, for instance, Kiuila, 2018 and Antosiewicz et al., 2020).

However, IAMs provide no insight on how these costs will materialise in the budgets and welfare of households. To what extent will the burden of climate policy affect households through an increase in prices of consumption goods (consumption channel) and to what extent through changes in productivity and wages (wage channel)?

The relevance of this question stems from the heterogeneity of households. If consumers were homogeneous, the distinction between consumption and wage channels would not matter in general equilibrium: increase in consumption price index and drop in wage has exactly the same effect on real income and welfare. However, when each household is differently affected by changes in prices and wages, the distinction between the two channels is necessary for determining the ultimate distribution of burden of the transition across society.

The purpose of this article is to review the existing literature and devise a new conceptual framework for understanding how the change in households' welfare due to climate policy depends on their pattern of consumption and allocation of labour. Our analysis will focus on the effects that are induced by carbon tax. We consider all effects in general equilibrium setting, that is, we will analyse not only the consequences of changes in prices of carbon-intensive goods, but also the changes of all prices and wages in the economy, including those associated with the production of carbon-free goods.

Although our endeavour is purely theoretical, it has two direct practical motivations. First, it addresses the question of whether potential compensation for the losers of low-carbon transition should be based purely on criteria related to consumption of carbon-intensive goods (such as energy) or also on consumption of other goods and employment in carbon-free and carbon-intensive sectors. Such compensation is feasible, because it could be, at least partly, financed by revenue from carbon tax. It can be partly financed also by foreign governments or supranational organisations that are willing to encourage and support the de-carbonisation in regions where the costs of low-carbon transition are high. An example of the planned compensation fund is a Just Transition Fund in the European Union (European Commission, 2020), which is financed from the common EU budget.

Second, our study sheds new light on the interpretation of cost projections generated by IAMs. Specifically, we use our framework to argue that general equilibrium IAMs that assume homogeneity across labour types are not able to show the costs of climate policy that affect households through the wage channel. As a result, such models underestimate the total macroeconomic costs of climate policy.

Indeed, the results of our study show that households employed in carbon-intensive sectors need to be compensated to prevent them from being worse off after the transition, even though predictions of standard economic models would deny there is such a need. The reason for this compensation is that workers will lose part of their productivity (and labour income) after moving from their current first-best choice of sector to the second-best. Moreover, we argue that households that do not consume carbon-intensive goods and are not employed in sectors producing these goods do not require any compensation, even when all general equilibrium effects are taken into account.

The remaining part of this article is structured as follows: in Section 2 we review the literature, focusing on works related to general equilibrium modelling of labour market and welfare in the context of climate policy. Section 3 presents the set-up of our model and the key theoretical results. Section 4 concludes the article.

2. Literature Review

The literature review consists of two parts. We first survey a broader stream of research on the economic effects of climate policies, discussing how our study fits into that context. Subsequently, we analyse in more detail the contributions that take a similar methodological perspective to the one adopted in our work, namely the top-down, general equilibrium setting. While we do not explicitly follow the ways in which labour heterogeneity has been addressed in the CGE models, as reviewed below, the discussion of related methodological concepts facilitates exposition of our approach.

There has been an emerging literature on just transition and the distributional consequences of climate policies. One strand of this literature is descriptive studies that analyse the difficulties associated with moving labour away from carbon-intensive sectors (Spencer et al., 2018, Sartor, 2018, Swilling et al., 2016, Leipprand and Flachsland, 2018, Turnheim and Geels, 2012 and Skoczkowski et al., 2020).

The second strand is studies that analyse the impact of climate policy on households in different income deciles using microdata (e.g. Levinson, 2019, Davis and Knittel, 2019, Cronin et al., 2019, da Silva Freitas et al., 2016, Bureau, 2011, Antosiewicz et al., 2020). Those models, however, do not account for changes in wages (with few exceptions, such as the study by da Silva Freitas et al., 2016 and Antosiewicz et al., 2020). Moreover, they consider only changes in prices that are directly induced by the change in carbon tax and do not account for feedback between changes of demand and changes of all prices in general equilibrium.

Numerical IAMs used in designing socially optimal transition pathways generate predictions by considering either cost-minimising choice between a large set of technologies (bottom-up approach) or the optimal decisions of firms and consumers in general equilibrium (top-down approach, which we review below). The recent article by Baran et al. (2020) demonstrated with an analytical model that the costs of transition projected by bottom-up models ignore the costs associated with frictional movement of labour across sectors. Our study develops an analytical model that extends this argument to costs projected by top-down CGE models.

CGE models have been workhorses of numerous studies of economic effects of climate policies, largely due to their detailed, industry-level representation of energy demand and supply, and greenhouse gas emissions. However, as noted by Boeters and Savard (2013, p. 1645), labour market has not been in the focus of the CGE modelling field, and this also holds in the case of climate- and energy-related applications. Common simplifying assumptions include homogeneity of labour force and fixed labour supply.

The starting point of the theoretical approach proposed in this article is the explicit differentiation between productivity of the same person employed in different sectors. To our knowledge, such a specific setting has not been explored so far. Yet, various related concepts are present in the CGE field. These include, inter alia, heterogeneous agents, welfare decomposition, and labour adjustment costs. Below we briefly review these methodological viewpoints.

One straightforward way to distinguish different labour varieties is by means of constant elasticity of transformation (CET) function (Boeters and Savard, 2013, p. 1659–1660). The basic formulation assumes that aggregate labour supply – e.g. total available hours of work – is allocated between two or more 'uses', to maximise total labour income, given relative wages. Such an approach allows the capturing of (i) differences in wages of distinct labour varieties and (ii) costs for the economy that are related to reallocation of labour between occupations or sectors, e.g. invoked by tax policy. On the other hand, since this formulation relies – at least in a literal interpretation – on the assumption of a representative agent who earns income from all labour varieties, it does not allude to the explicit analysis of welfare effects for distinct household or worker groups.

Dixon and Rimmer (2002, p. 289–299) propose a framework in which labour market adjustment costs are recognised explicitly. Adjustment costs are associated with year-to-year flows of people between different states in the labour market, such as between occupations, regions or industries of employment, from or into unemployment, or from or into labour force. For example, a flow of a worker from one occupation to another one may impose a cost related to training, modelled in terms of productivity loss in a given year. Notably, such an approach requires a dynamic model setting. Adjustment costs are temporary (one-off) – contrary to the CET-based formulations, in which changes in allocative efficiency are sustained. In the approach proposed by Dixon and Rimmer (2002, p. 289–299), aggregate adjustment cost generally depends on the rate of structural changes – in case that rate is low, adjustment will largely be accommodated by retirements and inflows of new workers, whereas with larger changes, labour force movements will impose a higher adjustment cost.

The above-mentioned approaches introduce labour disaggregation; yet, they stick to the (multiple) representative agent's paradigm. With recent advances in trade theory, pioneered by Melitz (2003), a new perspective on heterogeneity has made its way to the CGE field. CGE models introducing Melitz in place of the standard, Armington specification of foreign trade (see Balistreri and Rutherford, 2013; Dixon et al., 2016) assume that each industry is composed of a continuum of firms with different productivities. Productivity distribution is characterised by probability density. An implication of such a framework is that, for example, increase in trade protection has an adverse effect on productivity in domestic trade-exposed industries, because trade barriers allow certain less productive firms to remain in the market.

As demonstrated by Dixon et al. (2016), with a choice of a specific distribution of firm productivity levels – namely the Pareto distribution – the micro-founded model is transformed into straightforward aggregate equations. In the same vein, other authors have shown that constant elasticity of substitution (CES) demand functions can be interpreted as an aggregate representation of a discrete choice model of heterogeneous individuals (Anderson et al., 1987, 1988; Matveenko, 2020). Similarly, Growiec (2013) provides a micro-foundation for CES production functions with factor-augmenting technical change. Our article follows an analogous general strategy.

CGE-based studies that considered low-carbon transition, leaning towards the labour-market perspective, sometimes did so by examining the impact on unemployment (see, for example, Küster et al., 2007 and Böhringer et al., 2012). In some studies, the picture of employment/unemployment effects is enriched with equity impacts. Huang et al. (2020) adopt such a perspective, as they simulate clean energy transformation in China using the CGE framework, addressing equity issues in the context of migration and urbanisation. An example of a simulation study in a more comprehensive theoretical setting, beyond typical CGE models, is the work by Rengs et al. (2020). They use an agent-based model with interacting heterogeneous households and firms, subject to bounded rationality, to study the effects of different scenarios of carbon taxation and the use of carbon tax revenues. They show that alternative combinations of policy instruments may lead, for example, to similar environmental outcomes with varying impacts on unemployment. The multi-agent setting (5,000 households, 250 firms) allows explicit tracking of distributional consequences of policies.

It is not a very frequent practice to report and decompose CGE model results in the field of climate policy analysis in terms of welfare effects, using equivalent variation (EV) measures, although relevant methodological approaches have been proposed in the literature. Hanslow (2000) provides a general framework for a comprehensive decomposition of a change in welfare, breaking it down into, among other things, contribution of a change in endowments, terms of trade, asset prices, allocative efficiency, technical efficiency, etc. Huff and Hertel (2001) formulate a similar decomposition, tailored to the well-known GTAP model. Dixon and Rimmer (2008) is an example of welfare decomposition related to unilateral tariff change. In the context of climate policy analysis, welfare decomposition techniques have been applied by, for example, Böhringer (2000) and Böhringer and Rutherford (2000). The latter work tracks welfare changes in specific countries to specific policy instruments, such as emission taxes or emission caps, as applied by other countries.

We believe that this article adds to the CGE literature in two aspects. First, it provides micro-foundations – distribution of individual productivities and preferences and a corresponding discrete-choice labour supply model – for the analysis of sectoral allocation of labour, and its consequences for aggregate productivity. Second, it provides a decomposition of the impact of 'dirty' goods taxation on aggregate welfare, in a theoretical general equilibrium setting, referring to the characteristics of the distributions of productivity and preferences.

3. Model

To compute cost of climate policy for individuals, we will determine EV, i.e. the amount of money that would need to be deducted from income of an individual in the situation with no policy to set his or her utility to the same level as in the situation when the policy is present.

In the first step, we will derive EV as a function of prices and incomes, using money metric indirect utility function. Next, we determine the equilibrium changes in prices and income for each individual resulting from the implementation of a policy. At this stage we also make assumptions regarding the distribution of types of individuals with respect to their preferences and human capital.

It is emphasised that the model developed in this section is meant to imitate the logic of top-down models; however, its structure is far less detailed. Indeed, our intention is to simplify the model to the level that ensures tractability and allows us to construct a micro-founded narrative.

3.1. Money metric indirect utility function

We assume that consumer derives utility from two goods, dirty (subscript $_d$) and clean (subscript $_c$). This simple distinction is borrowed from the literature of directed technological change. In the context of climate policy, dirty goods could stand for a composite of carbon-intensive goods, such as fuels used for transportation, fuels for heating or coal-based electricity. Clean goods stand for the composite of carbon-neutral goods, including energy derived from carbon-free sources. In Section A1 in Appendix, we provide an alternative specification with consumers deriving utility from a variety of goods, each produced using a Cobb–Douglas technology that combines carbon-intensive and carbon-free inputs. Although this alternative specification is more realistic and closer to the specification of the top-down models, it also adds to complexity of the model applied in this article. Since, as we demonstrate in Appendix, the predictions of the two specifications are the same, in the main text of this article we use the simpler specification with just two goods.

We also assume that the direct utility function takes the Cobb–Douglas form; therefore, $u = x_c^{\beta} x_d^{1-\beta}$.

Later in the article, we will assume that the share parameter β is a random variable that takes different values for different individuals in the economy. However, at this stage, when our derivations are focused on an individual consumer, we can treat β to be constant.

Finally, we assume that the before-tax prices of dirty and clean goods are p_c and p_d. The dirty goods are taxed at the rate κ, so that after-tax price of these goods is $(1+\kappa)p_d$. We will model climate policy by increasing $(1+\kappa)$ from unity (no policy case) to $(1+\kappa)>1$. We assume there are no taxes on clean goods.

We derive money metric indirect utility function (which is the basis for computing EV) in two steps. First, we find expenditure function and then we find indirect utility function (see Mas-Colell et al., 1995)

Expenditure function could be derived from the consumer minimisation problem: $\min p_c x_c + p_d x_d$ subject to $x_c^{\beta} x_d^{1-\beta} = u$, where u is the utility level. The optimal value function for that problem is given by

$$e(p,u) = \frac{p_c^{\beta}\left((1+\kappa)p_d\right)^{1-\beta} u}{\beta^{\beta}(1-\beta)^{\beta}},$$

where $p = \left(p_c, (1+\kappa)p_d\right)$ is a vector of after-tax prices.

Next, we find an indirect utility function by inverting the function above, thus giving rise to the following equation:

$$v(p,Y) = \beta^{\beta}(1-\beta)^{1-\beta} \frac{Y}{p_c^{\beta}\left((1+\kappa)p_d\right)^{1-\beta}} \quad (1),$$

where Y is the income of an individual.

We can now state the money metric indirect utility function by evaluating expenditure function at the reference price level, $p^R = \left(p_c^R, p_d^R\right)$ and at the utility level for prices (p_c, p_d) and income Y, in the form of the following equation:

$$e\left(p^R, v(p,Y)\right) = Y\left(\frac{1+\kappa_R}{1+\kappa}\right)\frac{\left(p_c^R\right)^{\beta}\left(p_d^R\right)^{1-\beta}}{p_c^{\beta} p_d^{1-\beta}} \quad (2).$$

When reference prices are treated as constant, money metric indirect utility function is an indirect utility function (it may be noted that the function is a simple monotonous transformation of indirect utility function in Eq. (1)). In addition, if we set reference price at the level with no policy ($(1+\kappa)=1$), we can compute EV as:

$$EV = e\left(p^R, v(p,Y)\right) - e\left(p^R, v\left(p^R, Y^R\right)\right)$$
$$= e\left(p^R, v(p,Y)\right) - Y^R \quad (3),$$

where Y_R is the income in the situation when climate policy is absent.

3.2. Heterogeneous workers and their choices

In this subsection, we clarify our assumption regarding the distribution of types of individuals. Next, we find general equilibrium level of prices for the aggregate economy.

Goods $j=(c,d)$ are produced by competitive firms using only one input, namely labour. The production function is given by $X_j = A_j L_j$, where L_j denotes efficient units of labour (which are not the same as physical units of labour). Since the production function features constant returns to scale, firms generate no profit.

Each individual possesses one unit of physical labour of type i. In the remaining part of this article, we label that unit as worker of type i. A worker could be employed either in clean or in the dirty sector; however his or her productivity differs between sectors. Specifically, we assume that the productivity of worker of type i in sector j is θ_{ij}. θ_{ij} could be also interpreted as the potential amount of efficient labour delivered to sector j by worker i if he or she decides to choose that sector.

Supposing that the compensation per efficient unit of labour in sector j is w_j, then, we can postulate that worker i employed in that sector receives $\theta_{ij} w_j$. Finally, we suppose that there is a continuum of labour types and that θ_j are random variables with distribution described by the cdf $F(\theta_j)$, and θ_{ij} are the realisations of this random variable for an individual i. Let f denote the probability density function (pdf) of the distribution. Worker i chooses to work in the dirty sector if and only if $\theta_{id} w_d \geq \theta_{ic} w_c$.

Consider now workers of type i with productivity in the clean sector given by θ_{ic}. Within this group, the fraction of workers who decide to work in the dirty sector is given by:

$$P(\theta_{id} w_d \geq \theta_{ic} w_c \mid \theta_{ic}) = F\left(\frac{\theta_{ic} w_c}{w_d}\right).$$

Therefore, the fraction of all workers (fraction of physical labour) who decide to choose the dirty sector, n_d, is given by $n_d = \int F\left(\frac{\theta_c w_c}{w_d}\right) f(\theta_c) d\theta_c$.

At this step, we need to assume the functional form of F. To ensure that general equilibrium prices could be determined with closed form solution, we assume that the distribution-of-productivity parameter θ_j has a Frechet distribution whose cumulative density function is given by:

$$F(\theta_j) = \exp\left(-\left(\frac{\theta_j}{s_j}\right)^{-\alpha}\right),$$

where α is the shape parameter and s_j is the sector specific scale parameter. The probability density function is given by:

$$f(\theta_j) = \exp\left(-\left(\frac{\theta_j}{s_j}\right)^{-\alpha}\right)\left(\frac{\theta_j}{s_j}\right)^{-\alpha-1} \frac{\alpha}{s_j}.$$

It may be noted that when $\alpha \to \infty$, all workers become identical.

In this case, the fraction of workers who choose to work in sector j becomes:

$$n_j = \left(\frac{s_j w_j}{\left(\sum_k (s_k w_k)^{\alpha}\right)^{\frac{1}{\alpha}}}\right)^{\alpha} \int g(\theta_j) d\theta_j,$$

where $g(\theta_j) = \exp\left(-(K_j \theta_j)^{-\alpha}\right)(K_j \theta_j)^{-\alpha-1} \alpha K_j$

and $K_j = \frac{w_j}{\left(\sum_k (s_k w_k)^{\alpha}\right)^{\frac{1}{\alpha}}}$.

It may be noticed that $g(\theta_j)$ is the pdf of the Frechet distribution with parameters α and $\tilde{s}_j = K_j^{-1}$ (which is different from s_j), so that $\int g(\theta_j) d\theta_j = 1$.

Therefore, the fraction of workers choosing sector d can be reduced to the following simple equation:

$$n_d = \frac{(s_d w_d)^{\alpha}}{(s_d w_d)^{\alpha} + (s_c w_c)^{\alpha}}.$$

Two remarks follow this result. First, α determines the slope of the supply curve of physical labour in the dirty sector. We will use this interpretation of α in propositions further in the article. Second, the expression above determines the fraction of workers who wish to work in the dirty sector as a function of wages and parameters of productivity distribution. This is not the same as the supply of efficiency units delivered by those workers, because each worker could have a different productivity. We determine that supply at the beginning of the forthcoming section.

3.3. Relative prices in general equilibrium

Let L_j be the amount of efficient labour in sector j supplied by workers:

$$L_j = \int \prod_k F\left(\frac{\theta_j w_j}{w_k}\right) f\left(\theta_j\right) \theta_j d\theta_j .$$

It may be noted that L_j is not the same as the physical supply of labour, which is denoted by n_j.

Using the cdf and pdf of the Frechet distribution, this could be stated as $L_j = s_j^{\alpha} K_j^{\alpha} \int g\left(\theta_j\right)\theta_j d\theta_j$.

To evaluate the integral, we note again that $g\left(\theta_j\right)$ is the pdf of the Frechet distribution with parameters α and $\tilde{s}_j = K_j^{-1}$, and thus $\int g\left(\theta_j\right)\theta_j d\theta_j$ must be equal to expected value of random variable under this distribution, which is given by $K_j^{-1}\Gamma\left(1-\frac{1}{\alpha}\right)$, where Γ is the well-known Gamma function. Consequently, supply of efficiency units of labour in sector j could be expressed as a function of wages and parameters of the distribution:

$$L_j = s_j \left(\frac{s_j w_j}{\left(\left(s_d w_d\right)^{\alpha} + \left(s_c w_c\right)^{\alpha}\right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} \Gamma\left(1-\frac{1}{\alpha}\right).$$

Using the production function in each sector and setting $p_j = \frac{w_j}{A_j}$ (due to perfect competition between firms; see the more detailed derivations in Section A2 in Appendix), we can express the supply of good j as:

$$X_j = A_j s_j \left(\frac{A_j s_j p_j}{\left(\left(A_d s_d p_d\right)^{\alpha} + \left(A_c s_c p_c\right)^{\alpha}\right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} \Gamma\left(1-\frac{1}{\alpha}\right).$$

Meanwhile, demand for dirty goods could be obtained by deriving individual demand from first-order conditions to consumer's minimisation problem and aggregating across consumer types. This results in

$$X_d = \frac{E\left[\left(1-\beta\right)Y\right]}{\left(1+\kappa\right)p_d} \text{ and } X_c = \frac{E\left[\beta Y\right]}{p_c}.$$

Since we assumed that β and θ are independent, it must be correct that β and $Y = \max\left\{\theta_c w_c, \theta_d w_d\right\}$ are also independent and that $E\left[\left(1-\beta\right)Y\right] = E\left[1-\beta\right]E\left[Y\right]$. Finally, equalising relative demand with relative supply allows the determination of equilibrium relative prices, as follows:

$$\frac{p_d}{p_c} = \left(\frac{A_d s_d}{A_c s_c}\right)^{-1} \left(\frac{1-\bar{\beta}}{\bar{\beta}\left(1+\kappa\right)}\right)^{\frac{1}{\alpha}}, \text{ where } \bar{\beta} = E\left[\beta\right].$$

On the one hand, relative prices are determined by the parameters of the distribution of productivity. For instance, if a relatively large share of workers has high productivity in the dirty sector (s_d / s_c is large), this can be an indication that a large number of workers wish to choose to work in that sector. In this case, the labour supply curve in the dirty sector would be moved to the right relative to the one in the clean sector. Therefore, wages per efficiency unit in the dirty sector would be relatively low. Intuitively, if everyone could work in the dirty sector but only few could offer productive labour in the clean sector, the wage would need to be higher in the clean sector to reflect the scarcity of talent there.

On the other hand, relative prices are determined by the production technology and preferences of consumers. If, on average, consumers demand more clean goods ($\bar{\beta}$ is high) or if the clean sector has relatively low productivity (A_d / A_c is low), the relative demand for workers in that sector is high. The clean sector would need to attract not only those who are productive in the clean sector but also those who have relatively high productivity in the dirty sector. To do so, firms in the clean sector would need to offer relatively a high wage per efficiency unit.

We notice also that this result (and indeed all other results in this article) do not require assumptions on the shape of the distribution of β. The only parameter of this distribution, which is relevant for the results, is the expected value, $\bar{\beta}$.

3.4. Level of prices and the choice of numeraire

The level of prices depends on the choice of numeraire. We choose the consumer price index (CPI) of the representative consumer as follows:

$$p_c^{\bar{\beta}}\left(\left(1+\kappa\right)p_d\right)^{1-\bar{\beta}}=1 \quad (4).$$

In this case, the prices of dirty and clean goods become[3]:

$$p_d=\left(\left(\frac{\bar{\beta}}{1-\bar{\beta}}\right)^{\frac{\rho-1}{\rho}}\frac{A_d s_d}{A_c s_c}\right)^{-\bar{\beta}}\left(1+\kappa\right)^{\frac{\bar{\beta}-\rho}{\rho}} \quad (5)$$

and

$$p_c=\left(\left(\frac{\bar{\beta}}{1-\bar{\beta}}\right)^{\frac{\rho-1}{\rho}}\frac{A_d s_d}{A_c s_c}\right)^{1-\bar{\beta}}\left(1+\kappa\right)^{\frac{-(1-\bar{\beta})}{\rho}} \quad (6)$$

where $\rho=\dfrac{\alpha}{\alpha-1}$.

To ensure interior solution later on, we assume $\alpha\geq 1$; therefore, $\rho\geq 1$.

Finally, we recover levels of wages in each sector to be the following:

$$w_c=A_c p_c=\varphi\left(1+\kappa\right)^{\frac{-(1-\bar{\beta})}{\rho}}\frac{\omega_c}{s_c}$$

and

$$w_d=A_d p_d=\varphi\left(1+\kappa\right)^{\frac{-(\rho-\bar{\beta})}{\rho}}\frac{\omega_d}{s_d},$$

where $\varphi=\left(A_c s_c\right)^{\bar{\beta}}\left(A_d s_d\right)^{1-\bar{\beta}}$, $\omega_c=\left(\dfrac{\bar{\beta}}{1-\bar{\beta}}\right)^{\frac{(1-\bar{\beta})(\rho-1)}{\rho}}$ and $\omega_d=\left(\dfrac{1-\bar{\beta}}{\bar{\beta}}\right)^{\frac{\bar{\beta}(\rho-1)}{\rho}}$.

3.5. EV for an individual

The result in the previous subsection allows us to state the income for individual i to be:

$$Y=\max\left\{\theta_{ic}w_c,\theta_{id}w_d\right\}=$$
$$=\varphi\left(1+\kappa\right)^{\frac{-(1-\bar{\beta})}{\rho}}\max\left\{\frac{\theta_{ic}}{s_c}\omega_c,\frac{\theta_{id}}{s_d}\omega_d\left(1+\kappa\right)^{\frac{-(\rho-1)}{\rho}}\right\}.$$

This, together with expression for prices evaluated above, allows us to express money metric utility as a function of our policy variable $(1+\kappa)$:

$$e\left(p^R,v\left(p,Y\right)\right)=\frac{Y}{\left(\left(1+\kappa\right)p_d\right)^{1-\beta}p_c^{\beta}}=$$
$$=\left(1+\kappa\right)^{\frac{\bar{\beta}-\beta}{\rho}}\varphi\left(1+\kappa\right)^{\frac{-(1-\bar{\beta})}{\rho}}\max\left\{\frac{\theta_{ic}}{s_c}\omega_c,\frac{\theta_{id}}{s_d}\omega_d\left(1+\kappa\right)^{\frac{-(\rho-1)}{\rho}}\right\}=$$
$$=\varphi\left(1+\kappa\right)^{\frac{-(1-\beta)}{\rho}}\max\left\{\frac{\theta_{ic}}{s_c}\omega_c,\frac{\theta_{id}}{s_d}\omega_d\left(1+\kappa\right)^{\frac{-(\rho-1)}{\rho}}\right\}.$$

The term $\left(1+\kappa\right)^{\frac{-(1-\beta)}{\rho}}$ captures the effect on the side of consumption: every individual, regardless of where he or she is employed, will suffer from utility loss due to an increase in price of dirty goods. The size of this effect depends on the share of expenditure that the particular individual devotes for consumption of dirty goods, $(1-\beta)$.

The term

$$\max\left\{\frac{\theta_{ic}}{s_c}\omega_c,\frac{\theta_{id}}{s_d}\omega_d\left(1+\kappa\right)^{\frac{-(\rho-1)}{\rho}}\right\}$$

captures the effect on the labour side: individuals who were employed in the dirty sector before the implementation of the policy will suffer from utility loss due to falling wages in that sector. Some of those individuals (with relatively high θ_{id}) will stay in the

3 Note that price of clean goods is a function of taxes because we chose the CPI of the representative consumer to be a numeraire (see Eq. (4)) in Section 3.4. Since CPI depends on taxes, the price of clean goods also depends on taxes. If, instead, we chose a numeraire that is independent of taxes (e.g. before-tax CPI), the price of clean goods would be independent of taxes.

dirty sector and suffer from wage loss. Others could shift from the dirty to the clean sector but their wages in the clean sector will be lower than the wages they received in dirty sector. Otherwise, they had not chosen to work in the dirty sector before the change.

To analyse this last argument, we observe that individuals who chose employment in the dirty sector earlier must have received higher compensation from work in the dirty sector than in the clean sector, i.e. $\theta_{ic} w_c^R \le \theta_{id} w_d^R$, where $w_j^R \equiv \frac{\varphi \omega_j}{s_j}$ is the wage per efficiency unit of labour in sector j before the introduction of a tax (i.e. for $\left(1+\kappa^R\right)=1$). After setting $\left(1+\kappa\right)>1$, wages in the clean sector decreases to $\theta_{ic} w_c = \varphi \left(1+\kappa\right)^{\frac{-(1-\beta)}{\rho}} \frac{\omega_c}{s_c} < \frac{\varphi \omega_c}{s_c} \le \frac{\varphi \omega_c}{s_c} = \theta_{id} w_d^R$.

We can now express the ratio of EV to individual expenditure in the reference situation of no policy, which is given by

$$e^R \equiv e\left(p^R, v\left(p^R, Y^R\right)\right) = \varphi \max\left\{\frac{\theta_{ic}}{s_c}\omega_c, \frac{\theta_{id}}{s_d}\omega_d\right\}:$$

$$\frac{EV}{e^R} \equiv \frac{e\left(p^R, v(p,Y)\right) - e\left(p^R, v\left(p^R, Y^R\right)\right)}{e\left(p^R, v\left(p^R, Y^R\right)\right)} = \\ = \left(1+\kappa\right)^{\frac{-(1-\beta)}{\rho}} \frac{\max\left\{\frac{\theta_{ic}}{s_c}\omega_c, \frac{\theta_{id}}{s_d}\omega_d \left(1+\kappa\right)^{\frac{-(\rho-1)}{\rho}}\right\}}{\max\left\{\frac{\theta_{ic}}{s_c}\omega_c, \frac{\theta_{id}}{s_d}\omega_d\right\}} - 1 \quad (7).$$

This allows us to derive first conclusions regarding the distribution of compensation across individuals.

Proposition 1. *Assuming constant returns to scale production technology and utility function in the Cobb–Douglas form, the general equilibrium amount of EV to an introduction of carbon tax relative to total household spending*

a) *is null for households that work in the clean sector before the tax is introduced and do not consume any dirty goods;*

b) *is independent of any idiosyncratic productivity parameter (and thus wages) for households that work in the clean sector before the tax is introduced;*

c) *depends on (i) the share of spending on dirty goods and (ii) the slope of the sectoral supply curve (ρ) for households that worked in dirty sectors and did not want to change the sector after introduction of the tax; and*

d) *depends on (i) the share of spending on dirty goods, (ii) the slope of the sectoral supply curve and (iii) relative idiosyncratic productivity in the clean and dirty sectors for households that switched between sectors.*

We emphasise that the results in point (a) of the proposition would be trivial in a partial equilibrium setting: if the prices of exclusively dirty goods vary and all other prices and wages are constant, the tax cannot affect households that do not derive utility from the consumption of dirty goods. The proposition generalises this result to general equilibrium setting.

The reason why point (a) holds in general equilibrium is the presence of constant returns to scale in production technology. If returns to scale were decreasing, an inflow of workers to the clean sector would depress the wages of those who were already there. Similarly, higher demand for clean goods would lead to an increase in its price, thus affecting those households who consumed only clean goods earlier. Constant returns to scale imply that these two mechanisms are absent. Since most CGE models assume constant returns to scale, we expect that the same result will hold also in the CGE setting.

The EV relative to households' spending (derived in (7)) can be decomposed into three components:

$$\frac{EV}{e^R} = = \left(\left(1+\kappa\right)^{\frac{-(1-\beta)}{\rho}} - 1\right) \\ + \left(\frac{\max\left\{\frac{\theta_{ic}}{s_c}\omega_c, \frac{\theta_{id}}{s_d}\omega_d \left(1+\kappa\right)^{\frac{-(\rho-1)}{\rho}}\right\}}{\max\left\{\frac{\theta_{ic}}{s_c}\omega_c, \frac{\theta_{id}}{s_d}\omega_d\right\}} - 1\right) \\ + \left(\left(1+\kappa\right)^{\frac{-(1-\beta)}{\rho}} - 1\right)\left(\frac{\max\left\{\frac{\theta_{ic}}{s_c}\omega_c, \frac{\theta_{id}}{s_d}\omega_d \left(1+\kappa\right)^{\frac{-(\rho-1)}{\rho}}\right\}}{\max\left\{\frac{\theta_{ic}}{s_c}\omega_c, \frac{\theta_{id}}{s_d}\omega_d\right\}} - 1\right) \quad (8)$$

The first term captures the amount of money necessary to compensate the loss of individuals on the consumption side. It may be noted that it depends only on parameters β (specific to each individual), ρ and the size of the tax. In particular, it is independent of productivity of labour provided by that individual in the two sectors. The second term captures the amount necessary to compensate the loss due to reduction in labour income. This part is independent of β and depends only on the productivity parameters $(\theta_{ic},\theta_{id})$. The third term is an interaction term.

3.6. Aggregation of loss

In the last subsection we computed aggregate loss (or aggregate EV) at the economy level. Since population is normalised to unity, aggregate loss could be computed as the expected value of EV. Using Eq. (3), this can be stated as:

$$E[EV]=E\left[e\left(p^R,v(p,Y)\right)\right]-E\left[Y^R\right].$$

The first term can be evaluated using Eqs (2), (5) and (6) as:

$$E\left[e\left(p^R,v(p,Y)\right)\right]=E\left[\frac{p_{Rd}^{1-\beta}p_{Rc}^{\beta}}{\left((1+\kappa)p_d\right)^{1-\beta}p_c^{\beta}}Y\right]=$$

$$=E\left[(1+\kappa)^{\frac{\beta-\bar{\beta}}{\rho}}\max\{\theta_{ic}w_c,\theta_{id}w_d\}\right].$$

Under independence of β and (θ_c,θ_d),

$$E\left[e\left(p^R,v(p,Y)\right)\right]=E\left[(1+\kappa)^{\frac{\beta-\bar{\beta}}{\rho}}\right]E\left[\max\{\theta_{ic}w_c,\theta_{id}w_d\}\right].$$

$E\left[\max\{\theta_{ic}w_c,\theta_{id}w_d\}\right]$ is the expected labour income in the economy. It could be found by determining the distribution of income. Let $G(m)$ be the cumulative density function of that distribution. Under the Frechet distribution-of-productivity parameters (θ_c,θ_d), it can be shown that:

$$G(m)=\exp\left(-\left(\frac{m}{\left(\sum_j(w_js_j)^{\alpha}\right)^{\frac{1}{\alpha}}}\right)^{-\alpha}\right)$$

and that average income in the economy is given by:

$$E[Y]=\Omega(1+\kappa)^{\frac{-(1-\bar{\beta})}{\rho}}\left(\bar{\beta}+\frac{1-\bar{\beta}}{(1+\kappa)}\right)^{\frac{\rho-1}{\rho}},$$

where $\Omega=\dfrac{A_d^{1-\bar{\beta}}A_c^{\bar{\beta}}\Gamma\left(1-\frac{1}{\alpha}\right)}{\left(\bar{\beta}^{\bar{\beta}}(1-\bar{\beta})^{1-\bar{\beta}}\right)^{\frac{(\rho-1)}{\rho}}}$,,

with Γ being the Gamma function (see the detailed derivations in Section A3 in Appendix).

Combining this with previous results in the following expression for expected money metric utility:

$$E\left[e\left(p^R,v(p,Y)\right)\right]=E\left[(1+\kappa)^{\frac{\beta-\bar{\beta}}{\rho}}\right]$$

$$\Omega(1+\kappa)^{\frac{-(1-\bar{\beta})}{\rho}}\left(\bar{\beta}+\frac{1-\bar{\beta}}{(1+\kappa)}\right)^{\frac{\rho-1}{\rho}}=$$

$$=E\left[(1+\kappa)^{\frac{(1-\beta)}{\rho}}\right]\Omega\left(\bar{\beta}+\frac{1-\bar{\beta}}{(1+\kappa)}\right)^{\frac{\rho-1}{\rho}}.$$

It may be noted also that we can find $E\left[Y^R\right]=E\left[e\left(p^R,v\left(p^R,Y^R\right)\right)\right]$ by evaluating the expression above at $(1+\kappa)=1$, which in this case reduces to $E\left[Y^R\right]=\grave{\text{U}}$.

Finally, aggregate EV relative to aggregate income in the reference situation becomes:

$$\frac{E[EV]}{E\left[Y^R\right]}=E\left[(1+\kappa)^{\frac{(1-\beta)}{\rho}}\right]\left(\bar{\beta}+\frac{1-\bar{\beta}}{(1+\kappa)}\right)^{\frac{\rho-1}{\rho}}-1\cdot$$

Proposition 2. *CGE models that assume flat labour supply curve underestimate the total welfare loss due to an introduction of carbon tax if in reality supply curve is upward sloping.*

Proof. *Flat labour supply curve is equivalent to an assumption that* $\rho=1$. *Models making such assumption would predict that EV relative to GDP would be given by* $E\left[(1+\kappa)^{(1-\beta)}\right]-1$ *(using the expression derived above, evaluated at* $\rho=1$*). Since* $\frac{\rho-1}{\rho}\geq 0$ *and* $\rho\geq 1$ *it must be correct that* $(1+\kappa)^{\frac{(1-\beta)}{\rho}}\leq(1+\kappa)^{(1-\beta)}$ *and* $\left(\bar{\beta}+\frac{1-\bar{\beta}}{(1+\kappa)}\right)^{\frac{\rho-1}{\rho}}\leq 1$ *for* $(1+\kappa)>1$. *Moreover, if the assumption of flat supply curve is wrong (as suggested by empirical evidence) and* $\rho>1$, *then all inequalities are slack and the EV is strictly larger (in absolute terms) than that predicted by the model.*

QED

Indeed, empirical evidence suggests that the supply curve at the sectoral level is upward sloping, although the range of estimates is very wide. For instance, Booth and Katic (2011) and Manning (2003) estimate elasticity for monopsonies and obtained the estimates in the range 0.71–0.75. Estimation of long-run elasticity of supply using the methodology proposed by Manning (2003) and estimates of separation rates reported in Ashenfelter et al. (2010) suggest that the long-run elasticity of supply is in the range 3–8.

As before, we can decompose the expected EV relative to GDP into three parts:

$$\frac{E\left[EV\right]}{E\left[Y^R\right]}=\left(E\left[\left(1+\kappa\right)^{\frac{(1-\beta)}{\rho}}\right]-1\right)$$
$$+\left(\left(\bar{\beta}+\frac{1-\bar{\beta}}{\left(1+\kappa\right)}\right)^{\frac{\rho-1}{\rho}}-1\right)$$
$$+\left(E\left[\left(1+\kappa\right)^{\frac{(1-\beta)}{\rho}}\right]-1\right)\left(\left(\bar{\beta}+\frac{1-\bar{\beta}}{\left(1+\kappa\right)}\right)^{\frac{\rho-1}{\rho}}-1\right).$$

The first component determines the size of a hypothetical fund that would be used to compensate individuals for the loss that is captured in the first term of expression in Eq. (8). This fund would be distributed among consumers using consumption pattern as the only criterion for distribution. The second component aggregates the compensations necessary to cover the loss captured in the second term of Eq. (8). This fund would be distributed among workers using relative loss in wages as the only criterion. The third part would be a fund that would need to use both consumption and labour criteria.

4. Conclusions

In this article, we have proposed a heterogeneous agents model, in which individual worker productivity depends on the sector of employment. Taking the climate policy analysis perspective, we have considered two broad sectors – clean (carbon-free) and dirty (carbon-intensive). Each person supplies work to the sector in which he or she obtains higher income, given individual productivity characteristics and sector-specific wages per efficient labour unit. Each worker is also characterised by specific preferences in relation to the consumption of clean and dirty goods. Distributions of productivities and preferences are represented by continuous probability density functions.

We have derived a general equilibrium solution of the above theoretical model, along with the formula for the welfare cost of dirty goods' taxation (e.g. introduction of a carbon tax). The latter is measured in terms of EV, at both individual and aggregate economy level. Furthermore, welfare impact is decomposed to distinguish the cost on the consumption side, which is related to the increase in price of the dirty goods, and the cost related to labour income loss, which stems from productivity decline following labour reallocation.

The following conclusions can be formulated: (i) In general equilibrium, under constant returns to scale in production and the Cobb–Douglas utility function, percentage change in individual household welfare (expressed as a ratio of EV to original spending of the household) due to a carbon tax for households employed (before the tax is introduced) in the clean sector does not depend on their individual productivity, but depends on the consumption pattern. On the other hand, for households employed in the dirty sector, welfare cost depends on the share of spending on dirty goods and the slope of the sectoral supply curve that stems from the shape of productivity distribution in the population. For workers switching from dirty to clean sector, that cost additionally depends on relative productivity in the clean and dirty sectors. (ii) CGE models assuming homogeneous labour force (and thus flat sectoral supply curves) may underestimate the economy-wide cost of carbon taxation.

Envisaged next research steps include calibration of the proposed theoretical model to data, and applying it—in a wider framework of a multi-sector CGE model with energy- and emissions-accounting—to a real-world policy case. This would include a comparison of results with and without the proposed extension. An empirical approach, accompanying the theoretical formulation and allowing the estimation of model parameters, would also be an interesting avenue of further inquiry.

Implementing the complete setup of the model in Section 2 with a continuum of workers types would be challenging due to numerical issues; however, the model could use an equivalent of Eq. (4) as a reduced-form equation relating supply of labour to wages in the clean and dirty sectors.

Quantifying the total welfare loss for different groups of household would also require a more careful treatment of elasticity of substitution between clean and dirty goods. In our framework we assumed a Cobb–Douglas form of utility function, which implies that elasticity of substitution between different types of goods is one and mixed price elasticity of demand is equal to zero. Altering these elasticities could affect the welfare effects of carbon tax. Introducing a more general form of utility function, such as CES, would allow exploration of this dependence.

From a theoretical viewpoint, possible extensions could address the question of whether differential productivity of individuals' work in the clean or dirty sectors should be interpreted as a persistent feature, or whether it should be endogenous, or, in other words, dependent on the time-scope, e.g. change with in-work training or human capital investment. One could also consider allowing for non-optimal or non-deterministic choices of the labour supply of individual workers, in relation to imperfect information or other barriers.

References

Anderson, S. P., De Palma, A., & Thisse, J. F. (1987). The CES is a discrete choice model? *Economics Letters*, 24(2), 139–140.

Anderson, S. P., De Palma, A., & Thisse, J. F. (1988). The CES and the logit: Two related models of heterogeneity. *Regional Science and Urban Economics*, 18(1), 155–164.

Antosiewicz, M., Nikas, A., Szpor, A., Witajewski-Baltvilks, J., & Doukas, H. (2020). Pathways for the transition of the polish power sector and associated risks. *Environmental Innovation and Societal Transitions*, 35, 271–291. https://doi.org/10.1016/j.eist.2019.01.008.

Ashenfelter, O. C., Farber, H., & Ransom, M. R. (2010). Labor market monopsony. *Journal of Labor Economics*, 28(2), 203–210.

Balistreri, E. J., & Rutherford, T. F. (2013). Computing general equilibrium theories of monopolistic competition and heterogeneous firms. In P. Dixon, D. Jorgenson (Eds.), *Handbook of computable general equilibrium modeling* (pp. 1513–1570). Elsevier.

Baran, J., Szpor, A., & 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.

Boeters, S., & Savard, L. (2013). The labor market in computable general equilibrium models. In P. Dixon, D. Jorgenson (Eds.), *Handbook of computable general equilibrium modeling* (pp. 1645–1718). Elsevier.

Böhringer, C. (2000). Cooling down hot air: A global CGE analysis of post-Kyoto Carbon Abatement Strategies. *Energy Policy*, 28(11), 779–789.

Böhringer, C., & Rutherford, T. F. (2000). Decomposing the cost of kyoto: A global CGE analysis of multilateral policy impacts. ZEW Discussion Paper No 00-11. https:// doi.org/10.2139/ssrn.374764.

Böhringer, C., Rivers, N. J., Rutherford, T. F., & Wigle, R. (2012). Green jobs and renewable electricity policies: Employment impacts of ontario's feed-in tariff. *The BE Journal of Economic Analysis and Policy*, 12(1). https://doi.org/10.1515/1935-1682.3217.

Booth, A. L., & Katic, P. (2011). Estimating the wage elasticity of labour supply to a firm: What evidence is there for monopsony? *Economic Record*, 87(278), 359–369. https://doi.org/10.1111/j.1475-4932.2011.00728.x.

Bureau, B. (2011). Distributional effects of a carbon tax on car fuels in France. *Energy Economics*, 33(1), 121–130. https://doi.org/10.1016/j.eneco.2010.07.011.

Cronin, J. A., Fullerton, D., & Sexton, S. (2019). Vertical and horizontal redistributions from a carbon tax and rebate. *Journal of the Association of Environmental and Resource Economists*, 6(S1), S169–S208.

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 Economics*, 59, 37–44. https://doi.org/10.1016/j.eneco.2016.07.021.

Davis, L. W., & Knittel, C. R. (2019). Are fuel economy standards regressive? *Journal of the Association of Environmental and Resource Economists*, 6(S1), S37–S63. https://doi.org/10.1086/701187.

Dixon, P., & Rimmer, M. T. (2002). *Dynamic general equilibrium modelling for forecasting and policy: A practical guide and documentation of MONASH* (Vol. 256). Elsevier.

Dixon, P., & Rimmer, M. T. (2008). Welfare effects of unilateral changes in tariffs: The case of motor vehicles and parts in Australia. Working Paper No. G-177, Centre of Policy Studies (CoPS).

Dixon, P., Jerie, M., & Rimmer, M. T. (2016). Modern trade theory for CGE modelling: The Armington, Krugman and Melitz models. *Journal of Global Economic Analysis*, 1(1), 1–110.

European Commission. (2020). 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 4 January 2021].

Growiec, J. (2013). A microfoundation for normalized CES production functions with factor-augmenting technical change. *Journal of Economic Dynamics and Control*, 37(11), 2336–2350.

Hanslow, K. (2000). A General Welfare Decomposition for CGE Models. GTAP Technical Paper No. 19, Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University. https://www.gtap.agecon.purdue.edu/resources/download/185.pdf.

Huang, H., Roland-Holst, D., Wang, C., & Cai, W. (2020). China's income gap and inequality under clean energy transformation: A CGE model assessment. *Journal of Cleaner Production*, 251, 119626.

Huff, K., & Hertel, T. W. (2001). Decomposing welfare changes in GTAP. GTAP Technical Paper No. 308, Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University. https://ideas.repec.org/p/gta/techpp/308.html.

IPCC (2014). Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar5/syr/.

Kiuila, O. (2018). Decarbonisation perspectives for the polish economy. *Energy Policy*, 118(C), 69–76. https://doi.org/10.1016/j.enpol.2018.03.048.

Küster, R., Ellersdorfer, I. R., & Fahl, U. (2007). A CGE analysis of energy policies considering labor market imperfections and technology specifications. FEEM Working Paper No. 7.2007. https://doi.org/10.2139/ssrn.960725.

Leipprand, A., & Flachsland, C. (2018). Regime destabilization in energy transitions: The German Debate on the future of coal. *Energy Research & Social Science*, 40, 190–204. https://doi.org/10.1016/j.erss.2018.02.004.

Levinson, A. (2019). Energy efficiency standards are more regressive than energy taxes: Theory and evidence. *Journal of the Association of Environmental and Resource Economists*, 6(S1), S7–S36.

Manning, A. (2003). *Monopsony in motion: Imperfect competition in labor markets*. New Jersey: Princeton University Press.

Mas-Colell, A., Whinston, M. D., & Green, J. R. (1995). *Microeconomic theory* (Vol. 1). New York: Oxford University Press.

Matveenko, A. (2020). Logit, CES, and rational inattention. *Economics Letters*, 186, 108537.

Melitz, M. J. (2003). The impact of trade on intra-industry reallocations and aggregate industry productivity. *Econometrica*, 71(6), 1695–1725.

Rengs, B., Scholz-Wäckerle, M., & van den Bergh, J. (2020). Evolutionary macroeconomic assessment of employment and innovation impacts of climate policy packages. *Journal of Economic Behavior & Organization*, 169, 332–368.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., … & Tavoni, M. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., … & Tavoni, M. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, 8(4), 325–332.

Sartor, O. (2018). Implementing coal transitions. Insights from case studies of major coal-consuming economies. IDDRI and Climate Strategies.

Skoczkowski, T., Bielecki, S., Kochański, M. & Korczak, K. (2020). Climate-change induced uncertainties, risks and opportunities for the coal-based region of Silesia: Stakeholders' perspectives. *Environmental Innovation and Societal Transitions*. 35, 460–481. https://doi.org/10.1016/j.eist.2019.06.001.

Spencer, T., Colombier, M., Sartor, O., Garg, A., Tiwari, V., Burton, J., … & Wiseman, J. (2018). The 1.5 °C target and coal sector transition: At the limits of societal feasibility. *Climate Policy*, 18(3), 335–351. https://doi.org/10.1080/14693062.2017.1386540.

Swilling, M., Musango, J., & Wakeford, J. (2016). Developmental states and sustainability transitions: Prospects of a just transition in South Africa. *Journal of Environmental Policy & Planning*, 18(5), 650–672, 2016. https://doi.org/10.1080/1523908X.2015.1107716.

Turnheim, B., & Geels, F. W. (2012). Regime destabilisation as the flipside of energy transitions: Lessons from the history of the British Coal Industry (1913–1997). *Energy Policy*, 50(C), 35–49. https://doi.org/10.1016/j.enpol.2012.04.060.

Appendix

A1. Alternative utility function and production function.

Supposing that consumers derive utility from the variety of final goods, we propound that j:

$$U = \prod q_j^{\gamma_j}.$$

The production function of each final good j is a Cobb–Douglas aggregator of two intermediate goods: dirty (carbon-intensive) and clean (carbon-free):

$$Q_j = B_j X_{jd}^{\theta_j} X_{jc}^{1-\theta_j},$$

where A_j is the productivity parameter and θ are the share parameters. By duality, the price of good is then given by:

$p_j = \Psi p_d^{\theta_j} p_c^{1-\theta_j}$, where Ψ is a constant.

Further, money metric indirect utility function is given by:

$$e\left(p^R, v(p,Y)\right) = \frac{Y}{(1+\kappa)^{1-\beta}} \frac{\prod p_{Rj}^{\gamma_j}}{\prod p_j^{\gamma_j}} =$$

$$= \frac{Y}{(1+\kappa)^{1-\beta}} \frac{p_{Rd}^{\Sigma\gamma_j\theta_j} p_{Rc}^{\Sigma\gamma_j(1-\theta_j)}}{p_d^{\Sigma\gamma_j\theta_j} p_c^{\Sigma\gamma_j(1-\theta_j)}},$$

which is equivalent to the money metric indirect utility function derived in Section 3.1 when $\beta = \sum \gamma_i \theta_i$.

A2. Detailed derivations of general equilibrium

Recall that production function for sector j is given by:

$$X_j = A_j L_j.$$

Thus, the amount of efficient units of labour required to ensemble one unit of output is given by $\frac{1}{A_j}$. Given the wage per efficiency unit, w_j, the unit costs of production are given by $\frac{w_j}{A_j}$. Due to the assumption of perfect competition between firms, the equilibrium price is exactly equal to unit costs, i.e. $p_j = w_j / A_j$, which sets the relation between price of output and wages in sector j. Using this in the expression for the supply of efficiency labour, we obtain:

$$L_j = s_j \left(\frac{A_j s_j p_j}{\left((A_d s_d p_d)^{\alpha} + (A_c s_c p_c)^{\alpha} \right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} \Gamma\left(1-\frac{1}{\alpha}\right),$$

which sets the relation between supply of efficiency labour and the level of price of output in sector j. Finally, combining this with the production function, we obtain supply of output in sector j, as a function of prices:

$$X_j = A_j s_j \left(\frac{A_j s_j p_j}{\left((A_d s_d p_d)^{\alpha} + (A_c s_c p_c)^{\alpha} \right)^{\frac{1}{\alpha}}} \right)^{\alpha-1} \Gamma\left(1-\frac{1}{\alpha}\right).$$

A3. Distribution of income

It may be noted that if $G(m)$ is a cumulative density function of income distribution in the economy, it must be correct that: $G(m) = P(\max \theta_{ij} w_j < m)$.

Further, we could also express $G(m)$ as:

$$G(m) = \prod_{j=(c,d)} P(\theta_{ij} w_j < m) =$$

$$= \prod_j F\left(\frac{m}{w_j}\right).$$

Since we assumed that the distribution of θ is a Frechet distribution, this becomes:

$$G(m) = \exp\left(\sum_j - \left(\frac{m}{w_j s_j}\right)^{-\alpha} \right) =$$

$$= \exp\left(- \left(\frac{m}{\left(\sum_j (w_j s_j)^{\alpha} \right)^{\frac{1}{\alpha}}} \right)^{-\alpha} \right),$$

which is the cdf of Frechet with parameter $\left(\sum_j (w_j s_j)^{\alpha}\right)^{\frac{1}{\alpha}}$. Therefore, the expected value is:

$$E[Y] = \left(\sum_j (w_j s_j)^{\frac{\rho}{\rho-1}} \right)^{\frac{\rho-1}{\rho}} \Gamma\left(1-\frac{1}{\alpha}\right).$$