Department of Labour Economics

Hochschule der
Bundesagentur für Arbeit
University of Applied Labour Studies

HdBA Discussion Papers in Labour Economics

No. 23-02

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Targeted Policies to Address Adverse Effects of Phasing Out Coal[*]

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April 12, 2024

Abstract

Reaching the temperature targets of the Paris Agreement requires a fast and drastic reduction in coal use. Yet, phasing out coal could lead to undesirable effects such as decreasing wages and rising electricity prices. Which policies are most efficient in counteracting these potential negative effects? To address this question, we introduce a general equilibrium model that combines firm heterogeneity and endogenous market entry with an electricity sector that, inter alia, uses clean and dirty (coal) resources. Within our model, we implement a coal phase-out as well as different complementary policy measures, which subsidize (1) market entry, (2) production, (3) wages, or (4) electricity prices. Solving our model numerically, we find that a wage subsidy of 3.5 % allows to raise the wage to its prior coal phase-out level at a welfare loss of 0.016 %. Subsidies for market entry (production) result in more than 12 (21) times larger welfare loses to achieve this goal. Similarly, subsidizing electricity prices implies a reduction of those prices at lower welfare costs compared to the other policy measures. Targeted policies are hence superior in addressing adverse effects of a coal phase-out and lead to significantly lower welfare reductions.

Keywords: Coal Phase-out, Policy Choice, Welfare, Regulation, Structural Change, General Equilibrium Model

JEL Classification: Q38, Q48, Q52, Q58

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[*] We are grateful to Monica Giulietti and Elmar Hillebrand for helpful comments and fruitful debates. We also thank participants of the 50th Annual EARIE Conference at LUISS University in Rome for the inspiring discussion. Declarations: This work was funded by the German Federal Ministry for Education and Research, grant no. 01LA1826B (PEGASOS project). We declare that there are no competing interests.

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1 Introduction

Coal-based electricity production accounts for about one third of global CO_2-emissions and represents the single most important source of emissions in many countries (Oberschelp et al., 2019; IEA, 2019). A prompt coal phase-out is essential if we were to limit climate change and reach the goals of the Paris Agreement (Rinscheid and Wüstenhagen, 2019). Phasing out coal, though, will lead to challenging structural transformations as coal fired power plants are the reliable and cheap backbone of many countries' electricity system (Jakob et al., 2020; Kalkuhl et al., 2019). A phase-out of coal could lead to spiking electricity prices that give rise to undesirable distributional effects. Also, the coal industry is geographically located in particular regions, even within countries. Job and income losses would hence be highly concentrated, resulting in an uneven distribution of the potential burden. This implies that the political hurdles that must be overcome to abandon coal are immense.

Against this background, there exists a discussion on which policy measures can be taken to alleviate undesirable consequences and distributional effects of a coal phase-out. This may also be an important factor for its political feasibility as a just transition is more than a moral imperative (see OECD, 2019, Jakob et al., 2020, Muttitt and Kartha, 2020 or Bang, Rosendahl, and Böhringer, 2022). Offering an economic perspective to coal regions and new employment opportunities to workers are important parts of a successful phase-out (Rinscheid and Wüstenhagen, 2019; Green and Gambhir, 2020). New opportunities also help to prevent outward migration and economic hardship, which otherwise pose a threat to the affected regions (Oei, Hermann, et al., 2020; Oei, Brauers, and Herpich, 2020). However, not only the economic situation of coal regions is of great concern, but also the burden of rising electricity prices. They affect production opportunities and pose a major challenge to poor households (Mayer, Smith, and Rodriguez, 2020; Cheon and Urpelainen, 2013; Ohlendorf, Jakob, and Steckel, 2022). Taking these concerns into account is necessary to achieve an equitable transition, and to ensure that the coal phase-out is politically feasible (Mayer, Smith, and Rodriguez, 2020; He et al., 2020).

Complementary policy measures are therefore part of a successful real-world phase-out. In the German case, for example, the federal government appointed the so-called Coal Commission in 2018, which comprised of representatives from academia, energy industry, environmental organizations, labor unions, and political parties. Its goal was to develop a time-line for the coal phase-out in Germany and to identify complementary policy measures in order to support affected regions and to promote their economic development. The Coal Commission published its recommendations as a report in early 2019, and it is rather specific about what measures should be implemented. They range from support for local companies and transfer payments for affected workers all the way to subsidies for electricity consumers (BMWK, 2019). There is, however, a lack of knowledge on the particular consequences of the recommended policies and whether they lead to the desired outcomes.

In this paper, we address this issue by setting up a general equilibrium framework, which accounts for an electricity producing sector inspired by Acemoglu et al. (2012) and Löschel and Otto (2009) as well an endogenous market structure with heterogeneous consumption good firms in the spirit of Melitz (2003). Within this framework, we implement a stylized coal phase-out (refraining to use coal for electricity production) as well as additional policy interventions inspired by the German Coal Commission's proposal. This includes (1) a market entry subsidy, (2) a production subsidy, (3) a wage subsidy, and (4) an electricity price subsidy.[1] We solve our model numerically, using parameters from related literature, and analyze the general equilibrium effects of the coal phase-out as well as the policies. This provides the basis for a more informed discussion about which policies may be more helpful to mitigate adverse effects in order to achieve a high level of social acceptance and political feasibility for a coal phase-out.[2]

Our results show that phasing out of coal leads to an increase in the electricity price by 21.7 % and a decrease in the wage by 2.5 %. The market structure does not change with a coal phase-out, i.e., both the number of firms in the market and their average productivity stay the same. Firms are nevertheless affected by a coal phase-out as they sell lower quantities. The reason is that decreasing wages cause labor income and hence demand for consumption goods to decrease. Welfare decreases under the coal phase-out. This is not surprising as we do not model negative externalities caused by burning coal explicitly. We deliberately refrain from modeling these externalities, because we take the coal phase-out for granted and do not take a stand on its overall welfare effects. We are more interested in the extent to which potential policy measures can address frequently communicated public worries, namely rising electricity prices and worse economic prospects in terms of wages and jobs in the affected regions (ILO, 2015; Heinrichs et al., 2017).

Regarding the policy interventions, we find that in general each of them counteracts the negative effects of a coal phase-out on wages and electricity prices. But they also decrease welfare in all scenarios. This welfare result is in line with previous literature (Jung, 2012; Jung, 2015) and arises from the fact that the only additional friction in our model is due to the monopolistic market structure, which in general equilibrium does not play a role because all relative prices are solely determined by marginal costs (see, Pearce, 1952 for a similar argument).[3]

The main result is that the policies we consider are characterized by different degrees of welfare losses. Targeted policies, which aim at counteracting negative consequences of a coal phase-out by subsidizing the respective variable directly, are associated with a substantially lower welfare loss compared to other policy measures. Subsidizing the wage by 3.5 %, for example, allows to raise the wage to its initial level prior to the coal phase-out at a welfare loss of 0.016 %. For comparison, raising the wage to its initial level subsiding market entry or production results in a welfare loss that is 12 and 21 times larger, respectively. Analogously, an electricity price subsidy is most efficient in reducing the electricity price, compared to the other considered policy measures. In this case, however, no subsidy will bring the electricity price down to its pre-phase out level. Our

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[1] The real-world policy instruments to subsidize market entry include, for example, start up grants and establishing innovation labs, while investments in public infrastructure are a means to subsidize production. In order to subsidize wages and electricity prices, the Coal Commission recommends to compensate workers for wage losses and to reduce grid charges (BMWK, 2019).

[2] We abstain from modeling a dynamic general equilibrium set-up. The aim of our paper is to understand first the reallocation resulting from the coal phase-out and the considered policy interventions by comparing the respective equilibrium outcomes. We do not look at the transition process because it would be harder then to determine the central mechanisms at work. Analyzing the variation over time is hence a task for future research.

[3] This result could be different if we would complement our differentiated consumption good sector by a numeraire sector that produces a homogeneous good under constant returns to scale, like Pflüger and Südekum (2013) do. Including such numeraire sector induces a mark-up distortion because the numeraire good is priced at social marginal costs whereas the differentiated varieties are priced above social marginal costs (due to mark-up pricing). Consumers spend too little on the differentiated varieties and too much on the numeraire. This distortion can be reduced by policy measures such as a market entry subsidy, which in turn leads to positive welfare effects. However, we use a one-sector setup without a numeraire sector because we want to start from a first-best solution rather than a second-best solution in order to observe the pure effect of our policies without creating friction or interaction with any additional imperfections.

main result is robust over a wide variety of different parameter constellations.

Our paper adds to two strands of literature. On a conceptual level, we contribute to the literature on the consequences of phasing out coal and on the measures which can be taken to address them. This literature, on the one hand, examines the effects of past declines in coal mining including the decline in Germany during the past 60 years (Oei, Brauers, and Herpich, 2020; Morton and Müller, 2016), but also the decline in other countries such as the US (Black, McKinnish, and Sanders, 2005) or the UK (Aragón, Rud, and Toews, 2018). On the other hand, it takes a forward-looking position to assess the consequences of upcoming phase-outs of coal-based electricity production. In doing so, it most frequently considers the effects on carbon emissions as well as on the labor and energy market (Gillich, Hufendiek, and Klempp, 2020; Keles and Yilmaz, 2020; Kittel et al., 2020; Heinisch, Holtemöller, and Schult, 2021; Oei, Hermann, et al., 2020). Some studies, however, also address local environmental and health benefits (Rauner et al., 2020) or the public attitudes towards a phase-out (Heinrichs et al., 2017; Rinscheid and Wüstenhagen, 2019). What has not been taken into account so far is that the coal phase-out as well as the proposed policy interventions might also affect the market structure. In fact, some of the policy interventions even specifically aim to change the market structure by encouraging market entry through start up grants and innovation labs, or by supporting production of new firms via investment in public infrastructure. We pick up on this point by analyzing the coal phase-out and the additional policy interventions under firm heterogeneity and endogenous firm entry. This allows us to better understand the selection and reallocation effects of different policies.

On an operative level, we contribute to the literature which investigates the allocative effects of policies using the heterogeneous firm model by Melitz (2003). Within this framework, not only trade policies such as import tariffs (Demidova and Rodríguez-Clare, 2009), border carbon adjustment mechanisms (Böhringer, Balistreri, and Rutherford, 2012; Balistreri and Rutherford, 2012; Balistreri, Böhringer, and Rutherford, 2018) or subsidies for foreign direct investment (Chor, 2009) have been analyzed, but also questions concerning the optimal market structure (Jung, 2012; Pflüger and Südekum, 2013). We build upon these insights when analyzing policies that aim at alleviating the negative effects of a coal phase-out. However, we extend the Melitz model to account for an electricity sector. This offers a new perspective for applications of the standard heterogeneous firm framework.

The remainder of our paper is structured as follows. Section 2 outlines the basic setup of our model, how firms behave, as well as the aggregation over firms and consumers. In section 3, we derive the equilibrium conditions of our model, and show how they change if we allow for policy interventions by the government. Section 4 presents the numerical solution of our model. That includes our parameter choice, our main results, and multiple robustness checks. Section 5 concludes and discusses limitations as well as potential extensions of our model.

2 The Model

2.1 Set-Up

We consider a closed economy which is endowed with labor $\bar{L}$, a dirty resource $\bar{R}$ and a clean resource $\bar{V}$. The dirty resource will be interpreted as fossil fuels (part of which is coal) and the clean resource as renewables. There is an energy sector, where the three inputs are used to produce electricity, and there is a consumption goods sector, where labor and electricity are used to produce differentiated varieties of a commodity. Workers are mobile across both sectors.[4] Since the labor market is perfectly competitive, there is no unemployment and each worker receives the same wage w.

2.1.1 Representative Consumer

A representative consumer decides upon the level of demand for any given variety. The utility U of the representative consumer is given by the CES-aggregate over all available varieties M, which reads

$$U = \left[\int_0^M x(\omega)^\rho d\omega\right]^{\frac{1}{\rho}} \qquad \rho \equiv \frac{\sigma - 1}{\sigma}, \tag{1}$$

where $x(\omega)$ denotes the consumed quantity of variety ω and σ (> 1) measures the elasticity of substitution between any two varieties. Because each firm produces and sells one unique variety, M represents also the mass of operating firms.

Maximizing (1) and taking into account that income I equals expenditures yields the demand function

$$x(\omega) = IP^{1-\sigma}p(\omega)^{-\sigma} = Ip(\omega)^{-\sigma}, \tag{2}$$

with $p(\omega)$ denoting the price of variety ω and

$$P = \left(\int_0^M p(\omega)^{1-\sigma} d\omega\right)^{\frac{1}{1-\sigma}} \equiv 1 \tag{3}$$

denoting the associated CES price index (minimum expenditure for one unit of U), which is our numeraire.

Welfare is measured by the consumer's utility (1). Using (2) and (3) shows that $U = I$ holds, implying that welfare equals income in our model.

2.1.2 Consumption Good Sector

The consumption good sector is characterized by monopolistic competition, endogenous entry and firm heterogeneity à la Melitz (2003). We, however, allow for two inputs, labor l and electricity e. The production function for output x is

$$x(\theta) = \theta l^\alpha e^{1-\alpha} \quad 0 < \alpha < 1, \tag{4}$$

with α denoting the output elasticity of labor in the consumption good sector. We assume that firm productivity θ is Pareto distributed with density $g(\theta)$, shape parameter c ($> \sigma - 1$), and lower bound b (> 0). The distribution function reads $G(\theta) = 1 - (b/\theta)^c$. Operating profits are

$$\pi(\theta) = p(\theta)x(\theta) - wl(\theta) - P_E e(\theta), \tag{5}$$

where P_E denotes the (unit) price of electricity which is purchased from the energy sector.

As in Melitz (2003), firms learn about their productivity after market entry, while they decide upon production afterwards. Both market entry and production require investments, which are expressed by fixed costs measured in labor units. Market entry costs are $w \cdot F$, which all firms have to bear in order to be endowed with some productivity. Production fixed costs $w \cdot F_D$ are only incurred if firms decide to take up production.

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[4] Haywood, Janser, and Koch (2024) estimate a simple job search framework using data on employment biographies of former German coal workers. They show that former coal workers rarely become unemployed, because they are typically highly educated, which makes a career switch or a switch to other industries fairly easy.

2.1.3 Energy Sector

In the energy sector, there is perfect competition with an exogenously given unit mass of competitors. The production function is

$$e = L_E^{\beta} \left(R^{\varphi} + V^{\varphi} \right)^{\frac{1-\beta}{\varphi}}, \tag{6}$$

where L_E is labor that is used for the production of electricity and R and V denote the clean and dirty resource, respectively, that is used in producing electricity. The parameter β measures the output elasticity of labor in the energy sector. The elasticity of substitution between the two types of resources in the composite is given by $\sigma_E \equiv 1/(1-\varphi)$.[5]

Profits are given by

$$\pi_E = P_E e - wL_E - p_R R - p_V V, \tag{7}$$

where p_R and p_V denote the (unit) prices of the dirty and clean resource, respectively.[6]

2.2 Firm Behavior

2.2.1 Consumption Good Sector

In the consumption good sector, firms first decide upon market entry and whether to start producing. After this decision, they optimally choose how much to produce and thereby how many inputs to employ.

By backwards induction, we first solve the input and production choice of a firm with productivity θ producing variety ω. Cost minimization for producing x gives the demand functions for electricity and labor. The solution is

$$e(\theta, x) = \frac{x}{\theta} \left(\frac{\alpha}{1-\alpha} \frac{P_E}{w} \right)^{-\alpha}, \tag{8}$$

$$l(\theta, x) = \frac{x}{\theta} \left(\frac{\alpha}{1-\alpha} \frac{P_E}{w} \right)^{1-\alpha}. \tag{9}$$

The cost function of a firm endowed with productivity θ is then given by

$$C(x, \theta) = x \frac{\Psi P_E^{1-\alpha} w^{\alpha}}{\theta}, \tag{10}$$

with $\Psi \equiv \left(\frac{1}{1-\alpha}\right)\left(\frac{\alpha}{1-\alpha}\right)^{-\alpha}$. The firm chooses output such that operating profits are maximized. Combining the resulting output level with the demand function (2) yields the profit-maximizing price

$$p(\theta) = \frac{1}{\rho} \frac{dC(x,\theta)}{dx} = \frac{1}{\rho} \frac{C(x,\theta)}{x}. \tag{11}$$

Operating profit in equilibrium can hence be expressed as

$$\pi(\theta) = (1-\rho) p(\theta) x(\theta) = \tau(\theta)/\sigma, \tag{12}$$

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[5] This modeling approach is inspired by papers like Acemoglu et al. (2012), Löschel and Otto (2009), Otto, Löschel, and Reilly (2008) as well as Otto, Löschel, and Dellink (2007), where clean and dirty inputs are used for production under constant elasticity of substitution. However, we explicitly add labor as an input to energy production, assuming a unit elasticity of substitution between labor and the resource composite.

[6] In the setup we present here, electricity producing firms buy the resources from resource owners at fixed prices p_R and p_V. Alternatively, we could have assumed a setup in which energy firms are vertically integrated owners of the resources. In this case, the profit is just $\pi_E = P_E e - wL_E$, which is then also the resource rent.

where $\tau(\theta)$ denotes firm revenue. Using (11) and (2), equilibrium revenue reads

$$\tau(\theta) \equiv p(\theta)x(\theta) = Ip(\theta)^{-(\sigma-1)} = I\left(\frac{1}{\rho}\frac{\Psi P_E^{1-\alpha}w^{\alpha}}{\theta}\right)^{-(\sigma-1)}, \tag{13}$$

which implies that τ (and hence π) is decreasing in wage and electricity price and increasing in productivity and the overall market size measured by income in the economy.

A firm starts production only if operating profits (weakly) exceed production fixed costs. At the margin, we have

$$\pi(\underline{\theta}) = wF_D, \tag{14}$$

where $\underline{\theta}$ denotes the lowest productivity of all firms operating in the consumption good sector. This is the Zero-Profit-Cutoff condition (ZPC). Moreover, a firm will enter the market, i.e., being endowed with a productivity, only if expected profits (weakly) exceed market entry costs. This free-entry condition (FE) is binding and can thus be written as

$$\int_{b}^{\infty} \max\left[0, (\pi(\theta) - wF_D)\right] g(\theta)d\theta = wF. \tag{15}$$

2.2.2 Energy Sector

Firms in the energy sector maximize profits π_E by choosing employment L_E. Considering a situation in which the resources are supplied inelastically at $\bar{R}$ and $\bar{V}$, labor demand in the energy sector is given by[7]

$$L_E = \left(\beta\frac{P_E}{w}\right)^{\frac{1}{1-\beta}}\left(\bar{R}^{\varphi} + \bar{V}^{\varphi}\right)^{\frac{1}{\varphi}}. \tag{16}$$

Further, we can write down the electricity supply as[8]

$$E_S = \left(\beta\frac{P_E}{w}\right)^{\frac{\beta}{1-\beta}}\left(\bar{R}^{\varphi} + \bar{V}^{\varphi}\right)^{\frac{1}{\varphi}}. \tag{17}$$

2.3 Aggregation

In the consumption sector, total employment and electricity demand are defined by

$$L_X = M\int_{\underline{\theta}}^{\infty} l(\theta)\mu(\theta)d\theta, \tag{18}$$

$$E_X = M\int_{\underline{\theta}}^{\infty} e(\theta)\mu(\theta)d\theta, \tag{19}$$

respectively, where we used the truncated distribution of active firms

$$\mu(\theta) \equiv g(\theta \mid \theta \geq \underline{\theta}) = \frac{g(\theta)}{1 - G(\underline{\theta})}. \tag{20}$$

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[7] In appendix A, we show that the general structure of the labor demand function in the energy sector remains by and large the same if we consider positively supplied resources R and V. The difference is, however, that the adjustment need in the labor market in case of a coal phase-out is larger under positively supplied resources. The case of a fixed resource base that we consider in the main text hence represents the conservative case concerning the distributional effects and the needs for policy adjustment under a coal phase-out.

[8] The same supply structure would apply in the vertically integrated energy firm.

Similarly to Melitz (2003), we can calculate the average productivity of firms operating in the market as

$$\tilde{\theta} = \left[\int_{\underline{\theta}}^{\infty} \theta^{\sigma-1} \mu(\theta) d\theta \right]^{\frac{1}{\sigma-1}}. \tag{21}$$

Then, aggregate employment can be expressed as $L_X = Ml(\tilde{\theta})$ and aggregate electricity use is given by $E_X = Me(\tilde{\theta})$. Aggregate operating profits are given by $\Pi = M\pi(\tilde{\theta})$. This implies that the aggregate levels are identical to a scenario where M identical firms with productivity $\tilde{\theta}$ would produce in the consumption good sector.

Since we normalize the mass of firms in the energy sector at unity, aggregate employment L_E in this sector and aggregate electricity supply E_S are given by (16) and (17), respectively.

Income consists of labor income, profits in the consumption good sector, profits in the energy sector, and the resource rent. Formally, we obtain

$$\begin{aligned} I &= w(L_X + MF_D + M_eF + L_E) + \Pi - w(MF_D + M_eF) \\ &\quad + P_E E_S - wL_E - p_R \bar{R} - p_V \bar{V} + p_R \bar{R} + p_V \bar{V}, \\ &= w(L_X + MF_D + M_eF + L_E) + \Pi - w(MF_D + M_eF) + P_E E_S - wL_E, \end{aligned} \tag{22}$$

where $M_e = M(1 - G(\theta))^{-1}$ denotes the mass of firms entering the market.

3 Equilibrium

When deriving the equilibrium, we consider two scenarios. In the baseline framework, the economy is described as in the previous section. Then, we allow for policy interventions by the government, which alter the equilibrium conditions and outcomes compared to the baseline setting.

3.1 Baseline Framework

3.1.1 Firm-Selection

Firm-selection is measured by productivity $\underline{\theta}$ of the least productive active firm. The higher this cutoff productivity, the more intense is the firm-selection and the higher is the average productivity $\tilde{\theta}$ of operating firms (see equation (21)).

To determine $\underline{\theta}$, note that

$$\frac{\pi(\tilde{\theta})}{\pi(\underline{\theta})} = \left(\frac{\tilde{\theta}}{\underline{\theta}} \right)^{\sigma-1}. \tag{23}$$

Inserting the ZPC (14) into (23) and applying the Pareto distribution, we obtain

$$\pi(\tilde{\theta}) = \left(\frac{\tilde{\theta}}{\underline{\theta}} \right)^{\sigma-1} wF_D = \frac{c}{c - (\sigma - 1)} wF_D. \tag{24}$$

This shows that the average profits in the consumption good sector do not depend on the cutoff productivity. This is a well-known consequence of the assumed Pareto distribution (Egger and Kreickemeier, 2009; de Pinto and Michaelis, 2016). Moreover, we see that average profits are affected by production fixed costs, which are a function of the ensuing equilibrium wage in the economy.

In equilibrium, expected operating profit can be written as

$$\begin{aligned}\pi(\tilde{\theta}) = \int_{\underline{\theta}}^{\infty} \pi(\theta)\mu(\theta)d\theta &= \left(\int_{\underline{\theta}}^{\infty} \theta^{\sigma-1}\mu(\theta)d\theta\right) P_E^{-(\sigma-1)(1-\alpha)} w^{-(\sigma-1)\alpha} \left(\frac{\Psi}{\rho}\right)^{-(\sigma-1)} I \\ &= \tilde{\theta}^{\sigma-1} P_E^{-(\sigma-1)(1-\alpha)} w^{-(\sigma-1)\alpha} \left(\frac{\Psi}{\rho}\right)^{-(\sigma-1)} I.\end{aligned} \tag{25}$$

Using this, the FE (15) in equilibrium reads

$$\int_{\underline{\theta}}^{\infty} \pi(\theta)\mu(\theta)d\theta = \frac{wF}{1-G(\underline{\theta})} + wF_D = b^{-c}\underline{\theta}^c wF + wF_D, \tag{26}$$

where the last line results from using the Pareto distribution. Inserting (24) into (26) and using (21) as well as the Pareto distribution yields

$$\underline{\theta}^* = b\left(\frac{\sigma-1}{c-(\sigma-1)}\frac{F_D}{F}\right)^{\frac{1}{c}}, \tag{27}$$

$$\tilde{\theta}^* = b\left(\frac{c}{c-(\sigma-1)}\right)^{\frac{1}{\sigma-1}} \underline{\theta}^*. \tag{28}$$

The superscript $*$ indicates equilibrium outcomes.

3.1.2 Income, Mass of Firms and Input Prices

In equilibrium, income (22) is a function of aggregate revenue only, i.e.,[9]

$$I = M\tau(\tilde{\theta}). \tag{29}$$

Using (12) and (24), we obtain

$$I = M\frac{\sigma c}{c-(\sigma-1)}wF_D. \tag{30}$$

The CES price index can be expressed as

$$P = M^{-\frac{1}{\sigma-1}}\left[\int_{\underline{\theta}}^{\infty} p(\theta)^{-(\sigma-1)}\mu(\theta)d\theta\right]^{-\frac{1}{\sigma-1}} = M^{-\frac{1}{\sigma-1}}p(\tilde{\theta}) \equiv 1. \tag{31}$$

The mass of firms has to adjust in equilibrium such that P is identical to one, as the normalization requires.

Using the labor market clearing condition $\bar{L} = L_E + L_X$ and the energy market clearing condition $E_X = E_S$ together with (29) and (31), we can then formulate a system of four equations in four unknowns (w, P_E, M, I):

$$\bar{L} = \underbrace{Ml(\tilde{\theta}^*, w, P_E, I)}_{L_X} + MF_D + M(1-G(\underline{\theta}^*))^{-1}F + \underbrace{\left(\beta\frac{P_E}{w}\right)^{\frac{1}{1-\beta}}\left(\bar{R}^{\varphi} + \bar{V}^{\varphi}\right)^{\frac{1}{\varphi}}}_{L_E}, \tag{32}$$

$$\underbrace{Me(\tilde{\theta}^*, w, P_E, I)}_{E_X} = \underbrace{\left(\beta\frac{P_E}{w}\right)^{\frac{\beta}{1-\beta}}\left(\bar{R}^{\varphi} + \bar{V}^{\varphi}\right)^{\frac{1}{\varphi}}}_{E_S}, \tag{33}$$

$$I = M\frac{\sigma c}{c-(\sigma-1)}wF_D, \tag{34}$$

$$M = p(\tilde{\theta}^*, w, P_E)^{\sigma-1}. \tag{35}$$

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[9] See appendix B for a derivation of the equilibrium income.

This system of equations implicitly determines the equilibrium input prices w^* and P_E^*, the equilibrium mass of firms M^* and equilibrium income I^* as function of model parameters only, for instance of the amount of dirty resource $\bar{R}$.

3.2 Policy Interventions

We model the market entry subsidy S_F as a reduction in market entry cost to $wF \times (1 - S_F)$. Analogously, a subsidy S_{F_D} on production implies that firms' payments to start production decrease to $wF_D \times (1 - S_{F_D})$. The wage subsidy S_w lowers the wage that consumption good firms and energy firms have to pay in our model to $w \times (1 - S_w)$. Workers, however, earn the full wage w. Finally, the electricity price subsidy S_{P_E} reduces the (unit) price that firms in the consumption sector must pay for electricity to $P_E \times (1 - S_{P_E})$, while firms in the energy sector still receive P_E. All interventions are financed by a lump-sum tax paid by the representative consumer.

The equilibrium conditions for our policy measures are derived in appendix C.

4 Numerical Solution

Our goal is to determine and quantify the allocative effects of the coal phase-out and the associated policy measures. Furthermore, we also want to identify the policy instruments that are most effective in alleviating the effects of a coal phase-out. To do so, we rely on a numerical solution of our model. We first provide detailed information about our parameterization strategy. Afterwards, we present our main results and discuss robustness checks, where we have varied a number of parameter constellations.

4.1 Parameterization

To solve our model numerically, we choose our parameter values carefully based on the relevant literature and reflecting real world constellations. A summary of our parameter values is presented in table 1.

Table 1: Parameter Values Used for Numerical Solution

Parameter	Description	Value	Source
σ	Elasticity of substitution	3.8	Bernard, Eaton, et al., 2003
c	Shape parameter	4.582	Balistreri, Hillberry, and Rutherford, 2011
$\underline{b}$	Minimum productivity	0.2	Bernard, Redding, and Schott, 2007
$\overline{L}$	Labor endowment	7,083	Federal Statistical Office
F	Market entry fixed cost	2	Bernard, Redding, and Schott, 2007
F_D	Production fixed cost	0.33	Balistreri, Hillberry, and Rutherford, 2011
$\overline{R}$	Dirty resource endowment (pre phase-out)	62.75	BMWK, 2021
$\underline{R}$	Dirty resource endowment (post phase-out)	33.89	BMWK, 2021
$\overline{V}$	Clean resource endowment	58.75	BMWK, 2021
α	Output elasticity of labor (X prod.)	0.9097	Federal Statistical Office
β	Output elasticity of labor (E prod.)	0.0427	Federal Statistical Office
$\sigma_E = \frac{1}{1-\phi}$	Resource elasticity of substitution (E prod.)	1.85	Papageorgiou, Saam, and Schulte, 2017

For the distribution of productivities and the production fixed costs, we use parameters from Balistreri, Hillberry, and Rutherford (2011), who structurally estimate a Melitz (2003)-type model. Specifically, they estimate the shape parameter c of the Pareto distribution and the production fixed costs F_D for a variety of European countries and geographical regions, using data from the Global Trade Analysis Project. To obtain their estimates, the authors use parameters from previous studies by Bernard, Eaton, et al. (2003) and Bernard, Redding, and Schott (2007), which we adopt as well.

Bernard, Eaton, et al. (2003) estimate the elasticity of substitution σ between varieties. To obtain this parameter, they set up a theoretical model that reflects basic facts about manufacturing plants like firm heterogeneity or higher productivity among exporters. Afterwards, they fit their model to bilateral trade data on 47 countries and more than one million different consumption goods. Bernard, Redding, and Schott (2007) estimate further key parameters of the Melitz model. Specifically, they estimate the minimum productivity b and the market entry fixed cost F using plant-level U.S. manufacturing data.

The output elasticities of labor, α and β, correspond to the cost share of labor in producing consumption goods and electricity, respectively. Data on the cost shares are taken from the Genesis data base of the German Federal Statistical Office.[10] The labor endowment $\overline{L} = 7,083$ is the sum of employees (in 1,000) working in the energy sector (250) as well as the manufacturing sector (6,833) in Germany, obtained from the German Federal Statistical Office.[11]

The elasticity of substitution σ_E between clean and dirty energy resources is taken from Papageorgiou, Saam, and Schulte (2017), who estimate this parameter within the energy aggregate of macroeconomic production functions. To do so, they exploit cross-country data on energy use by fuel for 26 countries from the new World Input Output Database (WIOD). Their estimated elasticity parameter is 1.85 for the electricity sector, which implies that clean and dirty energy resources are (gross) substitutes.

The resource endowments, $\bar{R}$ and $\bar{V}$, are chosen such that (implicitly) the underlying electricity production from the two sources reflect their shares in the electricity mix in Germany for 2019. The reduced dirty resource endowment after the coal phase out is then calculated reflecting the 'loss' of electricity due to not using coal fired power plants anymore which is 23.57 % in gross electricity production in Germany (BMWK, 2021). We keep $\bar{V}$ constant since we focus on the contemporaneous effects of restraining part of the fossil resource base. More details behind the rationale for these choices and explicit calculations can be found in appendix D.

4.2 Results

In this subsection, we present our main results. First, we analyze the effects of a coal phase-out on wages, the electricity price, the market structure, consumption good prices and welfare. Second, we investigate the impact of the aforementioned policy measures. Third, we evaluate which of our policy instruments might be the most suitable to soften or even reverse potential negative effects of a coal phase-out.

4.2.1 Coal Phase-Out

The coal phase-out is modeled by continuously reducing the amount of dirty energy resources used for electricity production from $\overline{R}$ to $\underline{R}$. The results are shown in figure 1. Here, relative values of the respective variable are plotted, i.e., compared to the initial (i.e. pre-phase-out) level. Consequently, values smaller (larger) than one indicate decreases (increases) of the considered outcome.

In the energy market, phasing out coal leads to lower supply of electricity, which causes the electricity price to rise. At the same time, energy firms demand less labor when they reduce their production, which leads to layoffs. Workers who lose their job in the energy sector reallocate to the consumption good sector because workers are perfectly

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[10] Data on the cost shares are taken from Genesis data bases 43221 and 42251, respectively.

[11] Sectoral employment data can be found in Genesis data base 13111.

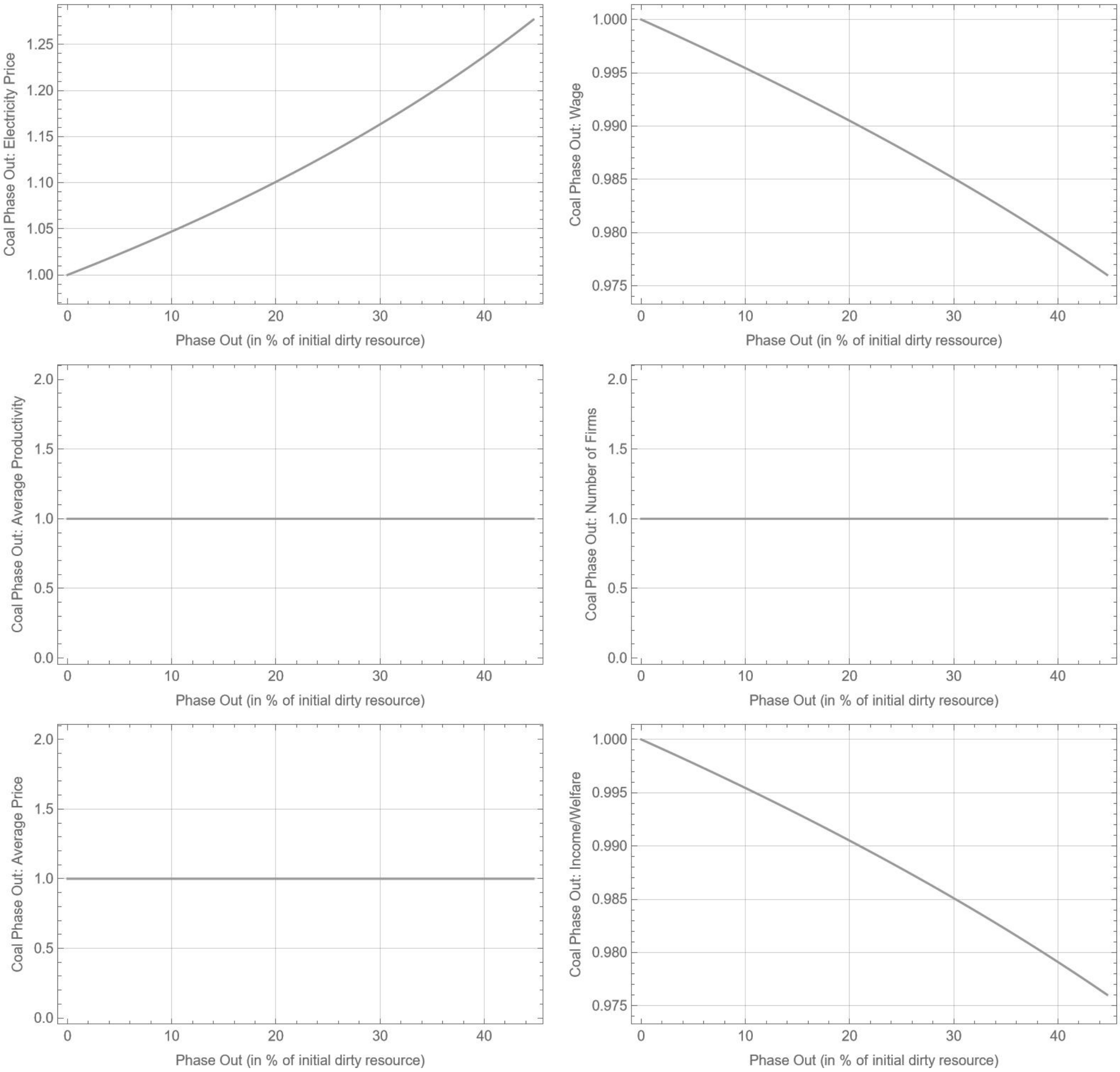

Figure 1: Effects of a Coal Phase Out

mobile between sectors. This process of reallocating workers to the consumption good sector leads to lower wages since labor demand in the energy sector decreases and labor supply in the consumption good sector increases. Although the wage and the electricity price change, marginal costs for any given productivity level remain constant, because the increase in electricity costs is perfectly offset by the decrease in wage costs. This reflects the linear-homogeneous production structure of our model where marginal costs do not vary with the size of the economy. A coal phase-out leads hence to a decline in both electricity supply and labor demand. This inevitably causes consumption good firms to pay a higher price for electricity, while workers receive lower wages (or face worse employment prospects in a rigid wage setting).[12]

The market structure, which is described by the mass of firms operating in the market and their average productivity, is unaffected by a coal phase-out. Intuitively, expected

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[12] For comparable results regarding the effects of a coal phase-out on the labor and electricity market, see Heinisch, Holtemöller, and Schult (2021) and Keles and Yilmaz (2020), respectively.

profits increase because the decline in wages implies a reduction of fixed costs. This reduces, ceteris paribus, the cutoff productivity. If more firms are sufficiently productive to earn positive operational profits, though, the mass of firms increases. This leads to fiercer competition and raises, ceteris paribus, the cutoff productivity. Due to our model specification, all firms are equally affected by these two effects, such that they off-set each other and the cutoff productivity remains constant.[13] Accordingly, the average productivity of active firms also remains constant. With respect to the mass of firms, there is also an offsetting mechanism. Since energy prices are higher, expected profits, ceteris paribus, decline, which reduces the mass of firms to its initial level. An implication of the constant average productivity, combined with the constant marginal costs discussed above, is that the average price of consumption goods remains the same.

Finally, the decrease in usable resource endowment decreases income and hence welfare. Note, however, that this does not say anything about the desirability of a coal phase since we have not taken the effect on climate change due to CO_2 emissions into account. This is not the focus of the paper. We instead want to better understand the value of different policy options when phasing out of coal is exogenously given. Still we can do a quick back of the envelope calculation of the implied cost of reducing carbon emission. In 2019, German Carbon emissions from coal were 218 megatons of CO_2. The model implies an income decrease of around 2.4%. With national income in 2019 in Germany being 3474.11 billion euro, this reduction amounts to 83378 million euro. This implies yearly costs of around 382 Euro per ton of CO_2. Compared to standard measures of the social costs of carbon (see for example Nordhaus (2018), Golosov et al. (2014) or Folini et al. (2021)), this is fairly large. Note, however, that the social costs of carbon are derived within a dynamic framework as the marginal effect of a unit of CO_2 emission per marginal value of capital. Our measure based on flows is hence only an approximation to this.

4.2.2 Policy Measures

When analyzing the effects of our considered policy interventions, the starting point is the (new) equilibrium after implementing a coal phase-out. To understand how the policy instruments affect the model's outcomes, we investigate each of them individually. We depict the effect of the subsidy on respective key variables of the model. For easier comparison, we plot the outcome relative to the no-policy situation. Additionally, we also check whether the subsidy does not violate the economies budget constraint. We mark those levels by a dashed line. Subsidy levels past this threshold are not economically feasible.

Because we start from a first-best situation where the implicit externality which results from coal-fired electricity generation has been internalized by limiting coal use via command and control, each subsidy will distort the allocation and will hence lead to a decline in welfare. We therefore abstain from discussing the welfare effects of the subsidies separately. The more important question will be, which of these instruments allows to stabilize electricity prices and wages at minimal welfare costs. We address this question below.

Market Entry Subsidy

One of the major concerns associated with a coal phase-out is that it might deteriorate the economic production base of affected regions. This fear is deeply rooted among citizens

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[13] This result is analogous to papers like Egger and Kreickemeier (2009) and de Pinto and Michaelis (2016), where the market structure is also independent of the input quantities.

living in coal areas, mainly because of negative experiences with structural change in the past (Johnstone and Kivimaa, 2018; Brauers and Oei, 2020; Campbell, Coenen, et al., 2017; UBA, 2022). In order to stabilize the industry structure when regions face a coal phase-out, it is often considered to support market entry of new firms. This is also reflected in the suggestions of the German Coal Commission, which aim to facilitate market entry through multiple tools. This includes, for example, providing financial support through start up grants and establishing innovation labs, which encourage creative ideas and foster swift product development (BMWK, 2019). In our model, a market entry subsidy varies the equilibrium outcomes as illustrated in figure 2.

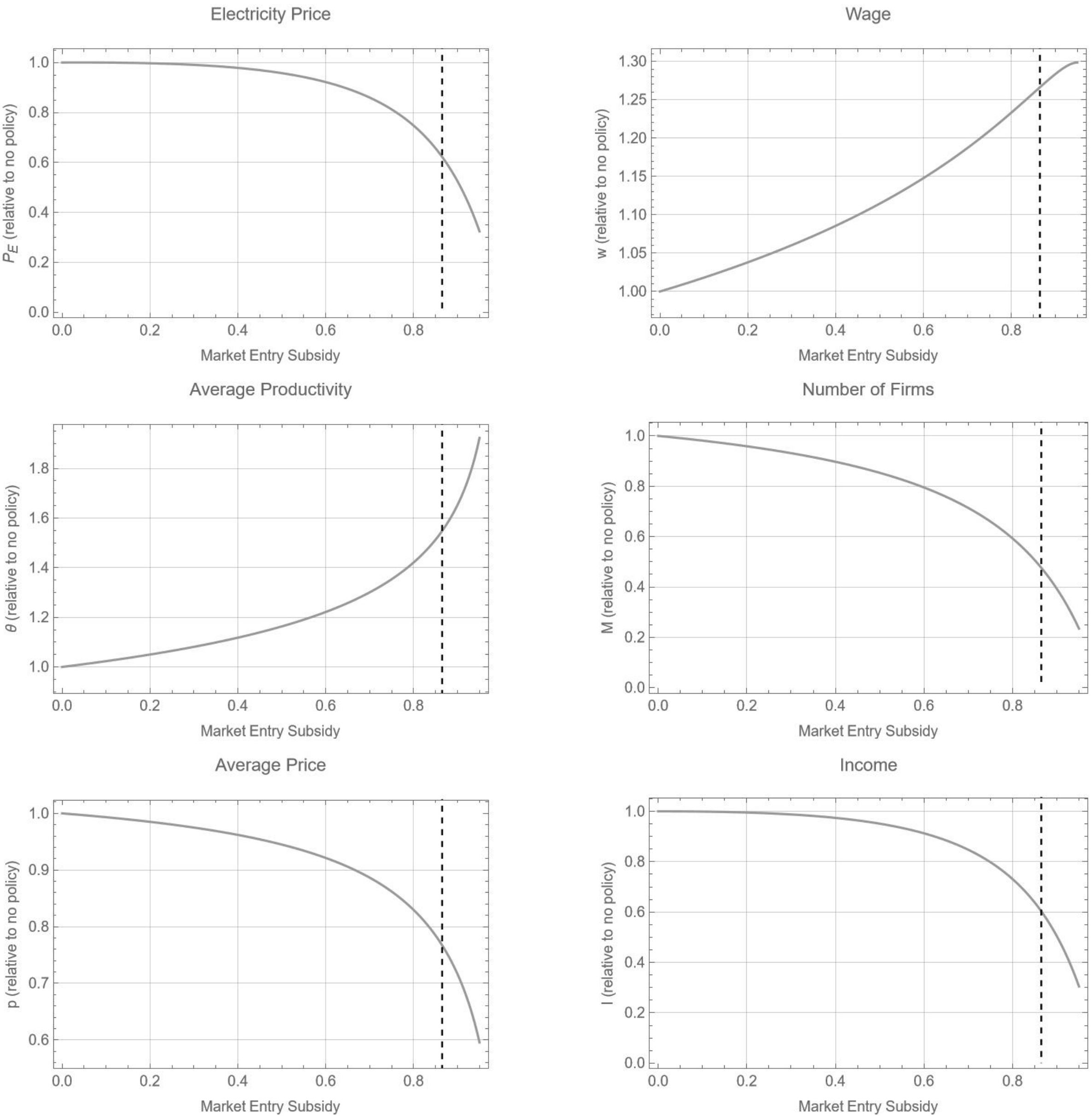

Figure 2: Effects of a Market Entry Subsidy

With a market entry subsidy, productivity draws will be cheaper than before. As such, labor demand (for market entry purposes) increases and hence the wage. Additionally, firms will be more willing to forego a productivity draw. Both results in an increase in the cutoff productivity such that the average productivity will increase as well. With firms being more productive, they will charge lower prices and will hence produce more (i.e., they are larger) such that in equilibrium the economy only supports fewer firms. The increase of production in a given firm increases the demand for energy and labor, but in aggregate, a higher cutoff productivity and fewer firms will exert downward pressure on input demand. The electricity price decreases. The wage increases because the rise of the labor demand for market entry purposes overcompensates the labor demand reducing effect from production firms.

Production Subsidy

Subsidizing production aims at stabilizing the industry structure in a similar way as a market entry subsidy. One implicit way to reduce production fixed costs, which is considered a priority by the German Coal Commission, is investment in public infrastructure (Egger and Falkinger, 2006; Bougheas, Demetriades, and Mamuneas, 2000; BMWK, 2019). The implications of a production subsidy in our model are shown by figure 3.

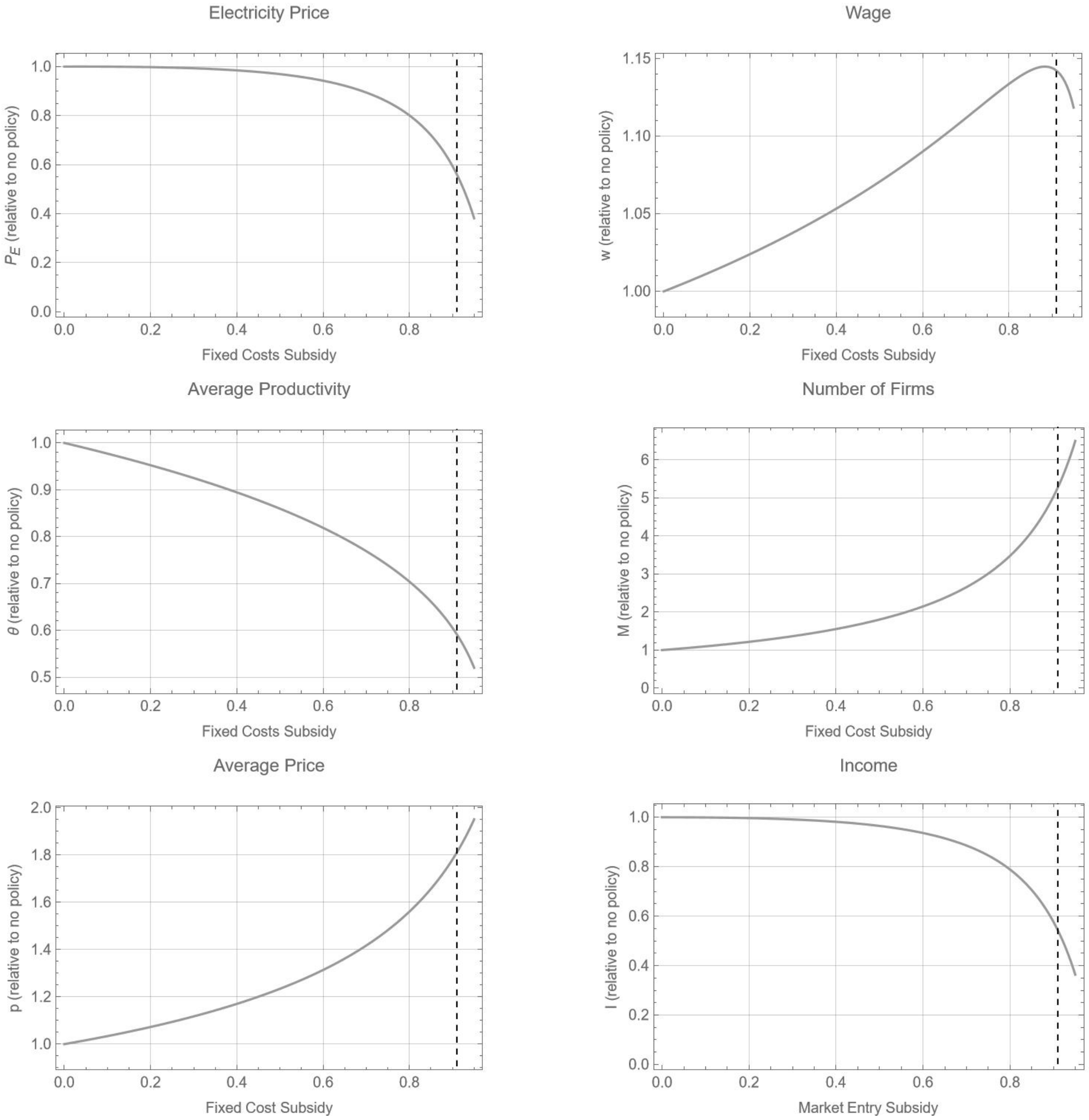

Figure 3: Effects of a Production Subsidy

When production is subsidized, the expected profit from entering the market increases.

A firm with a given productivity draw is more eager to start producing. The cutoff productivity and hence the average productivity decrease. The average price for consumption goods therefore increases. As a consequence, firms will be smaller in the sense of producing less on average. However, due to entry being more attractive, more firms will be active in the economy.

The changes in the market structure and firm behavior also affects the equilibrium in input markets. More firms would point to an increase in input demand. At the same time, firms will produce less such that on aggregate input demand decreases which implies in general lower input prices. Indeed, the electricity price decreases. The wage, however, increases which is driven by the effect of more firms using labor for fixed production purposes. Only for high levels of the subsidy, we find that wages decline, i.e., the implied downward pressure on the input price dominates.

Wage Subsidy

Among the main arguments raised by opponents of a coal phase-out is that workers in the energy industry lose their jobs and hence face worse wage prospects (or employment prospects in a rigid wage setting). They frequently refer to threatened livelihoods and emphasize that those workers would be disproportionately burdened (Leipprand and Flachsland, 2018). The German Coal Commission therefore proposes to address these concerns directly by subsidizing wages (BMWK, 2019). Figure 4 illustrates the results in our framework.

The production factor labor has a dual purpose in our economy. It is first of all used in the production part of the consumption and energy sector. Moreover, it is also used for market entry purposes and as a fixed factor for producing consumption goods. A wage subsidy addresses both roles.

The wage subsidy is an implicit subsidy on market entry as well as on production. Since both is subsidized simultaneously, the cutoff productivity does not change. At the same time, marginal costs of consumption good firms decrease such that the price decreases as well and every firm increases its production. With firms being larger, the economy can only support fewer firms such that the number of firms decreases. With a larger production of every firm, but fewer firms in aggregate, we have countervailing effects on input demand and hence on input prices. In equilibrium, the electricity price declines. The wage, however, increases because the wage subsidy will also make firms substitute labor for electricity and the demand from market entry increases. The producer wage decreases due to the subsidy.

Electricity Price Subsidy

Low (or at least stable) electricity prices are being perceived as an important prerequisite for the acceptability of any reform or transformation in the energy sector. Firms need reliable and cheap electricity for production purposes and households consider cheap electricity as an important factor determining their subjective well-being (Welsch and Biermann, 2014). One way to achieve this objective is an electricity price subsidy, which could be implemented, for example, through a reduction in grid charges (BMWK, 2019). In our model, such a subsidy has the in figure 5 depicted effects.

We model the electricity price subsidy as a subsidy that is paid to consumption good firms.[14] In the consumption good sector, this results in a substitution away from labor, putting downward pressure on the wage. But since electricity producing firms expand

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[14] Alternatively, we could also assume that electricity producing firms receive a subsidy such that the market price for electricity decreases. Both has identical allocative effects.

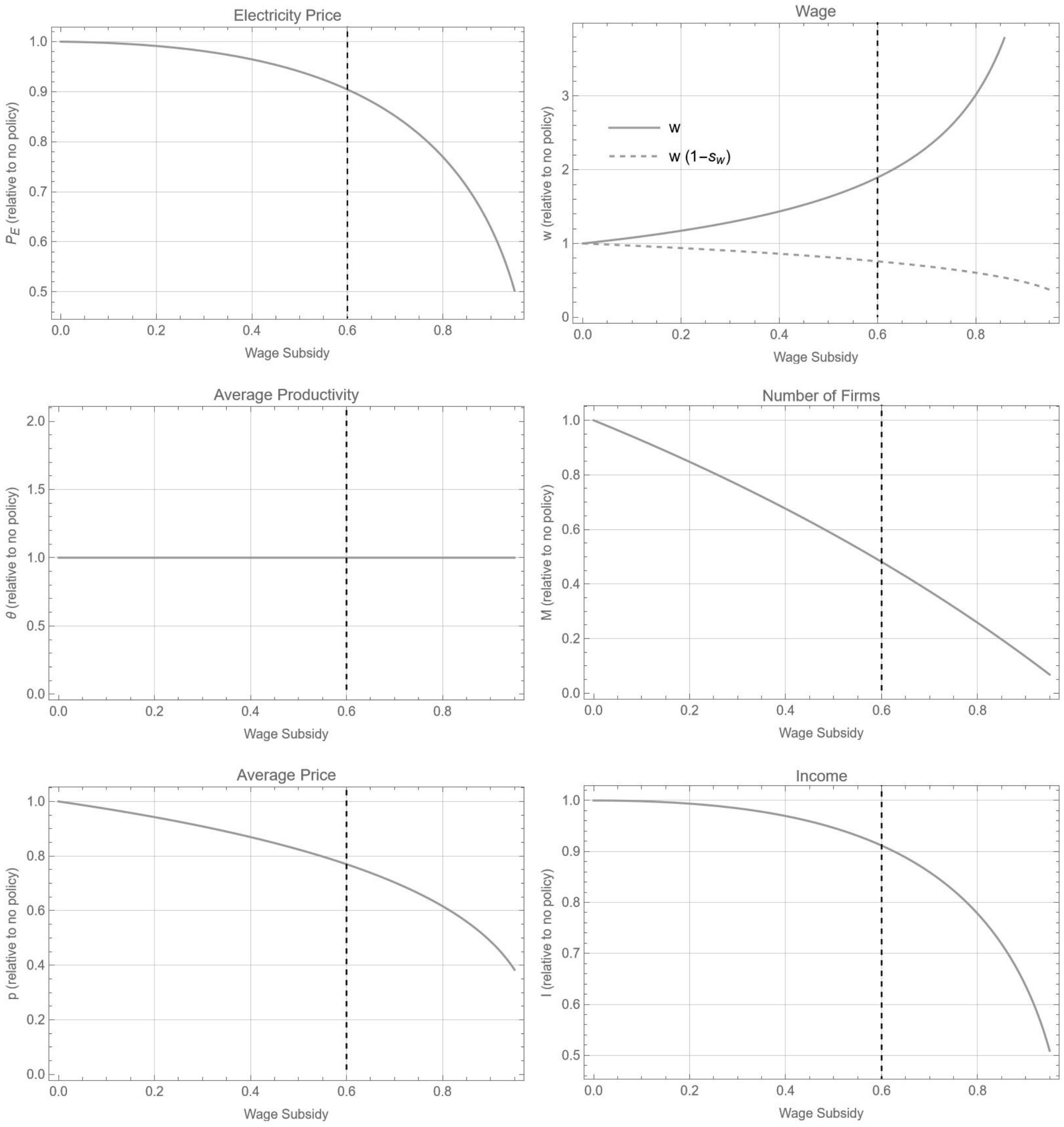

Figure 4: Effects of a Wage Subsidy

and increase their labor demand, this is overcompensated, causing the wage to increase (except for very high level of the subsidy). Because marginal costs decrease, the (average) price in the consumption good sector will decrease as well. Firms expand and produce more such that then again the economy can only support fewer firms and the number of firms decreases. Neither the incentive to enter the market nor the one to start producing are affected such that the cutoff productivity (and therefore average productivity) remains constant.

Note that the market price for electricity strongly increases due to the increased demand and that therefore the electricity price dampening effect of the subsidy is small. Below we show, that this effect is indeed so small that the electricity price cannot be

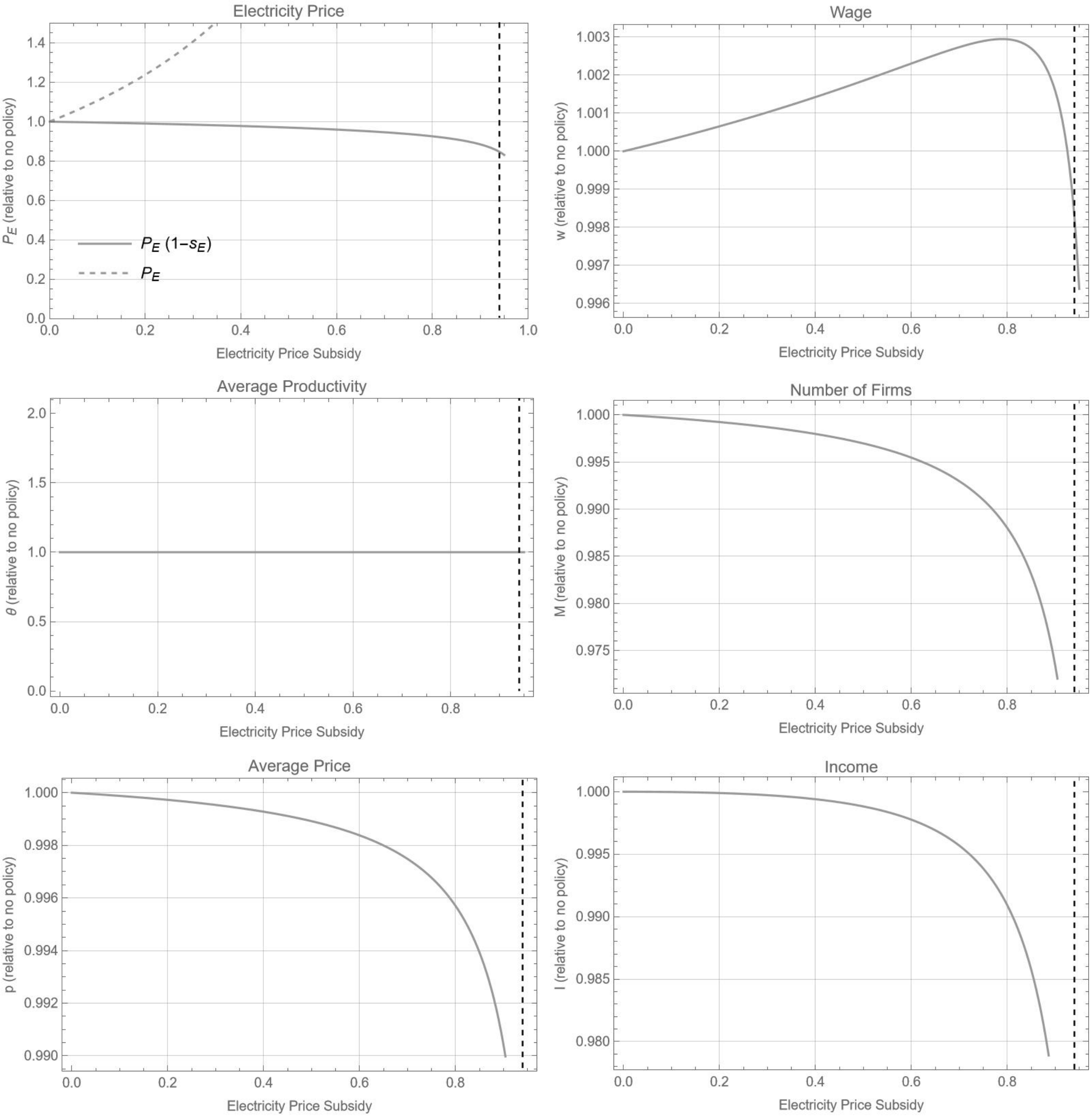

Figure 5: Effects of an Electricity Price Subsidy

stabilized to pre-phase out levels.

4.2.3 Policy Evaluation

The negative consequences of a coal phase-out on labor and energy market outcomes, specifically decreasing wages and increasing energy prices, tend to result in strong political opposition. They diminish voters' trust in political institutions as well as their support for political measures (Jensen, Quinn, and Weymouth, 2017; Im et al., 2019; Margalit, 2019; Baccini and Weymouth, 2021; Egli, Schmid, and Schmidt, 2022), while at the same time boosting efforts to prevent or soften policies via lobbying (Kim, Urpelainen, and Yang, 2016; Gullberg, 2008; Markussen and Svendsen, 2005; Li, Xu, and Shiroyama, 2019; Cadoret and Padovano, 2016). Keeping energy prices stable and creating employment opportunities for workers are hence key elements of a politically feasible coal phase-out.

We have argued in the previous section that a set of policy instruments help stabilizing wages and electricity prices. All those policy instruments, however, come at the costs of distorting the efficient no-policy equilibrium (again ignoring the externality that is caused by fossil fuel emissions) resulting into welfare/income losses. As was already foreshadowed, those welfare looses differ substantially between the policy instruments that we consider. This begs the question which policy instrument is the most efficient one when it comes to realizing higher wages and lower electricity prices.

To answer this question, we build upon our numerical results and depict the welfare loss associated with achieving a specific wage or electricity price using the different policy instruments. Hence, we derive transformation curves which depict how income losses can be transformed into higher wages respectively lower electricity prices using the different policy instruments.

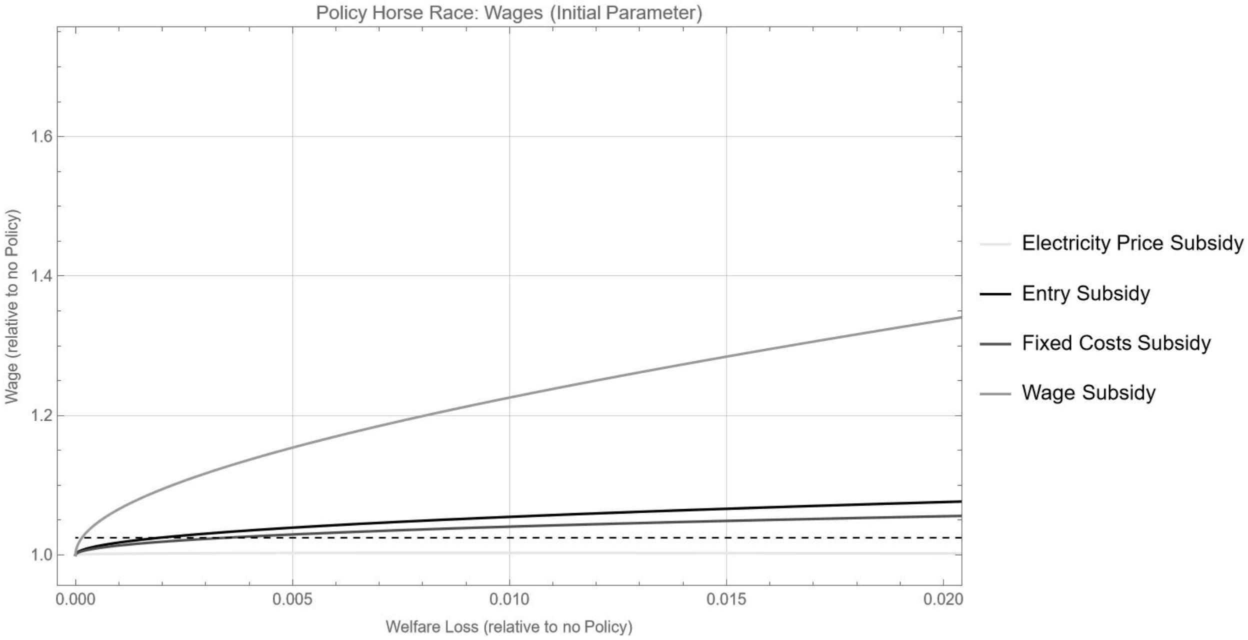

Figure 6: Transformation Curves – Wage Increase

Figure 6 illustrates these transformation curves for the case of a wage increase. The ordinate shows the wage (relative to the no-policy wage after the coal phase-out) that can be achieved by (implicitly) forgoing welfare using the different policy instruments. The abscissa depicts the welfare loss (again relative to the no-policy coal phase-out case). The dashed line highlights the pre-coal phase-out wage (relative to the no-policy wage after phasing out coal). When a policy measure raises the wage up to this level, the initial wage is restored.

The figure shows that the wage subsidy is the most efficient way (in terms of minimal welfare loss) in order to achieve a given wage goal. This is not too surprising because intuitively, the direct instrument, and thereby the targeted policy, seems to be the least costly one. The interesting point here is that subsidies on firm activity (subsidizing entry and production) are way more expensive. Although, these policies also are capable of restoring the wage to the initial pre-phase out level, they are of a magnitude of 12 times (entry subsidy) and 21 times (production subsidy) more expensive. The most expensive way of increasing the wage is to use an electricity price subsidy.

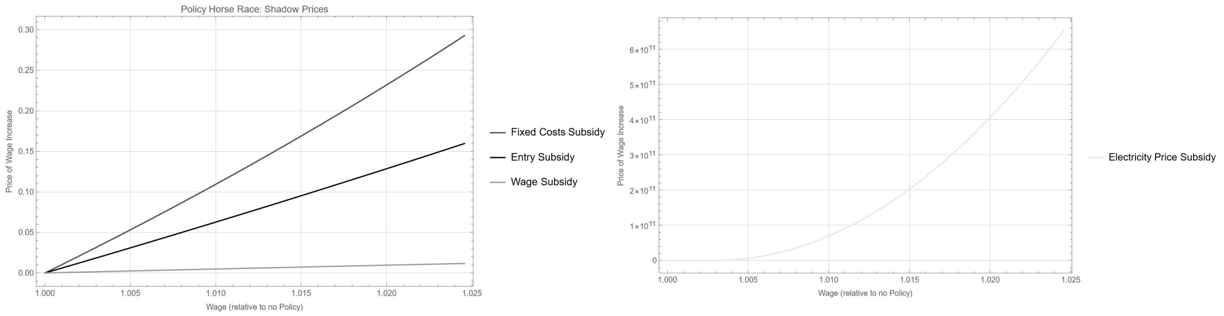

Figure 7: Shadow Value – Wage

These results are reinforced when we look at the shadow price of the different policy instruments. The shadow price depicts the marginal welfare loss for a given marginal wage increase.[15] These shadow values are depicted in figure 7. The figures show the price for increasing the wage for all policy instruments. Moreover, the plots stress the huge heterogeneity in the costs associated with the different policy instruments. These results have also policy implications. Our findings indicate that in cases where implementing a direct wage subsidy proves impractical, providing subsidies for market entry is more favorable than subsidizing production for established firms.

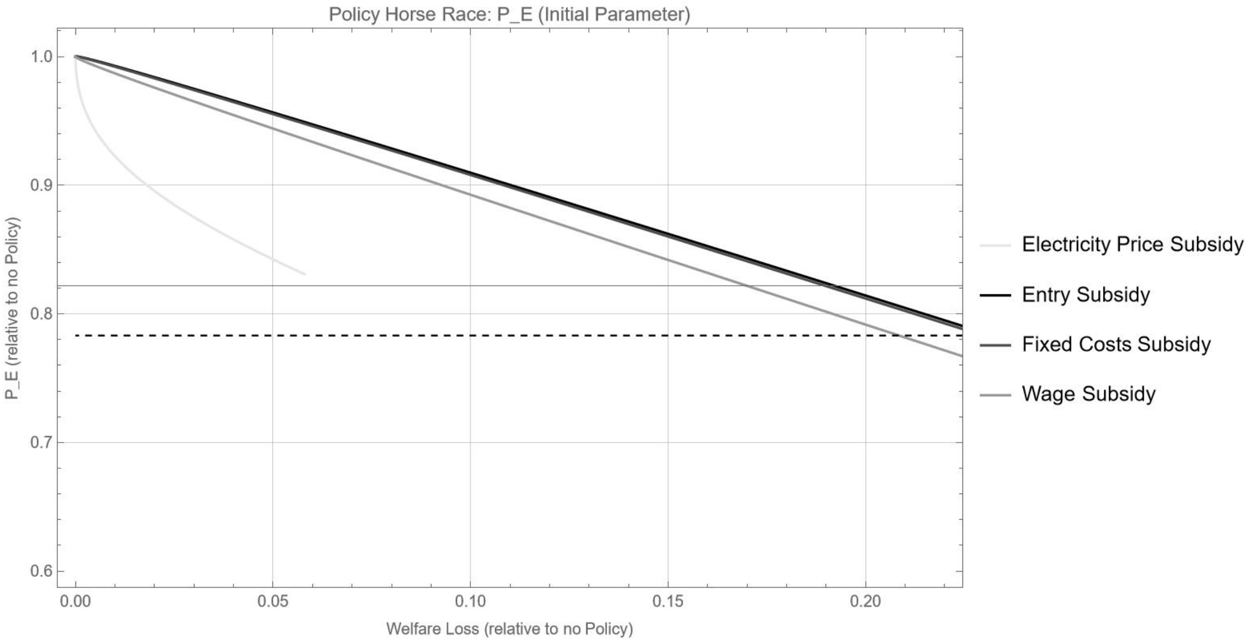

Figure 8: Transformation Curves – Reducing the Electricity Price

The transformation curves for the electricity price are shown in figure 8. Here, the targeted electricity price subsidy is again the most efficient way to decrease the electricity price. Due to the large price spike caused by the coal phase-out, however, the electricity subsidy to restore the initial price (marked by the dashed line) would be so massive that this is not possible. The other policy instruments are capable of decreasing the electricity price to its initial level due to the different mechanism of those instruments (basically by dampening electricity demand). Within those, the wage subsidy is the most efficient one in achieving this goal.

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[15] This is implicitly given by the inverse of the slope of the transformation curves in figure 6.

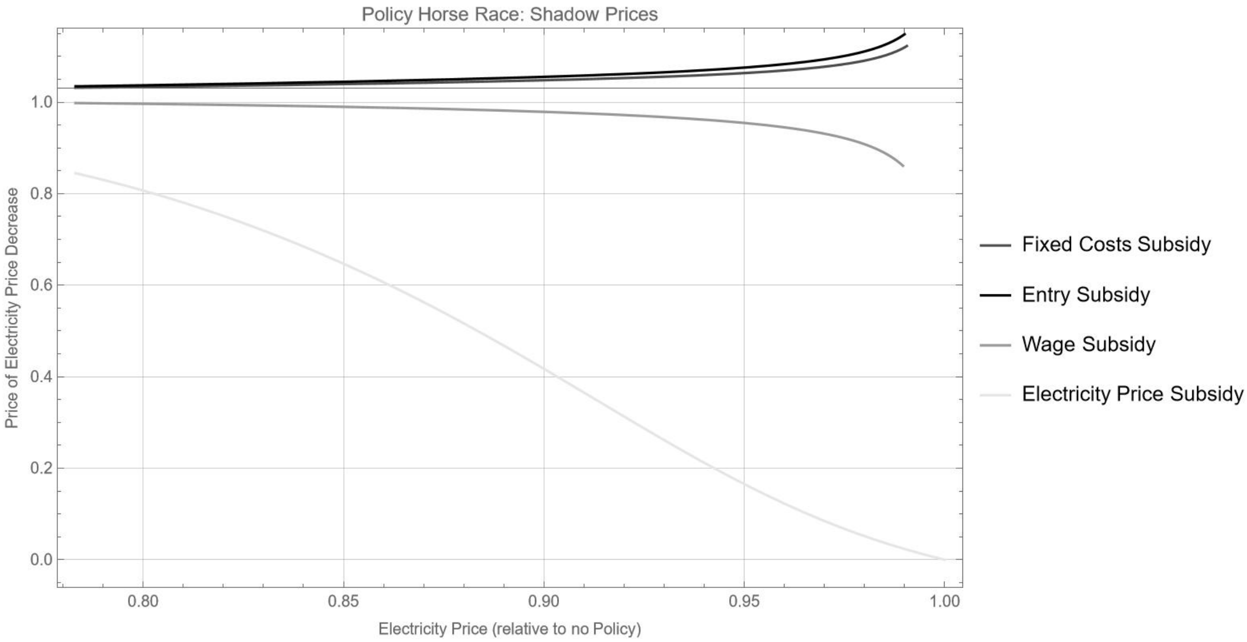

Figure 9: Shadow Value – Electricity Price

Figure 9 depicts the shadow values for the policy instruments under consideration. The heterogeneity in this case (except for the electricity price subsidy) is, specifically for already lower prices, substantially smaller than before. With this, restricting the set of policy instruments (except again for the targeted subsidy) is less relevant than it was the case when stabilizing the wage.

Summarizing, we find that the wage and the electricity price can be stabilized at lower welfare costs if we address them with a targeted policy in form of the wage and electricity price subsidy, respectively. These results are consistent with previous studies which focus on transformation curves in different policy contexts. Fischer and Newell (2008), for example, assess different policy options (emissions tax, fossil fuels tax, direct renewables subsidy, renewables R&D subsidy) to increase renewable energy production, and evaluate their performance with respect to welfare. They find that targeted subsidies are the most efficient policy to boost renewables production. In addition to this strand of literature, we point out that the benefits of targeted policies are quantitatively substantial and that a wage subsidy is even able to re-gain the initial labor market outcome at a comparable low welfare reduction.

4.3 Robustness

In the previous section, we solved the model numerically under a given set of parameters and analyzed the impact of different policy measures. To test whether our results are robust, we additionally consider different sets of parameters. This helps us to get a better understanding about how broadly our insights from the relative costs of different policies can be applied also to other settings.

We vary for example the share of renewable and fossil resource endowment and analyze whether these relative scale effects are important for size and shape of our results. Moreover, we consider a different output elasticity in the consumption good sector. The reason for this is that there is a debate on whether they correspond to their cost shares or not. Kümmel, Lindenberger, and Weiser (2015), Kümmel and Lindenberger (2014), Kümmel, Ayres, and Lindenberger (2010), Ayres et al. (2013), and Lindenberger and Kümmel (2011) argue that the output elasticity must be smaller for labor and larger for electricity to reflect historical economic growth in Germany, Japan, or the US. To account for this possibility, we test the robustness of our results against a lower output elasticity of labor, which comes hand-in-hand with a higher output elasticity of electricity. The parameter value that we use for this parameterization is an estimate from Lindenberger and Kümmel (2011). To the best of our knowledge, their estimate is the lowest value in the literature and hence the one that differs most from our main parameterization. As an alternative, we consider a higher output elasticity for labor and hence a lower output elasticity of resources. In addition to the output elasticity for electricity, we consider a parametrization with a higher elasticity of substitution between fossil and renewable resources in electricity production. Specifically, we assume a value of $\sigma_E = 3$, which is taken from Acemoglu et al. (2012). We do not consider the case of complementary energy resources ($\sigma_E < 1$), because the case of substitutes ($\sigma_E > 1$) seems to be the empirically more relevant benchmark (Stern, 2012).[16]

Finally, we employ a battery of alternative parameterizations which we draw from the related literature. This includes Pflüger and Südekum (2013), Chor (2009), de Pinto and Lingens (2019), Felbermayr and Prat (2011), Cui (2017) and Bernard, Redding, and Schott (2007). Their parameterizations differ in terms of the elasticity of substitution, distribution of productivities (shape and minimum productivity), labor endowment as well as fixed costs for market entry and production.

The parameter values that have been chosen and the ensuing transformation curves for wages and electricity prices can be found in appendix E. The general insight from these variations is that the main results from our initial parametrization is fairly robust. Between all the different scenarios considered, it remains true that the implied welfare costs of increasing the wage or lowering the electricity price is heterogeneous, with targeted policies being the most efficient ones.

5 Conclusion

This paper contributes to the (scientific and public) debate on which policy instruments might be helpful to counteract negative effects of a coal phase-out. To investigate the allocative effects of a coal phase-out and potential policy responses as well as to shed light on the underlying mechanisms, we set up a general equilibrium framework with heterogeneous firms and endogenous market entry à la Melitz (2003) and an electricity sector in the spirit of Acemoglu et al. (2012) and Löschel and Otto (2009). We solve our model numerically using parameters from the related literature, and analyze the general equilibrium effects of a coal phase-out. Moreover, we determine how the equilibrium outcomes adjust when policy makers implement different subsidies after a coal phase-out financed by a lump-sum tax. These subsidies, namely on market entry, production, wages and electricity price, are analyzed separately in order to compute and compare the respective associated welfare loss.

Our results show that a coal phase-out leads to rising electricity prices, falling wages as well as declining income, whereas the market structure (measured by the number of producing firms in the consumption good sector and their average productivity) remains unaffected. For the policy measures, we find that all of them help to counteract the negative effects of the coal phase-out on wages and the electricity price. They differ

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[16] In a meta-analysis, Stern (2012) summarizes the results of 47 studies on the elasticity of substitution between different energy resources and none of them reports complementary energy resources.

substantially, however, in what welfare loss they imply. A comparison indicates that falling wages and rising electricity prices can be counteracted with lower welfare losses if they are subsidized directly via a wage and electricity price subsidy, respectively. In particular, a wage subsidy allows to raise the wage to its initial level prior to the coal phase-out at a minor welfare loss of 0.016 %, which is 12 times less compared to raising the wage with a market entry subsidy.

When we think about the validity of our policy analysis, though, we need to be aware of potential limitations of our approach. A first limitation is that we consider an economy under autarky rather than an open economy. This simplification allows us to keep the effects of the coal phase-out and the policy interventions tractable. It also implies, however, that we neglect potential additional effects (and potential strategic interaction by choosing optimal policies) that could arise through trade channels. In an open economy model without an energy sector, Pflüger and Südekum (2013) show that it becomes more difficult for foreign firms to enter the export market, if domestic firms receive a market entry subsidy. Domestic firms become more productive, charge lower prices, and hence become more competitive on average. This lowers the expected export profits and hence the export incentives of foreign companies, and strengthens the market position of domestic firms. A similar argument applies to the wage subsidy and the electricity price subsidy. As inputs get cheaper, firms face lower marginal costs and charge lower prices. This creates a competitive advantage for domestic firms and allows to gain market share. In contrast, a production subsidy may weaken the market position of domestic firms, as they become less productive, charge higher prices, and hence become less competitive.

A second limitation is that we consider a static model with exogenous technology. Under endogenous technological change, investment in more efficient technology is typically affected by the relative prices of inputs, with higher investment being directed towards technologies that substitute more expensive inputs (Acemoglu, 2002; Acemoglu et al., 2012; Otto, Löschel, and Dellink, 2007; Otto, Löschel, and Reilly, 2008; Löschel and Otto, 2009; Linn, 2008; Newell, Jaffe, and Stavins, 1999). An electricity price subsidy could hence diminish the incentive to invest in renewable clean resources or energy-efficient technology as is makes electricity relatively cheaper (Fouquet, 2016; Ley, Stucki, and Woerter, 2016). The same applies to the other considered subsidies since they imply a decline in energy prices as well. Discouraging or delaying technological change might be costly, as it could result in an extended transition period with slow growth in the future (Acemoglu et al., 2012; Löschel and Otto, 2009).

Still, our analysis provides the basis for a more informed discussion about which policies may be helpful to mitigate adverse effects of the coal phase-out on consumers and industry in order to achieve a high level of social acceptance and political feasibility. In addition, our paper might offer political guidance beyond the coal phase-out. A recent example is that Germany and other European countries face a decline in Russian energy supplies, which are difficult to substitute in the short and medium run (Bachmann, Baqaee, Bayer, Kuhn, Löschel, Moll, et al., 2022; Bachmann, Baqaee, Bayer, Kuhn, Löschel, McWilliams, et al., 2022; IEA, 2022; Hausmann et al., 2022). In response to that, the German Federal Government implemented (among other measures) a temporary tax cut on fuels (BMF, 2022). The interesting point here is that the effects of both the initial reduction in resource supply and the tax cut are consistent with the results of our model. The former caused rising energy prices (Hausmann et al., 2022; Halser and Paraschiv, 2022) as well as decreasing wages and employment (Kagerl et al., 2022; Weyerstrass et al., 2022), while the latter has been widely criticized for raising the prices suppliers receive rather than lowering the prices consumers have to pay (Bach, 2022; Duso, 2022). This emphasizes that energy price subsidies might not be the preferable political measure to address energy resource scarcity, and highlights that our model might have important implications for how to deal with energy resource shortages more generally.

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A Appendix: Positively Supplied Resources

In the main text, we have assumed that the clean and dirty energy resource are supplied inelastically, which made the labor demand function of the energy sector straightforward. Subsequently, we will show that the general structure of this demand function remains by and large the same if we consider positively supplied resources R and V.

For convenience, we repeat the production function in the energy sector (see (6)):

$$e = L_E^{\beta} \left(R^{\varphi} + V^{\varphi}\right)^{\frac{1-\beta}{\varphi}}. \tag{A.1}$$

Accounting for the price taking behavior of energy firms, the demand system for the three inputs reads

$$\beta L_E^{\beta-1} \left(R^{\varphi} + V^{\varphi}\right)^{\frac{1-\beta}{\varphi}} = w, \tag{A.2}$$

$$L_E^{\beta}(1-\beta) \left(R^{\varphi} + V^{\varphi}\right)^{\frac{1-\beta}{\varphi}-1} R^{\varphi-1} = P_R, \tag{A.3}$$

$$L_E^{\beta}(1-\beta) \left(R^{\varphi} + V^{\varphi}\right)^{\frac{1-\beta}{\varphi}-1} V^{\varphi-1} = P_V. \tag{A.4}$$

Suppose the (inverse) supply functions for the two inputs are given by

$$P_R = \vartheta_R R^{\gamma}, \tag{A.5}$$

$$P_V = \vartheta_V V^{\gamma}, \tag{A.6}$$

with $\gamma, \vartheta_R, \vartheta_V > 0$. We assume the general functional form to be identical and only consider differences in (absolute) marginal costs.

Using the demand relations (A.3) and (A.4) yields

$$\frac{P_R}{P_V} = \left(\frac{R}{V}\right)^{1/(\varphi-1)}, \tag{A.7}$$

which determines the 'dirtyness' of the energy input in equilibrium as a function of relative prices. Combining this with the supply functions (A.5) and (A.6) leads to the expansion path implying

$$\frac{\vartheta_R}{\vartheta_V}\left(\frac{R}{V}\right)^{\gamma} = \left(\frac{R}{V}\right)^{1/(\varphi-1)}, \tag{A.8}$$

which results in

$$\left(\frac{\vartheta_R}{\vartheta_V}\right)^{\frac{\varphi-1}{1-\gamma\varphi-\gamma}} V = R. \tag{A.9}$$

Inserting this into the demand relation for the clean resource (A.4) yields

$$\begin{aligned} L_E^{\beta}(1-\beta)\left(\left(\frac{\vartheta_R}{\vartheta_V}\right)^{\frac{\varphi^2-\varphi}{1-\gamma\varphi-\gamma}} + 1\right)^{\frac{1-\beta}{\varphi}-1} V^{1-\beta-\varphi} V^{\varphi-1} &= P_V \\ \Leftrightarrow L_E^{\beta}(1-\beta)\Theta V^{-\beta} &= P_V \\ \Leftrightarrow L_E\left(\frac{1-\beta}{P_V}\Theta\right) &= V, \end{aligned} \tag{A.10}$$

with

$$\Theta := \left(\left(\frac{\vartheta_R}{\vartheta_V}\right)^{\frac{\varphi^2-\varphi}{1-\gamma\varphi-\gamma}} + 1\right)^{\frac{1-\beta}{\varphi}-1}.$$

As a final step, we substitute (A.10) into the labor demand function (A.2), which gives

$$\begin{aligned} \beta L_E^{\beta-1}\left(R^{\varphi} + V^{\varphi}\right)^{\frac{1-\beta}{\varphi}} &= w \\ \Leftrightarrow \beta L_E^{\beta-1} V^{1-\beta}\Theta^{(1-\beta)/(1-\beta-\varphi)} &= w \\ \Leftrightarrow \left(\frac{1-\beta}{P_V}\Theta\right)^{1-\beta} \Theta^{(1-\beta)/(1-\beta-\varphi)} &= w. \end{aligned} \tag{A.11}$$

This shows that the labor demand of the energy sector becomes horizontal if energy firms have an adjustment margin along the energy inputs, which is due to the assumed linear homogeneity of production. In this case, policies that reduce the use of the dirty (coal) resource imply an increase in ϑ_R, which results in a downward shift of the labor demand curve. This is similar to the case of a fixed resource base where $\bar{R}$ is reduced. The difference here is that the adjustment need in the labor market, i.e., the wage decrease that is needed to absorb labor in the consumption good sector from the energy sector, is now larger. As such, the adjustments are qualitatively identical, but they are quantitatively larger. The case with a fixed resource base that we consider in the main text hence represents the conservative case concerning the distributional effects and the needs for policy adjustment.

B Appendix: Equilibrium Income

Income is defined by (22), which we can be simplified to

$$I = wL_X + \Pi + P_E E_S. \tag{B.1}$$

Given that aggregate operating profits are

$$\Pi = M \int_{\underline{\theta}}^{\infty} \tau(\theta)\mu(\theta)d\theta - wL_X - P_E E_X, \tag{B.2}$$

we get

$$I = M \int_{\underline{\theta}}^{\infty} \tau(\theta)\mu(\theta)d\theta + P_E E_S - P_E E_X. \tag{B.3}$$

In equilibrium, the energy market clearing condition $E_X = E_S$ then implies

$$I = M \int_{\underline{\theta}}^{\infty} \tau(\theta)\mu(\theta)d\theta. \tag{B.4}$$

Inserting (13) and taking into account the average productivity of firms operating in the market (21), equilibrium income can be written as

$$I = M\tau(\tilde{\theta}). \tag{B.5}$$

C Appendix: Policy Interventions

C.1 Subsidy on Market Entry or Production

In case of the market entry subsidy, the cutoff productivity (27) must be transformed to

$$\underline{\theta}(w) = b\left(\frac{\sigma-1}{c-(\sigma-1)}\frac{wF_D}{wF*(1-S_F)}\right)^{\frac{1}{c}}, \tag{C.1}$$

which also implies $\tilde{\theta}(w)$. The equilibrium conditions then read

$$\begin{aligned} \bar{L} &= Ml(\tilde{\theta}(w), w, P_E, I) + MF_D + M\left[1 - G(\underline{\theta}(w))\right]^{-1} F \\ &+ \left(\beta \frac{P_E}{w}\right)^{\frac{1}{1-\beta}} \left(\bar{R}^{\varphi} + \bar{V}^{\varphi}\right)^{\frac{1}{\varphi}}, \end{aligned} \tag{C.2}$$

$$Me(\tilde{\theta}(w), w, P_E, I) = \left(\beta \frac{P_E}{w}\right)^{\frac{\beta}{1-\beta}} \left(\bar{R}^{\varphi} + \bar{V}^{\varphi}\right)^{\frac{1}{\varphi}}, \tag{C.3}$$

$$I = M \frac{\sigma c}{c - (\sigma - 1)} wF_D, \tag{C.4}$$

$$M = p(\tilde{\theta}(w), w, P_E)^{\sigma - 1}, \tag{C.5}$$

$$T = wF * S_F * \underbrace{\frac{M}{1 - G(\underline{\theta}(w))}}_{=M_e}, \tag{C.6}$$

with T denoting the lump-sum tax. (C.1) - (C.6) implicitly determine the equilibrium levels of $\underline{\theta}^*_F$, w^*_F, $P^*_{E_F}$, M^*_F, I^*_F and T^*_F, where the subscript F is used to indicate the subsidy on market entry.

In a similar vein, the modified cutoff productivity in a situation where the government implements a subsidy on production is given by

$$\underline{\theta}(w) = b\left(\frac{\sigma - 1}{c - (\sigma - 1)} \frac{wF_D * (1 - S_{F_D})}{wF}\right)^{\frac{1}{c}}. \tag{C.7}$$

The equilibrium conditions are

$$\begin{aligned} \bar{L} &= Ml(\tilde{\theta}(w), w, P_E, I) + MF_D + M\left[1 - G(\underline{\theta}(w))\right]^{-1} F \\ &+ \left(\beta \frac{P_E}{w}\right)^{\frac{1}{1-\beta}} \left(\bar{R}^{\varphi} + \bar{V}^{\varphi}\right)^{\frac{1}{\varphi}}, \end{aligned} \tag{C.8}$$

$$Me(\tilde{\theta}(w), w, P_E, I) = \left(\beta \frac{P_E}{w}\right)^{\frac{\beta}{1-\beta}} \left(\bar{R}^{\varphi} + \bar{V}^{\varphi}\right)^{\frac{1}{\varphi}}, \tag{C.9}$$

$$I = M \frac{\sigma c}{c - (\sigma - 1)} wF_D * (1 - S_{F_D}), \tag{C.10}$$

$$M = p(\tilde{\theta}(w), w, P_E)^{\sigma - 1}, \tag{C.11}$$

$$T = w * F_D * S_{F_D} * M. \tag{C.12}$$

(C.7) - (C.12) implicitly determine the equilibrium levels of $\underline{\theta}^*_{F_D}$, $w^*_{F_D}$, $P^*_{E_{F_D}}$, $M^*_{F_D}$, $I^*_{F_D}$ and $T^*_{F_D}$, where the subscript F_D is used to indicate the subsidy on production.

C.2 Subsidy on Wages or Electricity Prices

If a subsidy is paid on wages, firm-selection is not affected. The equilibrium conditions are

$$\begin{aligned}\bar{L} = {} & Ml(\tilde{\theta}^*, w(1-S_w), P_E, I) + MF_D + M(1-G(\underline{\theta}^*))^{-1}F \\ & + \left(\beta \frac{P_E}{w(1-S_w)}\right)^{\frac{1}{1-\beta}} \left(\bar{R}^{\varphi} + \bar{V}^{\varphi}\right)^{\frac{1}{\varphi}},\end{aligned} \tag{C.13}$$

$$Me(\tilde{\theta}^*, w(1-S_w), P_E, I) = \left(\beta \frac{P_E}{w(1-S_w)}\right)^{\frac{\beta}{1-\beta}} \left(\bar{R}^{\varphi} + \bar{V}^{\varphi}\right)^{\frac{1}{\varphi}}, \tag{C.14}$$

$$I = M \frac{\sigma c}{c-(\sigma-1)} w F_D (1-S_w), \tag{C.15}$$

$$M = p(\tilde{\theta}^*, w(1-S_w), P_E)^{\sigma-1}, \tag{C.16}$$

$$T = w * S_w * (L_X(\tilde{\theta}^*, w(1-S_w), P_E, I, M) + L_E(w(1-S_w), P_E)). \tag{C.17}$$

(C.13) - (C.17) implicitly determine the equilibrium levels of w^*_w, $P^*_{E_w}$, M^*_w, I^*_w and T^*_w, where the subscript w is used to indicate the subsidy on wages.

The electricity price subsidy has no effect on firm-selection as well. Thus, we get

$$\begin{aligned}\bar{L} = {} & Ml(\tilde{\theta}^*, w, P_E(1-S_{P_E}), I) + MF_D + M(1-G(\underline{\theta}^*))^{-1}F \\ & + \left(\beta \frac{P_E}{w}\right)^{\frac{1}{1-\beta}} \left(\bar{R}^{\varphi} + \bar{V}^{\varphi}\right)^{\frac{1}{\varphi}},\end{aligned} \tag{C.18}$$

$$Me(\tilde{\theta}^*, w, P_E(1-S_{P_E}), I) = \left(\beta \frac{P_E}{w}\right)^{\frac{\beta}{1-\beta}} \left(\bar{R}^{\varphi} + \bar{V}^{\varphi}\right)^{\frac{1}{\varphi}}, \tag{C.19}$$

$$I = M \frac{\sigma c}{c-(\sigma-1)} w F_D, \tag{C.20}$$

$$M = p(\tilde{\theta}^*, w, P_E(1-S_{P_E}))^{\sigma-1}, \tag{C.21}$$

$$T = P_E * S_{P_E} * E_X(\tilde{\theta}^*, w, P_E(1-S_{P_E}), I, M). \tag{C.22}$$

(C.18) - (C.22) implicitly determine the equilibrium levels of $w^*_{P_E}$, $P^*_{E_{P_E}}$, $M^*_{P_E}$, $I^*_{P_E}$ and $T^*_{P_E}$, where the subscript P_E is used to indicate the subsidy on electricity.

D Appendix: Energy Resource Endowments

In this appendix, we present in more detail how we retrieved the parameters $\bar{R}$ and $\bar{V}$ as well as $\underline{R}$. To do so, we start from the aggregate electricity production function (6) (plugging in the inelastically supplied energy resources), which we repeat for convenience:

$$e = L_E^{\beta} \left(\bar{R}^{\varphi} + \bar{V}^{\varphi}\right)^{\frac{1-\beta}{\varphi}}. \tag{D.1}$$

We rewrite this as

$$e = \left((L_E^{\frac{\beta}{1-\beta}} \bar{R})^{\varphi} + (L_E^{\frac{\beta}{1-\beta}} \bar{V})^{\varphi}\right)^{\frac{1-\beta}{\varphi}}, \tag{D.2}$$

where we interpret the overall energy e that is produced as a CES aggregate of dirty and clean energy.

From the data, we know that aggregate energy production is 245 TWh and that 51.65% of this are from using dirty energy resources and accordingly 48.35% are from clean resources. We use this information such that our production structure reflects the real world allocation of energy production between dirty and clean resources although we model both dirty and clean energy as imperfect substitutes in aggregate energy production. As such, we assume that

$$L_E^{\frac{\beta}{1-\beta}}\bar{R} = \frac{0.5165}{0.4835}\cdot L_E^{\frac{\beta}{1-\beta}}\bar{V}. \tag{D.3}$$

Plugging this into (D.2), we can determine $\bar{V}$ as

$$\begin{aligned}
e &= \left(\left(\frac{0.5165}{0.4835}\cdot L_E^{\frac{\beta}{1-\beta}}\bar{V}\right)^{\varphi} + (L_E^{\frac{\beta}{1-\beta}}\bar{V})^{\varphi}\right)^{\frac{1-\beta}{\varphi}} \\
\Leftrightarrow e &= \left((L_E^{\frac{\beta}{1-\beta}}\bar{V})^{\varphi}\left(\left(\frac{0.5165}{0.4835}\right)^{\varphi}+1\right)\right)^{\frac{1-\beta}{\varphi}} \\
\Leftrightarrow e &= L_E^{\beta}\bar{V}^{1-\beta}\left(\left(\frac{0.5165}{0.4835}\right)^{\varphi}+1\right)^{\frac{1-\beta}{\varphi}} \\
\Leftrightarrow \bar{V} &= \left(e\cdot L_E^{-\beta}\cdot\left(\left(\frac{0.5165}{0.4835}\right)^{\varphi}+1\right)^{-\frac{1-\beta}{\varphi}}\right)^{1/(1-\beta)},
\end{aligned} \tag{D.4}$$

where the expression on the lhs is determined by (known) parameters. Using this, we can also determine $\bar{R}$ as

$$\bar{R} = \frac{0.5165}{0.4835}\cdot\left(e\cdot L_E^{-\beta}\cdot\left(\left(\frac{0.5165}{0.4835}\right)^{\varphi}+1\right)^{-\frac{1-\beta}{\varphi}}\right)^{1/(1-\beta)}. \tag{D.5}$$

In order to determine $\underline{R}$, we use again the production structure from before, taking $\bar{V}$ pre-phase out and taking into account that on impact (in the short run) electricity production will decrease from 245 TWh to 187.25 TWh since coal makes up 23.57% of gross electricity production. Using this, we can write

$$\underline{R} = \left(\left(\frac{e(1-0.2357)}{L_E^{\beta}}\right)^{\frac{\varphi}{1-\beta}} - \bar{V}^{\varphi}\right)^{1/\varphi}. \tag{D.6}$$

E Online Appendix: Robustness

One of the main take aways from our analysis is that targeted policies are preferable when it comes to stabilize wages and electricity prices (which is a main focus in the policy debate). We have documented a substantial differential in the welfare costs between the targeted policies and the more indirect ones which aim at stimulating firm entry or production. We have also shown that the welfare costs of stabilizing the electricity price is far higher in terms of welfare costs than that of stabilizing the wage. In this appendix, we look at the robustness of our results by considering different parameterization along the lines discussed in the text.

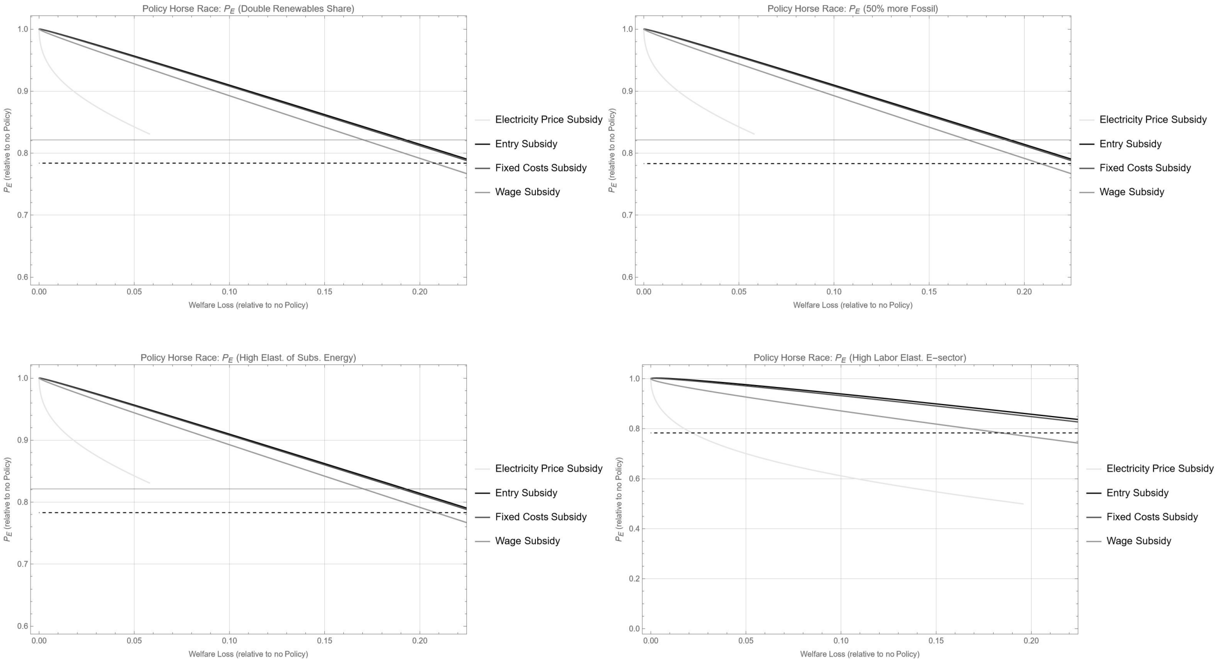

Figure 10: Robustness I: Energy Price

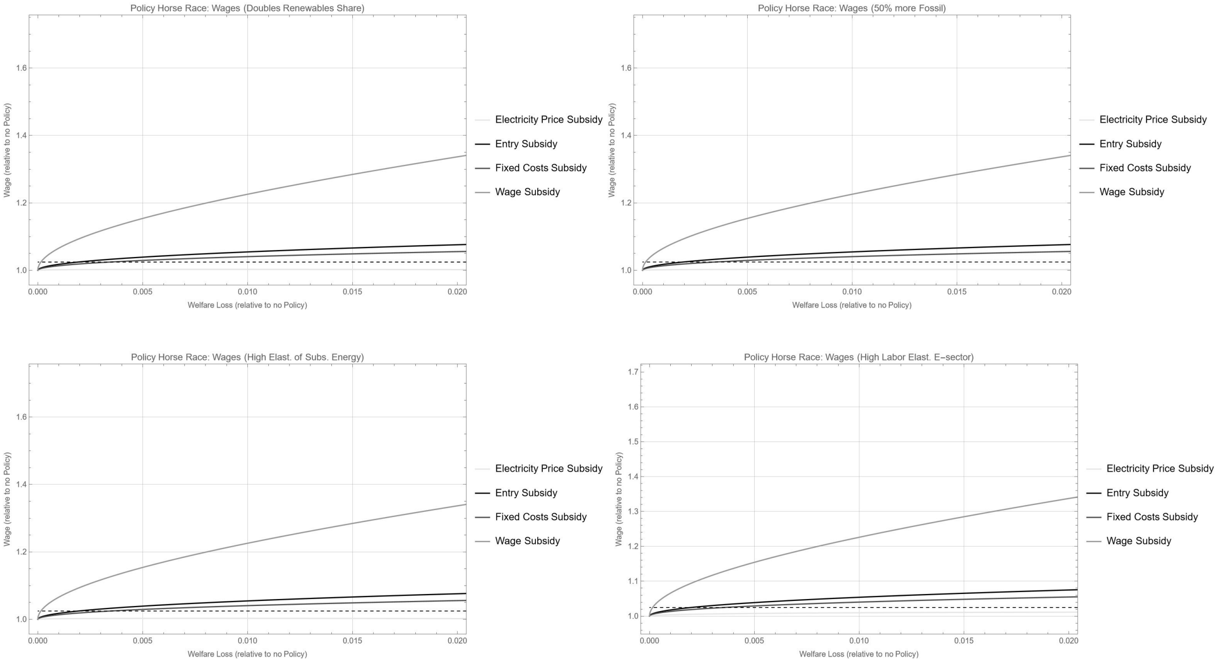

Figure 11: Robustness I: Wages

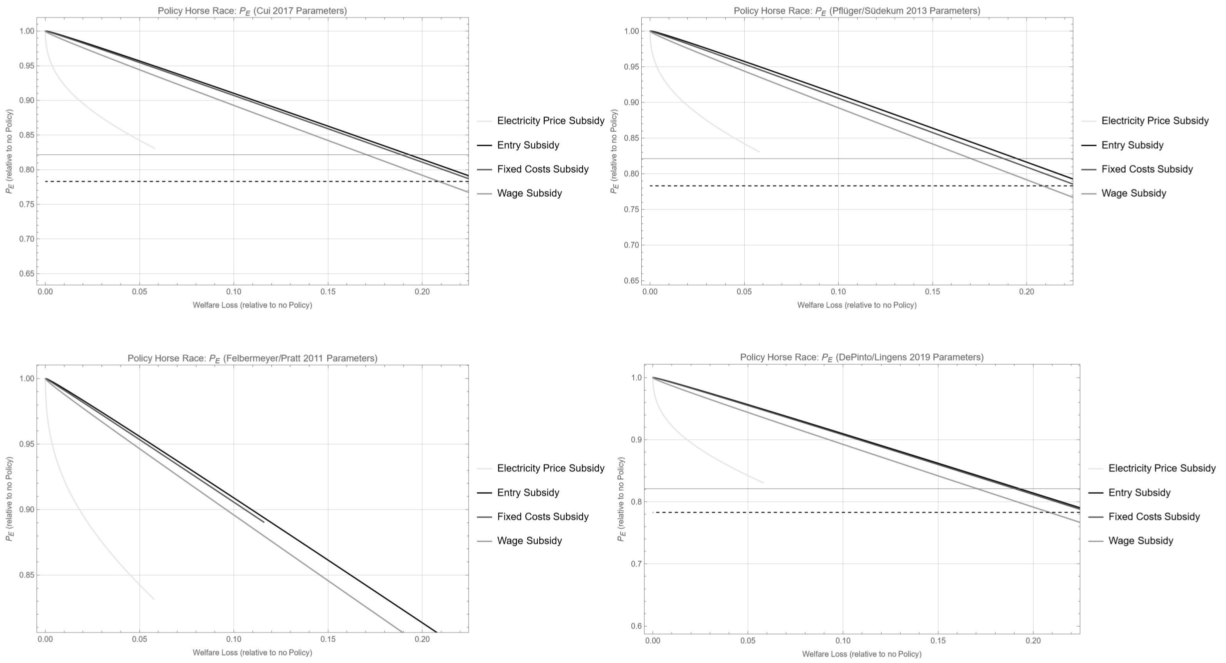

Figure 12: Robustness II: Energy Price

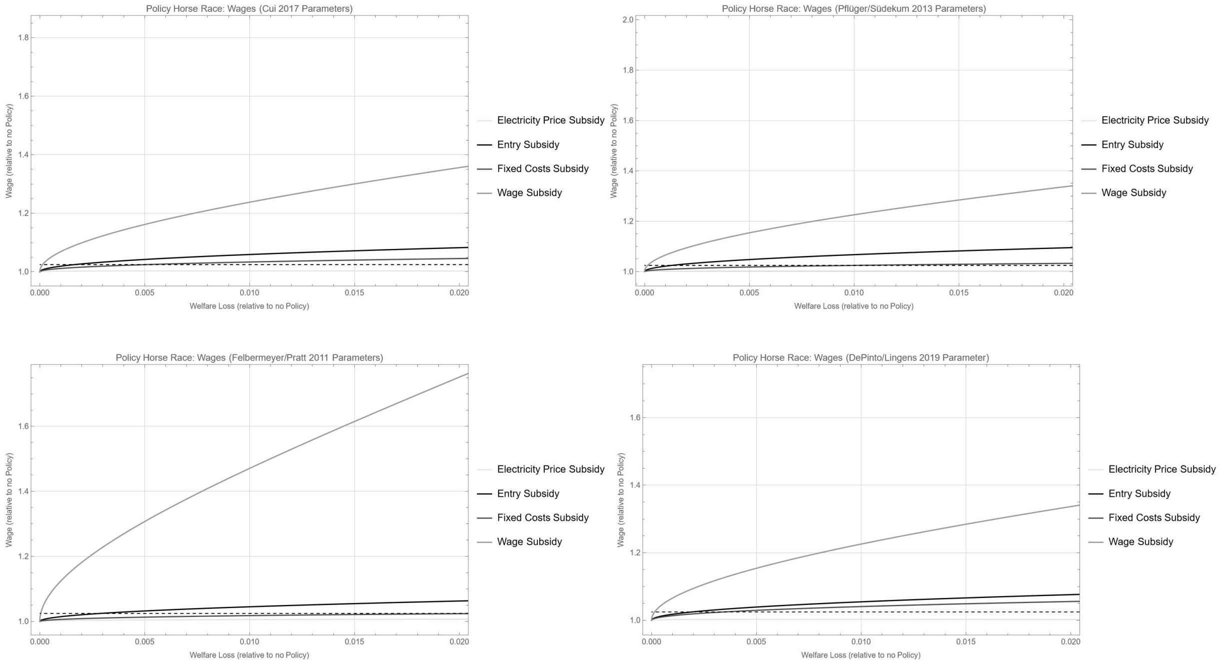

Figure 13: Robustness II: Wages

Table 2: Parameter Values Used for Numerical Solution: Robustness I

	Initial Parameters	High Share Renewables	High Share Fossil	High Elast. of Subst. Energy	Low α
σ	3.8	3.8	3.8	3.8	3.8
c	4.582	4.582	4.582	4.582	4.582
L	7083	7083	7083	7083	7083
F	2	2	2	2	2
FD	0.33	0.33	0.33	0.33	0.33
g	1	1	1	1	1
b	0.2	0.2	0.2	0.2	0.2
α	0.9097	0.9097	0.9097	0.9097	0.53
β	0.0427	0.0427	0.0427	0.0427	0.0427
σresource	1.85	1.85	1.85	3	1.85
V	52.3973	161.183	26.7882	83.7333	52.3973
Rup	55.9736	5.50056	92.1383	89.4483	55.9736
Rdown	30.9386	0.422772	58.3004	48.6081	30.9386

Table 3: Parameter Values Used for Numerical Solution: Robustness II

	Initial Parameters	Cui 2017	Pflueger/Suedekum 2013	Felbermeyer/Pratt 2011	DePinto/Lingens 2019
σ	3.8	4	3.8	8.6	3.8
c	4.582	4.25	3.4	9.23	4.582
L	7083	7083	7083	7083	7083
F	2	1	2	0.6	2
FD	0.33	1	1	0.01	0.251
g	1	1	1	1	1
b	0.2	0.2	0.2	0.2	0.2
α	0.9097	0.9097	0.9097	0.9097	0.9097
β	0.0427	0.0427	0.0427	0.0427	0.0427
σresource	1.85	1.85	1.85	1.85	1.85
V	52.3973	52.3973	52.3973	52.3973	52.3973
Rup	55.9736	55.9736	55.9736	55.9736	55.9736
Rdown	30.9386	30.9386	30.9386	30.9386	30.9386