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# Evaluating the socio-economic impacts of the energy system transition: the implications of wage-setting mechanisms

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ABSTRACT

Achieving net-zero greenhouse gas emissions requires large-scale investment in clean energy infrastructure, with potentially far-reaching system-wide consequences for employment and wages. Computable General Equilibrium (CGE) and Input-Output (IO) models are widely used to assess these impacts but typically rely on stylised labour market assumptions that can substantially distort projections. This paper addresses that gap by developing a unified analytical wage-setting framework. This framework encompasses nominal and real wage rigidities, money illusion, inflation expectations, and unemployment responsiveness. These factors are integrated into a dynamic CGE model linked to a bottom-up energy system optimisation model. Our results re-emphasise that labour market specification is a first-order determinant of potential outcomes. Under fixed-wage assumptions, as used in standard IO analyses, employment rises substantially above baseline by 2045 (due to the large-scale investments). However, using our preferred, empirically grounded wage curve specification, the gain is more modest. Under the most restrictive Phillips curve specification, gains are near-zero, and employment can temporarily decline during the peak investment period. Similarly, endogenous GDP, wages, and household consumption impacts vary across scenarios. These contrasting results demand fundamentally different policy responses. Optimistic fixed-wage projections may appear to justify passive policy, while empirically grounded specifications point to the potential need for active labour market intervention. We conclude that the employment dividend of green investment is modest, that assessments relying on fixed-wage assumptions risk overstating it substantially, and that impact assessment and policies should therefore be based on empirically grounded wage-setting specifications rather than the optimistic closures common in current practice.

## 1. Introduction

Countries worldwide have committed to achieving net-zero greenhouse gas emissions [1], with Germany legally bound to reach this target by 2045 [2]. Meeting this goal requires substantial investment in clean energy infrastructure and a corresponding shift away from fossil fuels, a transition with potentially significant implications for employment, wages, and the broader economy. Evaluating the system-wide macroeconomic effects of this transition is therefore essential for policymakers.

Computable General Equilibrium (CGE) models are widely used for this purpose to capture comprehensive macroeconomic interdependencies.[1] However, a critical and underexplored aspect of these models is their simplified treatment of wage-setting and labour market dynamics. The existing literature demonstrates that the choice of labour market closure, whether wages are fixed, set by a wage curve, or governed by a Phillips curve, can substantially alter outcomes for GDP, employment, and wages (e.g., [12–14]). Yet this issue has not been systematically examined in the context of the energy transition. In particular, existing treatment of wage-setting omits inflation expectations and money illusion and rarely moves beyond a single default specification.

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[1] These models can be integrated with bottom-up energy system optimisation models [3–5], incorporated into fully Integrated Assessment models [6–8], or operated independently [9–11].

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This paper contributes to the literature across three dimensions. First, it develops a unified analytical framework which allows an enhanced range of wage-setting closures. These comprise fixed nominal and real wage, wage curve, general and traditional Phillips curve, and consistent and asymmetric money illusion options. These closures are derived as specific parameterisations of a single general equation, distinguishable from one another by the values taken by four identifiable parameters. Our framework extends the taxonomy of labour market closures in Boeters et al. [15] by making the quantitative and qualitative differences between these closures analytically traceable to a common set of parameters. The framework also explicitly incorporates inflation expectations and money illusion which are both theoretically important and empirically relevant. For instance, certain asymmetries in inflation expectations can produce employment outcomes that fall outside the range bounded by symmetric specifications.

Second, the CGE simulation results confirm the predictions made by the analytical model, including the ordering of outcomes across closures, the behaviour of money illusion variants, and the long-run zero employment change under the traditional Phillips curve. This verification provides both confidence in the model's theoretical integrity and a diagnostic template for practitioners. It does so by integrating these mechanisms into a CGE model of Germany, specifically DEMACRO [16,17]. The quantitative and qualitative effects of alternative labour market closures on key elements of the macroeconomy are then identified. This is achieved by integrating the capital and operational expenditures required to meet net-zero goals.[2] The scale and timing of these costs are determined using a bottom-up energy system optimisation model [18], and a one-way soft linking approach is used to connect these costs to the CGE model.

Third, it identifies a specific and practically consequential bias in standard practice. Many applied energy transition assessments assume a fixed nominal wage. This least empirically defensible labour market specification lies at the most optimistic extreme of the employment-impact distribution. The gap between this and the traditional Phillips curve outcome is more than an order of magnitude and large enough to reverse the policy conclusion about whether active labour market intervention is required. As an example, in our simulations, with fixed-wage assumptions, employment rises substantially above baseline. But for our preferred, empirically grounded, wage curve specification, the employment gain is modest. Alternatively, under the most restrictive Phillips curve specification, gains are near-zero, and employment can temporarily decline during the peak investment period. GDP, wages, and household consumption also diverge comparably across scenarios.

These contrasting results demand fundamentally different policy responses. Optimistic fixed-wage projections may appear to justify passive policy, while empirically grounded specifications point to the potential need for active labour market intervention, wage support mechanisms, and targeted retraining investment. Failure to explore different options risks generating misleading projections and misguided (climate) policy recommendations.

The paper's focus on wage-setting mechanisms is a deliberate choice. Wage-setting occupies a unique position in macroeconomic modelling because it is the primary interface between labour market behaviour and the system-wide price and output dynamics that CGE models are designed to capture. Boeters et al. [15], the standard reference treatment, catalogues labour market closure options but omits inflation expectations and money illusion, provides no unified analytical framework explaining why different closures produce different outcomes, and does not verify those predictions in a calibrated model.

Other labour market features, including skills mismatch, retraining, regional mobility, and union bargaining structures, are undoubtedly important for the distributional and sectoral dimensions of a just transition. However, in a general equilibrium setting, they operate primarily through their effect on the effective labour supply and on the wage at which that labour is offered. These features are downstream of wage-setting in the model's structure, and their aggregate effects are reflected in the labour demand elasticity and the slope of the wage-setting curve. Sectoral and regional disaggregation, together with explicit modelling of skills and mobility barriers, are natural extensions that operate within the wage-setting framework developed here. Additionally, the specific gap in the CGE literature that this paper addresses is the treatment of wage-setting. Skills mismatch and mobility have considerably more developed literatures, particularly at the level of the individual firm. Wage-setting, and in particular the role of inflation expectations and money illusion at the system-wide level, is the dimension that remains neglected.

Our results show that labour market specification is a first-order determinant of potential outcomes. While the quantitative results are Germany-specific, the analytical framework and the qualitative ordering of outcomes are likely to generalise to a wide range of economies facing a large demand-side investment shock. Official and academic assessments of the employment impacts of energy transitions should, as a matter of practice, report the sensitivity of their results to alternative labour market specifications.

The paper is organised as follows. Section 2 outlines the theoretical labour market framework. Section 3 describes the empirical CGE model, data, and simulation strategy. Section 4 presents the results. Section 5 sets out policy implications. Section 6 provides a discussion and conclusions.

## 2. Theoretical labour market framework

The central aims of this paper are to identify key labour market options available in a CGE model, to analyse how they operate and to quantify their influence on the system-wide impacts. Some contributions to this literature mistakenly claim that CGE models cannot represent labour markets in sufficient detail. To address this, we clearly present various wage-setting options based on a robust theoretical framework. This helps practitioners compare different labour market options, understand their relative impacts, and consider their broader implications for wage-setting and employment. Additionally, the theoretical analysis provides important context for interpreting the empirical results that follow.

The empirical analysis in Section 4 of this paper simulates the impact of a sequence of demand- and supply-side shocks, where these exogenous interventions are derived from an energy system optimisation model. For tractability and clarity, however, the theoretical analysis is limited to studying the labour market effects of a single continuing demand-side shock with different wage-setting procedures. The shock produces a shift in the aggregate labour demand curve and the analysis focuses on the long-run outcomes in a unified national labour market. The long run is defined as the period in which all product markets are in equilibrium and full adjustment has been made to the levels of employment, wages, and capital stock. A unified labour market means that there is no disaggregation along, for example, skill or geographical lines. The approach here is purely analytical, but Appendix A shows how these theoretical long-run results are replicated in simulations using the empirical model outlined in Section 3 of the paper.

In discussing wage setting, key concepts include the distinction between the real and nominal wage and the notion of money illusion. The

[2] The analysis in the CGE model focuses solely on assessing the system-wide impacts of these interventions, as the only exogenous shocks to the economy. This approach allows for tractability, and both emphasises and isolates the effects of different labour market closures on the outcomes associated with these expenditure shocks. This enables a broader generalisation of the implications of labour market specifications in this context. While the explicit quantitative effects identified are specific to Germany, the qualitative effects, particularly those directly related to employing different labour market settings, are applicable more widely. Further, the analytical model developed in Section 2 of this paper is generalisable to any demand-side shock.

nominal wage, $w^N$, is the wage expressed in current monetary units (as distinct from the real wage, deflated by the consumer price index). In the simulations that are reported in Section 4 and in Appendix A, changes in the nominal wage are measured relative to the price of imports, which remain unchanged.

The real wage, $w^R$, is the nominal wage divided by the consumer price index, p.

$$w^R = \frac{w^N}{p} \rightarrow lnw^R = lnw^N - lnp \tag{1}$$

Eq. (1) implies that the proportionate change in the real wage is equal to the proportionate change in the nominal wage minus the proportionate change in consumer prices. However, changes in the nominal wage have a direct impact on consumer prices by increasing the costs of domestically produced goods. Further, because in the simulation model we assume that the interest rate and import prices remain constant, the only source of domestic price changes is variation in the nominal wage. This implies:

$$lnp = \theta lnw^N \tag{2}$$

In Eq. (2) the value of the parameter $\theta$ lies between zero and one. It is the share of domestic wages in the production of consumer goods and services. It takes a value less than one because of imports, which make up some of the intermediate inputs in domestic production and direct household consumption.[3]

Combining Eqs. (1) and (2) gives:

$$lnw^R = (1-\theta)lnw^N \rightarrow lnw^N = \frac{lnw^R}{1-\theta} \tag{3}$$

Eq. (3) reveals that there is a close correspondence between the change in the real and nominal wage rates. In the context of a straightforward exogenous increase in labour demand, where the outcome of the wage-setting procedure is an increase in the real wage, there is a corresponding, but greater, increase in the nominal wage.[4] Alternatively, a labour market mechanism that governs the change in the nominal wage will automatically be associated with a determinate lower change in the real wage.

Where workers bargain for the nominal wage, they mistake nominal income changes for real changes. In doing so, they exhibit 100% money illusion, failing to account for any past or future changes in consumer prices [19]. On the other hand, where bargaining is over the real wage, there is zero money illusion; workers translate their bargaining power gains fully into real wage increases. In addition to the conventional nominal and real wage analyses, we also consider situations where there is a degree of money illusion between the two extremes. In this case, Eq. (1) can be adjusted to generate the money-illusion wage, $w^M$, as:

$$lnw^M = lnw^N - \sigma lnp \tag{4}$$

where $1 \geq \sigma \geq 0$, with $\sigma = 0$ implying total money illusion and $\sigma = 1$ no money illusion.

The relevant aggregate labour demand curve represents the trade-off between the nominal, real or money-illusion wage and the employment rate. Note that this is a general equilibrium labour demand curve, calculated where all adjustments to prices and outputs have been made. In Fig. 1, the origin represents the initial equilibrium wage/employment combination. The vertical and horizontal axes indicate proportionate nominal/real/money-illusion wage changes and employment rate changes from that initial position. These proportionate changes are represented by the dot notation. An exogenous demand-side stimulus to the economy, such as an increase in export demand, will shift the labour demand curve outwards, representing the fact that at any existing wage employers will wish to take on additional workers.

The shift in the long-run nominal wage labour demand is shown as $AD_1$ and, using expression (3), any given nominal wage change implies a proportionately lower increase in the real wage. The corresponding real wage labour demand curve is represented by $AD_2$. Note that both the nominal and the real labour demand curves pass through the same point A on the horizontal axis. This is where the proportionate change in the nominal, and therefore the real, wage is zero. Where each curve intersects the vertical axis, $0D_2 = (1-\theta)0D_1$. Similarly, for any change in the employment rate, the change in the nominal wage, identified as a point on $AD_1$, has a corresponding change in the real wage which can be read vertically below on the real wage labour demand curve $AD_2$.

We are interested in three broad forms of wage-setting procedures. These are: the fixed wage, wage curve [20] and the Phillips curve [21] outcomes. We use the general Eq. (5) to discuss the operation of these alternative mechanisms:

$$\begin{aligned} lnw_t^N = {} & \sigma lnp_t + \alpha\left(lnw_{t-1}^N - \gamma lnp_{t-1}\right) - \beta lnu_t + [lnw_0(1-\alpha) \\ & + (\alpha\gamma - \sigma)lnp_0 + \beta lnu_0] \end{aligned} \tag{5}$$

In Eq. (5), $u$ is the unemployment rate, $p$ is the consumer price index, and these variables take logarithmic values. The $t$ and $t$-$1$ subscripts represent adjacent time periods, and $\alpha, \beta, \sigma \& \gamma$ are parameters. The expression in square brackets is the constant term, calibrated so that the labour market is in equilibrium in the initial (pre-shock) period 0.

Note first that in Eq. (5) the employment rate, which is shown on the horizontal axis in Fig. 1, is replaced by the unemployment rate, which takes a negative sign. Visual exposition is improved if the tightening of the labour market is represented by increases in the employment rate, but econometric studies of wage-setting behaviour favour reductions in the unemployment rate in this role. In the theoretical analysis, however, the unemployment rate is simply 1 minus the employment rate so that they are directly negatively correlated.

The different wage-setting arrangements can be represented as alternative combinations of the parameter values in Eq. (5). Section 2.1 discusses these arrangements in the context of directly determining the nominal wage, while Section 2.2 repeats the analysis for the real wage. Sections 2.3 and 2.4 explore the effects of varying the degree of money illusion, considering both symmetric and asymmetric cases.

### 2.1. Nominal wage setting

We begin by using Eq. (5) to consider all the nominal wage cases. Focusing on the nominal wage implies that $\gamma = \sigma = 0$.

#### 2.1.1. Fixed nominal wage (FNW)[5]

The most straightforward case is the fixed-wage option (the de facto assumption in standard Input-Output and Social Accounting Matrix-based models), governed by institutional nominal wage rigidity, where involuntary unemployment allows adjustments in labour demand to be accommodated solely through changes in employment levels [15]. In this case there is no link between the tightness of the labour market and the determination of the nominal wage, so that $\beta = 0$. Similarly, there are no explicit wage-setting dynamics, so that $\alpha = 0$. The fixed nominal wage-setting arrangement is therefore shown as:

[3] The model used in simulation is characterised by linear homogeneous production functions, no fixed inputs and competitive product markets. Capital goods are produced means of production so that the only non-produced inputs are labour and imports. Interest rates and foreign prices are held constant.

[4] If there is a similar exogenous reduction in labour demand, so that prices generally fall, the decline in the nominal wage will be accompanied by a smaller reduction in the real wage. However, shifts in labour demand resulting from efficiency changes generate a more complex relationship between the real and nominal wage.

[5] The acronyms identified in this section match the analysis with the empirical results discussed in Section 4.

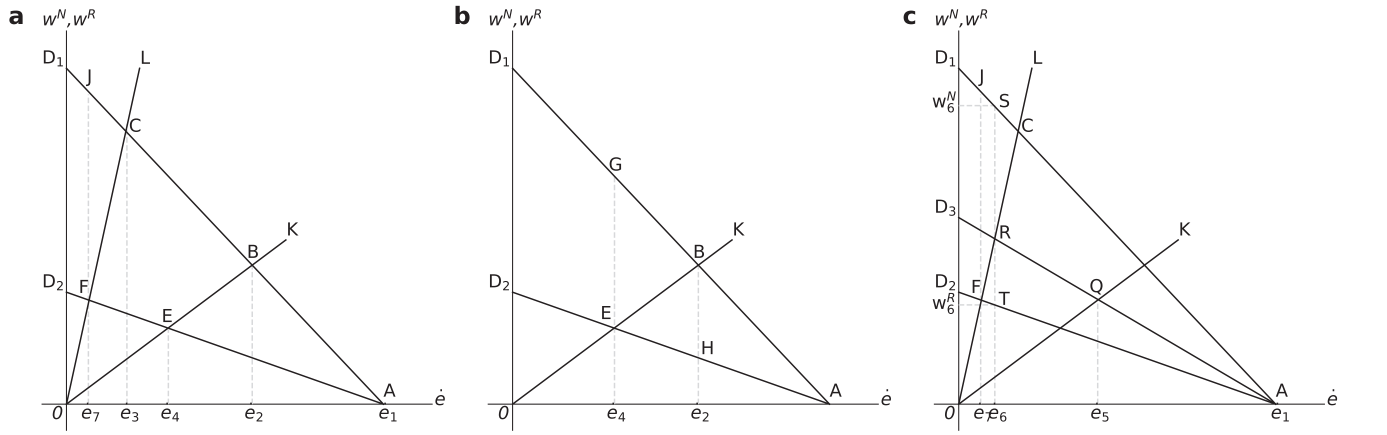


**Fig. 1.** Labour market wage-setting options (as percentage changes). Panel (a) shows the long-run employment and wage outcomes under real fixed wage, real wage curve, general real Phillips curve, and traditional real Phillips curve outcomes as A, E, F, and $D_2$ respectively. $AD_1$ and $AD_2$ are the nominal and real labour demand curves. Panel (b) illustrates the relationship between the real and nominal wage under the wage curve case. Panel (c) covers both consistent and asymmetric money illusion.

$$lnw_t^N = \left[lnw_0^N\right] \rightarrow w_t^N = w_0^N \tag{6}$$

In Fig. 1a the fixed nominal wage setting function is therefore a straight line through the origin, along the horizontal axis. In response to the demand shock the long-run equilibrium outcome is given where the labour demand curve $AD_1$ cuts the horizontal axis at point A. There is no change in the nominal wage, relative to the initial, base-year, value, and employment increases by $\dot{e_1}$.

### 2.1.2. Nominal wage curve (NWC)

Where the wage setting is determined via a wage curve [20], the proportionate change in the wage is positively related to the tightness of the labour market, which means that β takes a positive value.[6] Again there are no direct dynamics from the wage-setting side, implying that α = 0. The relevant formulation is therefore:

$$lnw_t^N = -\beta lnu_t + \left[\, lnw_0 + \beta lnu_0\right] \rightarrow ln\frac{w_t^N}{w_0^N} = -\beta ln\frac{u_t}{u_0} \tag{7}$$

In Fig. 1a the wage curve is given by the line 0K and the long-run equilibrium is where this cuts the nominal wage labour demand curve $AD_1$ at B, producing an employment change equal to $\dot{e_2}$. The wage curve can be motivated in several ways. The most straightforward is that it reflects the bargaining power of both workers and firms in the wage-setting process. In this case, a reduction in the unemployment rate strengthens the bargaining power of workers and increases the wage change that they can achieve. Alternative possibilities are that the wage curve is underpinned by efficiency wage or search cost considerations (e.g. [19,20]).

### 2.1.3. Nominal Phillips curve (SPC_N, TPC_N)

The labour market options discussed so far have determined the nominal wage levels. An alternative, the Phillips curve, focuses not on the level, but rather on the period-by-period proportionate change in the wage. This is driven by the tightness of the labour market, which is again measured by the unemployment rate. With reference to Eq. (5), α now takes a positive value, where 0 < α ≤ 1.

The general nominal wage Phillips curve specification (SPC_N) is therefore:

$$nw_t^N = \alpha lnw_{t-1}^N - \beta lnu_t + \left[(1-\alpha)lnw_0^N + \beta lnu_0\,\right] \tag{8}$$

An increase in the demand for labour will reduce the unemployment rate and produce an increase in the nominal wage. The wage rate rises until the labour market is brought back to equilibrium, where $w_t^N = w_{t-1}^N$. Substituting this requirement into Eq. (8) produces:

$$ln\frac{w_t^N}{w_0^N} = -\frac{\beta}{(1-\alpha)}ln\frac{u_t}{u_0} \qquad \alpha \neq 1 \tag{9}$$

Eq. (9) gives the long-run equilibrium wage-setting function. This is the proportionate change of the nominal wage from the base-year period as a function of the proportionate change in the unemployment rate from that same period. As can be seen from a comparison with Eq. (7), the long-run outcome resembles a nominal wage curve, but in this case the slope is determined by both parameters α and β.

Where α = 0, the nominal wage curve and the Phillips curve long-run results are identical; for 0 < α < 1, the outcomes are along a line such as 0L in Fig. 1a, with the equilibrium at C and the proportionate employment change $\dot{e_3}$. As the value of α increases, 0L pivots through the origin and becomes steeper. As α → 1, the slope approaches the vertical, tending towards infinity. Where $\alpha = 1$, Eq. (8) becomes Eq. (8a), the initial (traditional) formulation of the Phillips curve (TPC_N):

$$lnw_t^N = lnw_{t-1}^N - \beta lnu_t + [\beta lnu_0] \tag{8a}$$

Here Eq. (9) cannot be used to solve for the long-run proportionate change in the wage because setting $\alpha = 1$ involves dividing by zero. Rather, imposing $w_t^N = w_{t-1}^N$ gives $u_t = u_0$; the nominal wage rises until the unemployment rate returns to its original level. The long-run wage setting relationship now lies on the vertical line through the origin, implying a proportionate rise in the nominal wage equal to $0D_1$. This long-run outcome replicates the situation where there is a fixed, fully employed labour supply.

## 2.2. Real wage setting (FRW, RWC, SPC_R and TPC_R)

All wage-setting procedures discussed in Section 2.1 have real-wage counterparts, obtained by substituting the real wage for the nominal wage throughout; with reference to Eq. (5), in all cases σ = 1 and, where relevant, γ = 1. This implies that the same wage setting functions can be used except that the variable on the vertical axis is now the percentage change in the real wage, rather than the nominal wage. In these cases, the equilibrium will be where the relevant wage setting function intersects the real wage labour demand curve, $AD_2$.

In Fig. 1a, the real fixed wage, real wage curve, general real Phillips curve, and traditional real Phillips curve outcomes are shown as A, E, F and $D_2$ respectively, with the corresponding employment rate changes $\dot{e_1}, \dot{e_4}, \dot{e_7}$ and zero. Note that for the wage curve and the Phillips curve

[6] But recall that it enters with a negative sign.

results, the increase in the employment rate is lower, and the nominal wage increase is higher, where bargaining is over the real, as opposed to the nominal, wage.

As an example, the wage curve case is shown in more detail in Fig. 1b. As in Fig. 1a, the equilibrium outcomes are again E and B with the associated employment changes $\dot{e}_2$ and $\dot{e}_4$. However, the proportionate change in the nominal wage resulting from the real-wage equilibrium at E can be read off the nominal labour demand curve at point G. Similarly, where the wage is set by bargaining over the nominal wage, resulting in the equilibrium B, the corresponding real wage is given at H. These long-run equilibria are also the lower-bound values for the corresponding Phillips curve results, that is, where $\alpha = 0$. As the value of $\alpha$ increases, nominal wage bargaining generates nominal and real wages in the range $BD_1$ and $HD_2$ respectively.[7] The corresponding real wage bargaining gives nominal and real wage outcomes in the ranges $GD_1$ and $ED_2$.

### 2.3. Consistent money illusion (TPC_MI)

In Eq. (5), if there is a degree of money illusion, then $1 > \sigma, \gamma \geq 0$. Where the money-illusion wage, $w^M$, as defined in Eq. (4), is used in the fixed wage or wage curve settings, only the value of $\sigma$ is required. However, with the Phillips curve then if the values are set equal, so that $\gamma = \sigma$, there is consistent money illusion between the present and lagged wage. Imposing Eq. (2) in Eq. (4) produces[8]:

$$lnw^{CM} = (1 - \sigma\theta)lnw^{N} \tag{10}$$

In Fig. 1c, Eq. (10) is used to construct the consistent money illusion labour demand curve, $AD_3$. This lies between $AD_1$ and $AD_2$. The higher the degree of money illusion, that is, the lower the value of $\sigma$, the closer $AD_3$ is to $AD_1$ and as $\sigma \to 1$, the closer $AD_3$ is to $AD_2$. Essentially, this means that the nominal and real wage-setting procedures are the two limiting cases of consistent money illusion and the outcomes will lie along a range between these two extremes.

Where the relevant wage setting functions are determined in terms of the money-illusion wage, the equilibria are where the relevant functions cut $AD_3$: that is, A, Q, R and $D_3$, with employment rate increases of $\dot{e}_1$, $\dot{e}_5$, $\dot{e}_6$ and zero. For any given wage setting arrangement, the employment change will lie between the nominal and real wage options. Again, for the consistent money illusion equilibria, the accompanying nominal and real wage implications can be read off the $AD_1$ and $AD_3$ labour demand curves for the appropriate employment change value. Therefore, at equilibrium R with the general Phillips curve wage setting, 0L, the associated nominal and real wage increases are S and T respectively.

### 2.4. Asymmetric money illusion (APC_MI)

The final case is more complex. The Phillips curve specification remains in place, but workers have unequal levels of money illusion. They give different weight to past price changes as they perceive them, and to expected future price changes that result from current changes in nominal wages. This implies $\gamma \neq \sigma$.

To derive the long-run wage setting equilibrium in this case requires the use of Eq. (5). To be clear, Eq. (5) here determines the nominal wage that would accompany such wage setting. Using the superscript AM and imposing the equilibrium requirement $w_t^{N,AM} = w_{t-1}^{N,AM}$ produces:

$$ln\frac{w_t^{N,AM}}{w_0^{N,AM}} = -\frac{\beta}{(1 - \sigma\theta - \alpha(1 - \gamma\theta))}ln\frac{u_t}{u_0} \tag{11}$$

It is more difficult to analyse diagrammatically the effects of imposing Eq. (11) as the long-run wage-setting outcome, and therefore simulation is more valuable here. However, it is useful to investigate whether there are combinations of $\gamma$ and $\sigma$ which would generate long-run general Phillips curve results which would lie outwith the standard nominal ($\gamma = \sigma = 0$) or real ($\gamma = \sigma = 1$) results. That is to say, the outcome would not lie within the segment CJ on the $AD_1$ nominal labour demand curve in Fig. 1a.

This analysis is derived in detail in Appendix B. If the value of $\sigma$ lies within the range shown in expression (12), the asymmetric money illusion solution is located within the range CJ.

$$1 - \alpha + \alpha\gamma > \sigma > \alpha\gamma \tag{12}$$

If the LHS inequality does not hold, the value of $\sigma$ must be sufficiently larger than the value of $\gamma$: the worker puts greater weight on future, and less on past, price increases. It results in an equilibrium in the range $D_1J$ in Fig. 1c. If the RHS inequality does not hold, past price increases are given sufficiently higher weight, and the long-run equilibrium will lie on the line segment CA.

It would seem more likely that workers would be aware of the actual price increases that had accompanied their last period's wage increase, but discount possible future price increases caused by the present pay settlement [19]. Therefore, it is more plausible that the asymmetric money illusion will have $\gamma > \sigma$ and that this will therefore tend to limit the impact on the proportionate wage increases but have a positive impact on the change in the employment rate.

Individual closures are documented in the existing literature. However, our aim in this Section is not to claim novelty for any single closure, but to bring them into a common analytical structure in which inflation expectations and money illusion, which are typically neglected in standard formulations, are incorporated explicitly. Within this structure, we present what we believe is a new finding. Asymmetric money illusion can produce employment outcomes that lie outside the range established by symmetric models.

This section of the paper has compared the alternative labour market options available by contrasting the long-run outcomes. However, in Section 4, the empirical CGE model is exposed to a specific time path of exogenous shocks. The actual labour market impacts therefore never reach long-run equilibrium; rather the simulations show the effects of labour markets attempting to reach equilibria that are themselves constantly shifting. As a point of reference, Appendix A presents the various long-run labour market equilibria for the model, parameterised as in Section 4 and subjected to a hypothetical permanent, step 10% exogenous increase in export demand. These simulation results qualitatively align with the theoretical analysis discussed earlier and give a first indication of the quantitative significance of the chosen labour market option.

## 3. Empirical model

We now expand the theoretical analysis of Section 2 through a numerical exercise based on a dynamic multisectoral CGE model known as DEMACRO [16,17]. This model is a variant of the framework detailed in Lecca et al. [22]; it is specifically tailored for the German economy and calibrated using a 2020 Social Accounting Matrix.[9] In this analysis, the DEMACRO model has been further extended to incorporate the range of wage-setting mechanisms discussed in Section 2. Given the focus of this study, we provide a brief overview of the DEMACRO model, while directing the reader to Lecca et al. [22] and Ross et al. [16] for a

[7] This is shown generically by the wage-setting function 0 L in Figure 1.

[8] The superscripts CM and AM indicate consistent and asymmetric money illusion respectively.

[9] These data are constructed by aggregating the EXIOBASE 3 multi-regional Input-Output table [23] to include Germany and the rest of the world, supplemented with additional publicly available data, following the methodology outlined in Emonts-Holley et al. [24]. Using more up-to-date data or implementing a dynamic calibration approach would not alter the qualitative results presented in this paper.

comprehensive discussion of its structure, calibration, and implementation.[10] DEMACRO is used as a vehicle to verify that the analytical predictions of the framework described in Section 2 are preserved in a full general equilibrium setting with realistic calibration, since general equilibrium system-wide feedback can, in principle, overturn partial-equilibrium intuitions. This validation exercise is therefore informative regardless of which CGE model is used.

Germany is an appropriate case for this analysis for two reasons. It is legally bound to achieve net-zero greenhouse gas emissions by 2045 [2] and represents one of Europe's largest economies, meaning the results have direct policy relevance at scale. In addition, its labour market has well-documented institutional features that allow the model scenarios to be anchored empirically. Germany's labour market operates, at least in parts, as a centralised, sector-level collective bargaining system (e.g., Branchentarifverträge and Firmentarifverträge) [25–27]. Wage outcomes are broadly consistent with a wage curve or moderate Phillips curve specification, and there is a documented history of wage moderation as well as limited automatic inflation indexation [20,28–33]. These, taken together, place the German labour market between the real wage curve (RWC) and the partial money-illusion specifications. In our simulation exercise, therefore, the money illusion variants do not represent purely counterfactual scenarios but rather capture a plausible range of Germany's actual degree of wage compensation.

The model comprises $i = j = 25$ production sectors operating under perfect competition. Production in each sector combines value added with both domestically produced and imported intermediate inputs using a Constant Elasticity of Substitution (CES) function, with the general elasticity of substitution set to 0.3. Value added is obtained as a CES combination of capital and labour. Final goods are allocated to households, government, and investment demand (in the form of capital goods). While government consumption is fixed across sectors, household demand for different goods is price sensitive and determined through a CES function. Investment goods are produced by sector $i$ according to the demand for investment by sector j using a purpose-built capital matrix [22].

Investment demand follows a partial adjustment mechanism, whereby investment in each period is determined by the gap between the desired and actual levels of capital stock [34]. The capital stock evolves dynamically over time through gross investment less depreciation. The model treats Germany as a small open economy, implying that domestic investment can be financed by both internal and external sources, without an explicit balance of payments constraint. Imports are modelled using an Armington [35] aggregation framework, which assumes imperfect substitutability between domestic and foreign goods. Exports are specified through a reduced-form export function, which captures external demand sensitivity to relative prices. We set the trade elasticity to 2.7 [36].

The labour market features perfect sectoral mobility while wage formation is governed by alternative wage-setting mechanisms as introduced in Section 2, and their respective parameterisations are reported in Table 1. This should not be read as a sensitivity analysis. In a conventional sensitivity analysis, parameters vary within a fixed model structure and the analyst records how outcomes change. In this paper, however, we derive wage-setting specifications as parameterisations of a single general equation, generate analytical predictions about the direction, ordering, and magnitude of differences between closures, and then verify those predictions in a calibrated model. The contribution is therefore to analytically explain why specific closures lead to specific outcomes, to predict which will generate the largest employment gains and which will not, and to identify which specification is commonly used in standard practice and why it is the most empirically misleading. Moreover, the asymmetric money illusion derivation (Appendix B) is a novel analytical result showing that certain asymmetries in inflation expectations can produce employment outcomes outside the range bounded by symmetric specifications.

**Table 1**
Abbreviations and parameter values for the different wage-setting closures.

| Abbreviation | Wage-setting procedure | Equation | Parameter values (Eq. 5) | | | |
|---|---|---|---|---|---|---|
| | | | α | β | γ | σ |
| FNW | Fixed Nominal Wage | 6 | 0 | 0 | 0 | 0 |
| FRW | Fixed Real Wage | 5 | 0 | 0 | 0 | 1 |
| NWC | Nominal Wage Curve | 7 | 0 | 0.1 | 0 | 0 |
| RWC | Real Wage Curve | 5 | 0 | 0.1 | 0 | 1 |
| SPC_N | General Nominal Phillips Curve, Nominal | 8 | 0.5 | 0.1 | 0 | 0 |
| SPC_R | General Real Phillips Curve, Real | 5 | 0.5 | 0.1 | 1 | 1 |
| TPC_N | Traditional Phillips Curve, Nominal | 8a | 1 | 0.1 | 0 | 0 |
| TPC_R | Traditional Phillips Curve, Real | 8a | 1 | 0.1 | 1 | 1 |
| TPC_MI | Traditional Phillips Curve, Money Illusion | 8a | 1 | 0.1 | 0.8 | 0.8 |
| APC_MI(L) | Asymmetric Money Illusion Phillips Curve | 11 | 0.5 | 0.1 | 0 | 1 |
| APC_MI(H) | Asymmetric Money Illusion Phillips Curve | 11 | 0.5 | 0.1 | 1 | 0 |

Note: Real-wage cases are produced directly from Eq. (5) by substitution. γ is inoperative when β = 0.

The model is used to simulate a policy-relevant investment scenario derived from the energy system optimisation model ETHOS.NESTOR [18,37]. These studies assess pathways to achieving greenhouse gas neutrality in Germany, as mandated by the Bundes-Klimaschutzgesetz (KSG),[11] and quantify the required capital expenditures (CAPEX) and operational expenditures (OPEX) for transforming the energy system at individual sector and energy technology level. Fig. 2a (top-left panel of Fig. 2) provides the time paths for the aggregate costs. The energy system optimisation model has a planning horizon that extends to 2045. Its main objectives are to evaluate the implications of achieving net-zero greenhouse gas emissions by that year, as well as to analyse the effects of intermediate targets, such as a 65% reduction in emissions by 2030.

The sector-specific capital expenditures enter the DEMACRO model through an exogenous stimulus in investments, while the sector-specific operational expenditures enter through an exogenous demand-side shock.[12] In total, these costs amount to €1593 billion, consisting of €1429 billion in capital expenditures and €164 billion in operational expenditures. At the time of writing, this corresponds to $1735 billion, $1556 billion, and $178 billion, respectively. The investment expenditures required for the transformation are financed by a reduction in profits for firms, which in turn also affects households and the government, that would otherwise have occurred. As a result, household consumption, for example, is suppressed below the levels that would otherwise be observed.

[10] While DEMACRO supports skill disaggregation, including skill-specific labour supply and migration functions as documented in Ross et al. [16], this dimension is deliberately not activated here, as doing so would add a full additional layer of complexity that would risk obscuring the core wage-setting analysis.

[11] Raseta et al. [38] also utilise these cost data for an impact assessment of employment and output, employing a dynamic disequilibrium Input-Output model. However, their analysis is restricted to the short run and is comparatively limited in scope, as it does not take into account factors such as price-quantity interactions and trade dynamics.

[12] A simplified soft linking procedure is employed, allowing for the assessment of key changes in the economy; specifically, the investments needed to achieve greenhouse gas neutrality in isolation. This method also enables the generalisation of key results across various wage-setting labour market frameworks in response to demand shocks. The literature offers a wide range of approaches to effectively soft-link bottom-up and top-down approaches [5,8,9,38].

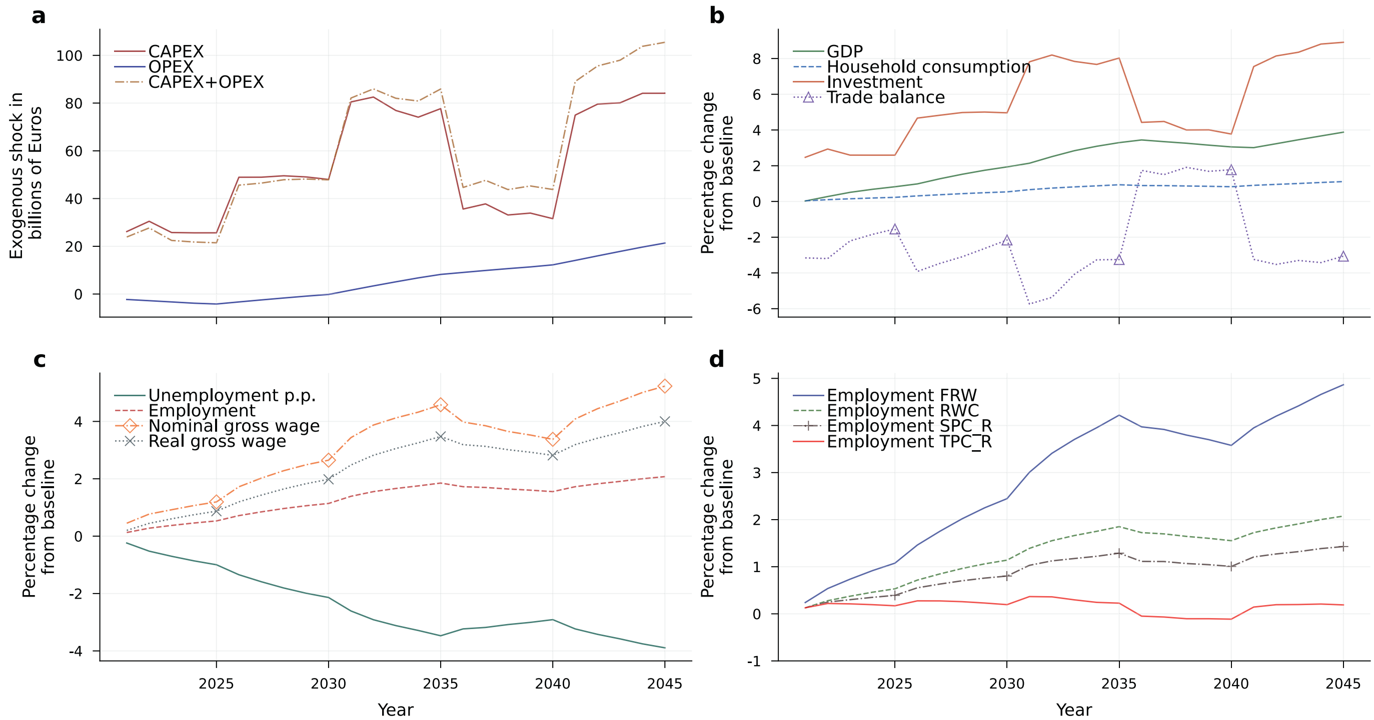


**Fig. 2.** Simulation results for Germany's energy system transition to net-zero carbon emissions. Panel (a): capital and operational expenditures and their sum (exogenous shock, billions of euros) adapted from [18,37]. Panel (b): gross domestic product, household consumption, investment and trade balance. Panel (c): unemployment rate, employment, nominal and real gross wages. Panel (d): employment under four wage-setting regimes, the fixed real wage, the real wage curve, the general real Phillips curve and the traditional real Phillips curve.

## 4. Empirical analysis

We begin with the standard real wage curve (RWC) specification.[13] This is our preferred wage-setting mechanism and the scenario most closely aligned with Germany's current labour market institutions, which are characterised by coordinated sectoral bargaining that ties real wages to labour market tightness. The wage curve specification is strongly supported by empirical evidence, making the RWC a policy-relevant baseline for Germany. The Fixed Nominal Wage (FNW) and Fixed Real Wage (FRW) cases are analytical upper bounds and are retained for diagnostic purposes. These results quantify how severely standard Input-Output analyses overstate employment gains. The Phillips curve variants and money illusion specifications represent credible downside scenarios. The general Phillips curve (SPC) and money-illusion specifications (APC_MI) lie just below the central estimate and represent plausible variation in the degree of inflation perception. We therefore interpret this band, anchored on the RWC, as the most reasonable range for employment and wage changes over the transition period.

### 4.1. Simulation results: real wage curve

Fig. 2b (top-right panel of Fig. 2) illustrates the evolution of GDP and its main components. Additionally, the results in the second data column of Table 2 give the relevant 2045 figures for a wider range of variables, all changes shown as percentage deviations from the base year. The temporary exogenous increase in investment in sectors directly involved in the energy system transformation boosts aggregate investment, which in all other sectors is determined endogenously. This investment-led growth produces a gradual rise in GDP, which fluctuates due to the dynamic profile of the exogenous shocks and the lagged capital stock adjustment process. After the exogenous shock ends (in 2045) the economy gradually transitions back to the original steady state (not shown in the figures).

Aggregate investment records greater percentage increases than GDP, highlighting investment as the primary driver of the initial expansion. Household consumption rises as well, albeit at a slower pace than GDP. Both imports and exports increase in response to rising production, but imports grow faster than exports, leading to a temporary deterioration of the trade balance. This surge in imports is necessary to meet the higher demand for intermediate and capital goods. Once the investment shock is withdrawn, the trade balance begins to improve, and the reduction in import growth supports a smoother transition back to the original steady state. Of course, these impacts are also influenced by the modelling of the OPEX costs as exogenous demands. Yet, these are negligible compared to the CAPEX costs.

As the investment shock boosts aggregate demand and stimulates economic activity, labour demand increases, leading to a decline in unemployment over time. As illustrated in Fig. 2c, this triggers a gradual rise in real wages, as a reduction in the unemployment rate leads to upward pressure on wages, in line with the wage curve specification. Employment generally increases steadily until the end of the shock, but shows a slight decline, just like the other measures of economic activity, over the period 2035 to 2040. Again, once the investment shock ends (in 2045), labour demand slows, and both real wages and employment begin a gradual convergence back to baseline, with percentage deviations approaching zero by the end of the simulation (truncated from

[13] Although this paper focuses on aggregate outcomes, the model is multi-sectoral and results could be presented at the sectoral level. We intend to revisit these in future work. We note here that in year 2045, on completing the investment shock, sectoral impacts are highly uneven. Key industrial and infrastructure sectors (like Non-Metallic Mineral Products, Machinery & Equipment, and Chemicals) see the largest value-added gains, while several consumer-focused sectors (such as Food, Hotels, and Transport Equipment) register small or negative changes. Overall, benefits are concentrated in upstream, investment-linked industries, while downstream and consumer sectors experience limited or negative effects.

**Table 2**
Key macroeconomic variables under alternative wage setting scenarios. Single period results for 2045. Values show percentage changes from baseline.

| | FRW | RWC | FNW | NWC | TPC_N | TPC_R | TPC_MI | SPC_N | SPC_R | APC_MI(H) | APC_MI(L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GDP | 5.40 | 3.67 | 5.48 | 3.86 | 2.45 | 2.41 | 2.42 | 3.41 | 3.24 | 3.53 | 3.07 |
| CPI | 0.24 | 1.14 | 0.20 | 1.04 | 1.77 | 1.80 | 1.79 | 1.28 | 1.36 | 1.21 | 1.45 |
| Unemployment | −8.67 | −3.75 | −8.91 | −4.27 | −0.51 | −0.39 | −0.42 | −3.05 | −2.60 | −3.39 | −2.14 |
| Employment | 4.66 | 2.00 | 4.79 | 2.27 | 0.27 | 0.21 | 0.22 | 1.63 | 1.39 | 1.81 | 1.14 |
| Nominal wage | 0.24 | 5.01 | 0.00 | 4.49 | 8.31 | 8.45 | 8.42 | 5.71 | 6.18 | 5.36 | 6.65 |
| Real wage | 0.00 | 3.82 | −0.20 | 3.41 | 6.43 | 6.53 | 6.51 | 4.38 | 4.75 | 4.10 | 5.13 |
| Household consumption | 1.19 | 1.06 | 1.20 | 1.08 | 0.96 | 0.96 | 0.96 | 1.04 | 1.03 | 1.05 | 1.02 |
| Investments | 9.28 | 8.81 | 9.31 | 8.86 | 8.50 | 8.49 | 8.49 | 8.75 | 8.70 | 8.78 | 8.65 |
| Imports | 6.34 | 7.75 | 6.29 | 7.60 | 8.76 | 8.79 | 8.78 | 7.96 | 8.10 | 7.86 | 8.24 |
| Exports | 6.10 | 4.33 | 6.18 | 4.52 | 3.09 | 3.05 | 3.06 | 4.06 | 3.89 | 4.19 | 3.72 |

the figure).

### 4.2. Simulation results: alternative wage settings

To assess how labour market assumptions affect aggregate results, we extend our analysis by replacing the real wage curve specification with the alternative wage regimes as described in Section 2. The parameter values for these wage equations are summarised in Table 1. The purpose of this section is to systematically compare different wage-setting regimes. This allows us to isolate the effects of nominal and real wage rigidities, inflation expectations, and the responsiveness of wages to unemployment in shaping how the investment shock derived from the energy system optimisation model is transmitted through the economy.

The results are presented in Table 2 and are expressed as percentage deviations from base-year values for a set of macroeconomic indicators in the year 2045, which marks the end of the investment shock. The simulation shows that wage rigidity and wage–price feedback mechanisms have a significant impact on the way the investment shock is transmitted throughout the economy and on key policy variables. In particular, the less sensitive the wage setting is to changes in labour demand, the greater the expansionary economic effect.

For example, the largest increases in GDP occur under the Fixed Real Wage (FRW) and Fixed Nominal Wage (FNW) regimes, with output rising by 5.40% and 5.48%, and employment by 4.66% and 4.79%, respectively, compared to the base year. These wage-setting regimes introduce rigidities that severely limit wage adjustment, enabling the investment-driven expansion to continue without being dampened by rising labour costs. While such labour market specifications are commonly used, in Input-Output analysis, for example, they do not align well with empirical observations. Instead, such simulations should be seen as representing extreme cases.[14]

In contrast, much more sensitive wage-setting regimes, such as the Traditional Real Wage Phillips Curve (TPC_R), result in significantly smaller GDP gains (2.41%). The analysis in Section 2 shows that with this wage setting mechanism, there is no long-run increase in employment and the whole impact of the increased labour demand is reflected in higher nominal and real wages. In this case, because of the varying sequence of exogenous shocks, the economy does not quite reach long-run equilibrium, but the expansion in employment is only 0.21%, while the nominal and real wages increase by 8.45% and 6.53% respectively.

Generally, although the nature of the shock in these simulations differs from that analysed in Section 2 and simulated with an illustrative shock in Appendix A, the numerical model closely replicates the theoretical insights. For example, changes in employment under the Real Wage Curve (RWC) are smaller than those observed under the Fixed Real Wage (FRW) or Fixed Nominal Wage (FNW) regimes. Moreover, when wage bargaining is based on the real rather than the nominal wage, the resulting nominal wage increases are higher. Specifically, nominal wages rise by 4.49% under the Nominal Wage Curve (NWC) and by 5% under the RWC with a correspondingly smaller increase in employment under the RWC than under the NWC.

Intermediate employment outcomes are observed for wage-setting variants incorporating wage inertia such as the General Phillips Curves (SPC_N, SPC_R) which exhibit moderate employment gains of 1.63% and 1.39% respectively. As we expect, under the most extreme asymmetric money illusion cases ($\gamma,\sigma = 1,0$ and $0,1$ respectively), employment outcomes diverge markedly ($\gamma \neq \sigma$). Here APC_MI(H) yields 1.81% and APC_MI(L) 1.14%.

Since the model applies the same exogenous shocks in all the wage-setting regimes, investment changes are similar across the scenarios, ranging from 8.5% under the TPC regimes to 9.31% under FNW. In contrast, household consumption is more sensitive to wage-setting dynamics. As discussed in Appendix A, the aggregate labour demand curve is relatively elastic. This implies that where the wage rate increases, total labour income falls. This is reflected in the household consumption figures. Under FRW and FNW, household consumption increases by approximately 1.2%, supported by strong employment growth even though wage growth is limited. By comparison, under the TPC and SPC_R regimes, consumption increases are smaller, 0.96% and 1.03%, respectively, reflecting lower employment gains and, in the case of SPC_R, higher inflationary pressures.

Finally, regarding trade, we observe that imports increase more sharply under wage-setting rules that allow for greater wage-price flexibility, such as the TPC regime, where imports rise by 8.76%. In contrast, the export response is strongest under the FRW and FNW regimes (6.10% and 6.18%, respectively) and weakest under the traditional Phillips curve (TPC) regimes. This highlights how rising domestic prices and wages reduce competitiveness in more flexible wage-setting regimes.

The empirical results reveal clear and substantial differences in the economic impacts across the various labour market closures. Fig. 2d (bottom-right panel of Fig. 2) identifies the time path of employment adjustments under a subset of wage-setting mechanisms. These are the fixed real wage (FRW), the real wage curve (RWC), the general real Phillips curve (SPC_R) and the traditional real Phillips curve (TPC_R). The FRW regime consistently produces employment levels that are substantially higher than baseline, but also greater than the other three closures throughout the adjustment period. The employment change under the RWC and SPC_R regimes follows the same qualitative trajectory, but both are lower and less volatile than the FRW results. Note particularly the results between 2030 and 2040. The traditional real Phillips curve reveals very small changes in employment and an adjustment path which differs qualitatively from the others. There are periods under the TPC_R scenario during which employment falls below the baseline level, specifically between 2030 and 2040 (and following the removal of the exogenous shock in 2045). In contrast, for the other

[14] It should be noted that where flow-equilibrium migration occurs, the original real wage and unemployment rate will be reinstated in the long run through endogenous adjustments to the labour force. In the present simulations we abstract from any possible migration. But, as outlined in Ross et al. [16], the model is able to incorporate complex migration dynamics.

three wage-setting mechanisms, employment is rising. The appropriate policy response to these divergent outcomes will necessarily differ substantially. Moreover, effective communication of these results is crucial. The findings highlight that, under certain wage-setting regimes, employment may contract below baseline levels because of the investment pathways associated with the energy system transformation towards net-zero carbon emissions.

## 5. Policy implications

The central policy implication of this paper follows directly from the simulation results. Under fixed-wage assumptions, as used in standard Input-Output analyses, the net-zero investment programme generates large employment gains with wages held constant by assumption. Under such a scenario, the case for active labour market intervention seems weak, as the transition appears to be self-financing in employment terms and wage pressures do not arise. This is the implicit policy baseline embedded in most existing assessments.

With empirically grounded specifications, the situation changes significantly. The closure of the Real Wage Curve, which most closely reflects Germany's actual wage-setting institutions, results in modest employment gains alongside rising real wages. Under Phillips curve specifications, employment gains could be near-zero, and temporary contraction during the peak investment period is possible. In both cases, the transition generates wage pressure, potential displacement in downstream sectors, and distributional consequences that fixed-wage assessments do not reveal. These results imply that some degree of active policy support is likely to be warranted, even if the precise scale and form depend on which wage-setting regime prevails. Three broad, well-established categories of labour market policy are prominently featured in the energy transition literature.

First, active labour market policy, including retraining and reskilling programmes targeted at workers displaced from fossil fuel and related industries, is indicated by the sectoral employment pattern the model identifies. Employment gains are concentrated in upstream, investment-linked sectors while downstream and consumer sectors experience limited or negative effects, suggesting that workers in declining sectors may not automatically transition into the sectors that expand.

Second, wage coordination and income support mechanisms are indicated by the wage and price dynamics the model generates under flexible wage-setting regimes. Rising consumer prices under Phillips curve specifications could erode real incomes for households not directly employed in the expanding sectors, which could point to the established rationale for income protection and wage indexation instruments.

Third, to the extent that sectors most exposed to transition costs are geographically concentrated, as is well-documented in the German case (e.g. Ruhr, Lausitz, Saarland), aggregate positive employment outcomes at the national level could potentially coexist with localised unemployment in specific regions. Geographical and skills mismatch between where fossil fuel jobs are lost and where clean energy jobs are created, in combination with labour mobility frictions in declining industrial regions [39], means that market adjustments alone are unlikely to reallocate displaced workers efficiently. This provides a potential basis for place-based transition support, which features prominently in the just transition literature.

Under wage pressure scenarios, higher German labour costs may erode export competitiveness. Since Germany's transition requires very large investment and given that other economies may not face the same wage pressure at the same time, there is a risk of competitive disadvantage during the transition period. This suggests that EU-level instruments, such as the Carbon Border Adjustment Mechanism, could be designed with such a competitiveness dimension in mind.

The results also bear on whether CGE models are appropriate tools for energy transition assessment. Royston et al. [40] highlight a misguided perception that (all) CGE models are defined by assumptions of full employment and perfect markets. This paper shows that characterisation to be incorrect. The fixed nominal wage closure, for example, which forms the basis of this criticism (and is the de facto standard in Input-Output analyses) along with specifications of "full employment", is a limited representation of many points within the space of CGE labour market specifications. That is, CGE models are not wedded to an extreme version of neoclassical economics, and this is clearly shown by the flexibility in the treatment of the labour market. The appropriate response is not to abandon CGE models but to ensure that the labour market closure is made explicit, justified empirically, and stress-tested across plausible alternatives. The framework developed in this paper provides the tools to do so.

## 6. Discussion and conclusions

Computable General Equilibrium (CGE) models are frequently employed to analyse the potential system-wide economic impacts of net-zero emissions transitions. Often stylised representations of wage and employment changes are assumed, with wages either fully flexible or entirely fixed. Such simplifications can result in misleading policy recommendations because the models may not capture the real-world complexities of how jobs and wages respond to large-scale changes in investment, technological advancement and diffusion, or industry structure.

The analysis in this paper seeks to address these gaps by systematically integrating several alternative wage-setting mechanisms into a CGE model tailored to the German economy. This model is linked to projections from a bottom-up energy system model, which provides estimates of the specific investments required to reach net-zero targets. The empirical analysis compares the outcomes under different labour market and wage-setting assumptions. The results demonstrate that the underlying labour market specifications yield substantially diverging responses to exogenous demand shocks. The range of endogenous economic variables influenced includes GDP, employment, wages, household consumption, and international trade. Our simulations indicate impacts on all these variables during Germany's investment-driven green transition.

The simulations show that when the CGE model imposes complete wage rigidity the surge of new investments required for the net-zero transition generates very strong positive effects on both GDP and employment. This is because, under these fixed-wage assumptions (the de facto assumption in standard Input-Output and Social Accounting Matrix-based models), the resulting increased demand for labour does not lead to higher wages. With wages held constant, as firms hire additional workers, labour costs remain fixed and do not erode profitability. Consequently, the model projects employment increases and greater overall economic output.

However, empirical observations suggest that wages typically rise as demand for labour increases and unemployment falls. To better reflect these dynamics, the analysis incorporates more flexible and empirically supported wage-setting mechanisms, such as those based on the wage or Phillips curve closures which relate the wage level and wage growth to unemployment in the economy. Under these alternative assumptions, as the labour market tightens, driven by the additional demand created by net-zero investments, wages begin to increase. This partially offsets the employment-creation benefits of increased labour demand. Firms facing higher payroll expenses, and therefore reduced competitiveness, are less likely to expand hiring. As a result, the projected gains in employment are smaller than under the rigid wage assumptions and, in some scenarios, employment may even decline slightly, as higher wages dampen hiring and potentially displace some workers. As highlighted in our analysis, additional factors such as inflation expectations (and money illusion) potentially play a significant role in shaping the outcomes of each wage-setting mechanism.

This highlights the need to move beyond the labour market assumptions traditionally employed in such analyses and consider alternative specifications that capture the labour market in greater detail. The system-wide consequences of these diverse labour market scenarios can differ significantly, potentially leading to unwarranted expectations about future labour market outcomes or resulting in ill-informed policy decisions. For example, our simulations suggest that, under the assumption of fixed wages, employment impacts remain positive compared to the baseline, whereas under traditional Phillips curve assumptions, employment can fall. Each of these scenarios would necessitate very different policy responses. Moreover, it is unwise to assume that labour markets in 2045 will retain the same (wage-setting) structures observed today. Consequently, conducting analysis around the potential structure of the future labour market is prudent. This is particularly important in light of the substantial changes that may result from shifts in labour/capital intensities, advances in AI and automation, and their system-wide impacts [16,41].[15]

The theoretical analysis, together with the empirical results, effectively challenges criticisms claiming that CGE models cannot adequately capture labour market effects. On the contrary, the analysis identifies a key strength of the CGE approach: its firm grounding in established economic theory enables it to represent, both flexibly and rigorously, diverse labour market dynamics. Nevertheless, to fully realise these advantages, such modelling approaches should be applied more broadly in policy analysis and research.

The results presented in this paper indicate that aggregate job creation can outpace job losses in fossil fuel and related industries, generating aggregate net-positive impacts. This suggests that investments in green technologies could generate sufficient employment opportunities to offset declines elsewhere. However, it is possible that, during certain periods of the transition, employment could temporarily fall below baseline levels. Additionally, the overall impact on employment will depend largely on the future condition of the economy and the labour market, particularly on how much bargaining power workers have over wages. Our benchmark model suggests that any net job gains are likely to be modest, and it appears unlikely that green investments alone will drive substantial economic growth. Furthermore, much will depend on the mechanism by which the transition to net-zero emissions is financed, and on the system-wide net effects that this financing may have. Although we do not examine this aspect systematically, in our simulations the investment expenditures required for the transformation are financed through a reduction in profits.

We also consider other key economic variables, such as wages and household consumption. In all our model configurations, wages do not always keep pace with rising prices. As a result, although more employment opportunities may be created, this does not necessarily lead to an increase in net take-home pay. This, in turn, raises important questions about a just transition and its potential distributional effects. Since the present analysis uses an aggregate labour specification, a deliberate scope choice given the paper's focus on wage-setting mechanisms, it does not assess how wage and employment changes are distributed across households with different incomes or skill levels. In practice, rising consumer prices, which are more pronounced under flexible wage-setting regimes, are likely to impose a proportionally greater burden on lower-income households.

Similarly, job gains in clean energy sectors may not be accessible to workers displaced from fossil fuel industries without significant retraining investment. These distributional risks are not merely secondary concerns. They have been widely identified as a potential constraint on the political feasibility and social legitimacy of green transitions and deserve dedicated analytical attention in future work. Such extensions lie within the capabilities of the DEMACRO framework employed in this paper. A further scope boundary concerns the treatment of labour as a homogeneous aggregate in this paper. While DEMACRO supports skill disaggregation (including skill-specific labour supply and migration functions) as evidenced in Ross et al. [16], this dimension is deliberately not activated here. Extending the analysis to incorporate skill-differentiated wage-setting and migration, building on the existing DEMACRO framework, is identified as a priority direction for future research.

## CRediT authorship contribution statement

**Andrew G. Ross:** Writing – original draft, Funding acquisition, Conceptualization. **Patrizio Lecca:** Writing – original draft, Software. **J. Kim Swales:** Writing – original draft.

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## Declaration of competing interest

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

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## Appendix A

The model outlined in Section 3 is now run for a hypothetical permanent 10% step increase in export demand under the range of labour market options detailed in Section 2. The empirical long-run results that correspond to the theoretical ones reported in Fig. 1 in the text are shown in Fig. A1a. These outcomes qualitatively replicate those in the theoretical analysis. In addition, the simulation outcomes give a quantitative indication of the impact of different wage-setting procedures. These results depend on the elasticities of the aggregate labour demand curve and the wage-setting mechanisms: that is, the proportionate changes in labour demand and supply with respect to proportionate changes in the wage. Given that in Figs. 1 and A1a employment and the wage are measured in terms of proportionate changes, the elasticities are given by the (inverse) of the slopes.

For any given labour demand curve, the more responsive the wage-setting function is to changes in the employment rate, that is, the steeper it is,

[15] Two distinct channels are relevant here [42–46]. First, automation and AI may reduce the labour intensity of new clean energy production, meaning that the same volume of investment generates a smaller outward shift in aggregate labour demand. In the context of the present model, under any wage-setting regime, this would imply smaller employment gains than the present results suggest, without altering the qualitative ordering of outcomes across closures. Second, AI and automation may alter the effective elasticity of labour supply, either by creating new categories of employment that expand the pool of available workers or by displacing workers in ways that generate structural unemployment. Under wage curve or Phillips curve specifications, a more elastic labour supply would dampen wage growth and support larger employment responses, while a less elastic supply would amplify inflationary wage pressure. Both channels therefore have direct implications for the range of outcomes reported in this paper, and a fuller treatment is an avenue identified for future work.

the higher the increase in the wage and the smaller the increase in employment resulting from an expansion in labour demand. The nature of these wage setting functions has been the central focus of Section 2, and their elasticities are determined by how these relationships are exogenously parameterised.

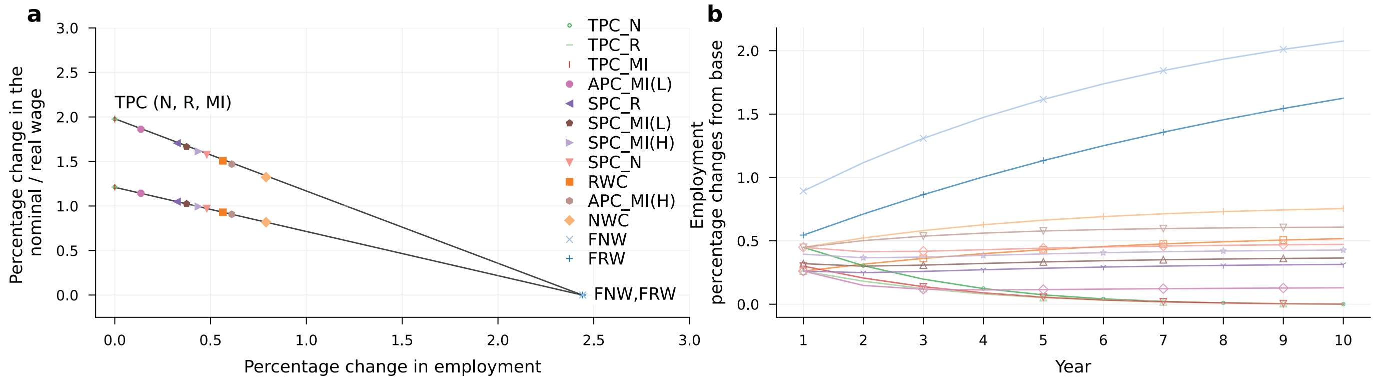


**Fig. A1.** Labour market outcomes under alternative wage-setting specifications following a hypothetical permanent 10% step increase in export demand. Panel (a): long-run equilibrium employment and wage changes for all specifications in Table 1. Panel (b): employment adjustment paths over the first 10 years.

The size of the labour market adjustments will also be affected by the system-wide elasticity of labour demand. The more elastic the labour demand curve (the shallower the negative slope), the lower both the change in employment and wages following an exogenous shift in labour demand. However, in a general equilibrium setting the elasticity of labour demand depends in a complex way on the structural characteristics of the economy and the price sensitivity of product demand and production techniques. It can only realistically be found by numerical simulation. In this case, the simulations reveal that the long-run labour demand function is both real- and nominal-wage elastic, with elasticity values of 2.0 and 1.23 respectively. Compare the employment and wage impact of introducing the wage and Phillips curve labour market closures with the fixed-wage outcome. With the employment sensitive wage-setting options, although the impact on the real wage is relatively small, 0.93% and 1.05% respectively, the change in employment is 0.56% and 0.33%, much lower than the 2.44% employment increase where the real and nominal wages are fixed. The simulations also confirm that where the traditional Phillips curve is adopted, in the long run the impact is solely on the wage with zero employment change.

In Fig. A1a each point is identified with the label given in Table 1 in the text. As in Fig. 1, the nominal wage impact lies vertically above the real wage effect. Therefore, for example, the nominal wage curve, NWC, cuts the nominal-wage labour demand curve where the employment and nominal wage increase by 0.79% and 1.32% respectively. The impact on the real wage is vertically below at 0.82%. Again, the General Real Phillips curve intersects the real labour demand curve at SPC_R, where the employment and real wage increase are 0.33% and 1.05%, with the nominal wage change 1.72% vertically above on the nominal wage demand curve.

Fig. A1a also shows the implications of making extreme asymmetric assumptions about money illusion. These are identified as APC_MI(L) and APC_MI(H). These clearly reveal that with this model, asymmetric money illusion assumptions can generate results outwith those with symmetric money illusion. Where there is symmetric money illusion, the extreme points represented on the $AD_1$ curve are the general real and nominal Phillips curve outcomes. These represent zero and 100% symmetric money illusion respectively. Note that on the nominal wage labour demand curve, APC_MI (H) has a lower increase in the nominal wage, and a higher employment change than SPC_N. Conversely, APC_MI(L) has a higher nominal wage increase and a lower employment change than SPC_R.

Finally, this appendix has focused on the impact of adopting different wage-setting options on the long-run labour-market simulation results. However, the short-run wage and employment dynamics can be affected too. Fig. A1b shows the percentage change in employment with the various labour market options over the first 10 periods. Because the model is parameterised on annual data, each period is taken to be one year.

Note first that the fixed real and nominal wage options, FNW and FRW, which have the same long-run employment change values of 2.44%, exhibit quite different short-term impacts. Because the consumer price index will rise initially with the export demand shock, so will the nominal value of the fixed real wage. This results in a lower expansion in output, employment and capital stock than occurs with the fixed nominal wage. As prices fall to their initial base-year level, the employment results for these two labour market options will converge, though this has not occurred in the first 10 years and this is particularly apparent in the FRW case.

All the other labour market options are based around a nominal or real wage curve relationship with a β parameter equal to 0.1. These wage-setting model closures show less variation over time, and also that they reach their long-run equilibrium values much sooner. Even the traditional Phillips curve case where employment change is ultimately reduced to zero has attained this value by year 8. Generally, the ordering of the employment effects across wage-setting procedures is constant over time. However, there are two cases whose position changes. The real wage curve moves up the ranking over time, and the traditional Phillips curve moves down.

## Appendix B

Where the nominal Phillips curve wage setting procedure is in operation, so that $\gamma = \sigma = 0$, the long-run equilibrium relationship (previously derived in Eq. (9)) is:

$$ln\frac{w_t^N}{w_0^N} = -\frac{\beta}{1-\alpha}ln\frac{u_t}{u_0} \tag{B1}$$

On the other hand, where the Phillips curve has a real wage formulation, implying $\gamma = \sigma = 1$, the long-run outcome is:

$$ln\frac{w_t^N}{w_0^N} = -\frac{\beta}{(1-\theta)(1-\alpha)}ln\frac{u_t}{u_0} \tag{B2}$$

These wage setting functions, producing the long-run outcomes given in Eqs. (B1) and (B2), are shown as points C and J respectively on the nominal-wage demand curve $AD_1$ in Fig. 1a in the text. It is of interest to see whether asymmetric money-illusion wage-setting mechanisms can generate outcomes outwith this range.

For the asymmetric nominal wage equilibrium to lie below C along $AD_1$ in Fig. 1a, the absolute value of the slope of the function in expression (11) in the text must be lower than that in expression (9). This requires:

$$1-\alpha < 1-\sigma\theta-\alpha(1-\gamma\theta) \tag{B3}$$

Condition (B3) will be satisfied where:

$$\sigma < \alpha\gamma \tag{B4}$$

This requires that the weight given to previous price increases is greater than that given to present price increases. In the simulations reported in Section 4 of the paper, for one of the asymmetric money illusion simulations, APC_MI(H), the parameter values $\sigma = 0$, $\gamma = 1$ are imposed. In this simulation the long-run increase in the nominal wage is expected to be below that for the nominal general Phillips curve SPC_N.

For the asymmetric nominal wage equilibrium to be located in the range $D_1J$ in Fig. 1c, the absolute slope of the function given in Eq. (11) of the text must be greater than that in (B2) so that:

$$1-\sigma\theta-\alpha(1-\gamma\theta) < (1-\theta)(1-\alpha) \tag{B5}$$

(B5) requires:

$$1-\alpha+\alpha\gamma < \sigma \tag{B6}$$

In this case $\sigma$ must be greater than $\gamma$, so that the weight given to present (anticipated) price increases must be greater than that given to previous price increases. Again, in the simulations APC_MI(L) the values of $\sigma$ and $\gamma$ are given as 1 and 0 respectively, so that we expect the long-run equilibrium to have a higher nominal wage increase than in the real general Phillips curve simulation SPC_R.

The results in (B4) and (B6) can be summarised in a slightly different way. If the value of $\sigma$ lies within the range given in expression (B7), then the asymmetric money illusion outcome still lies within the range of symmetric results.

$$1-\alpha+\alpha\gamma > \sigma > \alpha\gamma \tag{B7}$$

## Data availability

Data will be made available on request.

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