Capital Adjustment Costs and Nationally Determined Contributions - How to Avoid Double Transitions of Energy Capital?

Anna-Maria Goeth* Leopold Zessner-Spitzenberg† Carolyn Fischer‡

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Abstract

Capital adjustment costs and cross-country disparities in existing energy capital stocks are important factors in the net zero transition but are not often reflected in climate-macroeconomic models. This paper considers their implications for near-term investment shifts from CO2-intensive to carbon-free energy technologies under policies that constrain cumulative carbon emissions, net zero emissions targets, or both. A four-sector macroeconomic growth model is calibrated for representative major advanced and developing economies. It accounts for the empirical finding that a composite of clean energy technologies is initially 40% less productive than the dirty counterpart, reaching parity by 2050. Under the central calibration, compared to carbon budgets consistent with current nationally determined contributions, climate policies to phase out dirty energy by 2050 entail modest welfare costs for both regions. Compared to a simple net zero target, more stringent carbon budgets achieve the phaseout with lower emissions and fewer stranded assets but higher overall adjustment costs. Due to the expected productivity convergence, the developing economy always expands clean energy investment immediately to smooth its adjustment costs and meet its growth needs, and a modest climate policy is sufficient to avoid an initial buildup in dirty energy capital stocks. If capital adjustment costs are based on net—rather than gross—investment, the major challenges for the advanced economy are the adjustment costs attached to decommissioning its dirty energy capital stock. By contrast, the rapidly growing developing country mostly grapples with higher clean energy and non-energy capital adjustment costs.

JEL Codes: E22, H23, O41, Q43
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*PhD Candidate Humboldt-University, Spandauer Straße 1, Berlin, 10178, Germany, email: goethann@hu-berlin.de
†TU Wien, Wiedner Hauptstrasse 8/105-03, 1040 Wien, Austria. email: leopold.zessner@tuwien.ac.at
‡World Bank, 1818 H St. N.W.,Washington, D.C. 20433, email: cfischer2@worldbank.org

1 Introduction

Meeting the global challenge of a 1.5°- or 2°-degree climate goal will require all countries to make the green transition within the next decades. More than 140 countries, including many in the Global South, have made net-zero pledges, representing about 88% of global emissions UN (2023). Ambitious transitions will require enormous investments, to shift production from dirty (CO_2-intensive) to clean (carbon-free) technologies. According to some calculations (e.g., IMF (2021), additional cumulative investment needs for the decade 2021 to 2030 range between 2 to 14.6 percent of annual GDP at a global level. Moreover, these investment needs are not spread evenly. Across countries, large disparities in the size and composition of their existing energy capital stocks can be observed. World Bank (202?, CCDR synthesis report) estimates that lower income countries will require larger investments as a share of GDP.

Rapid changes in capital and investments, however, can entail significant adjustment costs. In the climate context, the green transition entails a buildup of clean energy capital and a phasedown of dirty energy capital, both of which should be done in an orderly way to balance needs for economic growth, meeting climate targets, and avoiding excessive adjustment costs and stranded assets. When to initiate those dual capital adjustments, how quickly to implement them, and the societal costs they entail will depend crucially on country characteristics: how large and dirty is the initial capital stock, how ambitious are the climate targets, what policy instruments are being used to achieve them, and how steep are the adjustment costs?

Nationally Determined Contributions (NDCs) under the Paris Climate Agreement typically elaborate two kinds of targets, and many pledges combine them. On the one hand there are emissions trajectories or cumulative targets, which climate policy modelers typically represent with emissions pricing policies that provide a relative price incentive to limit emissions and stay within a country's remaining carbon budget. On the other hand, there are simple net zero targets requiring all energy demands to be met with carbon-free sources by a certain point in time, after which CO_2 intensive technologies can no longer be used. This is essentially a future technology mandate that requires investment to prepare for it.

This paper characterizes optimal paths of capital adjustment for a green energy transition, under the two policy options in the two-sector model with unbalanced growth of Burda et al. (2024). We apply the model to examples for advanced (EU) and emerging (India) economies, characterized by different initial conditions. Further, it analyzes the role of capital adjustment costs and their impact on the optimal transition path and the cost of increased climate policy ambition.

The contribution of this paper is threefold. First, we add to the literature on dynamic,

cost-effective transition paths by considering different kinds of policy targets and levels of ambition: technological targets for achieving net zero emissions (NZE) and cumulative carbon emission targets, both of which are expressed in NDCs but entail different kinds of constraints and capital accumulation incentives. Second, we demonstrate the importance of the functional form and size of capital adjustment costs for the optimal paths and welfare costs of meeting these policy targets. We also show how country-specific characteristics—like levels of economic development, composition of starting capital stocks, and climate ambition—influence transition paths, particularly near-term investments in dirty energy, cumulative adjustment costs, and ultimately stranded assets.

We use the three-sector, carbon-constrained growth model of Burda et al. (2024). This model consists of a final output produced using capital, labor, and energy as inputs. Energy can be produced in an emission-free or an emission-intensive way. Both forms require capital and labor as inputs. Installed capital is sector-specific in the short run, and redeployment takes resources. While low emission and emission-intensive energy inputs are modelled as perfect substitutes, initial existing capital stocks, capital intensity and productivity differences, combined with sector-specific capital adjustment costs, limit their effective substitutability in the short run. Clean technology costs catch up over time. In addition to the carbon budget constraint in Burda et al. (2024), we add the possibility of a NZE target that requires all energy demands to be met with low emission sources by a certain time. Net zero commitments are a common policy which countries commit to in their nationally determined contribution (NDC) strategies. Capital adjustment costs play an important role in the transition to either of these targets, and they may be a function of the net (of depreciation and growth trend) or gross investment.

To capture clean technology catch-up, we create an index, comparing the levelized costs of a representative clean and dirty technology in five energy related sectors including buildings, electricity/heat, manufacturing and construction, and transportation. For both jurisdictions, we find that dirty technology initially is 40% more productive than clean energy technologies. However, clean energy technology approaches parity by 2050. Climate targets are drawn from NDCs, focusing on energy-related emissions.

We gather data for the EU and India and calibrate the model parameters to match seven empirical data targets: the initial dirty energy share in GDP, the initial growth rate of the capital stock, the initial capital output ratio, the initial emissions as share of the remaining carbon budget, the initial share of clean and dirty investment in total investment as well as the initial labor share.

We calibrate the model to the conditions in 2020 of the EU as an example of advanced economies and India as an emerging economy. The main challenge with respect to the clean energy transition differs between the EU and India. The EU overall has sufficient energy

production capacities to meet the energy demand of its economy. Therefore, transitioning to clean energy only for the EU means adjusting and repurposing their energy capital stock. The focus of the EU's energy investment has already shifted toward renewable energy, with 11.5 percent of capital investment going to clean energy compared to 2 percent into emission intensive energy. Additionally, due to historical responsibilities and capacity for ambition, the remaining carbon budget for the EU is quite limited.

In contrast, India has a relative lack of legacy energy generation systems and faces an increasing energy demand.Hence, India's main challenge for the clean energy transition is more about setting up an energy capital stock that can meet the needs of a growing economy. On the one hand, in line with India's claim of carving out a low-carbon, sustainable pathway for high levels of economic development that the rest of the global South could follow, India's investment into clean energy has picked up in the recent years (3.4 percent of total investment IEA (2021)). On the other hand, coal still accounts for 57 percent of India's primary energy consumption and India has a sustained high share of dirty energy investment of 8 percent. Low current emissions of Global South countries give them more time for the green transition but risk inefficient buildup of carbon-based energy generation in the interim period if inappropriate incentives guide investment decisions. Indeed, it is feared that some countries of the Global South are experiencing a coal renaissance. Jakob and Steckel (2022) claim that China, India, Indonesia, Vietnam, Turkey, Bangladesh, South Africa, and several other countries have planned or are already constructing coal-fired power equivalent to about 75 Gt of emissions. This risks a lock in into carbon intensive infrastructure in these countries and endangers global 1.5 degree efforts.

Our preliminary main results suggest that first, climate policy aiming at phasing out dirty energy by 2050 (1.5C) carries only modest welfare costs for India and the EU. Second, due to the expected productivity convergence, it is optimal for India to immediately increase investment into the clean energy technology – even without further climate policy – to avoid a double transition of the energy capital stocks. Third, with capital adjustment costs on net investment, the EU incurs more adjustment costs from disinvestment in dirty capital, while faster-growing India has higher clean energy and non-energy capital adjustment costs. This is since India is growing its energy but also its overall capital stock.

Some additional findings include that in both nations, the pursuit of phasing out dirty energy by 2050 (1.5°C) climate target significantly curtails emissions yet implies higher costs for the initially elevated investment needed for clean energy production. The overall clean energy capital stock needs to be bigger to substitute the initially more productive dirty energy capital stock. This leads to elevated adjustment costs for clean energy.

However, there are several differences for India and the EU. First, even though it is optimal for both economies to increase clean energy investment substantially immediately,

the different setup of the initial energy capital stocks leads to different policy implications. The carbon tax necessary for 1.5C is much higher for the EU than for India. In India, even a low carbon tax avoids an initial buildup in dirty capital. Second, more ambitious 1.5C climate policy has a different effect on energy prices in both economies. In India energy prices continue to decline, while in the EU it amplifies an overshooting of energy prices in the transition period.

When comparing the impact of the different climate policies we find that the optimal transition paths differ when using a NZE targets that require all energy demands to be met with low emission sources by a certain time with a carbon pricing policy. Replacing a cumulative carbon budget including optimal emission pricing with a net zero target with the same dirty energy production phase out date e.g. 2050 emissions used until the fossil phase out date almost double and the amount of stranded assets increases from 0.47 to 2 percent of GDP. The simple net zero target without any emission pricing further causes a increased front loading of emission use, which helps to benefit from the remaining inital advantage of dirty energy technology. When combining a cumulative carbon budget for 1.5 C with an overlapping and binding net zero eg. net zero by 2040 lowers the carbon price needed to meet the carbon budget but significantly increases stranded assets.

On a technical front we find that if adjustment costs are based on net investment, disinvestment is penalized and the EU reaches net zero with more stranded assets; if gross investment is the basis, dirty assets can depreciate costlessly, reducing stranding but raising overall adjustment and welfare costs of the transition.

Our findings highlight the interaction between the setup of energy related infrastructure and the stringency of climate policy. Policy makers with preferences for non-ambitious climate policies should consider the risk of a double transition of the energy capital stocks when planning the setup of their energy systems.

The remainder of the paper proceeds as follows. (Section 2 surveys the relevant literature.) The section 3 provides an overview of the three-sector unbalanced growth model of Burda et al. (2024) and the additional climate policy scenarios analyzed in this paper. Section 4 describes the calibration strategy. Section 5 provides an analysis of the net-zero transition paths comparing different policies in the EU and India. Section 6 provides a sensitivity analysis on the role of adjustment costs. Section 7 concludes.

2 Literature review

Our paper brings together two strands of literature: one on climate policy pathways for the low-carbon transition and another on capital adjustment costs in macroeconomics. Much of the climate macroeconomics literature to date has sidestepped adjustment costs by mod-

eling clean and dirty energy forms as imperfect substitutes (see, e.g., Golosov et al. (2014); Hassler et al. (2021); Fried (2018); Airaudo et al. (2023)). Given the aim for net-zero emissions and wholesale replacement of emitting energy technologies, we adopt a model in which low-carbon and emissions-intensive energy are perfect substitutes, but their effective substitutability is limited in the short run by costly adjustment of capital stocks. Dirty and clean energy production technologies differ in terms of their starting capital stocks, capital intensity, and productivity, and have sector-specific capital adjustment costs as well. This approach is also used in Burda et al. (2024), who study Ramsey-optimal paths of capital formation in the context of the green energy transition. They analyze the impact of different assumptions of technological change and their impact on the structural changes characterizing the green transition.

We modify the model of Burda et al. (2024) in two main aspects. First, we add another policy option in the form of a net zero emission target that requires all energy demands to be met with low emission sources and emission intensive energy phased out by a certain time. This constrains low emission capital accumulation and emission intensive capital utilization by time but does not include a carbon tax. Second, we analyze the impact of different sizes and functional forms of adjustment costs on the transition path.

Methodologically our paper closely relates to Arkolakis and Walsh (2023); Vogt-Schilb et al. (2018); Coulomb et al. (2019); Campiglio et al. (2022), who all analyze the optimal transition of an economy with clean and dirty capital given adjustment costs. Simliar to Arkolakis and Walsh (2023), we find that energy production will be dominated by renewables by 2040 in all scenarios, even in the absence of additional climate policy. Our results confirm the finding of Vogt-Schilb et al. (2018) that a growing carbon price is compatible with significant short-term investment to reduce these adjustment costs over time. Our paper adds to this finding that higher adjustment costs require a higher tax schedule to incentivize the transition. Vogt-Schilb et al. (2018) find that at any point in time, sectors where abatement capital is more expensive should receive more abatement investment, to smooth their transition and reduce adjustment costs. Similar to our findings, Campiglio et al. (2022) show that capital adjustment costs prevent an implausibly large shift from emission intensive to clean capital initially and that capital inertia therefore results in temperature inertia and higher carbon prices. We share Campiglio et al. (2022)´s definition of emission intensive capital being related to fossil energy usage. However, Campiglio et al. (2022) only differentiate between clean and emission intensive capital, whereas we introduce non-energy capital. Introducing non-energy capital allows for the assumption of clean and emission intensive energy as perfect input substitutes for final output in the long run. Our findings are closely related to Coulomb et al. (2019) who find that the presence of adjustment costs makes it optimal to invest in expensive renewable energy before phasing out fossil-fuel

consumption. In contrast to Coulomb et al. (2019) focus on the electricity sector, this paper adds the investment interactions with a non-energy sector and endogenizes the time when the carbon budget is optimally depleted. We further add to this strand of literature comparing the effect of a carbon price with simple net zero targets.

By analyzing the influence of different initial conditions on the optimal capital adjustment path, this project follows in the spirit of Fischer et al. (2004), who find that the socially optimal trajectory depends significantly on the initial state of the environment.

With respect to the choice of different mitigation instruments, most of the economics literature focused on technology and growth has not thought much about other policies than carbon prices. One exception is Rozenberg et al. (2020) who show that in contrast to carbon pricing, mitigation policies such as mandates, feebates, or standards on new investment can accomplish the transition to an economy dominated by clean capital but avoid stranded assets, the premature retirement of polluting capital. The reason is that these instruments do not tie a new cost to the utilization of existing capital which a carbon price does. We add to this literature by exploring the impact of net zero commitments which is a common policies countries commit to in their nationally determined contribution (NDC) strategies.

We bear a direct connection to the large body of work on convex adjustment costs for capital investment. Convex capital adjustment costs capture the increasing opportunity costs to use scarce resources, such as skilled workers, appropriate capital, or production lines, to perform the capital stock transition. The ability of an economy to switch from carbon-intensive to low-carbon capital overnight is limited. To capture this idea of limited switching possibilities our paper builds on the early literature on adjustment costs for capital investment Lucas (1987); Gould (1968); Mussa (1977). In the baseline scenario we use convex adjustment costs which are found to fit well the data of aggregate investment Cooper and Haltiwanger (2006).

In a more recent study, David and Venkateswaran (2019) confirm that adjustment frictions play an economically significant role in influencing observed investment dynamics. David et al. (2021) found that adjustment costs account only for a modest share of the observed capital misallocation and that adjustment costs are more salient in more developed countries. This contrasts with our finding that the overall level of adjustment costs is higher in the emerging market economy. In our analysis capital adjustment costs in India are larger because it still must grow its overall capital stock. Our results suggest that adjustment costs have a first order importance for the economic transition linked to switching its energy technology. Hence, an important question that needs further research is how and in which period adjustment costs are measured and what they include.

So far, macroeconomic literature commonly uses adjustment costs as a modelling tool since data shows that the change in the capital stocks occurs slowly. However, the liter-

ature has not been very precise when using adjustment costs on gross or net investment, neglecting the importance of certain implied features of the different functional forms. Using adjustment costs on gross investment implies additional adjustment costs for replacement investment but does not incur any costs for depreciation. This leads to an overall increased level of capital adjustment costs. Adjustment costs on net investment do not penalize replacement investment making it free to keep the capital stock constant or growing at a steady state growth rate. However, depreciation is costly in that case.

One paper touching upon the differences is Hall (2004). He finds in his empirical investigation strong evidence against substantial adjustment costs. However, he finds as well that the adjustment cost is understated when it applies to gross investment (Hall, 2004, p.922). Our results support Hall (2004)'s finding that gross adjustment increases the overall amount of adjustment costs in an economy. Further, we add to this literature that within an economic transformation from one technology to another technology adjustment costs on gross or net investment may affect the incidence of adjustment costs. In the context of a growth model, adjustment costs on net investment penalize excess investment below and beyond depreciation and growth, this implies an extra penalty on the decommissioning of the capital stock linked to the technology that needs to be phased out, in our case the high emission intensive energy technology. Using adjustment costs on gross adjustment where depreciation is costless, the adjustment costs for the capital stock of the technology that is to be phased out are negligible. But since replacement investment incurs additional costs the adjustment costs in the technology that is phased in incurs much higher costs than with when adjustment costs on net investment are assumed.

Hence what is missing in the literature is a proper micro-foundation for adjustment costs occurring when an economy is switching its energy technology, which requires the change of large shares of the capital stock and capital stocks of different sectors are affected distinctly. In the US about 10 percent of the total overall capital stock specialized to use fossil fuels needs to be repurposed or decommissioned Fried et al. (2022). And the capital stock for the clean technology still needs to be set up.

The importance of non-convex vs. convex adjustment costs for the plant level versus the aggregate level has been analyzed in various papers like Cooper and Haltiwanger (2006) but has not been applied to an example of a structural economic transition. In DSGE models like the one of Aguiar and Gopinath (2007a) adjustment costs on net investment are commonly chosen because adjustment costs on net investment do not influence the steady state which makes solving DSGE model easier. In contrast, Christiano et al. (2005) use in their model adjustment costs associated with the variation in the level of investment. This functional form implies that the costs are increasing in the change in investment and costs are zero at a steady state as well. This formulation is mainly used in business cycle literature since

it is useful to explain autocorrelation in investment found in data. Analyzing the role of non-convex adjustment costs and other functional forms of adjustment costs in light of the transition to net zero seems to be a question that should be addressed in future research.

3 Model

3.1 Preferences, Production and Emission Accumulation

The framework applied for studying the green transition uses the model developed in Burda et al. (2024), who extend the deterministic model of unbalanced growth of Acemoglu and Guerrieri (2008) by introducing capital adjustment costs and a cumulative emissions budget. This section shortly explains the central features of the baseline model. For a detailed description of the model and its solution see Burda et al. (2024).[1] Our focus is on exploring the implications of various policy scenarios for reaching dirty energy phase out for advanced (EU) and emerging economies (India).

Households have standard preferences over consumption C_t of a homogeneous final output good. They discount the future at rate $\frac{1}{\beta} - 1$ and their elasticity of intertemporal subsitution is $\frac{1}{\theta}$.

On the production side, there is an energy sector E and a non-energy sector N, which subsumes all other sectors. A final good producing sector combines energy and non-energy intermediate inputs with respective weights γ and $1 - \gamma$ in a production technology with constant substitution elasticity ϵ. Energy and non-energy are both produced using Cobb-Douglas technologies with constant returns to scale in capital and labor, which is in fixed supply. For energy, two production technologies are available: D for dirty, which causes greenhouse gas emissions, and C for clean, which does not. Clean and dirty energy are perfectly substitutable as inputs for final good production. The three technologies differ in their capital intensity $(1 - \alpha_i)$ and total factor productivity (M_{it}) for $i \in \{N, D, C\}$.

Environment The dirty technology causes greenhouse gas emissions, which accumulate in the atmosphere according to:

$$G_t = G_{t-1} + \mu Y_{Dt},$$

where μY_{Dt} is the flow of emissions at time t and G_t is the stock of accumulated emissions. For more details see Appendix A.

[1] For reference, we also present the model equations in Appendix A.

Adjustment costs The central feature of the Burda et al. (2024) model are convex capital adjustment costs $\Omega^i(K_{it}, K_{it-1})$ in each technology, which restrict the short-term substitution possibilities between energy sources, despite the perfect long-run substitutability:

$$\Omega^i(K_{it}, K_{it-1}) = \frac{c_i}{2}\left(\frac{I_{it}}{K_{it-1}} - \delta_i - z_i\right)^2 K_{it-1} \quad \forall\, i = C, D, N$$

Here c_i is the adjustment cost parameter, δ_i is the capital depreciation rate and z_i is the growth rate of the respective capital stock on the model's unbalanced growth path.[2] The presence of δ_i reflects the assumption that adjustment costs are only incurred on net investment, while replacement investment is free. The motivation for this is that maintaining the current capital stock is done routinely which makes it less costly than expanding production capacity by installing new machines or reducing it by selling and re-purposing old ones. Overall, excess investment below and beyond depreciation and growth incurs adjustment costs. We explore the robustness of our results with respect to this assumption in Section 6.

Technology and clean catch-up Total factor productivity of dirty energy and non-energy technology grows at constant and exogenous rates m_D and m_N respectively. To capture the fact that many clean energy technologies are not yet mature, but improving at a rapid pace, we introduce exogenous catch-up growth. We model catch-up growth in a simple manner, by assuming that TFP in the clean technology approaches that of the dirty technology in the long run. During the transition the distance between the productivities shrinks at a constant rate. Specifically, we define a catch-up factor

$$a_{Ct} = 1 - \frac{b_M}{(1+\kappa_M)^t}$$

where $\lim_{t\to\infty} a_{Ct} \to 1$, κ_M is the catch-up rate and b_M determines the initial distance to the long-run constant-rate growth path. The level of TFP in clean energy production then follows

$$M_{Ct} = a_{Ct} M_{Dt}.$$

The catch-up factor a_{Ct} captures our finding that for both countries there remains a dirty productivity advantage of about 10 percent in 2030 (see Figure 1 and Section 4.1). We calibrate κ_M and b_M such that they capture the different path of clean technological catch up we find in the data for the EU and India (see Section 4.1).

[2] This particular form ensures that adjustment costs do not affect long-run outcomes and follows Aguiar and Gopinath (2007b).

3.2 Policy scenarios

We consider several different policy scenarios. Each scenario corresponds to a social planner problem with a different objective regarding the path of emissions. These social planner solutions can also be implemented as an equilibrium in a decentralized economy by setting the optimal excise tax on dirty energy, τ_{Dt}.[3]

3.2.1 Optimal Growth Path under a Carbon Budget

As a baseline, we consider a carbon budget (cost-effectiveness approach), as in Burda et al. (2024). That is, the social planner chooses a feasible path of consumption to maximize welfare of the representative agent subject to the constraint:

$$\frac{G_T}{\bar{G}} \leq 1. \tag{1}$$

where $\bar{G}$ is the target carbon budget. Constraint (1) will bind at some finite time $\bar{T}$ on the optimal growth path, which implies, $L_{Dt} = 0$ for all $t \geq \bar{T}$. Because of adjustment costs, however, K_{Dt} might be positive after time $\bar{T}$. All K_D left in the economy after the carbon budget binds is considered stranded assets since it is not used for any production. In this approach the social planner can also choose the time $\bar{T}$ when the pre-given carbon budget is optimally depleted.

3.2.2 Optimal Growth Path with Net Zero Target

The second policy case we consider is a social planner who maximizes welfare of the representative agent subject to the constraint that dirty energy is phased out by time $\hat{T}$.

$$Y_{Dt} = 0 \quad \forall\, t \geq \hat{T}. \tag{2}$$

This constraint also implies that $L_{Dt} = 0$ for all $t \geq \hat{T}$. Comparing this to the Carbon Budget approach, however, the social planner has no direct incentive to reduce emissions during the transition phase, leading to a much more abrupt transition to net zero at time $\hat{T}$, moderated primarily by capital adjustment cost planning.

3.2.3 Optimal Growth Path with Net Zero Target and a Carbon Budget

The third case combines the first two. Here the social planner has to respect a cumulative emissions budget as in constraint (1) subject to the the additional restriction that emissions

[3]The fact that one instrument is sufficient to achieve one target is in line with the Tinbergen rule. See also Burda et al. (2024).

have to reach zero by $\hat{T}$ as in constraint (2). Notice that the solution to this problem will coincide with the pure carbon budget if $\bar{T} \leq \hat{T}$. That is, the second constraint is not binding, if it is optimal to reduce emissions to zero before $\bar{T}$ anyway.

4 Calibration Strategy

We calibrate the model parameters to match seven empirical targets found in the data for India and the EU. The empirical moments we target include (1) the initial dirty energy share in GDP, (2) the initial growth rate of the capital stock, (3) the initial capital output ratio, (4) the initial emissions as share of the remaining carbon budget, (5) the initial share of clean and (6) dirty investment in total investment as well as (7) the initial labor share.

We calibrate the model to the European Union and India at an annual frequency, starting our simulations in 2020. The model period is one year. We calibrate 7 parameters $\{\epsilon, \alpha_{C,D}, \delta_i, \theta, \beta, \mu_j\ \}$ with $i \in [N, D, C]$ and j=[India or EU] directly from the data and existing literature. Given these externally calibrated parameters, we jointly calibrate the remaining six parameters $\{\gamma, \sigma_0, \frac{K_{C0}}{K_0}, \frac{K_{D0}}{K_0}, Kf, \alpha_N\}$ internally so that seven parameters in the model match the seven empirical targets mentioned above. Table 8 and Table 10 report the parameter values that we calibrate externally and internally, respectively.

Several of the macroeconomic parameters are easily observed in the data, and these are detailed in C. Others—particularly empirical targets related to the dirty and clean energy sectors—require additional information and internal calibration. Since by 2020 (our starting date), some climate policies had already been in place and were expected to continue going forward, the calibration must be consistent with policy expectations at the time. We thus use a Stated Policies Scenario (STEPS) as our baseline, from which to analyze other, more ambitious policies. Similarly, technologies are expected to evolve over time. Here we describe in more detail our efforts to carefully calibrate the dirty productivity advantage and the starting variables consistent with STEPS.

4.1 Energy technologies calibration

In distinguishing between dirty and clean energy production, in addition to intial capital stocks, investment levels, and market shares, two important aspects of the technologies must be characterized: 1) the capital intensity of production $(1 - \alpha_i)$, 2) total factor productivity (M_{it}), reflecting the initial cost advantage of dirty energy, and the rate of catch up.

We calibrate the capital intensity in both energy sectors, assuming this feature of the technologies is identical across countries. We account for the finding in the literature that capital intensity in the clean energy sector is higher in general than in the dirty energy

sector. See Appendix C for more details.

Capital intensity Parameter	**Value EU**	**Value India**
Dirty energy sector $(1-\alpha_D)$	0.65	0.65
Clean energy sector $(1-\alpha_C)$	0.7	0.7
Non-energy sector $(1-\alpha_N)$	0.38	0.45

Table 1: Capital intensities in the different sectors in the EU and India

To measure these differences between clean and dirty technology in the EU and India we create an index comparing levelized costs of energy (LCOE) for clean and dirty technology in the primary sectors for energy-related emissions. The LCOE estimates provide an indication of relative costs, as well as of the share of those costs attributed to capital as opposed to operation.

Energy-related emissions stem from energy-intensive processes in several sectors, including buildings, electricity/heat, manufacturing and construction, and transportation. For each of these sectors, using mostly data from IEA (2023a), we approximate the dirty technology advantage by comparing the LCOE's of one dominantly used clean and one dirty technology in each sector. We then create an average of these productivity advantages for our dirty energy composite. (For details of the construction see B.2).

According to the productivity index we construct, we find that for 2021/2022 the dirty technology advantage is about 40% and declines to 9% in 2030. In India we find a slightly lower dirty productivity advantage of 26% in 2021/2022 which declines to 11% in 2030. Hence, for both countries there remains a dirty productivity advantage of about 10 percent in 2030. We capture this dynamic with our catch-up factor (see figure 1).

Figure 1 shows that clean energy technology catches up with dirty energy technology but does not overtake dirty technology until the end of the simulation.

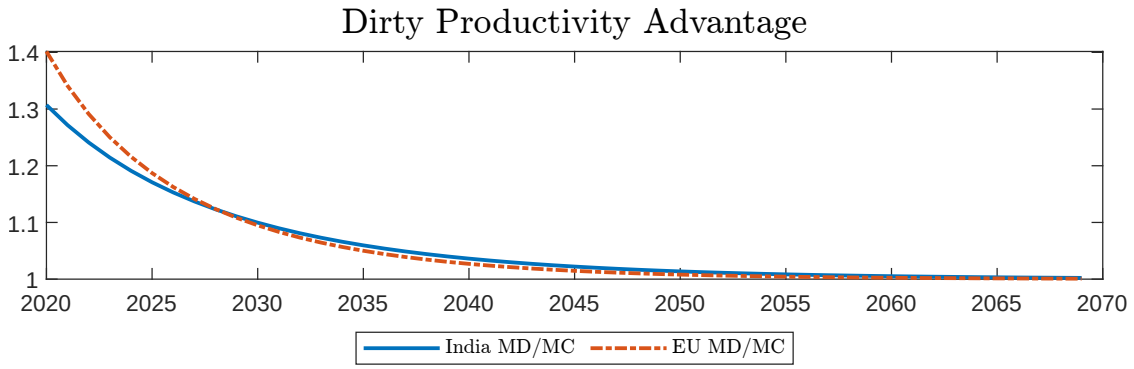


Figure 1: Development of the dirty productivity advantage in the EU and India in the stated policy scenario

4.2 Calibration of STEPS and carbon budgets

First, to calibrate our baseline scenario for the EU and India we use emissions projections from Climate Action Tracker, reflecting the stated NDCs as of 2022. This secenario serves as a basis for comparison to more ambitious climate policies. [4]

These estimates include all GHGs, converted to CO_2e. We calculate cumulative emissions using Climate Action Tracker annual emission projections until 2030 in the "Policies and Actions" scenario and add a linear extrapolation of the annual emission from 2030 until 2050. We use the same procedure for India and the EU. Second, since our model only represents energy-related emissions, we need to exclude other emissions, such as those from land-use change. The overall carbon budget is prorated according to the 2020 share of energy-related emissions to arrive at the accumulated carbon budget, which the social planner uses optimally over time. For details of the construction of the carbon budget see Appendix B.1.

4.3 Calibration caveats and interpreting carbon prices

The lack of a clean "No Policy" scenario raises some questions for how best to interpret the value of the (initial) carbon tax we find. (Optimal price paths subsequently grow exponentially at the rate of interest.) Is it the sufficient tax to meet the NDCs, or is it the tax that is needed in addition to unmodeled pre-existing policies? Our calibration must explain initially observed levels of variables, like clean energy shares, investment and emissions, which are a product both of historical policy interventions and policy expectations. Pre-existing policies are not explicitly captured by the carbon budget, but the preexisting subsidies and taxes were most likely substantial to the build up of the energy capital stocks found in 2020. Furthermore, many unrepresented policies do not take the form of carbon pricing, as exemplified by the EU Green Deal and a host of member state policies and programs. To the

[4]Our calibration starts in 2020 due to data limitations, however, the climate action tracker takes into account policies implemented in 2021 and 2022 as well. This may also lead so some inconsistencies.

extent these policies have contributed to making the NDCs easier to achieve, the absolute carbon price coming out of the model will be biased downward.

Another caveat regards the technology and emissions assumptions. First, we do not capture hard-to-abate sectors specifically. Although we do include their higher abatement costs in the cost advantage index of dirty energy, our energy composite does not capture compositional changes over time that would imply increasing marginal abatement costs and changes in the emission intensity of dirt energy. Second, clean and dirty energy are modeled as perfect substitutes, which may be appropriate for a large share of energy services, but ignores the final fraction of uses that are truly hard to avoid.[5] Therefore, our model simplifications of the abatement process may getting to net zero appear easier than it is in reality.

Given these shortcomings, as always with numerical modeling, the specific results should be taken with a grain of salt. Nevertheless, the model produces a number of useful insights into the role of capital adjustment costs and policies for the low-carbon transition. One outcome is consistent throughout all scenarios considered for the EU and India: underestimating adjustment costs has larger implications for transitional welfare costs than the incremental costs of greater ambition.

4.4 Calibration Results

The two main differences in the general economic context between the two economies we account for are the difference in the labor income share and the capital stock growth rate. The labor share in India is about 6 percentage points lower due to an abundant but low paid labor force. Since India is still accumulating its capital stock the initial capital stock growth rate is about 5 percentage points higher. Related to the net zero transition the main difference between the EU and India is that India has a much larger remaining carbon budget (104.8 $GtCO_2$ vs EU 48.5 $GtCO_2$) and is still investing a much higher share into dirty energy production (8 percent) than the EU (2 percent). The initial investment share into clean energy is much larger in the EU. However, India is facing an increasing energy demand requiring it to extend the energy capital stock to meet this growing demand with or without the transition to a net zero economy.

Table 2 shows the fit of the model moments with the empirical targets of the EU and India. Importantly, for the transition paths below, our best estimate of the output elasticity with respect to labor is 0.7 in the non-energy sector and 0.35 in the dirty energy sector and 0.3 in the clean energy sector. The energy and particularly the clean energy sector is thus

[5]Models assuming constant elasticity of substition have their own shortcomings, of course, compared to the reality of abatement options.

much more capital-intensive than the rest of the economy.

The best estimate of the initial share of dirty energy in total output 6% and 7% for the EU and India respectively. The initial shares of dirty and clean capital in total capital are set to 9% and 3% in India and 13% [6] and 9% in the EU. Energy capital is associated with energy use in different sectors, including manufacturing, construction, housing, electricity, transportation, and storage. Table 2 shows that both STEPS scenarios match the empirical targets quite closely.

		EU		**India**
Empirical Targets	**Model**	**Data**	**Model**	**Data**
Initial dirty energy share in GDP $\frac{Y_{D0}}{Y_0}$	5.6 %	6 %	7.75 %	7 %
Initial growth rate of the capital stock	1.87%	1.6 %	6.83%	7 %
Initial capital output ratio $\frac{K_1}{Y_1}$	2.85	2.5	2.04	2.1
Initial emissions as share of remaining carbon budget	5.1%	5.1 %	2.53 %	2.1 %
Initial share of clean investment $\frac{I_{C0}}{I_0}$	6.42%	11.5 %	4 %	3.4 %
Initial share of dirty investment $\frac{I_{D0}}{I_0}$	2.75 %	2 %	8.27 %	8 %
Initial labor share $\frac{wL}{Y}$	59.6 %	58 %	52.9 %	52 %

Table 2: Moments Matched

5 Analysis of the Net Zero Transition: Advanced Economy vs. Emerging Market Economy

In this section we compare the structural transformation of the economy as it optimally reaches zero greenhouse gas emissions in the EU and India. For the EU, we compare the trajectories of four main climate policy scenarios. In all scenarios, the social planner chooses the optimal path of emissions and the optimal time at which the carbon budget is depleted ($\bar{T}$). Implicitly, these choices define an optimal carbon price path.

1. **CBSTEPS**: The first scenario shows the transition path that is optimal for a carbon budget that corresponds to the stated policies scenario (STEPS), as described in 4.2 and B to form the baseline scenario with current and already implemented climate policy.

[6] In the back of the envelope estimations based on EU fixed asset by activity and assets, we find that the dirty to total capital ratio is about 10 percent.

2. **NZ2050** reflects a scenario of meeting the net zero technology constraint at 2050 without a corresponding carbon budget constraint. Hence, it requires all energy demands to be met with carbon-free sources by 2050, after which CO2 intensive technologies can no longer be used. The NZ2050 scenario does not require any carbon pricing policy.

3. **CB+1.5C** reflects a carbon budget under which it is optimal to phase out dirty energy by 2050. The budget is implemented with optimal carbon pricing, which induces greater emission reductions along the time path than NZ2050. Consulting the literature, we find these target budgets for the EU and India are in line with their suggestive shares of the global carbon budget that is associated with meeting the 1.5C goal. [7]

4. **CB+1.5C+NZ2040** models the path that meets the same carbon budget necesary to meet CB+1.5C (or the share of the 1.5C global budget) while also meeting a more ambitious net zero target of 2040. Adding the net zero target by 2040 forces the social planner to use only renewable energy technology already by 2040 instead of 2050 as in the previous scenario (CB+1.5C); a lower carbon price is thus required to meet the same carbon budget as CB+1.5C.

Scenarios 1-3 are thus associated with different levels of total emissions as well as costs and prices. Scenarios 2-3 compare those results for the same timing of the phaseout of dirty energy. Scenarios 3-4 then allow for a comparison of the cost-effectiveness of the overlapping net zero target, while maintaining the same carbon budget. The second scenario is essentially the combination of the cumulative energy emissions targets and net zero pledges.

For the calculation of the STEPS carbon budget we use the modelling assumptions of the Climate Action Tracker (CAT)'s "Policies and actions" scenario. CAT's "Policies and actions" scenario refers to what is actually happening in a country to reduce emissions. It estimates the expected level of emissions if all current policies are fully implemented.

The size of the carbon budget used for 1.5 C for India and the EU is within a range of estimates found in the literature (see Appendix B.1). The EU and India the CB+1.5C carbon budget is closest to the carbon budget size estimated by the average scenario of Du Robiou Pont et al. (2017). Du Robiou Pont et al. (2017) consider five distinct principles of distributive burden sharings of the globally necessary mitigation efforts to reach the 1.5° degree goal globally. In addition, India's CB+1.5C carbon budget is very close to the carbon budget based on the CAT's modelling assumptions for global least-cost mitigation efforts. The CAT's global least-cost scenario downscales the global least-cost mitigation pathway to a national level to assess whether a country is on track for full decarbonization domestically.

[7] See Appendix Figure 16 for a reference table that compares the cumulative carbon budgets for the EU and India with estimates found in the literature.

5.1 European Union

For the European Union, summary results are presented in Table 3. The STEPS carbon budget for energy emissions equals 48 $GtCO_2e$, and optimally allocated over time, it would require a 5 euro/ton CO_2 price, causing dirty energy to phase out in 2078. Requiring that phase out to occur by 2050 with a net zero technology constraint would cause cumulative emissions to fall by 10% below STEPS, with no carbon price needed. On the other hand, suppose that 2050 phase out were achieved using carbon pricing alone: the associated carbon budget would be 26 $GtCO_2e$, or a 46% reduction below STEPS, achieved with a 44 €/ton price.

In terms of transitional welfare measured in terms of foregone consumption, meeting this phaseout date with a carbon budget is a bit more than twice as costly as the net zero policy, but both are a fraction of a percent of total consumption, and the increment should be weighed against the value of the additional reductions. Although the carbon budget has higher average adjustment costs for the same 2050 phaseout, far fewer stranded assets remain at the end of the period. The final policy combining the 26 $GtCO_2e$ carbon budget with a more ambitious 2040 net zero target lowers the carbon price by 25% and significantly increases stranded assets.

EU Scenarios	**Phase-out year**	**Carbon budget**	**CO_2 Price 2020**	**Δ Welfare during transition**	**Stranded assets**	**Avg. adj. costs**
		$GtCO_2e$	€/ton	% ch. rel. to STEPS	$K_D(\bar{T})/Y(\bar{T})$	avg. Ω/Y to 2060
CBSTEPS	2078	48	5.26	0	0.04	0.13
NZ2050	2050	43	0	-0.05	2.01	0.16
CB+1.5C	2050	26	44.05	-0.12	0.47	0.22
CB+1.5C+NZ2040	2040	26	33.84	-0.14	3.19	0.23

Table 3: Summary results for transition scenarios in the EU

Next, a set of figures illustrates the transition paths under the different scenarios. The blue solid line shows our baseline scenario CBSTEPS; the orange dotted line plots NZ2050; the green, dot-dashed line shows the CB+1.5C scenario; and the red long dashed line shows CB+1.5C+NZ2040. The vertical lines show the dates when the carbon budget becomes binding (and dirty energy is phased out) in each scenario.

Figure 2 shows some overall economic indicators describing the transition paths of the different policies. All scenarios show that there is positive GDP growth of on average 2.4

percent (Figure 2 Panel 1). A more stringent carbon budget (CB+1.5C) leads to a small growth (0.05 percentage points) dip initially. Consumption shows an increasing dip of up to 0.4 percentage points until 2040. The pattern of decreased consumption can be explained by the second panel in the second row showing that overall investment in shares of GDP is increasing in all scenarios.

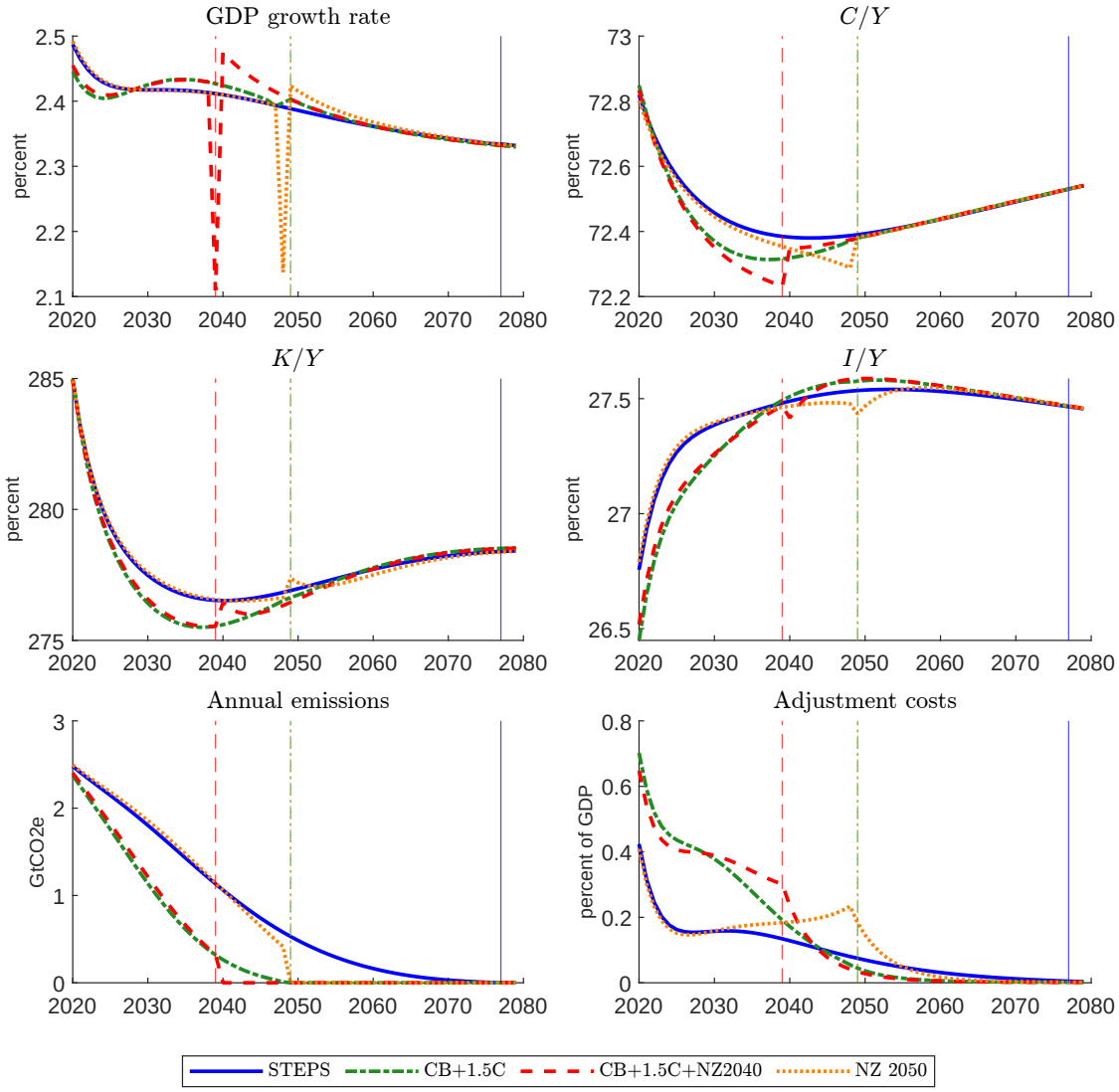


Figure 2: Overall Economic Indicators in the EU

Figure 4, showing sectoral investment, explains why the dip in consumption is largest in the case of ambitious climate policy. In the case of CB+1.5C and CB+1.5C+NZ2040, the initial investment increase mostly occurs in the at that time less productive clean energy sector. Hence, ambitious climate policy makes it optimal for the social planner to sacrifice some consumption growth during the early transition to invest into a less efficient technology helping to reach substantial emission reductions early on.

Using a net zero target leads in both cases to a larger growth dip immediately before the net zero constraint becomes binding. The overall capital output ratio declines while the

overall investment share increases in all scenarios.

The panel on annual emissions shows that the emission budget is depleted smoothly in case of a carbon budget whereas with a fix net zero target year there is a steep last decline shortly before the net zero target becomes binding. Additionally, more emissions are used in the beginning of the period when a net zero target is added. When comparing a fixed carbon budget optimally depleted by 2050 and a simple net zero target NZ 2050 the amount of emission used overall increases by around 65 percent. With the NZ 2050 policy most of the emissions are used early on when the productivity advantage of dirty energy is most pronounced and provides most additional welfare in terms of consumption.

Overall, adjustment costs increase in the stringency of the climate policy. However, the timing when adjustment costs accrue differs. A stringent carbon budget with carbon pricing only shows that adjustment costs are large in the beginning and then decline.

All in all, more stringent climate policy leads to a decline in growth of about 0.05 percentage points. However, more stringent climate policy is more costly in terms of adjustment costs and lost consumption. Including a fixed phase out date leads to a steep dip in the overall transition path shortly before the phase out date becomes binding. A carbon budget with a consistent carbon price makes the transition path much smoother. Hence, in terms of cost-effectiveness our results show that carbon pricing helps avoid the accumulation of costs around a certain phase out date. Figure 3 shows the transition paths of the production

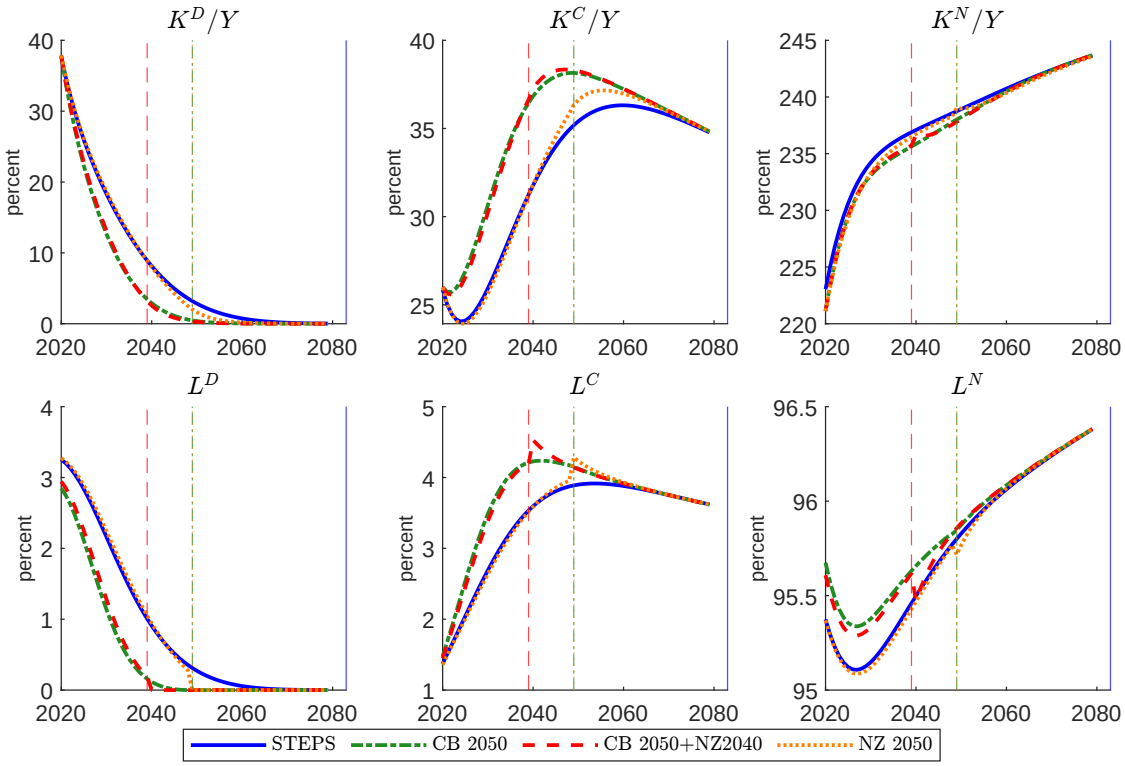


Figure 3: Factor allocation in the EU

factors capital and labor in the three different sectors. Panel 1 of Figure 3 shows that the dirty capital stock declines and the clean energy capital stock accumulated more rapid the more stringent the climate policy. Less stringent climate policy even causes a decline in the clean capital stock of 2 percentage points. As long as the emission constraint is not binding it is optimal for the social planner to use more dirty energy and use its initial productivity advantage. The decrease in the clean capital stock is caused by an insufficient level of clean energy investment to keep the already existing capital stock constant since we do not see any clean disinvestment (see Figure 4).

Dirty capital that is left in the economy after the dirty energy has been phased out is stranded. Panel 1 shows that stricter climate policy increases the amount of stranded assets in the economy. Using net zero targets increases the amount of stranded assets even further.

A higher carbon price (smaller carbon budget) causes dirty labor to decline faster and even more abrupt with a net zero target. Clean labor rises over time. However, with a net zero target more labor is pulled into clean than is leaving dirty causing a dip in the neutral sector as well. In the baseline scenario there is an increased amount of labor in the dirty sector pulled out of the non-energy sector for the next decade. More labor in the dirty energy sector helps to take advantage the higher productivity in this energy sector. Overall the amount of labor in the clean energy sector is smaller with less ambitious climate policy (STEPS and NZ 2050). Figure 4 shows the sectoral dynamics of investment, adjustment costs and the capital stocks. The first row of figure 4 displays the investment dynamics in the different sectors. Dirty investment declines and becomes negative temporarily in both more ambitious climate policy scenarios. Negative dirty investment means that dirty capital is being repurposed. However, in the CB+1.5C + NZ2040 scenario the initial dirty disinvestment is lower than in the CB 2040 scenario because the model is forced to use the same carbon budget of 26 $GtCO_2$ and hence it is optimal to use more dirty in the beginning taking advantage of the dirty productivity advantage. This pattern is reflected in the amount of dirty capital stock and the dirty adjustment costs as well. The additional net zero 2040 target does not increase the stringency of the climate policy but only changes the optimal use of emissions over time.

Clean investment accelerates and overshoots and neutral investment is crowded out to some extent during the transition. Overall, due to the higher capital intensity in the clean energy sector compared to the dirty energy sector the overall share of investment in the energy sector is higher. The clean energy investment in the long term reaches about 3.5 percent of GDP whereas dirty energy investment is only at 0.7 percent at its highest point.

The second row splits up the dynamics of the aggregate adjustment costs into sectors. Dirty adjustment costs clearly increase in the stringency of the climate policy. The spiky behavior of using net zero targets shows up in the transition path of sectoral investment and

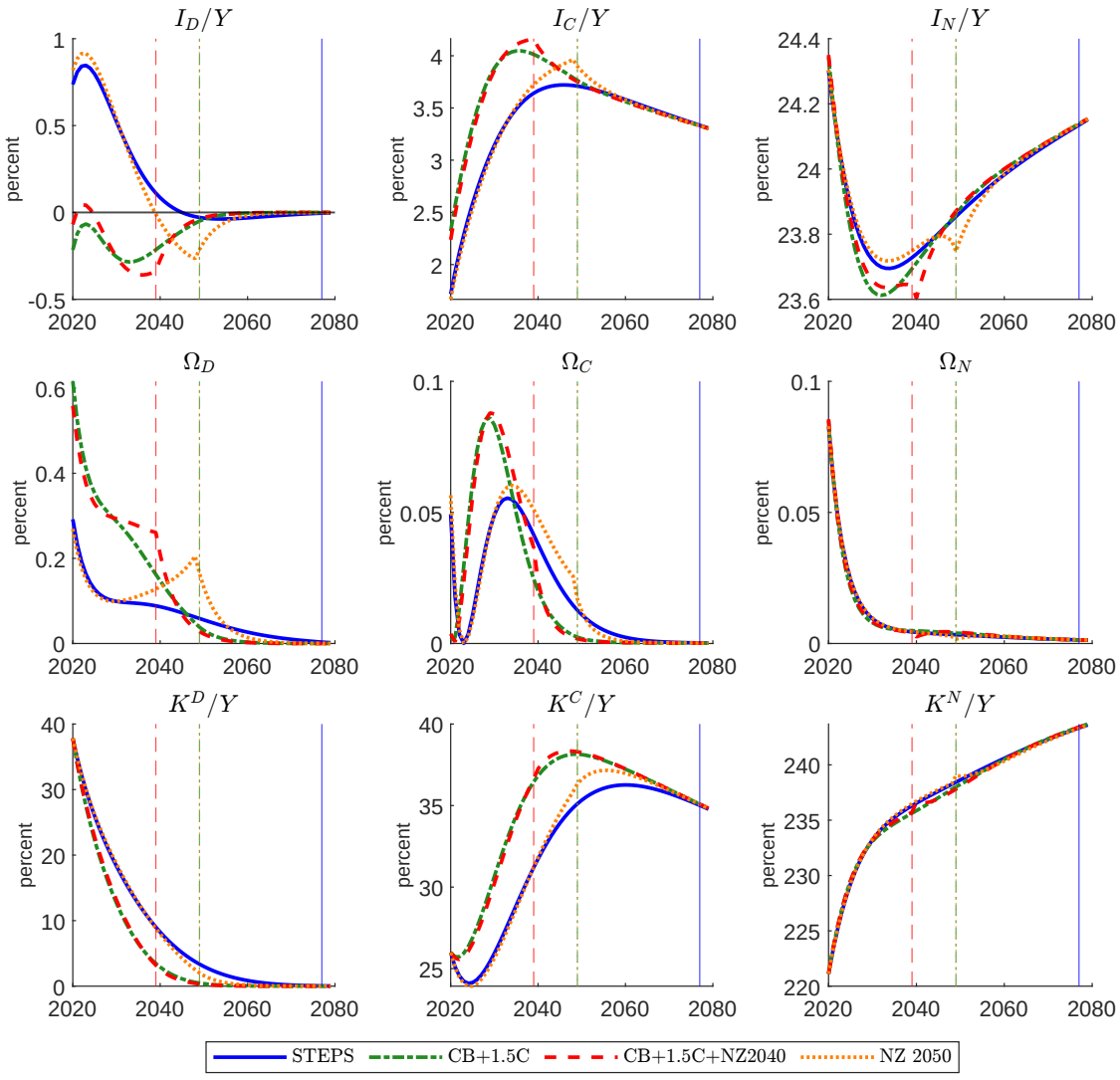


Figure 4: Investment and adjustment costs in the EU

adjustment costs again. There is a decrease in clean capital stock in the baseline scenario. This is associated with a double hike in the clean energy adjustment costs. Hence, low ambitions in climate policy would lead to a spike in clean energy capital adjustment costs within the next 30 years. The increase in climate ambitions could prevent the first clean adjustment cost spike but comes at an increased cost in terms of clean energy adjustment costs initially. The costs are higher since with more climate ambitions most of the clean capital accumulation takes place when the clean energy technology still has not caught up.

In general, the clean energy capital stock declines as soon as the clean energy technology as caught up and less energy capital is able to provide the same service (amount of energy) to/ for the economy.

Figure 5 shows how the policies lean on energy and technologies differently. Panel 1 shows the optimal dirty energy tax necessary to implement the corresponding carbon budget in a decentralized economy. Since the STEPS scenario already includes some carbon pricing the

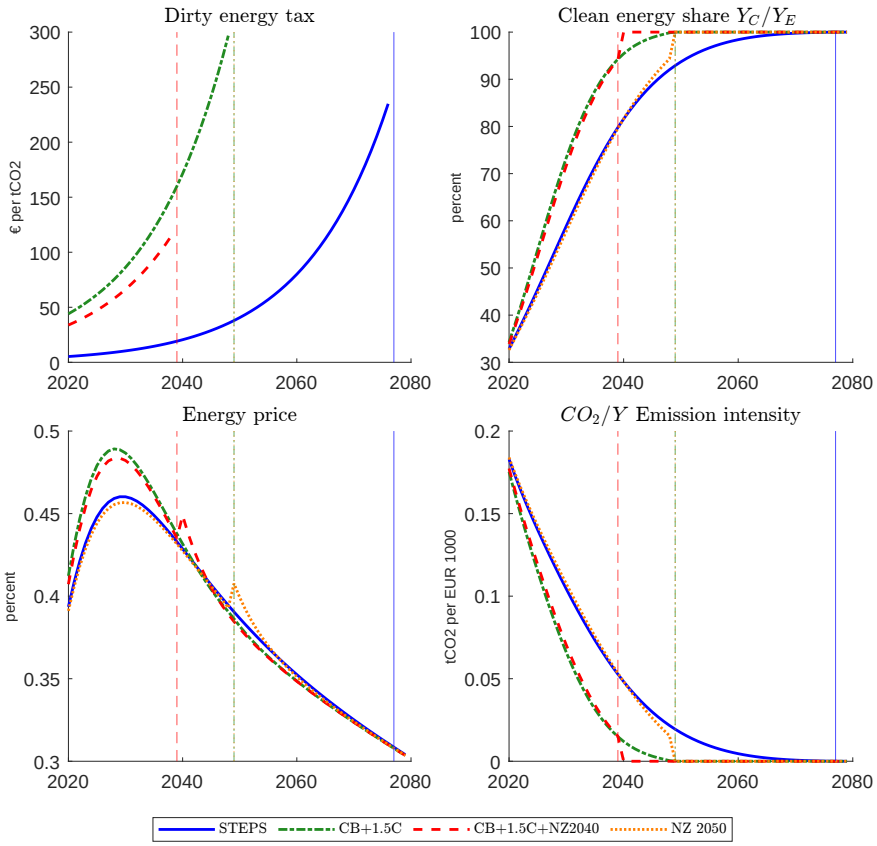


Figure 5: Transition dynamics and costs in the energy sector in the EU

dirty energy tax shown needs to be interpreted as an additional dirty energy tax, additional in terms of carbon pricing already included in the STEPS scenario. [8]

The more stringent climate policy scenario of the carbon budget 2050 requires a much stronger price signal than in STEPS. If a net zero constraint is added the pricing signal can be weaker because the quantity constraint pushes down the use of dirty energy as well. However, without reducing the overall amount of emissions used.

The clean energy share increases the steepest in the carbon budget 2050 scenario. However, it does so steadily. Whereas it jumps sharply shortly before the carbon budget constraint becomes binding when the net zero target 2040 is added.

The differences in the energy price mirror the development in the clean energy share of the economy. The energy price increases in the beginning by about 22 percent with more ambitious climate policy (CB+1.5C) implemented using carbon pricing. Since with net zero targets the dirty capital is used more intensively initially, the price hike is muted in the in the beginning. However, with net zero targets energy prices spike sharply shortly before the net zero target becomes binding.

The emission intensity of output declines in all scenarios but stronger the when ambitions are increased (CB+1.5C). Adding a NZ constraint leads to increased use of dirty energy

[8] For a discussion on the interpretation of the carbon price in our model see 4.2.

initially and hence an increased emission intensity in order to use the whole carbon budget of 26 $GtCO_2$. This is due to the model set up which does not allow for additional emission reductions when adding a net zero target. Figure 6 shows the compositional shift of the

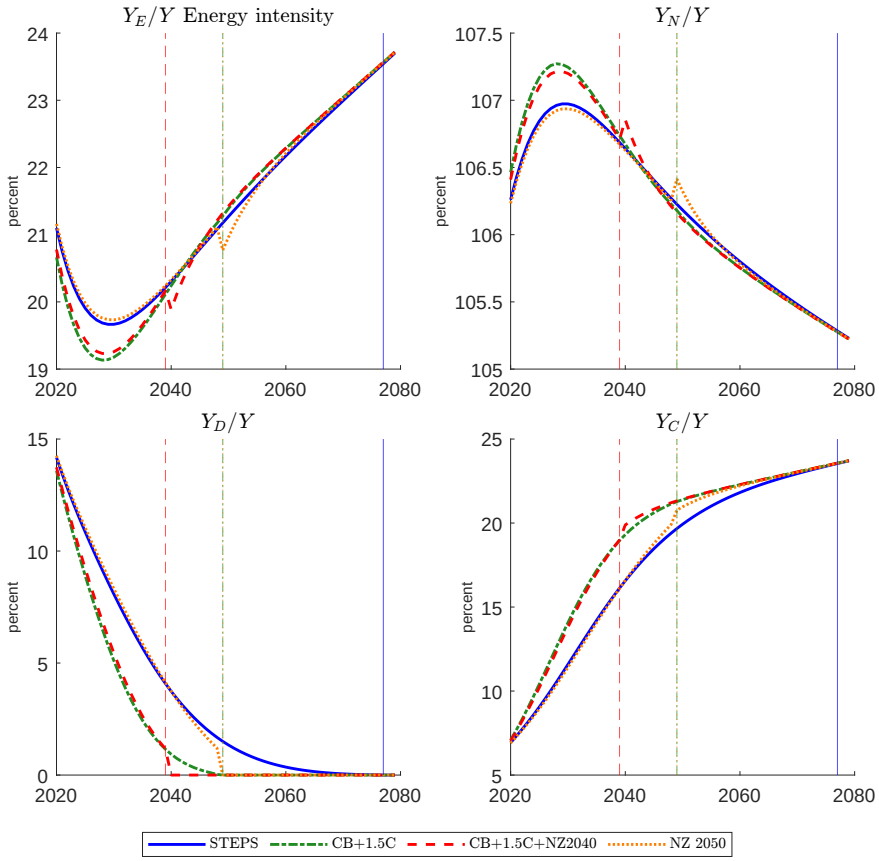


Figure 6: Compositional shifts in the sector shares in the EU

economy. Panel 1 shows that the energy intensity of the economy is lowest with the carbon budget 2050 policy. The carbon budget 2050 scenario shows the strongest increase in the production of non-energy sector. This is the case despite that stricter climate policy crowds out some investment in that sector. The production of non-energy rises because stricter climate policy leads to higher labor shares in the non energy sector compared to looser climate policy (see Figure 3.) The non-energy increases the most since the CB+1.5C scenario requires a more early switch to the clean technology. The more early the switch takes place the higher the productivity differences between the clean and the dirty energy technology. Hence, the technology disadvantage kicks in stronger the more early the transition takes place. Therefore, dirty energy production is crowded out stronger by non-energy production.

With the carbon budget 2050 scenario the share of dirty energy declines and the clean technology share increases fastest. Net zero targets make it optimal to delay the shifts from Y_D to Y_C in the beginning and make it necessary and optimal to rapidly change from dirty to clean shortly before the net zero target becomes binding.

Key findings. Several key findings stand out for the EU. First, looser climate policy allows to benefit from the initial technological advantage of dirty energy whereas ambitious climate policy forces the economy to forgo this advantage causing a small growth decline. Hence, there is a trade-off between taking advantage of the dirty productivity advantage in and reaching 1.5 degree. This severity of this trade-off is determined by the assumed type of technological progress (exogenous, learning by doing or embodied) as shown in Burda et al. (2024).

Second, no further climate policy action as in the baseline scenario might cause the clean capital stock to depreciate by about 2 percentage points since the initial dirty technology advantage makes it optimal to not keep the clean capital stock constant while the productivity disadvantage is most severe. This causes a small double transition of the clean energy capital stocks and comes in terms of two phases with increased clean adjustment costs.

Third, due to the higher capital intensity of clean energy transitioning to a clean energy system means that the share of investment in the energy sector is permanently higher by about 360 percent (or 2.75 percentage points in terms of GDP). This causes a crowding out of non-energy investment which drops by 3 percent (0.7-0.8 percentage points) until 2040 and stabilizes in the long term at a decrease of about 1 percent less non-energy investment before the transition in 2020. Nevertheless, non-energy production even increases due to elevated amounts of labor in the non-energy sector compared to looser climate policy.

5.2 India

For India we do a similar analysis as for the EU, however the scenarios differ in their stringency. India's stated net zero pledge is for 2070. For sensitivity analysis in the case of India, we consider what happens when the STEPS carbon budget is combined with the stated net zero target, while requiring the carbon budget to bind, as a way to compare cost-effectiveness consistently. In our primary calibration, this can drive carbon prices slightly negative. However, with higher adjustment cost parameters, the carbon budget binds earlier, and dirty energy is phased out before the net zero target.

The solid blue line shows the baseline transition scenario where the social planner can use a carbon budget of 104.8 $GtCO_2e$ for energy related use. This carbon budget aligns with the policies and actions already implemented (see scetion B.1 for the calculation of the carbon budget). The red dashed line shows a scenario with a more stringent carbon budget of 43 $GtCO_2e$ for energy related use which would be optimally depleted by 2050. So in 2050 there would not be any dirty energy production in the economy. A smaller carbon budget is associated with a higher carbon price. The orange dotted line shows the scenario (CB 2050) with a energy related carbon budget of 43 $GtCO_2e$ with an additional net zero requirement

India Scenarios	**Phase-out year**	**Carbon budget**	**CO_2 Price 2020**	**Δ Welfare during transition**	**Stranded assets**	**Avg. adj. costs**
		$GtCO_2e$	\$/ton	% ch. rel. to STEPS	$K_D(\bar{T})$ $/Y(\bar{T})$	avg. Ω/Y to 2080
CBSTEPS	2107	104	0.03	0	0	0.28
CBSTEPS+NZ2070	2070	104	-0.09	-0.02	0.53	0.28
NZ2050	2050	70	0	-0.03	2.02	0.31
CB+1.5C	2050	43	3.42	-0.02	0.57	0.33
CB+1.5C+NZ2040	2040	43	1.56	-0.06	3.72	0.34

Table 4: Welfare comparison between transition scenarios in India

by 2040. The vertical lines show again the date when the carbon budget becomes binding in each scenario.

Figure 7 shows some overall economic indicators describing the transition paths of the different policy scenarios. The result standing out the most is that the GDP growth rate is basically the same for all three scenarios. The more stringent climate policy (red dashed) including carbon pricing does not cause a decline in the growth rate. Only the additional net zero constraint by 2040 causes a dip in the growth path shortly before it becomes binding. The growth path is declining which is a common prediction for an emerging economy like India. However, the more stringent climate policy causes a dip in consumption. The biggest difference between the scenarios is in the usage of emissions. The use of annual emissions increases substantially until 2030 in the baseline scenario (blue). Overall adjustment costs are lowest in the baseline scenario but only slightly.

In contrast to the EU there is no initial growth dip due to more stringent climate policy but the dip in consumption is about the same in percentage points (~ 0.4). The biggest difference between the EU and India is that the capital output ratio is falling in the EU whereas in India it is increasing equally in all policy scenarios. This is due to the different stages of development. Adjustment costs start off much higher in India in all three scenarios and are much more similar across scenarios than in the EU. This is the case since the overall capital stock is growing in all policy scenario about the same.

Figure 8 shows the transition paths of the production factors capital and labor in the three different sectors. Most development in the sectoral capital stocks and labor employment are similar to the EU in three aspects. First, similar to the EU, Panel 1 shows that the dirty capital stock declines and the clean energy capital stock accumulated more rapid the more stringent the climate policy. Second, dirty capital that is left in the economy after the

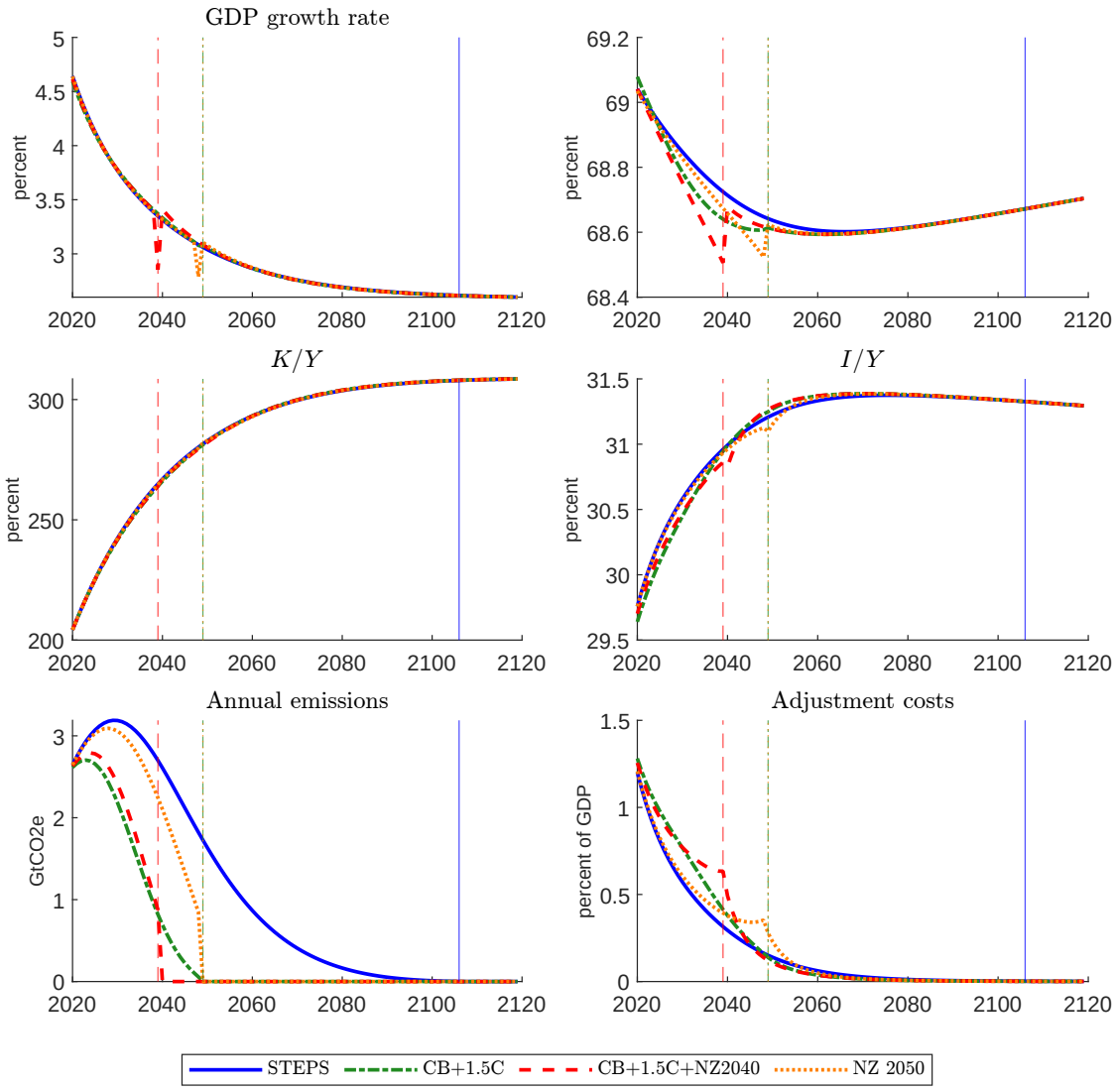


Figure 7: Overall Economic Indicators in India

dirty energy has been phased out (vertical line) is stranded. In India stricter climate policy results as well in an increased amount of stranded assets in the economy which increases even further with a net zero targets. Third, more stringent climate policy causes dirty labor to decline faster and even more abrupt with a net zero target and clean labor to rise faster.

The EU and India differ in two aspects. First, there is no clean decommissioning of the clean capital stock since India needs to provide for the growing energy demand of its economy and even with no climate policy it cannot afford loosing any energy production capacity. Second, India differs with respect to the use of non-energy labor. In the EU non-energy labor is pulled into the clean energy sector in contrast in India the clean energy sector does not need any additional labor from the non-energy sector. Therefore, the share in the non-energy labor force increases steadily throughout the transition and very similar in all scenarios.

Figure 9 shows the sectoral dynamics of investment, adjustment costs and the capital

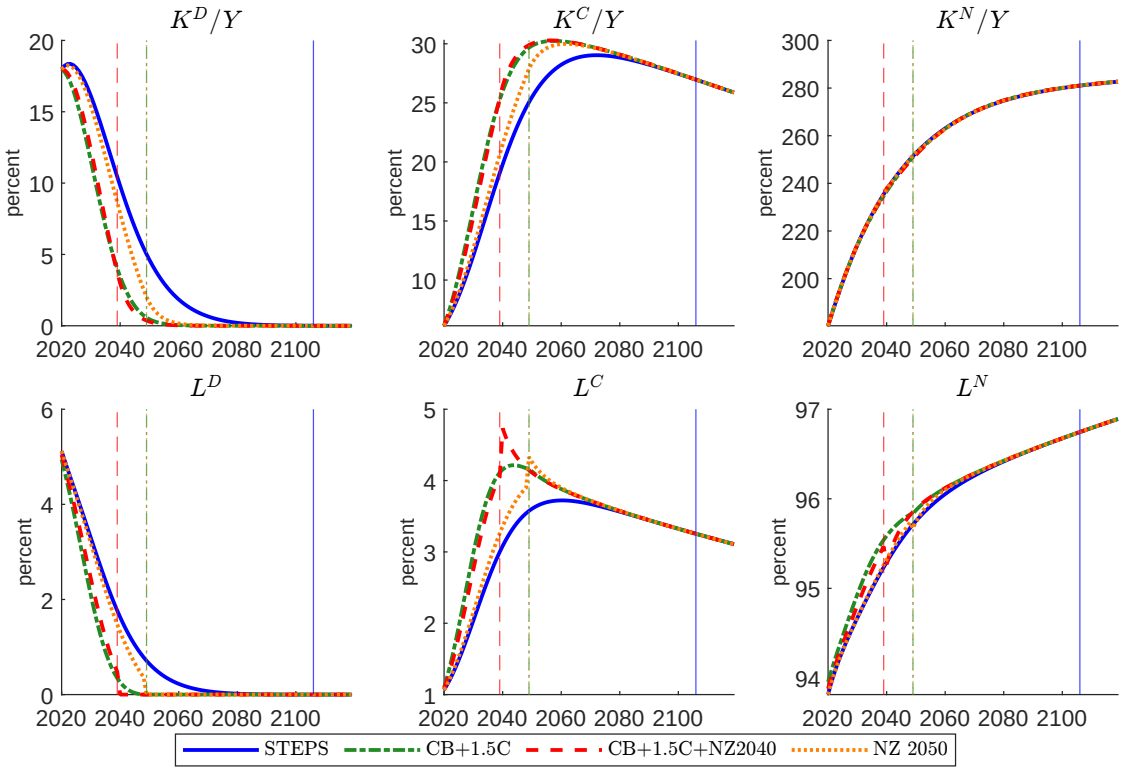


Figure 8: Factor allocation in India

stocks. The development of sectoral investment displayed in the first row shows similar dynamics to the EU. Dirty energy investment declines and clean energy investment increase and more ambitious climate policy enhances both dynamics.

However, the initial level of dirty energy investment is much higher and the initial level of clean energy investment is much lower than in the EU. In contrast to the EU, in India there is less dirty disinvestment with more stringent climate policy and their investment in non-energy increases whereas the non-energy investment declines in the EU. The non-energy sector is growing more in India due to the overall higher growth rates and higher capital accumulation in India. Part of the Indian growth is due to the increased capital accumulation typical for an emerging economy. They likely increase the intensity of dirty energy capital since they need all energy sources.

The second row of Figure 9 shows the adjustment costs split along sectoral lines. The dynamics of the sectoral adjustment costs show more differences between India and the EU. The dirty energy adjustment costs are in general lower for India with more ambitious climate policy in the beginning than in the baseline scenario. However, there is a double hike in adjustment costs for the dirty energy sector within the next sixty years in all three scenarios. The first hike is caused by the short period when the dirty capital stock increases initially. The second spike is due to costly depreciation and slight disinvestment of dirty capital stock. Clean energy capital adjustment costs are much higher for India in the case

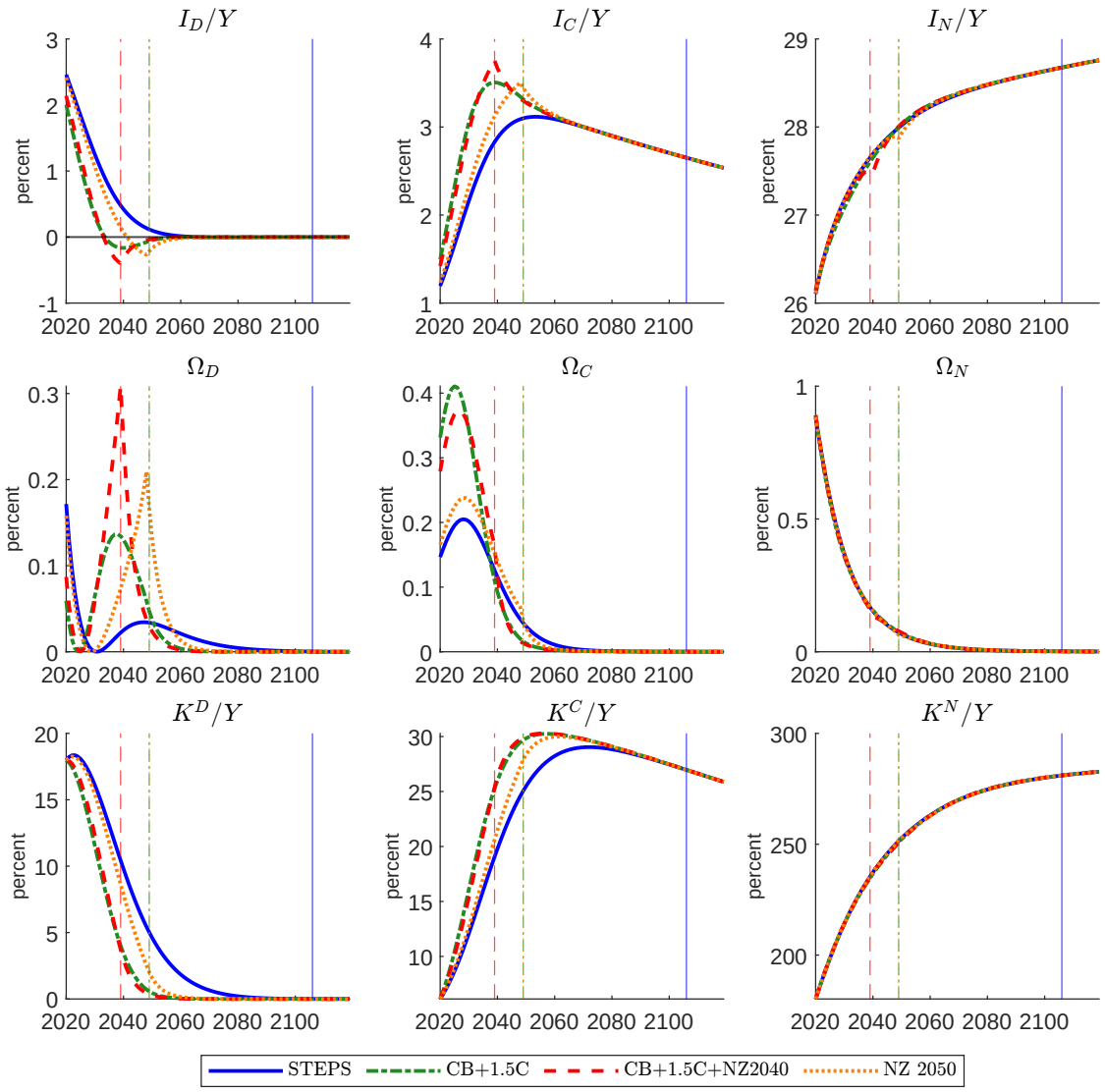


Figure 9: Investment and adjustment costs in India

of more ambitious climate policy.

In the baseline (solid blue) scenario the accumulation of the clean energy capital stock and its associated capital adjustment costs occur long before the carbon budget becomes binding $\sim$ 2100. The clean capital accumulation starts immediately and most of the clean capital accumulation occurs during the time when there still exists a dirty energy advantage. The difference in terms of clean capital accumulation that more ambitious climate policy can make is much smaller than in the case of the EU. The reason is that India has to meet the growing energy demand and has to increase its energy related capital stocks in any case. Forward looking agents in the model realize that setting up the clean capital stock immediately will be cheaper than building more dirty energy capital and wait with the build up of the clean capital stock until the carbon budget constraint becomes more binding. Building up dirty energy capital stocks, decommission them and rebuild it clean

would be a very inefficient strategy in terms of capital adjustment costs.

However, more ambitious climate policy (red and orange) cause elevated clean energy capital adjustment costs because more clean energy capital needs to be accumulated during a time when clean energy technology has not caught up with the dirty energy technology.

Since the investment into the non-energy sector does not differ across scenarios the non-energy capital adjustment costs do not differ across scenarios either. The non-energy capital adjustment costs have a convex shape because they mirror the concave non-energy investment pattern. With adjustment costs on net investment, elevated new investment leads to high adjustment costs and adjustment costs decrease with declining rates of new investment. Figure 10 shows how the policies affect the energy sector and technologies differently. Panel

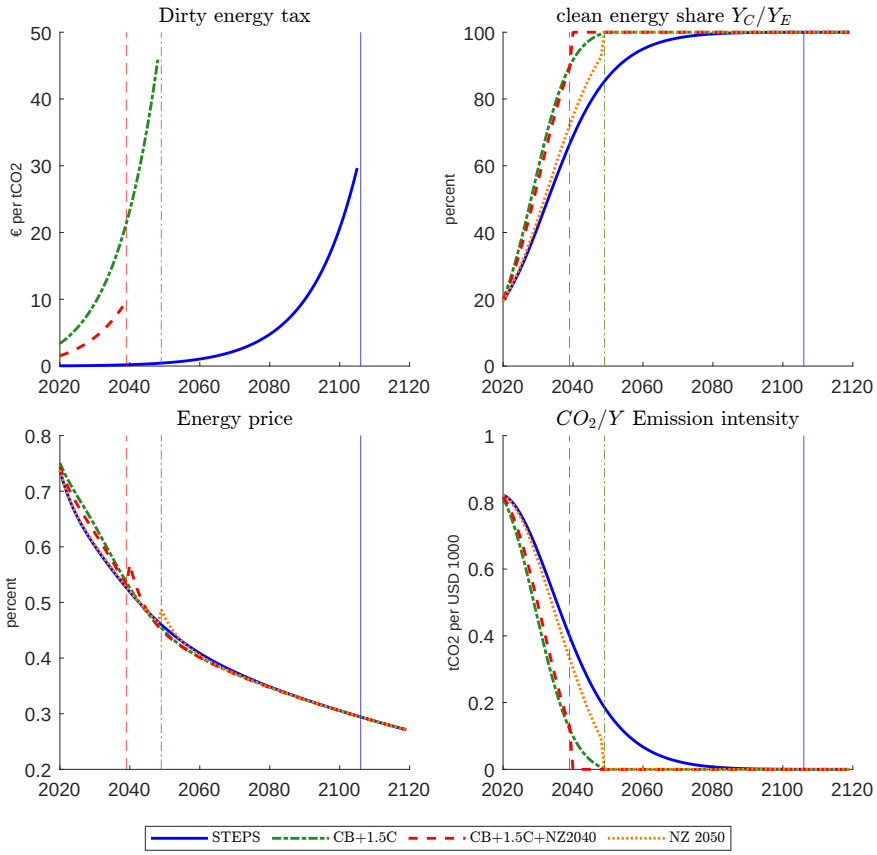


Figure 10: Transition dynamics and costs in the energy sector in India

1 shows the optimal dirty energy tax necessary to implement the corresponding carbon budget in a decentralized economy. Similar to the a EU case, a more stringent climate policy (red) needs a stronger pricing signal compared to the baseline scenario (blue). However, the carbon price needed in India is much lower than in the EU.

When a net zero constraint is included the necessary carbon price is reduced and partly substituted by a sharp phase out date. This explains the lower carbon price in the case when the carbon budget 2050 is topped up by a net zero target 2040. In terms of the development of the clean energy share in the baseline scenario India reaches a clean energy of $\sim$ 100

percent by 2080 whereas the EU reaches it in 2060. However, India reaches it much earlier than its phase out date. Decommissioning the last small fraction of dirty capital requires a high carbon tax.

In contrast to the EU, more ambitious climate policy does not lead to significant energy price increases. On the contrary, energy prices decline steadily. Energy emission intensity is more pronounced in India then in the EU but declines steadily. Figure 11 shows the

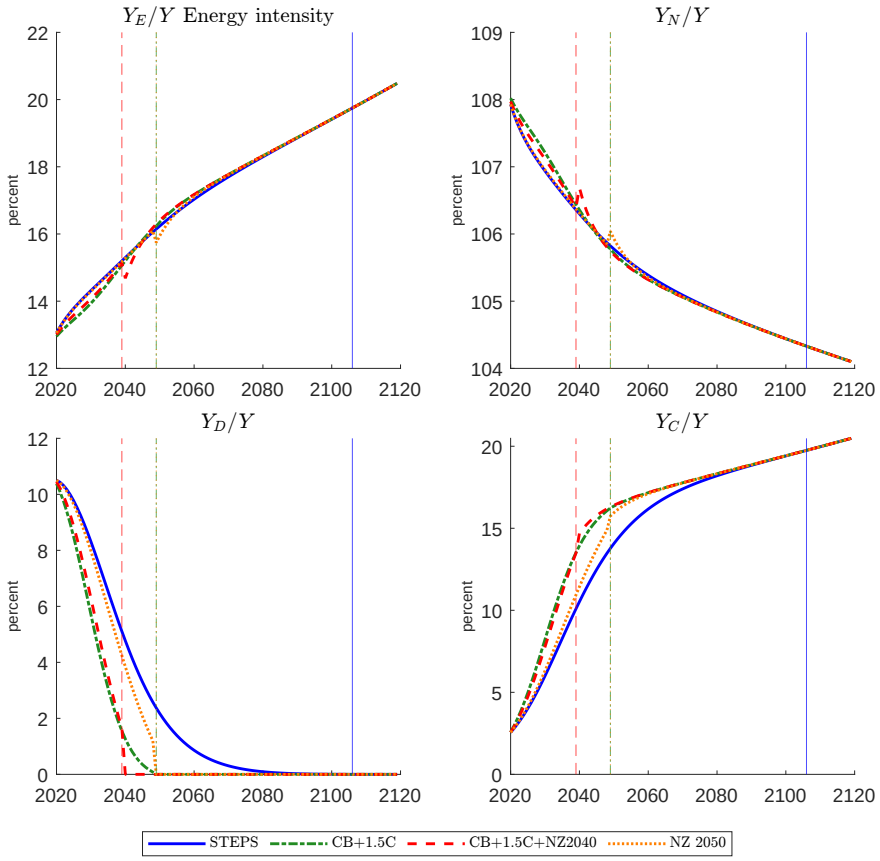


Figure 11: Compositional shifts in the sector shares in India

compositional shift of the economy. In contrast to the EU, the energy intensity of the Indian economy does not decline with more ambitious climate policy and there is no big increase in the share of the non-energy sector in overall GDP. Both economies show a similar behavior in terms of the development in the energy sector composition. The share of dirty energy production declines steadily and the share of clean energy increases. The shift from dirty to clean is more pronounced if climate policy is more ambitious.

Key findings. For a developing economy context as exemplified by the India parameterization, several different results stand out. First, most of the transition in the clean energy capital stock happens long before the carbon budget becomes binding in order to avoid a costly double transition of the energy capital stocks. Second, more ambitious climate policy can prevent the initial increase in the dirty energy capital stock and reduces emissions

drastically but comes at the cost of higher clean energy adjustment costs since more clean energy capital needs to be accumulated at a time when the clean energy technology has not caught up. Third, given the STEPS scenarios and trajectories, for India to pursue more ambitious climate policy does not affect its overall GDP growth rate, whereas in the EU it causes a small dip in growth. Aggregate consumption experiences a slight dip in both cases, since the whole economy becomes more capital intensive.

There are five key differences between the EU and India include. First, in the EU non-energy labor is pulled into the clean energy sector in contrast in India the clean energy sector does not need any additional labor from the non-energy sector. Second, in the EU the stated policy scenario causes a decrease in the already existing clean capital stock. [9]

Third, there are overall higher clean capital adjustment costs and non-energy adjustment costs for India. This is due to the fact that India is growing its energy but also its overall capital stock. Fourth, ambitious climate policies do not increase energy prices in India but they do increase energy prices in the EU. Fifth, the energy intensity of the Indian economy is almost unaffected by more ambitious climate policy. In contrast, climate ambitions lead to a lower energy intensity of the economy in the EU and more production capacity is shifted from dirty energy production to the non-energy sector.

6 Sensitivity Analysis: The Role of Adjustment Costs

Adjustment costs are key to the transition path and for our modeling strategy of an endogenously evolving elasticity of substitution between clean and dirty energy. Therefore this section investigates their role in more detail providing sensitivity checks for the transition path of the EU and India with respect to different functional forms and the effect of the size of adjustment costs.

The effect of the functional form of adjustment costs For the results in section 5 we use adjustment costs on net investment. Adjustment costs on net investment imply that investment in new capital $(K_{it} - K_{it-1})$ incur adjustment costs but replacement investment (δK_{it}) is free. However, depreciation is costly. Using adjustment costs on gross investment $\Omega = \frac{c}{2}\left(\frac{I_{it}}{K_{it-1}}\right)^2 K_{it-1}$ implies that replacement investment, and investment in new capital incur adjustment costs. Groth et al. 2006 argue that there is no clear distinction between replacement and other investment, as machines are rarely replaced at a one-for-one basis. Moreover, in an environment of rapid technological progress, new technology is embodied in

[9] Clean energy investment is not high enough to replace the depreciating clean capital stock. This could be a calibration problem because I cannot increase the initial clean energy investment share. A solution might be to increase clean capital share (decrease α_C).

new capital goods. However, depreciation of the capital stock does not incur any adjustment costs, hence it is cheaper to decommission capital than in the case of adjustment costs on net investment where depreciation incurs adjustment costs.

To make the results between net and gross adjustment costs comparable for the EU, we try to match the initial empirical targets with the gross adjustment costs as well. Since, gross adjustment costs imply adjustment costs for replacement investment, they incur higher total adjustment costs overall. Hence to match the empirical target we need to lower the adjustment cost parameter to $c_i = 1$.[10]

The effect of the size of adjustment costs. The other important feature impacting the transition path of an economy is the size of the adjustment cost parameter. Estimates of the adjustment cost parameter vary widely, depending on the method used. Hall (2004) uses Euler equations and finds a small value of 0.1, while studies using Tobin's Q models often estimate much larger values around 20 and up to 50 (see Gilchrist and Himmelberg (1995), Galeotti et al. (1994)). Econometric models using fundamental Tobin's Q find values closer to 5 Bontempi et al. (2004). DSGE models calibrated or estimated to match business cycle fluctuations in investment typically yield values between the extremes (for example, Garcia-Cicco, Pancrazi and Uribe, 2010). In choosing $c_i = 5$ we follow Bontempi et al. (2004) who find this value using adjustment costs on net investment into structures. We argue that this estimate is closest related to the investments into structures necessary for the net zero energy transition. Because of the lack of agreement over this parameter, we do robustness checks varying the adjustment cost parameter. As a high adjustment cost parameter, we choose $c_i = 20$, which is commonly used in the literature Hall (2004).

6.1 Adjustment Costs and the Net Zero Transition in the EU

Figure 12 highlights the impact on the EU's transition path of different functional forms and sizes of adjustment costs on sectoral investment, adjustment costs and capital stock dynamics.

Figure 12 shows the carbon budget 2050 in three variations. The straight blue line shows the baseline STEPS scenario with adjustment costs on net investment with a adjustment cost parameter of size $c_i = 5$, the blue dot dashed line shows the STEPS scenario with higher adjustment costs ($c_i = 20$), and the dotted blue line shows the STEPS scenario with gross adjustment costs of size $c_i = 1$.

The orange lines show the carbon budget 2050 with NZ 2040 scenario with baseline (adjustment costs on net investment) (orange straight line), with high adjustment costs

[10] Lowering it much further is not compatible with our model.

where $c_i = 20$ (orange dot dashed) and adjustment costs on gross investment of size $c_i = 1$ (dotted orange line).

With respect to investment dynamics the first row of figure 12 shows that gross adjustment costs lead to an initially higher level of dirty disinvestment and lower clean investment. However, the overall investment dynamics in the energy sector stay the same with both forms of adjustment costs. In the non-energy sector gross adjustment costs lead to a significantly lower level of investment.

With respect to capital stock dynamics the third row of figure 12 shows that dirty capital declines more slowly with high net adjustment costs, which incur adjustment costs on disinvestment as well as depreciation. Dirty capital declines more rapidly with gross adjustment costs, which does not incur costs on depreciation. Higher adjustment costs lead to more stranding of dirty capital. Clean capital accumulates rapidly except for an initial dip with gross adjustment costs. Higher adjustment costs lead to a lower accumulation of clean capital until 2070. Penalizing replacement investment when using gross adjustment costs, causes the overall size ot the capital stock in the non energy sector to shrink starkly until the end of the simulation period.

Figure 12 indicates that the functional form of adjustment costs largely determines in which sector the majority of the adjustment costs occur. With gross adjustment costs most of the costs occur in the non energy sector which has the largest capital stock and hence incurs large replacement investment costs but comparatively low adjustment costs in the dirty energy sector. In the clean energy sector both gross adjustment costs and higher adjustment costs incur higher sectoral adjustment costs. The clean energy capital stock still needs to be expanded hence it requires mostly new investment. Since gross adjustment cost penalize replacement investment as well they cause an additional increase in the adjustment costs of the clean energy sector.

However, the biggest cost increase in both energy sectors is caused by higher net adjustment costs. For the non-energy sector the implication of costly replacement investment makes an enormous difference in the size of overall sectoral adjustment costs. Dirty adjustment costs increase with climate policy ambitions due to more disinvestment/underreplacement, except with gross adjustment costs, which allow for more disinvestment (costless depreciation).

Figure 13 shows that during the transition with adjustment costs on gross investment or higher adjustment costs on net investment have detrimental impacts on the growth rate. Nevertheless, in the long term growth dynamics are not affected by the size or the functional form of the adjustment costs.

6.2 Welfare Comparisons EU

Table 3 provides a summary of all scenarios considered and shows their outcome with respect to the fossil phase out year, the carbon budget remaining until the fossil phase out and the welfare change during the transition until 2060 in percent relative to the reference scenario STEPS as well as to the STEPS sensitivity scenario. Welfare is determined by the percentage variation in consumption between 2020 and 2060 that would compensate the agent in any other scenario compared to living in the STEPS scenario. [11] Column 5 of Table 3 shows the amount of stranded assets remaining in the economy in the year when fossil energy is phased out. And the last column shows the average annual adjustment costs as a share of GDP until 2060. The carbon budget for the CBCAT scenario is backed out by the emission projections of the climate action tracker (for details of the construction see below B).

EU Scenarios	**Phase-out year**	**Carbon budget**	**CO_2 Price 2020**	**Δ Welfare during transition**		**Stranded assets**	**Avg. adj. costs**
		$GtCO_2e$	€/ton	% ch. rel. to STEPS Reference	Sensitivity	$K_D(\bar{T})$ $/Y(\bar{T})$	avg. Ω/Y to 2060
CBSTEPS	2078	48	5.26	0	0	0.04	0.13
CBSTEPS Ω^h	2056	48	30.75	-1.30	0	3.33	0.32
CBSTEPS Ω^g	2158	48	-0.05	-9.14	0	0.13	1.32
CB+1.5C	2050	26	44.05	-0.12	0	0.47	0.22
CB+1.5C Ω^h	2042	26	97.30	-1.82	-0.52	6.88	0.46
CB+1.5C Ω^g	2078	26	4.81	-9.12	0.02	0	1.32
CB+1.5C+NZ2040	2040	26	33.84	-0.14	0	3.19	0.23
CB+1.5C+NZ2040 Ω^h	2040	26	96.68	-1.82	-0.52	8.30	0.46
CB+1.5C+NZ2040 Ω^g	2040	26	-0.29	-9.14	0	1.09	1.33
NZ2050	2050	43	0	-0.05	0	2.01	0.16
NZ2050 Ω^h	2050	57	0	-1.35	-0.05	6.97	0.29
NZ2050 Ω^g	2050	29	0	-9.13	0.01	0.09	1.32

Table 5: Welfare comparison between transition scenarios in the EU

With respect to the functional form of adjustment costs we find that among all STEPS scenarios adjustment costs on gross investment the net zero transition are most costly in terms of welfare (-9.14 percent) and average adjustment costs (1.32 percent). However, adjustment costs mainly occur in the non-energy sector and are less severe for the transformation of the energy capital stocks. Since adjustment costs cause consumption to deteriorate

[11] For details of the calculation of transitional welfare see Appendix B.

this leads to high welfare losses. The reason for this result is that there has been higher dirty disinvestment and costless depreciation of dirty energy capital until the phase out date. Since the dirty capital stock is built back mainly by costless depreciation the carbon price necessary to implement the optimal path in a decentralized economy is even negative (-0.05 EUR) compared to 5.26 EUR with adjustment costs on net investment in the baseline scenario (CBSTEPS).

When comparing the optimal path of using the same carbon budget like in STEPS but facing higher adjustment costs (STEPS Ω^h) the phase out of dirty energy optimally happens even earlier in 2056 instead of in 2078 and the additional carbon price necessary to implement the STEPS carbon budget increases substantially (six fold to 30.75 EUR per ton). The welfare loss is much lower than with gross adjustment costs however still large with -1.3 percent. The same holds for average annual adjustment costs. Average annual adjustment costs are still lower than with gross adjustment but increase to on average 0.32 percent of GDP. However, in the case of high net adjustment costs most of the adjustment costs occur in the energy sector. Increased adjustment costs lead to the most detrimental outcome in terms of stranded assets, which make up to 3.33 percent when dirty energy needs to be phased out.

Higher climate policy ambitions (CB+1.5C) increases the welfare loss with respect to STEPS (baseline) by 0.12 percent and the amount of stranded assets increases to (0.47 percent). However, comparatively the losses are much smaller compared to the STEPS with higher adjustment costs scenario. The average adjustment costs increase as well with climate policy ambitions (0.22 percent of GDP), which is still less than in the STEPS scenarios with higher adjustment costs on net investment and adjustment costs on gross investment. Nevertheless, the more ambitious climate policy would require a much higher additional carbon price of 44 EUR per ton. Hence, the biggest detrimental effect of increased climate ambitions would be the increased energy costs as Figure 5 shows.

Combining higher climate ambitions with higher adjustment costs on net investment or adjustment costs on gross adjustment has similar and even stronger detrimental effects on all criteria.

When adding a more ambitious phase out date of 2040 to the 2050 budget the loss in welfare (-0.14 percent) and the increase in average adjustment costs (0.23 percent) are rather small. However, the amount of stranded assets increases rather strongly by about 3 percentage points.

6.3 Adjustment Costs and the Net Zero Transition in India

Figure 14 analyzes the impact of higher adjustment costs on sectoral investment, adjustment costs dynamics and the sectoral accumulation of capital stocks as well as the overall growth rate (Figure 15) in India. Both figures display the three scenarios investigated in the main results section and add higher adjustment costs ($c_i = 20$).

The main effect of higher adjustment costs on dirty and clean investment is that they slow down the decline (dirty) and the increase (clean) investment. For non-energy investment they lower the overall level of investment.

In terms of adjustment costs higher adjustment costs increase all sectoral adjustment costs. The higher adjustment costs inhibit the initial increase in the dirty energy capital stock and lower the overall amount of clean energy and non-energy capital in the economy. The vertical lines indicating when the carbon budget is depleted show that the carbon budget becomes binding much earlier since the decommissiong of the dirty energy capital stock is slowed down due to the high costs associated. This leads to an increased amount of stranded assets in all cases.

The overall growth rate of the economy is significantly lower with high adjustment costs (Figure 15) . Overall, the size of adjustment costs does not change the shape of the transitional dynamics but increases the costs of transition in terms of adjustment costs, lower growth, and more stranded assets.

6.4 Welfare Comparisons India

Similar to the EU table, 4 provides a summary of all scenarios in India considered and shows their outcome with respect to the fossil phase out year, the carbon budget remaining until the fossil phase out and the welfare change during the transition until 2080 in percent relative to the reference scenario STEPS as well as to the STEPS sensitivity scenario. Welfare is determined by the percentage variation in consumption between 2020 and 2060 that would compensate the agent in any other scenario compared to living in the STEPS scenario.[12] Column 5 of Table 4 shows the amount of stranded assets remaining in the economy in the year when fossil energy is phased out. And the last column shows the average annual adjustment costs as a share of GDP until 2080. The carbon budget for the CBCAT scenario is backed out by the emission projections of the climate action tracker (for details of the construction see below B).

Overall, table 4 shows that higher climate ambitions (CB 2050 and CB 2050+NZ2040) lead to a small welfare loss, increased stranded assets and adjustment costs. However, the more substantial losses in welfare, stranded asstets and average adjustment costs are asso-

[12]For details of the calculation of transitional welfare see Appendix B.

India Scenarios	Phase-out year	Carbon budget	CO_2 Price 2020	Δ Welfare during transition		Stranded assets	Avg. adj. costs
		$GtCO_2e$	\$/ton	% ch. rel. to STEPS Reference	% ch. rel. to STEPS Sensitivity	$K_D(\bar{T})/Y(\bar{T})$	avg. Ω/Y to 2080
CBSTEPS	2107	104	0.03	0	0	0	0.28
CBSTEPS Ω^h	2067	104	1.07	-4.96	0	1.81	0.69
CBSTEPS+NZ2070	2070	104	-0.09	-0.02	0	0.53	0.28
CBSTEPS+NZ2070 Ω^h	2067	104	1.07	-4.96	0	1.81	0.69
CB+1.5C	2050	43	3.42	-0.02	0	0.57	0.33
CB+1.5C Ω^h	2045	43	8.62	-5.22	-0.26	3.92	0.77
CB+1.5C+NZ2040	2040	43	1.56	-0.06	0	3.72	0.34
CB+1.5C+NZ2040	2040	43	6.34	-5.26	-0.30	6.33	0.78
NZ2050	2050	70	0	-0.03	0	2.02	0.31
NZ2050 Ω^h	2050	81	0	-5.12	-0.16	5.36	0.73

Table 6: Welfare comparison between transition scenarios in India

ciated with higher adjustment costs similar to the EU. Higher adjustment costs also require a higher initial carbon price to implement the social planner solution in a decentralized economy.

Overall, all functional forms of adjustment costs indicate that a quick adjustment of the capital stocks is expensive but the the transition dynamics in the energy sector are not affected by the choice of the functional form. However, the size and the functional form of adjustment costs have three main impacts.

First, higher capital adjustment costs increase the amount of stranded assets and the negative welfare impact more substantially than climate policy ambitions. Second, the functional form of adjustment costs determines in which sector the majority of the adjustment costs occur (energy sector or non-energy sector). Adjustment costs on gross investment imply adjustment costs for replacement investment and thus do affect the long run. Penalizing replacement investment in case of adjustment costs on gross investment affects strongest the non-energy sector since it has the largest overall capital stock. Therefore, they cause higher total adjustment costs in general and cause welfare impacts to deteriorate. With adjustment costs on gross investment depreciation can be done for free, therefore the decommissioning of the dirty capital stock does not incur large adjustment costs. Third, adjustment costs on gross investment decrease the necessary carbon tax substantially.

Overall, the size of adjustment costs does not change the shape of the transitional dy-

namics but increases the costs of transition in terms of adjustment costs, lower growth, and more stranded assets. With high adjustment costs carbon budget becomes binding much earlier since the decommissiong of the dirty energy capital stock is slowed down due to the high costs associated.

We choose adjustment costs on net investment for our general results since this formulation ensures that there are no adjustment costs in the long run on replacement investment. This property grants us that our model converges to the unbalanced growth path described in (Acemoglu and Guerrieri, 2008).

7 Conclusion

Our best estimates of the relative costs of clean energy technologies indicate that more ambitious climate policy does not incur a major growth loss, either in developed economy like the EU and even less in an emerging economy like India, which can also avoid costs of a double transition in energy capital stocks. Underestimating adjustment costs has larger implications for business-as-usual welfare than for the incremental costs of greater ambition. Raising the slope of adjustment costs increases the required carbon price to meet the cumulative budget and speeds the phaseout, reducing the incremental cost an overlapping NZE target. The form of adjustment costs matters too: if they are based on gross rather than net investment, stranded assets are less problematic, since dirty capital stock reductions are less costly, and phaseouts can occur more slowly. Greater clarity from the empirical macroeconomics literature on the form and magnitude of adjustment costs would help inform energy transition strategies.

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A Model equations

Preferences. The benchmark scenario considers the choice of a social planner who maximizes the present discounted utility of the representative agent:

$$\sum_{t=1}^{\infty} \beta^{t-1} \frac{C_t^{1-\theta} - 1}{1-\theta}. \tag{3}$$

Here C_t is consumption of the homogeneous output good, β is the discount factor and θ is the inverse of the elasticity of intertemporal substitution.

Production structure. Output is produced by combining intermediate inputs Y_{Nt} and Y_{Et}:

$$Y_t = \left(\gamma Y_{Nt}^{\frac{\epsilon-1}{\epsilon}} + (1-\gamma) Y_{Et}^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}}. \tag{4}$$

The strictly positive parameters γ and ϵ represent the weight on the intermediate input N and the elasticity of substitution between intermediate inputs N and E respectively. Input E can be produced using two different technologies D and C. Their outputs are perfectly substitutable:

$$Y_{Et} = Y_{Dt} + Y_{Ct}. \tag{5}$$

The constant-returns-to-scale production technologies $i \in \{N, D, C\}$ are all of Cobb-Douglas form using capital K_{it-1} and labor L_{it} as inputs:

$$Y_{it} = M_{it} K_{it-1}^{1-\alpha_i} L_{it}^{\alpha_i}.$$

Total factor productivity M_{it} and output elasticity with respect to labor α_i are both technology-specific.

Capital and investment. Capital in each sector obeys a respective accumulation equation:

$$K_{it} = (1 - \delta_i) K_{it-1} + I_{it}, \tag{6}$$

where δ_i is the sector-specific depreciation rate and I_{it} is investment in sector i. In our baseline we assume that adjustment costs occur only on net investment but replacement investment is free. This mean assuming that replacement investment is more routine and therefore less costly than other types of investment. Overall, excess investment below and beyond depreciation and growth incurs adjustment costs. This implies that depreciation is costly as well. In this formulation we follow (Aguiar & Gopinath, 2007)

$$\Omega^i(K_{it}, K_{it-1}) = \frac{c_i}{2} \left(\frac{I_{it}}{K_{it-1}} - \delta_i - z_i \right)^2 K_{it-1} \quad \forall\, i = C, D, N$$

Here z_i is the limit of the growth rate of capital stock K_i as $t \to \infty$. This formulation ensures that adjustment costs do not affect long-run outcomes.

Aggregation. The aggregate resource constraint of this closed economy is:

$$Y_t = C_t + I_t + \Omega_t. \tag{7}$$

Aggregate investment I_t and adjustment costs Ω_t are the sums over the three technologies:

$$I_t = \sum_{i \in \{N,D,C\}} I_{it} \quad \text{and} \quad \Omega_t = \sum_{i \in \{N,D,C\}} \Omega^i(\frac{I_{it}}{K_{it-1}}).$$

The economy is endowed with $\bar{L}$ units of labor, which can be flexibly deployed across the three technologies:

$$\bar{L} = L_{Nt} + L_{Dt} + L_{Ct} \tag{8}$$

Environment. The dirty technology causes greenhouse gas emissions, which accumulate in the atmosphere according to:

$$G_t = G_{t-1} + \mu Y_{Dt},$$

where μY_{Dt} is the flow of emissions at time t and G_t is the stock of accumulated emissions. The parameter μ represents the emissions intensity of dirty energy output. The cumulative carbon budget is $\bar{G}$, measured in $G_t CO_2 e$. In the numerical model, the carbon budget will be scaled such that the constraint is that cumulative emissions, relative to the carbon budget, do not exceed one:

$$\frac{G_T}{\bar{G}} \leq 1$$

and emissions accumulate as follows:

$$\frac{G_t}{\bar{G}} = \frac{G_{t-1}}{\bar{G}} + \frac{\mu}{\bar{G}} Y_{Dt}$$

The parameterization of μ should equate

$$\mu = \frac{E_{2020}}{Y_{2020}} \frac{Y_{2020}}{Y_{D,2020}}$$

where E is annual energy related emissions of $CO_2 e$.

Technological Progress. Total factor productivity of technology i grows at exogenous rate m_i:

$$M_{it} = M_{it-1}(1 + m_i). \tag{9}$$

Because of the different production technologies, growth is unbalanced in this economy. Following Acemoglu and Guerrieri (2008); Burda et al. (2024), we assume that $\frac{m_N}{\alpha_N} < \frac{m_C}{\alpha_C}$ and $\epsilon < 1$. Under these assumptions, the long-run growth path takes the shape described in Section Burda et al. (2024).

Clean catch-up growth. For our baseline scenario we choose the scenario of Burda et al. (2024) including catch-up growth in the clean technology. Many technologies which produce energy without greenhouse gas emissions relatively recent and thus not as mature as conventional energy production technologies. As a result, they are not currently cost

competitive but they improve at much faster rates. As shown in **??** from about 2030 on clean energy has caught up with dirty energy production. However, clean technology does not overtake dirty technology but both technologies stay equally productive until the end of the simulation. We model catch-up growth in a simple manner, by assuming that TFP in the clean sector approaches a long-run path with a constant rate. During the transition the distance to this path shrinks at a constant rate. In particular we define the catch-up factor

$$a_{Ct} = 1 - \frac{b_M}{(1+\kappa_M)^t}$$

where $\lim_{t\to\infty} a_{Ct} \to 1$, κ_M is the catch-up rate and b_M determines the initial distance to the long-run constant-rate growth path. The level of TFP then follows

$$M_{Ct} = a_{Ct}\tilde{M}_{Ct} \tag{10}$$

with

$$\tilde{M}_{Ct} = (1+m_C)\tilde{M}_{Ct-1}.$$

Except for the different exogenous process, the model is identical to the baseline version and all optimality conditions are the same. This economy still approaches the unbalanced growth path. We calibrate the model to the EU and India capturing their different path of clean technological catch up.

B Calculation Details Scenario Comparison Table

B.1 Calculation of the carbon budget in different scenarios

For the overview chart of the different scenarios we calculate the amount of carbon (carbon budget) that is used in the different policy scenarios. The way we back out the carbon budget, taking the EU as an example, is the following. We use Climate Action Tracker data of the average of their scenario "Policies and actions" until 2030. We use linear extrapolation to extend the path of emissions used until 2050. We take the sum of the emissions used in the period between 2020 and 2050. This "Policies and actions" scenario includes all policies a government has implemented or enacted to reduce emissions. We call it the Stated Policy Scenario (STEPS) for the EU the STEPS scenario implies that there is a carbon budget of 58 GtCO2 left until 2050.

We back out the share of energy related emissions which is about 80 percent according to data on historical sectoral emissions (Climate Watch). This leaves an energy related carbon budget of 46 $GtCO_2e$ until 2050 for the EU. For India we do a similar calculation. We take

their STEPS scenario using CAT emissions data projections for the "Policies and actions" until 2030, we use linear extrapolation until 2050 to get an overall emission budget of 139 GtCO2. From this overall emissions we back out the energy emission related STEPS budget. We use sectoral emissions data of Climate Watch. The energy emission share is about 74 percent of total emissions leaving an emission budget of 103 GtCO2. The calculations of the carbon budget of 26.4 GtCO2e optimally depleted by 2040 is approximately in line with calculations in the literature on a carbon budget for Europe that would be in line with achieving 1.5 degrees globally.

Du Robiou Pont et al. (2017) consider five distinct principles of distributive burden sharings of the globally necessary mitigation efforts to reach the 1.5° degree goal globally. We use the average remaining emission budget of the five scenarios (80 GtCO2e for the 1.5° goal and 114 GtCO2e for the 2°goal). Since their remaining budget is for the period from 2010 to 2050 and includes the UK we substract the cumulative emissions (45,2 GtCO2e) of the EU and the UK from 2010-2020 using data from Climate Watch (2023). These modifications leave a carbon budget of 34,8 GtCO2e for the 1.5° goal for overall emissions and when assuming that about 80 percent of emissions that leaves a budget of about 27.5 GtCO2e for energy related emissions.

The following graph shows how the carbon budgets we use relate to the carbon budgets found in the literature.

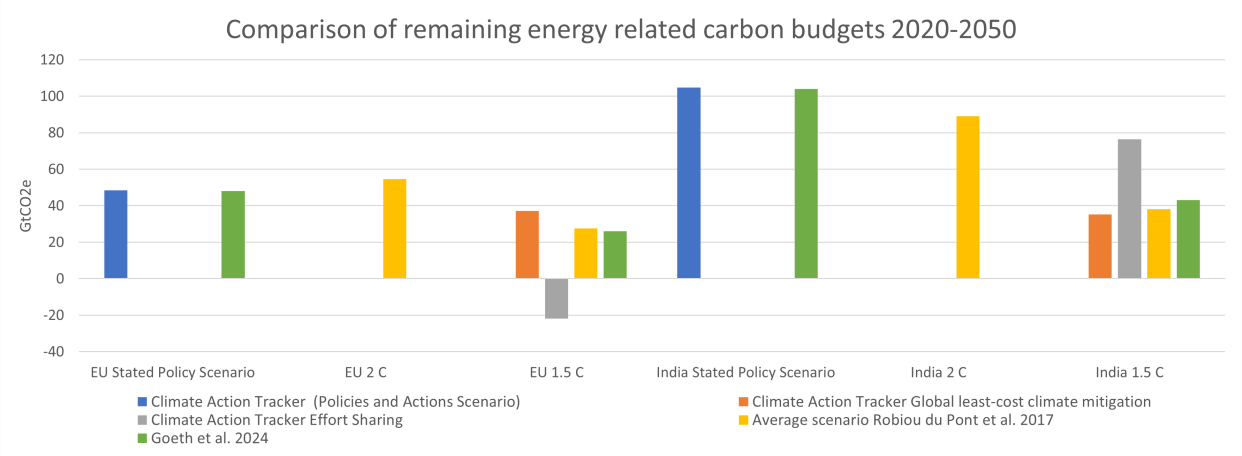


Figure 16: Comparison of remaining energy related carbon budgets 2020-2050 for the EU and India using different sources

B.2 Calculation of energy technology parameters

Overall, we find that in 2021/2022 dirty energy technology is 40% more productive in the EU and 26% more productive in India. Until 2030 the dirty productivity advantage decreases to 9% in the EU and 11% in India. We derive these results by comparing a dominatly used clean and a dominantly used dirty energy technology in four sectors. In the electricity

sector we compare the value adjusted levelized costs of electricity (VALCOE) (USD/MWh) of the different electricity technologies using IEA data on electricity costs in selected regions in the Stated Policies Scenario IEA (2023a).The value-adjusted levelised cost of electricity (VALCOE) incorporates information on both costs and the value provided to the system. Based on the LCOE, estimates of energy, capacity and flexibility value are incorporated to provide a more complete metric of competitiveness for power generation technologies. We take nuclear, solar PV, wind onshore and wind offshore as clean technologies and coal and gas CCGT as dirty technologies. We use the share of each technology in electricity generation to take a weighted average of the VALCOEs within the clean and within the dirty technology cluster. [13] We then compare the two weighted VALCOEs of clean and dirty to get a measure for dirty technology productivity advantage in the electricity generation. In the power generation we find that clean energy technologies are already even more productive in 2021/22. In the EU dirty electricity technology is only 0.57 times as productive as clean electricity generation technology. In India it is about 0.92 as productive as clean electricity. We compare data of the stated policy scenario hence, no additional policy is implemented. In India this leads to the outcome that the productivity of clean electricity technology compared to the dirty electricity technology would worsen until 2030.

For heating we compare the levelized costs of heating of a heat pump and a gas boiler. For 2022 we use data of the IEA (2023b) on the annual unsubsidized costs of clean energy versus conventional options for households in advanced economies in the Stated Policies Scenario (see IEA (2023b) figure 1.22). For the 2030 productivity index we use the data of the European heat pump association predicting that the heat pump cost will decline by 34 percent until 2030 `https://stats.ehpa.org/home/market-conditions/`. Hence, we apply a 34 percent cost reduction to the LCOH of heat pumps in 2030. We assume constant LCOH of gas boilers until 2030. This gives a dirty advantage of 0.78 in 2030. Due to lack of data on India we assume the same dirty advantages for both periods.

For the transportation sector we data on levelized cost of driving of conventional versus electric cars of the National Renewable Energy Laboratory (NREL) on the Transportation Annual Technology Baseline (ATB) Data (2020). Levelized cost of driving are an indicator of the cost of operation over the vehicle lifetime on a per-mile basis. We use their LCOD data on Midsize Light-Duty Vehicles for all different vehicle types available. We consider

[13]For the EU we take data on the electricity generation shares from EU. to split the share of electricity generation between on and offshore wind we use data of IRENA `https://www.irena.org/Energy-Transition/Technology/Wind-energy`. For India we data on EMBER to define the each technology's share in electricity generation `https://ember-climate.org/countries-and-regions/countries/india/`. We use the share in overall electricity generation in 2022 to weigh the different energy sources within clean and dirty for the productivity measure in 2020/21 as well as in 2030. So we assume that the share stays constant.

Gasoline Internal Combustion Engine Vehicle (ICEV) as dirty. [14] We choose the LCOE data of the "Constant Trajectory" for 2020 as well as for 2030. In the Constant trajectory, technology cost and performance from the base year are shown through 2050, without further advancement in R&D or markets. [15] We then take an average of the LCOD in both categories and get a dirty advantage of 1.56 in 2020, assuming no technology breakthroughs, increased public, private R&D investment, and other market conditions the dirty advantage stays the same in the transport sector until 2030.

In the industry sector we compare the production of clean and dirty steel. We base our sectoral dirty productivity advantage estimate on **?** Indicative production costs for crude steel via electrolytic hydrogen-based DRI in selected regions compared to current references.[16] For the calculation of clean steel production cost we use the average cost of variable renewable energy (VRE) and recent grid electricity.[17] For the EU we use the average value for Western Europe. For India, we use the average value of VRE and recent grid electricity of China since India is not considered separately. For the dirty steel production we take the value of 'Current reference'. [18] In 2021 we find a dirty productivity advantage of 2.27 in the EU and a dirty productivity advantage of 1.4 in India. Since the IEA does not show any data for a Stated Policy Scenario we take the values for the VRE APS (Announced Pledges Scenario) scenario for a cost projection of producing clean steel in 2030. We compare it with the current reference scenario assumed to represent production costs of dirty steel in 2030. For 2030 we find a reduction in the dirty productivity advantage to 1.5 in the EU and to 1.1 in India.

[14] We consider as clean the categories of Gasoline Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicles, the Battery Electric Vehicles and the Fuel Cell Electric Vehicles.

[15] This cost level is extended through 2050 for reference only; it does not imply that frozen costs and performance are anticipated. Technology advances include changes that may reduce costs or may increase costs while improving performance, which implies that costs do not always decline between less-advanced and more-advanced scenarios. However, while technology advancements that improve performance may increase vehicle cost, they may also result in a lower levelized cost of driving due to potential fuel savings **?**.`https://atb.nrel.gov/transportation/2020/technologies`.

[16] `https://www.iea.org/data-and-statistics/charts/indicative-production-costs-for-crude-steel-via-el`

[17] The VRE cost range represents electrolysis powered by solar PV, offshore wind or onshore wind. For ammonia and crude steel production, an additional hydrogen storage cost to guarantee a minimum load of 80 percent is considered.

[18] These values show production costs using the dominant incumbent means of production today with unabated fossil fuels. Recent prices for natural gas and grid electricity are used to compute the cost ranges in each region where relevant. The cost of capital is assumed at 5 percent.

	2021/22	2030	2021/22	2030	
	EU		**India**		
Sector	$\frac{M_D}{M_C}$		$\frac{M_D}{M_C}$		Unit of Measurement
Electricity Generation	0.57	0.52	0.89	0.98	VALCOE
Heating	1.19	0.78	1.19	0.78	LCOH
Transportation	1.56	1.56	1.56	1.56	LCOD
Industry (Steel)	2.3	1.5	1.4	1.1	Prod. cost
Average	1.4	1.09	1.26	1.11	

Table 7: Productivity advantage of dirty energy technology (M_D) over clean energy technology (M_C) in several sectors over time.

According to the IEA 2023 **?** the clean technology advantage in the electricity generation for clean in case of net zero compatible climate policies is much larger.

B.3 Welfare measure

As the measure to compare welfare across two scenarios A and B, we use the percentage variation in consumption between 2023 and 2060 that compensates agents in scenario B for living in scenario A permanently, following Burda and Zessner-Spitzenberg (2022). Specifically, we define Λ as

$$\sum_{t=2023}^{2060} \beta^t U\left(\left(1+\frac{\Lambda}{100}\right) C_t^B\right) + \sum_{t=2061}^{2273} \beta^t U(C_t^B) = \sum_{t=2023}^{2273} \beta^t U(C_t^A),$$

where 2273 is the last period in our simulation. The choice of the year 2060 only affects scaling of welfare effects, not their sign. We choose 2060, in order to relate transition costs to consumption during the time the transition occurs. If we were to choose a later point as the cutoff, welfare effects would be scaled down, as losses would be distributed over more periods. Importantly, we include the utility stream after 2060 in the comparison to ensure that differences in capital accumulation up to this point are reflected in the welfare measure. At the end of the simulation horizon, all paths have reached the same terminal capital stocks which makes the comparison meaningful.

By letting the interval on which the variation is computed approach infinity along with the simulation horizon, one recovers the standard measure of welfare in terms of permanent

consumption (see Lucas (1987) for example).

C Calibration Strategy Details

C.1 Externally calibrated parameters

European Union and India We set α_D to 0.35 because the average labor share of the electricity, gas, steam, and air conditioning supply in the EU in 2017 was 29 % (EU KLEMS, 2023). Similarly, Acemoglu and Guerrieri (2008) find a capital share of 77% for mining and utilities. Fried et al. (2022) (AEJ Climate Policy Innovation?) assume a labor share of 0.28 in the fossil energy sector and a labor share of 0.09 for green energy. So the capital share in the green energy sector might be even higher than in the dirty energy sector. However, the sectoral definition used for the labor and capital share is not exactly based on the way that we construct the energy capital stocks which include the energy related capital in several sectors (transport storage, housing, electricity, manufacturing, and construction). It is therefore likely that the capital share in clean energy is higher but it is not straightforward by how much. For this reason we set the clean labor share α_C only slightly lower to 0.3. However, there is a consensus that the capital share in the energy sector is much higher than in the general economy.

For the elasticity between the capital and labor composite and energy, we use the estimate of Bretschger and Ara (2022), who use firm-level data from the French manufacturing sector to estimate the elasticity of substitution between labor and energy, ranging between 0.45 and 0.80. This implies that labor and energy tend to be strong complements in most firms. Airaudo et al. (2023) assume a slightly lower elasticity of substitution (0.35) between physical capital and energy. [19] We calibrate the adjustment parameter $c_{N,D,C}$ to 5 in our baseline calibration following Bontempi et al. (2004). We conduct robustness checks with respect to c_i since our model captures dynamics of structural change within the energy sector for which we did not find a precise estimate in the literature. Therefore, we calculate a scenario with $c_{N,D,C} = 20$ the highest parameter value for quadratic adjustment costs we found

[19] **?** review empirical evidence on this elasticities of substitution (which also equals the own-price elasticity of energy)

They provide a summary of the existing estimates on own-price elasticities for energy consumption differentiated between the short run (less than one year) and the long run (after one year). The relevant short-run average short-run elasticity for energy is -0.22, for natural gas it is -0.18, and the least elastic in the short run is heating oil with -0.02. Differences between residential and industrial consumers are small. They find that the long term average energy product elasticities in the empirical literature range between -0.584 - (-0.608). Dissou and Karnizova (2016) argue that in the literature is no consensus on the nature of the interaction between capital, labor, and energy in a production function or their degree substitution. Kim and Loungani (1992), Carlstrom and Fuerst (2006), and Leduc and Sill (2004) are examples of three alternative means of introducing energy in production functions in business cycle models.

in the literature (Hall, 2004). For the depreciation rate, the inverse of the intertemporal substitution elasticity as well as the discount factor we assume values commonly used in the literature.

Parameter	**Value**
Elasticity of substitution between intermediate inputs N & E ϵ	0.45
Output elasticity wrt labor α_D	0.35
Output elasticity wrt labor α_C	0.3
Depreciation rate $\delta_{N,C,D}$	0.075
Inverse of intertemporal substitution elasticity θ	2
Discount factor β	0.98
Adjustment cost parameter $c_{N,D,C}$	5-20

Table 8: Parameter Values: External calibration

Parameter	**Value EU**	**Value India**
μ: CO_2 intensity of dirty energy ($\frac{tCO_2}{1000EUR\ or\ USD}$)	3.05[a]	11.68
CO_2 intensity of GDP ($\frac{tCO_2}{1000EUR\ or\ USD}$)	0.18	0.82

Table 9: Parameter Values: External calibration Differences between EU and India

[a]Calculation of μ exemplified for the EU: $\mu_{EU} = \frac{2.47\ GtCO_2e}{0.06*13.5\ trEUR} = 0.18\frac{tCO_2}{1000\ EUR}$.

C.2 Internally calibrated parameters and empirical targets

To compute the quantitative predictions of the model we set its structural parameters $\{\gamma, \frac{K_{C0}}{K_0}, \frac{K_{D0}}{K_0}, Kf, \sigma, \alpha_N\}$ to match the following seven empirical moments: the initial dirty energy share in GDP, the initial growth rate of the capital stock, the initial capital output ratio, the initial emissions as a share of remaining carbon budget, the initial share of clean and dirty energy investment as well as the initial labor share.

European Union. First, the model needs to match the initial dirty energy share in GDP which we assume to be 6%. We base this guess on the fact that the energy sector, covering extraction, production and distribution directly corresponds to 4% of value added of the non-financial EU business economy. `https://eucloudedgeiot.eu/energy/` In the literature it

is widely assumed that the fossil energy share of GDP equals 0.04 Golosov et al. (2014); Fried et al. (2022). Yet, we argue that 0.04 is too small, if we define energy as consisting of the energy-related production in the sectors of transport storage, housing, electricity, manufacturing, and construction. Therefore, we add roughly 2% of GDP. These extra 2 % should account for e.g. all transport services that use fossil fuel-based energy like combustion engines, the service of warming a house done by a gas therme and all machinery in the industry sector that runs using fossil based energy. [20]
Second, based on the IMF Investment and Capital Stock Dataset **?** we calibrate the initial growth rate of the EU capital stock to be 1.6%, representing the average capital stock growth rate between 2000 and 2019. Third, based on the same data set we calibrate the capital to output ratio to 2.5 corresponding to the EU capital output ratio in 2019. To match the second and third target we adjust Kf accordingly.

Third, we match the initial flow of energy related emission in t = 2020 of 2.47 $GtCO_2e$ (Climate Watch, 2023) for the EU to be 5.1 % of the remaining energy emission related carbon budget of 51 $GtCO_2e$ (see Section **??**) for the calculation of the remaining carbon budget).

We use Climate Action Tracker data of the average of their scenario "Policies and actions" until 2030. We use linear extrapolation to extend the path of emissions used until 2050. We take the sum of the emissions used in the period between 2020 and 2050. This "Policies and actions" scenario includes all policies a government has implemented or enacted to reduce emissions. We call it the Stated Policy Scenario (STEPS). For the EU the STEPS scenario implies that there is a carbon budget of 65 $GtCO_2e$ left until 2050. To back out the carbon budget for energy related emissions we scale the carbon budget by $\frac{2.47\ GtCO_2e}{3.3\ GtCO_2e}$. 2.47 $GtCO_2e$ are the energy related emissions in 2020 of the EU taken from the historical emissions of (Climate Watch, 2023). And 3.3 $GtCO_2e$ are the total emissions excluding LULUCF taken from the Climate Action Tracker **?**. This leaves an energy related carbon budget of 48.5 $GtCO_2e$

For India we do a similar calculation. We take their STEPS scenario using CAT emissions data projections for the "Policies and actions" until 2030, we use linear extrapolation until 2050 to get an overall emission budget of 145 $GtCO_2e$. From this overall emissions we back out the energy emission related STEPS budget using the same procedure as for the EU. In 2020 energy related emissions in India are about 2.22 $GtCO_2e$. The energy related carbon budget is about 104.8 $GtCO_2e$. This tells us that about 2.12 percent of the energy related carbon budget are used already in 2020.

[20] A possible approximation could be to use the energy expenditure share for end use-energy like in `https://www.eia.gov/todayinenergy/detail.php?id=53620` U.S. energy expenditures accounted for 4.8 % of gross domestic product (GDP) in 2020) (lowest share since 1970)).

The calculations of the carbon budget of 26.4 $GtCO_2e$ optimally depleted by 2040 is approximately in line with calculations in the literature on a carbon budget for Europe that would be in line with achieving 1.5 degrees globally. Du Robiou Pont et al. (2017) consider five distinct principles of distributive burden sharings of the globally necessary mitigation efforts to reach the 1.5° degree goal globally. We use the average remaining emission budget of the five scenarios (80 $GtCO_2e$ for the 1.5° goal and 114 $GtCO_2e$ for the 2°goal). Since their remaining budget is for the period from 2010 to 2050 and includes the UK we substract the cumulative emissions (45,2 $GtCO_2e$) of the EU and the UK from 2010-2020 using data from Climate Watch (2023). These modifications leave a carbon budget of 34,8 $GtCO_2e$ for the 1.5° goal for overall emissions and when assuming that about 80 percent of emissions that leaves a budget of about 27.5 $GtCO_2e$ for energy related emissions.

The fourth and fifth moment we match is the share of clean energy investment in total investment (11.5%) and the share of dirty energy investment in total investment (2%). To calculate the clean investment share we use the data on Gross Fixed Capital Formation (nominal in domestic currency) from the IMF International Financial Statistics ("data by country - GDP and Components") of all European countries to get the total investment in the EU. We use ECB data on different exchange rates to transform all values into EUR. To transform the nominal values into real values we use the HIPC - Overall index (series key ICP.M.U2.Y.000000.3.INX). We include Switzerland, Norway and the UK into the sample to make it consistent with the data on clean energy investment we take from Klaaßen and Steffen (2022). Klaaßen and Steffen (2022) provide a meta-analysis on necessary investment shifts to reach net zero pathways in Europe. We use the data of Klaaßen and Steffen (2022) Figure 4 to calculate the average investment of clean energy investment in 2020 using their mean value for the new EU targets. We classify Klaaßen and Steffen (2022) the technologies CO2 networks & storage, district heating, electricity grids, electricity storage, hydrogen pipelines/grids/storage, bio gas/fuel, low-carbon hydrogen, synthetic gas/fuel, EV charging points, H2 refueling stations, rail infrastructure, nuclear power plants, renewables - other, solar PV, wind offshore, wind onshore as clean energy investment. To make the clean investment share consistent with our definition of energy related capital stocks we include 150 billion as the current level of investment into greening buildings. `https://www.cer.eu/publications/archive/policy-brief/2022/eu-fiscal-rules-net-zero#FN-12` [21] We define the technologies of conventional fuel production, gas pipelines/grids/storage, oil pipelines/grids/storage, coal-fired power plants, fossil - other, gas-fired power plants as fossil related investment. We add 30% for investment

[21]Total investment in the greening of buildings should reach around €300 billion per year by 2030, twice the current levels.12 12 From European Commission, 'Climate target plan impact assessment', 2020, and McKinsey, 'Net zero Europe report', 2020.

into housing to take into account the ongoing dirty investment into housing https://www.bruegel.org/blog-post/how-much-investment-do-we-need-reach-net-zero (we used FIg 1 to conclude this somehow... is this really correct?). Overall, this approach yields a share of 11.5 % of clean energy investment in total real gross fixed capital formation and a share of 2 % of dirty energy investment in total real gross fixed capital formation.
As the sixth moment we match the growth rate of clean energy investment between 2020 and 2030. We calculate the growth rate using the data of clean energy investment of

The last empirical target we match the model with, is the initial share of labour compensation in GDP at current national prices ($\frac{wL}{Y}$) of the economy. For the EU this is 58 % which is the GDP weighted average of the share of labor compensation within the EU based on Penn World Table version 10.01.

India. For India we assume the initial dirty energy share in GDP to be 7 percent we assume it to be slightly higher than in the EU. We assume it to be 7 percent weighting the EU share by the dirty share of total primary energy consumption of India and the EU. [22] We take the data moments for the initial growth rate of the capital stock and the initial capital output ratio from the IMF Investment and Capital Stock Dataset **?**. This data shows a capital stock growth rate of 7 percent from 2018 to 2019 and a capital to output ratio of 2.1 in 2019.

For the calculation of the share of the initial emissions in the remaining carbon budget we use the emission flow data of Climate Watch (2023). India used about 3.17 $GtCo2$ in 2020. This amounts to a share of 3.1 percent of the remaining carbon budget of 103 $GtCo2$ (for carbon budget calculations see B.1).

For the calculations of the clean (3.4 percent) and dirty (8 percent) investment shares in India we used the data of Investment Data Explorer of the IEA (2021). We used the data on the total energy investment by GDP and the share of clean energy investment in total energy investment. To back out the ratio of clean and dirty energy investment in total investment we used the ratio of investment over GDP taken from the IMF Investment and Capital Stock Dataset **?**.

For the labor share in India we use the Share of Labour Compensation in GDP at Current National Prices for India, Ratio, Annual, Not Seasonally Adjusted from **?** showing that the labor share in 2019 was about 52 percent.

[22] The data on Primary energy consumption of the EIA (2023) shows that the dirty share in energy consumption is 89 percent and for the EU it is 72 percent ($6*\frac{89}{72}$=7 percent).

Parameter	**Value EU**	**Value India**
Weight on non-energy input in production γ	0.988	0.99
Initial emission share in carbon budget $\frac{M_D}{M_N}$	1	1
Initial emission share in carbon budget $\frac{M_C}{M_N}$	0.71	0.77
Share of initial dirty energy capital $\frac{K_{D0}}{K_0}$	0.13	0.088
Share of initial clean energy capital $\frac{K_{C0}}{K_0}$	0.09	0.03
Determining level of init. capital stock Kf	0.66	0.26
Non-energy technology output elasticity wrt labor α_N	0.62	0.55

Table 10: Parameter Values: Internal calibration

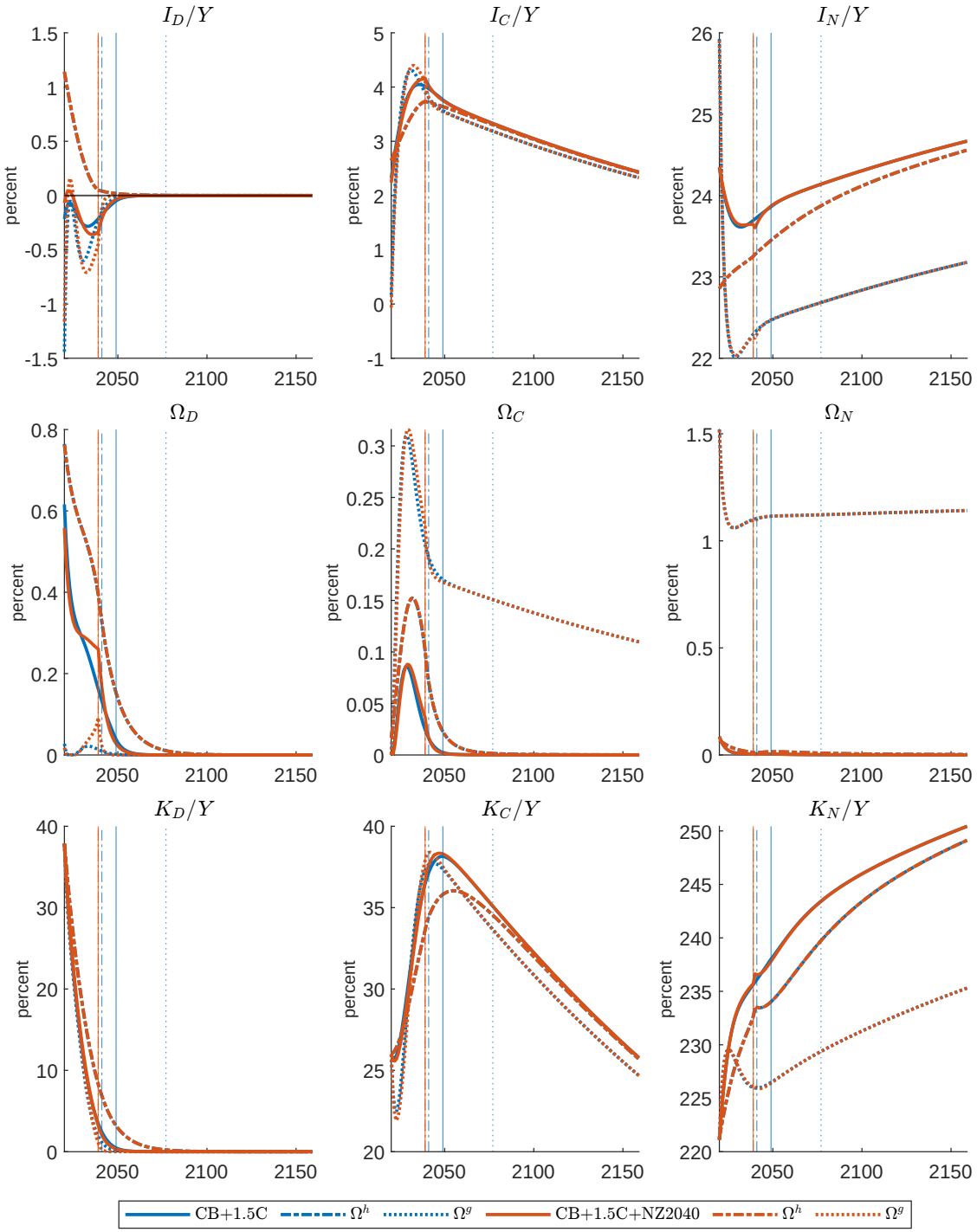


Figure 12: Transitional dynamics and different adjustment costs in the EU

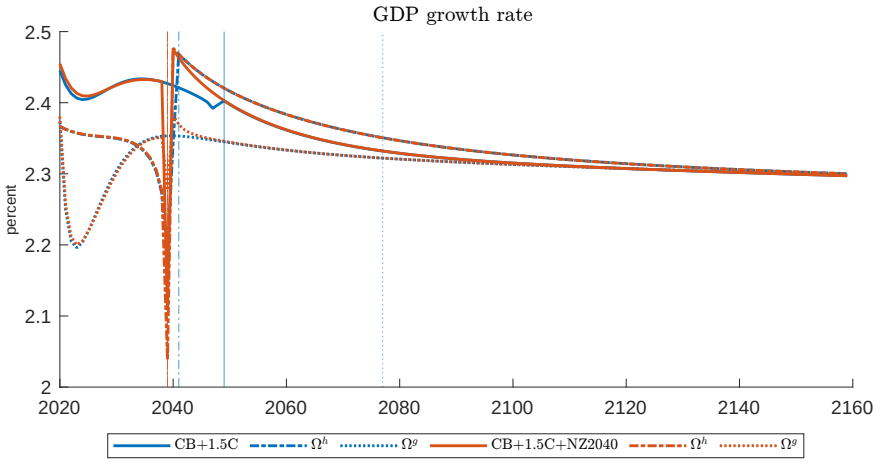


Figure 13: Growth patterns and adjustment costs in the EU

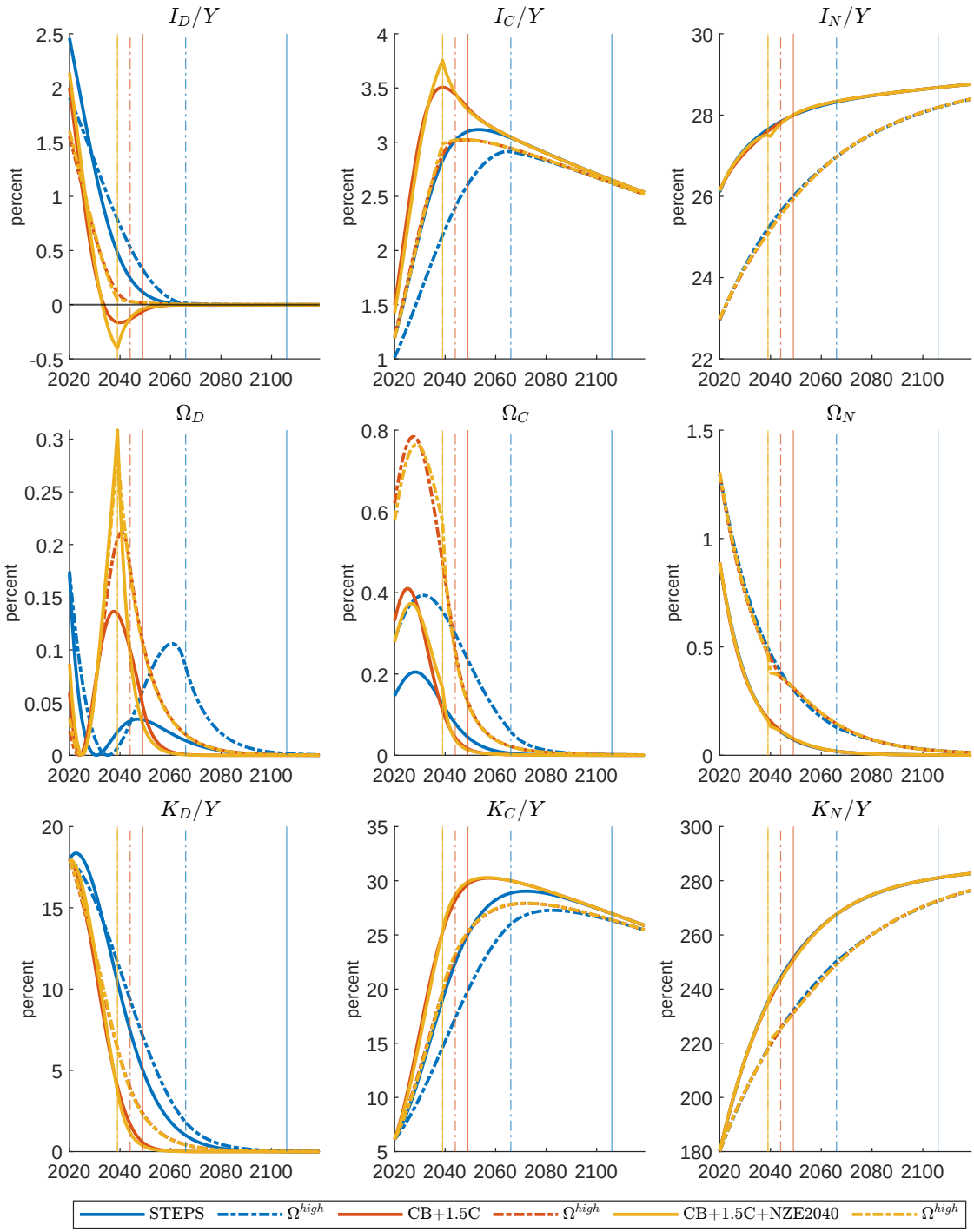


Figure 14: Transitional dynamics and different adjustment costs in India

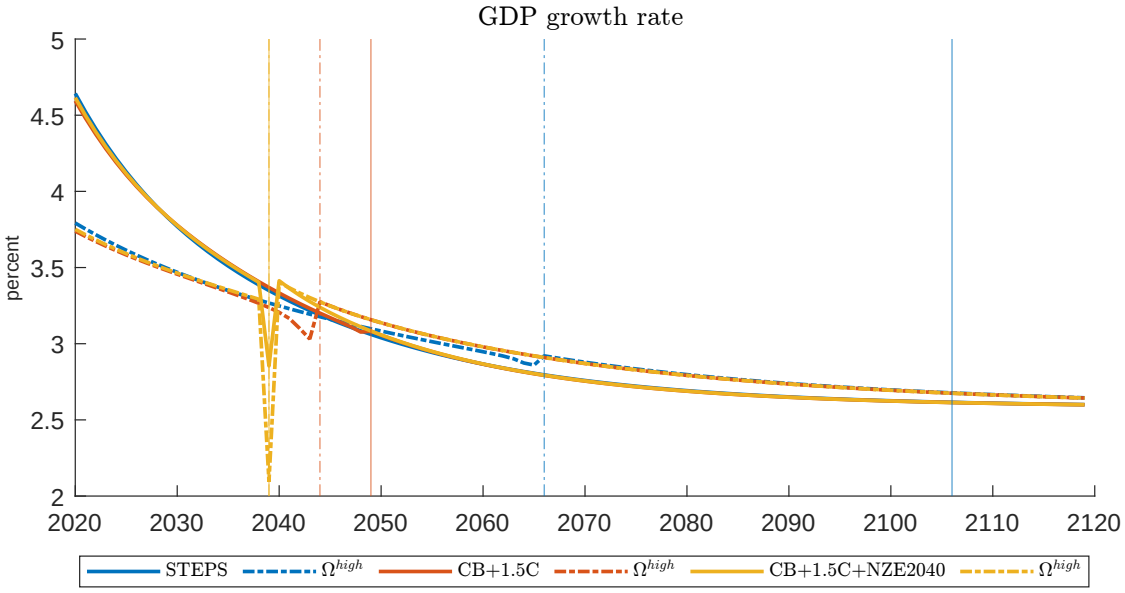


Figure 15: Growth patterns and adjustment costs in India