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ABSTRACT

Capital Adjustment Costs and Stranded Assets in an Optimal Energy Transition*

In the context of a green energy transition, capital adjustment costs render effective substitution between clean and dirty energy sources finite and endogenous, despite infinite long-run substitutability. Ramsey optimal paths robustly frontload clean investment before exhaustion of a given carbon budget, but also generally imply some capital stranding. Along the path of emissions reduction, new investment is quantitatively more important than reduced output or labor redeployment. An ambitious climate goal in our benchmark calibration implies modest levels of stranded capital at 1.5% of GDP, but this rises to more than 7% if implementation is delayed by a decade.

JEL Classification: E22, H23, O41, Q43

Keywords: growth model, energy transition, optimal investment, capital adjustment costs, carbon pricing

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1 Introduction

Energy-related emissions account for roughly 80% of total greenhouse gas emissions in the European Union (Climate Watch, 2023). Meeting the current goal of net-zero emissions by 2050 will necessitate a dramatic switch from fossil-based to renewable sources in relatively short time. Of central importance will be a significant transformation of the capital stock; the energy system is highly capital-intensive, capital is technology-specific, and its replacement or repurposing entails substantial costs (Fried et al., 2022).[1] Crucially, the more rapidly this capital is transformed, the higher the economic costs, a principle well-established in macroeconomics (Lucas, 1967; Mussa, 1977, among others). Recognizing this tension between urgency of emissions reduction and high costs of a rapid transition, we address two questions: First, how does this trade-off shape the optimal clean energy transition? and second, how large are the transition costs under different policy scenarios?

We construct and calibrate a parsimonious unbalanced growth model (Acemoglu and Guerrieri, 2008) to answer these questions. Final goods production combines two intermediate inputs, each produced with capital and labor. Energy is capital-intensive while the other intermediate is labor-intensive and a stand-in for all remaining sectors. Energy, in turn can be produced either with a "dirty" technology that generates greenhouse gas emissions, or a "clean" one that does not. While clean and dirty energy are perfect substitutes in final output production, capital is technology-specific and subject to convex adjustment costs. A key feature of this production structure is that substitution of clean for dirty energy is endogenous and time-dependent. In the short run, the economy's capacity to generate and use clean energy is constrained by quasi-fixed capital stocks. Over time, as capital is reallocated, clean energy can substitute for dirty energy throughout the production process. The speed of this transition and the associated losses depend on the magnitude of adjustment costs. Provided the infrastructure is in place, clean technologies, such as wind, solar, and electric vehicles, can perform the same functions as fossil-fueled alternatives. In contrast, many existing macro-climate models assume constant elasticity of substitution between low emission and emissions-intensive energy generation based on short- or medium-term estimates (Acemoglu et al., 2012; Golosov et al., 2014; Barrage, 2020; Hassler et al., 2021; Fried, 2018; Airaudo et al., 2023) .

Our first contribution is an analytic characterization of the optimal green energy transition as the solution to a Ramsey planner's problem maximizing social welfare subject to an exogenous cumulative carbon budget.[2] We show that the planner chooses to exhaust

[1] Goeth et al. (2025) estimate that 10% of the overall capital stock must be transformed.

[2] Our focus is on optimal paths, taking the limit on cumulative emissions as given. The optimal size of the carbon budget is not part of our analysis and we abstract from direct effects of climate change on GDP or welfare, which are likely to be substantial. For example, Bilal and Känzig (2024) find that 1°C of global

the carbon budget in finite time, after which production of dirty energy ceases.[3] In this context, we identify an analytic condition under which capital stranding occurs. We define stranded capital as productive dirty energy capital that can no longer be used when the carbon budget is exhausted. Stranded capital represents foregone output and consumption opportunities and serves as a potential metric for otherwise unobservable capital adjustment costs. Under plausible model parameter values, some capital stranding is a robust feature of optimal policy. A central result of this paper is to show that capital stranding arises even in the absence of uncertainty or policy frictions, and reflects the inherent economic limits of reallocating capital between technologies when an upper bound on climate emissions is operative.

Our second contribution is a quantitative assessment of an optimal transition and its economic costs. We compare current climate policy (CCP), based on current projections of emissions, with an ambitious climate policy (ACP) involving a tighter carbon budget. Along the lines of Brock and Taylor (2005), we develop a decomposition of optimal use of three macroeconomic adjustment channels: 1) reducing overall energy consumption through energy savings, 2) redeploying labor to the clean energy sector, and 3) increasing clean energy investment. Our decomposition yields a period-by-period account of the contributions to total emissions reduction. New clean energy investment is by far the dominant adjustment channel, accounting for over 60% of cumulative emissions reductions. Our findings underscore the central and dynamic role of capital formation in a clean energy transition.

Adjustment costs and the environmental limit interact to generate significant resource losses that increase with climate policy ambition as well as inaction. Under CCP, the value of stranded capital amounts to 0.76% of annual GDP, rising to 1.43% under ACP. Annual capital adjustment costs average 0.43% and 0.48% of GDP over four decades, respectively. In welfare terms, moving from CCP to ACP is equivalent to a 0.27% reduction in consumption over the same time frame, abstracting from the benefits of lower emissions. Costs rise sharply in postponement of time until implementation. Starting in 2020, delaying a shift from CCP to ACP until 2030 increases stranded capital to more than 7% of GDP.

Section 2 reviews the literature relating green transition to capital adjustment and stranded assets. Section 3 presents our model and the analytics of a Ramsey-optimal energy transition. In Section 4, we quantify the role of the three adjustment channels and the associated transition costs under different policy scenarios. Section 5 concludes.

warming reduces world GDP by 12%.

[3]This contrasts with standard analyses such as Chakravorty et al. (2006), which predict use of the dirty technology into the indefinite future. Below, we elaborate reasons for this divergent prescription.

2 Green Energy Transition, Capital Formation, and Stranded Assets

Our analysis builds on the well-established macroeconomic modeling tool of convex capital adjustment costs dating back to Lucas (1967); Mussa (1977); Gould (1968) and still widely in use today (e.g. David and Venkateswaran (2019); David et al. (2021). Capital adjustment costs also play a fundamental role in the growing literature on optimal investment strategies for preventing climate disaster (Campiglio et al., 2022; Arkolakis and Walsh, 2023; Coulomb et al., 2019; Hambel et al., 2020; Rozenberg et al., 2020; van der Ploeg and Rezai, 2020a; Vogt-Schilb et al., 2018). In the context of the green transition, adjustment costs are relevant only for the transition process and capture limited availability of specialized resources for re-deploying and refitting the capital stock (skilled workers, specialized equipment, production lines, etc.).

In our context, capital adjustment costs represent a friction that impedes perfect short-run substitutability between clean and dirty energy. This modeling strategy contrasts with the standard approach of assuming fixed and constant elasticity of substitution between clean and dirty energy inputs (Acemoglu et al., 2012; Golosov et al., 2014; Barrage, 2020; Hassler et al., 2021; Fried, 2018; Airaudo et al., 2023). In a setting of fixed and constant elasticities of substitution, model calibrations rely on short-run estimates that inherently understate substitution possibilities in the long run, when capital has fully adjusted.

An important contribution of our analysis is to demonstrate and quantify the interaction of capital adjustment costs with a binding upper bound on cumulative carbon emissions, in particular to show that they robustly lead to capital stranding. We thus contribute to a rapidly growing literature on stranded assets. Pfeiffer et al. (2018); Mercure et al. (2018); Tong et al. (2019); Fofrich et al. (2020) provide estimates of stranded-asset magnitudes across a variety of sectors and countries. Campiglio et al. (2022) show, in a DSGE context, that it is optimal to disinvest from dirty capital and deliberately strand parts of the capital stock. In an analytical model van der Ploeg and Rezai (2020a) demonstrate how policy action shapes both the timing and the extent of asset stranding in the global oil and gas industry.[4] Our modeling strategy allows for the separation of disinvestment from repurposing of the dirty energy capital stock while the latter is in use. Following van der Ploeg and Rezai (2020b) we define asset stranding as purposeful abandonment of sector-specific capital when the carbon budget is exhausted and dirty energy production must cease. Abandoned capital remains unemployed until it is repurposed at a cost or depreciated, thus representing foregone consumption and investment opportunities. We demonstrate that asset stranding

[4] van der Ploeg and Rezai (2020b) present a structured review of the literature on stranded assets.

is a necessary by-product of the energy transformation, even when a Ramsey planner makes time-consistent and welfare-optimal decisions. In addition, we derive an analytic expression for the critical lower bound for the adjustment cost parameter above which asset stranding always occurs.[5]

Our research also relates to a strand of the literature on the role of expected future carbon policy for asset stranding. Kalkuhl et al. (2020); Campiglio et al. (2022, 2024); Schoder and Tercioglu (2024); van der Ploeg and Rezai (2020a,b) show that the extent of asset stranding will depend on expectations of future policy and the credibility of policy announcements. We find that stranded assets occur even in a fully anticipated and optimal climate policy setting. In particular, the extent of asset stranding is increasing in the current dirty capital stock and decreasing in the remaining carbon budget. Most importantly, it is increasing in the delay in implementing Ramsey optimal policy. Additionally, we quantify the difference in stranded assets between a scenario in which agents know that carbon pricing will be introduced in the future, and one in which agents do not anticipate future increases in carbon pricing.

Our quantification of the optimal economic adjustment to a tightening of the carbon budget is related to the approach of Brock and Taylor (2005). They identify three possible channels of emissions reduction (scale, composition and technique) *along* an economy's growth path. We decompose emissions reductions *between* the growth paths associated with CCP and ACP into 1) the reduction of overall energy production, 2) the redeployment of labor to the clean energy sector, and 3) the faster pace of clean energy investment. In a model without labor, Rozenberg et al. (2020) describe two channels of adjustment (changing the composition of capital and underutilizing polluting capital), but they do not provide an analytic characterization or quantification of the importance of either channel.

3 Non-balanced optimal growth in a model of the green energy transition with a carbon budget

The framework for our analysis is a deterministic unbalanced growth model with exogenous technical progress (e.g. Acemoglu and Guerrieri (2008)). We add two features to this setting: 1) capital adjustment costs and 2) a cumulative carbon (CO_2) emissions budget. The model is comprised of three sectors. A final goods sector combines energy (Y_e) and a non-energy intermediate good (Y_n) at a constant and finite elasticity of substitution to generate final output (Y). Final output can be consumed, invested, or expended for installation or de-

[5]Similarly, Rozenberg et al. (2020) show that a phased-in carbon price can avoid premature retirement but still result in stranded assets, that is in a drop of wealth for the owners of polluting capital.

installation of new capital (i.e. capital adjustment costs). Energy is produced with either of two different technologies. A dirty technology (d) is initially more productive, but causes greenhouse gas emissions, while the clean one (c) does not. Production of energy and the non-energy intermediate requires capital K and labor L as inputs, both of which are in fixed total supply at any point in time. Energy generation is more capital-intensive than intermediates production. Stylized, constant returns production functions serve as stand-ins for sectors with more complex input-output structures. Adjusting capital inputs employed in each technology is subject to convex costs, measured in terms of final output.

3.1 The Model

Preferences The benchmark for our analysis throughout the paper is the optimal choice of a social planner who maximizes the present discounted utility of the representative household:

$$\sum_{t=0}^{\infty} \beta^t \frac{C_t^{1-\theta} - 1}{1-\theta}. \tag{1}$$

C_t denotes consumption of the homogeneous output good, β is the discount factor with $1 > \beta > 0$ and θ is the inverse of the elasticity of intertemporal substitution.

Production structure Final output is produced from intermediate inputs Y_{nt} and Y_{et}:

$$Y_t = \left(\gamma Y_{nt}^{\frac{\epsilon-1}{\epsilon}} + (1-\gamma) Y_{et}^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}}. \tag{2}$$

The strictly positive parameters γ and ϵ stand for the weight on the intermediate input Y_n and the elasticity of substitution between intermediate inputs Y_n and energy Y_e respectively. In the long run, there is perfect substitutability between clean and dirty energy:

$$Y_{et} = Y_{dt} + Y_{ct}. \tag{3}$$

In the short run, effective substitutability between clean and dirty energy is limited by quasi-fixity of the energy capital stocks implied by adjustment costs. Adjustment costs therefore determine the pace at which dirty energy can be substituted with clean energy. Production technologies $i \in \{n, d, c\}$ all have constant returns to scale with Cobb-Douglas functional form with capital K_{it-1} and labor L_{it} as inputs:

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

where M_{it} denotes the level of total factor productivity (TFP) and α_i the output elasticity with respect to labor.

Capital, investment and adjustment costs Capital in each sector evolves according to an accumulation equation:

$$K_{it} = (1 - \delta_i)K_{it-1} + I_{it}, \tag{4}$$

where δ_i is the sector-specific depreciation rate and I_{it} is the volume of gross investment in sector i. Changes in the size of each capital stock, expressed as a rate, give rise to adjustment costs, which are modelled as quadratic in a measure of the net change:

$$\Omega^i(K_{it}, K_{it-1}) = \frac{c}{2}\frac{(K_{it} - (1+z_i)K_{it-1})^2}{K_{it-1}} \; i \in \{n, d, c\}. \tag{5}$$

or, equivalently,

$$\hat{\Omega}^i(I_{it}, K_{it-1}) = \frac{c}{2}\left(\frac{I_{it}}{K_{it-1}} - \delta_i - z_i\right)^2 K_{it-1} \quad \text{for } i \in \{n, d, c\}.$$

The parameter c captures adjustment costs, and z_i is the steady-state growth rate of sector i's capital stock along the unbalanced growth path, which are defined in Section 3.3. The presence of δ_i and z_i implies that adjustment costs are only incurred for deviations from the long-run trend in investment; maintaining the current capital stock in relation to its steady-state growth path can be done routinely and planned in advance, in contrast to rapidly scaling up production capacity or reducing it by selling and re-purposing old capital. This functional form, following Aguiar and Gopinath (2007), has two useful properties. First, adjustment costs do not affect long-run outcomes as capital stocks approach their trend levels. Second, costs are scaled by the size of the capital stock, implying that a 1% deviation from the long-run investment ratio requires an approximately constant share of GDP devoted to installation of capital in that period.[6] When taking the model to the data, we measure investment as gross expenditure on investment goods plus output represented by adjustment costs. As we show in Appendix A.1.3, this measure corresponds to the value of capital purchases in sector i in a decentralized market economy under conditions of perfect competition in product and factor markets when capital installation and refurbishment tasks are performed by external private sector firms.

Aggregation The aggregate resource constraint of this closed economy equates final output to the sum of all final uses, including adjustment costs:

$$Y_t = C_t + I_t + \Omega_t. \tag{6}$$

[6]The statement holds only approximately, because growth is unbalanced in the economy and there are long-run trends in the size of the sector-specific capital stocks relative to GDP.

Total gross investment expenditure I_t plus adjustment costs Ω_t are summed over the three productive activities:

$$I_t = \sum_{i \in \{n,d,c\}} I_{it} \quad \text{and} \quad \Omega_t = \sum_{i \in \{n,d,c\}} \Omega^i(K_{it}, K_{it-1}).$$

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

$$\bar{L} = L_{nt} + L_{dt} + L_{ct} \tag{7}$$

By ignoring labor frictions, we focus attention on the reproducible production factor and thereby place a lower bound on the adjustment necessary in a growing economy.

Greenhouse gas emissions Greenhouse gas emissions are produced by the dirty energy technology and accumulate in the atmosphere without absorption through natural sinks or negative emissions technologies according to:

$$G_t = G_{t-1} + \frac{1}{\sigma} Y_{Dt}, \tag{8}$$

where $\frac{1}{\sigma} Y_{Dt}$ is the flow of emissions at time t and G_t is the stock of accumulated emissions. The parameter σ is a measure of "CO_2 efficiency" of dirty energy production. The cumulative carbon budget is $\bar{G}$, measured in $GtCO_2e$. There is an absolute upper bound on cumulative emissions, given by:

$$G_t \leq \bar{G}. \tag{9}$$

Technological progress For $i \in \{n, d\}$ productivity growth is assumed constant for all t,

$$M_{it} = M_{it-1}(1 + m_i). \tag{10}$$

Most "clean" technologies that produce energy without greenhouse gas emissions have emerged more recently and are not yet entirely cost-competitive with "dirty" energy production. However, they are improving at faster rates and catching up quickly (Way et al., 2022). To capture this feature, we model a standard catch-up growth process in clean technology, similar to Mattauch et al. (2015). TFP in the initially disadvantaged clean sector approaches a long-run path that is characterized by a constant growth rate m_c. During the transition, the distance of total factor productivity to this path shrinks at a constant rate. Formally,

$$a_{ct} = 1 - \frac{b_M}{(1 + \kappa_M)^t} \tag{11}$$

where $\lim_{t\to\infty} a_{ct} \to 1$, $\kappa_M > 0$ is the catch-up rate and $b_M \geq 0$ parametrizes the initial distance to the long-run constant-rate growth path. The level of TFP in the clean sector then follows

$$M_{ct} = a_{ct}\tilde{M}_{ct} \tag{12}$$

with

$$\tilde{M}_{ct} = (1 + m_c)\tilde{M}_{ct-1}. \tag{13}$$

In our baseline calibration, clean energy technology is initially less efficient than the dirty technology ($b_M > 0$), but attains the same growth path in the long-run ($m_c = m_d$ and $\tilde{M}_c = M_d$).[7] Because production technologies differ across sectors, long-run growth is unbalanced in this economy. Following Acemoglu and Guerrieri (2008), we only consider parametrizations such that $\frac{m_n}{\alpha_n} < \frac{m_c}{\alpha_c}$ and $\epsilon < 1$. Under these conditions, the long-run growth path will take the form described in detail in Section 3.3.

3.2 The Social Planner Problem

We now consider the choice of a social planner who selects a set of paths of household consumption, labor allocations, capital allocations, and cumulative greenhouse gas to maximize welfare of the representative household. Formally, she chooses $\{C_t, \{L_{it}, K_{it}\}_{i\in\{n,d,c\}}, G_t\}_{t=1}^{\infty}$ to maximize utility (1) subject to constraints (2)-(9) and the initial conditions $\{K_{i-1}\}_{i\in\{n,d,c\}}$ and G_{-1} as well as the exogenous paths of $\{M_{it}\}_{i\in\{n,d,c\}}$ defined by (10) - (13).

Alternative formulation and solution We show below that the constraint (9) might bind at some finite time $\bar{T}$ on the optimal growth path, implying $Y_{dt} = 0$ for all $t > \bar{T}$. Since labor can be flexibly deployed and has positive shadow value, $L_{dt} = 0$ for all $t > \bar{T}$ in the optimal allocation. Because of adjustment costs, however, K_{dt} might be positive after time $\bar{T}$. In this case, the marginal product of L_{dt} is infinite and its first order condition is not defined. To characterize the social optimum using the Karush-Kuhn-Tucker method under these conditions, we state an alternative, equivalent optimization problem in which $\bar{T}$ is an explicit choice variable. In this formulation, the social planner chooses $\left\{\{C_t, \{L_{it}\}_{i\in\{n,c\}}, \{K_{it}\}_{i\in\{n,d,c\}}\}_{t=1}^{\infty}, \{L_{dt}, G_t\}_{t=1}^{\bar{T}}, \bar{T}\right\}$ subject to constraints (2)-(9).

Since $\bar{T}$ is defined as the time at which the constraint is reached optimally, (9) must hold with equality. Therefore $G_{\bar{T}} = \bar{G}$ holds, which implies $G_t = \bar{G}$ and $L_{dt} = 0$ for $t > \bar{T}$, because negative emissions are not possible. By imposing these conditions on the optimization problem for a given $\bar{T}$, L_{dt} is no longer a choice variable for $t > \bar{T}$, eliminating

[7] This assumption is non-essential for our analysis and it would be possible in principle for clean energy technology to overtake dirty technology in finite time.

the possibility of infinite marginal productivity in the first order conditions. Note that we do not impose that $\bar{T}$ is finite. We prove in Section 3.6, however, that $\bar{T} = \infty$ is an admissible outcome only if the existence of the carbon budget has no effect on the growth path.

Since $\bar{T}$ is a discrete choice variable, its optimal choice cannot be characterized by a first order necessary condition. We will therefore solve the problem in two steps. First, we solve the well-defined optimization problem for all possible values of $\bar{T}$ using the Karush-Kuhn-Tucker method.[8] Second, we identify the optimal $\bar{T}$ by choosing the value associated with the highest value of utility. The first problem yields a standard Lagrangian conditional on $\bar{T}$ which is then differentiable with respect to all other decision variables:

$$\begin{aligned}
\mathcal{L}\Big(\{C_t, \{L_{it}\}_{i\in\{n,c\}}, \{K_{it}\}_{i\in\{n,d,c\}}\}_{t=0}^{\infty}, \{L_{dt}, G_t\}_{t=1}^{\bar{T}}\Big) &= \sum_{t=1}^{\infty} \beta \Big\{ \frac{C_t^{1-\theta} - 1}{1-\theta} \\
&+\lambda_t \Big[\Big(\gamma \left(M_{nt} K_{nt-1}^{1-\alpha_n} L_{nt}^{\alpha_n} \right)^{\frac{\epsilon-1}{\epsilon}} + (1-\gamma) \left(\mathbb{1}_{t\leq\bar{T}} M_{dt} K_{dt-1}^{1-\alpha_d} L_{dt}^{\alpha_d} + M_{ct} K_{ct-1}^{1-\alpha_c} L_{ct}^{\alpha_c} \right)^{\frac{\epsilon-1}{\epsilon}} \Big)^{\frac{\epsilon}{\epsilon-1}} \\
&\quad - C_t - \sum_{i\in\{n,d,c\}} (K_{it} - (1-\delta_i)K_{it-1}) - \Omega^i(K_{it}, K_{it-1}) \Big] \\
&+\nu_t \mathbb{1}_{t\leq\bar{T}} \left[G_t - G_{t-1} - \frac{1}{\sigma} M_{dt} K_{dt-1}^{1-\alpha_d} L_{dt}^{\alpha_d} \right] \\
&+\mu_{\bar{T}} [\bar{G} - G_{\bar{T}}] + \eta_t [\bar{L} - L_{nt} - \mathbb{1}_{t\leq\bar{T}} L_{dt} - L_{ct}] + \xi_t^{Kd} K_{dt} \Big\}
\end{aligned} \tag{14}$$

Here λ_t is the shadow value in utility of an extra unit of output, η_t is the shadow value of an extra unit of labor and ξ_t^{Kd} is the multiplier on the non-negativity constraint $K_{dt} \geq 0$ in period t.[9] The multipliers ν_t and $\mu_{\bar{T}}$ have the interpretations of shadow prices of a marginal reduction of the greenhouse gas stock G_{t-1} i.e. the price of carbon in period t, and of a relaxation of the upper bound $\bar{G}$ in period $\bar{T}$, respectively. We restrict our discussion to those optimality conditions related to the environmental side of the model and relegate the full set of conditions to Appendix A.1. Labor employed in the dirty energy technology obeys:

$$\left(\lambda_t \frac{\partial Y_t}{\partial Y_{et}} - \frac{\nu_t}{\sigma} \right) \frac{\partial Y_{dt}}{\partial L_{dt}} = \eta_t \tag{15}$$

for $t \in [1, \bar{T}]$. The multiplier ν_t drives a wedge between the marginal product of labor in the dirty energy technology and the marginal value of an extra unit of labor η_t. Similarly, the

[8] In the light of Proposition 1 in Section 3.6, $\bar{T} = \infty$ would be equivalent to solving the problem without the constraint.

[9] In principle we would need to add such constraints for all inputs. However, it is straightforward to see that this is the only constraint which could bind at the optimum.

optimality condition for K_{dt} reads:

$$\begin{aligned}&\lambda_t\left[1+\Omega_1^d(K_{dt},K_{dt-1})\right]=\\&\quad\beta\lambda_{t+1}\left[\frac{\partial Y_{dt+1}}{\partial K_{dt}}\frac{\partial Y_{t+1}}{\partial Y_{et+1}}+(1-\delta_d)-\Omega_2^d(K_{dt+1},K_{dt})\right]-\beta\frac{\nu_{t+1}}{\sigma}\frac{\partial Y_{dt+1}}{\partial K_{dt}}\end{aligned} \tag{16}$$

for $t\in[1,\bar{T}-1]$. Here the cost associated with future emissions appears on the right, as investment in dirty capital leads to higher future emissions. For $t\geq\bar{T}$, the optimality condition becomes

$$\lambda_t\left[1+\Omega_1^d(K_{dt},K_{dt-1})\right]-\xi_t^{Kd}=\beta\lambda_{t+1}\left[(1-\delta_d)-\Omega_2^d(K_{dt+1},K_{dt})\right]. \tag{17}$$

with an associated sequence of complementary slackness conditions $K_{dt}\xi_t^{Kd}=0$, $K_{dt}\geq 0$, and $\xi_t^{Kd}\geq 0$.[10] Crucial for model dynamics are the optimality conditions for G_t, which in turn determine the evolution of ν_t:

$$\nu_t=\beta\nu_{t+1}\quad\text{for}\quad t\in[1,\bar{T}-1]\quad\text{and}\quad\nu_{\bar{T}}=\mu_{\bar{T}}, \tag{18}$$

with $\mu_{\bar{T}}\geq 0$. Before $\bar{T}$, ν_t grows exponentially at rate $\beta^{-1}-1$, the rate of subjective time preference of the representative household. At time $\bar{T}$, the constraint is binding, which leads to a positive shadow value of the cumulative carbon budget (constraint), $\mu_{\bar{T}}$, which in turn pins down the value of $\nu_{\bar{T}}$. By backwards induction, the first equality in (18) determines the entire path of ν_t.

3.3 Ramsey-optimal unbalanced growth

If $\bar{T}$ is finite, then for all $t\geq\bar{T}$ it must be the case that $Y_{dt}=0$; from that point on, the model collapses to the two-sector model of Acemoglu and Guerrieri (2008) and inherits its long-run growth properties.[11] In particular, Y, Y_n, K_n all grow at rate $g=g_n=z_n=(1+m_n)^{\frac{1}{\alpha_n}}-1$ as $t\to\infty$. K_c grows at rate $z_c=\frac{1+g}{(1+\omega)^{1-\epsilon}}-1<z_n$ with $\omega=(1+m_c)/(1+m_n)^{\frac{\alpha_c}{\alpha_n}}-1$. Y_c grows at rate $g_c=(1+g)(1+\omega)^{\epsilon}-1>g$. Finally, $L_n\to\bar{L}$. In the long run, the slow-growing and labor intensive sector absorbs all of the available production factors. Even though the share of factors devoted to sector Y_e declines, output of that sector grows faster than output sector of Y_n. The non-energy sector thus becomes the limiting factor for long-run economic growth.

[10] The constraint $K_{dt}\geq 0$ cannot be binding before time $\bar{T}$, because the marginal product of dirty capital would then be infinite.

[11] The only important differences are adjustment costs and modeling in discrete as opposed to continuous time. Adjustment costs are designed to leave long-run dynamics unaffected.

3.4 Decentralization of the Ramsey-optimal outcome

Under the appropriate regularity conditions, allocation characterized above can be decentralized in a market economy by means of an optimal carbon tax. Studying the decentralized economy has two purposes. First, it allows us to compute relative prices for all production factors and goods, which are necessary for defining value added shares in the quantitative analysis of the model. Second, we interpret transition paths presented in Section 4 as the outcome of privately optimal decisions in the presence of an optimal carbon tax rather than choices directly imposed by a social planner.

Because this decentralization is standard, we only summarize it here, leaving details to Appendix A.1.3. There, we set up an economy with identical fundamentals (preferences, production technologies, etc.) in which consumption, investment, labor and production decisions are made by optimizing households and firms in general equilibrium. Markets for all production factors, inputs and final output are competitive. New capital is produced by firms which purchase old capital and operate a capital production technology subject to quadratic adjustment costs described above. A benevolent social planner chooses a time-dependent tax τ_{dt} on CO_2 emissions paid by firms producing dirty energy. In this setting, we show that the dirty energy tax is sufficient for implementing the allocation which solves the problem described in Section 3.2.

We close this discussion by defining and characterizing some variables which are important for the economic interpretation of our quantitative results. Using the final output good in each period as the numeraire, market clearing implies

$$p_{nt} = \gamma \left[\frac{Y_{nt}}{Y_t}\right]^{-\frac{1}{\epsilon}} \quad \text{and} \quad p_{et} = (1-\gamma)\left[\frac{Y_{et}}{Y_t}\right]^{-\frac{1}{\epsilon}}$$

Shares in total value added for the components of total output are:

$$s_{nt} = \frac{p_{nt}Y_{nt}}{Y_t}, \quad s_{dt} = \frac{p_{et}Y_{dt}}{Y_t}, \quad s_{ct} = \frac{p_{et}Y_{ct}}{Y_t} \quad \text{and} \quad s_{et} = \frac{p_{et}Y_{et}}{Y_t}.$$

where $s_{dt} + s_{ct} = s_{et}$ and $s_{nt} + s_{et} = 1$. The optimal carbon tax per unit of emissions is

$$\tau_{dt} = \frac{\nu_t}{\lambda_t} \text{ for } t \leq \bar{T} \quad \text{and} \quad \tau_{dt} = \infty \text{ for } t > \bar{T}. \tag{19}$$

Recall that ν_t grows exponentially at rate $\beta^{-1}-1$ until the upper bound on G_t, $\bar{G}$, is reached. The same applies to the optimal carbon tax τ_{dt} as λ_t declines along the optimal growth path. After period $\bar{T}$, dirty energy generation is shut down completely via a prohibitive tax.

3.5 Calibration

We calibrate the model to data from the European Union (EU), with a starting date in 2020.[12] Here we only discuss choices of important parameters related to the production structure, capital adjustment costs and the carbon budget, relegating the rest to Appendix B. In line with the literature, we set ϵ, the substitution elasticity between energy and non-energy inputs, to 0.45, significantly below unity (Bretschger and Ara, 2022). Since energy production is capital intensive (Fried et al., 2022), we choose high capital-output elasticities (and thus low labor-output elasticities) in the energy compared to non-energy sector ($\alpha_c = \alpha_d = 0.3, \alpha_n = 0.65$). Second, capital in the energy sector is typically more long-lived than the average unit of capital in the economy. Following Goeth et al. (2025) we define energy-related capital as capital employed in energy use and generation in electricity generation, heating, transport and industry. In line with Arkolakis and Walsh (2023), we set technology-specific depreciation rates to $\delta_c = 0.02$, $\delta_d = 0.03$, and $\delta_n = 0.07$. For the clean technology catch-up process, we assume a dirty technology advantage of 37% in 2020 but that reaches cost parity by 2030 (for details on the estimation see Goeth et al. (2025)).

The adjustment cost parameter in our analysis, c, plays a crucial role in our analysis and merits more detailed discussion. Estimates based on both calibration and econometric studies vary widely, depending on the application and method used. Hall (2004) finds a relatively small value of 0.1 using estimated Euler equations, while studies based on Tobin's Q models frequently estimate values as high as 20 (Hayashi, 1982; Hayashi and Inoue, 1991; Gilchrist and Himmelberg, 1995). DSGE models calibrated or estimated to match business cycle fluctuations in investment typically yield values between these extremes (Garcia-Cicco et al., 2010). Following Bontempi et al. (2004) and Bloom (2009), we set $c = 5$ from the range of plausible values. The wide range of adjustment cost estimates suggest robustness checks from a low value of $c = 1$ to a higher value of $c = 20$.

In the analysis of model dynamics that follows in Section 4, we evaluate two different scenarios for climate policy. In both, the Ramsey-planner implements the optimization problem (14). The scenarios only differ with respect to the remaining carbon budget $\bar{G}$ facing the EU. First, we consider a current climate policy scenario ("CCP") of 51 $GtCO_2e$[13], based on data from the Climate Action Tracker (2024). An EU carbon budget of 51 $GtCO_2e$ is roughly in line with reaching 2.0°C globally with a certain probability according to estimates from the literature.[14] Second, we consider a more ambitious climate policy associated with

[12]That is, we treat the EU as a closed economy. For a study of climate policy in a global setting with multiple open economies see Hémous (2016).

[13]Carbon dioxide equivalents (CO_2e) are a measure of the climate impact of different greenhouse gases (GHGs). By converting different emissions to the equivalent amount of carbon dioxide (CO_2e), their impacts can be compared.

[14]Selecting an appropriate value for the remaining carbon budget for the EU for a given global budget

a "1.5°C " scenario, in which the EU carbon budget is only 30 $GtCO_2e$ based on European Scientific Advisory Board on Climate Change (2023). We emphasize that our analysis does not speak to the optimality of the carbon budget itself, as it is imposed on the planner exogenously. Instead, we focus on optimal macroeconomic adjustment to different levels of the carbon budget.

Two important remarks about the CCP scenario are warranted at this point. First, it does not represent a "no policy" benchmark, but rather is associated with a carbon budget and an associated carbon price. While it is technically straightforward to solve for the optimal growth path in the economy with no carbon budget at all, this is not a valid or interesting point of comparison. Second, we assume that the social planner implements optimal policy with respect to the carbon budget under CCP. This is a strong assumption, given the difficulty of implementing climate policies for both technical and political economy reasons, but it allows us to represent and decompose the economic adjustments necessary to reach the 1.5°C -budget from the current path. Comparing a sub-optimal current policy scenario and 1.5°C scenarios would confound the consequences of climate policy ambition and policy mistakes. We consider sub-optimal climate policies below in Section 4.3.

3.6 An Analytical Perspective on Capital Stranding: Two Propositions

Under robust conditions, our model exhibits asset stranding in the sense that a dirty energy capital stock remains in place after dirty energy production has ceased. This capital stock can no longer be used until it has either been repurposed or lost to depreciation. This result follows from two propositions. Proposition 1 states that dirty energy production ceases at a finite point in time, $\bar{T}$, if the carbon budget is a relevant constraint for the economy, in the sense that the associated Lagrange multipliers assume a positive value. Proposition 2 then shows that if the capital adjustment cost parameter c exceeds some critical value, it is not optimal to run down, or reduce, dirty energy capital to zero immediately upon reaching $\bar{T}$. Dirty energy capital unemployed after $\bar{T}$ is therefore stranded. For the proofs of these propositions see Appendix A.2.

Proposition 1 *The economy's growth path satisfies one of the two following conditions:*

I) There is a finite time $\bar{T}$, such that $G_t = \bar{G}$ and $Y_{dt+1} = 0$ for all $t \geq \bar{T}$.

poses thorny positive and normative questions. See the literature review in European Scientific Advisory Board on Climate Change (2023) on existing estimates of EU fair share carbon budget estimates from 2020). We provide more details on the computation in the Appendix B.

II) The solution to the social planner problem without a carbon budget is identical to the solution to the problem with a carbon budget and $\mu_t = \nu_t = 0$ for all t. That is, the carbon budget is not a relevant constraint.

This proposition establishes the sub-optimality of growth paths along which the shadow value of emissions reduction is strictly positive, but the carbon budget is never fully exhausted ($\nu_t > 0$ and $\mu_t = 0$ for all t). While similar paths are familiar from the resource extraction literature, for example the seminal DHSS model (Dasgupta and Heal, 1974; Solow, 1974; Stiglitz, 1974), they are not optimal in our model.[15] This is an important result, as capital stranding in our sense would not occur, if dirty energy production were to approach zero in the infinite time, but never fully ceases.

Proposition 2 *Assume the economy exhausts the carbon budget in period $\bar{T}$ and the growth rate of consumption is equal to its long-run value g_n for all $t \geq \bar{T}$. Then there exists a critical value for the adjustment costs parameter $\bar{c} = \frac{2\left((1+g_n)^\theta - (1-\delta_d)\beta\right)}{2(1+g_n)^\theta - \beta} > 0$ such that:*

I) if $c \leq \bar{c}$, the dirty energy capital stock is consumed immediately and equals zero for all $t > \bar{T}$

II) if $c > \bar{c}$, the dirty energy capital stock is strictly positive at $t = \bar{T}$ (capital stranding) and declines at a constant rate for all $t \geq \bar{T}$.

Generally, the capital stock employed in dirty energy production does not decline immediately to zero if adjustment costs are sufficiently large. Instead, it is optimal to smooth out capital stock reduction although dirty capital is unemployed (i.e. stranded) and unproductive for some time. In our preferred calibration exercise, $c = 5$ and $\bar{c} = 0.19$, the adjustment cost parameter exceeds the critical threshold by a factor of 25. For the expression characterizing the rate at which capital shrinks after $\bar{T}$, see the proof in Appendix A.2.

Proposition 2 implies that the size of the capital stock in place when Ramsey optimal policy is implemented is irrelevant for whether capital stranding occurs. It does, however affect the size of the stranded capital stock. The incidence of capital stranding depends only on the capital adjustment cost parameter relative to the rate of capital depreciation, the rate of technical progress in the produced good, the discount factor, and the elasticity of intertemporal substitution.

[15] In the DHSS model, a resource is scarce (positive shadow value at all points in time), yet it is never fully exhausted (the non-negativity constraint never binds).

4 Decomposing An Efficient Green Transition

The model of the previous section lends itself in a natural way to an analysis of structural change implied by clean energy transitions as well as the consequences of different policies. Comparing transition paths of the model economy for two policy scenarios described in Section 3.5 allows us to inspect the economic mechanisms that shape an optimal green transition and reveals the sectoral shifts and overall costs associated with a tighter carbon budget. When analyzing the transition, we study economic dynamics through the lens of individual agents' optimal decisions in a decentralized general equilibrium, in which a carbon tax implements the Ramsey-optimal solution.

To recall, the CCP represents an optimistic characterization of current EU climate policy mandating an EU carbon budget consistent with a global increase in temperature no greater than 2.0°C and executed in a Ramsey optimal fashion as described in the previous section. The second, ambitious climate policy denoted as ACP, adopts a more aggressive goal of maximal 1.5°C increase and implies a much tighter carbon budget. Figure 1 summarizes the main results of this section by showing the transition paths of important aggregate and sectoral variables. In all panels, blue solid and orange dashed lines correspond to the CCP and ACP scenarios, respectively. After 2073 the green transition is complete and the economy converges to its long-run unbalanced growth path discussed in Section 3.3. The transition is characterized by a steady slowdown in growth, accompanied by a secular shift in sectoral composition. The high initial growth rate is driven by the energy sector, which is more capital intensive and thus benefits more from rising productivity. Thus, production of intermediate goods is the limiting factor on growth, absorbing an increasing share of labor. In contrast, the price of energy falls as it becomes increasingly abundant, while output becomes more energy intensive ($\frac{Y_{et}}{Y_t}$). For details on these dynamics see Acemoglu and Guerrieri (2008).

Although long-run outcomes are identical across scenarios, a more ambitious climate policy exerts a strong influence on economic dynamics during the transition phase. For each of the two scenarios, the vertical line of the same color in the first panel indicates the year of carbon budget exhaustion and cessation of dirty energy production (2073 versus 2055). In both scenarios carbon taxes rise exponentially until the carbon budget is exhausted, as characterized in Section 3.4. At this time, dirty energy generation is ceases in response to the prohibitive carbon tax. Overall, the associated carbon tax is approximately twice as high under ACP than under CCP, incentivizing a more rapid emission reduction and accelerated transformation of the economy's production structure. While aggregate growth differences appear to be small, we will see that welfare losses in terms of forgone consumption and resources used for capital adjustment are moderately larger for the more ambitious climate policy. We analyze the difference between the two policy scenarios in detail in Section 4.1 and quantify the differences in transition costs in Section 4.2.

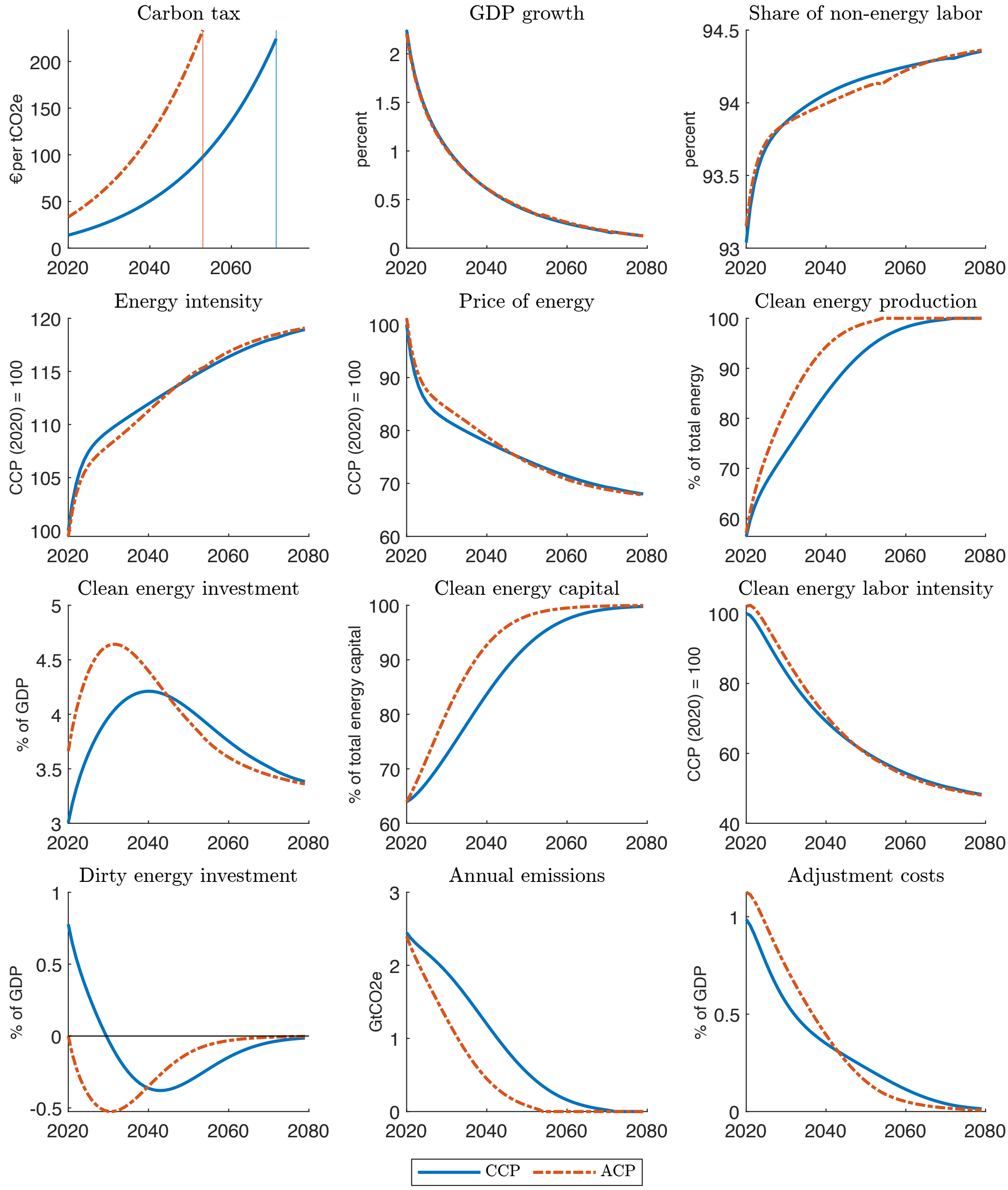

Figure 1: Transition paths with current and ambitious climate policy.

4.1 Optimal Emissions Reduction: Three Channels

How does the economy implement the ambitious climate policy (ACP) scenario limiting the global temperature increase to 1.5°C ? The reduction in emissions is achieved in our model through three channels, which we define formally and analyze in this section. The first channel reduces total energy consumption in production (*energy savings*). The second channel reallocates labor to the clean energy production, holding the sectoral allocation of capital constant (*labor redeployment*). The final channel expands clean energy capacity through new investment (*clean energy investment*). The Ramsey-optimal carbon tax incentivizes economic agents to use these channels in the most efficient way possible.

Figure 2 quantifies the importance of each channel for the transition. It decomposes the additional reduction in dirty energy generation under the ACP scenario compared to the current climate policy (CCP) scenario ($Y_{dt}^{CCP} - Y_{dt}^{ACP}$) caused by each channel in every year t from 2020 to 2060. By construction, the three channels add up to the total reduction in dirty energy. The left panel of Figure 2 shows the contribution of each channel to emissions reduction in levels, converting energy units into emissions in $GtCO_2e$. The right panel shows each channel's contribution in relative terms, meaning the fraction of additional emission reduction in ACP attributed to that channel is divided by the overall additional emissions reduction in year t.[16]

I) Energy savings. At the outset, the higher carbon tax imposed in the ACP scenario raises the relative price of dirty energy directly and immediately. Since clean energy capacity is limited by installed capital, the price of energy rises. Final goods producers respond by substituting non-energy inputs for energy inputs, but the scope of this is limited by the low elasticity of substitution ($\epsilon = 0.45$). Energy intensity of output Y_{et}/Y_t declines by 2% relative to the baseline at the trough in 2030. We measure the importance of the energy savings channel as difference in the total energy consumption

$$ES_t = Y_{et}^{CCP} - Y_{et}^{ACP}. \tag{20}$$

The result is depicted as the green line in Figure 2. The energy savings channel initially accounts for over 70% of emissions reduction, but overall reduction is modest at this point. As the economy scales up emissions reduction, energy savings increase until reaching 25% of total emissions reduction. After 2030, clean energy supply has caught up with demand, the price of energy begins to decline and with it, the importance of the energy savings channel.

II) Labor redeployment. Clean energy producers respond to a higher carbon tax-induced energy price by increasing supply. Their installed capital stock is costly to adjust in the short run, so they initially expand employment faster than capital. By 2030, the ratio of workers to capital is 7% higher in the ACP scenario than under current policy. Since capital and labor are imperfect substitutes, this adjustment raises the cost of producing

[16] The relative decomposition only makes sense when the difference $Y_{dt}^{CCP} - Y_{dt}^{ACP}$ is positive, which is the case throughout.

clean energy, which equates to the higher market price of dirty energy because they are perfect substitutes. To measure the labor redeployment channel we construct hypothetical clean energy production using the capital stock under CCP and the capital-labor-ratio of the ACP scenario. We then compute the difference to the actual level of clean energy production under CCP. Formally, hypothetical clean energy output is

$$\tilde{Y}_{ct}^{CCP} = M_{ct} \left(K_{ct}^{CCP}\right)^{1-\alpha_c} \left(\frac{K_{ct}^{CCP}}{K_{ct}^{ACP}} L_{ct}^{ACP}\right)^{\alpha_c}. \tag{21}$$

and the labor redeployment channel is

$$LD_t = \tilde{Y}_{ct}^{CCP} - Y_{ct}^{CCP}. \tag{22}$$

The labor redeployment channel is the least important margin of adjustment, with its contribution following a similar pattern to that of the energy savings channel. The reason is that energy production is highly capital intensive and its output elasticity with respect to labor is low, so a large-scale increase in clean energy supply through an expansion of employment is prohibitively costly.

III) Clean energy investment. The higher implied price path of energy stimulates clean energy capital formation. Adjustment costs make it optimal to build up the capital stock to meet the higher demand for clean energy only gradually. For the first 15 years, annual clean energy investment comprises an additional percentage point of GDP under the ACP, leading to an accelerated build-up of the capital stock. By 2030, 80% of energy capital is clean under ACP compared to 70% under CCP. To measure the importance of this channel in terms of energy production, we compute the difference between clean energy output under ACP, Y_{ct}^{ACP}, and the hypothetical clean energy output with the capital stock of CCP, $\tilde{Y}_{ct}^{CCP}$ constructed above:

$$CI_t = Y_{ct}^{ACP} - \tilde{Y}_{ct}^{CCP}. \tag{23}$$

Summing over the three channels, our decomposition reads

$$ES_t + LD_t + CI_t = \underbrace{Y_{et}^{CCP} - Y_{et}^{ACP}}_{\text{Energy savings}} + \underbrace{\tilde{Y}_{ct}^{CCP} - Y_{ct}^{CCP}}_{\text{Labor redeployment}} + \underbrace{Y_{ct}^{ACP} - \tilde{Y}_{ct}^{CCP}}_{\text{Clean investment}} \tag{24}$$

$$= Y_{et}^{CCP} - Y_{ct}^{CCP} - \left(Y_{et}^{ACP} - Y_{ct}^{ACP}\right) \tag{25}$$

$$= Y_{dt}^{CCP} - Y_{dt}^{ACP}.$$

confirming that the three channels add up to the total difference in dirty energy production across the two scenarios.

Since all capital stocks are predetermined at the outset, the contribution of the clean energy investment channel is initially zero, and it remains small initially due to adjustment costs. However, it overtakes the other channels within 4 years, reaching almost 100 percent by 2049. Over the entire transition it is by far the most important channel. A central insight from this decomposition is that capital is the main driver of an optimal green transition.

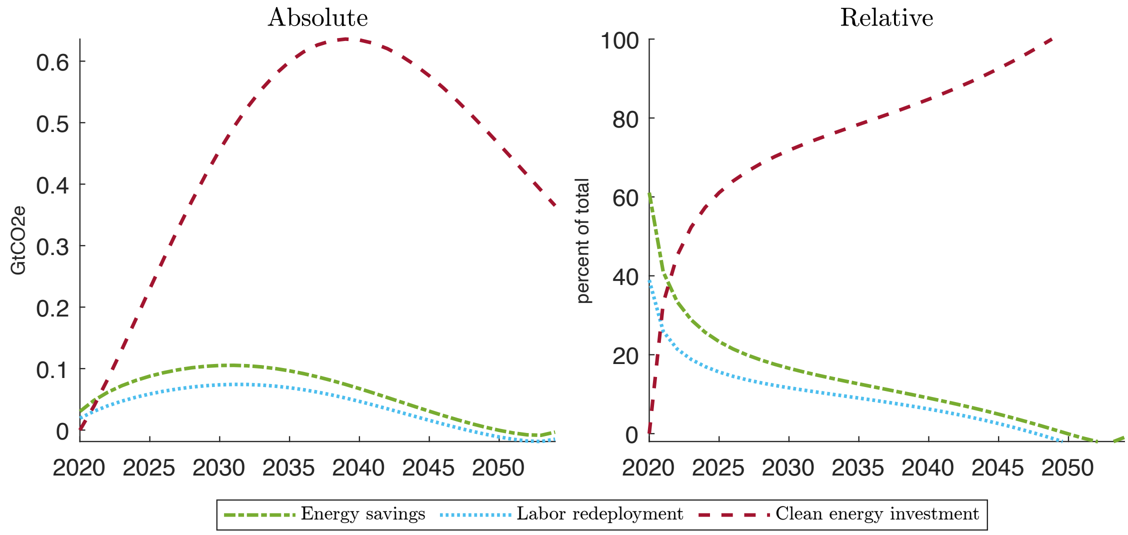

Figure 2: Decomposition of contributions to emissions reduction of energy savings, labor redeployment and clean energy investment channels in the ambitious climate policy scenario (ACP) compared to current climate policy (CCP) over time. The left panel shows the contribution of each channel to emissions reduction in levels, converting energy units into emissions measured in $GtCO_2e$. The right panel shows each channel's contribution to emissions reduction in ACP as share of overall additional reduction in emissions in each year 2020-2050.

4.1.1 Capital Adjustment Costs and the Shape of the Transition

Our numerical results show that the transformation of the energy capital stock is the primary channel through which the economy adopts to a clean energy system. The optimal pace of the energy transformation will depend heavily on the feasibility of scaling up the capital stock quickly and therefore on capital adjustment costs. As discussed in the calibration section, however, the magnitude of adjustment costs is difficult to pin down. To better understand the economic mechanisms at play and to investigate the sensitivity of our quantitative results, we compare transition paths for CCP and ACP policy scenarios in an economy with high and low adjustment costs ($c = 20$ and $c = 1$) but with otherwise identical parameters to the baseline calibration ($c = 5$).

Transition paths for the CCP and ACP scenario in the high-adjustment cost economy compared to the same policy scenarios in the economy with baseline parameters are shown in Figure 3. Naturally, higher adjustment costs imply larger shares of output are devoted to

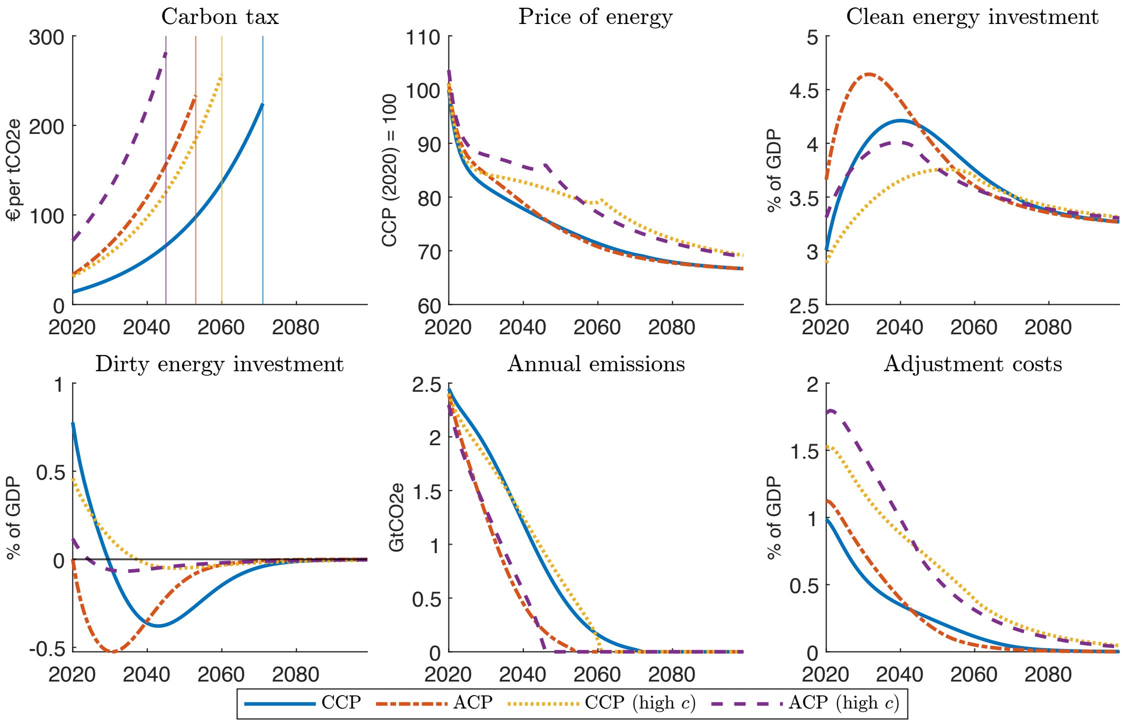

Figure 3: Transition paths for selected variables under CCP and ACP with baseline ($c = 5$) and high adjustment costs $c = 20$.

capital adjustment and higher carbon taxes are required to incentivize the transition. The details of the paths are more nuanced, however. Higher adjustment costs imply that firms smooth out changes in the capital stock more. Thus firms initially invest less in clean as well as dirty energy capital to avoid large swings in investment. The transformation ramps up less rapidly and the economy exhausts the carbon budget earlier than in the baseline. When dirty energy generation ceases, clean energy supply is still inadequate to satisfy total energy demand and energy prices spike upward, indicating a more abrupt transition.

In the light of these results, we revisit the channel decomposition of the adjustment to more ambitious climate policy for the high adjustment cost economy depicted in Figure 4. The most striking result is the diminished importance of the investment channel relative to the two other channels. Consistent with the earlier result, the clean energy capital stock is not sufficiently large when the carbon budget is exhausted. As a result, the phase-out of dirty energy is accompanied by a significant reduction in energy use and a larger labor redeployment to the clean energy sector. Neither of these adjustment are quantitatively significant in our baseline (Figure 2).

Figure 5 displays the transition paths for the CCP and ACP policy scenario under low adjustment costs ($c = 1$).[17] In line with expectations, adjustment costs are smaller and lower carbon taxes are needed to respect the carbon budgets. The most striking difference

[17]We omit the low-adjustment-cost equivalent of Figure 4, which offers few additional new insights.

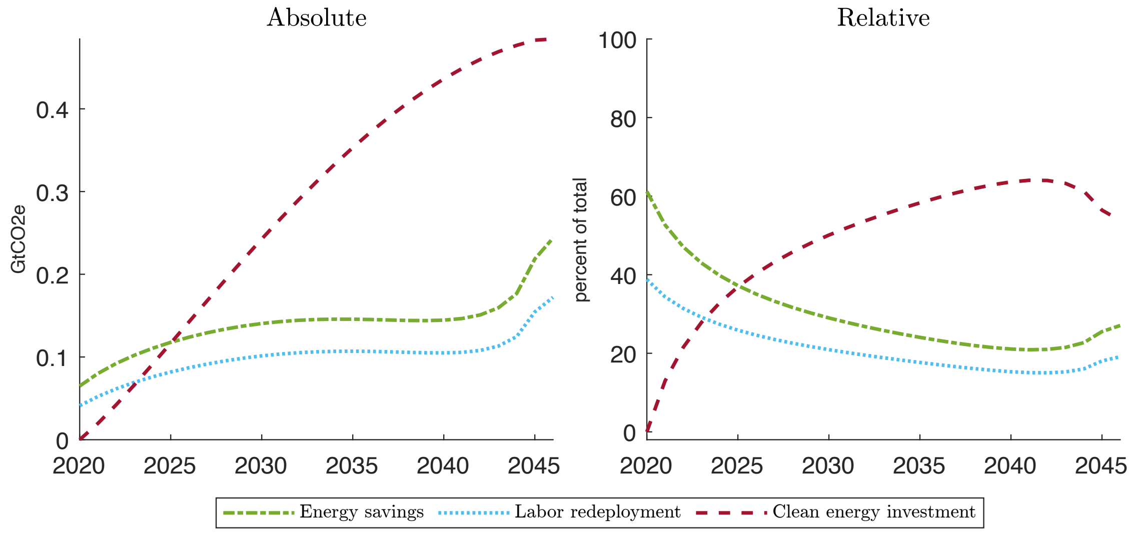

Figure 4: Decomposition of contributions to emissions reductions from current to ambitious climate policy scenarios under high adjustment costs ($c = 20$)

lies in the paths of clean and dirty energy investment. With lower adjustment costs, clean energy investment initially falls below the baseline but accelerates more rapidly over time. The opposite pattern holds for dirty energy: it is substantially higher in the early years but declines more sharply than in the baseline. Because adjustment costs are low, it is efficient to rely more heavily on dirty energy at first, when its productivity advantage is greatest, and then to transition swiftly to clean energy once the carbon budget nears exhaustion. The findings in this section underscore the role of capital adjustment costs for the green transition. Their magnitude not only affects optimal carbon prices quantitatively, but also alters the shape of the transition path qualitatively.

4.2 How Costly is the Green Transition?

Our model can quantify resource and welfare costs of different policy scenarios. While Figure 1 shows only slight differences, it would be incorrect to conclude that the costs of policy ambition are negligible, as (i) small differences in growth rates cumulate over time[18] and (ii) GDP is not equivalent to welfare. In Table 1, we quantify the costs of the transition for the CCP and ACP policy scenarios in economies with the baseline, high, and low values for the capital adjustment cost parameter. Before we do so, it is useful to define these costs.

Welfare measure Because carbon budget is exogenous, the only relevant variable for measuring welfare in our model is consumption. To measure the difference in welfare across two transition paths A and B with associated consumption paths C_t^A and C_t^B, we use the

[18]Indeed, the difference in GDP reaches a trough of -0.26% in 2039 and it takes until the 2070 for GDP under ambitious policy to recover fully.

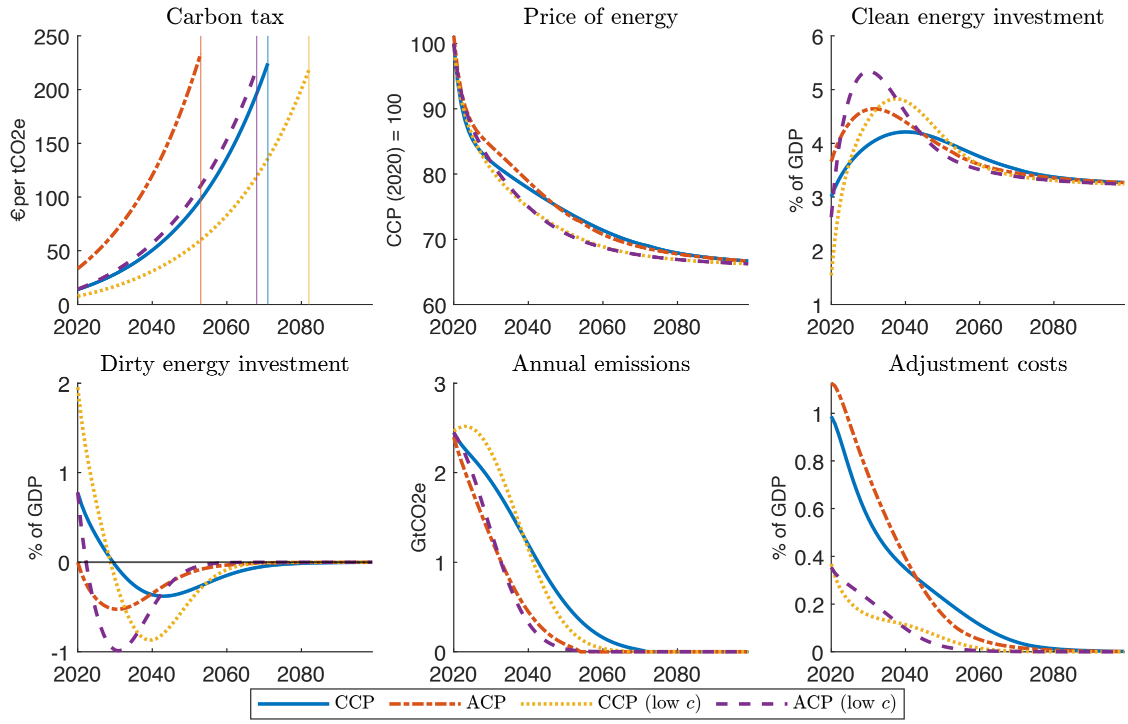

Figure 5: Transition paths for selected variables under current and ambitious climate policy with baseline ($c = 5$) and low adjustment costs ($c = 1$).

percentage variation in consumption between 2020 and 2060 that compensates agents in scenario B for living in scenario A permanently, following Burda and Zessner-Spitzenberg (2022). Specifically, we define $\Lambda(A, B)$ implicitly as

$$\sum_{t=2020}^{2060} \beta^t U\left(\left(1 + \frac{\Lambda(A,B)}{100}\right) C_t^B\right) + \sum_{t=2061}^{\mathcal{T}} \beta^t U(C_t^B) = \sum_{t=2020}^{\mathcal{T}} \beta^t U(C_t^A),$$

where $\mathcal{T}$ is the last period in our simulation. We choose 2060 to ensure a fair comparison of transition costs to consumption during the transition period. Importantly, we include the utility stream after 2060 such that differences in capital accumulation up to this point are reflected in the welfare measure. We ensure that $\mathcal{T}$ sufficiently large so as to not bias the comparison. 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)).

The fifth column of Table 1 displays a welfare comparison between the CCP and ACP scenario for different values of the adjustment cost parameter c. Increasing climate policy ambition from CCP to ACP is associated with a welfare equivalent loss of 0.27% of consumption. The figure decreases to 0.14% with low adjustment costs, increasing to 0.54% with high adjustment costs. Capital adjustment costs are of first-order importance for transition costs.[19]

Direct measures of adjustment costs To complement the consumption-based welfare measure, we also compute two descriptive measures of transition costs that highlight the role played by capital adjustment. The first measure is simply the average output lost due to adjustment costs during the transition. Specifically, the share of adjustment costs of GDP $\frac{\Omega_t}{Y_t}$ is computed for every year between 2020 and 2060 and then the average for a given transition path is taken. The second measure is the extent of asset stranding. We compute this measure by dividing quantity of dirty capital stranded when dirty energy production ceases in period $\bar{T}$ by GDP in 2020 under CCP. For example, stranded capital with ACP and baseline adjustment costs is given by $\frac{K_{d2055}^{ACP}(c=5)}{Y_{2020}^{CCP}(c=5)}$.

In the benchmark economy, the average share of GDP lost due to adjustment costs is 0.43% under CCP and 0.48% under ACP between 2020 and 2060, so the additional loss under ACP is 0.05 percentage points each year on average. Since consumption is approximately 75% of GDP in the model, this amounts to 0.08 ppts of consumption. Capital adjustment costs thus contribute around 25% of the welfare loss associated with ACP relative to CCP (0.27% of consumption). In contrast, capital stranding amounts to 0.76% of 2020 GDP with CCP and 1.46% of GDP with ACP. The difference is 0.7% of 2020 GDP, which is small relative to the welfare loss which is computed over 40 years.[20]

Our results are sensitive to the choice of the capital adjustment cost parameter. With low adjustment costs, capital stranding is zero and adjustment costs are less than 0.15% of GDP in both policy scenarios. In contrast, with high adjustment costs, output lost roughly doubles relative to the baseline. Stranded dirty energy capital measured as a share of annual GDP exceeds 8.1% of GDP even under CCP, while it is almost 10.5% under ACP. Overall, we find low to moderate impacts on welfare and growth in our baseline scenarios with and without increased climate ambitions. However, higher adjustment costs can substantially increase consumption based welfare costs and stranded assets.

4.3 Capital Stranding and the Cost of Sub-Optimal Policy

In our baseline calibration, welfare costs and the quantity of stranded dirty capital are modest under Ramsey-optimal policies in the ACP scenario. It is important to recall that our analysis does not speak to the question of the optimal climate goals, as the benefits of emissions reduction are not modeled. We have so far characterized optimal transition paths

[19]As emphasized above, effects of ambitious climate policy are biased downward, because we take the carbon target as given. A complete welfare analysis would consider climate-related damages and non-consumption sources of utility.

[20]Capital adjustment costs also cause indirect losses, which are not measured here, by distorting the use of production factors relative to the efficient static allocation.

and associated costs under different carbon budgets, CCP and ACP. However, real-world policies could be far from optimal even for a given carbon budget, leading to larger costs. To quantify these cost of sub-optimal policy, we study two cases in which ambitious climate policy is introduced with delay. In both, carbon taxes follow the CCP scenario for an initial period of $\tilde{t}$ years; thereafter, the carbon budget associated with the 1.5°C goal is imposed, i.e., cumulative emissions are identical to the ACP scenario. The more ambitious carbon budget is attained through Ramsey-optimal carbon taxation, which is implemented after $\tilde{t}$ years.

These two cases differ only with respect to expectations of economic agents over the path of taxes. In the first, which we denote as a "delayed carbon tax", agents correctly anticipate the entire path of taxes. That is, they foresee already in the initial period that taxes will be raised in $\tilde{t}$ years to implement the more ambitious 1.5°C goal. In the second class of policies labeled "regime switch", the carbon tax is subject to an unanticipated shift after $\tilde{t}$ years, upon which agents reoptimize. The regime switch is an "MIT shock": until it occurs, agents expect the carbon tax to follow the same path as in the CCP scenario forever. But after $\tilde{t}$ years, the carbon tax jumps to the optimal path that implements the 1.5°C target. From this point $\tilde{t}$ onward, agents expect taxes to follow the new Ramsey-optimal path forever with certainty. Details on the implementation of the two cases are provided in Appendix A.3.

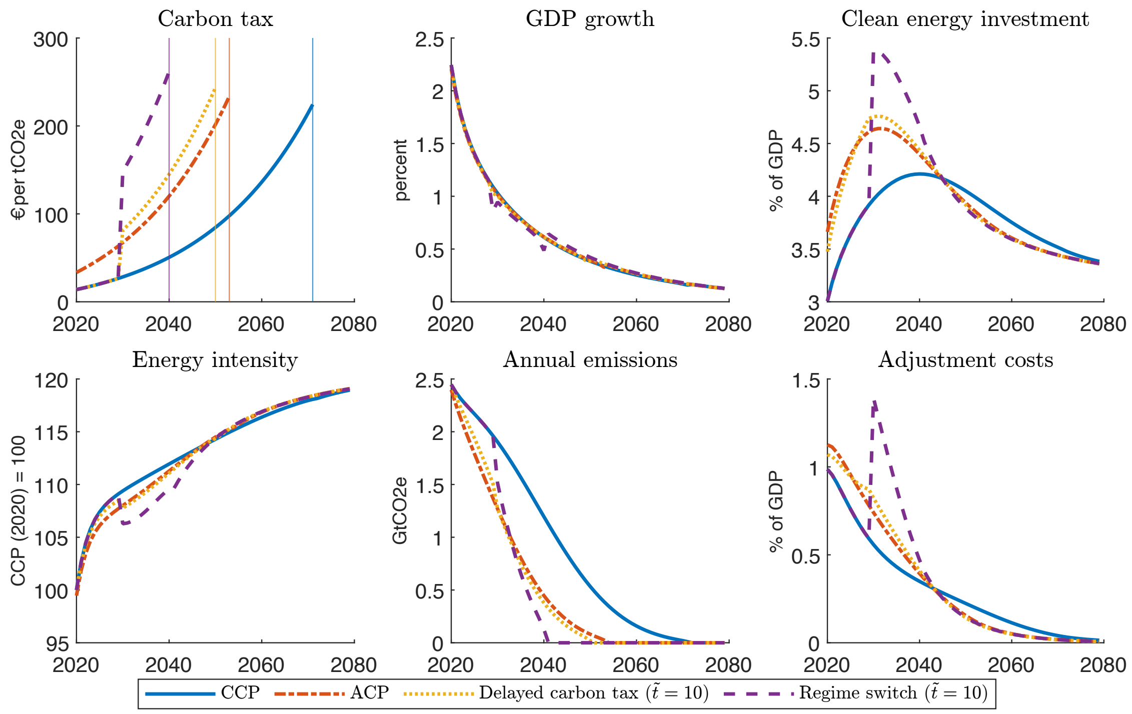

Figure 6: Transition paths with sub-optimal policy. The shown paths correspond to the delayed carbon tax and regime switch after $\tilde{t} = 10$ years compared to CCP and ACP.

Figure 6 shows transition paths for sub-optimal policies under delayed implementation,

$\tilde{t} = 10$ in comparison to the CCP and ACP scenarios for our baseline parametrization. To understand dynamics, consider first the carbon tax in the top left panel. Until 2030, the carbon tax is identical to the CCP scenario under the two sub-optimal policy regimes by assumption. In 2030, when the Ramsey-optimal policy consistent with the 1.5°C goal is implemented, the carbon tax increases above the ACP level. Emissions exceed those under ACP while carbon taxes are still low. In order to reach the same cumulative emissions budget as ACP, emissions must then be lower going forward under sub-optimal policy. Both sub-optimal policy scenarios imply reductions in GDP growth and energy intensity of output as well as increases in clean energy investment and adjustment costs after 2030.

While qualitatively similar, the two sub-optimal policies have very different quantitative implications. The path under the delayed carbon tax is closest to the ACP scenario throughout. The expected increase in carbon taxes leads to front-loaded clean energy investment and a reduction in emissions in advance of the tax implementation. In contrast, the regime switch ("MIT shock") scenario is associated with significant economic disruption. Since emissions are identical to the CCP scenario until 2030, a much smaller carbon budget remains at the time when the regime change arrives. To achieve the 1.5°C target, the carbon tax must be increased immediately to twice the level of the ACP scenario in 2030 with dramatic consequences for all variables.

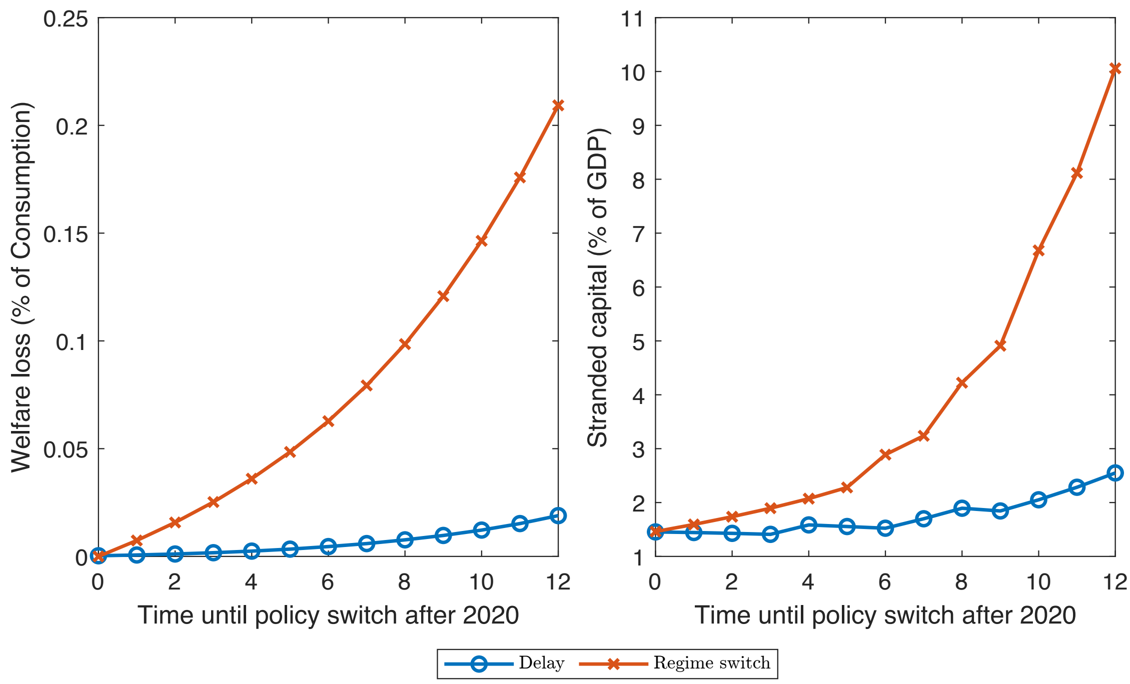

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Figure 7: Welfare loss and stranded dirty energy capital under sub-optimal policy. The welfare loss is relative to the ACP scenario. Stranded dirty energy capital is measured at time $\bar{T}$ when dirty energy is no longer generated. The time $\tilde{t}$ indicates by how many years the optimal 1.5C compatible carbon tax is delayed and after how many years regime switch takes place in the two sub-optimal policy cases. The values at $\tilde{t} = 0$ correspond to the ACP scenario.

To highlight costs of these sub-optimal policies, Figure 7 displays welfare losses relative to the ACP scenario as well as the extent of asset stranding for values of $\tilde{t}$ between 0 and 12 years for both sub-optimal policy scenarios. In both cases, the welfare loss relative to ACP and asset stranding rise exponentially with the number of years optimal policy is postponed. However, in the delayed carbon tax scenario they remain modest. The welfare loss in consumption equivalents remains below 0.02% of consumption, while the amount of stranded dirty energy capital rises from 1.46% to around 2.5%. The increases in costs are much larger in the regime switch scenario. The additional welfare cost of a regime switch to the 1.5°C goal after 12 years relative to ACP is 0.2%. Recall that the cost of reaching the 1.5°C goal optimally, i.e. implementing the ACP immediately, is 0.27% of consumption relative to CCP. Sub-optimal policy roughly doubles the welfare cost of climate ambition. The numbers are even more striking for stranded dirty capital, which increases more than 10-fold to 10% of GDP in 2020.

Differences of these magnitudes between policies are remarkable, and highlight the importance of creating and communicating credible plans to align expectations with future climate policies. They imply that a relatively smooth transition is possible under an ambitious climate goal, even if policy action is delayed by more than a decade. It is essential to convince economic agents, however, that the ambitious policy will be implemented. If this is not the case, emissions remain high and energy systems reliant on dirty energy for too long, leading to a disruptive and costly transition later on. These results should not be interpreted as support for short-run passive climate policy while announcing policies in the future. In contrast, they emphasize the value of credible policy announcements, as promises of future policies that fail to set the right expectations lead to significantly higher welfare costs and asset stranding.

5 Conclusion

An efficient energy transition requires installing the right energy capital stock. In this paper, we study the green energy transition in a three-sector growth model with a binding carbon budget calibrated to the EU. Despite an infinite long-run elasticity of substitution between clean and dirty energy, our analysis explicitly recognizes that rapid accumulation of an alternative capital stock is increasingly costly due to limited availability of specialized workers and other inputs needed for its installation. These scarcities are captured by convex capital adjustment costs.

Increasing climate policy ambition from current policy to the 1.5°C goal leads to reduction in welfare equivalent to 0.27% of consumption in the transition phase (2020-2060), a figure that roughly doubles under high adjustment costs. Assigning optimal CO_2 emission reduction to three channels – energy savings, labor redeployment, and green capital formation, the investment channel is the most important. Ramsey optimal paths typically dictate front-loaded clean investment long before complete phaseout of dirty energy generation, but also robustly imply stranding of dirty capital stranding. The quantity of capital that is left stranded under optimal policy is modest at 1.5% of GDP even for ambitious climate goals. In the presence of capital adjustment costs sub-optimal policies can be costly both in welfare terms and in the form of capital stranding. Switching unexpectedly from a 2.0°C to a more ambitious 1.5°C target after 10 years increases the associated welfare cost by more than 70% relative to a scenario in which the 1.5°C goal is implemented optimally from the start. Even more strikingly, stranded capital rises to 7% of GDP.

Scenario	**Net zero**	**Carbon Budget**	**Carbon Tax**	**Δ Welfare**	**Stranded Assets**	**Adjustment Costs**
	Year achieved	GtCO_2e	€/tCO_2e	% of Cons.	K_D/Y (%)	$\Omega/Y(\%)$
Baseline ($c = 5$)						
CCP	2073	51	28.3	-	0.76	0.43
ACP	2055	30	67.37	-0.27	1.46	0.48
High adj. costs scenario						
CCP($c = 20$)	2062	51	57.33	-	8.1	0.94
ACP($c = 20$)	2047	30	129.7	-0.54	10.36	1.03
Low adj. costs scenario						
CCP($c = 1$)	2084	51	16.97	-	0	0.12
ACP($c = 1$)	2070	30	31.21	-0.14	0	0.13

Table 1: Costs of the green energy transition. For definitions see the main text in Section 4.2.

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A Appendix

A.1 Derivations

A.1.1 Derivations for baseline model

Adjustment costs The derivatives of the adjustment cost function with respect to the first and second arguments are given by

$$\Omega_1^i(K_{it}, K_{it-1}) = c\frac{K_{it} - (1+z_i)K_{it-1}}{K_{t-1}^i}$$
$$\Omega_2^i(K_{it}, K_{it-1}) = -c(1+z_i)\frac{K_{it} - (1+z_i)K_{it-1}}{K_{t-1}^i} - \Omega^i(K_{it}, K_{it-1})\frac{1}{K_{it-1}}$$

Marginal Products For $i \in \{n, d, c\}$ the marginal factor products are:

$$\frac{\partial Y_{it+1}}{\partial K_{it}} = (1-\alpha_i)M_{it+1}K_{it}^{-\alpha_i}L_{it+1}^{\alpha_i} = (1-\alpha_i)\frac{Y_{it+1}}{K_{it}} \quad \text{and} \quad \frac{\partial Y_{it}}{\partial L_{it}} = \alpha_i M_{it}K_{it-1}^{1-\alpha_i}L_{it}^{\alpha_i - 1} = \alpha_i\frac{Y_{it}}{L_{it}}.$$

The marginal products of intermediate inputs n and e in final production are

$$\frac{\partial Y_t}{\partial Y_{nt}} = \gamma\left(\frac{Y_{nt}}{Y_t}\right)^{-\frac{1}{\epsilon}} \quad \text{and} \quad \frac{\partial Y_t}{\partial Y_{et}} = (1-\gamma)\left(\frac{Y_{et}}{Y_t}\right)^{-\frac{1}{\epsilon}}.$$

A.1.2 Social Planner optimality conditions

The first order conditions for the Lagrangian (14), repeating those already given in equations (15)-(18), are

C_t:

$$C_t^{-\theta} = \lambda_t$$

L_{nt} :

$$\lambda_t \frac{\partial Y_{nt}}{\partial L_{nt}} \frac{\partial Y_t}{\partial Y_{nt}} = \eta_t$$

L_{ct} :

$$\lambda_t \frac{\partial Y_{ct}}{\partial L_{ct}} \frac{\partial Y_t}{\partial Y_{et}} = \eta_t$$

L_{dt} :

$$\left(\lambda_t \frac{\partial Y_t}{\partial Y_{et}} - \frac{\nu_t}{\sigma} \right) \frac{\partial Y_{dt}}{\partial L_{dt}} = \eta_t$$

for $t \in [1, \bar{T}]$.

K_{nt} :

$$\lambda_t \left[1 + \Omega_1^n(K_{nt}, K_{nt-1}) \right] = \beta \lambda_{t+1} \left[\frac{\partial Y_{nt+1}}{\partial K_{nt}} \frac{\partial Y_{t+1}}{\partial Y_{nt+1}} + (1 - \delta_n) - \Omega_2^n(K_{nt+1}, K_{nt}) \right]$$

K_{ct} :

$$\lambda_t \left[1 + \Omega_1^c(K_{ct}, K_{ct-1}) \right] = \beta \lambda_{t+1} \left[\frac{\partial Y_{ct+1}}{\partial K_{ct}} \frac{\partial Y_{t+1}}{\partial Y_{et+1}} + (1 - \delta_c) - \Omega_2^c(K_{ct+1}, K_{ct}) \right]$$

K_{dt} :

$$\begin{aligned} &\lambda_t \left[1 + \Omega_1^d(K_{dt}, K_{dt-1}) \right] = \\ &\quad \beta \lambda_{t+1} \left[\frac{\partial Y_{dt+1}}{\partial K_{dt}} \frac{\partial Y_{t+1}}{\partial Y_{et+1}} + (1 - \delta_d) - \Omega_2^d(K_{dt+1}, K_{dt}) \right] - \beta \frac{\nu_{t+1}}{\sigma} \frac{\partial Y_{dt+1}}{\partial K_{dt}}. \end{aligned}$$

for $t \in [1, \bar{T} - 1]$. In addition:

$$\lambda_t \left[1 + \Omega_1^d(K_{dt}, K_{dt-1}) \right] - \xi_t^{Kd} = \beta \lambda_{t+1} \left[(1 - \delta_d) - \Omega_2^d(K_{dt+1}, K_{dt}) \right].$$

for $t \geq \bar{T}$ with the associated sequence of complementary slackness conditions $K_{dt} \xi_t^{Kd} = 0$.

G_t

$$\nu_t = \beta \nu_{t+1} \quad \text{for} \quad t \in [1, \bar{T} - 1] \quad \text{and} \quad \nu_{\bar{T}} = \mu_{\bar{T}}.$$

The remaining conditions are the resource constraint (6), labor market clearing condition (7), accumulation equation for G_t (8) and evolution of M_{it} (10). Initial values for K_{n0}, K_{d0}, K_{c0}, M_{n0}, M_{d0}, M_{c0} and G_0 are given.

A.1.3 Decentralized economy

The economy is populated by 7 types of firms and a representative household who owns the firms. Firms are comprised of final good producers, three different types of intermediate goods producers and three types of capital goods producers for each $i \in \{n, d, c\}$. All firms operate constant returns to scale technologies in competitive markets and in a competitive equilibrium earn zero profits. Firms operating the dirty energy technology pay a tax τ_{dt} per unit of emissions generated in production. All private agents perceive greenhouse gas emissions as an externality, so that their behavior is not influenced by the presence of the upper bound on cumulative emissions, but only by the CO_2 tax.

Households. The Lagrangian associated with the optimization problem of the representative household then is

$$\begin{aligned}\mathcal{L}^P\Big(\{C_t, \{(L_{it}, K_{it})\}_{i\in\{n,d,c\}}\}_{t=1}^{\infty}\Big) &= \sum_{t=0}^{\infty}\beta^t\Big\{\ \frac{C_t^{1-\theta}-1}{1-\theta} \\ &+\lambda_t^P\left(w_t(L_n+L_d+L_c)+\sum_{i\in\{n,d,c\}}((q_{it}^o+r_{it})K_{it-1}-q_{it}K_{it})+T_t-C_t\right) \\ &+\eta_t^P(L_n+L_d+L_c-\bar{L})\Big\}.\end{aligned} \tag{A1}$$

where λ_t^P and η_t^P are the private shadow values of output and the labor endowment, which in the absence of optimal taxation could be different from the social planner's values λ_t and η_t. T_t are revenues from the carbon tax which are redistributed as a lump sum back to households.

The first order condition for consumption is identical to the social planner problem:

$$C_t^{-\theta} = \lambda_t^P.$$

For the three capital choices, the first order conditions are:

$$\lambda_t^P q_{it} = \beta\lambda_{t+1}^P\left(q_{it+1}^o + r_{it+1}\right).$$

For the three labor choices the first order conditions are identical:

$$\lambda_t^P w_t = \eta_t^P.$$

Final goods producers. The final good serves as the numeraire. Competitive final goods producers take output and input prices as given and maximize

$$\Pi_{Ft} = \max_{Y_{nt},Y_{et}} \left(\gamma Y_{nt}^{\frac{\epsilon-1}{\epsilon}} + (1-\gamma) Y_{et}^{\frac{\epsilon-1}{\epsilon}}\right)^{\frac{\epsilon}{\epsilon-1}} - p_{nt}Y_{nt} - p_{et}Y_{et}$$

with the first order conditions

$$p_{nt} = \frac{\partial Y_t}{\partial Y_{nt}} \quad \text{and} \quad p_{et} = \frac{\partial Y_t}{\partial Y_{et}}.$$

Final goods producers operate constant returns to scale technologies under perfect competition, so their profits are zero.

Intermediate goods producers. Competitive intermediate goods producers operating technology i take factor prices and the price of their output as given and maximize

$$\Pi_{it} = \max_{K_{it-1},L_{it}} p_{jt} M_{it} K_{it-1}^{1-\alpha_i} L_{it}^{\alpha_i} - w_t L_{it} - r_{it} K_{it-1} - \tau_{it} \frac{Y_{it}}{\sigma}$$

for $(i, j) \in \{(n, n), (d, e), (c, e)\}$. Here $\tau_{nt} = \tau_{ct} = 0$. Optimal factor choices for d, using the energy price obtained from the final goods producers' problem, imply:

$$w_t = \left(\frac{\partial Y_t}{\partial Y_{et}} - \frac{\tau_{dt}}{\sigma}\right) \frac{\partial Y_{dt}}{\partial L_{dt}}$$

and

$$r_{dt} = \left(\frac{\partial Y_t}{\partial Y_{et}} - \frac{\tau_{dt}}{\sigma}\right) \frac{\partial Y_{dt}}{\partial K_{dt-1}}.$$

For n and c optimal factor choices similarly imply

$$w_t = \frac{\partial Y_t}{\partial Y_{nt}} \frac{\partial Y_{nt}}{\partial L_{nt}} \quad \text{and} \quad w_t = \frac{\partial Y_t}{\partial Y_{et}} \frac{\partial Y_{ct}}{\partial L_{ct}}$$

and

$$r_{nt} = \frac{\partial Y_t}{\partial Y_{nt}} \frac{\partial Y_{nt}}{\partial K_{nt-1}} \quad \text{and} \quad r_{ct} = \frac{\partial Y_t}{\partial Y_{et}} \frac{\partial Y_{ct}}{\partial K_{ct-1}}.$$

The rental rate of capital r_{it} is technology-specific due to capital adjustment costs. Because labor is perfectly mobile, the wage w_t is equalized across sectors. Like final goods producers, intermediate goods producers operate under constant returns to scale technologies under perfect competition so their profits are zero.

Capital producers. After production takes place, capital goods producers purchase old capital of type i from households at price q_{it}^o on a competitive market and combine it with new investment to produce new capital which they sell to households at price q_{it}. The production process is subject to quadratic capital adjustment costs described in the main text. The profits of a capital good producer of type i are given by:

$$\Pi_{it}^K = \max_{K_{it}, K_{it-1}} q_{it}K_{it} - K_{it} - \Omega^i(K_{it}, K_{it-1}) + (1-\delta_i)K_{it-1} - q_{it}^o K_{it-1}$$

First order conditions imply prices for old and new capital of

$$q_{it} = 1 + \Omega_1^i(K_{it}, K_{it-1}) \quad \text{and} \quad q_{it}^o = 1 - \delta_i - \Omega_2^i(K_{it}, K_{it-1}).$$

Like the other firms, capital producers operate under constant returns to scale so their profits are zero. Notice also that investment in sector i, measured as net purchases of capital goods, is equal to

$$\hat{I}_{it} = q_{it}K_t - q_{it}^o K_{it-1} = (1+\Omega_1^i(K_{it}, K_{it-1}))K_t - (1-\delta_i - \Omega_2^i(K_{it}, K_{it-1}))K_{it-1} = I_{it} + \Omega_1(K_{it}, K_{it-1})$$

i.e. the sum of investment goods and capital adjustment costs. The last equality follows immediately from first-order homogeneity of capital adjustment costs.

For a given sequence of taxes τ_{dt}, we now have a complete set of decentralized equilibrium conditions which determine sequences for all quantities $\{C_t\}$, $\{L_{it}, K_{it}\}_{i\in\{n,d,c\}}$ and $\{G_t\}$ as well as prices $\{w_t\}$, $\{r_{it}\}_{i\in\{n,d,c\}}$ and $\{p_{it}\}_{i\in\{n,e\}}$.

A.1.4 Optimal carbon tax

We now characterize the path of optimal carbon taxes τ_{dt} such that all quantities in the decentralized equilibrium coincide with the optimal allocation chosen by the social planner. To this end, we conjecture that all quantities are identical and then construct a path for τ_{dt}, such that all decentralized equilibrium conditions are satisfied.

First, since the social planner economy and the decentralized economy are identical, the social planner allocation is feasible in the decentralized economy. This can be verified by computing all incomes in the household budget constraint (factor income, lump-sum transfer) after imposing the social planer factor choices to recover the same consumption level as obtained under the social planner. Then, plugging in the expressions for the wage w_t, capital prices q_{it}^o and q_{it} as well as rental rates r_{it} into the household optimality conditions for non-energy and clean energy capital and labor $(K_{nt}, L_{nt}, K_{ct}, L_{ct})$, yield equations identical to the social planner's optimality conditions.

It only remains to construct taxes τ_d, such that the social planner's choices for dirty energy capital and labor (K_{dt}, L_{dt}) satisfy the equilibrium conditions in the decentralized economy. Then all private equilibrium conditions are satisfied. To proceed, we use that $\lambda_t w_t = \eta$ following from the planner's and intermediate goods firms' choices for non-energy labor and the fact that consumption levels are equal which implies $\lambda_t = \lambda_t^P$. We can then combine social planner's optimality (15) with the intermediate goods firms' optimality condition for dirty energy labor to write

$$\left(\lambda_t \frac{\partial Y_t}{\partial Y_{et}} - \frac{\nu_t}{\sigma}\right) \frac{\partial Y_{dt}}{\partial L_{dt}} = \lambda_t \left(\frac{\partial Y_t}{\partial Y_{et}} - \frac{\tau_{dt}}{\sigma}\right) \frac{\partial Y_{dt}}{\partial L_{dt}} \tag{A2}$$

for $t \in [1, \bar{T}]$. It follows that the optimal τ_{dt} is:

$$\tau_{dt} = \frac{\nu_t}{\lambda_t}$$

for $t \in [1, \bar{T}]$. After time $\bar{T}$, the planner needs to set an infinitely large tax or prohibit dirty energy production outright to prevent further emissions.

The last step is to verify that the planner's choice of the dirty energy capital stock also satisfies the decentralized equilibrium conditions for this particular tax. To see that the path of taxes also implements the optimal path for capital, compare the private optimality condition for K_{dt} for $t \in [1, \bar{T} - 1]$.:

$$\begin{aligned} &\lambda_t \left[1 + \Omega_1^d(K_{dt}, K_{dt-1})\right] = \\ &\quad \beta \lambda_{t+1} \left[\left(\frac{\partial Y_{t+1}}{\partial Y_{et+1}} - \frac{\tau_{dt}}{\sigma}\right) \frac{\partial Y_{dt+1}}{\partial K_{dt}} + (1 - \delta_d) - \Omega_2^d(K_{dt+1}, K_{dt})\right], \end{aligned}$$

where we have rearranged terms, plugged in the equilibrium values of q_{dt}, q_{dt+1}^o and r_{dt+1} and used $\lambda_t^P = \lambda_t$, to the planner's optimality condition:

$$\begin{aligned} &\lambda_t \left[1 + \Omega_1^d(K_{dt}, K_{dt-1})\right] = \\ &\quad \beta \lambda_{t+1} \left[\frac{\partial Y_{t+1}}{\partial Y_{et+1}} \frac{\partial Y_{dt+1}}{\partial K_{dt}} + (1 - \delta_d) - \Omega_2^d(K_{dt+1}, K_{dt})\right] - \beta \frac{\nu_{t+1}}{\sigma} \frac{\partial Y_{dt+1}}{\partial K_{dt}}. \end{aligned}$$

Substituting for the tax $\tau_{dt+1} = \frac{\nu_{t+1}}{\lambda_{t+1}}$, shows that the two equations are identical. It is straightforward to see that conditions are also identical to each other for $t \geq \bar{T} - 1$, when $L_{dt} = 0$.

Thus for $\tau_{dt} = \frac{\nu_t}{\lambda_t}$, the optimal allocation of the social planner problem satisfies all decentralized equilibrium conditions and is therefore also the decentralized equilibrium. Since there is only one externality in the model, it is no surprise that one instrument is enough to address it as the Tinbergen Rule would predict Tinbergen (1952).

A.2 Proofs of Propositions 1 and 2

Proof of Proposition 1. The second case $\nu_t = 0$ is occurs if the growth path with $\nu_t = 0 \; \forall \; t$ satisfies $G_t < \bar{G} \; \forall \; t$. We need to prove that the only other case, $\nu_t > 0$ for some t, implies that there exists a $\bar{T}$, such that $\mu_{\bar{T}} > 0$ the constraint is binding.

To prove this assertion, we start with some observations. It must be the case that $\lim\limits_{t \to \infty} Y_{dt} = 0$, otherwise the carbon budget will be violated. This implies that the long-run growth path must converge to the two-sector economy of Acemoglu and Guerrieri (2008) with only non-energy and clean energy sectors. Along this growth path, consumption grows at a positive and asymptotically constant rate, so $\lim\limits_{t \to \infty} \lambda_t = 0$. Furthermore, the marginal product of energy in the production of final output approaches zero, as energy becomes abundant, $\lim\limits_{t \to \infty} \frac{Y_{et}}{Y_{nt}} = 0$.

We are now ready to prove our assertion by contradiction. Assume that constraint (9) does not bind at any finite time but is reached only asymptotically. By equation (18), ν_t must grow exponentially forever. However, equation (15) establishes an upper bound $\nu_t < \sigma \lambda_t \frac{\partial Y_t}{\partial Y_{et}}$ because $\eta_t > 0$. Since the upper bound is shrinking asymptotically, permanent exponential growth in ν_t is not possible. ∎

Proof of Proposition 2.

First evaluate the Euler equation for dirty capital at $t \geq \bar{T}$, assuming $C_{t+1} = (1 + g_n) C_t$ and $K_{dt} > 0$

$$1 + c\gamma_{Kdt} = \gamma_\lambda \beta \left((1 - \delta_d) + c\gamma_{Kdt+1} + \frac{c}{2} \gamma_{Kdt+1}^2 \right). \tag{A3}$$

Here we have denoted the growth rate of dirty capital as $\gamma_{Kdt} = \frac{K_{dt} - K_{dt-1}}{K_{dt-1}}$ and the growth factor of λ_t as $\gamma_\lambda = \frac{\lambda_{t+1}}{\lambda_t} = (1 + g_n)^{-\theta}$. After rewriting, the Euler equation does not depend on t except for γ_{Kdt} and it is purely forward-looking. Since the equation is the same for all future periods, we are looking for a constant $\gamma_{Kd} = \gamma_{Kdt} = \gamma_{Kdt+1}$ for all $t \geq \bar{T}$.

Solving for the optimal growth rate of K_{dt} is therefore the same as solving the quadratic equation in γ_{Kdt}

$$\frac{1}{2} \gamma_{Kd}^2 + \left(1 - \frac{1}{\beta \gamma_\lambda} \right) \gamma_{Kd} - \frac{1}{c} \left(\frac{1}{\beta \gamma_\lambda} - (1 - \delta_d) \right) = 0. \tag{A4}$$

Being quadratic, this equation has two solutions given by

$$\gamma_{Kt}^* = \left(\frac{1}{\beta \gamma_\lambda} - 1 \right) \pm \sqrt{ \left(\frac{1}{\beta \gamma_\lambda} - 1 \right)^2 + \frac{2}{c} \left(\frac{1}{\beta \gamma_\lambda} - (1 - \delta_d) \right) } \tag{A5}$$

Since $\frac{1}{\beta} > 1 > 1 - \delta_d$ and because $\gamma_\lambda < 1$, the terms $\left(\frac{1}{\beta\gamma_\lambda} - 1\right)$ and $\left(\frac{1}{\beta\gamma_\lambda} - (1 - \delta_d)\right)$ are both positive. This implies that both roots of (A4) are real-valued and the larger root is always positive, because the square root is always positive. This rules out the larger root as the solution: it implies a positive growth rate which cannot be optimal, as investment in dirty energy capital does not bring any benefits. Only the smaller of the two roots can therefore be the optimal choice. Indeed, this root is always negative. The reason is that the term under the radical always exceeds value of the first term.[21]

It remains to find the condition characterizing the value of c for which a -100% growth rate of K_{dt}, is optimal. We are thus looking for the value c such that $\gamma^*_{KD} = -1$:

$$-1 = \left(\frac{1}{\beta\gamma_\lambda} - 1\right) - \sqrt{\left(\frac{1}{\beta\gamma_\lambda} - 1\right)^2 + \frac{2}{\bar{c}}\left(\frac{1}{\beta\gamma_\lambda} - (1 - \delta_d)\right)} \tag{A6}$$

Which can be solved for $\bar{c}$

$$\bar{c} = \frac{\frac{1}{\beta\gamma_\lambda} - (1 - \delta_d)}{\frac{1}{\beta\gamma_\lambda} - \frac{1}{2}} \tag{A7}$$

Since $\beta\gamma_\lambda < 1$, $\bar{c}$ is strictly greater than zero. For reasonable restriction of the parameter $\delta_d < 1/2$, implies $\bar{c} < 1$. ■

Recall that the assumption of a constant consumption growth rate is needed for the proof of the proposition. Since it does not hold exactly in our simulations, the threshold value for c might differ slightly from the value $\bar{c}$. In our numerical simulations we find that the analytical value is a good approximation.

A.3 Details on Sub-optimal Policies

Delayed preannounced implementation of ACP In this scenario, the growth path of the economy is defined by the competitive equilibrium conditions with τ_{dt} equal to its values in the CCP scenario for the initial $\tilde{t}$ years. After $\tilde{t}$ years, a policy maker, who maximizes household welfare subject to the law of motion of cumulative emissions (8) and the cumulative emissions budget (9), is introduced. From that point onward, she sets the Ramsey-optimal tax on dirty energy production.

This scenario is characterized by two central assumptions. First, from the beginning private agents rationally expect the introduction of the policy and its effect on the economy's growth path. They understand in advance that carbon prices will rise after $\tilde{t}$ years and can adjust their behavior immediately. The longer is the delay (i.e. the higher is $\tilde{t}$), the more emissions occur before the policy shift, which means carbon prices must rise faster in order to enforce the emissions budget. Second, the policy maker does not have commitment over

[21]The expression is of the form $a - \left(a^2 + b\right)^{\frac{1}{2}}$ with $a, b > 0$. Clearly $\left(a^2 + b\right)^{\frac{1}{2}} > a$ holds for all b¿0.

policies ex-ante. That means, she will implement the policy which is optimal once the time arrives. Private agents foresee that the policy maker will choose a socially optimal path of carbon prices after $\tilde{t}$. Therefore, the future tax increase is predictable for all agents and provides incentives to implement the green energy transition.

Transition paths are solved for in a manner similar to the Ramsey-optimal policy scenarios. We use the private first order conditions in the absence of a tax for the periods preceding $\tilde{t}$ and the social planner's first order conditions along with the cumulative emissions budget for the periods following $\tilde{t}$.

Regime Switch as an MIT shock For the regime switch scenario, the economy is on the growth path of the CCP scenario for the initial $\tilde{t}$ years and private agents expect the economy to remain on this growth path forever. However, after $\tilde{t}$ years the cumulative emissions budget is reduced to be consistent with the 1.5°C goal. This requires an immediate increase in carbon prices.

The crucial difference to the previous scenario is that the sharp increase in carbon prices does not have any effect on private behavior before the policy shift, as it is completely unanticipated. As a result, more dirty and less clean capital will be accumulated, requiring an even larger shift in policy.

We solve for the transition path in two steps. First, we use the path from the CCP scenario for the initial $\tilde{t}$ years. We then solve for a new Ramsey-optimal transmission path beginning after $\tilde{t}$ years. Here we use the capital stocks and cumulative emissions up to $\tilde{t}$ as the initial condition and impose the carbon budget consistent with the 1.5°C goal.

B Calibration Strategy

For the calibration of our baseline scenario, current policy with exogenous technological catch up for clean technologies we follow Goeth et al. (2025). The goal of this calibration is to match four empirical moments: (1) the initial dirty energy share in GDP, (2) the initial capital output ratio, (3) the initial emissions as share of the remaining carbon budget, (4) the initial labor share. The model exhibits annual frequency and simulations start in 2020.

Goeth et al. (2025) calibrate 9 parameters $\{\epsilon, \alpha_{c,d}, \delta_i, \theta, \beta, \mu_j, \frac{K_{c0}}{K_0}, \frac{K_{d0}}{K_0}\}$ with $i \in [n, d, c]$ based on existing literature. Given these externally calibrated parameters, they jointly calibrate the remaining four parameters $\{\gamma, \sigma_0, Kf, \alpha_N\}$ internally so that four parameters in the model match the four empirical targets mentioned above.

We also use same exogenous catch up growth as Goeth et al. (2025) based on their productivity index for clean and dirty energy technology. Their productivity index approximates the dirty energy technology advantage by comparing the levelized cost of electricity

(LCOE) of one dominantly used clean and one dirty technology in four sectors (transport, industry, electricity and heating) in 2021/22 and LCOE forecasts for 2030. They use the average of all four sectors to define their productivity index in 2021/22 and 2030. For the EU they find a dirty technology advantage of 37% in 2021/2022 which vanishes in 2030.

Following Goeth et al. (2025) the current policy scenario assumes a remaining carbon budget of 51 $GtCO_2e$. The carbon budget is constructed using the Climate Action Tracker (2024) for the policies and actions scenario. The policy scenario is linearly extrapolated to 2050 and then cumulated. When simulating the optimal transition path for 1.5°C compatible climate policy we reduce the carbon budget to 30 $GtCO_2e$.

Table A1 and Table A2 report parameter values that we calibrate externally and internally, respectively. Externally calibrated parameter values correspond to the values reported by Goeth et al. (2025) for the EU.

Parameter	**Value**	**Source**
Elasticity of substitution ϵ btw. interm. inputs Y_n & Y_e	0.45	Bretschger and Ara (2022)
Output elasticity wrt labor α_d	0.3	EU KLEMS (2023); Acemoglu and Guerrieri (2008)
Output elasticity wrt labor α_c	0.3	EU KLEMS (2023); Acemoglu and Guerrieri (2008)
Depreciation rate δ_n	0.07	Arkolakis and Walsh (2023)
Depreciation rate δ_c	0.03	Arkolakis and Walsh (2023)
Depreciation rate δ_d	0.02	Arkolakis and Walsh (2023)
Inverse of intertemporal substitution elasticity θ	2	common in literature
Discount factor β	0.98	common in literature
Adjustment cost parameter $c_{n,d,c}$	5; 20	Goeth (2025)
Rel. prod. of dirty energy tech. $\frac{M_{d0}}{M_{c0}}$	1.37	IEA & own calc.
Clean initial disad. b_m	0.208	set to match $\frac{M_{dt}}{M_{ct}}$
Clean catch up rate κ_m	0.45	set to match $\frac{M_{dt}}{M_{ct}}$
Exogenous growth rate of TFP $m_{n,c,d}$	0.00015	
Share of initial dirty energy capital $\frac{K_{D0}}{K_0}$	0.11	Goeth et al. (2025)
Share of initial clean energy capital $\frac{K_{C0}}{K_0}$	0.195	Goeth et al. (2025)

Table A1: Common Parameter Values: External calibration

Parameter	Value EU
Weight on non-energy input in production γ	0.9663
Level of init. capital stock K_{-1} (K_f)	0.4241
CO_2 efficiency of dirty energy production σ	3.2351
Non-energy technology output elasticity wrt labor α_n	0.6279

Table A2: Parameter Values: Internal calibration to match empirical moments

Table A3 shows the fit of the model moments with the empirical target of the EU for the current policy scenario with exogenous clean catch up growth.

Empirical Targets	Model	Data
Initial dirty energy share in GDP $\frac{Y_{D0}}{Y_0}$	6 %	6 %
Initial capital output ratio $\frac{K_1}{Y_1}$	2.55	2.55
Initial emissions as share of remaining carbon budget	4.8 %	4.8%
Initial labor share $\frac{wL}{Y}$	58.2%	58.2%
Average output growth rate	2.24%	1.7%

Table A3: Empirical targets matched in 2020.