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Overcoming the carbon trap: Climate policy and technology tipping*

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Abstract

We construct an overlapping generations model in which the choice between dirty and clean technology hinges on the economy's capital stock, susceptible to climate-induced depreciation. The process of capital accumulation contributes to environmental emissions, yet their intensity can be mitigated through a shift to cleaner production methods. The tipping point of technological transition is endogenously determined, leading to a diverse range of potential long-term outcomes shaped by capital endowment, pollution intensity, climate vulnerability, and clean factor productivity. Our analysis reveals the possibility of an economy converging into a "carbon trap", characterized by a sustained equilibrium marked by elevated pollution and diminished income, despite the feasibility of pursuing green growth. Additionally, we present optimal policy measures and simulations that highlight the temporal disparities between the socially optimal timing for transitioning to green technology and the timing dictated by market forces. Finally, to account for the high upfront costs of starting clean production, we extend the model by including a non-convexity in the production structure of the clean technology.

Keywords: Carbon trap, technology tipping, climate damages, climate policy

JEL Classification:

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1 Introduction

According to standard growth theory, economic development is driven by the accumulation of capital stocks. Capital refers to the productive capacities of an economy, such as machinery, roads, buildings, infrastructure or arable land. Recent years have shown that negative climate events, e.g. floods, hurricanes and landslides, destroy some of the existing capacities. As a consequence, climate change not only reduces current production, but also generates negative growth effects, as the destruction of capital and infrastructure reduces net capital formation (Dietz & Stern, 2015). Empirical evidence suggests that less developed countries are disproportionately more affected by these damages than industrialized countries, even though they are often the least responsible for the greenhouse gas emissions that drive climate change (IPCC, 2023). After a climate shock, production capacities need to be rebuilt, which takes time and requires a reduction in consumption to enable additional investments.

To curb global warming and avoid major economic damages from climate change, a rapid transition to fossil fuel-free technologies is of utmost importance. Since climate change is a global externality, the transformation of the energy system must take place not only in rich countries but also in the developing world. It is widely acknowledged that the transition to cleaner technologies requires a certain amount of production capacity in the form of physical capital.[1] As a consequence, the transition is becoming increasingly difficult or even infeasible for some climate-vulnerable and capital-constrained countries, as climate-related natural disasters adversely affect the existing capital stock — a potential development barrier that has been largely neglected by the existing literature. More specifically, if developing countries have to devote an increasing share of their scarce capital to replacing the existing capital stock, they will not be able to build the capital stock needed for technology transition and thus to generate long-term economic growth based on fossil-free technologies; even though clean and decentralized renewable energy technologies offer great potential to drive electrification and economic development especially in remote and poor rural areas without centralized energy access (Edenhofer et al., 2013).

Hence, there is growing concern that developing countries will be caught in an "environmental poverty trap" that is, a long-term equilibrium of low income and high pollution (Leichenko & Silva, 2014).[2] The experts of IPCC (2022) conclude with high con-

[1] There is ample empirical evidence for this capital requirement, see e.g. Komen et al. (1997), Varvarigos (2014) and Charlier et al. (2022); and a large body of theoretical work relies on this assumption. Specifically, economic models in which a critical stock of physical capital must be accumulated before the economy can transition from dirty to clean technologies include, among others, Stokey (1998), Iwaisako (2002), Matsuyama (2007), Cunha-E-Sa & Reis (2007), Pommeret & Schubert (2009), Damsgaard (2012), Varvarigos (2014) and Charlier et al. (2022). This is also in the spirit of the Environmental Kuznets Curve (EKC) hypothesis, which posits an inverted U-shape relationship between per capita income and pollution (Grossman & Krueger, 1995).

[2] For instance, Bretschger & Valente (2011) use an endogenous growth model to show that climate-induced capital depreciation may lead to "climate poverty traps" especially in climate-vulnerable and

fidence that "impacts of climate change together with non-climatic drivers can create poverty–environment traps that may increase the probability of long-term and chronic poverty".

The relationship between capital accumulation, pollution and technology transition is complex, but a suitable model can reduce complexity to a small number of well-specified relationships and identify the factors that determine the transition to cleaner technologies. By developing and using such a tractable dynamic macroeconomic framework, we illustrate the dual role of capital accumulation for technology transition and long-term economic development: On the one hand, large-scale capital investments in infrastructure, machinery and other physical assets enable the transition to low-carbon technologies. On the other hand, installing capital today leads to pollution and thus climate change, which harms capital in the future and makes it increasingly difficult to maintain or increase capital levels, potentially delaying the point in time at which the economy accumulates enough capital to transition to clean production. We show that economies that are unable to build the production capacities needed for technology transition may be trapped in a perpetual state of low income and high pollution, even if the clean technology is technologically available and sufficiently productive to generate long-term economic growth. We refer to this outcome as a carbon trap in the following.

To analyze the emergence and the possible avoidance of carbon traps, we construct a two-period overlapping generations (OLG) model in which the choice of technology is endogenous and capital investment is the driver of economic growth. With the goal of maximizing the return on investment, households can invest in either a dirty or a clean technology, which differ in terms of their capital–, learning– and pollution intensity. Since the returns are monotonous, it follows that the economy in equilibrium uses only one technology. Pollution is a negative externality of capital accumulation, and climate change causes damages to the stock of physical capital which constitutes the productive capacity of the economy. Pollution intensity of capital can be reduced by switching to cleaner production — but only after the economy has paid a fixed costs in terms of capital. Our framework allows each generation to reassess the return on investment and thus to revert to dirty production in any period, which may occur, for example, if the clean technology is not productive enough or if the necessary physical capital (e.g. in the form of fossil-free infrastructure) is lacking.[3]

When modelling the clean technology, we incorporate several stylized facts into our model. First, we take into account the fact that clean technologies tend to be more capital intensive than dirty technologies (IEA, 2022). Second, following the empirical literature

capital-poor countries. Other related contributions involving an "environmental poverty trap" are, e.g., Xepapadeas (1997), Palivos et al. (2010), Antoci et al. (2011), Fodha & Seegmuller (2014), Golub & Toman (2016), Dao & Edenhofer (2018) and Barbier & Hochard (2019).

[3]A recent example for such a technology shift is the switch from gas to more polluting coal in Germany (LeMonde, 2022).

on learning rates[4] (Rubin et al., 2015) and knowledge spillovers (Dechezleprêtre et al., 2013), we consider the fact that newer and cleaner technologies tend to have relatively high learning– and spillover intensities compared to mature fossil-based technologies. Accordingly, we assume that the clean technology is subject to higher learning effects in the process of capital accumulation compared to the dirty technology. Third, since a large part of the existing capital stock is designed for fossil-based technologies, the transition to cleaner production leads to “stranded assets” (McKibben, 2012). Hence, we assume that the available productive capacity in the form of physical capital is reduced as the economy transitions from the dirty to the clean technology, which is captured by a fixed fraction of capital that is lost at the time of the transition. Indeed, during the energy transition, part of the capital such as the distribution infrastructure for electricity can be preserved, while another part, such as the coal plants for power generation, is lost. Put differently, changing to a clean technology such as solar panels renders the coal plants obsolete but continues to use the existing infrastructure for delivering energy to firms and households. Finally, in an extension, we realize that clean technologies typically require large upfront investments in capital infrastructure before they can become productive, see e.g. Nelson & Shrimali (2014).[5] As a consequence, there exist huge non-convexities when building a fossil-free infrastructure e.g. in the form of charging stations for electric vehicles. To account for this feature, we extend the baseline model by incorporating a non-convexity in the production structure of the clean technology in the form of a minimum threshold for capital.

In this framework, we find that the economy's technology choice depends on an endogenous threshold for capital: Economies whose capital stock exceeds this capital threshold — henceforth denoted as tipping point — invest in the clean technology, while it is optimal for economies below this tipping point to invest in the dirty technology.[6] This results in a rich set of possible long-run dynamics for the economy depending on the interaction of two conditions, the “transition condition” and the “green growth condition”. The transition condition establishes a threshold for clean factor productivity above which a transition to clean technologies can occur before the economy converges to the non-growing polluting steady-state. The green growth condition provides a threshold for clean factor productivity above which the economy can achieve long-run growth with the clean technology. The actual growth pattern of the economy is then determined by the TFP value of the clean technology and it's initial capital endowment.

[4]As e.g. documented by McDonald & Schrattenholzer (2001) and Rubin et al. (2015), the cost of renewable technologies decreases with cumulative installed capacity at a stable rate, and no comparable effect exists for dirty, mature technologies.

[5]The upfront capital costs for wind, solar, and hydro energy are 84-93% of the total project costs while for coal and gas they amount to only 24-37% (Nelson & Shrimali, 2014).

[6]We use the term tipping point to indicate that the stage of development can trigger a sudden and significant shift in the adoption or dominance of a particular technology, see e.g. Otto et al. (2020) for a more detailed discussion.

Our model shows that capital-poor economies that possess a low clean factor productivity converge to a non-growing dirty steady state, even though a steady state with sustained green growth would be achievable, i.e., a carbon trap arises. This trap does not occur with a high TFP value for the clean technology. If an economy possesses a particularly low clean factor productivity, the steady state with positive growth vanishes and the economy converges to the dirty steady state regardless of its initial capital endowment. Because less developed economies tend to have a low clean factor productivity and capital endowment, and are more exposed to the impacts of climate change, they are less likely to build the capital stock needed for technology transition, and are therefore particularly at risk of being caught in a carbon trap or in a dirty steady state, where economic growth necessarily comes to an end.

The introduction of a minimum capital requirement for the clean technology represents an additional barrier to sustained green growth and expands the set of possible long-term outcomes for the economy. In particular, we show that in the presence of a capital threshold, a carbon trap can arise even when the economy has a relatively high clean factor productivity. Moreover, our model reveals that in the presence of a capital threshold, the economy can be caught in a carbon trap even after the transition to clean production.

We further derive the socially optimal tipping point which internalizes all non-market effects related to climate change, learning, and transition costs in switching from dirty to clean capital. Using standard parameter values, we find that this tipping point is lower than the tipping point that arises in the market economy. To determine the difference in transition times between the market outcome and the social optimum, we perform numerical simulations and show that the socially optimal tipping point occurs three generations or, equivalently, about 90 years before the market tipping point. We then analyze policies to promote a timely transition to clean production. We show both theoretically and numerically that a tax on dirty production or a subsidy for clean production can induce the socially optimal tipping point in the market economy, reducing the risk of falling into a permanent state of low income and high pollution.

Our analysis is related to different strands of literature. First, we build on the aforementioned work of Bretschger & Valente (2011), which introduces climate-induced capital depreciation into an endogenous growth model and shows that climate change can lead to negative consumption growth and stagnation traps due to its impact on capital depreciation, especially in climate-vulnerable and less developed economies.[7] While we use an OLG model instead of a continuous time model, we extend their analysis by including a discrete technology choice that allows the economy to escape stagnation by switching to cleaner production.

[7]Other related papers in which climate change damages the stock of physical capital include Bretschger & Suphaphiphat (2014), Bretschger (2017), and Bretschger & Karydas (2019).

Second, we rely on OLG models in which the choice of technology is endogenous and dependent on a critical stock of capital, as in Iwaisako (2002) and Matsuyama (2007), and with Asano et al. (2021) and Asano et al. (2022) being more recent contributions.[8] We recast this analysis in an environmental context where technologies differ in terms of their pollution intensity, thereby damaging the stock of physical capital to varying degrees.

Third, we also contribute to the analysis of the optimal timing for the adoption of clean technologies. In this context, the optimal capital stock and timing of technology transition is endogenously determined in Cunha-E-Sa & Reis (2007), Pommeret & Schubert (2009) and Damsgaard (2012), and exogenously specified in Charlier et al. (2022). The latter presents economic development as a process of structural change and demonstrates for different policy schemes that it is always optimal to reach the capital stock that coincides with structural change as quickly as possible. Cunha-E-Sa & Reis (2007) analyze the optimal timing for adopting a greener technology when that technology offers higher productivity but entails some adjustment costs, and find that the optimal timing depends on the marginal utility of environmental quality with respect to consumption; Pommeret & Schubert (2009) introduce uncertainty in this framework and find that higher uncertainty leads to an earlier adoption of the green technology. Damsgaard (2012) shows that the optimal timing for the introduction of a green technology depends on the size of the capital stock relative to the non-renewable resource stock, with a small capital stock leading to a delayed adoption of the alternative fossil-free technology.

We extend this strand of literature in several ways. First, the presented papers omit the negative impacts of climate change on growth. For instance, they assume that climate change affects utility (e.g. Cunha-E-Sa & Reis (2007), Pommeret & Schubert (2009) and Charlier et al. (2022)) or abstract completely from climate change impacts (e.g. Damsgaard (2012)). However, by destroying part of the existing production capacities, global warming has a significant and long-lasting impact on the growth prospects of economies and thus on their choice of technologies. Second, in addition to the existing literature, we numerically determine the difference in transition times between the market outcome and the social optimum.[9] Third, we extend the analysis from a constellation in which the economy can change technology only once to a model with overlapping generations, in which it may be optimal for agents to revert to dirty production in any period, depending on the evolution of the investment returns of the technologies.[10]

[8]Other related contributions are Narita (2010), Asano et al. (2012) and Umezuki & Yokoo (2019).

[9]In this respect, closest to our contribution is Pommeret & Schubert (2009), who also derive the capital stock needed for technology transition for both the market economy and the social optimum, but they do not determine the difference in transition timings.

[10]In growth models with a representative infinite-lived household, there is no incentive to revert to the dirty technology once the transition costs for the technology change have been incurred, regardless of how the economy performs with the clean technology, see e.g. Cunha-E-Sa & Reis (2007) and Pommeret & Schubert (2009).

Finally, our work is closely related to the strand of literature on environmental poverty traps induced by the negative effects of pollution on life expectancy and the resulting reduced incentives for long-term capital accumulation, see Dugan et al. (2022) for a recent survey on this matter.[11] In this framework, Ikefuji & Horii (2007), Varvarigos (2014) and Dao & Edenhofer (2018) introduce a discrete technology choice into an overlapping generations model in which survival probability depends on both pollution and income, and multiple equilibria can emerge due to a virtuous cycle[12] of pollution, longevity, and investment.[13] We abstract from the health channel and focus exclusively on the impact of capital formation on technology transition and show that carbon traps can arise even if we neglect the interplay between the environment, life expectancy, and capital accumulation.

The remainder of the paper is structured as follows: In Section 2 we present the baseline model and its dynamics. Section 3 provides the social optimum of the economy, and Section 4 discusses the impact of a carbon tax and a subsidy on market outcomes. The numerical simulations are performed in Section 5, and Section 6 extends the baseline model by introducing a non-convexity in the production structure of the clean technology in form of a minimal threshold for capital. Section 7 discusses the results and, finally, Section 8 concludes.

2 The Model

In this section, we present our model framework and motivate the assumptions, starting with the changing climate and then proceeding with the households, technologies, firms, and technology choices, in turn.

2.1 Climate change

We consider a discrete time OLG world economy, in which either a clean (c) or a dirty (d) technology can be employed for production. Total labor endowment $\bar{L}$ is normalized to unity, so that aggregate and per-capita variables coincide. Pollution is a by-product of capital accumulation. The stock of pollution at instant t is denoted by P_t and increases proportionally with the stock of capital used in production, $k_{i,t}$, where the index $i \in \{c, d\}$ refers to the employed technology. The intensity of pollution varies depending on the used technology. For an economy that operates with the dirty technology, pollution evolves

[11] This strand builds on the seminal contributions of Chakravorty et al. (2008) and Mariani et al. (2010).

[12] This cycle underlies the following reasoning: Higher environmental quality extends life expectancy, which in turn increases the incentives to save and accumulate capital. This allows the economy to reach the level of capital that enables the transition to clean production, which in turn increases environmental quality and thus life expectancy.

[13] To generate multiple equilibria, Dao & Edenhofer (2018) introduce a nonlinear regeneration function for the environment in addition to the presented cycle.

according to

$$\Delta P_t = \varphi k_{d,t}, \tag{1}$$

where $\varphi > 0$ is the constant pollution intensity of capital.[14] With a switch from dirty to clean technology the economy can reduce its pollution intensity by a constant amount $\iota \in (0, 1]$, so that (1) changes to

$$\Delta P_t = \varphi(1 - \iota)k_{c,t}, \tag{2}$$

where $\iota = 1$ implies that a pollution-free technology is employed. Building on Bretschger & Valente (2011) and the references therein, we assume that climate change affects capital accumulation by increasing the rate of capital depreciation. In what follows, we assume that over the lifetime of a generation (i.e., over $\approx$ 30 years) capital can adapt to a higher pollution level without suffering from additional depreciation losses, so that capital destruction is determined by the change in pollution stock.[15] We denote the amount of capital that is destroyed as a result of increased pollution by $D(\Delta P_t)$; it is added to the conventional depreciation rate (i.e., the rate of capital that is depreciated in the absence of climate change) measured by $\delta \in (0, 1)$. Assuming that the change in pollution stock impacts capital depreciation by a proportional factor η, we obtain

$$D(\Delta P_t) \equiv \eta \Delta P_t,$$

where $\eta > 0$ is a constant impact intensity parameter which represents the sensitivity of the capital stock to climate change. Depending on the technology in use, total depreciation amounts to

$$\delta k_{d,t} + D(\Delta P_t) = \delta k_{d,t} + \eta \Delta P_t = [\delta + \varphi\eta]\, k_{d,t} \equiv \Lambda_d k_{d,t}, \tag{3}$$
$$\delta k_{c,t} + D(\Delta P_t) = \delta k_{c,t} + \eta \Delta P_t = [\delta + (1 - \iota)\varphi\eta]\, k_{c,t} \equiv \Lambda_c k_{c,t}, \tag{4}$$

where Λ_i denotes the total rate of capital depreciation associated with the employment of technology $i \in \{d, c\}$, and is used below to simplify expressions. The size of capital depreciation depends on the pollution intensity of capital, which varies depending on the technology in use and the impact intensity of climate change.

[14] For simplicity, we abstract from a natural decay rate.

[15] A similar assumption is applied in Bretschger & Valente (2011), Bretschger & Suphaphiphat (2014) and Bretschger (2017). Considering the differences between the effects of the level and the rate of change of pollution, Tahvonen (1995) concludes that, especially in the context of climate change, damage also depends on the change of the pollution stock. Using an OLG model with a longer time horizon we restrict the analysis to the change of the stock pollutant assuming that capital after a generation is adapted to higher pollution levels.

2.2 Households

We assume a representative household with a two-period lifetime, so that at any point in time two generations coexist. An agent is labeled "young" in the first period and "old" in the second period. Young agents are endowed with one unit of labor which they supply inelastically to firms in exchange for wage income $w_{i,t}$. Capital is owned by old agents, who bequeath the capital stock net of depreciation to the young generation at the end of each period.[16] The amount of capital inherited depends on the size of climate-related capital losses and thus on the technology choice of the old. Because they make their investment decisions solely with the goal of maximizing returns and without taking climate-related externalities into account, their choice of technology constitutes an intergenerational externality that affects the wealth of the young and thus their ability to save.

A young agent decides how much to consume (c_t^1) and save (s_t) out of total wealth, which consists of the inherited capital stock net of depreciation $(1 - \Lambda_i)k_t$ and wage income $w_{i,t}$. An old agent simply consumes its savings, where the return on investment for technology $i \in (c, d)$ in period $t+1$ is denoted by $r_{i,t+1}$ and is specified in more detail in Section 2.5. Further, we introduce transition costs expressed by $\theta \in (0, 1)$, which reflect that part of the capital stock becomes obsolete when capital moves from dirty to clean technology, see Cunha-E-Sa & Reis (2007) and Pommeret & Schubert (2009) for a similar treatment.[17] For simplicity, we assume that the reverse change, i.e., from clean to dirty, does not involve such costs.[18] From that, we obtain the following budget constraints for an agent when being young and old, respectively:

$$w_{i,t} + (1 - \theta\psi - \Lambda_i)k_t = c_t^1 + s_t, \quad \text{and}$$

$$c_{t+1}^2 = r_{i,t+1}s_t,$$

with $\theta\psi + \Lambda_i \leq 1$ and ψ being an indicator variable which accounts for the fixed costs in terms of capital; it takes the value of either zero or one, depending on whether or not a

[16]The reason for this may be altruistic motives or uncertainty about life expectancy, see e.g. Lines (2001) for a discussion. A similar assumption is used, e.g., in Cremers (2006), Dam (2006) and Karp et al. (2021). Alternatively, we could assume that the old household bequeaths only the share $q(1 - \Lambda_i)k_t$ with $q \in [0, 1]$ to the young generation and consumes the remaining share $(1-q)(1-\Lambda_i)k_t$ when they are old. However, this would not change our main results. For simplicity, we assume that the old generation bequeaths the entire capital stock to the young agent at the end of each period, i.e., $q = 1$.

[17]As outlined in the introduction, the part of the capital stock that becomes obsolete due to the switch in technology can be interpreted as "stranded" capital.

[18]More generally, we posit that switching back from clean to dirty energy generation methods is much less costly because old power plants can be recommissioned and do not have to be built from scratch.

technology change from dirty to clean occurs in a given period t:

$$\psi = \begin{cases} 1 & \text{if} \quad t = t^{TP}, \\ 0 & \text{if} \quad t \neq t^{TP}, \end{cases}$$

where $t = t^{TP}$ refers to the point in time at which the technology transition from dirty to clean occurs. By isolating s_t, the two period budget constraints can be consolidated to the following intertemporal budget constraint

$$w_{i,t} + (1 - \theta\psi - \Lambda_i)k_t = c_t^1 + \frac{c_{t+1}^2}{r_{i,t+1}}. \tag{5}$$

Moreover, lifetime utility of an individual born in t is specified as

$$U_t(c_t^1, c_{t+1}^2) = \log(c_t^1) + \beta \log(c_{t+1}^2), \tag{6}$$

where $\beta \in (0, 1)$ is the discount factor. Individuals maximize lifetime utility (6) subject to their intertemporal budget constraint (5), which leads to the familiar Euler equation:

$$c_{t+1}^2 = \beta r_{i,t+1} c_t^1. \tag{7}$$

By combining the Euler equation (7) with the intertemporal budget constraint (5), we obtain the following optimal saving function:

$$s_t = \frac{\beta}{1+\beta} \left[w_{i,t} + (1 - \theta\psi - \Lambda_i)k_t \right], \quad i \in \{c, d\}, \tag{8}$$

which is independent of $r_{i,t+1}$ due to the logarithm utility and states that the household saves a constant share of total wealth. We note that the young household receives income only from supplying labor while the old household receives income only from renting out capital. Hence, we consider the young as workers and the old as investors.

2.3 Technologies

There is one good in the economy whose output we denote by Y. This good is used for consumption and investment and is produced with either the clean or the dirty technology, with the respective outputs being Y_c and Y_d. There are infinitely many identical firms that are all price-takers and the production function for firm j that operates with either the clean or dirty technology reads

$$Y_{i,j} = \tilde{A}_i K_{i,j}^{\alpha_i} L_{i,j}^{1-\alpha_i}, \quad i \in \{c, d\},$$

where K_i is capital, L_i denotes labor and $\alpha_i \in (0, 1)$ refers to the capital intensity in production. Capital accumulation is assumed to have a positive effect on total factor productivity through learning-by-doing as in Romer (1986). Specifically, $\tilde{A}_i$ is a measure of learning-by-doing effects and depends on the average capital ratio in production:

$$\tilde{A}_i = A_i k_i^{\nu_i}, \quad i \in \{c, d\},$$

where $\nu_i \geq 0$ and $A_i > 0$ are technology-specific parameters for the strength of the learning-by-doing effect and total factor productivity, respectively. Each firms is small compared to the total market and takes k_i as given. In particular, if $\nu_i > 0$ then positive externalities exist in production and if $\nu_i = 0$ learning effects are absent.[19] Assuming that all firms are identical, we can express the production function for a firm operating with technology i as:

$$y_i = \tilde{A}_i k_i^{\alpha_i},$$

while actual output is determined by

$$y_i = A_i k_i^{\alpha_i + \nu_i}.$$

For labor, we assume perfect mobility, while for capital the previously established transition costs apply. Moreover, we assume in the following that the clean technology lags relatively behind the dirty technology in terms of total factor productivity, i.e., $A_c < A_d$.

2.4 Firms

The factor markets are perfectly competitive so that firms take prices for labor and capital as given. All prices are normalized using the final good as numeraire. Neglecting its individual impact on climate change and capital accumulation, a representative firm operating with either the dirty or clean technology maximizes its profit in every period by choosing how much labor and capital it employs. Since labor supply is equal to one and inelastic, we can express the factor prices as functions of the capital stock:

$$p_i(k_i) = \alpha_i A_i k_i^{\alpha_i + \nu_i - 1}, \tag{9}$$

$$w_i(k_i) = (1 - \alpha_i) A_i k_i^{\alpha_i + \nu_i}, \tag{10}$$

where w_i and p_i stand for the wage and the rental price of capital for technology $i \in \{c, d\}$, respectively. As a result, we get the familiar optimality conditions, that is, the marginal product of capital corresponds to the rental price of capital and the marginal product of

[19]For simplicity, we abstract from negative externalities in production.

labor is equal to the wage. The shape of the marginal productivity of capital depends on the value of $\nu_i + \alpha_i$ and, for simplicity, we will write $\gamma_i = \alpha_i + \nu_i$. An overview of the factor prices for both technologies is provided in Table 1. Throughout this paper,

Technology:	Rental rate (p):	Wage (w):
Dirty technology:	$p_d = \alpha_d A_d k_d^{\gamma_d - 1}$	$w_d = (1-\alpha_d) A_d k_d^{\gamma_d}$
Clean technology:	$p_c = \alpha_c A_c k_c^{\gamma_c - 1}$	$w_c = (1-\alpha_c) A_c k_c^{\gamma_c}$

Table 1: Factor prices for both technologies

we assume that $\gamma_c > \gamma_d$ which is based on two empirical observations: First, empirical evidence argues in favor of higher learning rates for clean technologies compared to dirty ones (Rubin et al., 2015). Accordingly, we assume that the learning intensity in capital formation is higher for the clean as compared to the dirty technology, i.e., $\nu_c > \nu_d$. Second, capital intensity tends to be higher for clean as compared to dirty technologies (IEA, 2022), which implies that $\alpha_c \geq \alpha_d$, so that overall $\gamma_c > \gamma_d$.

2.5 Tipping points and the choice of technology

The household invests the entire capital stock in either the clean or the dirty technology, depending on which yields a higher return. Recall that a technology transition from dirty to clean involves transition costs (i.e., capital used in dirty production cannot be fully deployed in clean production), so that at the time of transition we have $k_c = (1-\theta)k_d$ with $\theta \in (0, 1)$. Since switching from clean to dirty technology does not involve such costs, the household's investment decision depends on which technology was used in the previous period. Hence, we distinguish four different cases of transitions and thus four different investment returns, where we denote the investment return for technology $i \in \{c, d\}$ by r_i. Using a standard definition of a return, r_i is specified as

$$r_i(k_{i,t}) = \frac{p_i(k_{i,t}) \cdot k_{i,t}}{k_t}, \quad i \in \{c, d\},$$

where $p_i(k_{i,t})$ is the rental price of capital and k_t stands for the aggregate capital stock regardless of the technology for which it is used. We derive the returns in all four cases in the Appendix and focus for now on the case where the economy transitions from dirty to clean technology.

Given these returns, the household chooses in each period the technology whose investment return is higher than the alternative, without taking into account climate-related externalities. Thus, the investment problem of the household reads

$$\max_{i \in \{c,d\}} \quad r_i(k_i).$$

Next, we determine the aggregate capital stock for which the household is indifferent between both technologies. Given a technology change from dirty to clean, the appropriate non-arbitrage condition reads $r_d(k) = r_c(k)$ or, equivalently,

$$p_d(k) = p_c[(1-\theta)k] \cdot (1-\theta).$$

Using the expressions for p_d and p_c from Table 1 yields

$$\alpha_d A_d k^{\gamma_d - 1} = \alpha_c A_c \left[(1-\theta)k\right]^{\gamma_c - 1} \cdot (1-\theta).$$

Note that the returns in our economy are monotonous, so the economy uses only one technology in equilibrium. Finally, solving for k yields

$$\bar{k}^{TP} \equiv k = \left(\frac{\alpha_d A_d}{\alpha_c A_c (1-\theta)^{\gamma_c}}\right)^{\frac{1}{\gamma_c - \gamma_d}}, \tag{11}$$

with $\gamma_c > \gamma_d$ and thus $\bar{k}^{TP} \geq 0$. This critical value of k represents a tipping point at which the technology change from dirty to clean occurs. Accordingly, we refer to $\bar{k}^{TP}$ as the first tipping point in the economy. If k_t is above this tipping point, then the return with the clean technology exceeds the one with the dirty technology and vice versa if k_t lies below. Hence, (11) represents the minimum level of capital above which it is optimal for the household to invest in the clean instead of the dirty technology.

We find that this tipping point increases with the cost to switch (high θ) and decreases with the distance in the learning intensities (high $\gamma_c - \gamma_d$) between the two technologies. The higher the strength of the learning-by-doing effect with the clean as compared to the dirty technology, the more rewarding an early transition to clean production and thus the lower the tipping point. Beside that, in line with intuition, high values of A_c and α_c and low values of A_d and α_d promote a technology switch in favor of the clean technology by reducing $\bar{k}^{TP}$.

Analogously, we can study the change from clean to dirty. Repeating the same steps, a second tipping point can be derived, which is given by

$$\underline{k}^{TP} \equiv k = \left(\frac{\alpha_d A_d}{\alpha_c A_c}\right)^{\frac{1}{\gamma_c - \gamma_d}}. \tag{12}$$

This tipping point provides the level of aggregate capital below which it is optimal for the household to invest in the dirty instead of the clean technology. Note that this second tipping point is smaller than the first one, i.e., $\underline{k}^{TP} < \bar{k}^{TP}$, as the costs θ play no role.

We summarize our findings in the following proposition:

Proposition 1. *Depending on the economy's technology choice in period $t-1$ (its initial technology choice), the following tipping points arise in the economy in period t:*

i. Given that in $t-1$ the economy invested in the dirty technology, then in t the economy invests in the clean technology if $k_t \geq \bar{k}^{TP}$.

ii. Given that in $t-1$ the economy invested in the clean technology, then in t the economy invests in the dirty technology if $k_t < \underline{k}^{TP}$.

In summary, the model reveals that different characteristics, as for example the existence of high transition costs or differences in the learning and capital intensities may lead to different tipping points for different economies. There is ample empirical evidence suggesting that it is worthwhile for an economy in early stages of development to use the most productive, but also the dirtiest technology to build-up physical capital. Once the economy is rich enough, it begins to adopt greener technologies, which are typically costly to implement, and carbon emissions eventually fall.[20] Applied to our model framework, this corresponds to the shift in technology from dirty to clean. Therefore, we will focus on the first tipping point and discuss the second one only where it is necessary.

2.6 Equilibrium dynamics

We define an equilibrium for the market economy as a sequence of prices $\{w_{i,t}, p_{i,t}\}_{t=0}^{\infty}$ and allocations $\{y_{i,t}, k_{i,t}, c_t^1, c_t^2\}_{t=0}^{\infty}$ with $i \in \{c, d\}$ such that the market for the final good clears, i.e.,

$$y_t = c_t^1 + c_t^2 + s_t,$$

the markets for factor inputs clear, which implies that all labor is hired, i.e. $\bar{L} = 1$, and that investment in capital is equal to savings which leads to the following dynamic equation for capital:

$$k_{i,t+1} = s_t, \quad i \in \{c, d\}. \tag{13}$$

To study the dynamics of the economy, we assume that $\gamma_c = 1$ and $\gamma_d \in (0, 1)$, so we have $\gamma_c > \gamma_d$ as specified before.[21] The assumption of $\gamma_c = 1$ implies that the

[20] See e.g. Varvarigos (2014) and the references therein. Following Charlier et al. (2022), the technology shift from dirty to clean can also be interpreted as a change in the nature of the production process, which becomes less energy intensive as the economy develops; e.g., the transition from an economy based predominantly on manufacturing to one in which services dominate. The proposition that the transition to more environmentally friendly production methods occurs at higher stages of development is also consistent with the EKC hypothesis (Grossman & Krueger, 1995). Using an endogenous growth model with different technologies which vary in terms of in their dirtyness, Stokey (1998) provides an early theoretical explanation for the observed hump shaped pattern often found in empirical research. In our study, the transition in the pollution pattern is modelled as a technology shift from dirty to clean.

[21] The AK structure in clean production simplifies the growth dynamics and enhances the traceability of the model. However, our main results do not depend on the AK assumption, we could also assume a concave function for the clean technology where $\gamma_c > \gamma_d$ with $\gamma_c \in (0, 1)$ and $\gamma_d \in (0, 1)$.

marginal product of capital is constant and does not depend on the capital stock, reflecting the main property of a standard AK-model of endogenous growth (Romer, 1986). As a consequence, the return to capital of the clean technology is constant, allowing the economy to grow in the long run as the incentives for capital accumulation persist over time. The return to capital of the dirty technology, however, is decreasing over time which prevents the economy from achieving steady economic growth. From (3), (4), (8), (10), (11) and (13), the dynamics of the decentralized economy can be fully characterized by the equilibrium dynamics of physical capital and pollution:

$$k_{t+1} = \begin{cases} \frac{\beta}{1+\beta}\left[(1-\alpha_d)A_d k_t^{\gamma_d} + (1-\delta-\eta\varphi)k_t\right] & \text{if } k_t < \bar{k}^{TP}, \\ \frac{\beta}{1+\beta}\left[(1-\alpha_c)A_c(1-\theta)k_t + (1-\theta-\delta-\eta\varphi(1-\iota))k_t\right] & \text{if } k_t \geq \bar{k}^{TP} \text{ and } t = t^{TP}, \\ \frac{\beta}{1+\beta}\left[(1-\alpha_c)A_c k_t + (1-\delta-\eta\varphi(1-\iota))k_t\right] & \text{if } k_t \geq \bar{k}^{TP} \text{ and } t > t^{TP}, \end{cases}$$

$$\Delta P_t = \begin{cases} \varphi k_t & \text{if } k_t < \bar{k}^{TP}, \\ \varphi(1-\iota)(1-\theta)k_t & \text{if } k_t \geq \bar{k}^{TP} \text{ and } t = t^{TP}, \\ \varphi(1-\iota)k_t & \text{if } k_t \geq \bar{k}^{TP} \text{ and } t > t^{TP}, \end{cases}$$

for given $P_0 > 0$, $k_0 > 0$ and with t^{TP} corresponding to the point in time at which the technology transition from dirty to clean occurs.

We now turn to the steady states of the economy under different technology choices. In order to show how the productivity of the clean technology determines the dynamic properties of the model, we will introduce two conditions to divide the values for A_c into three regions; each of which exhibits a different pattern of growth. Let us begin with the steady state under the dirty technology. From the dynamic equation for k_t, we find

$$k_d^{SS} = \left(\frac{(1-\alpha_d)A_d}{\beta^{-1}+\delta+\eta\varphi}\right)^{\frac{1}{1-\gamma_d}}. \tag{14}$$

In this steady state, all capital is allocated to the dirty technology and, due to diminishing returns to capital, long-term growth necessarily comes to an end. However, such a state only arises if the economy does not switch from the dirty to the clean technology along its transition path, which occurs if $\bar{k}^{TP} < k_d^{SS}$ or, equivalently,

$$\left(\frac{\alpha_d A_d}{\alpha_c A_c(1-\theta)}\right)^{\frac{1}{1-\gamma_d}} < \left(\frac{(1-\alpha_d)A_d}{\beta^{-1}+\delta+\eta\varphi}\right)^{\frac{1}{1-\gamma_d}}. \tag{15}$$

This inequality represents the key condition for the transition from dirty to clean technologies to occur. We summarize this finding in Proposition 2.

Proposition 2. *The economy can transition to the clean technology if the tipping point arises before the polluting steady state i.e. if $\bar{k}^{TP} < k_d^{SS}$.*

We find that an economy is more likely to switch to clean production along its transition path, the lower the transition costs (θ), the lower the pollution intensity of capital (φ), the lower the sensitivity of the capital stock to climate change (η), the higher the discount factor (β) and the higher clean factor productivity (A_c). Beside that, a high value of α_c and low values of δ and α_d also promote a switch to clean production by increasing the likelihood that (15) is fulfilled.

The reasoning behind the impact of η goes as follows: Economies that are frequently affected by climate-induced capital losses cannot build up the minimal capital stock needed for technology transition. This is because the old generation, i.e., the investors, do not consider climate-related externalities in their investment decisions, which implies that the tipping points in the market economy does not depend on the parameters related to climate change while the dirty steady state does. Note that the determinants of the tipping points change as we turn to the social optimum of the economy.

Next, we express this condition by the TFP parameter of the clean technology. In doing so, we solve Inequality (15) for A_c:

$$A_c > \frac{\alpha_d(\beta^{-1} + \delta + \eta\varphi)}{(1-\alpha_d)\alpha_c(1-\theta)} \equiv \bar{A}_c^T, \tag{16}$$

where $\bar{A}_c^T$ denotes a threshold value for productivity with the clean technology above which the tipping point arises before the steady state under the dirty technology. In other words, a productivity value higher than this threshold ensures that the clean technology can be adopted before the economy converges to the steady state with the dirty technology and we will refer to this condition as the "transition condition".

Next, we turn to the steady state of the clean technology. The production function of the clean technology is linear in capital and thus allows for sustained growth under the following condition:

$$\frac{k_{c,t+1}}{k_{c,t}} = \frac{\beta}{1+\beta}\left[(1-\alpha_c)A_c + (1-\delta-\eta\varphi(1-\iota))\right] > 1,$$

which is, among others, more likely to hold the higher the technological upgrading in terms of pollution savings (ι). From that, we can derive a second condition for A_c, which reads

$$A_c > \left(\frac{1}{\beta} + \delta + \eta\varphi(1-\iota)\right)\frac{1}{1-\alpha_c} \equiv \bar{A}_c^G, \tag{17}$$

where $\bar{A}_c^G$ corresponds to a second threshold for clean factor productivity above which the economy can sustain economic growth by investing in the clean technology. We call this condition the “green growth condition” in the following.

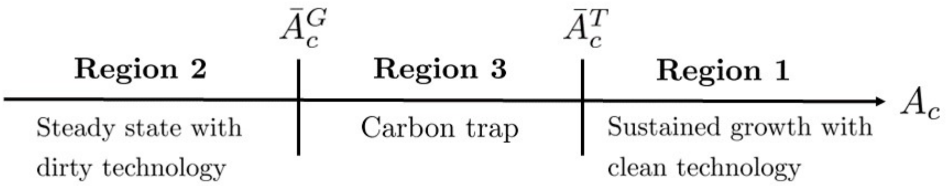

Figure 1: Clean factor productivity: threshold values and the corresponding regions

Having found two threshold values for clean factor productivity $\bar{A}_c^T$ and $\bar{A}_c^G$, we show in the Appendix that under fairly general conditions it holds that $\bar{A}_c^G < \bar{A}_c^T$. This means that a relatively low clean factor productivity is sufficient for an economy to sustain economic growth with the clean technology, but a relatively high value for A_c is required to reach the tipping point.

We display the two thresholds in Figure 1, taking into account their order derived in the Appendix. The figure shows that the choice of technology and thus the dynamic properties of the economy depend on the value of A_c. In particular, we can distinguish three different regions for A_c. In Region 1, the clean technology is very productive and exceeds both thresholds. As a result, the transition condition is satisfied and the tipping point of the economy lies before the steady state under the dirty technology ($\bar{k}^{TP} < k_d^{SS}$), which ensures that the clean technology can be adopted before the economy converges to k_d^{SS}. In addition, due to its high clean factor productivity, such an economy fulfills the green growth condition and thus experiences sustained growth with the clean technology.

We provide the dynamics when A_c exceeds both thresholds in the phase diagram of Case 1 in Figure 2, where the savings function under the dirty technology is given by the concave function while the one under the clean technology by the linear function. For readability, we draw the second tipping point, $\underline{k}^{TP}$, only when it directly affects the growth dynamics, i.e., in Case 2 of Figure 2 and in Figure 3 further below. In Case 1, we see that regardless of the initial level of k, the economy accumulates sufficient capital to reach the tipping point, switches to clean production and experiences sustained growth with the clean technology.

Contrary, in Region 2 of Figure 1, the productivity parameter A_c is below both thresholds, implying that the clean technology is comparatively unproductive. Thus, such an economy does not meet either of the two conditions and converges to a unique steady state under the dirty technology, as is shown under Case 2 in Figure 2. Since the transition condition is not met, the economy’s tipping point lies to the right of the steady state under the dirty technology ($\bar{k}^{TP} > k_d^{SS}$), which prevents the economy from making a successful transition to clean production. Moreover, due to its low factor productivity, the clean technology no longer implies sustained growth so that the capital formation

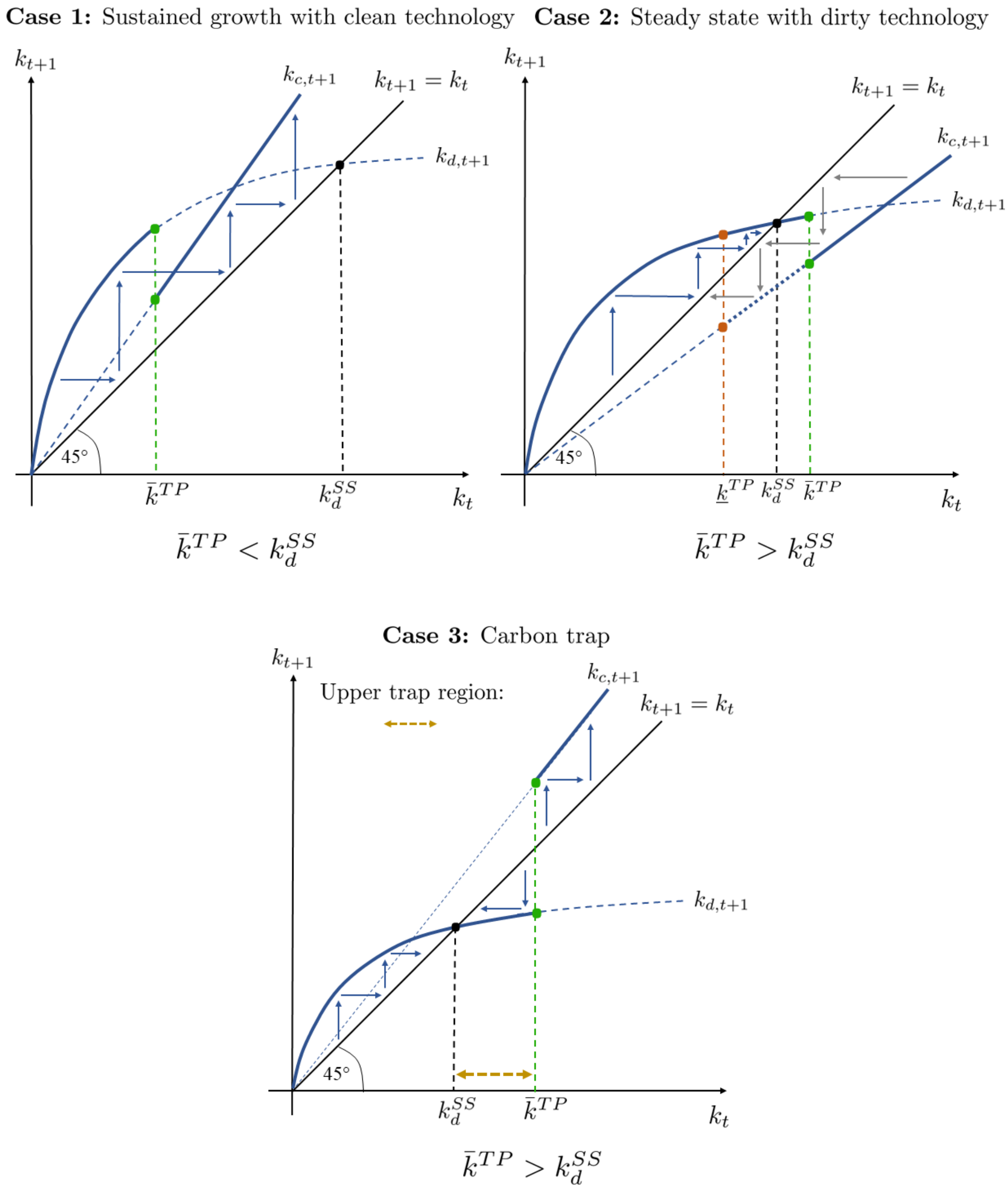

Figure 2: Phase diagrams

line of the clean technology now lies below the 45 degree line. As a result of these effects, the transitional dynamics of the economy now depend on its initial endowment with capital: Economies who are poorly endowed, i.e., those with less capital than $\bar{k}^{TP}$, will converge to the dirty steady state k_d^{SS}, only employing the dirty technology along their convergence path. Richer economies whose endowment exceeds the tipping point $\bar{k}^{TP}$ will utilize the clean technology, but only for a limited time, since the clean technology is so unproductive that the capital stock declines over time until it falls below the tipping point $\underline{k}^{TP}$, whereupon a switch to the dirty technology occurs. From there on, the economy again converges to the dirty steady state.

In Region 3 of Figure 1, the TFP value of the clean technology takes intermediate values, that is $\bar{A}_c^G < A_c < \bar{A}_c^T$, and the resulting outcome is a carbon trap. Economies with a productivity parameter A_c in between the two thresholds fulfill the green growth condition but not the transition condition. Although the clean technology is sufficiently productive to generate permanent economic growth, the violation of the transition condition implies that the steady state with dirty technology arises prior to the tipping point ($\bar{k}^{TP} > k_d^{SS}$), which prevents the economy from conducting a technology switch from dirty to clean.

The phase diagram for such values of A_c can be found in Case 3 of Figure 2 where the initial capital endowment again decides about the long-term prospects of the economy. Similar to Case 2, an initial value of capital below $\bar{k}^{TP}$ will set the economy on a convergence path to the dirty, low-income steady state, k_d^{SS}, although green growth would be technologically feasible. We refer to such a constellation as a "carbon trap", where the trap region is given by the interval between the origin and $\bar{k}^{TP}$. Moreover, we refer to the interval between k_d^{SS} and $\bar{k}^{TP}$ as the "upper trap region" (indicated by the ocher dashed arrow in Figure 2), which denotes the critical interval that an economy must overcome for the technology transition from dirty to clean to occur, and we examine how policies can affect the size of this upper trap region in Section 4. In line with our previous findings, the size of the upper trap region is larger for economies with a high climate exposure since $\partial k_d^{SS}/\partial\eta < 0$ while $\partial\bar{k}^{TP}/\partial\eta = 0$ in the market economy. For wealthier economies the outcome is much more optimistic, as an endowment higher than the tipping point propels them on a sustained growth path with the clean technology.

We summarize our findings in the following proposition.

Proposition 3. *Depending on the parameter value for A_c, we can distinguish three possible patterns of growth:*
Case 1: *The economy is subject to sustained growth with the clean technology if its productivity A_c is (sufficiently) high such that $A_c > \bar{A}_c^T > \bar{A}_c^G$.*
Case 2: *The economy converges to a unique dirty steady state if its clean factor productivity A_c is (sufficiently) low such that $A_c < \bar{A}_c^G < \bar{A}_c^T$.*
Case 3: *If clean factor productivity A_c is subject to intermediate values such that $\bar{A}_c^G < A_c < \bar{A}_c^T$, a carbon trap exists and the economy will converge to this trap when the initial level of capital k_0 is lower than $\bar{k}^{TP}$.*

Let us consider the opposite threshold order, that is, $\bar{A}_c^G > \bar{A}_c^T$ and the resulting outcomes for the economy. Then, the types of possible steady states change: The carbon trap disappears and instead permanent cyclical fluctuations emerges, while sustained growth with the clean technology and the steady state with the dirty technology remain

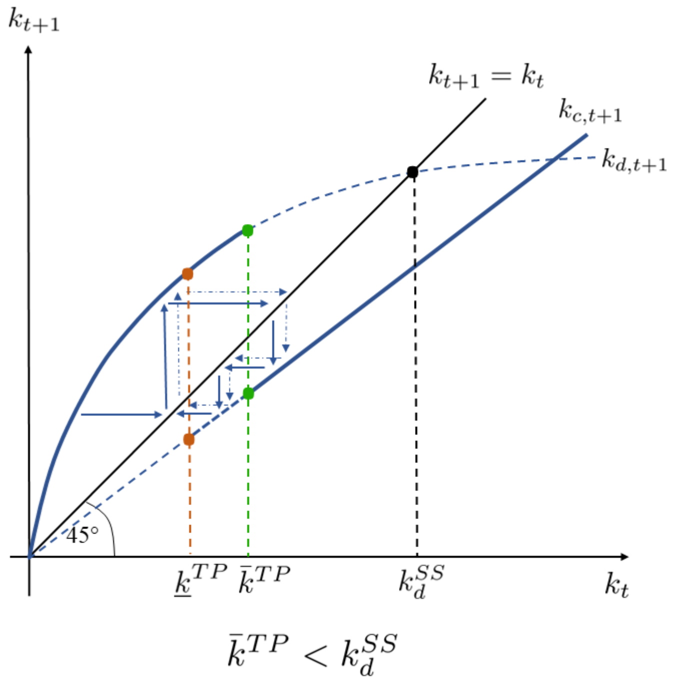

Figure 3: Phase diagram with cyclical fluctuations

as possible growth patterns for the economy. If $A_c > \bar{A}_c^G > \bar{A}_c^T$ holds, then the economy will experience continuous growth under the clean technology, as in Case 1 of Figure 2. However, a novel growth pattern arises if A_c exceeds $\bar{A}_c^T$ but not $\bar{A}_c^G$, that is, if the transition condition is satisfied but not the green growth condition. Thus, the tipping point of the economy is to the left of the steady state under the dirty technology ($\bar{k}^{TP} < k_d^{SS}$), allowing the economy to switch to the clean technology along its transition path. However, as the green growth condition is not met, the capital stock shrinks over time as the productivity of the clean technology is too low to enable long-term growth. Due to this contraction, the economy will eventually pass below $\underline{k}^{TP}$ and return to the dirty technology sooner or later. This process is repeated and permanent cyclical fluctuations emerge, as illustrated in Figure 3. Once A_c is below both threshold values, the steady state under the dirty technology arises and the relative size of $\bar{A}_c^G$ and $\bar{A}_c^T$ becomes irrelevant, which corresponds to Case 2 in Figure 2.

We summarize our findings in the following proposition:

Proposition 4. *The set of possible long-run dynamics for the economy depends on the relative size of $\bar{A}_c^T$ and $\bar{A}_c^G$:*

i. If $\bar{A}_c^T > \bar{A}_c^G$ holds, then the economy inhibits the growth dynamics described in Proposition 3.

ii. If $\bar{A}_c^T < \bar{A}_c^G$ holds, then the economy inhibits the growth dynamics described in Propo-

sition 3, whereby permanent cyclical fluctuations emerge instead of a carbon trap.

3 Social planner

Next, we turn to the social optimum for the economy. Given the model framework, non-market effects i.e., negative and positive externalities are a crucial part of the analysis. The social planner takes into account the positive learning effects in capital accumulation from both the clean and dirty technology as well as the negative externality related to climate change. In addition, the social planner internalizes that part of the capital stock becomes obsolete when the economy transitions from the dirty to the clean technology, which reduces the stock of capital available for future generations. Accordingly, the maximization problem of the social planner reads

$$\max_{\{c_t^1, c_{t+1}^2, k_{t+1}, k_{d,t}, k_{c,t}\}_{t=0}^{\infty}} \quad W = \sum_{t=0}^{\infty} \beta_s^t \left(\log(c_t^1) + \beta \log(c_{t+1}^2) \right)$$

subject to

$$c_t^1 + c_t^2 + k_{t+1} - (1 - \delta - \eta\varphi) k_{d,t} - \left(1 - \frac{\delta + \eta\varphi(1-\iota)}{(1-\theta)^\kappa} \right) k_{c,t} = A_c k_{c,t}^{\gamma_c} + A_d k_{d,t}^{\gamma_d},$$

$$k_t = \frac{k_{c,t}}{(1-\theta)^\kappa} + k_{d,t},$$

$$k_0 > 0,$$

where $\beta_s \in (0,1)$ is the social planner's discount factor and W denotes social welfare. Furthermore, κ accounts for the transition costs and takes the value of either zero or one, depending on whether there is a transition from the dirty to clean technology or vice versa. In each period, the social planner can decide on the capital stock in the next period k_{t+1}, which can be allocated to either the clean or the dirty technology. Accordingly, we maximize for the aggregate capital stock over k_{t+1} while for the technology-specific stocks over $k_{c,t}$ and $k_{d,t}$ and we provide a detailed solution to the social planner's maximization problem in the Appendix. Any solution must also satisfy the transversality condition. By setting up the Lagrangian and combining the first-order conditions, it follows that

$$(1-\theta)^\kappa \left(\gamma_c A_c k_{c,t+1}^{\gamma_c - 1} + 1 - \frac{\delta - \varphi\eta + \iota\eta\varphi}{(1-\theta)^\kappa} \right) = \gamma_d A_d k_{d,t+1}^{\gamma_d - 1} + 1 - \delta - \eta\varphi. \tag{18}$$

To draw comparisons to the market outcome, we again assume that $\gamma_c = 1$ whereas $\gamma_d \in (0,1)$, so that the previous equation changes to

$$(1-\theta)^\kappa (1 + A_c) - \delta - \eta\varphi(1-\iota) = \gamma_d A_d k_{d,t+1}^{\gamma_d - 1} + 1 - \delta - \eta\varphi. \tag{19}$$

Let us study the tipping point for the transition from dirty to clean, so that $\kappa = 1$. The social returns to both technologies are the same, and the social planner is indifferent between investing the entire capital stock in the clean or the dirty technology if:

$$\bar{k}^{SP} = \left(\frac{\gamma_d A_d}{(1-\theta)A_c - \theta + \eta\varphi\iota} \right)^{\frac{1}{1-\gamma_d}}. \tag{20}$$

Since the right-hand side of (19) is falling in k, this tipping point is the lower bound for the technology transition from dirty to clean to occur.

Let us discuss the factors that determine this tipping point in turn. The term $\gamma_d A_d$ reflects the internalized learning effects of the dirty technology that increase the stock of capital after which the social planner decides to invest in the clean technology. The reverse holds for the term $(1-\theta)A_c$ that represents the internalized learning spillovers of the clean technology. Since a change to the clean technology is associated with costs, however, these spillovers are reduced by the factor $(1-\theta)$. The term $-\theta$ also increases the tipping point, as it captures the fact that changing to the clean technology today makes some of today's aggregate capital stock obsolete and thus will reduce the capital that is available tomorrow. This effect is not internalized by agents in the market economy, because they do not care what happens to the capital stock after they are old. Finally, unlike the market economy, the social planner takes into account the effects related to climate change.

In particular, the higher the pollution intensity of capital (φ) and the greater the sensitivity of the capital stock to climate change (η), the lower is the tipping point of the social planner. Moreover, the higher the technological enhancement in terms of pollution savings (ι), the more worthwhile a technology switch and thus the lower the socially optimal tipping point. Using standard parameter values, we numerically demonstrate in Section 5.2 that the tipping point of the social planner is lower that the market tipping point, i.e. $\bar{k}^{SP} < \bar{k}^{TP}$.

Similar to the decentralized economy, we can derive a second tipping point for the transition from clean to dirty by setting $\kappa = 0$ in Equation (19). Thus, we obtain

$$\underline{k}^{SP} = \left(\frac{\gamma_d A_d}{A_c + \eta\varphi\iota} \right)^{\frac{1}{1-\gamma_d}}.$$

If the social planner has invested in the clean technology and the aggregate capital stocks passes below $\underline{k}^{SP}$, a transition from the clean to the dirty technology will occur. Note that this tipping point is unambiguously smaller than the corresponding tipping point in the market economy, i.e., $\underline{k}^{SP} < \underline{k}^{TP}$.

4 Policy analysis

We consider and compare two policies to implement the social planner's tipping point in the market economy and ask whether such policies can prevent economies from falling into a carbon trap. In addition, we assess whether these policies can reduce the upper trap region and thus pave the way for trapped economies to achieve sustained green growth. The first policy is a carbon tax imposed on dirty production and whose proceeds are given to the young. The second instrument is a subsidy granted to the clean technology and financed by an income tax on the young generation. Whether we make the green technology more productive or the dirty technology less productive affects capital accumulation differently and yields new insights regarding the dynamic properties of the model. Both policies are aimed at providing an incentive for households to invest in the clean technology in an optimal way with respect to the development level of the economy. However, these policies do not guarantee that the market economy will follow the same transition path as in the social optimum. They merely ensure that the market economy switches to the clean technology for a level of capital that corresponds to the one chosen by the social planner. In what follows, we refer to such a policy as being an "optimal instrument" even though the transition dynamics are not fully considered.

4.1 Carbon tax

Firms must pay a carbon tax proportional to the pollution they generate. Since pollution is complementary to output, the carbon tax is equivalent to a tax on dirty production. Let τ_d stand for a constant tax rate imposed by the government on dirty production. Under this tax, output with the dirty technology is given by

$$y_{d,t} = (1-\tau_d)A_d k_{d,t}^{\gamma d}.$$

When maximizing profits, firms incorporate the tax in their decision making so that the factor prices change accordingly. The modified prices for labor and capital are summarized in the appendix. Assuming again that the household chooses the investment opportunity whose return is higher than the alternative, we obtain the following tax-adjusted tipping point:

$$\tilde{k}^{TP} = \left(\frac{(1-\tau_d)\alpha_d A_d}{\alpha_c A_c (1-\theta)}\right)^{\frac{1}{1-\gamma_d}}. \tag{21}$$

From that, we can observe that $\tilde{k}^{TP}$ and τ_d are inversely related and thus $\tilde{k}^{TP} < \bar{k}^{TP}$. Therefore, a higher carbon tax lowers the critical capital stock and thus promotes a switch in favor of the clean technology. Along with imposing a tax on dirty production, the government redistributes the tax revenue to the contemporary young agents as a lump-sum transfer so that the government's budget will be balanced. Accordingly, when operating with the dirty technology, the intertemporal budget constraint and the optimal saving function change to

$$w_{d,t} + \tau_d y_{d,t} + (1 - \theta\psi - \Lambda_d)k_t = c_t^1 + \frac{c_{t+1}^2}{r_{d,t+1}}, \quad \text{and}$$
$$s_t = \frac{\beta}{1+\beta}\left[w_{d,t} + \tau_d y_{d,t} + (1 - \theta\psi - \delta - \eta\varphi)k_t\right].$$

The tax has a positive impact on savings and thus fosters capital formation with the dirty technology. While the dynamic equation for pollution and capital formation in the case of $k_t \geq \bar{k}^{TP}$ remains the same as in the baseline model, capital accumulation under the policy changes as follows:

$$k_{t+1} = \frac{\beta}{1+\beta}\left[(1 - \alpha_d + \alpha_d\tau_d)A_d k_t^{\gamma_d} + (1 - \delta - \eta\varphi)k_t\right] \qquad \text{if } k_t < \bar{k}^{TP},$$

for given $k_0 > 0$. Overall, the introduced carbon tax promotes the shift from dirty to clean technology twofold: First, by reducing the tipping point and second by fostering capital formation so that the economy is more likely to be able to build the capital stock needed to reach the (reduced) tipping point. These two effects have an impact on both the level of A_c, which enables the transition to the clean technology, as well as on the upper trap region, which is shown below.

With regard to the threshold value $\bar{A}_c^T$, we find that the carbon tax appears in two instances in the relevant expression

$$A_c > \frac{(1-\tau_d)\alpha_d(\beta^{-1} + \delta + \eta\varphi)}{(1 - \alpha_d + \alpha_d\tau_d)\alpha_c(1-\theta)} \equiv \tilde{A}_c^T, \tag{22}$$

where it reduces the threshold from $\bar{A}_c^T$ to $\tilde{A}_c^T$.[22] Therefore, the transition condition is satisfied for a wider range of values for A_c, making it more likely for less productive economies to switch to the clean technology along their transition paths. The green growth condition described by $\bar{A}_c^G$ remains unchanged compared to the model without policy intervention.

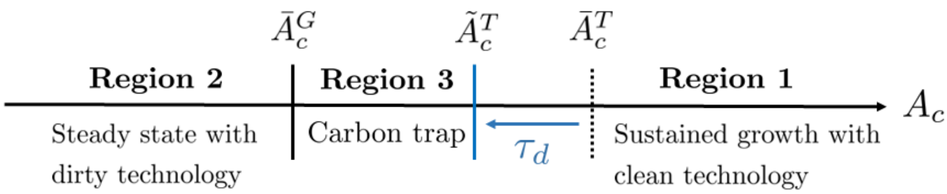

Figure 4: Threshold values and regions with a carbon tax

Figure 4 indicates the new threshold associated with the modified transition condition.

[22]The tax-adjusted steady state of the dirty technology is given by Equation (34) in the Appendix.

The carbon tax makes Region 1 (where long-term growth with the clean technology exists) broader and Region 3 (carbon traps) narrower. Thus, a carbon tax whose proceeds are redistributed to the young generation helps a capital-poor economy, where green growth would be technologically feasible, to transition to clean production and thus to escape the carbon trap.

In the following, we show that a carbon tax constrains not only the set of values for A_c under which a carbon trap exists but also the interval for capital endowments that pitch the economy into the carbon trap. The reason for this is twofold: First, the tax policy gives households an incentive to adopt the clean technology by lowering the tipping point from $\bar{k}^{TP}$ to $\tilde{k}^{TP}$, and second, it provides workers with an incentive to save because they receive the redistributed tax revenues that shift the capital accumulation equation upward from $k_{d,t+1}$ to $\tilde{k}_{d,t+1}$, raising the dirty steady state from k_d^{SS} to $\tilde{k}_d^{SS}$. We illustrate both effects in Figure 5, where upper trap region shrinks from $[k_d^{SS}, \bar{k}^{TP}]$ to $[\tilde{k}_d^{SS}, \tilde{k}^{TP}]$ and consequently the set of capital values from which the economy converges to the carbon trap becomes smaller.

We summarize our findings in the following proposition:

Proposition 5. *A tax on the dirty technology whose proceeds are transferred to the young has the following effects:*

1. *It reduces the set of values for A_c under which a carbon trap emerges in the economy.*
2. *Given that a carbon trap exists, the tax narrows the upper trap region from $[k_d^{SS}, \bar{k}^{TP}]$ to $[\tilde{k}_d^{SS}, \tilde{k}^{TP}]$.*

To find the optimal tax, we equalize the tax-adjusted market tipping point derived in (21) with the tipping point of the social planner derived in (20) such that $\tilde{k}^{TP} = \bar{k}^{SP}$. Solving yields

$$\tau_d^* = 1 - \frac{\gamma_d \alpha_c (1-\theta) A_c}{\alpha_d \left((1-\theta)A_c - \theta + \eta\varphi\iota\right)}, \quad \in (0,1). \tag{23}$$

In light of Equation (23), we can conclude that the optimal tax depends, among others, positively on the parameters related to climate change: The higher the technological upgrading in terms of pollution savings (ι), the higher the pollution intensity of capital (φ), and the greater the sensitivity of capital stock to climate change (η), the higher the optimal carbon tax that induces households to adopt the clean technology at the socially optimal level of development.

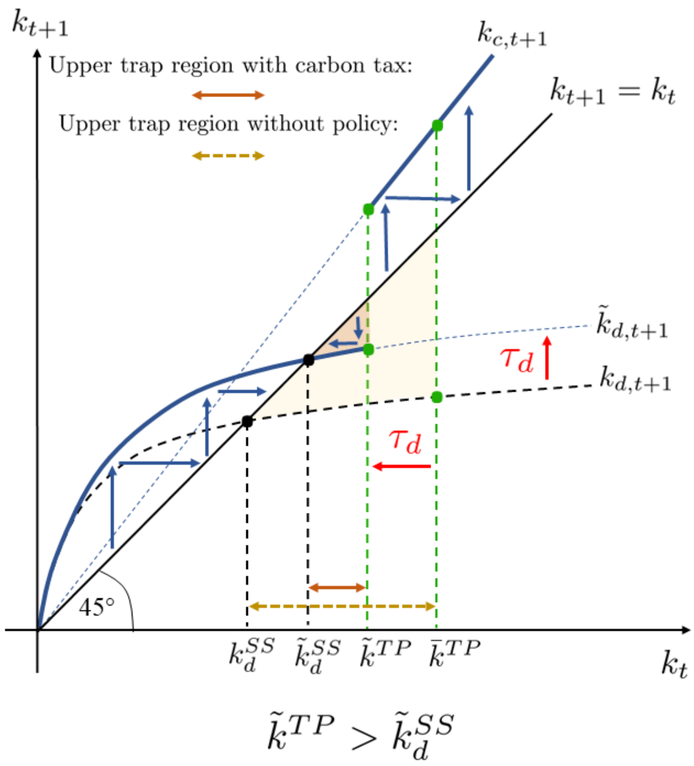

Figure 5: Phase diagram: Carbon trap with tax policy

4.2 Subsidy

As a second policy instrument we consider a subsidy strategy. Let τ_c denote a time-invariant subsidy granted to the clean technology such that

$$y_{c,t} = (1 + \tau_c) A_c k_{c,t}.$$

Under the same assumptions as for the tax and with an analogous procedure, we obtain the following tipping point:

$$\hat{k}^{TP} = \left(\frac{\alpha_d A_d}{(1 + \tau_c)\alpha_c A_c (1 - \theta)} \right)^{\frac{1}{1-\gamma_d}}.$$

Intuitively, a subsidy on clean production lowers the tipping point and thus $\hat{k}^{TP} < \bar{k}^{TP}$. The subsidy is financed by an income tax on the young such that the government runs a balanced budget in every period. Given that the clean technology is employed, the intertemporal budget constraint and the optimal saving function of the household change to

$$w_{c,t} - \tau_c y_{c,t} + (1-\theta\psi - \Lambda_c)k_t = c_t^1 + \frac{c_{t+1}^2}{r_{c,t+1}}, \quad \text{and}$$

$$s_t = \frac{\beta}{1+\beta}\left[w_{c,t} - \tau_c y_{c,t} + (1-\theta\psi - \delta - \eta\varphi(1-\iota))k_t\right].$$

Given the policy design, a subsidy impacts both the tipping point and capital accumulation. While the dynamic equations for the change in pollution and capital accumulation with the dirty technology remain the same as in the baseline framework, capital with the clean technology evolves over time according to

$$k_{t+1} = \begin{cases} \frac{\beta}{1+\beta}\left[(1-\alpha_c-\alpha_c\tau_c)A_c(1-\theta)k_t + (1-\theta-\delta-\eta\varphi(1-\iota))k_t\right] & \text{if } k_t \geq \bar{k}^{TP} \text{ and } t = t^{TP}, \\ \frac{\beta}{1+\beta}\left[(1-\alpha_c-\alpha_c\tau_c)A_c k_t + (1-\delta-\eta\varphi(1-\iota))k_t\right] & \text{if } k_t \geq \bar{k}^{TP} \text{ and } \; t > t^{TP}, \end{cases}$$

for given k_0. Subsidizing clean production has an ambiguous effect on the tipping point and capital formation: A higher level of subsidy τ_c facilitates the technology transition by reducing the tipping point from $\bar{k}^{TP}$ to $\hat{k}^{TP}$. On the other hand, a too high subsidy in a relatively poor country dampens capital accumulation with the clean technology and thus future growth prospects preventing an economy to conduct a technology switch from dirty to clean. The first of those effects is captured by the transition condition:

$$A_c > \frac{\alpha_d(\beta^{-1}+\delta+\eta\varphi)}{(1-\alpha_d)(1+\tau_c)\alpha_c(1-\theta)} \equiv \hat{A}_c^T, \tag{24}$$

where the subsidy reduces the threshold from $\bar{A}_c^T$ to $\hat{A}_c^T$. All else remaining the same, it is straightforward to see that this inequality is more likely to hold in the presence of a subsidy. Thus, the implementation of such a policy increases the likelihood that the economy can pass the critical capital stock and not get stuck with the dirty technology in an early stage of development. However, unlike the tax policy, the subsidy affects the green growth condition

$$A_c > \left(\frac{1}{\beta} + \delta + \eta\varphi(1-\iota)\right)\frac{1}{(1-\alpha_c-\alpha_c\tau_c)} \equiv \hat{A}_c^G, \tag{25}$$

by increasing the threshold from $\bar{A}_c^G$ to $\hat{A}_c^G$ and thus constraining the set of A_c values under which this condition is fulfilled. Hence, a subsidy policy designed in this way, has a negative impact on a country's economic development. This is because the public funds needed to finance the subsidy are paid by young people, reducing their disposable income and thus their savings, which has a negative impact on future capital formation and growth. The subsidy narrows Region 3 (carbon traps) but extends Region 2 (non-growing dirty steady state). Figure 6 visualizes the countervailing effects of the subsidy policy by means of the modified threshold values.

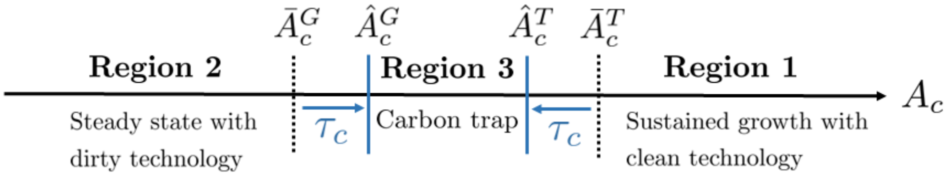

Figure 6: Threshold values and regions with subsidy

While the subsidy should be high enough to incentivize the adoption of the clean technology, overly stringent policies may deprive a country of its economic ability to escape the carbon trap and may encourage the use of the dirty technology in the long–run.

As in the case of the carbon tax, the effect of the subsidy is not limited to the values of A_c that lead to a carbon trap. The subsidy also influences the set of initial capital endowments under which an economy converges to the carbon trap, as we show in Figure 7. Due to the policy's impact on the transition condition, the upper trap region shrinks from $[k_d^{SS}, \bar{k}^{TP}]$ to $[k_d^{SS}, \hat{k}^{TP}]$. Note, however, that this reduction of the upper trap region is smaller than under the tax policy, since there is no additional capital formation under the dirty technology that helps the economy to overcome the upper trap region. In addition, the negative impact of the subsidy on capital formation stemming from the green growth condition translates into a decline of the capital accumulation equation under the clean technology from $k_{c,t+1}$ to $\hat{k}_{c,t+1}$. If this capital dampening effect were so pronounced that the capital accumulation function fell below the 45 degree line, the economy would only have a steady state with the dirty technology, corresponding to the growth pattern of Case 2 in Figure 2. In such a case, the capital stock shrinks under the clean technology and, regardless of the initial capital stock, the economy converges to k_d^{SS}. Clearly, such a subsidy would not be optimal but it demonstrates that climate policy should be carefully calibrated, keeping in mind that the funds used to promote clean technologies need to be financed, which reduces the resources available for capital investments and thus adversely affects future growth prospects.
We summarize our findings related the subsidy policy in Proposition 6.

Proposition 6. *Providing subsidies to the clean technology (by financing the subsidies through an income tax on the young generation) has the following effects:*

1. *It reduces the set of A_c–values under which a carbon trap exists in the economy.*

2. *Given that a carbon trap exists, it reduces the upper trap region from $[k_d^{SS}, \bar{k}^{TP}]$ to $[k_d^{SS}, \hat{k}^{TP}]$. However, this reduction is smaller than under the tax policy as k_d^{SS} remains unaffected.*

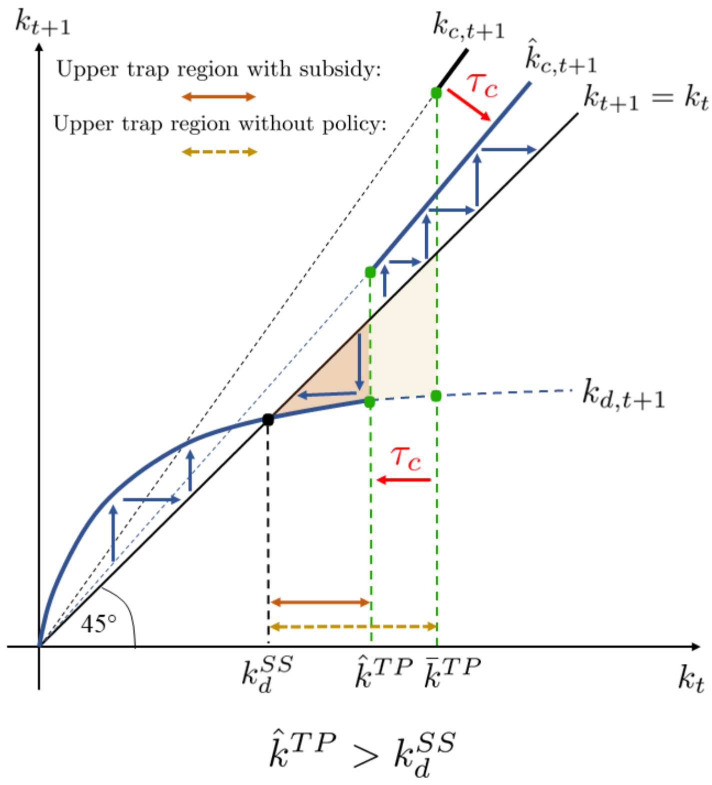

Figure 7: Phase diagram: Carbon trap with subsidy

The optimal subsidy τ_c^* is obtained by comparing the socially optimal tipping point with the tipping point that arises in the market economy under the subsidy policy, i.e. $\hat{k}^{TP} = \bar{k}^{SP}$, which yields

$$\tau_c^* = \frac{\alpha_d\left((1-\theta)A_c - \theta + \eta\varphi\iota\right)}{\gamma_d\alpha_c A_c(1-\theta)} - 1, \quad \in (0,1). \tag{26}$$

The optimal subsidy is, among other things, an increasing function of the parameters related to climate change: a high pollution intensity (φ), a high capital sensitivity (η) and high pollution savings (ι) generate a higher subsidy in order to foster adoption in the market economy.

In the policy analysis so far, we have assumed that the young household receives the revenues from the tax on the dirty technology and finances the subsidies for the clean technology, leading to the following key conclusion: For an economy locked in a carbon trap our analysis reveals that the tax policy is better suited to trigger the socially optimal tipping point because unlike the subsidy, the public funds released by the carbon tax provide an additional stimulus to capital accumulation which further reduces the upper trap region.

Instead, one could assume that the old generation receives the revenues from the tax and has to pay for the subsidy. We do so in the Appendix and find that these policies lead to a "wage effect" and an "anticipation effect," both of which affect the incentives to accumulate capital. Given that tax revenues are transferred to the old generation, the "wage effect" states that a firm can pay lower wages to young households because of the tax burden, which reduces their disposable income and thus their incentive to save and accumulate capital. Moreover, young households anticipate the increase in disposable income in old age so that their incentives to save for old-age consumption is reduced, which in turn lowers capital accumulation. This corresponds to the "anticipation effect".

Overall, by shifting resources from the young to the old, such a tax policy not only reduces the tipping point but also the incentives for capital accumulation, reflecting the widespread concern that (overly) stringent climate policies could harm economic development and thus possibly delay rather than accelerate the technology transition.[23] Using standard parameter values, we show in the Appendix that the negative effect of the tax on capital accumulation quantitatively outweighs the tax-induced reduction in the tipping point, enlarging the overall size of the upper trap region. This illustrates that the implementation of well-intended climate policies in capital-poor economies should take into account potential unintended side effects that may weaken incentives for capital accumulation and thus favour the emergence of carbon traps.

When the subsidy is financed by the old generation, the same effects occur as with the tax policy, where both the wage– and the anticipation effect stimulate capital accumulation and, together with the reduced tipping point, encourage the adoption of clean technologies. More specifically, the young anticipate that they will have to finance the clean technology in old age and compensate for this decrease in disposable income by increasing capital formation, which represents the "anticipation effect." Together with the subsidy-induced increase in wages, i.e., the "wage effect", capital formation is stimulated, which promotes the adoption of the clean technology as a whole.

We summarize our results for all constellations of policies and redistribution schemes:

1. Regardless of the policy and redistribution scheme, the tipping point $\bar{k}^{TP}$ is reduced.
2. While every policy that removes resources from the young, reduces capital accumulation, the opposite holds for policies that take resources from the old.
3. The tax on the dirty technology leaves A_c^G unaffected while the subsidy for the clean technology leaves k_d^{SS} unaffected.

[23]See e.g. Charlier et al. (2022) for a more detailed discussion.

5 Numerical simulation

Above, we have analytically demonstrated the difference between the tipping points in the social optimum and the market economy. However, in order to determine by how many periods the tipping points are apart, we have to resort to a numerical simulation of the model.

5.1 Calibration

We rely on various data sources for the calibration of the parameter values. The length of one period is around 30 years. We set capital depreciation to $\delta = 0.3$ which corresponds to a depreciation rate of 4% per annum. The discount factor β is equal to 0.7; slightly higher than in Dao & Edenhofer (2018) who employed an OLG model to examine fiscal strategies to avoid poverty-environment traps. Since green technologies tend to be relatively capital intensive, we set $\alpha_c = 0.35$, while we assume a standard capital intensity of $\alpha_d = 0.3$ for the polluting technology (IEA, 2022). The learning intensities are $\nu_c = 0.65$ and $\nu_d = 0.4$, reflecting the gap in learning rates between clean and dirty technologies in the empirical literature, see e.g. Rubin et al. (2015). Concerning the pollution intensity of capital, we assume $\varphi = 1.11$ as in Dao & Edenhofer (2018). For the transition costs in terms of capital we rely on Pommeret & Schubert (2009) and assume $\theta = 0.15$. For climate change vulnerability, we set $\eta = 0.3$ in line with Bretschger & Komarov (2023).[24] With a technology switch from dirty to clean, the economy can reduce its pollution intensity by 90%, so that $\iota = 0.9$.[25] For the TFP values of the technologies, we impose that the clean technology lags relatively behind the dirty technology, assuming that A_c is between 2.7 and 4, while A_d is set to 5. The range of A_c values is used below to simulate the different growth patterns presented in the theoretical part. We summarize the parameter values in Table 2.

5.2 Simulation

Using the parameter values described above and setting $A_c = 4$ leads to unbounded green growth in the long run, as the productivity value of the clean technology exceeds the two productivity thresholds given by $\bar{A}_c^G = 2.7$ and $\bar{A}_c^T = 3$. Accordingly, the market economy can adopt the clean technology regardless of its initial capital endowment. The evolution of the capital stock and total consumption for the social planner and the market economy is shown in Figure 8. We find that the socially optimal tipping point occurs 3 periods, i.e., 90 years, before the decentralized tipping point, so that the social planner switches

[24] For economies that are particularly exposed to the consequences of global warming, we set $\eta = 0.5$ and demonstrate in the appendix that this can lead to a climate-induced carbon trap.

[25] We also investigated the case of a pollution-free technology, i.e., $\iota = 1$ but this does not change our results.

Parameter	Description	Value
β	Discount factor	0.7
α_d	Capital intensity dirty technology	0.3
α_c	Capital intensity clean technology	0.35
ν_d	Learning intensity dirty technology	0.4
ν_c	Learning intensity clean technology	0.65
δ	Depreciation of capital	0.3
φ	Pollution intensity	1.11
η	Impact intensity	0.3
A_c	Productivity clean technology	2.7-4
A_d	Productivity dirty technology	5
θ	Transition costs	0.15
ι	Pollution savings	0.9

Table 2: Parameter values

to clean production significantly earlier than the market economy. There are two reasons for this result: First, the critical capital stock at which the social planner transitions to the clean technology ($\bar{k}^{SP} = 1$) is smaller than the market tipping point ($\bar{k}^{TP} = 2.2$), reflecting that the social planner internalizes all externalities (including the transition costs). Due to the non-internalized transition costs in the market economy, capital accumulation flattens out at the time of transition, i.e., in $t^{TP} = 6$, which temporarily delays economic development (Panel A).

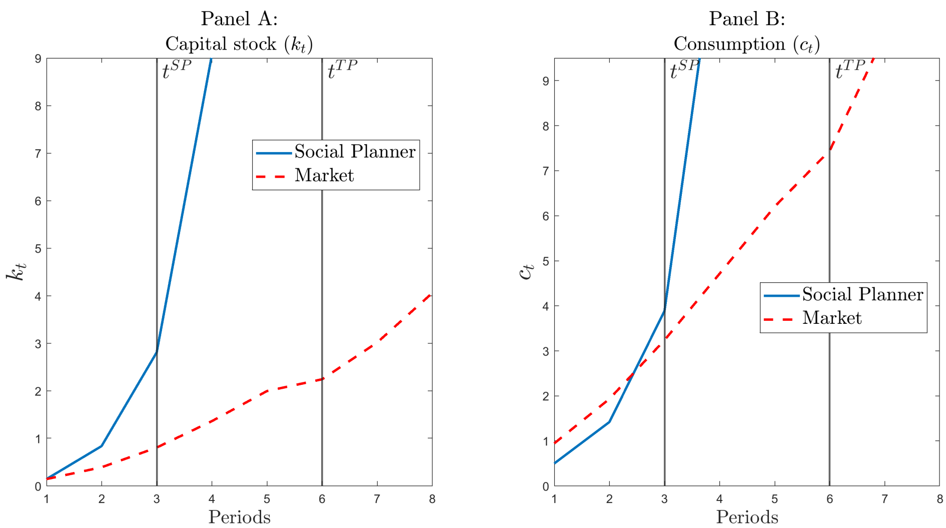

Figure 8: Sustained growth with clean technology

Second, the social planner accumulates capital much faster than the market economy, both before and after the tipping point occurs. This fast capital accumulation and resulting rapid transition to clean production leads to a large increase in consumption in the long run, but at the expense of low consumption in the first 2 periods ($\approx$ 60 years), during which consumption in the social optimum is lower than in the market economy (Panel B). To isolate the sole effect of the external effects on the transition timings, we modify the saving function of the market economy later in this section.

We provide further insights into the investment decisions of the social planner and the market economy in Figure 9. As illustrated in Panel A and Panel B, aggregate consumption and savings in the market economy are a constant fraction of total wealth, amounting to 0.59 and 0.41 respectively. In contrast, we find that the socially optimal savings rate is already significantly higher in the first period under the dirty technology, taking a value of 0.62. Moreover, this savings rate temporarily jumps to 0.68 in the period before the tipping point occurs and then adopts — from the tipping point period onward — a constant value of 0.65. We observe the opposite pattern for the socially optimal consumption rate (Panel B) and consumption growth rate (Panel C), respectively, with both dropping in the period before the technology transition occurs. The reason for these temporal peaks lies in the transversality condition of the social planner as well as in the tipping point condition: As is common in AK-models, the ratio of consumption to capital takes a fixed value that is determined by the aforementioned transversality condition. To achieve this desired ratio, the social planner needs to increase savings to compensate for the additional capital losses resulting from the transition to clean production. The growth rate of consumption in the market economy steadily decreases until the tipping point is reached (Panel C), reflecting the concave production structure of the dirty technology. After passing the tipping point, the growth rate of consumption is 0.35%, well below the growth rate of consumption in the social optimum, which is 2.26%. Regarding the optimal policies, our simulation reveals that a tax rate of $\tau_d^* = 0.21$ or a subsidy of $\tau_c^* = 0.27$ can implement the socially optimal tipping point in the market economy.

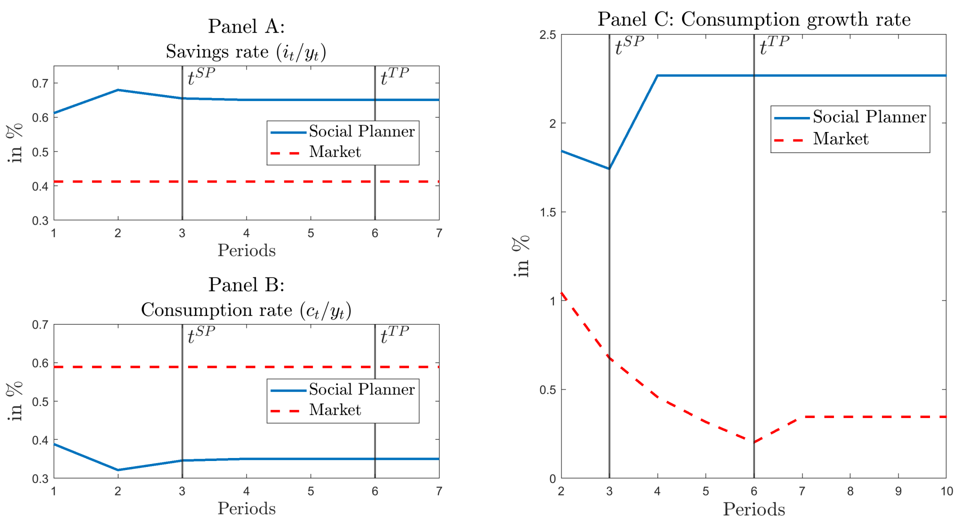

Figure 9: Sustained growth with clean technology

Next, we illustrate the case of a carbon trap. In doing so, we leave the other parameter values unchanged and lower the TFP value of the clean technology to $A_c = 2.75$ so that the green growth condition is satisfied ($\bar{A}_c^G = 2.7$), but not the transition condition ($\bar{A}_c^T = 3$).[26] The resulting plots are shown in Figure 10, where the tipping period in the market economy, t^{TP}, vanishes because the transition condition is not satisfied and thus the economy cannot transition to clean production in the market economy in the absence of climate policies. The upper trap region resulting from the simulation is shown in Panel C and is determined by the interval between $\bar{k}^{TP} = 7.5$ and $k_d^{SS} = 5.8$. All initial values of capital below $\bar{k}^{TP} = 7.5$ form the trap region from which the economy converges to the dirty steady state with a convergence time of about 20 periods in the present illustration.[27] The consumption growth rate shown in Panel D also follows this pattern and eventually converges to zero.[28] Initial values of capital above $\bar{k}^{TP} = 7.5$ allow the economy to generate sustained growth with the clean technology.

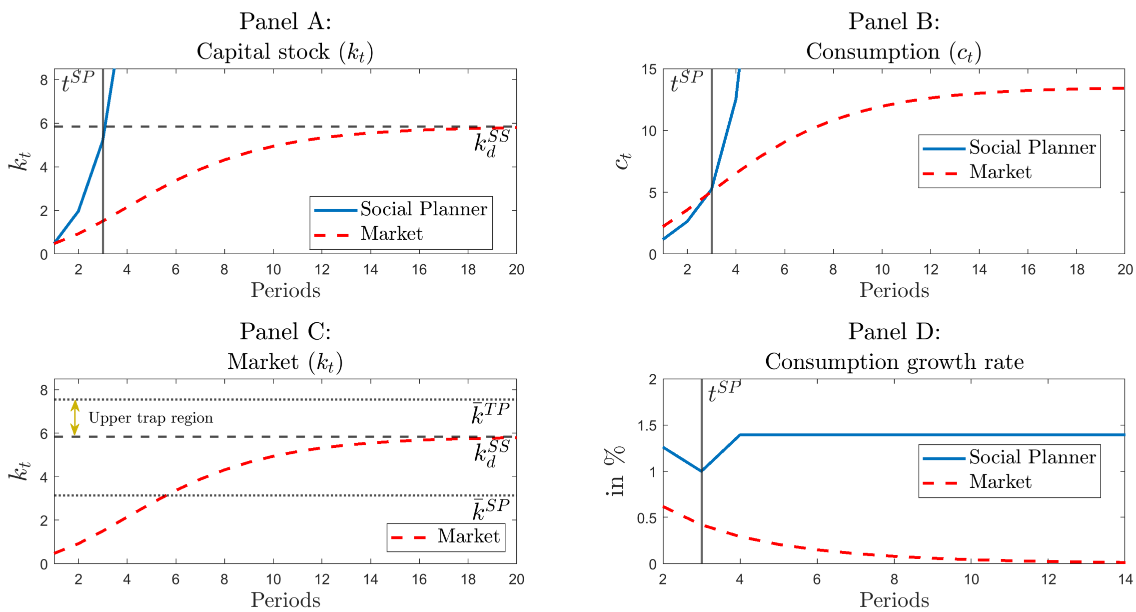

Figure 10: Carbon trap

The social optimum changes only slightly compared to the previous simulation with the higher TFP value. The social planner again switches to clean production after three periods, and experiences sustained green growth in the long run. In this process, the economy consumes less than the market economy until the technology switch occurs, i.e., for 3 periods (Panel B). The socially optimal growth rate of consumption after the

[26] In the Appendix, we show that a carbon trap can also arise from a combination of higher climate exposure and lower clean factor productivity, where the corresponding parameter values are $\eta = 0.5$ and $A_c = 3$.

[27] The convergence time depends on the initial stock of capital and does not hold generally.

[28] We omit the case where the steady state with dirty technology is the only long-run outcome, as this is just a generalization of the case of a carbon trap, where convergence to the trap is global.

transition is about 1.39% and thus lower compared to the previous simulation where the higher A_c-value was employed (Panel D). By accumulating sufficient capital and internalizing all non-market effects, the social planner ensures, unlike the market economy, that the transition condition is satisfied.[29] However, the gap between $\bar{k}^{TP} = 7.5$ and $\bar{k}^{SP} = 3.1$ in Panel C can be closed using the optimal policies derived in Section 4. Specifically a tax of $\tau_d^* = 0.23$ or a subsidy of $\tau_c^* = 0.3$ can implement the socially optimal tipping point in the market economy and thus ensure that the economy can switch to clean production and not get stuck in the carbon trap in the long run.

Finally, we perform the simulations for the case of cyclical fluctuations. Increasing the capital intensity of the clean technology to $\alpha_c = 0.4$ leads to a reversal of the productivity thresholds, which are now given by $\bar{A}_c^T = 2.6$ and $\bar{A}_c^G = 2.95$. Specifying $A_c = 2.7$, gives rise to cyclical fluctuations, which is illustrated in Figure 11. As in the previous simulations, the social planner switches to clean production after three periods. As shown in Panel B, consumption in the social optimum is lower than in the market economy for about 90 years. In Panel C we see that the capital stock of the market economy oscillates between the two tipping points introduced in the theoretical section. Initially, the capital stock increases until the tipping point ($\bar{k}^{TP} = 5.1$) is reached after 10 periods, whereupon the economy switches to the clean technology for the first time. However, this transition leads to a contraction of the capital stock due to the low productivity with the clean technology until the economy falls below $\underline{k}^{TP} = 2.9$ and returns to dirty production after 18 periods. Thereafter, total capital rises again until the economy shifts back to the green technology; this process repeats itself creating a stagnating economy with recurring technology cycles.[30] As shown in Panel B, total consumption follows the same pattern. Accordingly, the growth rate of consumption shown in Panel D fluctuates around zero, taking positive and negative values intermittently, while the growth rate of consumption in the social optimum is constant, adopting a value of 1.36%.

5.3 Simulation with modified saving function

As mentioned before, one of the two possible reasons why the social planner switches to clean production earlier than the market economy is its higher savings rate. To control for this channel and to determine the extent to which the difference in adoption times is due to the difference in actual tipping values and the involved externalities rather than savings rates, we modify our model by including an additional term in the utility function:

$$U_t(c_t^1, c_{t+1}^2, s_t) = \log(c_t^1) + \beta \log(c_{t+1}^2) + \epsilon \log(s_t).$$

[29] In Panel C, we see that $\bar{k}^{SP} < k_d^{SS}$ while $\bar{k}^{TP} > k_d^{SS}$, with the corresponding values given by $\bar{k}^{TP}$=7.5, $\bar{k}^{SP} = 3.1$ and $k_d^{SS} = 5.8$.

[30] Note that the optimal policies derived in Section 4 cannot provide a way out of stagnation, since the obstacle to long-term green growth is not the transition to clean production, but the unproductive green technology.

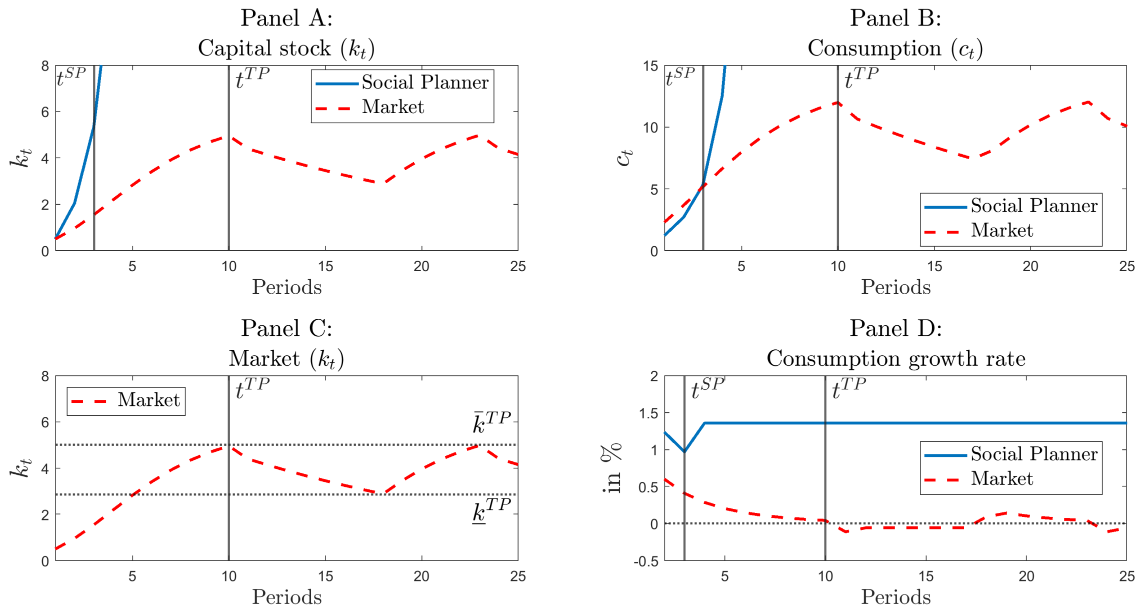

Figure 11: Cyclical fluctuations

Hence, agents have an explicit preference for savings now, reflecting some "warm-glow" or additional altruism motive; the strength of this effect is captured by the parameter ϵ.[31] Given this modification, savings are now given by

$$s_t = \frac{\beta + \epsilon}{1 + \beta + \epsilon} \left[w_{i,t} + (1 - \theta\psi - \Lambda_i) k_t \right], \quad i \in \{c, d\}.$$

In the following, the obtained results with this modified savings function are compared to the case of sustained growth with the clean technology, in which the original savings function was applied (see Figure 7 and 9). In doing so, we use the parameter values listed in Table 2 and again set $A_c = 4$. Thus, growth occurs in both the market economy and the social optimum in the long run, regardless of the initial capital endowment of the economy. The modified savings function enhances capital accumulation in the market economy while the tipping points given by $\bar{k}^{SP} = 1$ and $\bar{k}^{TP} = 2.2$ as well as the social planner solution remain unchanged.[32] The parameter ϵ is calibrated to align the savings rate of the market economy with that of the social optimum, which yields $\epsilon = 1.15$.

We see in Figure 12 that the savings rate (0.65) and consumption rate (0.35) of the social planner and the market economy displayed in Panel D and Panel E coincide, ensuring that any differences in adoption times are now entirely attributable to the non-market effects and the resulting differences in the tipping capital stocks. The temporary

[31] We assume that the social planner does not internalize this altruism, as otherwise the relative difference in savings rates between the social optimum and the market economy would remain the same.

[32] As a result, the optimal tax ($\tau_d^* = 0.21$) and subsidy ($\tau_c^* = 0.27$) to implement the social planner's tipping point in the market economy remain also unchanged.

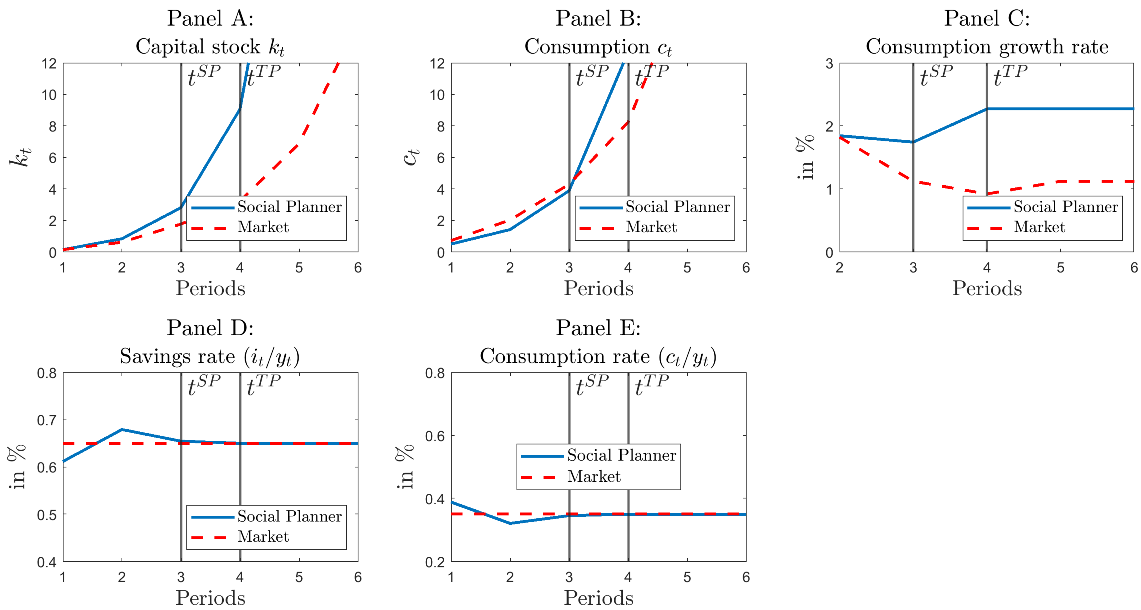

Figure 12: Simulation with modified savings function

increase (decrease) in the savings rate (consumption rate) of the social planner in the second period arises again due to the compensation of the transition costs. Figure 12 shows that despite the same propensity to save as in the social optimum, the market economy transitions to the clean technology later than socially optimal, with the time difference now being reduced to a single period (≈ 30 years). This suggests that differences in savings behavior is not the only factor delaying the adoption of green technologies in the market economy; the non-internalized externalities related to learning, climate change, and stranded capital also contribute to the delayed transition. Intuitively, the capital stock (Panel A) and total consumption (Panel B) of the social planner and the market economy evolve more similarly due to the higher savings rate. As shown in Panel C, the growth rate of consumption in the social optimum after the transition to clean production is 2.26%, about twice as high as in the market economy, where the growth rate of consumption is estimated to be 1.12%. Due to the higher propensity to save, the growth rate of consumption in the market economy is now significantly higher than with the original saving function, where consumption could only grow at 0.35%(compare with Panel C of Figure 9).

6 Extension: Non-convexity in clean production

In this section, we modify the production function of the clean technology to account for the fact that, in addition to the already implemented transition costs, large-scale infrastructure investments are required before the clean technology can become operational. To account for this characteristic, we extend the baseline model by imposing a non-convexity in the production structure of the clean technology. In particular, we assume that the clean production function cannot generate positive output until capital attains a minimum value $\bar{k}$, leaving the remaining assumptions of the model unchanged.[33] By generating a non-convexity in the production structure of the clean technology, this sort of "set-up cost" specification provides scope for multiple steady states making the characterization of the growth patterns substantially more complex.

As in the baseline model, capital formation with the clean technology entails productivity gains which are not internalized by individual firms. Due to symmetry, the clean production function is given by

$$y_c = A_c \left(k_c - \bar{k}\right)^{\alpha_c + \nu_c},$$

where $\bar{k} > 0$ denotes the minimal capital requirement while ν_c and α_c continue to represent the strength of the learning-by-doing effect and capital intensity, respectively. Firms using the clean technology maximize their profits by choosing labor and capital inputs. Assuming that $\alpha_c + \nu_c = \gamma_c$, we obtain the factor prices summarized in Table 3. As in

Technology:	Rental rate (p):	Wage (w):
Dirty technology:	$p_d = \alpha_d A_d k_d^{\gamma_d - 1}$	$w_d = (1-\alpha_d) A_d k_d^{\gamma_d}$
Clean technology with $\bar{k}$:	$p_c = \alpha_c A_c (k_c - \bar{k})^{\gamma_c - 1}$	$w_c = (1-\alpha_c) A_c \left(k_c - \bar{k}\right)^{\gamma_c}$

Table 3: Factor prices: clean technology with capital threshold

the baseline model, the household rents out the capital to the technology that yields the highest return. Since the minimum capital requirement $\bar{k}$ does not affect the investment returns due to the AK-structure in clean production, the tipping points from the baseline economy given by (11) and (12) also remain unchanged.

Unlike the tipping points, capital formation changes due to the minimum capital requirement revealing novel insights regarding the growth patterns of the economy. As above, we set $\gamma_c = 1$, so that capital evolves over time according to

$$k_{t+1} = \begin{cases} \frac{\beta}{1+\beta}\left[(1-\alpha_c)A_c(1-\theta)(k_t - \bar{k}) + (1-\theta-\delta-\eta\varphi(1-\iota))k_t\right] & \text{if } k_t \geq \bar{k}^{TP} \text{ and } t = t^{TP}, \\ \frac{\beta}{1+\beta}\left[(1-\alpha_c)A_c(k_t - \bar{k}) + (1-\delta-\eta\varphi(1-\iota))k_t\right] & \text{if } k_t \geq \bar{k}^{TP} \text{ and } t > t^{TP}, \end{cases}$$

for given $k_0 > 0$ and with t^{TP} referring to the point in time at which the transition dirty to clean occurs.[34]

[33] Our model is similar to the work by Golub & Toman (2016), who also incorporate a minimum capital threshold into the production function of the clean technology. Using numerical simulations, the authors show that a lower capital threshold is associated with a lower probability of an economy falling into an environmental trap.

[34] Note that the dynamics for ΔP_t and k_{t+1} when $k_t < k^{TP}$ do not change compared to the baseline

Turning to the steady state analysis, the minimum capital threshold and the resulting non-convexity in the production structure gives rise to multiple steady states that differ in terms of their stability properties. Since the steady state under the dirty technology (14) and the tipping point (11) remain unchanged from the baseline framework, the transition condition described by (16) does not change either. However, with a fixed capital requirement in clean production, we find a steady state with a constant level of capital not only for the dirty technology but also for the clean technology. The latter is unstable[35] and reads

$$k_c^{SS} = \frac{\bar{k}}{1 - \underbrace{\frac{\beta^{-1} + \delta + \eta\varphi(1-\iota)}{(1-\alpha_c)A_c}}_{=\chi}}. \tag{27}$$

For k_c^{SS} to take a positive value, $\chi < 1$ must hold in (27), which is equivalent to satisfying the green growth condition from the baseline model described by (17).[36] If this is not the case, k_c^{SS} does not exist, and thus the capital stock cannot grow under the clean technology. Therefore, meeting the green growth condition is a first prerequisite for generating long-term green growth in the presence of a capital threshold. The second condition that must be satisfied for the clean technology to generate sustained growth is $k_{c,t+1}/k_{c,t} > 1$ or, equivalently,

$$\frac{k_{c,t+1}}{k_{c,t}} = \frac{\beta}{1+\beta}\left[(1-\alpha_c)A_c\left(1 - \frac{\bar{k}}{k_{c,t}}\right) + (1 - \delta - \eta\varphi(1-\iota))\right] > 1. \tag{28}$$

Unlike in the baseline model, this condition is now increasing in $k_{c,t}$ and equal to unity at k_c^{SS}, which implies that

$$\frac{k_{c,t+1}}{k_{c,t}} \gtreqless 1 \quad \Leftrightarrow \quad k_{c,t} \gtreqless k_c^{SS}.$$

Hence, in presence of a capital threshold, a permanent growth path under the clean technology can only occur if the accumulated stock of capital exceeds the steady state for the clean technology, i.e., $k_{c,t} > k_c^{SS}$. This corresponds to a scale effect induced by the capital threshold, which states that the clean technology can generate long-term growth only beyond a certain size of accumulated capital. Thus, the economy must not only have a high clean factor productivity ($A_c > \bar{A}_c^G$) to ensure the existence of the clean steady state, but also be sufficiently rich in capital so that the capital stock actually increases with the clean technology. The latter poses an additional barrier to long-term

model.

[35]It is straightforward to show that $k_{c,t+1} < k_{c,t}$ for $k_{c,t} < k_c^{SS}$ and $k_{c,t+1} > k_{c,t}$ for $k_{c,t} > k_c^{SS}$.

[36]From $\chi < 1$ in (27), it directly follows that $A_c > \left(\beta^{-1} + \delta + \eta\varphi(1-\iota)\right)\frac{1}{1-\alpha_c} = \bar{A}_c^G$.

green growth.

From Equation (27), we can conclude that the clean steady state k_c^{SS} is low and thus sustained green growth is more feasible when both the minimum capital requirement $\bar{k}$ and χ are low. A low χ (and thus a low k_c^{SS}), in turn, is associated with a steep slope of the $k_{c,t+1}$-function, which will be an important relation for the subsequent graphical analysis.[37] Therefore, economies with high values of A_c, ι, and β and low values of $\bar{k}$, φ and η are, ceteris paribus, more likely to meet $k_{c,t} > k_c^{SS}$ and thus to achieve green growth in the long run.

Providing the analogue to Figure 1 is not trivial, as the dynamics of the economy now depend on the constellation of the three critical values for capital, namely k_d^{SS}, k_c^{SS} and $\bar{k}^{TP}$. Assuming $\bar{A}_c^G < \bar{A}_c^T$ yields seven different outcomes for the economy and for the opposite case, $\bar{A}_c^G > \bar{A}_c^T$, we arrive at five different outcomes. We discuss all possible constellations and the resulting growth dynamics in the Appendix. For consistency with the previous analysis, we again focus on the case where $\bar{A}_c^G < \bar{A}_c^T$ (which holds under fairly general conditions), and we show in Figures 13 and 14 the graphical representations for a subset of the possible long-run constellations. In particular, we illustrate the following cases: Sustained growth with the clean technology (Case 1), the coexistence of cyclical fluctuations and sustained growth (Case 2), the steady state with the dirty technology (Case 3), and the carbon trap (Case 4).

We illustrate sustained growth with the clean technology in Case 1 of Figure 13. For this growth pattern to occur, the productivity of the green technology must be sufficiently high so that both the transition and the green growth condition are satisfied, i.e., $A_c > \bar{A}_c^T > \bar{A}_c^G$. This, as we have shown above, ensures the existence of the steady state with the clean technology. This clean steady state, k_c^{SS}, must be smaller than k_d^{SS} and $\bar{k}^{TP}$, which is equivalent to A_c being large. This is fairly intuitive, since the capital threshold exerts pressure on the productivity of the clean technology: To compensate for the need of a sufficiently large capital stock, the clean technology must entail rapid capital formation or, equivalently, a steep capital accumulation function, $k_{c,t+1}$. For all $k_t < \bar{k}^{TP}$, the economy uses the dirty technology until it transitions to the clean one. At this point, due to the steep $k_{c,t+1}$-function, the economy has surpassed k_c^{SS} so that growth becomes unbounded. Accordingly, sustained growth with the clean technology is the only possible long-run outcome.

If, however, k_c^{SS} is greater than k_d^{SS} and $\bar{k}^{TP}$ (while $A_c > \bar{A}_c^T > \bar{A}_c^G$ still holds), both permanent cyclical fluctuations and sustained growth with the clean technology can emerge, depending on the economy's initial capital endowment. We refer to the Appendix for the proof and illustrate this growth pattern in Case 2 of Figure 13. The key difference between Case 1 and Case 2 is the speed at which the economy can accumulate capital

[37] Formally, the growth rate of the clean technology with a capital threshold converges to that without a threshold as $k_{c,t}$ increases i.e., $\lim_{k_{c,t}\to\infty}(1 - \bar{k}/k_{c,t}) = 1$.

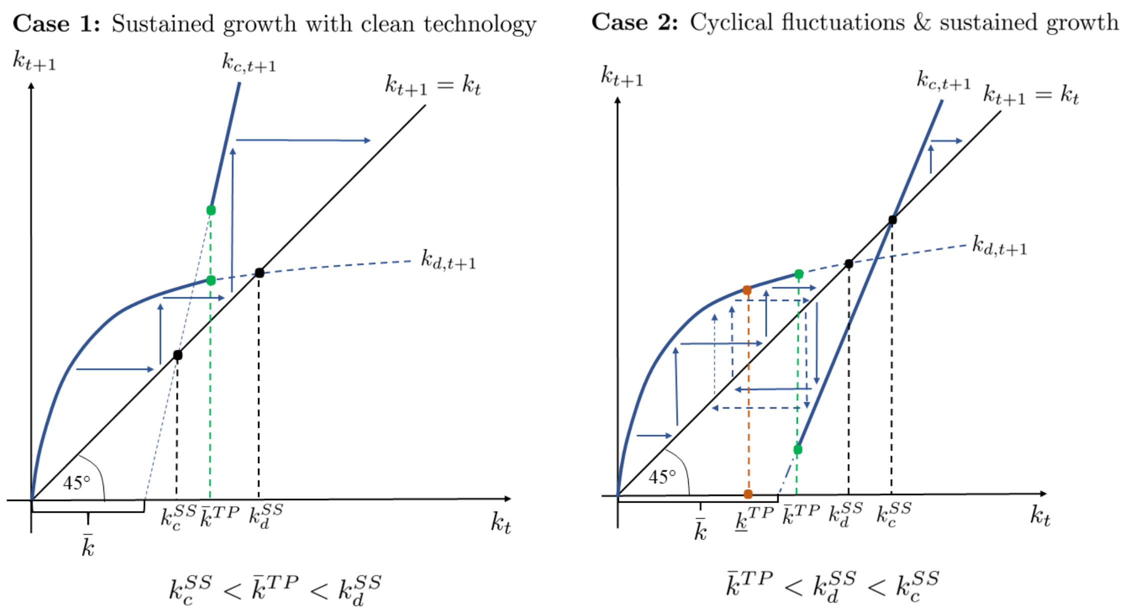

Figure 13: Phase diagrams with capital threshold $\bar{k}$

with the clean technology. The lower speed in Case 2 compared to Case 1 is reflected in the flatter slope of the $k_{c,t+1}$-function, which leads to $k_c^{SS} > \bar{k}^{TP}$ (while $k_c^{SS} < \bar{k}^{TP}$ holds in Case 1). All economies with a capital stock above k_c^{SS} experience unbounded green growth while those with a capital stock below k_c^{SS} fall into permanent cyclical fluctuations. These economies are subject to such fluctuations even though green growth would be technologically feasible, so that with a minimal capital threshold a type of carbon trap can emerge even if clean factor productivity is high.[38] This new insight is summarized in the following proposition:

Proposition 7. *If the clean technology is subject to a minimal capital threshold and one of the following conditions is fulfilled*

i. capital accumulation with the clean technology proceeds only slowly (i.e., the slope of the $k_{c,t+1}$-function is relatively flat),

ii. and/or the minimal capital requirement $\bar{k}$ is relatively high,

[38] Proposition 7 indicates that sufficiently rapid capital accumulation is required with the clean technology in order to prevent adverse growth effects and/or a return to dirty technology. This finding is in line with Golub & Toman (2016) who conclude that "achieving sufficiently rapid growth in use of the new technology is one key element for avoiding an environmental growth trap." This conclusion can also be applied to the current situation in the European Union, where several member states including France and Germany are now dependent on alternative forms of energy due to the war-induced gas shortage (LeMonde, 2022). In the past, however, not enough has been invested in the infrastructure of renewable technologies, which are therefore unable to close the current energy gap, forcing these member states to return to dirty coal and liquid gas, although these countries have a relatively high total factor productivity. This return not only complicates the achievement of the Paris climate goals but also seems to have negative growth effects on these economies LeMonde (2022).

a capital–poor economy may be trapped in a state of permanent cyclical fluctuations, even if its clean factor productivity is high.

If A_c is below $\bar{A}_c^T$ and $\bar{A}_c^G$, a unique steady state with the dirty technology arises, which is shown in Case 3 of Figure 14. This growth pattern is not affected by the capital threshold because the productivity of the green technology is so low that the green growth condition is not met. Accordingly, there is no steady state with the clean technology, and the transitional dynamics follow the same pattern as described in Case 2 of Figure 2 of the baseline model.

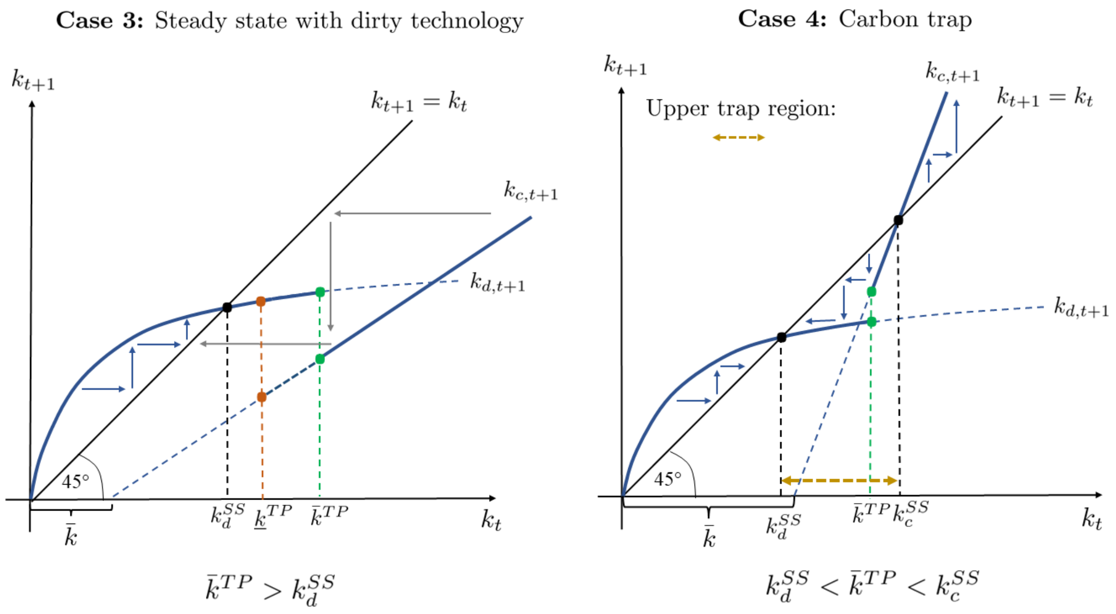

Figure 14: Phase diagrams with capital threshold $\bar{k}$

Finally, we turn to the carbon trap which arises if the green growth condition is satisfied but not the transition condition, i.e. $\bar{A}_c^G < A_c < \bar{A}_c^T$. This growth pattern is illustrated in Case 4 of Figure 14. Since the green growth condition is satisfied, there is a steady state with the clean technology and, the capital threshold affects the resulting growth dynamics by influencing the set of capital values from which an economy falls into the carbon trap. The upper trap region is now given by the interval between k_d^{SS} and k_c^{SS}, where its size depends positively on $\bar{k}$ and negatively on the rate at which the economy can accumulate capital with the clean technology: The lower the rate of capital accumulation with the clean technology (i.e., the flatter the slope of the $k_{c,t+1}$-function), the larger is the size of the upper trap region.

Notably, an economy exposed to high climate-related capital losses not only reaches a lower dirty steady state ($\partial k_d^{SS}/\partial \eta < 0$), as in the baseline model, but also experiences a simultaneous increase of the clean steady state ($\partial k_c^{SS}/\partial \eta > 0$) caused by a downward shift of the $k_{c,t+1}$-function, with both effects enlarging the upper trap region. Moreover, because of the interval between $\bar{k}^{TP}$ and k_c^{SS}, economies revert to k_d^{SS} also after passing the tipping point $\bar{k}^{TP}$, so that an economy remains stuck in the carbon trap even after the technology transition. This is in stark contrast to our findings from the baseline model; we observe that a capital endowment that ensures the transition to clean production does not necessarily translate into sustained growth anymore. We summarize this finding in the following proposition:

Proposition 8. *With a minimal capital requirement in clean production, the economy may be trapped in a low-income, polluting steady state even after the transition to clean production.*

Proposition 8 suggests that providing clean technologies to capital-constrained economies may not be enough to overcome the carbon trap. To escape the upper trap region, clean technologies must be complemented by sufficient physical capital, e.g., in the form of a fossil–free infrastructure. The coexistence of cyclical fluctuations and sustained growth (Case 2) as well as the carbon trap (Case 4) provide a theoretically sound foundation for technology-enhancing public policies. A temporary exogenous shock may enable the economy to overcome the critical gap between $\bar{k}^{TP}$ and k_c^{SS} (see Case 2 and 4) and to transition from the inferior dirty steady state to the superior steady state with unlimited green growth.

7 Discussion

So far, we have considered a global economy. However, we can also adopt a country perspective in which case pollution is exogenous. Because climate change damages an economy's productive capacity, countries that are regularly hit by capital-destroying environmental disasters cannot build up sufficient physical capital to reach the level of development where clean technologies are more profitable than dirty ones. Due to unfavorable geographical conditions, low clean factor productivity, and capital endowments, less developed countries (e.g. sub-Saharan countries, small island states or coastal lowlands) are generally less likely to build the capital stock needed for technology transition and are therefore particularly at risk of falling into a carbon trap or a polluting steady state in which long-term growth is not feasible.

A policy recommendation that emerges from the model is to facilitate access to clean and efficient technologies for capital-constrained countries. Beside the climate policies discussed further possible policies are promoting technology and knowledge transfers or granting financial resources (e.g. technology funds) for technology adoption to capital-poor countries.

Moreover, our model suggests that the choice of technology has a direct impact on a country's long-term growth prospects, with the reason being twofold. First, the technology change enhances capital accumulation through an increase in capital productivity due to stronger spillover effects in clean production. Second, the lower pollution intensity of the clean technology translates into a lower rate of depreciation and thus into higher capital accumulation. Hence, climate policies that support technology transition may serve as a tool to improve development prospects in less developed economies.[39]

8 Conclusion

This paper develops a tractable two-period overlapping generations model in which capital accumulation, capital depreciation, technology choice and economic growth are endogenous. On the one hand, economies can invest in a conventional dirty technology that is readily available but entails high pollution. On the other hand, economies can adopt a clean technology that causes less pollution — but only after the economy has borne the costs of the transition. We highlight the ambiguous role of capital accumulation for technology transition and long-term economic development: While some capital stock is required for the transition to cleaner technologies, pollution caused by capital accumulation can impede this transition by damaging physical capital.

In this framework, we derive two endogenous tipping points for capital that govern the technology transition from dirty to clean technologies and vice versa, creating a variety of potential long-term outcomes that depend, among others, on the economy's capital endowment, pollution intensity, climate vulnerability, and clean factor productivity. We find that economies with a wide range of clean factor productivities can fall into a carbon trap, defined as a long-term steady state with high pollution and low income. Such a trap emerges in our model even without the interaction of pollution, life expectancy and capital accumulation. As a form of a long-term hidden trap, we also show that an economy can fall into a state of permanent cyclical fluctuations with recurring technological changes.

We show numerically that the social planner switches to clean production three generations ($\approx$ 90 years) earlier than the market economy. Once the savings rates of the household and the social planner are aligned, the socially optimal tipping point occurs one period ($\approx$ 30 years) before the market tipping point, and this time lag is entirely attributable to the non-market effects in the economy. Moreover, we demonstrate theoretically and numerically that a tax levied on dirty production or a subsidy for clean production can implement the socially optimal tipping point in the market economy, reducing the risk of being kept in a perpetual state of low development and high pollution. To overcome the carbon trap, the tax seems to be the preferred instrument in our model framework, as the released public funds provide an additional incentive for capital accumulation, which in turn further reduces the size of the upper trap region.

[39]We refer to Bretschger & Valente (2011), Bretschger & Suphaphiphat (2014) and Bretschger (2017) for a more detailed discussion on the growth effects of global warming and climate policy.

In an extension of the model, we introduce a non-convexity in the production structure of the clean technology in the form of a minimal threshold for capital, which represents an additional barrier to sustained green growth. To avoid a carbon trap in the presence of a capital threshold, the relevant clean technologies need to be complemented by sufficient physical capital, underlying the need to provide a fossil-free infrastructure to support the technology transition. For example, fossil-free heating systems need to be supported by building insulation, which requires additional capital investments in existing buildings, or electric vehicles need to be complemented by charging stations in addition to their deployment to prevent a carbon trap in the long term.

This research can be further developed in several directions, and we highlight two of them here. First, it might be interesting to consider an open economy to examine the role of international capital flows in reaching the tipping point. An open economy may attract additional foreign capital investments, which can help to accelerate the technology transition; especially in the less developed countries where credit constraints are often seen as a major obstacle to long-term capital formation. Second, a non-renewable resource stock could be included in the model. An increasing resource price according to the Hotelling rule could facilitate the transition to low-carbon technologies and possibly prevent economies from falling into a carbon trap. However, this is left for future research.

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Appendix: Basic model

Investment returns

We provide a more detailed derivation of the investment returns used in the main text based on Table 4. Using a standard definition of a return, r_i is defined as

$$r_i(k_{i,t}) = \frac{p_i(k_{i,t}) \cdot k_{i,t}}{k_t}, \quad i \in \{c, d\},$$

where $p_i(k_{i,t})$ corresponds to the rental price of capital and k_t represents the aggregate capital stock regardless of the technology for which it is used.

We start with Case 1 from Table 4, where capital was employed in dirty production in period $t-1$ and thus $k_{t-1} = k_{d,t-1}$. In period t, the household decides whether to rent the entire capital stock, k_t, to the dirty or to the clean technology. Assuming that the household invests in the dirty technology in two consecutive periods, we obtain $k_t = k_{d,t}$ in period t and the associated return on investment reads

$$r_d(k_{d,t}) = r_d(k_t) = \frac{p_d(k_t) \cdot k_t}{k_t} = p_d(k_t),$$

which corresponds to the rental price of capital derived in Equation (9) in the main text.

Cases	Period $(t-1)$	Period (t)	Return on Investment (r)
Case 1	dirty	dirty	$r_d(k_t) = p_d(k_t)$
Case 2	dirty	clean	$r_c(k_t) = p_c[(1-\theta)k_t] \cdot (1-\theta)$
Case 3	clean	dirty	$r_d(k_t) = p_d(k_t)$
Case 4	clean	clean	$r_c(k_t) = p_c(k_t)$

Table 4: Returns on investment

Next, we consider the transition from dirty to clean technology (Case 2), which is more involved as the transition costs now affect the return. In particular, as part of the capital stock becomes obsolete, the clean technology can only use the share $(1-\theta)$ of the total capital stock in production. Accordingly, the rental price of capital for the technology transition from dirty to clean is equal to $p_c[(1-\theta)k_t]$ and higher than in Case 1 since the marginal product of capital decreases with the stock of capital used in production. Note, however, that the household receives the return on investment only for the capital stock $(1-\theta)k_t$ that does not become obsolete due to the technology transition. Accordingly, the return on investment associated with the shift in technology from dirty to clean reads

$$r_c(k_{c,t}) = \frac{p_c(k_{c,t}) \cdot k_{c,t}}{k_t},$$

and using $k_c = (1-\theta)k_t$ yields

$$r_c[(1-\theta)k_t] = \frac{p_c[(1-\theta)k_t] \cdot (1-\theta)k_t}{k_t} = p_c[(1-\theta)k_t] \cdot (1-\theta),$$

which deviates from its rental price of capital due to the transition costs.

Let us turn to the Cases 3 and 4, in which the economy uses the clean technology in period $t-1$ and thus $k_{t-1} = k_{c,t-1}$. In period t, the household can invest the entire capital stock either in the dirty technology (Case 3), which leads to $k_t = k_{d,t}$, or in the clean technology (Case 4) which leads to $k_t = k_{c,t}$. Since the transition costs are irrelevant for both investment options, the investment returns do not differ from the rental prices of capital and we have

$$r_i(k_{i,t}) = r_i(k_t) = \frac{p_i(k_t) \cdot k_t}{k_t} = p_i(k_t), \quad \text{with} \quad i \in \{c, d\}.$$

As a result, regardless of whether the economy transitions from clean to dirty technology or employs the clean technology in two consecutive periods, the household's return to both investments is equal to the corresponding rental price of capital derived in Equation (9) in the main text.

Threshold conditions

Note that $\bar{A}^G < \bar{A}^T$ iff

$$\frac{\beta^{-1} + \delta + \eta\varphi(1-\iota)}{(1-\alpha_c)\alpha_d} < \frac{\beta^{-1} + \delta + \eta\varphi}{(1-\alpha_d)\alpha_c(1-\theta)},$$

and since $\iota \in (0, 1]$, it also holds that

$$\frac{1-\alpha_d}{1-\alpha_c} < \frac{\alpha_d}{\alpha_c(1-\theta)}.$$

This condition is satisfied if α_d and α_c are not too different. It would be violated if α_d were significantly smaller than α_c, so that the capital share in dirty production is so small that the capital loss associated with the technology transition would not matter.

Social planner

The corresponding Lagrange function is

$$\begin{aligned}\mathcal{L} = &\sum_{t=0}^{\infty} \beta_s^t \left(\log(c_t^1) + \beta \log(c_{t+1}^2)\right) \\ &+ \lambda_t \left[A_c k_{c,t}^{\gamma_c} + A_d k_{d,t}^{\gamma_d} - c_t^1 - c_t^2 - k_{t+1} + \left(1 - \frac{\delta - \eta\varphi(1-\iota)}{(1-\theta)^\kappa}\right) k_{c,t} + (1 - \delta - \eta\varphi)\, k_{d,t}\right] \\ &+ \zeta_t \left[k_t - \frac{k_{c,t}}{(1-\theta)^\kappa} - k_{d,t}\right].\end{aligned}$$

We define λ_t as the Lagrange multipliers on the aggregate budget constraint and ζ_t as the multiplier on the capital constraint, and obtain the following first-order conditions:

$$\begin{aligned}\frac{\partial \mathcal{L}}{\partial c_t^1} &= 0 \Leftrightarrow \beta_s^t \left(\frac{1}{c_t^1} - \lambda_t\right) = 0, \\ \frac{\partial \mathcal{L}}{\partial c_{t+1}^2} &= 0 \Leftrightarrow \beta_s^t \left(\frac{\beta}{c_{t+1}^2} - \beta_s \lambda_{t+1}\right) = 0, \\ \frac{\partial \mathcal{L}}{\partial k_{t+1}} &= 0 \Leftrightarrow -\lambda_t + \beta_s \zeta_{t+1} = 0, \\ \frac{\partial \mathcal{L}}{\partial k_{c,t}} &= 0 \Leftrightarrow \lambda_t \left(\gamma_c A_c k_{c,t}^{\gamma_c - 1} + 1 - \frac{\delta - \eta\varphi(1-\iota)}{(1-\theta)^\kappa}\right) - \frac{\zeta_t}{(1-\theta)^\kappa} = 0, \\ \frac{\partial \mathcal{L}}{\partial k_{d,t}} &= 0 \Leftrightarrow \lambda_t \left(\gamma_d A_d k_{d,t}^{\gamma_d - 1} + 1 - \delta - \eta\varphi\right) - \zeta_t = 0,\end{aligned}$$

where $\mathcal{L}$ is the Lagrange function. For optimality, any solution must also satisfy the transversality condition which is given by

$$\lim_{t\to\infty} \beta_s^t \zeta_t k_{t+1} = 0.$$

The first three conditions are common, but the last two deserve attention. By simplifying the last two first order conditions we get

$$\frac{1}{c_t^1} = \frac{\beta(1-\theta)^\kappa}{c_{t+1}^2} \left(\gamma_c A_c k_{c,t+1}^{\gamma_c - 1} + 1 - \frac{\delta - \eta\varphi(1-\iota)}{(1-\theta)^\kappa}\right), \quad \text{and} \tag{29}$$

$$\frac{1}{c_t^1} = \frac{\beta}{c_{t+1}^2} \left(\gamma_d A_d k_{d,t+1}^{\gamma_d - 1} + 1 - \delta - \eta\varphi\right). \tag{30}$$

From these two expressions it follows that

$$(1-\theta)^\kappa \left(\gamma_c A_c k_{c,t+1}^{\gamma_c - 1} + 1 - \frac{\delta - \varphi\eta + \iota\eta\varphi}{(1-\theta)^\kappa}\right) = \gamma_d A_d k_{d,t+1}^{\gamma_d - 1} + 1 - \delta - \eta\varphi,$$

which corresponds to Equation (18) in the main text.

Policy analysis

Carbon tax

We denote by τ_d the constant tax rate imposed by the government on dirty production. Under this carbon tax, output with the dirty technology is given by

$$y_{d,t} = (1 - \tau_d) A_d k_{d,t}^{\gamma d}. \tag{31}$$

Firms operating with the dirty technology are assumed to maximize their profits in every period by choosing the amount of labor and capital given the carbon tax τ_d levied on output y_d, which yields

$$p_d = (1 - \tau_d)\alpha_d A_d k_d^{\gamma_d - 1}, \quad \text{and} \tag{32}$$

$$w_d = (1 - \tau_d)(1 - \alpha_d) A_d k_d^{\gamma_d}. \tag{33}$$

The factor prices for the clean technology remain unchanged and are given in Table 1.

Assuming again that the household chooses the investment opportunity whose return is higher than the alternative, we obtain the following tax-adjusted tipping point:

$$\tilde{k}^{TP} = \left(\frac{(1 - \tau_d)\alpha_d A_d}{\alpha_c A_c (1 - \theta)} \right)^{\frac{1}{1 - \gamma_d}}.$$

From that, we can observe that $\tilde{k}^{TP}$ and τ_d are inversely related. Therefore, a higher carbon tax lowers the critical capital stock and thus promotes a switch in favor of the clean technology.

To find the optimal carbon tax τ_d^*, we equate the socially optimal capital stock with the one resulting in the market economy such that $\tilde{k}^{TP} = \bar{k}^{SP}$ or, equivalently,

$$\left(\frac{(1 - \tau_d^*)\alpha_d A_d}{\alpha_c A_c (1 - \theta)} \right)^{\frac{1}{1 - \gamma_d}} = \left(\frac{\gamma_d A_d}{(1 - \theta) A_c - \theta + \eta \varphi \iota} \right)^{\frac{1}{1 - \gamma_d}}.$$

Solving for τ_d^* yields

$$\tau_d^* = 1 - \frac{\gamma_d \alpha_c (1 - \theta) A_c}{\alpha_d \left((1 - \theta) A_c - \theta + \eta \varphi \iota \right)}, \quad \in (0, 1),$$

which corresponds to Equation (23) in the main text. In the following, we assume that tax revenues are redistributed to the young or old generation, respectively, so that the government budget remains balanced in any case, and we examine how these redistribution schemes affect the dynamics of the economy.

Carbon tax redistributed to the young household (main text)

Assuming that tax revenues are redistributed to the young generation, we present a more detailed derivation of the transition condition presented in the main text. We begin with the steady state for the dirty technology. From the dynamic equation for k_t, we find

$$\tilde{k}_d^{SS} = \left(\frac{(1 - \alpha_d + \alpha_d \tau_d) A_d}{\beta^{-1} + \delta + \eta\varphi} \right)^{\frac{1}{1-\gamma_d}} . \tag{34}$$

For the transition from dirty to clean to occur, we need $\tilde{k}^{TP} < \tilde{k}_d^{SS}$ or, equivalently,

$$\left(\frac{(1 - \tau_d)\alpha_d A_d}{\alpha_c A_c (1 - \theta)} \right)^{\frac{1}{1-\gamma_d}} < \left(\frac{(1 - \alpha_d + \alpha_d \tau_d) A_d}{\beta^{-1} + \delta + \eta\varphi} \right)^{\frac{1}{1-\gamma_d}} .$$

From that, we can solve for A_c, the productivity of the clean technology:

$$A_c > \frac{(1 - \tau_d)\alpha_d(\beta^{-1} + \delta + \eta\varphi)}{(1 - \alpha_d + \alpha_d \tau_d)\alpha_c(1 - \theta)} \equiv \tilde{A}_c^T, \tag{35}$$

which corresponds to Equation (22) in the main text. As equation (35) shows, a tax levied on dirty production alters the transition condition two times; both of which reduce the productivity threshold from $\bar{A}_c^T$ to $\tilde{A}_c^T$. The green growth condition remains the same as in the baseline model.

Carbon tax redistributed to the old household

In this section we illustrate the case where tax revenues are refunded as a lump-sum transfer to the contemporary old agents so that the budget of the government is balanced. When operating with the dirty technology, the intertemporal budget constraint and the optimal savings function change to

$$\begin{aligned} w_{d,t} + (1 - \theta\psi - \Lambda_d)k_t + \frac{\tau_d y_{d,t+1}}{r_{d,t+1}} &= c_t^1 + \frac{c_{t+1}^2}{r_{d,t+1}}, \quad \text{and} \\ s_t = \frac{\beta}{1+\beta}\left[w_{d,t} + (1 - \theta\psi - \Lambda_d)k_t\right] &- \frac{1}{1+\beta}\frac{\tau_d y_{d,t+1}}{r_{d,t+1}}. \end{aligned}$$

Substituting $y_{d,t+1}$ from (31), $p_{d,t}$ from (32), and $w_{d,t}$ from (33) into the optimal saving function and using $p_{d,t+1} = r_{d,t+1}$, we obtain the following dynamics for capital accumulation under the tax policy:

$$
k_{t+1} = \begin{cases} \frac{\beta}{1+\beta}\left(\underbrace{(1-\tau_d)(1-\alpha_d)A_d k_t^{\gamma_d}}_{\text{Wage effect (-)}} + (1-\Lambda_d)k_t\right)\left(1+\underbrace{\frac{\tau_d}{(1+\beta)(1-\tau_d)\alpha_d}}_{\text{Anticipation effect (-)}}\right)^{-1} & \text{if } k_t < \bar{k}^{TP}, \\ \frac{\beta}{1+\beta}\left[(1-\alpha_c)A_c(1-\theta)k_t + (1-\theta-\Lambda_c)k_t\right] & \text{if } k_t \geq \bar{k}^{TP};\ t = t^{TP}, \\ \frac{\beta}{1+\beta}\left[(1-\alpha_c)A_c k_t + (1-\Lambda_c)k_t\right] & \text{if } k_t \geq \bar{k}^{TP};\ t > t^{TP}, \end{cases}
$$

for given $k_0 > 0$. The dynamic equation for pollution remains the same as in the baseline framework. Unlike before, a refund of tax revenues to the old generation has a clear negative impact on savings and thus reduces capital formation with the dirty technology. This result is due to two effects, which we call the "wage" and "anticipation" effect in the following. The wage effect in the capital accumulation equation states that a firm that uses the dirty technology pays workers a lower wage because of the tax burden, which reduces their disposable income and thus savings and capital formation. The anticipation effect says that young households anticipate that they will have more disposable income tomorrow due to the tax rebate, which reduces their incentive to save at a young age and thus lowers capital accumulation.

Next, we determine the transition condition under the tax policy. Given the redistribution scheme, the steady state for the dirty technology reads

$$
\tilde{k}_d^{SS} = \left(\frac{(1-\tau_d)(1-\alpha_d)A_d}{\beta^{-1}+\delta+\varphi\eta+\frac{\tau_d}{\beta(1-\tau_d)\alpha_d}}\right)^{\frac{1}{1-\gamma_d}}.
$$

An economy can transition to the clean technology if $\tilde{k}^{TP} < k_d^{SS}$ or, equivalently,

$$
\left(\frac{(1-\tau_d)\alpha_d A_d}{\alpha_c A_c(1-\theta)}\right)^{\frac{1}{1-\gamma_d}} < \left(\frac{(1-\tau_d)(1-\alpha_d)A_d}{\beta^{-1}+\delta+\varphi\eta+\frac{\tau_d}{\beta(1-\tau_d)\alpha_d}}\right)^{\frac{1}{1-\gamma_d}},
$$

and solving for A_c yields

$$
A_c > \frac{\alpha_d\left(\beta^{-1}+\delta+\eta\varphi\right) + \overbrace{\frac{\tau_d}{\beta(1-\tau_d)}}^{\text{Anticipation effect (+)}}}{(1-\alpha_d)\alpha_c(1-\theta)} \equiv \tilde{A}_c^T.
$$

The anticipation effect raises the productivity threshold above which the economy can transition to the clean technology from $\bar{A}_c^T$ to $\tilde{A}_c^T$, while the wage effect cancels out and plays no role in the transition condition. Therefore, a narrower range of values for A_c satisfies the transition condition, which reduces the likelihood that economies can transition to clean production on their transition path. The green growth condition described by $\bar{A}_c^G$ remains unchanged compared to the model without policy intervention.

Figure 15 indicates the new threshold associated with the modified transition condition. A carbon tax, whose proceeds are redistributed to the old generation, narrows

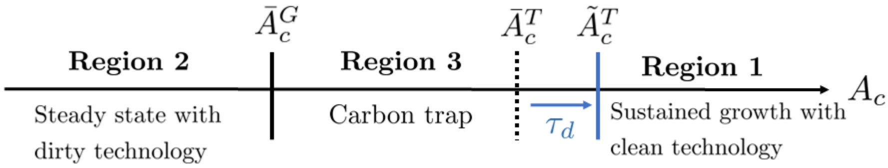

Figure 15: Thresholds and regions with carbon tax

Region 1 (where long-term growth with clean technology is possible) and widens Region 3 (carbon traps). Therefore, such policies reduce the chances for capital-constrained economies, where green growth would be technologically feasible, to switch to clean technologies, thus increasing the risk of remaining in a state of low income and high pollution.

Overall, the considered tax policy reduces the tipping point but also lowers capital accumulation, so that the economy is less likely to be able to build the capital stock needed to reach this (reduced) tipping point. The latter reflects the widespread concern that (overly) stringent climate policies may have detrimental effects on the process of economic development, thereby potentially delaying rather than accelerating technology transition. This illustrates that the implementation of well-intended climate policies in capital-poor economies should take into account potential unintended side effects that may weaken incentives to accumulate capital and thus foster the emergence of carbon traps.

In the following, we show that a carbon tax whose proceeds are redistributed to the old generation affects not only the set of values for A_c under which a carbon trap exists but also the interval for capital endowments that pitch the economy into the carbon trap. While such a tax policy gives households an incentive to adopt the clean technology by lowering the tipping point from $\bar{k}^{TP}$ to $\tilde{k}^{TP}$, both the wage and anticipation effect work in the opposite direction. In particular, by reducing the household's incentive to save, both effects shift the capital accumulation equation downward from $k_{d,t+1}$ to $\tilde{k}_{d,t+1}$, which lowers the dirty steady state from k_d^{SS} to $\tilde{k}_d^{SS}$.

We illustrate these effects in Figure 16, where the carbon tax moves the upper trap region from $[k_d^{SS}, \bar{k}^{TP}]$ to $[\tilde{k}_d^{SS}, \tilde{k}^{TP}]$ and consequently the set of capital values from which the economy converges to the carbon trap. While it is unambiguous that the tax shifts the upper trap region to the left, it is not clear whether this region becomes wider or narrower. Therefore, to determine the size of the upper trap region with and without the carbon tax, we employ the parameter values used in the simulation for the case of the carbon trap. In particular, by setting $A_c = 2.75$ and $\tau_d^* = 0.23$, we find that the upper trap region without the tax policy specified by the interval $[k_d^{SS}, \bar{k}^{TP}] = [5.84, 7.54]$ is

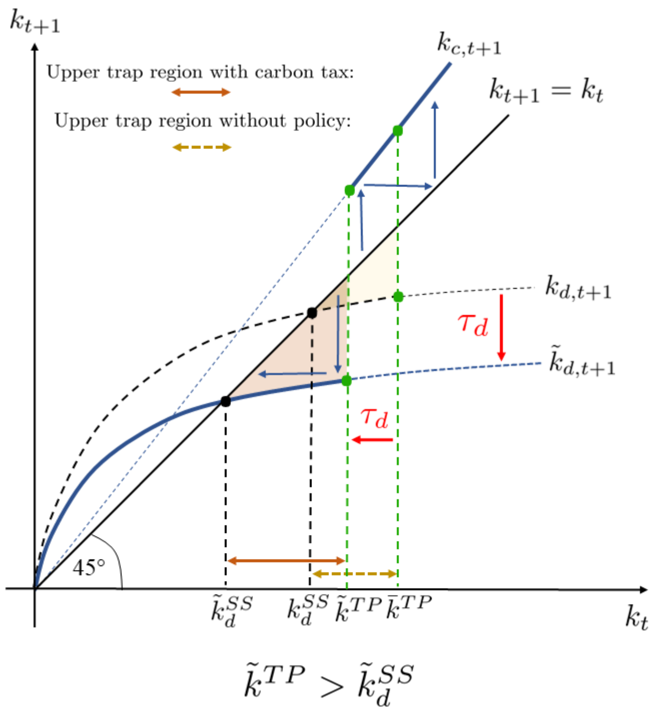

Figure 16: Phase diagram: Carbon trap with tax policy

smaller than the upper trap region with the tax policy given by $[\tilde{k}_d^{SS}, \tilde{k}^{TP}] = [0.41, 3.12]$. Overall, a tax policy designed in this way enlarges the interval of the upper trap region from 1.7 to 2.71 and thus increases the set of initial capital endowments from which economies fall into a carbon trap. Hence, as illustrated in Figure 16, the negative effect of the tax on capital accumulation quantitatively outweighs the tax-induced reduction of the tipping point.

Subsidy

As a second policy instrument, we consider a time-invariant subsidy for the clean technology, denoted by τ_c, such that

$$y_{c,t} = (1 + \tau_c) A_c k_{c,t}. \tag{36}$$

When maximizing profits, firms incorporate the subsidy into their decision making, leading to the following factor prices:

$$p_c = (1 + \tau_c)\alpha_c A_c, \tag{37}$$
$$w_c = (1 + \tau_c)(1 - \alpha_c) A_c k_c. \tag{38}$$

The rental rate of capital and wage for the dirty technology remain as before and are given in Table 1. Equating investment returns yields the following subsidy-adjusted tipping point:

$$\hat{k}^{TP} = \left(\frac{\alpha_d A_d}{(1+\tau_c)\alpha_c A_c (1-\theta)} \right)^{\frac{1}{1-\gamma_d}}.$$

Intuitively, a subsidy on clean production facilitates technology transition by reducing the tipping point from $\bar{k}^{TP}$ to $\hat{k}^{TP}$.

To find the optimal subsidy τ_c^*, we equate the optimal capital stock of the social planner with the market tipping point under the subsidy police, i.e. $\hat{k}^{TP} = \bar{k}^{SP}$, which implies

$$\left(\frac{\alpha_d A_d}{(1+\tau_c^*)\alpha_c A_c (1-\theta)} \right)^{\frac{1}{1-\gamma_d}} = \left(\frac{\gamma_d A_d}{(1-\theta)A_c - \theta + \eta\varphi\iota} \right)^{\frac{1}{1-\gamma_d}}.$$

Solving for τ_c^* yields

$$\tau_c^* = \frac{\alpha_d \left((1-\theta)A_c - \theta + \eta\varphi\iota \right)}{\gamma_d \alpha_c A_c (1-\theta)} - 1, \quad \in (0,1),$$

which corresponds to Equation (26) in the main text. In the following, we study the effect of the subsidy depending on which generation has to pay for it.

Subsidy financed by young generation (main text)

Assuming that the subsidy is financed by the young generation, we provide a more detailed derivation of the transition and green growth condition presented in the main text. Let's start with the steady state under the dirty technology, which remains unchanged from the baseline model and can only be reached if the economy does not switch from dirty to clean technology on its transition path, which occurs if $\hat{k}^{TP} < k_d^{SS}$ or, equivalently,

$$\left(\frac{\alpha_d A_d}{(1+\tau_c)\alpha_c A_c (1-\theta)} \right)^{\frac{1}{1-\gamma_d}} < \left(\frac{(1-\alpha_d)A_d}{\beta^{-1} + \delta + \eta\varphi} \right)^{\frac{1}{1-\gamma_d}}.$$

From that, we can solve for A_c, which yields

$$A_c > \frac{\alpha_d(\beta^{-1} + \delta + \eta\varphi)}{(1-\alpha_d)(1+\tau_c)\alpha_c(1-\theta)} \equiv \hat{A}_c^T,$$

which refers to Equation (24) in the main text. In light of the subsidy-adjusted transition condition, we can observe that the subsidy lowers the productivity threshold above which the economy can switch to the green technology. Next we turn to the green growth condition. The clean technology can sustain economic growth if $\hat{k}_{c,t+1}/\hat{k}_{c,t} > 1$ or, equivalently,

$$\frac{\hat{k}_{c,t+1}}{\hat{k}_{c,t}} = \frac{\beta}{1+\beta}\left[(1-\alpha_c-\alpha\tau_c)A_c + (1-\delta-\eta\varphi(1-\iota))\right] > 1.$$

Solving for A_c implies

$$A_c > \left(\frac{1}{\beta}+\delta+\eta\varphi(1-\iota)\right)\frac{1}{(1-\alpha_c-\alpha_c\tau_c)} \equiv \hat{A}_c^G,$$

which corresponds to Equation (25) in the main text. A subsidy policy designed in this way raises the threshold for clean factor productivity above which sustained green growth is feasible.

Subsidy financed by old generation

In this section, we assume that the subsidy is financed by a tax on the savings of the old generation, so that the government maintains a balanced budget. Given that the clean technology is used, the intertemporal budget constraint and the optimal savings function of the household change to

$$\begin{aligned} w_{c,t} + (1-\theta\psi-\Lambda_c)k_t - \frac{\tau_c y_{c,t+1}}{r_{c,t+1}} &= c_t^1 + \frac{c_{t+1}^2}{r_{c,t+1}}, \quad \text{and} \\ s_t &= \frac{\beta}{1+\beta}\left[w_{c,t} + (1-\theta\psi-\Lambda_c)k_t\right] + \frac{1}{1+\beta}\frac{\tau_c y_{c,t+1}}{r_{c,t+1}}. \end{aligned}$$

While the dynamic equation for pollution remains the same as in the baseline model, capital accumulation modifies under the subsidy policy. In particular, substituting $y_{c,t+1}$ from (36), $r_{c,t+1}$ from (37), and $w_{c,t}$ from (38) into the optimal savings function yields

$$k_{t+1} = \begin{cases} \frac{\beta}{1+\beta}\left[(1-\alpha_d)A_d k_t^{\gamma_d} + (1-\Lambda_d)k_t\right] & \text{if } k_t < \bar{k}^{TP}, \\ \frac{\beta}{1+\beta}\left[(1+\tau_c)(1-\alpha_c)A_c k_t(1-\theta) + (1-\theta-\Lambda_c)k_t\right]\left(1-\frac{\tau_c}{(1+\beta)(1+\tau_c)\alpha_c}\right)^{-1} & \text{if } k_t \geq \bar{k}^{TP};\ t = t^{TP}, \\ \frac{\beta}{1+\beta}\left(\underbrace{(1+\tau_c)(1-\alpha_c)A_c k_t}_{\text{Wage effect }(+)} + (1-\Lambda_c)k_t\right)\left(1-\underbrace{\frac{\tau_c}{(1+\beta)(1+\tau_c)\alpha_c}}_{\text{Anticipation effect }(+)}\right)^{-1} & \text{if } k_t \geq \bar{k}^{TP};\ t > t^{TP}, \end{cases}$$

for given $k_0 > 0$. Subsidizing clean production clearly has a positive effect on capital formation. This is due to the wage and anticipation effect introduced in the previous section, both of which stimulate capital accumulation. Specifically, firms that adopt the clean technology can pay higher wages because of the additional funds they receive, and this increases the young generation's savings, which in turn stimulates capital formation. This corresponds to the wage effect. In addition, young households anticipate that they will have to finance the clean technology in old age. In order to still be able to cover old-age consumption, the young generation compensates for these additional expenses through additional savings, which in turn increases capital formation. This corresponds to the anticipation effect. The subsidy scheme under consideration not only fosters capital accumulation with the clean technology, but also the transition from dirty to clean technology by lowering the tipping point from $\bar{k}^{TP}$ to $\hat{k}^{TP}$, so that overall an economy is more likely to transition to clean production under the subsidy policy.

Given the redistribution design, we now determine the conditions for technology transition and green growth. The technological transition from dirty to clean requires that $\hat{k}^{TP} < k_d^{SS}$ or, equivalently,

$$A_c > \frac{\alpha_d(\beta^{-1} + \delta + \eta\varphi)}{(1-\alpha_d)(1+\tau_c)\alpha_c(1-\theta)} \equiv \hat{A}_c^T,$$

where $\partial \hat{A}_c^T / \partial \tau_c < 0$. Note that this transition condition is the same as in the case where the subsidy is financed by the young generation, since $\hat{k}^{TP}$ and k_d^{SS} are also the same.

Next we turn to the green growth condition. Given that the subsidy is financed by the old generation, sustained growth with the green technology can be achieved if $\hat{k}_{c,t+1}/\hat{k}_{c,t} > 1$ or, equivalently,

$$\frac{\hat{k}_{c,t+1}}{\hat{k}_{c,t}} = \frac{\frac{\beta}{1+\beta}\left[(1+\tau_c)(1-\alpha_c)A_c + (1-\delta-\eta\varphi(1-\iota))\right]}{1 - \frac{\tau_c}{(1+\beta)(1+\tau_c)\alpha_c}} > 1,$$

and solving for A_c yields

$$A_c > \frac{\beta^{-1} + \delta + \eta\varphi(1-\iota) - \overbrace{\frac{\tau_c}{\beta(1+\tau_c)\alpha_c}}^{\text{Anticipation effect (-)}}}{\underbrace{(1-\alpha_c)(1+\tau_c)}_{\text{Wage effect (-)}}} \equiv \hat{A}_c^G.$$

From that, we can see that the wage and anticipation effect both lower the productivity threshold above which sustained green growth is feasible. Therefore, in the presence of a subsidy policy, economies with lower A_c levels can achieve sustained growth with the clean technology, preventing these economies from converging to the dirty steady state in the long run. Figure 17 indicates the new productivity thresholds associated with the modified transition and green growth condition, respectively. The subsidy narrows Region 2 (non-growing polluting steady state) and extends Region 1 (sustained growth with the clean technology).

The subsidy also influences the set of initial capital endowments under which an economy converges to the carbon trap, as we show in Figure 18. Due to the subsidy's impact on the transition condition, the upper trap region shrinks from $[k_d^{SS}, \bar{k}^{TP}]$ to

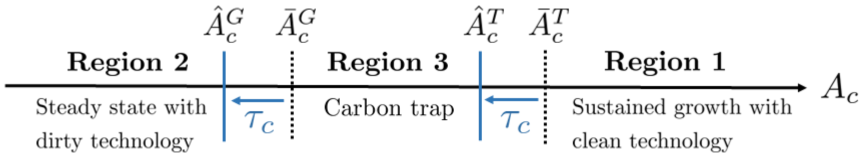

Figure 17: Thresholds and regions with subsidy

$[k_d^{SS}, \hat{k}^{TP}]$. In addition, the positive impact of the subsidy on capital formation stemming from the wage and anticipation effect leads to an increase in the capital accumulation equation under the clean technology from $k_{c,t+1}$ to $\hat{k}_{c,t+1}$. Figure 18 illustrates the case where the economy converges to the polluting steady state in the long run without the subsidy of the clean technology. However, the introduction of the subsidy shifts the capital accumulation equation of the clean technology, $\hat{k}_{c,t+1}$, above the 45-degree line, making the clean technology productive enough to allow for long-run green growth once the capital needed for technology transition has been built up.

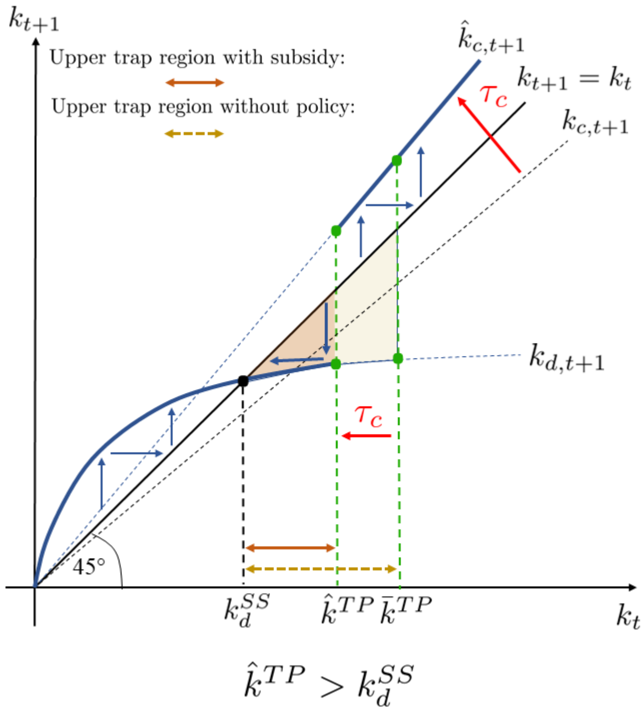

Figure 18: Phase diagram: Carbon trap with subsidy

Appendix: Numerical simulation

Welfare

Table 5 demonstrates that welfare in the social optimum is higher than in the market economy for each of the simulated growth patterns in the main text.

Growth Patterns	Social Welfare $[W]$	Market Welfare $[U]$
Sustained green growth	7.9	2.2
Carbon trap	8.2	5
Climate-induced carbon trap	7.4	3
Cyclical fluctuations	9.1	5.2
Modified savings function	7.9	6

Table 5: Welfare: social optimum and market economy

Climate-induced carbon trap

In this section, we demonstrate that a carbon trap can also arise if an economy is highly exposed to the consequences of global warming. As we have seen in the main text, when climate exposure is given by $\eta = 0.3$, a TFP value of $A_c = 3$ leads to sustained growth with the clean technology, as both the transition condition ($\bar{A}_c^T = 3$) and the green growth condition ($\bar{A}_c^G = 2.7$) are satisfied. However, once we increase climate change vulnerability to $\eta = 0.5$, a value of $A_c = 3$ leads to a climate-induced carbon trap which is shown in Figure 19.

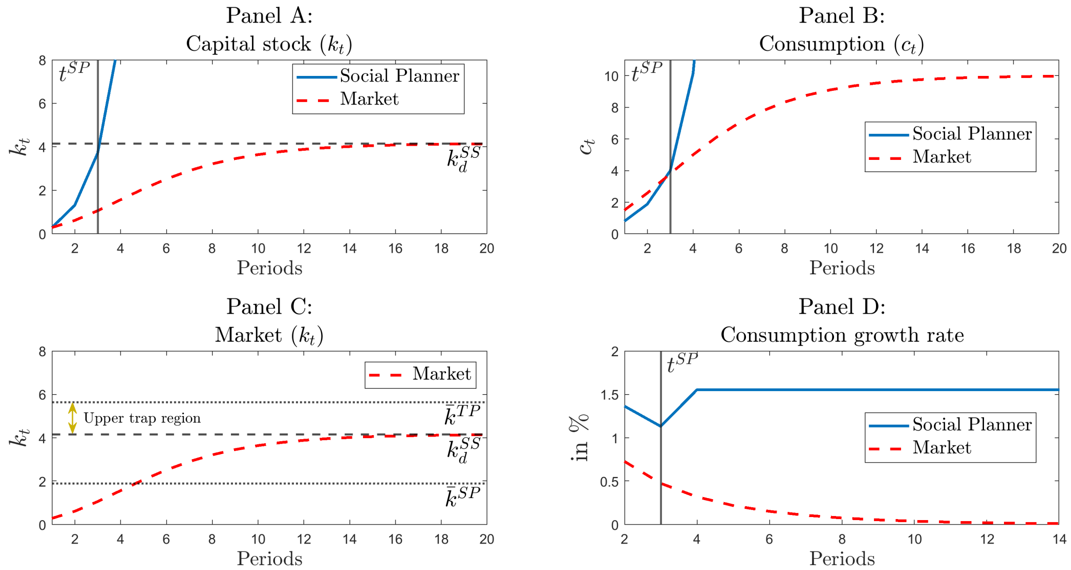

Figure 19: Carbon trap due to high climate exposure

To see, economies with $\eta = 5$ and $A_c = 3$ fulfill the green growth condition ($A_c^G = 2.75$), but not the transition condition ($A_c^T = 3.3$). Unlike the market economy, the social planner satisfies the transition condition with corresponding values given by $\bar{k}^{TP} = 5.6$, $\bar{k}^{SP} = 1.9$ and $k_d^{SS} = 4.2$. An optimal tax of $\tau_d^* = 0.28$ or subsidy of $\tau_c^* = 0.39$ can induce the socially optimal tipping point in the market economy. The transitional dynamics follow the same reasoning as in Figure 19 in the main text.

Technical details

We begin by outlining the dynamics of the model and some mathematical analysis. The social planner tipping point reads

$$\bar{k}^{SP} = \left(\frac{\gamma_d A_d}{(1-\theta)A_c - \theta + \eta\varphi\iota} \right)^{\frac{1}{1-\gamma_d}}.$$

Intuitively, it means the following: In period t, the economy uses the dirty technology and consumption is given by c_t; in period $t+1$ the economy will use the clean technology, if doing so we allow consumption to grow at the same rate as when the economy remains with the dirty technology. Denoting the period of technology change by $t = TP$, the linear law of motion for consumption reads

$$c_{TP} = \beta\left((1+A_c)(1-\theta) - \delta - \eta\varphi(1-\iota)\right)c_{TP-1}. \tag{39}$$

Note that this equation describes the dynamics for aggregate per capita consumption, because in the social optimum consumption of both generations is the same, i.e., $c_t^1 = c_t^2$. After the tipping point, we have that

$$c_{TP+1} = \beta\left(1 + A_c - \delta - \eta\varphi(1-\iota)\right)c_{TP}, \tag{40}$$

which also holds for all subsequent periods. Furthermore, it holds that

$$k_{TP+1} = ((1+A_c)(1-\theta) - \delta - \eta\varphi(1-\iota))k_{TP} - c_{TP}, \quad \text{but afterwards}$$

$$k_{TP+2} = (1 + A_c - \delta - \eta\varphi(1-\iota))k_{TP+1} - c_{TP+1}.$$

The second equation together with (40) constitute a system of two linear difference equations in two variables which can be solved by backwards induction, so that we obtain

$$k_{TP+2} = \beta(1 + A_c - \delta - \eta\varphi(1-\iota))k_{TP+1}.$$

This outcome is not surprising as the AK-model does not possess transitional dynamics and k_t and c_t grow at the same rate. Using the transversality condition, we arrive at

$$c_{TP+1} = (1-\beta)(1 + A_c - \delta - \eta\varphi(1-\iota))k_{TP+1}.$$

We can use this relation in the Euler-equation (29) with $\kappa = 0$ to obtain

$$c_{TP} = \frac{1-\beta}{\beta} k_{TP+1},$$

and therefore

$$k_{TP+1} = \beta((1 + A_c)(1-\theta) - \delta - \eta\varphi(1-\iota))k_{TP}.$$

This gives us

$$c_{TP} = (1-\beta)((1 + A_c)(1-\theta) - \delta - \eta\varphi(1-\iota))k_{TP}$$

and from (29) with $\kappa = 1$, we have

$$c_{TP-1} = \frac{1-\beta}{\beta} k_{TP}.$$

This means that if assume a value for k_{TP}, we are able to find c_{TP-1} and all previous values of k_t and c_t. We do so in the following way: Given k_{TP} and c_{TP-1}, we can find k_{TP-1} by using the budget-constraint

$$c_{TP-1} + k_{TP} = A_d k_{TP-1}^{\gamma_d} + (1 - \delta - \eta\varphi)k_{TP-1},$$

where we analytically solve for k_{TP-1} using that the left-hand side is given. From this, we find

$$c_{TP-2} = c_{TP-1}(1 + \gamma_d A_d k_{TP-1}^{\gamma_d - 1} - \delta - \eta\varphi)^{-1}/\beta$$

and then k_{TP-2}

$$A_d k_{TP-2}^{\gamma_d} + (1 - \delta - \eta\varphi)k_{TP-2} = c_{TP-2} + k_{TP-1}. \tag{41}$$

Note, however, that the choice of k_{TP} is not arbitrary. The reason is that $\bar{k}^{SP}$ is given by parameter values, constituting a lower bound k_{TP}, while the upper bound stems from

$$k_{TP}^{max} = \beta \left[A_d(\bar{k}^{SP} - \epsilon)^{\gamma_d} + (1 - \delta - \eta\varphi)(\bar{k}^{SP} - \epsilon) \right],$$

with ϵ small. If k_{TP} lies above this value than it holds than $k_{TP-1} > \bar{k}^{SP}$, and the technology switch occurs earlier.

Grid points and simulation

We create a grid between the points $\bar{k}^{SP}$ and $\bar{k}_{TP}^{max}$, and for all the grid points we calculate the convergence path in the manner described above and the balanced growth path after the tipping, also as described above, simply relying on the fact that capital and consumption grow at the same constant rate along this path. Hence we have a set of grid points $k_{TP,1}$, $k_{TP,2}$, $k_{TP,3}$, ..., k_{TP}^{max} and their respective predecessors $k_{TP-1,1}$, $k_{TP-2,1}$, $k_{TP-3,1}$ and so on. When we want to simulate the dynamics for an economy with initial stock of capital k_0 it might be that there is no value $k_{TP-j,i}$ equal to k_0, where j reflects the time distance to the tipping point and i is the number of the grid point. Hence, we had to write the code such that it can handle any possible values of the economy's initial endowment k_0, and to allow for this feature we wrote the following procedure: First, take some arbitrary k_0. Matlab finds the value of k_t in the set of convergences that is closest to k_0 and calculates the subsequent values of k_1, k_2 and so on as the linear interpolation of the sequences that bracket k_0. To see, assume that we have some value $k^*_{TP-j,i}$ that is smaller but close to k_0, so that k_0 is bracketed by $k^*_{TP-j,i}$ and $k^*_{TP-j,i+1}$. For these two values we have already calculated the sequence of capital, i.e. $k^*_{TP-j+1,i}$, $k^*_{TP-j+2,i}$,...., and $k^*_{TP-j+1,i+1}$, $k^*_{TP-j+2,i+1}$ and so on. Thus, we can calculate the capital stocks that follow k_0, for instance k_1, as an linearly interpolated value between $k^*_{TP-j+1,i}$ and $k^*_{TP-j+1,i+1}$.

Appendix: Extension

Minimum capital threshold

In this section, we discuss all the possible configurations and growth patterns when we introduce a minimum capital threshold for the clean technology. First, we begin with the threshold order of $\bar{A}_c^G < \bar{A}_c^T$. We assume that if the capital stock becomes sufficiently small under the clean technology, the economy switches to the dirty technology. Recall that to the left of k_c^{SS}, due to its instability, the capital stock decreases, while to the right the opposite is true.

1. $\bar{A}_c^G < \bar{A}_c^T < A_c$: This constellation implies $\bar{k}^{TP} < k_d^{SS}$ and we can distinguish the following cases:

   (a) $k_c^{SS} < \bar{k}^{TP} < k_d^{SS}$: For all $k_t < \bar{k}^{TP}$, the economy utilizes the dirty technology until it switches to the clean one. At this point, the economy has surpassed the point k_c^{SS} so that growth becomes unbounded. Accordingly, sustained growth with the clean technology is the only possible long-run outcome. This constellation is represented in Case 1 of Figure 13 in the main text.

(b) $\bar{k}^{TP} < k_c^{SS} < k_d^{SS}$: For all $k_t < \bar{k}^{TP}$, the economy employs the dirty technology and accumulates capital until the tipping point is reached where the transition to the clean technology occurs. Note, however, that the capital stock is contracting with the clean technology over the course of time until the economy passes below $\underline{k}^{TP}$ and switches back to the dirty technology; a cycle is established. For all $k_t > k_c^{SS}$, the economy utilizes the clean technology and unbounded growth with that technology arises. Thus, overall, sustained growth with the clean technology as well as permanent cyclical fluctuations are possible long-run outcomes. Which one is realized depends on whether the economy's capital initial endowment exceeds k_c^{SS}.

(c) $\bar{k}^{TP} < k_d^{SS} < k_c^{SS}$: The argumentation is the same as in the previous case. This constellation is illustrated in Case 3 of Figure 14 in the main text.

2. $\bar{A}_c^G < A_c < \bar{A}_c^T$: This constellation implies $k_d^{SS} < \bar{k}^{TP}$ and we can distinguish the following cases:

(a) $k_c^{SS} < k_d^{SS} < \bar{k}^{TP}$: For all $k_t < \bar{k}^{TP}$ the economy utilizes the dirty technology and converges monotonously to the respective steady state. In the opposite case, the economy relies on the clean technology and sustained growth is feasible, since the economy has passed the point k_c^{SS}. The steady state with the dirty technology and sustained growth with the clean technology are possible long-run outcomes. Which one is realized depends on whether the initial endowment of the economy exceeds $\bar{k}^{TP}$.

(b) $k_d^{SS} < k_c^{SS} < \bar{k}^{TP}$: The argumentation is the same as in the previous case.

(c) $k_d^{SS} < \bar{k}^{TP} < k_c^{SS}$: For all $k_t < \bar{k}^{TP}$ the economy employs the dirty technology and converges to the dirty steady state. For all k_t that lie in between of $\bar{k}^{TP}$ and k_c^{SS} the economy temporarily employs the clean technology until it switches back to the dirty one and only capital values that exceed k_c^{SS} lead to long-run growth. The steady state with the dirty technology and sustained growth with the clean technology are possible long-run outcomes. Which one is realized depends now on whether the initial endowment of the economy exceeds k_c^{SS}. This corresponds to the carbon trap illustrated in Case 4 of Figure 14 in the main text.

3. $A_c < \bar{A}_c^G < \bar{A}_c^T$: This case implies $k_d^{SS} < \bar{k}^{TP}$ and there is no positive value for k_c^{SS}. Hence, this case is the same as in the model without a minimal capital threshold.

The only possible long-run outcome is a steady state with the dirty technology, which is illustrated in Case 2 of Figure 13 in the main text.

The alternative threshold order, $\bar{A}_c^T < \bar{A}_c^G$, is somewhat simpler. As long as $A_c < \bar{A}_c^G$ there is no positive value for k_c^{SS} and the model behaves as in the case without the capital threshold $\bar{k}$. If, however, $\bar{A}_c^G < A_c$, the economy behaves as in the case when $\bar{A}_c^G < \bar{A}_c^T$, i.e., Case 1 from above. The relative size of $\bar{A}_c^T$ and $\bar{A}_c^G$ is irrelevant and, in total, five constellations arise.

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