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# Low-Carbon Transition Policies, Skill-Driven Inequality, and Endogenous Political Cleavages

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**CAMA Working Paper 37/2025**
**July 2025**

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Drawing on the political science literature, we develop a heterogeneous agents macro model that differentiates between left- and right-wing voting preferences in two political dimensions: the economic-distributive (ED) and the socio-cultural (SC) in particular regarding climate change. The model is compatible with the emergence of “ED-left/SC-left”, “ED-left/SC-right”, “ED-right/SC-left”, and “ED-right/SC-right” coalitions, each associated with a tax rate on the skill wage premium and on carbon emissions. Human capital accumulation regarding results in a wage differential that influences production and feedback on inequality. Through induced technical change, taxing emissions impacts the development of carbon-neutral production techniques, affecting output and ultimately feeding political attitudes. We study analytically and through numerical simulations the conditions resulting in the coexistence of multiple stable equilibria and the possible implications for carbon emissions. Three results are worth highlighting. First, when income inequality, captured by the skill premium, is the primary motivation to become more educated, left-wing ED coalitions generate higher inequality than their right-wing counterpart. Second, it is shown that the consensus required to implement a carbon tax is only the first part of the problem. Absolute decoupling requires a sufficiently strong response from technology favouring carbon-neutral production techniques. Finally, our model suggests that the SC dimension matters most under medium levels of inequality. When inequality is very high, as in the pre-war period, ED dominates the debate, and there is a right-wing SC consensus. As inequality fell during the 1950s and 1960s, socio-cultural aspects gained importance. This change led to a situation where “ED-left/SC-left”, “ED-left/SC-right”, “ED-right/SC-left”, and “ED-right/SC-right” stable coalitions became possible, creating a disconnect between education and left-wing support.

**Keywords**

political cleavages, climate change, inequality, human capital, carbon tax

**JEL Classification**

C62, D72, Q01, Q54

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**ISSN 2206-0332**

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# Low-Carbon Transition Policies, Skill-Driven Inequality, and Endogenous Political Cleavages*

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June 30, 2025

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Drawing on the political science literature, we develop a heterogeneous agents macro model that differentiates between left- and right-wing voting preferences in two political dimensions: the economic-distributive (ED) and the socio-cultural (SC) in particular regarding climate change. The model is compatible with the emergence of "ED-left/SC-left", "ED-left/SC-right", "ED-right/SC-left", and "ED-right/SC-right" coalitions, each associated with a tax rate on the skill wage premium and on carbon emissions. Human capital accumulation regarding results in a wage differential that influences production and feedback on inequality. Through induced technical change, taxing emissions impacts the development of carbon-neutral production techniques, affecting output and ultimately feeding political attitudes. We study analytically and through numerical simulations the conditions resulting in the coexistence of multiple stable equilibria and the possible implications for carbon emissions. Three results are worth highlighting. First, when income inequality, captured by the skill premium, is the primary motivation to become more educated, left-wing ED coalitions generate higher inequality than their right-wing counterpart. Second, it is shown that the consensus required to implement a carbon tax is only the first part of the problem. Absolute decoupling requires a sufficiently strong response from technology favouring carbon-neutral production techniques. Finally, our model suggests that the SC dimension matters most under medium levels of inequality. When inequality is very high, as in the pre-war period, ED dominates the debate, and there is a right-wing SC consensus. As inequality fell during the 1950s and 1960s, socio-cultural aspects gained importance. This change led to a situation where "ED-left/SC-left", "ED-left/SC-right", "ED-right/SC-left", and "ED-right/SC-right" stable coalitions became possible, creating a disconnect between education and left-wing support.

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*An earlier version of this paper was presented at the 12th NED Conference, Kristiansand, Norway; at the 2nd Workshop on Heterogeneity, Evolution and Networks in Economics, Florence, Italy; the 47th AMASES Annual Meeting, Milan, Italy; the 7th ASTRIL Conference, Rome, Italy; and the 50th EEA Annual Meeting, Boston, United States, and the 1st Workshop on Economic Complexity and Macroeconomic Dynamics in Valencia, Spain. We thank the participants, particularly Giorgos Galanis, Ivan Savin, Leonardo Bargigli, Lilit Popoyan, and Roberta Terranova, Pedro Romero, Santiago Gangotena and Thomas Lux for their insightful comments and suggestions. This research was supported by the F-New Frontiers Funding Program, University of Siena. The content is solely the responsibility of the authors and usual caveats apply.

# Contents

# 1 Introduction

One of the most important developments that has taken place in particular in Western democracies in the last two decades is the increasing polarization of the political debate. The drivers behind this phenomenon are multifaceted, ranging from cultural and globalization related factors (Inglehart and Norris, 2016) to the increasing income and wealth inequality (Proaño et al., 2024). In recent years, however, the ongoing global warming, as well as the proper policies to tackle (or not) this problem, seem to play an increasing role in the policy debate. Indeed, despite the near-global consensus among the scientific community about the urgency to fight climate change, the public perceptions of it differ between countries and have fluctuated over time (Clegg, 2019; Clegg, 2021). Of course, such a lack of consensus in the public debate is highly problematic because limiting global warming to 2 C° requires cohesion and coordination among the leading players of the socio-economic system (Lee et al. (2023)).

A major reason for the rising importance of climate change in the policy debate, and the possible adaption and/or mitigation policies, are their non-trivial distributional consequences not only due to rising natural disaster risks, but due to their fiscal and labor market-related effects. Indeed, the transition to a low-carbon society requires – at least in the short run – the levying of carbon-related taxes to speed up or enforce the development and implementation of green technologies, on the one hand, and a change in the skill mix of the labor force towards more green skills (i.e. technical-operational skills needed in a low-carbon economy) in the medium run. This implies that, at least in the short run, climate change adaptation may affect some part of the labor force negatively, driving a wedge between winners and losers from this development.

In more general terms and from a more historical perspective, a significant transformation of political cleavages seems also to have occurred since the end of World War II. Exploiting a novel database covering more than 300 elections in 21 high-income countries after World War II, Gethin et al. (2022) document that while in the 1950s and 1960s the vote for left-oriented social-democratic and affiliated parties was associated with less-educated and lower-income voters, in the 2010s, most educated citizens voted for the left, and the highest-income voters continued to support the right. The forces behind the apparent decoupling between income and education effects on political preferences remain controversial. There is not even a consensus on the most appropriate theoretical or modeling framework where to place the analysis (e.g. Evans and De Graaf, 2013; Ford and Jennings, 2020; Di Guilmi and Galanis, 2021). For example, we can study this phenomenon as a gradual shift in structural socio-economic parameters that changed the unique equilibrium point of the system. Alternatively, we could conceive a multi-stable system where critical events altered the boundaries of the respective basins of attraction, leading to a transition between equilibria.

Against this background, this paper investigates how the interplay between low carbon transition policies and political preferences regarding the economic and socio-cultural dimension may affect the emergence of alternative political cleavages and different political majorities. For such a purpose and drawing on the recent political science literature on party ideology (e.g. Bakker and Hobolt, 2013), we develop a heterogeneous agents macro model (HAM) that differentiates between "left" and "right" preferences in two main political dimensions: The Economic-Distributive (ED) and Socio-Cultural (SC) dimensions. The first represents more traditional concerns with economic policy and inequality. We formalize this dimension following Di Guilmi and Galanis (2021), who provide a baseline framework to study the coexistence of different political arrangements using a continuous-time version of Brock and Hommes (1997) discrete-choice approach. The second dimension is related to preferences over climate change (as in Cafferata et al., 2021; Sordi and Dávila-Fernández, 2023).

More specifically, conditional to the population composition in both ED and SC spheres, the prevailing political majority chooses the level of the skill wage premium and the carbon taxes. The former relates to human capital accumulation, generating a wage differential that influences production, feeds inequality, and interacts with politics. Moreover, taxing emissions influences the development of carbon-neutral production techniques, thus impacting output and pollution, which feedback on political attitudes. We study analytically and numerically the conditions leading to the coexistence of stable equilibria and the implications of such a result to carbon emissions. Among our main findings, three deserve special attention. First, when the skill wage premium is the primary motivation to become more educated, left-wing ED coalitions generate higher wage inequality than their right-wing counterpart. This result follows from the "left" taxing the wage differential, thus reducing overall human capital accumulation. In such a scenario, studying the basin of attraction reveals that society is likelier to choose either a "left-left" or a "right-right" equilibrium. On the contrary, when people care relatively little about the wage differential and rely more on a public infrastructure for skill accumulation, left-wing ED coalitions can effectively reduce inequality. However, in this case, "left-right" or "right-left" arrangements are more likely to occur.

Second, we show that achieving negative emissions is quite challenging. Implementing a carbon tax is only the first part of the problem. To avoid reducing living standards, absolute decoupling requires a sufficiently strong element of induced technical change favouring carbon-neutral production techniques. Our numerical experiments suggest that, in the most favourable scenario, a 1 per cent increase in the carbon tax should reduce the emissions-output growth rate by three percentage points. Finally, we provide additional insights to explain some of main findings by Gethin et al. (2022). The model developed here indicates that the SC dimensio matters most under intermediate levels of inequality. The ED dimension dominates the debate when wage premiums are very high or low, the former implying a right-wing SC majority while the latter being associated with the opposite case. Given the high inequality rates of the pre-war period, our analysis seems to support social-democratic and affiliated parties being associated with less-educated and lower-income voters at the time. The reduction in inequality documented during the 1950s and 1960s resulted in a scenario where "left-left", "left-right", "right-left", and "right-right" stable coalitions became possible, creating a disconnect between income and education effects on political preferences.

Our contribution relates to a growing HAM literature exploring how bounded rational heterogeneous agents interact and lead to emergent macro behaviours as the aggregate outcome of micro-interactions (see Hommes, 2021). Applications to climate-related questions have been limited so far, though they share a baseline logit structure. Pioneering efforts include Hommes and Zeppini (2014) and Zeppini (2015), who propose a discrete choice model to assess firms decision to transition from dirty to clean technologies (for a specific reference to fossil fuels and renewables, see Zeppini and Van Den Bergh, 2020). The political economy of international climate agreement is studied by Galanis et al. (2023). They show peer effects might explain the formation of country clusters with high or low levels of cooperation. Scholars such as Annicchiarico et al. (2024) have investigated the role of expectations and monetary policy on the economy's response to climate actions, suggesting the uncertainty regarding the impact of a climate policy might threat to the ability of central banks to maintain price stability. Uncertainty around policy commitment to a climate agenda and conflicting beliefs on future transition dynamics motivate the analysis by Cahen-Fourot et al. (2023) and Campiglio et al. (2024), highlighting the emergence of multiple equilibria and the existence of high-carbon traps.

Moreover, the present study also relates to a family of Agent-Based Models (ABMs) dedicated to the political economy of climate change. For example, scholars such as Janssen and De Vries (1998) and Geisendorf (2016) use a multi-agent framework to assess the dynamics of heterogeneity in ecological thinking to environments corresponding to or failing to correspond to their beliefs. Others have dedicated special attention to the climate policy stringency and public support, emphasising variations in carbon tax acceptability (e.g. Foramitti et al., 2021; Konc et al., 2022; Lackner et al., 2025 for a review of controversies and future research avenues, see van den Bergh and Savin, 2021). We innovate concerning current HAMs and ABMs by unveiling the environmental implications of the interplay between ED/SC political dimensions and their relation with education-inequality dynamics. In that respect, Torren-Peraire et al. (2024) is a close reference to our work. Using concepts from network theory, they develop an ABM that goes deep into the SC part of the problem. Our efforts complement theirs by including ED considerations in the analysis.

The remainder of the article is organised as follows. Section 2 presents our modelling framework. We describe in detail the main transmission channels and underlying mechanisms. In Section 3 we investigate the model's properties analytically. Numerical experiments including scenarios under secularisation and the asymmetric effects of carbon taxes on low/high-skilled workers are discussed in Section 4, where we also illustrate the conditions necessary for the emergence of endogenous political coalitions and the respective basins of attraction. Some final considerations follow in Section 5.

# 2 The Model

Drawing on the recent political science literature on party ideology (e.g. Bakker and Hobolt, 2013), the determinants of voting behaviour can be broadly categorized along two main dimensions: The Economic-distributive (ED) and the Socio-Cultural (SC). The ED dimension is related to preferences regarding the state of the economy and economic inequality, while the SC dimension is related generally to preferences over multiculturalism, law and order, immigration and attitudes towards climate change. Given our interest in the ongoing global warming debate, we abstract from all other elements of SC dimension to focus the analysis on attitudes towards the importance of climate change mitigation and adaptation policies only. More specifically, we will represent the SC dimension by allowing agents to either believe or not about the existence of climate change, or just disagreeing on the necessity of levying a carbon tax as a mitigation policy. The extent to which a policy can be implemented is conditional to its relative support, as captured by the population composition among the two political dimensions.

Our framework shares many similarities with Di Guilmi and Galanis (2021) who provide a baseline framework to study the coexistence of different political arrangements using a continuous-time version of the discrete-choice approach in Brock and Hommes (1997). While their model was mainly concerned with the interplay between group effects and redistribution, Di Guilmi et al. (2023) extend it to investigate its interplay with business cycle fluctuations. However, both contributions reduced political cleavages to the ED dimension. The present paper draws on those efforts and extends them through the introduction of the missing SC dimension. Our goal is to provide a sound theoretical framework that sheds some light on mechanisms that might be involved in the endogenous transformation of political cleavages documented by Gethin et al. (2022).[1]

The model is divided into four main blocks of equations. First, we describe the political environment and how green sentiments can be introduced. The second block consists of the production technology and its relationship with inequality, captured by the skill premium. Though there is substitutability between low- and high-skilled workers, Leontief technology rules the energy-labour relationship (as in Dutt and Veneziani, 2020). The third part deals with CO2 emissions and their relationship with economic growth. Finally, we present the closing behavioural rules, which include determining the two crucial policy variables of the model: the tax rate on the wage-differential and on carbon emissions. The former is associated with who prevails in the $ED$ domain, while the latter depends on $SC$ preferences.

## 2.1 Political Preferences along the Economic-Distributive (ED) and Socio-Cultural (SC) Dimensions

In the following we will assume that both the economic-distributive (ED) and the socio-cultural (SC) dimensions can be fully described along left-right one-dimensional axes. On the left-end of the ED axis, individuals will identify with social-democratic and/or socialist ideals favoring low levels of economic inequality or, for that effect, redistributive policies, while the right-end represents a more market-based, even libertarian approach favoring efficiency over equality. On the left-end of the SC axis, on the contrary, individuals acknowledge the need for action against global warming/climate change, and would favor the levying of carbon taxes and other policies towards a low-carbon economy. On the right-end of the SC axis, by contrast, individuals would be sceptical about the existence of climate change, or the need for action against it. Using a binary classification has the major advantage of simplifying the analysis while maintaining, broadly speaking, the most frequent coalitions that have effectively built political majorities. Hence, suppose the population $N$ is constant and divided into two groups – left ($L$) and right ($R$) – for each political dimension $i = \{ED, SC\}$, so that:

$$N = N_i^L + N_i^R.$$

The fractions of left- and right-wing agents in the $ED$ dimension evolve according to a continuous-time version of the discrete-choice approach (e.g. Brock and Hommes, 1997), namely

$$\frac{\dot{N}_{ED}^L}{N} = p_{ED}^L(\mathbf{U}) - \frac{N_{ED}^L}{N} \qquad \text{and} \qquad \frac{\dot{N}_{ED}^R}{N} = p_{ED}^R(\mathbf{U}) - \frac{N_{ED}^R}{N} \tag{1}$$

where $p_{ED}^L$ and $p_{ED}^R$ are the probabilities of belonging to each group that, in turn, depend on observable factors comprised in the column vector $\mathbf{U}$. We assume the same variables influence both groups with

[1] Our model relates to a behavioural literature formalising large population of agents facing two alternatives. The discrete-choice Brock and Hommes (1997) and the transition probabilities approach (Lux, 1995) are among the most common modelling choices (see the review by Franke and Westerhoff, 2018). We rely on the first as it was initially used by Di Guilmi and Galanis (2021). For an application of the transition probabilities to the political economy of climate change, see Dávila-Fernández and Sordi, 2020.

the opposite sign. Moreover, $\beta$ is a row vector capturing the relative importance of each element:

$$p_{ED}^{R}(\mathbf{U}) = \frac{\exp(\beta\mathbf{U})}{\exp(\beta\mathbf{U}) + \exp(-\beta\mathbf{U})} \qquad \text{and} \qquad p_{ED}^{L}(\mathbf{U}) = \frac{\exp(-\beta\mathbf{U})}{\exp(\beta\mathbf{U}) + \exp(-\beta\mathbf{U})} \tag{2}$$

Political preferences regarding $ED$ depend on three observable factors. First, the so-called *group* or *peer effect*, i.e. the tendency for people to adopt certain behaviours, styles, or attitudes simply because others are doing so (e.g. Nickerson, 2008, Harmon et al., 2019). For instance, if a person is surrounded by people with a certain view on how the government should manage the economy and its redistributive policies, this peer effect increases the probability for this agent to share similar opinions. The second factor is the so-called *responsibility hypothesis* (Nannestad and Paldam, 1997; Lockwood and Rockey, 2020) according to which politicians and parties will likely be penalised electorally for negative economic performance and reap some benefits from positive results. We capture macroeconomic performance by changes in output. Finally, the third factor is inequality, and we assume that left voters, in general, tend to support more redistribution. Significant experimental evidence suggests people have an innate desire for fairness and are ready to punish unfair behaviour (see Alesina and Angeletos, 2005). Agents seem to desire equality relative to some reference point. Considering this element, we suppose increasing inequality increases the probability of voting "left". These three ingredients together imply:

$$\mathbf{U} = \begin{bmatrix} x \\ \frac{\dot{Y}}{Y}x \\ -\frac{\dot{\sigma}}{\sigma} \end{bmatrix}$$

such that

$$\beta\mathbf{U} = \underbrace{\beta_x x}_{\text{Peer effect}} + \underbrace{\beta_Y \frac{\dot{Y}}{Y} x}_{\text{Resp. hypoth.}} - \underbrace{\beta_\sigma \frac{\dot{\sigma}}{\sigma}}_{\text{Ineq. aver.}} \tag{3}$$

where $\beta_x x$ corresponds to the group effect. A higher share of right-wing agents makes it more likely to adopt right-wing views, intermediate by a parameter $\beta_x > 0$. On the contrary, the dominance of the "left" increases the probability of adopting less conservative positions. The responsibility hypothesis is represented by the term $\beta_Y(\dot{Y}/Y)x$, which allows macroeconomic performance measured by output's growth rate $(\dot{Y}/Y)$ to influence sentiments in favour of the ruling party by a factor $\beta_Y > 0$. Furthermore, increasing inequality captured by variations in the wage ratio between high and low-skilled labour $(\dot{\sigma}/\sigma)$ increases the probability of favouring redistribution, $\beta_\sigma > 0$, thus being more left-wing.

As previously mentioned, regarding the SC dimension, we abstract from other elements that may influence the $SC$ dimension and focus on its green component exclusively. In fact, the findings by Gethin et al. (2022) indicate half of the positive link between education and support for the left in the most recent years can be explained by the rise of green parties. Here, we do not impose such a relationship a priori but will study the conditions under which it might emerge endogenously later. For the moment, assume the composition of the population in the $SC$ also changes according to:

$$\frac{\dot{N}_{SC}^{L}}{N} = p_{SC}^{L}(\mathbf{V}) - \frac{N_{SC}^{L}}{N} \qquad \text{and} \qquad \frac{\dot{N}_{SC}^{R}}{N} = p_{SC}^{R}(\mathbf{V}) - \frac{N_{SC}^{R}}{N} \tag{4}$$

where $p_{t,SC}^{L}$ and $p_{t,SC}^{R}$ are the probabilities of belonging to one of the two groups given by:

$$p_{SC}^{R}(\mathbf{V}) = \frac{\exp(\rho\mathbf{V})}{\exp(\rho\mathbf{V}) + \exp(-\rho\mathbf{V})} \qquad \text{and} \qquad p_{SC}^{L}(\mathbf{V}) = \frac{\exp(-\rho\mathbf{V})}{\exp(\rho\mathbf{V}) + \exp(-\rho\mathbf{V})}. \tag{5}$$

As in the ED case, we assume that green sentiments depend on observable variables belonging to a column vector

$$\mathbf{V} = \begin{bmatrix} 1 \\ \frac{\dot{P}^e}{P^e} \end{bmatrix}$$

and a row vector $\rho$ stands for their relative importance, so that

$$\rho \mathbf{V} = \underbrace{\rho_{SC}}_{\text{Secular Trend}} + \underbrace{\rho_P \frac{\dot{P}^e}{P^e}}_{\text{Efficacy/Threat}} \tag{6}$$

While one could think of $\rho_{SC}$ as a constant that comprises all variables not relevant for the current analysis, we will interpret this constant in the numerical simulations as as describing a *secular trend* in the socio-cultural dimension towards more climate change consciousness (for $\rho_{SC} < 0$). Indeed, ceteris paribus, more negative values of $\rho_{SC}$ lead to a lower probability of becoming more conservative in the socio-cultural sense, i.e. denying the importance or even existence of climate change.

The second element in (6) represents the response of attitudes to the expected rate of growth of CO2 emissions ($\dot{P}^e/P^e$).[2] Indeed, research on environmental psychology suggests that the *outcome expectancy-efficacy* (Van Valkengoed and Steg, 2019) and that the *threat appraisal* (Bamberg et al., 2017) are the strongest predictors of individual adaptation behaviour (for an overview of the related literature, see Bechtoldt et al., 2021). The first effect relates to the belief in individual or group capabilities to organise and execute the actions required to produce certain attainment so that adaptation will effectively protect against climate risks and hazards. In the context of the present model, outcome efficacy is associated with $\rho_P > 0$. If agents expect emissions to continue rising, they are more likely to feel discouraged and to *reduce* their support for a green agenda. On the contrary, negative expected emissions signal the feasibility of environmental action, thus increasing the probability of aligning with it. By contrast, threat appraisal is associated with $\rho_P < 0$. In that case, higher emissions increase the probability of adopting more favourable attitudes towards green policies because people see the negative consequences of pollution. Paradoxically, this implies that achieving negative emissions might backfire and reduce support to SC-left as individuals feel less threatened by climate change. In the numerical simulations below we will explore this issue in more detail.

Subtracting the first from the second expression in (1) and in (4), respectively, we obtain a set of differential equations that describes the change in the composition of the population in the political spectrum in the ED and the SC dimensions:

$$\begin{aligned} \dot{x} &= p^R_{ED}(U) - p^L_{ED}(U) - x \\ \dot{\Phi} &= p^R_{SC}(V) - p^L_{SC}(V) - \Phi \end{aligned} \tag{7}$$

where

$$x = \frac{N^R_{ED} - N^L_{ED}}{N} \in [-1, 1], \qquad \text{and} \qquad \Phi = \frac{N^R_{SC} - N^L_{SC}}{N} \in [-1, 1]$$

[2]Note that we do not claim here that people are aware or keep themselves informed about the rate of growth of CO2 emissions. Still, individuals see the consequences of global warming through, e.g., an increase in natural disasters such as fires, floods, and heat waves, among others. Their voting decisions might respond to the growing intensity of these phenomena (Hart et al., 2015; Drews and Van den Bergh, 2016), the latter being a function of the expansion of the carbon stock in the atmosphere. Therefore, the variation of $P$ becomes our variable of interest.

are indexes of the population composition in both dimensions. The pair $(x, \Phi) = (0, 0)$ characterises a society equally divided between left and right-wing actors in their ED and SC preferences. On the other hand, $(x, \Phi) = (1, 1)$ stands for the case in which everybody is strongly right-wing in economic and socio-cultural matters. On the contrary, the case in which $(x, \Phi) = (-1, -1)$ represents a left-wing oriented population in both ED and SC dimensions.

Notice that, in principle, an agent might identify or not with the same political orientation in both dimensions. For example, a person might be left-wing from an economic-distributive perspective but with right-wing socio-cultural values. The model is thus compatible with "left-left", "left-right", "right-left", and "right-right" political views. Indeed, nothing forbids having a combination between cases, that is, societies with $x > 0$ and $\Phi < 0$ and vice-versa. Similar indexes have been used over the years in financial and environmental heterogeneous agent models and come with the advantage of being quite intuitive (for a review, see Dieci and He, 2018; empirical insights on climate change attitudes can be found in Sordi and Dávila-Fernández, 2023).

## 2.2 Production Technology and Skill-Driven Wage Inequality

Aggregate output $(Y)$ is produced using low-skilled labour $(L)$, and high-skilled labour $(H)$, i.e.

$$Y = f(L, H). \tag{8}$$

There is substitutability between low- and high-skilled labour (Acemoglu and Autor, 2011).

CO2 emissions $(P)$ are assumed to be linked linearly to economic activity, i.e.:

$$P = \varepsilon Y \tag{9}$$

where $\varepsilon$ measures environmental efficiency to the extent it captures CO2 discharges per unit of output. We could think of it as a technical coefficient representing the degree of "greenness" of the current technology. Of course, in a carbon-neutral economy, we have $\varepsilon = 0$.

Labour demand for high- and low-skilled workers is the result of the following cost minimization problem:

$$\begin{aligned} \min\ w_L L + w_H H \qquad & \text{s.t.} \\ Y = f(L, H) \end{aligned} \tag{10}$$

where $w_L$ and $w_H$ are low- and high-skilled labour wages, respectively.[3]

Further, assume, for the sake of analytical convenience, a Cobb-Douglas specification for $f(\cdot)$ with constant returns:

$$f(H, L) = AL^{\theta} H^{1-\theta} \tag{11}$$

where $A$ is an efficiency parameter, while $\theta \in (0, 1)$ and $(1 - \theta)$ are the output elasticity of $L$ and $H$. Thus, we obtain from (10) that the skill wage premium $\sigma$, i.e. the ratio between skilled and unskilled

[3]Note that while we could relate low-skilled labour with "brown" economic tasks, and high-skilled labour with green, low-carbon activities, we do not do this explicitly in the following (assuming this that workers do not take environmental factors in their occupational considerations), and assume instead that the firms' environmental production efficiency is directly affected by the CO2 taxes raised by the government, see (22).

wages is given by:

$$\sigma = \frac{w_H}{w_L} = \left(\frac{1-\theta}{\theta}\right)\frac{L}{H} \tag{12}$$

Hence, a more highly-skilled workforce is related to a lower $L/H$, which delivers a lower wage premium. Analogously, a higher proportion of low-skilled workers relative to the high-skill increase the gap.

Log-differentiating Eq. (12) with respect to time, we have:

$$\frac{\dot{\sigma}}{\sigma} = \frac{\dot{L}}{L} - \frac{\dot{H}}{H} \tag{13}$$

which immediately follows from the assumption that $\theta$ is a constant parameter. Wage inequality will increase as long as $\dot{L}/L > \dot{H}/H$, decreasing when the inequality is reverted.

Under the assumption that the labour force is equal to the population,

$$N = H + L$$

and that $N$ is constant for the sake of simplicity, i.e. $\dot{N}/N = 0$, it follows that:

$$\frac{\dot{L}}{L} = -\frac{\dot{H}}{H}\left(\frac{H}{L}\right) \tag{14}$$

Substituting Eq. (14) into (13), and making use of (12), we obtain:

$$\frac{\dot{\sigma}}{\sigma} = -\left[1 + \left(\frac{1-\theta}{\theta\sigma}\right)\right]\frac{\dot{H}}{H}. \tag{15}$$

Given that $0 < \theta < 1$, an increase in the number of high-skilled workers ($\dot{H}/H > 0$) reduces the corresponding wage rate, and thus the skill premium between high- and low-skilled workers, and thus the wage inequality between the two groups.

## 2.3 Carbon Emissions and Economic Activity

Log-differentiating (9) with respect to time yields the growth rate of domestic pollution

$$\frac{\dot{P}}{P} = \frac{\dot{\varepsilon}}{\varepsilon} + \frac{\dot{Y}}{Y}, \tag{16}$$

an expression that comes with an important message. As long as net-zero emissions are not achieved, output growth necessary implies higher CO2 levels. However, absolute decoupling with improving living standards is possible, provided that $\dot{\varepsilon}/\varepsilon$ is sufficiently negative.

Log-differentiating (11) with respect to time and assuming that $\frac{\dot{A}}{A} = \alpha > 0$ delivers the following expression for the rate of growth of output:

$$\frac{\dot{Y}}{Y} = \alpha + \theta\frac{\dot{L}}{L} + (1-\theta)\frac{\dot{H}}{H} \tag{17}$$

Substituting (12) into (14) and the resulting expression into (17), we obtain output growth rate as a function of variations in the number of high-skilled workers and their wage premium:

$$\frac{\dot{Y}}{Y} = \alpha - (1-\theta)\left(\frac{1}{\sigma} - 1\right)\frac{\dot{H}}{H} \tag{18}$$

Recalling that $\sigma > 1$ (otherwise, there is no point in accumulating high skills) it is easy to see economic growth fundamentally depends on two main forces. First, improvements in efficiency ($\alpha > 0$)that are not necessarily related to the environment, and second, the increase in the number of high skilled workers.

Unsurprisingly, as emissions are a sub-product of economic activity, substituting (18) into (16), it follows that the rate of growth of the CO2 stock is given by:

$$\frac{\dot{P}}{P} = \frac{\dot{\varepsilon}}{\varepsilon} + \alpha - (1-\theta)\left(\frac{1}{\sigma} - 1\right)\frac{\dot{H}}{H} \tag{19}$$

and to keep our narrative as simple as possible, we assume expectations about emissions are fully realised so that:

$$\frac{\dot{P}^e}{P^e} = \frac{\dot{P}}{P}.$$

In reality, expectations are subject to a significant degree of uncertainty and are likely to be directly endogenous to specific policy instruments and the credibility of the policy maker (e.g. Campiglio et al., 2024). Our results should be interpreted taking into account this limitation. Future research on the topic is certainly to be encouraged.

## 2.4 Income-Related and Carbon Tax Policies

The government is assumed to raise two types of taxes in the economy: One is linked to the workers' income (and thus indirectly, to their skills), and the other is related to the firms' carbon emissions.

The last block of equations consists of the connecting bridges between the economy, environment, and politics. Our narrative depends on two fundamental premises. Contrary to right-wing ED coalitions, left-wing groups have strong preferences for redistribution. Thus, the composition of the population will be crucial for deciding whether to tax the wage premium, which in turn feeds human capital accumulation. Furthermore, the distribution of agents in the SC dimension will be related to the choice of the carbon tax.

### 2.4.1 Human Capital Accumulation and the ED Dimension

The dynamics of the wage skill-premium, which is a *proxy* for economic inequality, crucially depend on the growth rate of the high-skilled workers. We assume the latter depends on the *relative wage income* between high- and low-skilled wages following Dutt and Veneziani (2020), as well as on the provided public infrastructure for the accumulation of high skills, i.e.

$$\begin{aligned}\frac{\dot{H}}{H} &= h(\sigma, \tau_H) \\ &= -h_0 + \underbrace{h_\sigma \sigma (1-\tau_H)}_{\text{Relative wage income}} + \underbrace{h_{\tau_H}\tau_H}_{\text{Public infrastructure}}\end{aligned} \tag{20}$$

where $h_\sigma \geq 0$ and $h_{\tau_H} \geq 0$ capture the marginal effects of each component on $\dot{H}/H$. Without private- or public-driven high-skill accumulation, human capital depreciates at a rate of $h_0$.

According to the above expression, a high skill premium reflects higher returns to education, to which agents respond by accumulating more skills. In addition to this market-based channel, the government or the society might choose to implement a progressive or a regressive wage tax scheme – represented here as a tax ($\tau_H > 0$) or a subsidy ($\tau_H < 0$) to the wage premium –. In the first case, such a tax would reduce the disposable wage premium, while in the second it would increase it (thus effectively implementing a regressive tax scheme). We assume that the government uses the raised taxes to finance the accumulation of human capital through a different channel that we, for the sake of simplicity, refer to as *public infrastructure* to high skill accumulation, such as the funding of public education, better skills-related infrastructure, etc. In the second case ($\tau_H < 0$), the government bets on private market-related incentives: Instead of taxing wage inequality, such a scenario would imply a trickle-down type of policy in which the more skilled would have a relative higher disposable income, at the expense, however, of investment on public infrastructure.

To keep the exercise as simple as possible, we assume that $\tau_H$ are a function of the political majority prevailing in the $ED$ dimension, namely:

$$\begin{aligned} \tau_H &= \tau_H(x) \\ &= -x \end{aligned} \tag{21}$$

This specification implies that when the majority of agents support left-wing views ($x < 0$), the society will tax the skill premium, $\tau_H > 0$, increasing the relative importance of *public infrastructure* over *relative wage income* incentives to human capital accumulation. Alternatively, a right-wing coalition, $x > 0$, by subsidising the relative wage income to high skilled work ($\tau_H < 0$) and defunding public infrastructure, makes human capital accumulation mainly dependent on market forces.

### 2.4.2 Carbon Emissions and the SC Dimension

Pollutant emissions depend negatively on the adoption of the carbon tax ($\tau_{CO_2}$), which for the moment is assumed not to have implications for income distribution. The transmission channel we are modelling involves a process of induced technical change. Firms respond to taxation by increasing their search for production techniques that pollute less (e.g. Acemoglu et al., 2012; Steenkamp, 2021; Sordi and Dávila-Fernández, 2023). The simplest possible representation is:

$$\begin{aligned} \frac{\dot{\varepsilon}}{\varepsilon} &= e\left(\tau_{CO_2}\right) \\ &= -e_{\tau_{CO_2}} \tau_{CO_2} \end{aligned} \tag{22}$$

where $e_{\tau_{CO_2}} > 0$ captures the marginal effect of increases in the carbon tax on decoupling emissions from the output. Under no taxation, there are no incentives to develop or adopt new technologies that pollute less and $\varepsilon$ remains constant.

Finally, $\tau_{CO_2}$ depends on the population composition in the $SC$ sphere:

$$\begin{aligned} \tau_{CO_2} &= \tau_{CO_2}(\Phi) \\ &= -\Phi \end{aligned} \tag{23}$$

Left-wing voters in the $SC$ dimension support adopting a higher tax rate on emissions. On the other hand, conservatives do not see global warming as a climate emergency. They might recognise it exists and even that it is human-made, but they do not concede it as a top priority. Therefore, if they prevail as a majority in the composition of the population, one should expect a lower $\tau_{CO_2}$.

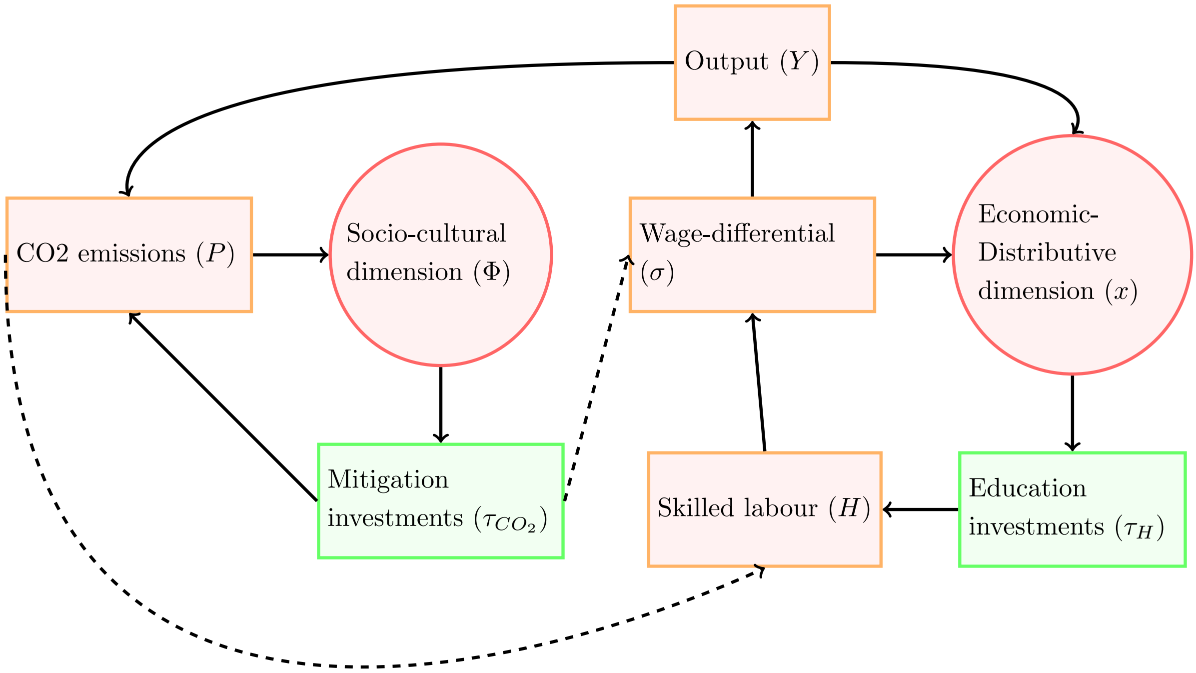


Figure 1: A summarising diagram of the ED-SC system. Continuous lines indicate mechanisms studied analytically and numerically. Dashed lines stand for transmission channels explored only in our numerical experiments.

Fig. 1 provides a summarising diagram of the ED-SC system. The red circles indicate the two political dimensions, while in green, we mark the direct policy-controlled variables. As it can be observed, economic activity (output $Y$) affects the ED dimension directly, generating CO2 emissions which, in turn, affect the SD dimension. In turn, the SC and ED dimensions determine the mitigation and education investments, respectively, affecting the wage differential directly, and indirectly, through the workers' accumulation of high skills. Finally, the wage differential feeds back into output per (18).

Continuous arrows indicate mechanisms studied both analytically (in the next section) and numerically (in section 4). Dashed lines correspond to channels addressed only in our numerical experiments (also in section 4).

# 3 The Dynamical System

Substituting the probability functions in (2) and (5) into (7), we obtain the dynamics of political preferences depending on group effects, economic growth, inequality, and CO2 emissions. Further substituting (18) and (19) in the resulting expressions and making use of (15), using the closing behavioural rules (20)-(23) for the determination of taxes, which in turn impact the growth rate of skilled workers and the decoupling rate, our 3D nonlinear dynamic system becomes:

$$\begin{aligned}
\dot{x} &= \tanh\left(\left\{\beta_x + \beta_Y\left[\alpha - (1-\theta)\left(\frac{1}{\sigma}-1\right)h\left(\sigma, \tau_H(x)\right)\right]\right\}x + \beta_\sigma\left(1+\frac{1-\theta}{\theta\sigma}\right)h\left(\sigma, \tau_H(x)\right)\right) - x \\
\frac{\dot{\sigma}}{\sigma} &= -\left(1+\frac{1-\theta}{\theta\sigma}\right)h\left(\sigma, \tau_H(x)\right) \\
\dot{\Phi} &= \tanh\left(\rho_{SC} + \rho_P\left[e\left(\tau_{CO_2}(\Phi)\right) + \alpha - (1-\theta)\left(\frac{1}{\sigma}-1\right)h\left(\sigma, \tau_H(x)\right)\right]\right) - \Phi
\end{aligned} \tag{24}$$

System (24) highlights how human capital accumulation and income inequality pervade both political dimensions. Given its positive relationship with output growth, $\dot{H}/H = h\left(\sigma, \tau_H(x)\right)$ favours the coalition in power through the responsibility hypothesis mechanism. Still, it increases the probability of being ED-right by reducing inequality and thus also the perception of the need for redistributive policies. Moreover, a side effect of a more skilled population capable of producing more is that it will also pollute more, what feeds back in the SC dimension. Provided that $\rho_P > 0$, an increasing rate of emissions ceteris paribus might reduce the support to the SC-left because it damages the belief in climate adaptation.

In steady-state, $\dot{x} = \dot{\sigma} = \dot{\Phi} = 0$, implying the following equilibrium conditions:

$$\begin{aligned}
\bar{x} &= \tanh\left(\left(\beta_x + \beta_Y\alpha\right)\bar{x}\right) \\
0 &= \left(1+\frac{1-\theta}{\theta\bar{\sigma}}\right)h\left(\bar{\sigma}, \tau_H(\bar{x})\right)\bar{\sigma} \\
\bar{\Phi} &= \tanh\left(\rho_{SC} + \rho_P\left(e\left(\tau_{CO_2}\left(\bar{\Phi}\right)\right) + \alpha\right)\right)
\end{aligned} \tag{25}$$

with a bar over a variable indicating its equilibrium value. The existence of one or more solutions crucially depends on the properties of the hyperbolic tangent. From the first and third expressions in (25), we have that $\bar{x}$ and $\bar{\Phi}$ are determined in the ED and SC domains, respectively. The shape of the first is related to the sum of group and accountability effects captured by parameters $\beta_x$ and $\beta_Y$. On the other hand, the SC depends on the interaction between improvements in environmental efficiency induced by the carbon tax with other socio-cultural elements assumed to be exogenous to the model. Income inequality is determined later on, becoming endogenous to political choices. It will be influenced by the degree to which society relies more on private or public incentives for human capital accumulation.

Given that $L \neq 0$, the remainder of the paper will exclude cases in which $\bar{\sigma} \leq 0$. Making use of the respective functional forms for $h(\cdot)$, $\tau_H(\cdot)$, $e(\cdot)$, and $\tau_{CO_2}(\cdot)$, see (20)-(23), we proceed by stating and proving the following Proposition regarding the existence of equilibria.

**Proposition 1** *The dynamic system admits a set of equilibrium solutions defined by all triplets* $(\bar{x}, \bar{\sigma}, \bar{\Phi})$ *that satisfy:*

$$\begin{aligned}
\bar{x} &= \tanh\left(\beta_1\bar{x}\right) \\
\bar{\sigma} &= \frac{h_0 + h_{\tau_H}\bar{x}}{h_\sigma\left(1+\bar{x}\right)} \\
\bar{\Phi} &= \tanh\left(\rho_0 + \rho_1\bar{\Phi}\right)
\end{aligned} \tag{26}$$

*where*

$$\beta_1 = \beta_x + \beta_Y \alpha$$
$$\rho_0 = \rho_{SC} + \rho_P \alpha$$
$$\rho_1 = \rho_P e_{\tau_{CO_2}}$$

**Proof.** See Appendix A.1. ■

Depending on the value of $\beta_1$, $\rho_0$, and $\rho_1$, the system is compatible with 1, 3, or 9 equilibrium points. We report the necessary conditions for each scenario in Table 1. When the group and accountability effects are sufficiently weak, agents care little about their peers' views and ignore the current government's economic performance, i.e. $\beta_1 < 1$. In such a scenario, the population will be equally divided in the ED axis between left- and right-wing positions, as represented by the blue line in Fig. 2. However, if the peer and accountability effects are sufficiently strong, a Pitchfork bifurcation occurs, and two additional solutions emerge in the ED axis, depicted in yellow. They are not corner solutions and should be interpreted as right or left majorities in the economic-distributive (ED) sphere.

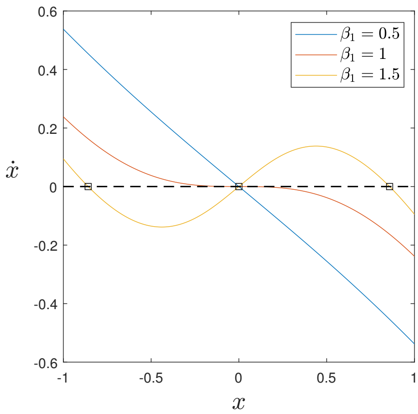


Figure 2: Determination of equilibria in the Economic-distributive (ED) political domain.

Regarding the SC axis, the number of equilibria fundamentally depends on the sign of $\rho_P$, which determines $\rho_1$. Let us begin with the case where outcome expectancy-efficacy effects prevail over threat appraisal, i.e. $\rho_1 > 0$. If sufficiently small, society will be equally divided between "left" and "right". This situation is shown in the top-left diagram of Fig. 3. Nonetheless, when the effects

Table 1: Number of equilibria with $\sigma \neq 0$

| | $\rho_1 \leq \tilde{\rho}_1$ | $\tilde{\rho}_1 < \rho_1$ $\lvert\rho_0\rvert < \lvert\tilde{\rho}_0\rvert$ | $\lvert\tilde{\rho}_0\rvert < \lvert\rho_0\rvert$ |
|---|---|---|---|
| $\beta_1 \leq 1$ | 1 | 3 | 1 |
| $\beta_1 > 1$ | 3 | 9 | 3 |

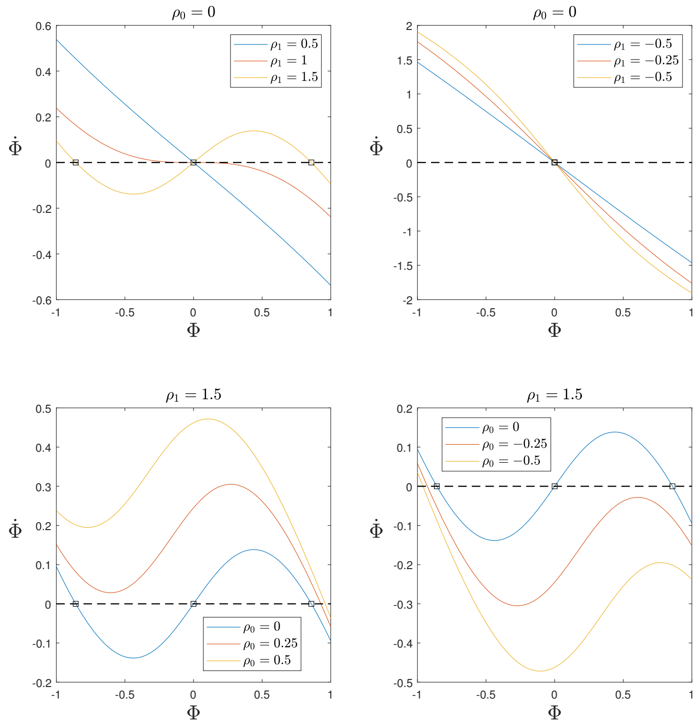


Figure 3: Determination of equilibria in the Socio-Cultural (SC) political dimension.

of global warming lead to starker views, the model admits two additional equilibria in which most agents are either left-wing or whether the majority holds a right-wing position. Which majority will prevail depends on the magnitude of $\rho_0$ that fundamentally rests on all other elements forming the SC dimension not explicitly considered in our analysis. If there is a "green/progressive" or an anti-conservative trend, then $\rho_0 < 0$. Likewise,an exogenous conservative movement is associated with $\rho_0 > 0$. Provided that one of them is sufficiently strong relative to a threshold $\tilde{\rho}_0$, the respective group will prevail over the other. Under a strong "green" trend represented by $\rho_0 < 0$ (depicted through the panel bottom-right in Fig. 3), the SC sphere will be controlled by left-wing agents. Right parties dominate the opposite scenario, as shown on the bottom-left diagram of the same figure. Two equilibria disappear as we move from the blue to the orange curve. Even under relatively high values of $\rho_1$, i.e. people are responsive to climate change, we might only have either $\bar{\Phi} > 0$ or $\bar{\Phi} < 0$ as possible solutions. We will return to this point later to address its link with absolute decoupling.

Things turn out quite different when climate threat appraisal prevails over outcome expectancy-efficacy effects, i.e. $\rho_P < 0 \rightarrow \rho_1 < 0$. The panel up-right in Fig. 3 reports what if the probability of voting right-wing on the SC axis was negatively related to higher emissions. Surprisingly, the population will be equally divided between the two groups. Such a scenario indicates permanent polarisation as agents are equally divided between the two groups. In the remainder of the paper, we will focus on the previous case as it allows for the emergence of "left-left", "left-right", "right-left", and "right-right" coalitions, leaving the scenario with $\rho_P < 0$ for future research.

Given the system's complexity in terms of its equilibrium solutions, we refrain from demonstrating analytically the existence of each solution. In the next Section, we perform a set of numerical experiments to bring economic insights into what is happening in the model. Here, we limit ourselves to stating and proving the following proposition regarding the conditions for the local stability of the equilibrium points.

**Proposition 2** *Provided that it exists, each of the equilibrium points* $(\bar{x}, \bar{\sigma}, \bar{\Phi})$ *of the dynamic system (24) is locally asymptotically stable in the region of the parameter space defined as:*

$$\left[1 - \tanh^2\left(\rho_0 + \rho_1 \bar{\Phi}\right)\right] \rho_P e_{\tau_{CO_2}} < 1$$

$$\left[1 - \tanh^2\left(\beta_1 \bar{x}\right)\right] \left\{\beta_1 + \left[\beta_\sigma \left(1 + \frac{1-\theta}{\theta \bar{\sigma}}\right) - \beta_Y \left(1-\theta\right) \left(\frac{1}{\bar{\sigma}} - 1\right) \bar{x}\right] \left(\frac{h_0 - h_{\tau_H}}{1 + \bar{x}}\right)\right\}$$
$$< 1 + \left(\bar{\sigma} + \frac{1-\theta}{\theta}\right) h_\sigma \left(1 + \bar{x}\right)$$

$$\left\{\beta_1 \left[1 - \tanh^2\left(\beta_1 \bar{x}\right)\right] - 1\right\} \left(\bar{\sigma} + \frac{1-\theta}{\theta}\right) h_\sigma \left(1 + \bar{x}\right) < 0$$

**Proof.** See Appendix A.2. ■

The remaining analysis will deal with scenarios under a sufficiently strong group and accountability effects. Our motivation is twofold. First, because in the political science and economics literature on voting behaviour, there is reasonable empirical support for both. Second, the endogenous emergence of "left-left", "left-right", "right-left", and "right-right" coalitions crucially depend on them. Thus, we aim to assess their robustness and stability, exploring the role of education and green technological change in the dynamics we obtain.

# 4 Numerical Analysis

To provide a more concrete view of the properties of the model, we calibrate the system choosing parameter values to obtain economically meaningful results. Whenever possible, we followed empirical studies in the field. That is specifically the case for human capital and the wage premium (see Dinerstein et al., 2022; Acemoglu and Autor, 2011). The proportion between skilled to unskilled is approximated using data for tertiary education attainment that indicates around 30% of the EU population has at least a college equivalent degree (Eurostat, 2021). Parameters related to economic growth and emissions were chosen or are compatible with trends from the World Development Indicators. Nonetheless, our selection has only an illustrative purpose, taking the United States and the European Union as general benchmarks. Similar qualitative dynamics can be obtained for a wider range of values. Our reference values are reported in Table 2. Overall, the number of parameters is relatively small, 11 in total, with six directly related to voting behaviour.

Table 2: Choice of parameters

| Parameters | Value | Source/Motivation |
|---|---|---|
| $h_0$ | 0.05 | Dinerstein et al. (2022) |
| $h_\sigma$ | 0.025 | To achieve $\sigma \approx 2$ as in Acemoglu and Autor (2011) |
| $h_{\tau_H}$ | $\in [0.025, 0.075]$ | To allow the ratio public/private education efficiency $\in [0.5, 2]$ |
| $\theta$ | 0.4 | Compatible with $\sigma \approx 2$ and $\frac{H}{N} = 0.4$ as in Eurostat (2021) |
| $\alpha$ | $0 - 0.02$ | World Development Indicators (WDI) |
| $e_{\tau_{CO2}}$ | 0.03 | Compatible with $\frac{\dot{\varepsilon}}{\varepsilon} \in [-0.03, 0.03]$ as in WDI |
| $\rho_{SC},\ \rho_P$ | $\in [-\infty, +\infty]$ | – |
| $\beta_x,\ \beta_\sigma,\ \beta_Y$ | $\in [0, +\infty]$ | – |

We begin reporting the endogenous emergence of multiple stable political coalitions in the ED-SC axis. For this purpose, we fixed:

$$\rho_{SC} = 0; \quad \rho_P = 35; \quad \beta_y = 0.25; \quad \beta_\sigma = 0.2$$

Recall that we assume citizens only care about climate change in the SC dimension and that accountability effects and inequality aversion are moderate. Fig. 4(a) considers a weak group effect, $\beta_x = 0.5$. If agents pay little attention to their peer's ED views, only the SC dimension will play a role in forming either a right-wing equilibrium (ED-right/SC-right), in blue, or a "leftist" counterpart (ED-left/SC-right), in red. However, as we increase peer effects to $\beta_x = 1.1$, the model becomes compatible with the emergence of "ED-left/SC-left", "ED-left/SC-right", "ED-right/SC-left", and "ED-right/SC-right" stable political arrangements, as shown in Fig. 4(b). This result implies that depending on initial conditions, the same country might implement four significantly different types of policies. In magenta, we show trajectories converging to the equilibrium in which a "left" agenda is pursued in economic-distributive and socio-cultural domains (ED-left/SC-left). Still, society could move towards a left agenda from an ED perspective but strongly right-wing from an SC point of view (ED-left/SC-right), in red. Alternatively, we show the possibility of a right-wing ED equilibrium with left-win SC features (ED-right/SC-left) in green. Finally, blue represents a case where a right-wing agenda prevails in both domains (ED-right/SC-right).

The existence of multiple equilibria opens the door to studying the respective basins of attraction. In this first experiment, we assume that the relative wage income and the public infrastructure channels have the same impact on skill accumulation, meaning $h_\sigma = 0.025$ and $h_{\tau_H} = 0.05$. Fig. 5 complements 4 (b) as it reports, using the same colours, all initial conditions leading to each of the four stable solutions. The third dimension in the diagram is income inequality. Notice that, independently of the winning coalition, inequality remains the same. That is a direct consequence of the assumption that human capital equally depends on private and public motives. While we will relax this assumption as a next step, the first message is that understanding the ongoing transformation of the social base supporting political choices requires recognising that history matters. All four majorities are feasible outcomes conditional to initial conditions.

Fig. 5 also provides additional insights on Gethin et al. (2022) main findings. Socio-cultural elements only really matter under intermediate levels of inequality. If the initial wage premium (or, broadly speaking, economic inequality) is very high, all the political debate is centered around a

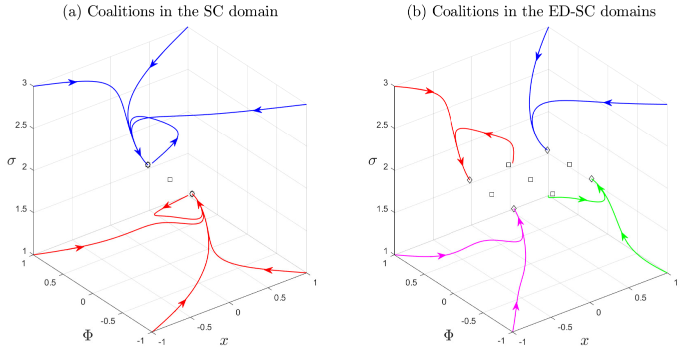


Figure 4: Multiple equilibria and the emergence of mixed majorities in both political spheres when $\alpha = 0$. Relative wage income and public infrastructure incentives have the same impact on skill accumulation, $h_\sigma = 0.025$ and $h_{\tau_H} = 0.05$, with a weak peer effect, $\beta_x = 0.5$ (Figure 4a) and a strong peer effect, $\beta_x = 1.1$ (Figure 4b) in the ED dimension.

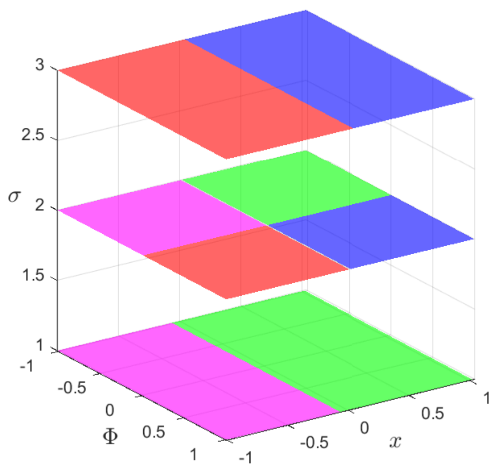


Figure 5: Basins of attraction when relative wage income and public infrastructure incentives have the same impact on skill accumulation, $h_\sigma = 0.025$ and $h_{\tau_H} = 0.05$, while $\alpha = 0$. Very high initial inequality necessarily leads to a blue (ED-right/SC-right) or red (ED-left/SC-right) coalition due to the strong peer effect ($\beta_x = 1.1$). Alternatively, a very low initial skill premium conducts to either a magenta (ED-left/SC-left) or green (ED-right/SC-left) solution.

potential income redistribution. The socio-cultural consensus is right-wing, with people not caring about the environment. Society will converge to a red (ED-left/SC-right) or blue (ED-right/SC-right) equilibrium point. Analogously, when the skill premium is very low, SC aspects become more secondary as this dimension has a left-wing consensus. The real debate regards whether to redistribute or not. Depending on initial conditions, we might end up in a magenta (ED-left/SC-left) or green (ED-right/SC-left) equilibrium. The "greens" push for fewer taxes on the highly educated, while a magenta equilibrium would implicate left-wing policies in both political dimensions.

The story changes under medium inequality rates. Redistributive preferences are not strong enough for ED considerations to prevail over the urgency of tackling climate change. The sort of balance between the two topics results in "ED-left/SC-left" (magenta), "ED-left/SC-right" (red), "ED-right/SC-left" (green), and "ED-right/SC-right" (blue) stable coalitions becoming feasible.

Putting these elements in historical perspective, the pre-war period was characterised by high levels of inequality. Our analysis seems to support social-democratic and affiliated parties being associated with lower-educated and low-income voters at the time. SC elements, in general, and climate change, in particular, were not the defining factors of the political debate. Still, the reduction in inequality documented during the 1950s and 1960s resulted in a scenario where the two additional coalitions, magenta and green, became achievable. This change could be part of the explanation for the disconnect between income and education effects on political preferences.

## 4.1 Relative Wage Income vs. Public Infrastructure Incentives to Skill Accumulation

As a second step, we relax the assumption that income-based and public infrastructure incentives have the same impact on skills. Suppose $h_\sigma = 0.025$ and $h_{\tau_H} = 0.025$ so that the market-determined wage differential has a relatively strong effect on education. Fig. 6(a) shows the four stable equilibria using the same colours. A remarkable difference, however, regards inequality in each of them. Notice that ED-left coalitions paradoxically create higher inequality than ED-right. The explanation lies in the rate of accumulation of skills. ED-left/SC-left (magenta) and ED-left/SC-right (red) majorities are strongly averse to inequality and highly tax the skill premium. The problem is that society cares a lot about that signal, so there is a reduction in the rate of human capital accumulation that the government cannot compensate for. But a reduction in $\dot{H}/H$ implies a reduction in the high- to low-skill ratio, ultimately increasing $\bar{\sigma}$. On the contrary, ED-right/SC-right (blue) and ED-right/SC-left (green) majorities will not tax the wage differential as they do not see inequality as a problem. Society relies on it when deciding whether to get educated, so the pool of skilled workers will be proportionally higher, allowing for a lower $\bar{\sigma}$.

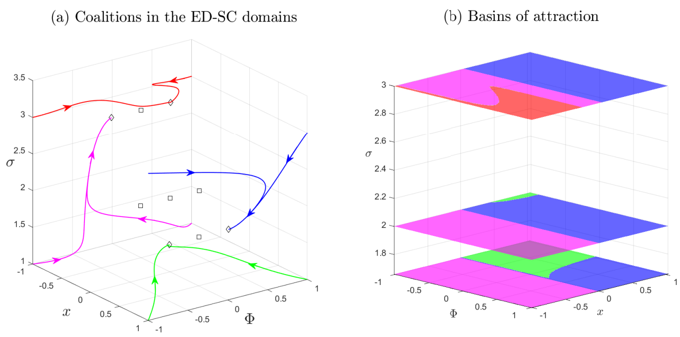


Figure 6: Multiple equilibria and the correspondent basins of attraction when the relative wage differential impacts skill accumulation more than public infrastructure, while $\alpha = 0$.

Moving on to Fig. 6(b), the two coalitions more likely to emerge are ED-left/SC-left (magenta) and ED-right/SC-right (blue). This result indicates a strong contraposition between "pure" left- and right-wing equilibria. Red and green colours are possible but require a particular combination of initial conditions. It is useful to compare this situation with the alternative case where $h_\sigma = 0.025$ and $h_{\tau_H} = 0.075$ so that the wage differential has a relatively weak effect on education. This case is depicted in Fig. 7.

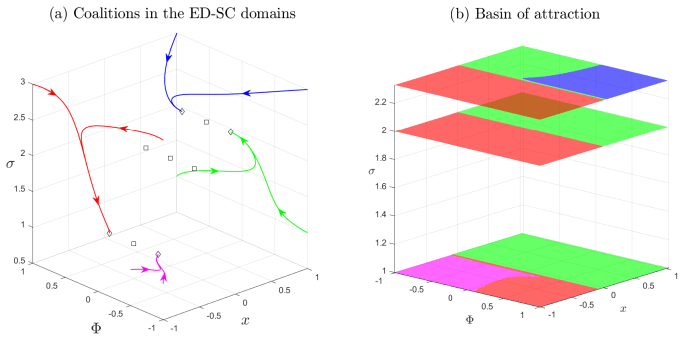


Figure 7: Multiple equilibria and the correspondent basins of attraction when public infrastructure has a greater impact on skill accumulation than relative wage differential, while $\alpha = 0$.

Panel (a) indicates that once public infrastructure incentives matter more than relative wage income motives, the ED-left can effectively reduce inequality. The main reason is taxing inequality does not harm human capital accumulation. On the contrary, more people can get an education as there is an increase in $\dot{H}/H$. Moreover, ED-left/SC-right (red) and ED-right/SC-left (green) majorities are the most important attractors, as indicated in panel (b). This scenario leaves little room for "pure" majorities. The dominant equilibrium is of the type "ED-left/SC-right" or "ED-right/SC-left".

## 4.2 Socio-cultural Secular Trends and the Relevance of Induced Technical Change

Political scientists have discussed whether the secularisation of contemporary societies could, in principle, be expected to influence directly or have influenced parties' positions on the socio-cultural dimension (for a general assessment, see Evans and De Graaf, 2013, pp. 3-26).[4] We incorporate this element in our discussion through parameter $\rho_{SC}$, which is now assumed to be less than zero, implying a socio-cultural secular trend towards more climate action consciousness. Fig. 8 allows us to compare cases of strong, panels (a)-(b), and weak, diagrams (c)-(d), secularisation. In all of them, only two coalitions proved to be stable. When a strong exogenous force pushes for SC-left views, the ED-left/SC-left (magenta) and ED-right/SC-left (green) arrangements are the only possible stable

[4]Secularisation is a multilayered concept; broadly speaking, it is connected to the idea that religious authority diminishes in all aspects of social life and governance. In the context of our model, we approach it in contraposition to cultural conservatism. The latter is associated with conservative moral and social values or traditionalist conservative stances on socio-cultural issues.

equilibria. Though such a result is not surprising, it is not obvious why, under weak secularisation, only the ED-right/SC-right (blue) and ED-left/SC-right (red) coalitions are possible.

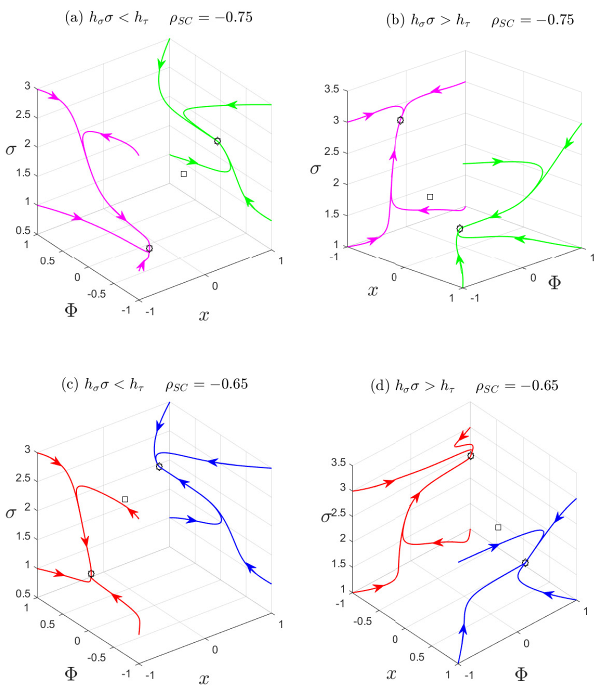


Figure 8: A comparison between scenarios under different intensities of secularisation and positive economic growth, $\alpha = 0.02$.

The answer lies in the interaction of $\rho_{SC}$ with $\rho_P \alpha$. Throughout this paper, we assumed that outcome expectancy efficacy prevails over threat appraisal regarding environmental attitudes. As a result, $\rho_0$ in Proposition 1 might be positive or negative depending on $\rho_{SC} \gtrless \rho_P \alpha$. A weak or no secularisation trend combined with positive growth implies a SC-right consensus represented by the blue (ED-right(SC-right) and red (ED-left/SC-right) trajectories. Alternatively, SC has a left-consensus under strong secularisation, $\rho_0 < 0$, as indicated by the magenta (ED-left/SC-left) and green (ED-right/SC-left) lines. Given our simplifying assumption that the socio-cultural sphere mainly regards environmental concerns, these findings have a somehow optimistic flavour as they indicate the formation of a climate-mitigation consensus is feasible. Is this enough to achieve carbon neutrality on a reasonable time horizon?

We proceed by reporting in Fig. 9 the behaviour of CO2 emissions for different values of $\rho_{SC} < 0$. Blue, orange, and yellow lines mark an increasingly strong transmission channel from the carbon tax to the production technology. When $\rho_{SC} = -0.65$ and $\alpha = 0.02$, we have that $\bar{\Phi} > 0$, meaning that all agents share SC-right-wing views. Therefore, a carbon tax is not adopted, and emissions remain positive, as indicated by the two bottom panels. Unfortunately, negative emissions are unlikely to occur even when there is an SC-left consensus, and $\rho_{SC} = -0.75$. To avoid reducing living standards, absolute decoupling requires a sufficiently strong element of induced technical change. That is, the carbon tax needs to induce the development of carbon-neutral production techniques. Our numerical experiments suggest that, in the most favourable yellow scenario, a one percent increase in the carbon tax should reduce the emissions-output growth rate by three percentage points.

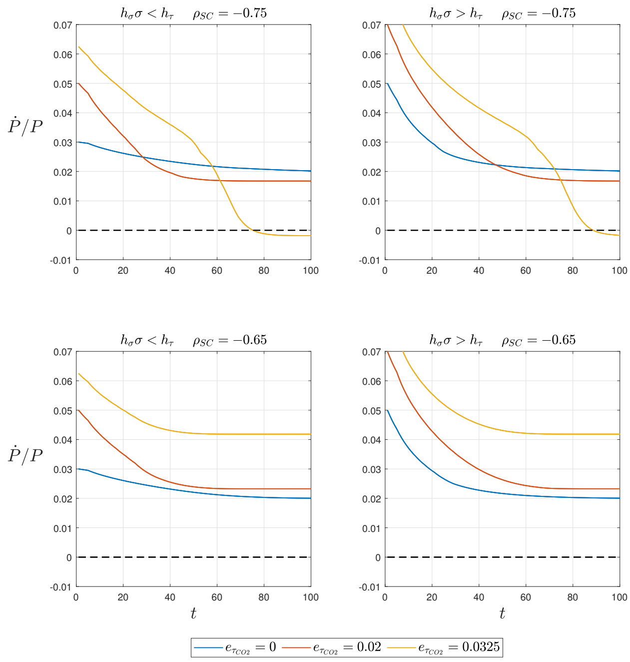


Figure 9: A comparison between pollution scenarios under different intensities of secularisation and positive economic growth, $\alpha = 0.02$. Initial conditions are given by the triplet $(x, \sigma, \Phi) = (1, 3, 1)$

### 4.3 Asymmetric Effects of Carbon Taxes on Inequality

Much empirical evidence suggests the environmental emergency will disproportionately harm the poor, with adopting a carbon tax amplifying existing inequalities (see Fremstad and Paul, 2019; Rüb, 2024). Low-income households spend more on carbon-intensive goods, making carbon taxes quite regressive. Furthermore, it has been argued that environmental degradation in general, and pollution in particular, can potentially damage human capital accumulation (e.g. Lavy et al., 2014; Sapci and Shogren, 2018). We evaluate the response of our model to the inclusion of these two additional mechanisms.

Regarding the first, suppose low-skilled workers are the only ones paying for the carbon tax:

$$w_L = (1 - \tau_{CO_2}) A\theta L^{\theta-1} H^{1-\theta} \tag{27}$$

This simplifies the algebraic steps significantly, providing a stylised representation of the argument we are trying to make. The wage premium is now given by:

$$\sigma = \frac{w_H}{w_L} = \left(\frac{1}{1 - \tau_{CO_2}}\right)\left(\frac{1-\theta}{\theta}\right)\frac{L}{H} \tag{28}$$

Log-differentiating to time, we have:

$$\frac{\dot{\sigma}}{\sigma} = -\left[1 + \frac{1-\theta}{\theta\sigma(1-\tau_{CO_2})}\right]\frac{\dot{H}}{H} + \frac{\dot{\tau}_{CO_2}}{1-\tau_{CO_2}} \tag{29}$$

Moreover, substituting (28) into (14) and the resulting expression into (17), we obtain the output growth rate weighted by the regressive distributive effect of the carbon tax:

$$\frac{\dot{Y}}{Y} = \alpha - (1-\theta)\left[\frac{1}{\sigma(1-\tau_{CO_2}(\Phi))} - 1\right]\frac{\dot{H}}{H} \tag{30}$$

A higher accumulation of skills improves economic performance. However, $\tau_{CO2}$ reduces this effect precisely because it penalises the low-skilled, making it more difficult to acquire education. Finally, we assume current environmental degradation damages human capital accumulation by $0 < 1-\delta < 1$. Thus, we modify (31) that becomes:

$$\frac{\dot{H}}{H} = \delta h(\sigma, \tau_H) \tag{31}$$

Our new 3D dynamic system is such that:

$$\begin{aligned}
\dot{x} &= \tanh\left(\left\{\beta_x + \beta_Y\left[\alpha - (1-\theta)\left(\frac{1}{\sigma(1-\tau_{CO_2}(\Phi))} - 1\right)\delta h(\sigma, \tau_H(x))\right]\right\}x\right. \\
&\quad \left. + \beta_\sigma\left[\left(1 + \frac{1-\theta}{\theta\sigma(1-\tau_{CO_2}(\Phi))}\right)\delta h(\sigma, \tau_H(x)) + \frac{\dot{\tau}_{CO_2}}{1-\tau_{CO_2}(\Phi)}\right]\right) - x \\
\frac{\dot{\sigma}}{\sigma} &= -\left[1 + \frac{1-\theta}{\theta\sigma(1-\tau_{CO_2}(\Phi))}\right]\delta h(\sigma, \tau_H(x)) + \frac{\dot{\tau}_{CO_2}}{1-\tau_{CO_2}(\Phi)} \\
\dot{\Phi} &= \tanh\left(\rho_{SC} + \rho_P\left[e(\tau_{CO_2}(\Phi)) + \alpha - (1-\theta)\left(\frac{1}{\sigma(1-\tau_{CO_2}(\Phi))} - 1\right)\delta h(\sigma, \tau_H(x))\right]\right) - \Phi
\end{aligned} \tag{32}$$

where from Eq. (23), it follows $\dot{\tau}_{CO2} = -\dot{\Phi}$.

We limit ourselves to numerical experiments that add to our previous discussion. Fig. 10 uses our baseline calibration and, in addition, sets $\delta = 0.9$. Both diagrams show that the model is compatible with persistent fluctuations with an important economic interpretation. Panel (a) captures when the wage income incentives have a greater impact on skill accumulation than public infrastructure. In such a scenario, only the ED-right/SC-left (green) coalition is stable. This stable equilibrium point coexists with a cycle around the ED-left/SC-right (red) and ED-left/SC-left (magenta) equilibria. Countries in its basin of attraction always pursue a left-wing ED agenda but alternate between left and right positions in the SC axis.

On the other hand, panel (b) in Fig. 10 reports the emergence of a similar cycle when society values more public infrastructure incentives for education. Still, we document the coexistence of three attractors. ED-left/SC-right (red) and ED-left/SC-left (magenta) majorities are stable, while an orbit englobes ED-right/SC-right (blue) and ED-right/SC-left (green) majorities. Under the basins of attraction of the latter, right-wing policies are always proposed in the ED axis, but policymakers alternate between more and less environmentally friendly actions over time. The compatibility of the model with persistent dynamics is a feature also present in Di Guilmi and Galanis (2021) and Di Guilmi et al. (2023). Voters' preferences endogenously evolve, feeding and responding to policy

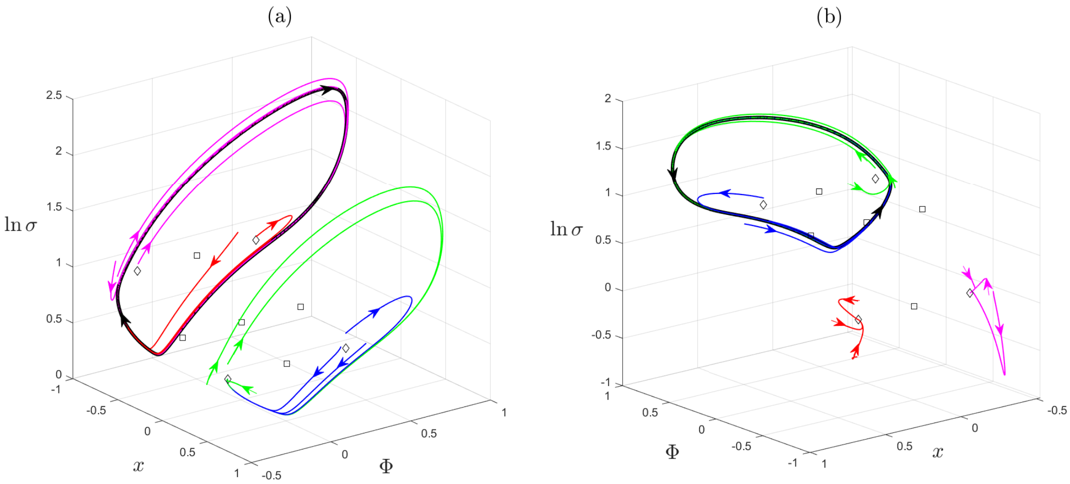


Figure 10: A comparison between basins of attraction when (a) relative wage income has a greater impact on skill accumulation than public infrastructure and (b) in the opposite case. Calibration parameters are comparable to those in Fig. 6 and 7.

outcomes. The convergence of political platforms postulated by the median voter theorem is a special case in various possible outcomes, including political cycles. By incorporating the environmental socio-cultural aspect of political cleavages, we show that the relative importance of the skill premium to the decision to get an education is at the basis of the formation and consolidation of different political arrangements.

The emergence of political cycles in the SC axis is deeply related to the regressive effects of the carbon tax that disrupt the support for this policy. Such an abrupt interruption introduces instability, allowing for the emergence of the periodic orbit. When society cares more about private educational incentives, a consensus regarding economic-distributive policies will likely emerge for initial conditions such as $x > 0$. As $\tau_{CO2}$ increases inequality, it reinforces the economic incentive for human capital accumulation, generating a reinforcing mechanism that makes the green coalition the main stable attractor. On the other hand, a similar society in the basins of attraction of a left-ED party responds to the regressivity of the carbon tax by taxing, even more, the skill premium. As this hurts getting educated, people alternate to more conservative SC values, abandoning taxing emissions. The improvement in income distribution that follows once more damages human capital accumulation, to which agents respond by adopting more SC-left positions. As a result, the society will alternate between ED-left/SC-right (red) and ED-left/SC-left (magenta) majorities.

If, instead, society cares more about public incentives for education, an ED policy consensus is more likely to emerge for initial conditions $x < 0$. Carbon taxes continue to increase inequality, but the government fights back, reinforcing the non-market incentive for human capital accumulation. The resulting reinforcing mechanism makes the ED-left/SC-right (red) and ED-left/SC-left (magenta) majorities stable. However, if the economy starts in the basins of attraction of a ED-right majority, it responds to the regressivity of the carbon tax by further reducing $\tau_H$. As this decision disincentives people from getting educated, people alternate to more liberal SC values, increasing the stringency of the CO2 tax. The deterioration in income distribution that follows once more damages human capital accumulation because both ED-right/SC-left (green) and ED-right/SC-right (blue) majorities subsidise the wage differential. Agents respond by adopting more SC-right positions. The process continues indefinitely, with this society alternating between ED-right/SC-left (green) and ED-right/SC-right (blue) states.

# 5 Concluding Remarks

This study developed a heterogeneous agents' macrodynamic model to study the endogenous emergence of political cleavages under heterogeneity in ecological thinking. It joins recent efforts to integrate dynamic voting and the economy, using an original treatment for popular discrete choice models and applying it to the greatest challenge of our generation. Drawing on the political science literature, we differentiated between economic-distributive (ED) and socio-cultural (SC) dimensions. The first represents more traditional economic policy and inequality concerns, while the latter explicitly refers to climate change. Our model provides an innovative representation of the coexistence between "ED-left/SC-left", "ED-left/SC-right", "ED-right/SC-left", and "ED-right/SC-right" majorities, each associated with a carbon and skill premium tax or subsidy.

We studied analytically and through numerical simulations the conditions resulting in the coexistence of multiple stable equilibria and the possible implications for carbon emissions. Three results are worth highlighting. First, when income inequality, captured by the skill premium, is the primary motivation to become more educated, left-wing ED majorities generate higher inequality than their right-wing counterparts. This finding follows from the "left" taxing the wage differential and penalising human capital accumulation. If society instead relies more on non-market or public incentives, ED-left majorities can effectively reduce inequality because they can tax the wage differential and use the resources to fund education through alternative channels.

Second, we showed that the consensus required to implement a carbon tax is only the first part of the problem. Absolute decoupling requires a sufficiently strong response from technology favouring carbon-neutral production techniques. If this last effect is relatively weak, then there is no political set-up capable of curbing emissions without damaging living standards. In that respect, the induced technological change mechanism from policy to technology is an important part of the story. Our numerical experiments suggest that, in the most favourable scenario, a one percent increase in the carbon tax should reduce the emissions-output growth rate by three percentage points.

Finally, we provided some additional insights into why there has been an apparent disconnect between income and education effects on political preferences. Our model suggests that the SC dimension matters most under medium levels of inequality. When inequality is very high, as in the pre-war period, the ED dimension dominates the debate, and there is a right-wing SC consensus. As inequality fell during the 1950s and 1960s, socio-cultural aspects gained importance. This change led to a situation where "ED-left/SC-left", "ED-left/SC-right", "ED-right/SC-left", and "ED-right/SC-right" stable coalitions became possible, creating a disconnect between education and left-wing support.

Our parsimonious framework is flexible enough to extend in several possible directions. The most evident is perhaps an explicit account of other elements that are part of the SC axis beyond the environment. Another avenue is a less naive treatment of expectations and the interaction between outcome expectancy-efficacy and the threat appraisal mechanisms behind climate adaptation behaviour. Expectations and uncertainty are deeply related, especially when considering the interaction between policy and the possible coexistence between green and brown technologies. A more elaborated formalisation of human capital accumulation in line with recent developments in endogenous growth theory could allow for refinements in the representation of the growth-inequality nexus. Finally, in this paper, our numerical experiments were mainly illustrative and future research improving them is to be encouraged.

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# A Mathematical Appendix

## A.1 Existence of equilibria

Recall that in steady-state, $\dot{x} = \dot{\sigma} = \dot{\Phi} = 0$, implying that system (**??**) has the following equilibrium conditions:

$$\bar{x} = \tanh\left(\left(\beta_x + \beta_Y \alpha\right)\bar{x}\right)$$
$$0 = \left(1 + \frac{1-\theta}{\theta\bar{\sigma}}\right) h\left(\bar{\sigma}, \tau_H(\bar{x})\right)\bar{\sigma}$$
$$\bar{\Phi} = \tanh\left(\rho_{SC} + \rho_P\left(e\left(\tau_{CO_2}\left(\bar{\Phi}\right)\right) + \alpha\right)\right)$$

with a bar over a variable indicating its equilibrium value.

To focus on the economically relevant cases, we disregard the trivial case in which $x = \sigma = \Phi = 0$, and further impose $\sigma > 0$. Thus, it follows that:

$$\bar{x} = \tanh\left(\left(\beta_x + \beta_Y \alpha\right)\bar{x}\right) \tag{A.1}$$
$$0 = h\left(\bar{\sigma}, \tau_H(\bar{x})\right) \tag{A.2}$$
$$\bar{\Phi} = \tanh\left(\rho_{SC} + \rho_P\left(e\left(\tau_{CO_2}\left(\bar{\Phi}\right)\right) + \alpha\right)\right) \tag{A.3}$$

We can recursively prove the existence of a nontrivial solution. Start by noting that $\bar{x}$ is determined independently of the other two variables. From Eq. (A.1), given that $\bar{x} \in [-1, 1]$, then:

$$\tanh\left(\left(\beta_x + \beta_Y \alpha\right)\bar{x}\right) = A(\bar{x}) \in [-1, 1]$$

Hence, $A : [-1, 1] \to [-1, 1]$, we have that$\bar{x}$ exists from Brouwer's fixed point theorem. Substituting this value into Eq. (A.2), we can solve for $\bar{\sigma}$. Finally, $\bar{\Phi}$ is also determined independently of $\bar{x}$ and $\bar{\sigma}$. From Eq. (A.3), given that $\bar{\Phi} \in [-1, 1]$, then:

$$\tanh\left(\rho_{SC} + \rho_P\left(e\left(\tau_{CO_2}\left(\bar{\Phi}\right)\right) + \alpha\right)\right) = B(\Phi) \in [-1, 1]$$

Therefore, $B : [-1, 1] \to [-1, 1]$, implying $\bar{\Phi}$ exists from Brouwer's fixed point theorem.

## A.2 Local stability analysis

Defining the following two functions:

$$Z(x, \sigma, \Phi) = \left\{\beta_x + \beta_Y\left[\alpha - (1-\theta)\left(\frac{1}{\sigma} - 1\right) h\left(\sigma, \tau_H(x)\right)\right]\right\} x$$
$$+\beta_\sigma\left(1 + \frac{1-\theta}{\theta\sigma}\right) h\left(\sigma, \tau_H(x)\right)$$

$$T(x, \sigma, \Phi) = \rho_{SC} + \rho_P\left[e\left(\tau_{CO_2}(\Phi)\right) + \alpha - (1-\theta)\left(\frac{1}{\sigma} - 1\right) h\left(\sigma, \tau_H(x)\right)\right]$$

and linearising the dynamic system around a generic equilibrium point with coordinates $\left(\bar{x}, \bar{\sigma}, \bar{\Phi}\right)$, such that:

$$\begin{aligned}
\bar{x} &= \tanh\left(\beta_1 \bar{x}\right) \\
\bar{\sigma} &= \frac{h_0 + h_{\tau_H}\bar{x}}{h_\sigma\left(1+\bar{x}\right)} \\
\bar{\Phi} &= \tanh\left(\rho_0 + \rho_1 \bar{\Phi}\right)
\end{aligned}$$

and

$$h\left(\bar{\sigma}, \tau_H\left(\bar{x}\right)\right) = 0$$

we obtain:

$$\begin{bmatrix} \dot{x} \\ \dot{\sigma} \\ \dot{\Phi} \end{bmatrix} = \underbrace{\begin{bmatrix} j_{11} & j_{12} & 0 \\ j_{21} & j_{22} & 0 \\ j_{31} & j_{32} & j_{33} \end{bmatrix}}_{\mathbf{J}|_{\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)}} \begin{bmatrix} x-\bar{x} \\ \sigma-\bar{\sigma} \\ \Phi-\bar{\Phi} \end{bmatrix}$$

where

$$\begin{aligned}
j_{11} &= \left[1-\tanh^2 Z\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)\right] \\
&\quad \times \left\{\beta_x + \beta_Y\alpha + \left[\beta_\sigma\left(1+\frac{1-\theta}{\theta\bar{\sigma}}\right) - \beta_Y\left(1-\theta\right)\left(\frac{1}{\bar{\sigma}}-1\right)\bar{x}\right]\left(h_\sigma\bar{\sigma}-h_{\tau_H}\right)\right\} - 1 \\
j_{12} &= \left[1-\tanh^2 Z\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)\right]\left[-\beta_Y\left(1-\theta\right)\left(\frac{1}{\bar{\sigma}}-1\right)\bar{x} + \beta_\sigma\left(1+\frac{1-\theta}{\theta\bar{\sigma}}\right)\right] h_\sigma\left(1+\bar{x}\right) \\
j_{21} &= -\left(\bar{\sigma}+\frac{1-\theta}{\theta}\right)\left(h_\sigma\bar{\sigma}-h_{\tau_H}\right) \\
j_{22} &= -h\left(\bar{\sigma},\tau_H\left(\bar{x}\right)\right) - \left(\bar{\sigma}+\frac{1-\theta}{\theta}\right) h_\sigma\left(1+\bar{x}\right) \\
&= -\left(\bar{\sigma}+\frac{1-\theta}{\theta}\right) h_\sigma\left(1+\bar{x}\right) \\
j_{31} &= -\left[1-\tanh^2 T\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)\right]\rho_P\left(1-\theta\right)\left(\frac{1}{\bar{\sigma}}-1\right)\left(h_\sigma\bar{\sigma}-h_{\tau_H}\right) \\
j_{32} &= -\left[1-\tanh^2 T\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)\right]\rho_P\left(1-\theta\right)\left(\frac{1}{\bar{\sigma}}-1\right) h_\sigma\left(1+\bar{x}\right) \\
j_{33} &= \left[1-\tanh^2 T\left(\bar{x},\bar{z},\bar{\Phi}\right)\right]\rho_P e_{\tau_{CO_2}} - 1
\end{aligned}$$

so that

$$\begin{aligned}
\left|\mathbf{J}|_{\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)} - \lambda\mathbf{I}\right| &= \begin{vmatrix} j_{11}-\lambda & j_{12} & 0 \\ j_{21} & j_{22}-\lambda & 0 \\ j_{31} & j_{32} & j_{33}-\lambda \end{vmatrix} \\
&= \left(j_{33}-\lambda\right)\begin{vmatrix} j_{11}-\lambda & j_{12} \\ j_{21} & j_{22}-\lambda \end{vmatrix} \\
&= \left(j_{33}-\lambda\right)\left[\lambda^2 - \left(j_{11}+j_{22}\right)\lambda + j_{11}j_{22} - j_{12}j_{21}\right] = 0
\end{aligned}$$

Thus, one of the characteristic roots is $\lambda_1 = j_{33}$, whereas the other two are found by solving:

$$\lambda^2 - \left(j_{11}+j_{22}\right)\lambda + j_{11}j_{22} - j_{12}j_{21} = 0$$

We can then conclude that we have $\lambda_2$, $\lambda_3 < 0$ when the succession of signs of the above equation is $+++$, i.e. when, the following two conditions are both satisfied:

$$j_{11} + j_{22} < 0$$

and

$$j_{11}j_{22} - j_{12}j_{21} > 0$$

In terms of the elements of the Jacobian matrix, the local stability conditions of the equilibrium points are the following:

$$\begin{aligned} j_{33} &< 0 \\ j_{11} + j_{22} &< 0 \\ j_{11}j_{22} - j_{12}j_{21} &> 0 \end{aligned}$$

The first condition can be expressed as

$$j_{33} = \left[1 - \tanh^2 T\left(\bar{x}, \bar{z}, \bar{\Phi}\right)\right] \rho_P e_{\tau_{CO_2}} - 1 < 0$$

In terms of the elements of the Jacobian matrix, the second condition can be written as:

$$\begin{aligned} j_{11} + j_{22} = \left[1 - \tanh^2 Z\left(\bar{x}, \bar{\sigma}, \bar{\Phi}\right)\right] & \left\{\beta_x + \beta_Y \alpha + \left[\beta_\sigma \left(1 + \frac{1-\theta}{\theta\bar{\sigma}}\right)\right.\right. \\ & \left.\left. -\beta_Y (1-\theta)\left(\frac{1}{\bar{\sigma}} - 1\right)\bar{x}\right]\left(h_\sigma \bar{\sigma} - h_{\tau_H}\right)\right\} - 1 - \left(\bar{\sigma} + \frac{1-\theta}{\theta}\right) h_\sigma (1 + \bar{x}) < 0 \end{aligned}$$

Finally, the third condition can be written as:

$$\begin{aligned} j_{11}j_{22} - j_{12}j_{21} = & -\left\{\left[1 - \tanh^2 Z\left(\bar{x}, \bar{\sigma}, \bar{\Phi}\right)\right]\left(\beta_x + \beta_Y \alpha + \left[\beta_\sigma \left(1 + \frac{1-\theta}{\theta\bar{\sigma}}\right)\right.\right.\right. \\ & \left.\left.\left. -\beta_Y (1-\theta)\left(\frac{1}{\bar{\sigma}} - 1\right)\bar{x}\right]\left(h_\sigma \bar{\sigma} - h_{\tau_H}\right)\right) - 1\right\}\left(\bar{\sigma} + \frac{1-\theta}{\theta}\right) h_\sigma (1 + \bar{x}) \\ & + \left[1 - \tanh^2 Z\left(\bar{x}, \bar{\sigma}, \bar{\Phi}\right)\right]\left[-\beta_Y (1-\theta)\left(\frac{1}{\bar{\sigma}} - 1\right)\bar{x}\right. \\ & \left. +\beta_\sigma \left(1 + \frac{1-\theta}{\theta\bar{\sigma}}\right)\right] h_\sigma (1 + \bar{x})\left(\bar{\sigma} + \frac{1-\theta}{\theta}\right)\left(h_\sigma \bar{\sigma} - h_{\tau_H}\right) > 0 \end{aligned}$$

i.e.:

$$\begin{aligned} & \left[1 - \tanh^2 Z\left(\bar{x}, \bar{\sigma}, \bar{\Phi}\right)\right]\left\{(\beta_x + \beta_Y \alpha) + \left[\beta_\sigma \left(1 + \frac{1-\theta}{\theta\bar{\sigma}}\right)\right.\right. \\ & \quad \left.\left. -\beta_Y (1-\theta)\left(\frac{1}{\bar{\sigma}} - 1\right)\bar{x}\right]\left(h_\sigma \bar{\sigma} - h_{\tau_H}\right)\right\}\left(\bar{\sigma} + \frac{1-\theta}{\theta}\right) h_\sigma (1 + \bar{x}) - \left(\bar{\sigma} + \frac{1-\theta}{\theta}\right) h_\sigma (1 + \bar{x}) \\ & \quad < \left[1 - \tanh^2 Z\left(\bar{x}, \bar{\sigma}, \bar{\Phi}\right)\right]\left[-\beta_Y (1-\theta)\left(\frac{1}{\bar{\sigma}} - 1\right)\bar{x} + \beta_\sigma \left(1 + \frac{1-\theta}{\theta\bar{\sigma}}\right)\right] \\ & \quad \times \left(h_\sigma \bar{\sigma} - h_{\tau_H}\right)\left(\bar{\sigma} + \frac{1-\theta}{\theta}\right) h_\sigma (1 + \bar{x}) \end{aligned}$$

i.e.:

$$\begin{aligned}
&(\beta_x+\beta_Y\alpha)\left[1-\tanh^2 Z\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)\right]\left(\bar{\sigma}+\frac{1-\theta}{\theta}\right)h_\sigma\left(1+\bar{x}\right)\\
&\quad+\left[1-\tanh^2 Z\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)\right]\left[\beta_\sigma\left(1+\frac{1-\theta}{\theta\bar{\sigma}}\right)-\beta_Y\left(1-\theta\right)\left(\frac{1}{\bar{\sigma}}-1\right)\bar{x}\right]\\
&\quad\times\left(h_\sigma\bar{\sigma}-h_{\tau_H}\right)\left(\bar{\sigma}+\frac{1-\theta}{\theta}\right)h_\sigma\left(1+\bar{x}\right)-\left(\bar{\sigma}+\frac{1-\theta}{\theta}\right)h_\sigma\left(1+\bar{x}\right)\\
&<-\beta_Y\left[1-\tanh^2 Z\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)\right]\left(1-\theta\right)\left(\frac{1}{\bar{\sigma}}-1\right)\bar{x}\left(h_\sigma\bar{\sigma}-h_{\tau_H}\right)\left(\bar{\sigma}+\frac{1-\theta}{\theta}\right)h_\sigma\left(1+\bar{x}\right)\\
&\quad+\beta_\sigma\left[1-\tanh^2 Z\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)\right]\left(1+\frac{1-\theta}{\theta\bar{\sigma}}\right)\left(h_\sigma\bar{\sigma}-h_{\tau_H}\right)\left(\bar{\sigma}+\frac{1-\theta}{\theta}\right)h_\sigma\left(1+\bar{x}\right)
\end{aligned}$$

i.e.:

$$\begin{aligned}
&(\beta_x+\beta_Y\alpha)\left[1-\tanh^2 Z\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)\right]\left(\bar{\sigma}+\frac{1-\theta}{\theta}\right)h_\sigma\left(1+\bar{x}\right)\\
&+\beta_\sigma\left(1+\frac{1-\theta}{\theta\bar{\sigma}}\right)\left[1-\tanh^2 Z\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)\right]\left(h_\sigma\bar{\sigma}-h_{\tau_H}\right)\left(\bar{\sigma}+\frac{1-\theta}{\theta}\right)h_\sigma\left(1+\bar{x}\right)\\
&-\beta_Y\left[1-\tanh^2 Z\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)\right]\left(1-\theta\right)\left(\frac{1}{\bar{\sigma}}-1\right)\bar{x}\left(h_\sigma\bar{\sigma}-h_{\tau_H}\right)\left(\bar{\sigma}+\frac{1-\theta}{\theta}\right)h_\sigma\left(1+\bar{x}\right)\\
&-\left(\bar{\sigma}+\frac{1-\theta}{\theta}\right)h_\sigma\left(1+\bar{x}\right)\\
&<-\beta_Y\left[1-\tanh^2 Z\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)\right]\left(1-\theta\right)\left(\frac{1}{\bar{\sigma}}-1\right)\bar{x}\left(h_\sigma\bar{\sigma}-h_{\tau_H}\right)\left(\bar{\sigma}+\frac{1-\theta}{\theta}\right)h_\sigma\left(1+\bar{x}\right)\\
&+\beta_\sigma\left(1+\frac{1-\theta}{\theta\bar{\sigma}}\right)\left[1-\tanh^2 Z\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)\right]\left(h_\sigma\bar{\sigma}-h_{\tau_H}\right)\left(\bar{\sigma}+\frac{1-\theta}{\theta}\right)h_\sigma\left(1+\bar{x}\right)
\end{aligned}$$

i.e.

$$(\beta_x+\beta_Y\alpha)\left[1-\tanh^2 Z\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)\right]\left(\bar{\sigma}+\frac{1-\theta}{\theta}\right)h_\sigma\left(1+\bar{x}\right)-\left(\bar{\sigma}+\frac{1-\theta}{\theta}\right)h_\sigma\left(1+\bar{x}\right)<0$$

i.e.

$$\left\{(\beta_x+\beta_Y\alpha)\left[1-\tanh^2 Z\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)\right]-1\right\}\left(\bar{\sigma}+\frac{1-\theta}{\theta}\right)h_\sigma\left(1+\bar{x}\right)<0$$

where:

$$\begin{aligned}
Z\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)&=\left\{\beta_x+\beta_Y\left[\alpha-\left(1-\theta\right)\left(\frac{1}{\bar{\sigma}}-1\right)h\left(\bar{\sigma},\tau_H\left(\bar{x}\right)\right)\right]\right\}\bar{x}+\beta_\sigma\left(1+\frac{1-\theta}{\theta\bar{\sigma}}\right)h\left(\bar{\sigma},\tau_H\left(\bar{x}\right)\right)\\
&=\beta_1\bar{x}\\
T\left(\bar{x},\bar{\sigma},\bar{\Phi}\right)&=\rho_{SC}+\rho_P\left[e_{\tau_{CO_2}}\bar{\Phi}+\alpha-\left(1-\theta\right)\left(\frac{1}{\bar{\sigma}}-1\right)h\left(\bar{\sigma},\tau_H\left(\bar{x}\right)\right)\right]\\
&=\rho_{SC}+\rho_P\alpha+\rho_P e_{\tau_{CO_2}}\bar{\Phi}\\
&=\rho_0+\rho_1\bar{\Phi}
\end{aligned}$$

and

$$
\begin{aligned}
\beta_1 &= \beta_x + \beta_Y \alpha \\
\rho_0 &= \rho_{SC} + \rho_P \alpha \\
\rho_1 &= \rho_P e_{\tau_{CO_2}}
\end{aligned}
$$

Summarising, the conditions for local stability of the equilibrium points are the following:

1.
$$\left[1 - \tanh^2\left(\rho_0 + \rho_1 \bar{\Phi}\right)\right] \rho_P e_{\tau_{CO_2}} < 1$$

2.
$$
\begin{aligned}
\left[1 - \tanh^2\left(\beta_1 \bar{x}\right)\right] \left\{\beta_1 + \left[\beta_\sigma \left(1 + \frac{1-\theta}{\theta\bar{\sigma}}\right) - \beta_Y \left(1-\theta\right) \left(\frac{1}{\bar{\sigma}} - 1\right) \bar{x}\right] \left(\frac{h_0 - h_{\tau_H}}{1+\bar{x}}\right)\right\} \\
< 1 + \left(\bar{\sigma} + \frac{1-\theta}{\theta}\right) h_\sigma \left(1+\bar{x}\right)
\end{aligned}
$$

3.
$$\left\{\beta_1 \left[1 - \tanh^2\left(\beta_1 \bar{x}\right)\right] - 1\right\} \left(\bar{\sigma} + \frac{1-\theta}{\theta}\right) h_\sigma \left(1+\bar{x}\right) < 0$$