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Green Road is Open: Economic Pathway with a Carbon Price Escalator

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Abstract

The paper develops the concept of "Economic Pathways" (EPs), which characterize theory-based scenarios for an economy that strives to achieve decarbonization by mid-century. The theoretical framework derives closed-from analytical solutions for consumption, innovation, emissions, and population. The EPs differ in the stringency of assumed policies and associated income and emission development. Unlike the well-known "Shared Socioeconomic Pathways", they allow important causalities between the economy and the environment to be included and significantly narrow the scope of likely future developments. The quantitative part serves to illustrate the long-term consequences of climate policy. I show that deep decarbonization only moderately delays economic development, but requires increasing escalation of the carbon price. Subsidies to the research sector support income development significantly. The paper argues that the adoption of more stringent climate policies becomes more likely as the phase-out of fossil fuels increases. The "Green Road" is not only feasible, but also attractive and realistic.

Keywords: Climate policies, consumption growth, population growth, endogenous innovation, economic pathways.

JEL Classification: *Q43, O47, Q56, O41*

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1 Future Pathways

If we are to succeed in decarbonizing the global economy by mid-century, we must bring our best capabilities to bear as a global community. The abilities to substitute, renew, learn, and sustain are in the foreground. Accordingly, knowledge about the effects and limits of substitutability, renewability, learnability, and sustainability lie at the heart of the economic contribution to solving the climate problem. However, society also faces serious inabilities in political decision-making, such as the inability to coordinate policies, design equitable policies, and identify economic opportunities. Depending on the assumptions about the interaction of abilities and inabilities in the economy and in politics, different predictions for the future emerge. The uncertainty of future development is often captured by using different possible scenarios, combining underlying trends and causalities. Scenarios show the policymakers the consequence of their actions and inactions today and are thus a central basis for current decision making. Therefore, the quality of the research used to determine scenarios and predicted pathways is of paramount importance.

To determine possible future trends, a consortium of climate scientists (Kriegler et al. 2012, O'Neill et al. 2014, Dellink et al. 2017, KC and Lutz 2017) has developed the so-called "Shared Socioeconomic Pathways" (SSPs). The SSPs are long-term global narratives describing the possible future evolution of key aspects of society. The identification of the determinants and their combination to specific storylines are based on expert opinion. Qualitative descriptions of future changes concern the areas demographics and human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources. Results arise in the form of "plausible" future conditions at the level of large world regions. The path to sustainability, labelled the "Green Road", is just one of several equally likely options for the future.

It is to the credit of the SSPs to cover a wide range of important topics of climate policy and future development in an interdisciplinary framework. The approach has also become popular because it provides memorable figures for concentration and emission pathways as well as population and income development. But there are various issues with the use of the SSPs in academia and in practice.[2] First, the pathways fully integrate the economy but disregard the economic discipline; all economic key performance indicators are treated

[2] The authors of the SSPs have stated that their approach does not aim directly at decision makers but at climate change analysts preparing climate policy analysis; however, also with this target group the following comments apply. Moreover, the SSPs have become so popular that decision makers are considering them seriously.

as exogenous variables. It appears especially problematic that economic development, demographics, innovations, and resource use are predicted without the use of state-of-the-art economic theory. Second, the links between economic development and emissions are not adequately addressed, which would be key to understand the effects of climate policy. Economic growth is predicted to be much higher with large emissions compared to decarbonization, suggesting that the potential for decoupling of production from resource use is very limited or even nonexistent. The SSPs do not establish any causalities between the economy and the emissions, while a consistent climate policy analysis should focus on how emission reduction affects the economy and the society.[3] Third, plausibility tests are lacking. Extreme results of the SSPs cover cases where emissions rise at significant constant rate until the end of the century or where economic growth of the world economy is almost zero for the next eighty years. Even as extreme cases such development is highly implausible, as resource scarcity and technical innovations must play a role at some point. Finally, there is no guidance for improving the policy design, the potential success of implementing green policies is not related to economic development. The intended diversity of issues and societal development opportunities within SSPs makes it difficult for decision makers to assess the impacts of climate policy.

With this paper I aim to show how economics makes an important contribution to providing useful future scenarios, which I label "Economic Pathways" (EPs). EPs rely on a consistent theoretical fundament, produce results in a limited range, incorporate all links and causalities between the economy and the ecology, and show the effects of different policies. I develop a dynamic model which contains all the necessary elements, yet is simple enough to provide sufficient guidance and intuition. Economic development, investments, natural resource use, innovations, and population size are endogenous variables, calculated with closed-form solutions. The EPs are presented as a function of adopted carbon policies, which are not necessarily optimal. I rather posit that policy makers should be informed about the different EPs to then choose a policy that is considered politically feasible. As a policy instrument I introduce carbon pricing but allow for a broader interpretation where carbon taxes represent the stringency of carbon policy. I discuss the plausibility and the effects of an increasing tax rate over time (the carbon price escalator) and the shape of the tax profile. Compared to the SSPs, the EPs reduce complexity of economic develop-

[3]Following earlier decomposition literature, IPCC WG III finds: "Globally, Gross Domestic Product (GDP) per capita and population growth remained the strongest drivers of CO2 emissions from fossil fuel combustion in the last decade (high confidence)", whereas in an economic approach causalities are different i.e. income is an endogenous variable and policy is a main driver of emissions, see also Bretschger (2021).

ment on a larger scale. As a consequence, EPs narrow down the range of possible future developments substantially, which should help to frame realistic expectations. The "Green Road" in terms of the EPs is characterized by full decarbonization and a minor delay in consumption development compared to a laissez-faire growth path.

The paper is related to various strands of climate economics that started with the RICE/DICE model of William Nordhaus (Nordhaus and Boyer 2000). This pioneering work triggered further theoretical work (Golosov et al. 2014) as well as a rich literature using Integrated Assessment Models for analyzing economies that are subject to climate change, see e.g. Bosetti et al. (2007). These models usually feature a detailed economic structure in terms of sectors and regions but have to rely on numerical methods to derive the solutions. The present paper includes the central model elements but focuses on the aggregate world level and on providing closed-form analytical solutions. It relates to the recent theoretical contributions of the ACE model (Traeger 2021) and the BCE model (Bretschger and Karydas 2019), which builds on the rich tradition of capital-resource models (Dasgupta and Heal 1974, Groth and Schou 2002, Groth 2007, Bretschger and Smulders 2012) and on models of endogenous sustainable growth (Barbier 1999, Smulders 2000, López et al. 2007). The link between development and endogenous population size is analyzed in Kremer (1993), Prskawetz et al. (1994), Dasgupta (1995), Schou (2002), Connolly and Peretto (2003), and Lanz et al. (2017). Endogenous innovation-driven growth was developed in the seminal contributions of Romer (1990) and Grossman and Helpman (1991); it is combined with endogenous population size and natural input use in Peretto and Valente (2015), Peretto (2020), and Bretschger (2013, 2020).

The present paper draws on the elements from the climate and macroeconomic literature to determine endogenous innovation, consumption growth, population growth, and emissions trends in a simple yet consistent manner. I take the decarbonization target of international climate policy as given and consider different decarbonization policy designs in the form of carbon price profiles.[4] Each carbon price profile defines a separate EP. I use a benchmarking approach to measure the relative performance of the different EPs using the metrics of consumption and emissions development. Assuming that this analysis is sufficiently general and robust, it provides an appropriate menu for policy makers to take a decision. This policy analysis is obviously broader than the single social planner solution of standard economics, which is often difficult to communicate in the political process, but

[4] For a detailed treatment of the climate system and its impacts on the economy, see e.g. Brock and Xepapadeas (2017).

more consistent than the SSPs which include a wide variety of options and do not derive instructions for action in the different scenarios.

I find that stricter policies are delaying economic development, but none of the EPs show negative consumption growth rates. In terms of annual per capita consumption growth I calculate for most EPs that the drag of climate policy is between 0.15 and 0.5 percentage points. The slowdown of development can be largely avoided when giving subsidies to the research sector. Population growth turns out to be neutral with respect to development of income and resource use. Emissions can be reduced when implementing a carbon price escalator but only an increasing rate of the escalator is forceful enough to bring about full decarbonization by mid-century.[5] Assuming that stricter climate policies are increasingly accepted by voters as the importance of fossil fuels declines, the "Green Road" is not only attractive, but also feasible and realistic.

The remainder of the paper is organized as follows. Section 2 develops the theoretical model. Section 3 provides the quantitative analysis describing the EPs up to 2050. Section 4 concludes.

2 Model

2.1 Production

At each time t, there is a mass of N_t atomistic firms producing heterogeneous x-goods in quantity x_i, $i \in [0, N_t]$, using labor L, capital K, and resources R as inputs, according to

$$x_{it} = L_{xit}^{\alpha} K_{it}^{\beta} R_{it}^{1-\alpha-\beta} \tag{1}$$

where $0 < \alpha, \beta < 1$. The production function in the Cobb-Douglas form allows for substitution between resources and the other inputs; however, substitution is strictly limited as resources are an essential input in production.[6] Eq. (1) has been widely used in capital-resource economics; it is fairly general and robust. Capital is not polluting; it includes clean renewable energy capital such as dams, windmills, and solar panels. Resource use represents the use of fossil fuels, it augments the stock of global greenhouse gases. Climate

[5] Price escalators for emissions have already been used in the UK, Sweden, and Switzerland.

[6] To assume an elasticity of input substitution below unity is not necessarily harming the decarbonization of a multisector economy (see Bretschger and Smulders 2012): In Bretschger (2020) it even supports sustainability during the transition while the Cobb-Douglas function emerges as a steady state solution to which the system converges. Poor input substitution would cause the resource share per GDP to increase with rising resource prices which has not been observed in reality. For these reasons the assumption of a Cobb-Douglas function is not only a convenient but also a theoretically and empirically relevant choice.

damages arise in the form of (additional) capital losses i.e. higher capital depreciation.[7] The x-firms maximize profits which are given by $p_{it}x_{it} - w_t L_{xit} - p_{Kt}K_{it} - p_{Rt}R_{it}$ where p with a subscript denote prices and w the wage rate. First-order conditions for profit maximization of x - firms read

$$w_t = \alpha p_{it} \frac{x_{it}}{L_{it}} \tag{2}$$

$$p_{Kt} = r_t + \nu + \delta = \beta p_{it} \frac{x_{it}}{K_{it}} \tag{3}$$

$$p_{Rt} = (1 - \alpha - \beta) p_{it} \frac{x_{it}}{R_{it}} \tag{4}$$

where r is the interest rate, ν the climate induced depreciation rate, and δ the standard depreciation rate of capital.[8] To determine the effects of decarbonization, long-run dynamics of the economy are key, which may consist of several elements. A first element is the increasing use of the different inputs, which entails higher output of x - goods. Most prominently, capital stock K is raised by investments; but Eq. (1) assumes decreasing returns to capital so that this growth mechanism - by itself - dries up in the long run. Further growth of resource use R is not desirable, given the effects of pollution and scarcity. The impact of the increase in labor L on wealth per capita is mostly viewed negatively in the literature. Hence, for the economic dynamics I additionally introduce a powerful and central growth mechanism that is used in endogenous growth theory (Romer 1990, Grossman and Helpman 1991). It is based on increasing gains from diversification in production that are driven by innovations and knowledge accumulation. To implement this in the model, I assume that x-goods are used to assemble final output Y, according to the well-known Spence-Dixit-Stiglitz approach,[9] reading

$$Y_t = a \left[\int_0^{N_t} x_{it}^{\eta} di \right]^{\frac{1}{\eta}} \tag{5}$$

with $a > 0$ and $0 < \eta < 1$ so that output grows not only with increasing input quantities x but also with rising product variety N. The x-goods are imperfect substitutes for each other and produced under the market form of monopolistic competition. Final good producers maximize profits which are given by $p_Y Y_t - \int_0^{N_t} p_{it}x_{it}di$ so that the optimal price of x_i is obtained by a markup over marginal costs $\tilde{c}_{it}$, i.e. $p_{it} = \frac{\tilde{c}_{it}}{\eta}$. For better tractability I use a symmetrical equilibrium where x-goods have equal production costs $\tilde{c}_{it} = \tilde{c}_t$ so that $p_{it} =$

[7] A decrease of capital input reduces output level in the same way as a negative productivity shock used in other climate models; for more details see Bretschger and Karydas (2019) and Bretschger (2020).

[8] A constant ν can be either a long-run value for the steady state or result from a suitable combination of damage and impact functions and apply throughout, see Bretschger (2020) for the details.

[9] Dixit and Stiglitz (1977)

p_t, $x_{it} = x_t$, and $Y_t = aN_t^{\frac{1-\eta}{\eta}} X_t$ where $X_t \equiv N_t x_t$. Doing so I have $p_t X_t = p_{Yt} Y_t$ and $\tilde{c}_t X_t = \eta p_Y Y_t$ while $(1-\eta) p_Y Y_t$ are the aggregate profits in the X-sector in time t.

2.2 Knowledge

Following the theory of innovation-driven endogenous growth (Romer 1990, Grossman and Helpman 1991), I assume that economic growth is driven by the expansion in the number of goods varieties. Each intermediate firm needs knowledge input in order to produce a specific heterogeneous good. In the literature, knowledge is usually introduced in the form of patents or blueprints that are required to start a business. In this paper, I assume that the knowledge needs of the firm are permanent, which holds for almost all activities but is especially true for many computer and communication-related knowledge services that are central in a modern economy. Accordingly, the knowledge sector receives compensation to cover its costs not only when a new product variety is introduced, but also at any time t thereafter. Like in standard endogenous growth theory, there are positive knowledge spillovers from private knowledge creation to the stock of public knowledge, which is a free input in subsequent knowledge creation.

Knowledge is produced in a separate sector, which uses skilled labour H as an input. Labour L can be transformed into skilled labour by continuous on the-job-training which requires part of total worktime. When labor devoted to research is L_N, skilled labour becomes $H = \kappa \cdot L_N$ with $0 \leq \kappa < 1$. Knowledge production and creation receive spillovers from existing knowledge stock, which is - by appropriate normalization - equal to the number of existing product varieties N. The intensity of the knowledge spillover is measured by the parameter ψ, $0 < \psi \leq 1$, reflecting the speed of knowledge diffusion and adoption. I normalize knowledge diffusion by population size which says that average spillovers N_t/L_t and not total spillovers add to the productivity of the knowledge sector. This is done to avoid the so-called "scale effect" of growth (Jones 1995); it is a cautious assumption in order not to be overly optimistic for the potential of the world research sector with a growing population. With $m > 0$ denoting the productivity of inputs in the sector, the increase in knowledge i.e. the number of varieties is given by

$$\dot{N}_t = m\kappa L_{Nt} \psi \left(N_t / L_t \right) \tag{6}$$

so that

$$\frac{\dot{N}_t}{N_t} \equiv g_t = m\kappa\psi \frac{L_{Nt}}{L_t} \tag{7}$$

where g_t is called the innovation rate. A higher employment share in the research sector L_N/L_t raises the innovation rate, a hypothesis that has been confirmed by empirical research (Bretschger 2015). I assume that knowledge production is not adversely affected by climate change, because information can be stored and secured worldwide and mortality of researchers is usually unaffected by climate change.[10] The government may support knowledge growth through subsidies, thereby increasing ψ.

Profits in the aggregate X-sector are used for the firms' payments of knowledge input, i.e.

$$(1-\eta)p_{Yt}Y_t = p_{Nt}N_t \tag{8}$$

where p_N is the market price of knowledge service per firm.[11] Research firms pay research labor a wage rate equal to the marginal productivity of research labor; it is obtained by taking the derivative of Eq. (6) with respect to labor and using Eq. (8) to write

$$w_{Nt} = m\kappa\psi(1-\eta)\frac{p_{Yt}Y_t}{L_t}.$$

Labor freely enters the knowledge sector as long as $w_{Nt} > w_t$ where w_t is determined in Eq. (2), while in equilibrium the two wage rates are equalized, $w_{Nt} = w_t$. Labor markets clear i.e. we have at any time

$$L_t = L_{Xt} + L_{Nt} \tag{9}$$

where L_t is total labor supply (equal to population size) and L_{Xt} denotes employment in the production sector. Only one x-firm produces a variety at the time, as a second company would face the same production cost but would have to pay again for the knowledge services. Two companies would never be able to fully recover their knowledge costs in Bertrand competition and would therefore suffer losses, leaving only one company per x-good to survive.

2.3 Households

Households derive utility from per-capita consumption c of final goods and of the mass of family birth flow b; they maximize intertemporal utility U

$$U_t = \int_0^\infty e^{-\rho t}\left[\log c_t + \phi \max(\log b_t, 0)\right] dt \tag{10}$$

[10] Also, exhaustible resources are not included as an essential input in research but the results remain valid when assuming so, see Bretschger (2020).

[11] If knowledge came in the form of a (eternal) patent, p_N would be determined by the present value of all future profits per firm i.e. we would have to apply a discount factor to determine p_N (see Romer 1990) which would not change the quality of our results.

where ρ is equal to the pure time preference rate plus the probability of death and $\phi > 0$ is the elasticity of instantaneous utility with respect to the (net) birth flow. Each agent owns a share of the capital stock $v_t = p_{Kt}K_t/L_t$; she offers one unit of labor to the labor market at wage rate w_t and consumes final goods in the amount $p_{Ct}c_t$ where $c_t \equiv C_t/L_t$. In addition, she pays for child-rearing and education for each additional family member (b_t) a cost p_{bt}. The dynamic budget constraint for each family member then is

$$\dot{v}_t = (r_t - \hat{L}_t)v_t + w_t - p_{Ct}c_t - p_{bt}b_t \tag{11}$$

where hats denote growth rates. The individual problem consists of maximizing Eq. (10) subject to Eq. (11) with c and b as control variables, and v as state variable.

Population development depends on mortality and fertility, where the latter is a function of preferences for birth flow ϕ, see Eq. (10), and of the costs of child rearing p_b. I assume that these costs are proportional to consumption expenditures (with a factor ζ) and a nonlinear function of population size. Specifically, I posit that for a low population size, additional birth flow is attractive because of scale effects in child-rearing and education. For a high population size, congestion effects become increasingly important so that birth flow becomes less attractive and eventually becomes zero. Formally, the costs of child rearing p_b are given by

$$p_{bt} = \frac{\zeta p_{Ct}C_t}{kL_t(1 - \frac{L_t}{L_\infty})} \tag{12}$$

where $k > 0$ is the growth parameter in the logistic function and L_∞ steady-state population size. As long as $L_t < L_\infty$, we have $b_t = \dot{L}_t > 0$; for $L_t = L_\infty$ it is $b_t = 0$.

From intertemporal optimization, see the Appendix, I obtain first order conditions for the decentralized economy which can be solved to obtain an expression for consumption growth according to the familiar Keynes-Ramsey rule

$$\hat{p}_{Ct} + \hat{C}_t = r_t - \rho. \tag{13}$$

Cumulative capital is foregone final output minus (regular and climate induced) depreciation. Given our setup with a log-utility function, we have $\hat{K}_t = \hat{Y}_t = \hat{C}_t \equiv \hat{c}_t + \hat{L}_t$. The economy develops thus along a path where total output, consumption, and capital stock grow at the same rate that is not necessarily constant. Below I will calculate different paths where $\hat{c}_t$ is constant, while $\hat{L}_t$ will only be constant in the long run, so that $\hat{K}_t$, $\hat{Y}_t$, and $\hat{C}_t$ will then also be constant in the long run. As the carbon price used below needs a firm benchmark, I adopt the convention to use the final good as the numeraire so that

$p_Y = p_C \equiv 1$. Then from Eq. (13) we have $\hat{C}_t = r_t - \rho$ and from Eq. (4) it follows that

$$\hat{R}_t = \hat{C}_t - \hat{p}_{Rt}. \tag{14}$$

2.4 Carbon Pricing

Extraction and production costs of the resource are a first determinant of their market price, but there are two additional cost components. First, from a societal perspective, negative externalities have to be considered. According to environmental economics, a carbon tax should cover the external costs of polluting resource use (Pigou 1920). Second, following resource economics, fossil fuels are nonrenewable resources that generate a growing scarcity rent affecting prices (Hotelling 1931). Following these basic results, the resource user price for firms depends on per-unit production cost, the scarcity rent, and a carbon tax. However, the reality of resource pricing does not follow the simple textbook, it is more complex. Carbon taxes are often designed with a view towards political acceptability rather than to be on an optimal level. As an example, there has been a tendency to lower fuel taxation recently because of higher market prices caused by political conflicts. Extraction and production of fossil fuels are subject to frequent shocks in international relations, causing huge cost fluctuations and price distortions. The Hotelling rule requires optimization over a very long time horizon, which can be questioned under realistic political conditions. Thus, in reality, resource user prices are determined by a complex mix of different impacts.

To show the characteristics of different economic paths (EPs) as clearly as possible, I adopt a benchmarking approach in which I specify particular EPs through particular policies, i.e., resource price profiles. For each EP, I then calculate the development of the economy, the population, and the environment. In the model, one may assume formally that the government owns the resource and sets the final resource user price for firms. I label growth in the end-user price of the resource the "escalator" and denote it by e_t

$$e_t \equiv \hat{p}_{Rt}. \tag{15}$$

Referring to Eq. (14), growth of resource use $\hat{R}$ is affected by resource price growth $\hat{p}_R$ and consumption growth $\hat{C}$; growth of carbon emissions are obtained by multiplying $\hat{R}$ with a constant factor. With positive economic growth, $\hat{C}_t > 0$, resource demand and emissions grow *ceteris paribus* but this can be countered when resource prices increase with the growth rate of consumption, $\hat{C}_t = \hat{p}_{Rt}$. For emissions to actually degrow, $\hat{R}_t < 0$, one needs to implement an escalator e_t exceeding the consumption growth rate $\hat{C}$. Following Eq. (14) the escalator e_t can be decomposed into $e_t = \bar{e} + \tilde{e}_t$ where $\bar{e}$ is equal to the consumption growth rate, $\hat{C}$, and $\tilde{e}_t > 0$ entails decarbonization.[12]

With public resource ownership, the government can decide not only on the carbon tax but also rule to ignore the scarcity rent and/or to deviate from the request to cover all production cost. Hence, e_t can in principle be constant, increasing or decreasing; it could take any value and even be zero or negative. How then does then the government choose e_t? A first possibility is to assume it acts like a social planner and implements an optimal price profile or an optimum carbon budget, including the correct scarcity rent. However, the ideal behavior is not the realistic behavior, it will not materialize.[13]

An assumption that is realistic in my view is that the government wants to meet climate targets - in principle - but at the same time is reluctant to adopt stringent climate policies when resource use is still widespread in the economy, i.e., popular with voters. When resource use is shrinking, i.e. when certain activities like private mobility increasingly abandon resource input, resources are less visible and less important, thereby reducing political resistance against climate policy. In such a development the government can then try to turn the tax rate screw steadily a little further.[14] In terms of the present model it means that the escalator is sufficiently high, $\tilde{e}_t > 0$, to ensure decreasing resource use over time. Carbon pricing then has a reinforcing effect on future pricing. To develop the hypothesis even further, I explore the possibility of a positive relationship between the greening of the economy and the size of the escalator, so that e_t is growing over time, $\dot{e}_t > 0$. Superexponential price development reflects a rapidly growing political willingness to accept stricter policies, i.e., higher carbon prices.

The general mechanism of a carbon price that depends on political majorities has already been used in the stochastic literature (Bretschger and Soretz 2021). However, it does not provide sufficient information to calculate the level or time profile of e_t that will ensure full decarbonization by mid-century at a cost that appears "acceptable" to society. The government and the public first need to know the impacts and especially the cost in terms of consumption reduction of the different escalators. This is exactly where the analysis using the EPs becomes very useful; it can inform policy makers about the consequences

[12] The size of $\bar{e}$ is also (negatively) affected by resource saving technical progress, which was significant in recent years.

[13] Optimal carbon prices recommended by economists vary widely and must be viewed with particular caution when derived from static models or models with exogenous growth.

[14] This tax rate development has been observed for tobacco taxes in many countries.

of their actions. I will thus explore different EPs below and show their characteristics in terms of the economy and the ecology.[15]

2.5 Solution

The model is now solved for our main variables of interest: growth of per-capita consumption, population, and emissions. We state the following

Proposition 1 *In a dynamic model with resources and innovation, growth of per capita consumption, population size, and emissions are determined as follows*

$$\hat{c}_t = \frac{(1-\eta)\, m\kappa\psi - \alpha\eta}{\alpha\eta} - \frac{1-\alpha-\beta}{\alpha} e_t \tag{16}$$

$$\hat{L}_t = \frac{\phi k}{\zeta}\left(1 - \frac{L_t}{L_\infty}\right) \tag{17}$$

$$\hat{R}_t = \hat{C}_t - e_t. \tag{18}$$

Proof: See Appendix ■

The proposition shows intuitive and simple expressions for the main variables of interest with decarbonization. It reveals that productivity of the research sector (m) and of education (κ) are important parameters for long-run consumption growth, because they have a direct positive effect on research. Moreover, the intensity of knowledge spillovers (ψ) and the gains from diversification ($(1-\eta)/\eta$) have a positive impact on the growth rate. The drag of rising resource prices is weighted by the factor $(1-\alpha-\beta)/\alpha$. Note that climate induced depreciation ν of Eq. (3) does not appear in the solution of the model as households are compensated by the firms with a rate that includes the depreciation of capital. Thus, ν does not show up in the Euler-equation. The proposition also shows the important effect of the carbon price escalator on resource use and thus emissions. Finally, it turns out that population development follows a logistic function which is driven by the population parameters of the model, independent of resource extraction path and climate policy. Population size does not affect growth of per capita consumption but is an endogenous variable and not an exogenous parameter like in the $IPAT$ and $Kaya$ approaches. The model predicts that population size is a sigmoid function of time which reaches a steady-state towards the end of the century; a view that is widely held in the population

[15] Carbon pricing in the model reflects the general stringency of climate policy in reality, which may include other instruments such as bans of certain technologies or fuels, which are equivalent to a tax rate of infinity.

science literature. Recall that in Eq. (18) $\hat{C}_t$ is determined by the sum of $\hat{c}_t$ and $\hat{L}_t$ which are given in Eqs. (16) and (17), so that (18) also presents a closed-form solution.

Three short remarks on the robustness of our results are warranted at this point. First, the effect of policy e_t on consumption growth in Eq. (16) is determined by the factor $(1-\alpha-\beta)/\alpha$ which is much closer to zero than to unity, because from Eq. (1) we have the output elasticity of resources, $1-\alpha-\beta$, reflecting the share of resource cost as a percentage of total cost in production (of the intermediates). While nobody would claim that, in any firm, doubling the oil input would double the output, some are still skeptical when the reduction of oil input is found to have minor consequences on production. But it is actually correct due to the empirically founded, highly nonlinear relationship between resource input and output.[16] The use of an appropriate production function limits the effect of climate policy on consumption growth. Second, consumption growth heavily depends on endogenous knowledge accumulation where the model is cautious by abstracting from a positive impact of population growth on innovation (see Kremer 1993, Bretschger 2020) and by not assuming proportional spillovers but only average spillovers. Third, population growth does not interfere with the climate problem in the present model because the different effects of labor cancel.[17] That the link is not of great importance can also be motivated by the fact that the few countries with still high population growth have very low carbon emissions (Blanco et al., 2014), but such heterogeneities are not included in the model.

3 Quantitative Analysis

For the time period 2022 − 2050 I calculate the economic and ecological effects of five different climate policies captured in five different EPs; I compare these EPs with a business as usual (BAU) path where $\tilde{e}=0$ (and thus $\hat{R}=0$). I label the EP with a moderate carbon price escalator ($\tilde{e}=0.03$) the "base case" and increase $\tilde{e}$ with a constant as well as a time-dependent term in the more ambitious climate policy scenarios giving rise to the other EPs. I set the knowledge diffusion coefficient ψ to 0.5, except for the last EP where I slightly increase it to 0.505 due to a subsidy to knowledge diffusion. The policies forming the different EPs are characterized in Table 1.

[16] The relationship can be derived or at least approximated by using the average energy share of firms in larger economies, which is 0.035 (International Energy Agency 2021), as an output elasticity for resources in a standard production function.

[17] To confirm, see the derivation of Eq. (A.8) and the derivation of the innovation rate below Eq. (A.8) in the Appendix.

$\tilde{e}_t$	ψ	EP label
0.03	0.5	1: Base case
0.04	0.5	2: Accelerated case
0.05	0.5	3: Ambitious case
$0.03 + t/100$	0.5	4: Super accelerated case
$0.03 + t/100$	0.505	5: Super smart accelerated case
0	0.5	6: BAU

$(t = year - 2022)$

Table 1: Policies and EPs

For the calibration of the parameter values, see Table 2, I use average labor and energy shares of larger economies (OECD 2022) so that $\alpha = 0.7$ and $1-\alpha-\beta = 0.035$; note that the latter only includes the cost for fossil fuels which are lower than total energy costs. I assume that training of researchers takes 20 percent of their work time, i.e. $\kappa = 0.8$. Productivity in the research lab m and the mark-up parameter η are calibrated to match the model with the 3% growth of the world economy which was observed in the recent (pre-COVID) years. I calibrate the preference and the cost parameter for child rearing (ϕ, ζ) jointly with growth parameter k in order to closely replicate long-run population development of the past; this leads to $\phi k/\zeta = 0.05$. Long-run steady state population is set at 11 billion which is the middle scenario of the UN projections (UN 2022).

Given these parameter values I present the expected values for the model variables but add a sensitivity analysis to show the effects of deviations from the assumed parameter values in a sensitivity analysis. I thus present parameter uncertainty in the form of likely and very likely ranges for the variables, by varying the central parameter values in a range of +/- 5 and +/- 10 percent.

η	m	κ	α	$1-\alpha-\beta$	$\phi k/\zeta$	L_∞
0.67	3.66	0.8	0.7	0.035	0.05	$11bn$

Table 2: Calibrated values

Figures 1-6 show the results for consumption per capita, population size, and carbon emissions for the different EPs in the period 2022 - 2050. I normalize the three variables of interest to the value of 100 in the year 2022.

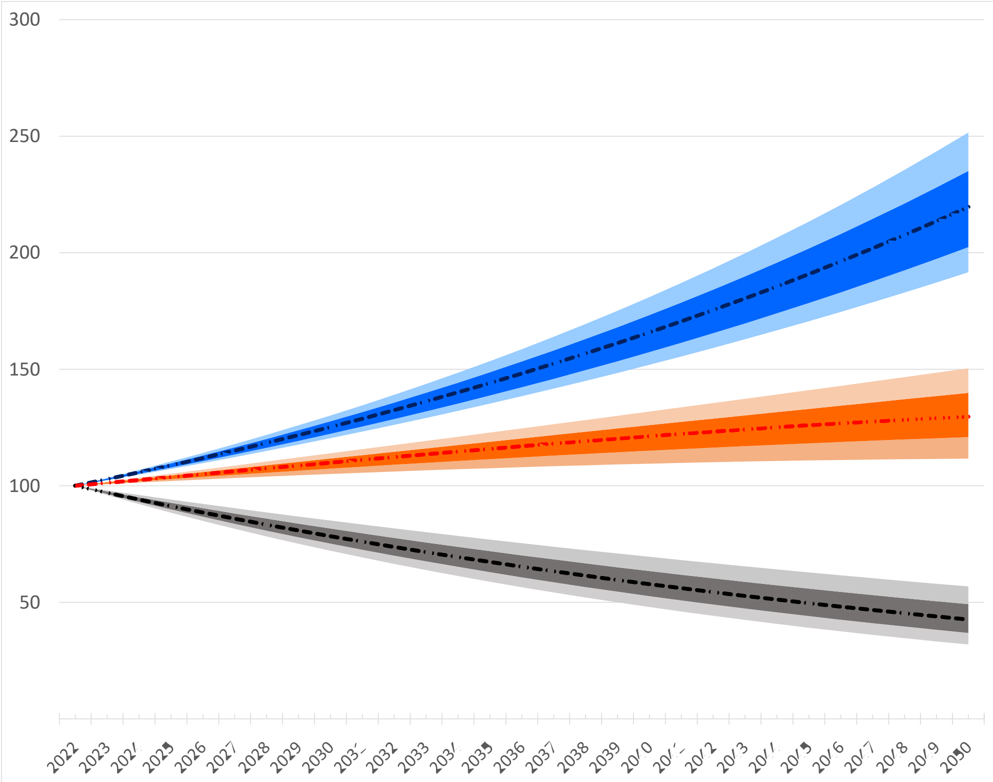

Fig. 1: Base case. Per capita consumption (blue), population (orange), emissions (grey)

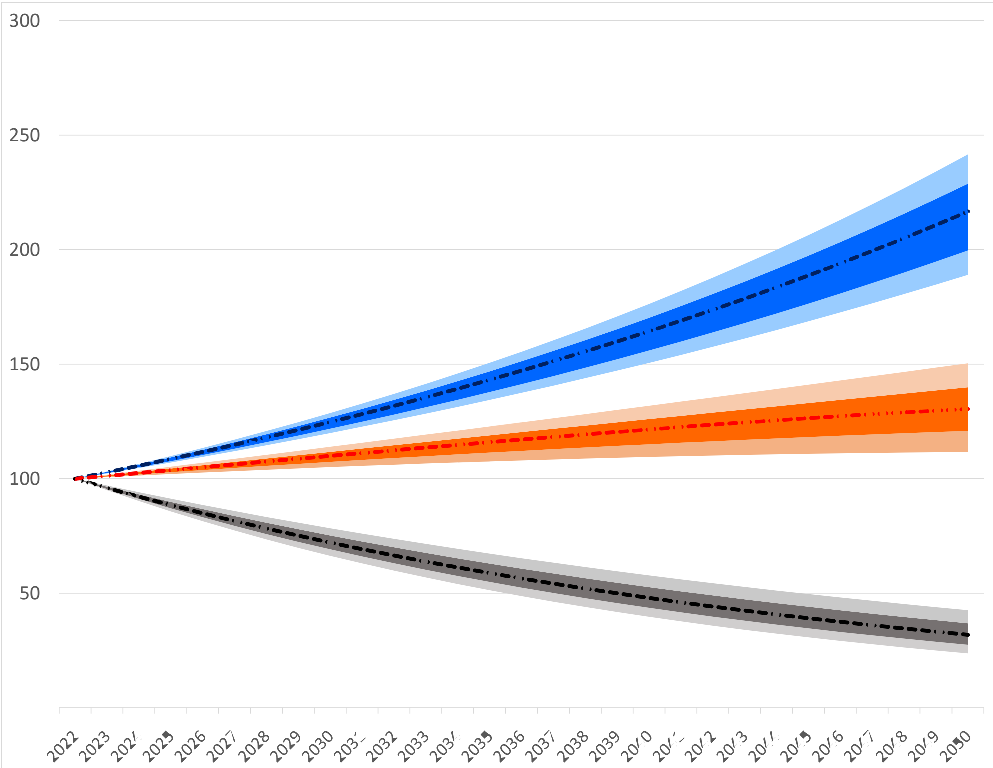

Fig. 2: Accelerated case. Per capita consumption (blue), population (orange), emissions (grey)

Figure 1-2: EPs 1 and 2

Figure 1 shows for EP1 that consumption per capita is steadily growing to a level in 2050 which is more than the double of 2022. Population converges to a steady state that is unaffected by climate policies, hence the predicted development applies for all EPs. Emissions are reduced with EP1 but only to a level of about 40 percent of 2022 which misses the target of decarbonization by a large amount. A higher escalator in EP2 and EP3 does not harm development of consumption significantly, but is not strong enough to bring about a carbon-free economy by 2050; in EP2 and EP3, 31 and 24 percent of emissions remain by mid-century. The policy analysis suggests that a more radical escalator needs to be implemented in order to succeed in climate policy, which is an escalator $\tilde{e}$ that increases over time. This is effectuated in EP4, where the escalator starts at 0.03 and then increases by 0.01 in each year. Now it can be seen that the decarbonization becomes very successful, emissions develop in a reverted S-curve toward zero. The only drawback is that consumption development is now significantly retarded. Growth is still positive throughout but its annual rate drops to almost 2 percent which is still a quite high value for the developed countries but may be seen as critically low for less developed countries. As a consequence, a combination of a rising escalator with a subsidy promoting knowledge diffusion is promising. EP5 reveals that the strict decarbonization is compatible with a high consumption growth rate when knowledge diffusion ψ is only slightly increased via a subsidy. An increase in education efficiency κ would have the same effect.

Figure 7 shows that consumption development is not very different between the different EPs except for the super accelerated EP without support of knowledge diffusion. It says that the even stringent climate policies do not have a significantly negative effect on the economy as a whole, it is more on the sectoral and equity level where the problems may arise. Moreover, it depends on the flexibility of the labor markets to establish the equilibrium assumed in this paper. Over the longer run and with a knowledge of future policies, this should be achievable. In Figure 8 it becomes clear that only a superexponential development of carbon pricing is suitable for decarbonization within the next 28 years. I come back to this central finding in the conclusions.

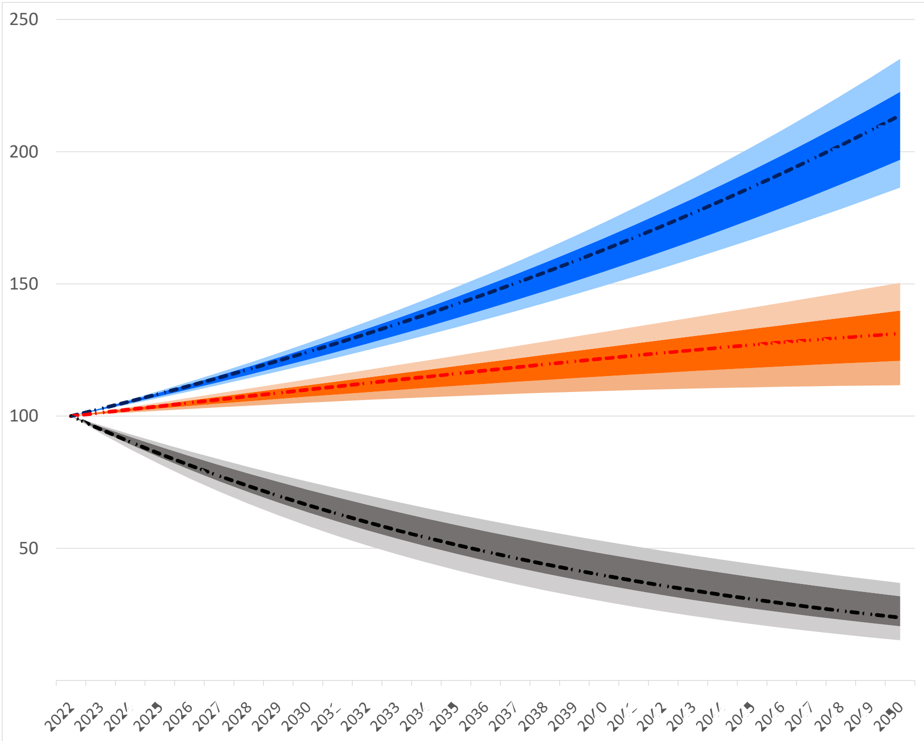

Fig. 3: Ambitious case. Per capita consumption (blue), population (orange), emissions (grey)

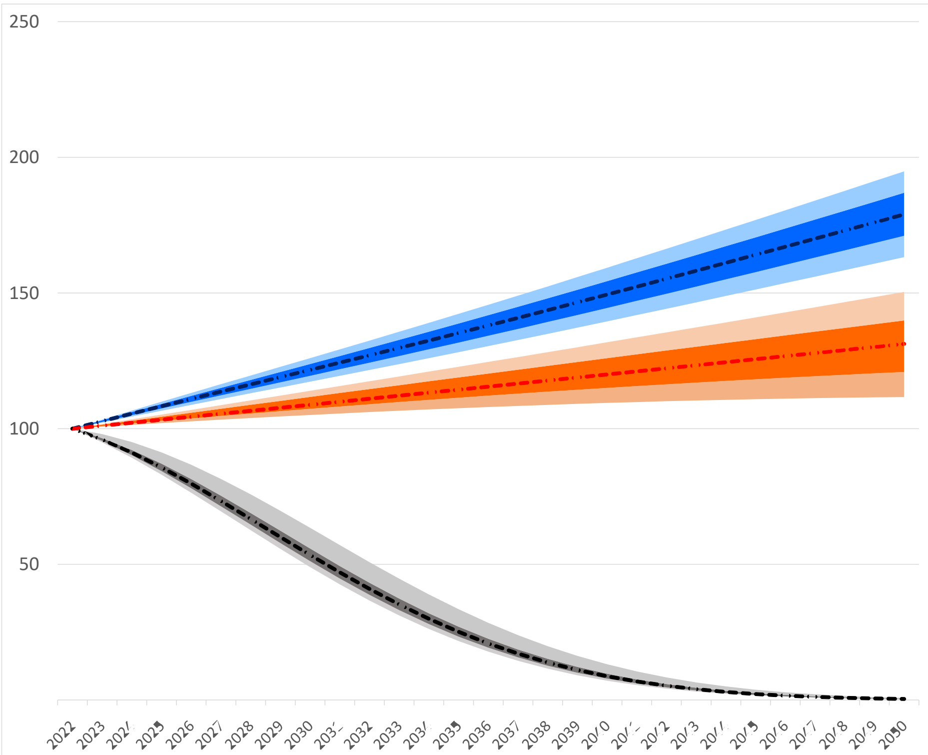

Fig. 4: Super accelerated case. Per capita consumption (blue), population (orange), emissions (grey)

Figure 3-4: EPs 3 and 4

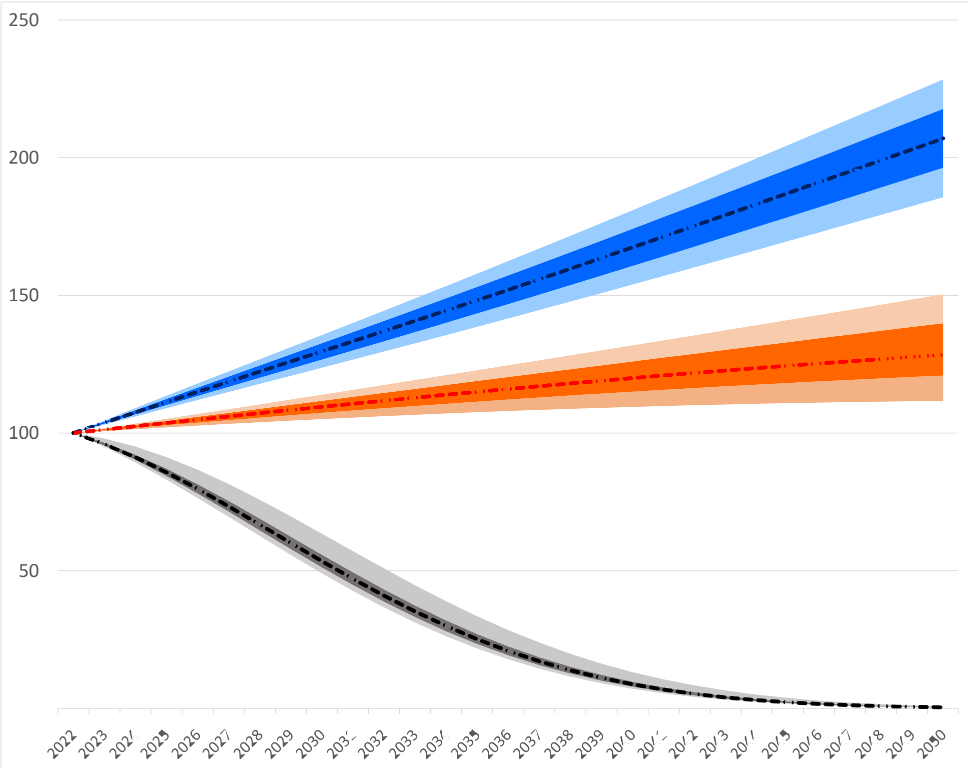

Fig. 5: Super smart accelerated case. Per capita consumption (blue), population (orange), emissions (grey)

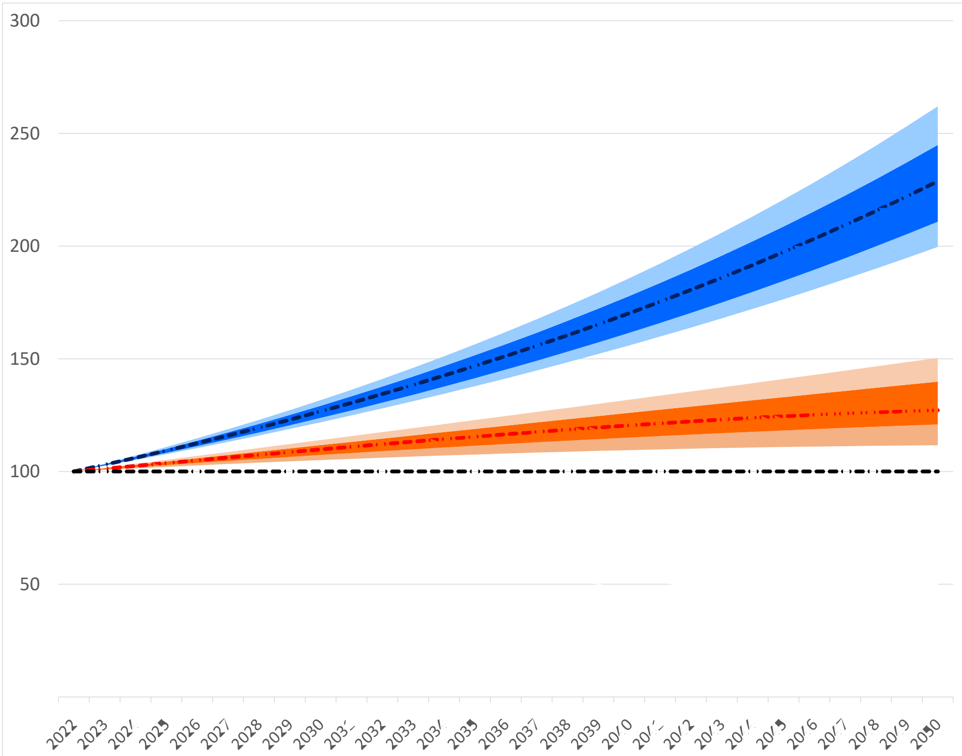

Fig. 6: BAU. Per capita consumption (blue), population (orange), emissions (grey)

Figure 5-6: EP 5, BAU

To compare the different EPs in single charts I plot the expected values for consumption and emissions development in Figures 7 and 8.

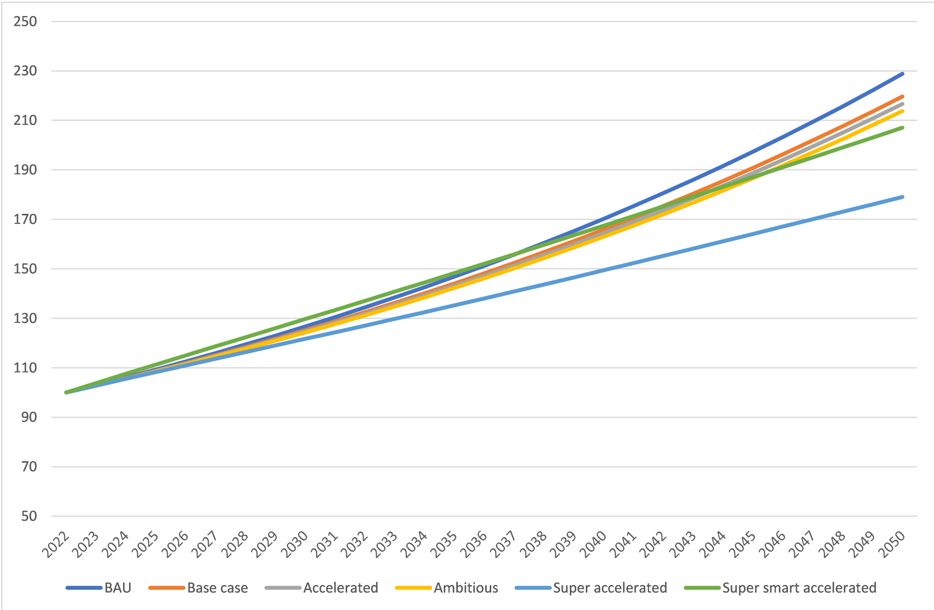

Fig. 7: EPs and consumption per capita

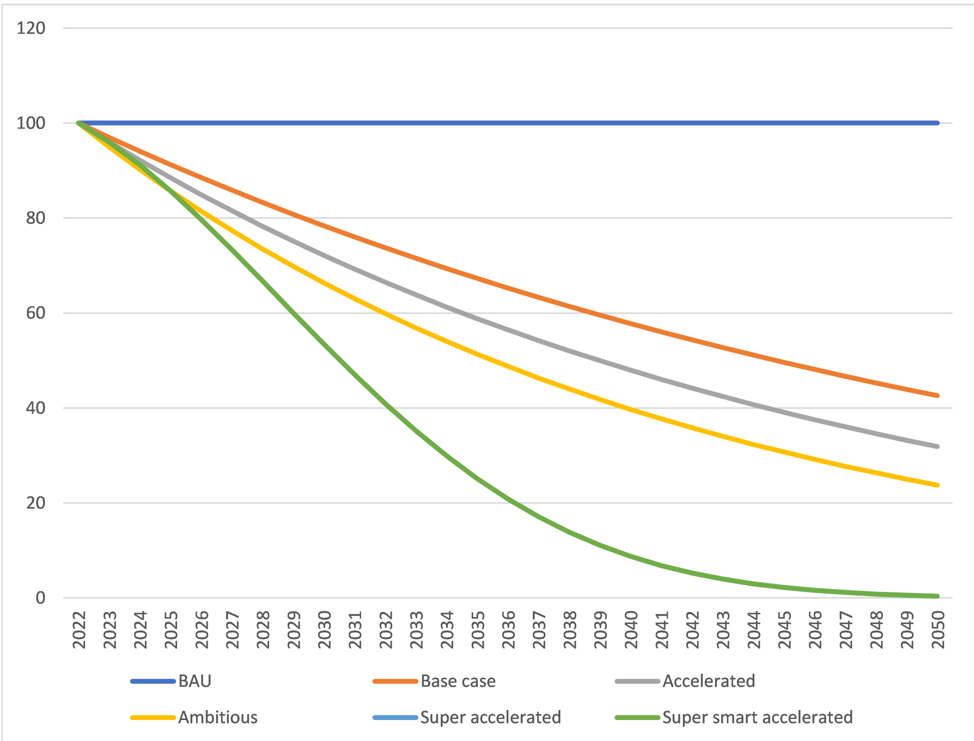

Fig. 8: EPs and emissions

Figures 7-8: Comparison of the EPS

4 Conclusions

The paper has shown that future development paths calculated on the basis of a comprehensive economic model are not only consistent but also limit the range of change in key variables. The future state of the economy and the climate depends on the adopted climate policies, which have been presented in the different EPs above. Understanding the concept of EPs should help policy makers to take adequate decisions.

Three general conclusions emerge from this exercise. First, the drag of stringent decarbonization on economic development is limited, causing a relatively minor delay in consumption levels compared to laissez faire. What is more, support of knowledge diffusion raises consumption growth significantly so that the drag can be largely avoided. Second, population will still grow on the planet but it is not a key topic in the climate change context. Third, the size and especially the time profile of the carbon price escalator are key for the success of the climate policy. One might argue that a superexponential growth of carbon price is unlikely. However, there are two argument in favor of such a policy development. First, the carbon price is the only environmental policy in this paper, while in reality the use of bans and norms are equally or even more important.[18] A ban is equivalent to an infinite carbon price, for the specific area e.g. private road transportation. With a low carbon price in some sectors of the economy and a rising number of bans in other parts of the economy the implicit carbon price might still increase quite sharply - on average. Second, the greening of the economy, presented by fading resource use with increasing resource prices in the model, raises the chances that a stringent climate policy becomes increasingly popular. Voters having switched to carbon-free technologies will not strongly oppose further increases in carbon prices. With more firms, households, sectors, and regions having switched to green the political process may well be moving faster. A cascade of tipping points in politics may induce a policy development consistent with our last scenario EP5. The most critical phase is now, at the beginning of a really stringent climate policy. The knowledge of the mechanisms provided in this paper can help to become bolder in current policy making. After going through the first and most difficult phase, the development may become self-propelling. Then the "Green Road" is definitely open and increasingly easier to drive on.

[18] Like the direct carbon pricing implemented in this paper, emission trading systems steer the economic decisions through the price of carbon.

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5 Appendix

The current-value Hamiltonian for the household problem is

$$H = \log c + \phi \log b + \mu_v \left[(r - \hat{L})v + w - p_Y c - p_b b \right], \tag{A.1}$$

where μ_v denotes the costate variable. The following first-order and transversality conditions provide the necessary conditions for an interior solution

$$1/c = p_Y \mu_v, \tag{A.2}$$

$$\phi/b = p_b \mu_v, \tag{A.3}$$

$$\dot{\mu}_v = (\rho - r + \hat{L})\mu_v, \tag{A.4}$$

$$\lim_{\tau \to \infty} \mu_v(\tau) v(\tau) e^{-\rho(\tau - t)} = 0. \tag{A.5}$$

Combining Eqs. (A.2) and (A.4) yields the Keynes Ramsey rule in Eq. (13). To derive the equations in Proposition 1 I use the FOCs and the balanced growth path assumptions as follows. First, I adopt the symmetry of intermediate goods in final goods production (Eq. 5) and take the logarithmic differentials to write

$$\hat{Y} = \left(\frac{1 - \eta}{\eta} \right) g + \hat{X} \tag{A.6}$$

where $g = \hat{N}$ and, following Eq. (1), we have

$$\hat{X} = \alpha\hat{L}_x + \beta\hat{K} + (1-\alpha-\beta)\hat{R}. \tag{A.7}$$

Inserting and using $\hat{Y} = \hat{K} = \hat{C}$, $\hat{L}_x = \hat{L}$, which arise due to the logarithmic utility function, I write for per-capita consumption growth $\hat{c}$

$$\begin{aligned}
\hat{c} &= -\hat{L} + \left(\frac{1-\eta}{\eta}\right) g + \alpha\hat{L} + \beta\left(\hat{c} + \hat{L}\right) + (1-\alpha-\beta)\hat{R} \\
(1-\beta)\,\hat{c} &= \left(\frac{1-\eta}{\eta}\right) g - (1-\alpha-\beta)\hat{L} + (1-\alpha-\beta)(\hat{c} + \hat{L} - \hat{p}_R) \\
\hat{c} &= \left(\frac{1-\eta}{\alpha\eta}\right) g - (\frac{1-\alpha-\beta}{\alpha})\hat{p}_R. \qquad \text{(A.8)}
\end{aligned}$$

To obtain the innovation rate, I take the derivative of Eq. (6) with respect to labor and use Eq. (8) to write

$$w_t = m\kappa\psi(1-\eta)\frac{Y_t}{L_t}.$$

I set the expression for the wage equal to the wage rate of Eq. (2) and solve for labor input in the X-sector

$$L_{Xt} = \frac{\alpha\eta L_t}{m\kappa\psi(1-\eta)}.$$

With labor market clearing Eq. (9) I can solve for innovation rate g building on Eq. (7)

$$g_t = m\kappa\psi\frac{L_t - L_{Xt}}{L_t}$$

which is inserted into Eq. (A.8) to yield Eq. (16) in the proposition with using Eq. (15).

To obtain the equation for population growth in the Proposition I employ Eqs. (A.3) and (A.2) to write

$$b_t = \dot{L}_t = \frac{\phi C_t}{p_{bt}}.$$

Now I use the expression for p_b in Eq. (12) to have

$$\dot{L}_t = \frac{\phi}{\zeta} k L_t (1 - \frac{L_t}{L_\infty}),$$

which directly yields Eq. (17) in the Proposition when dividing by population size L. Finally, resource use (= emission growth) in the proposition Eq. (18) follows from Eq. (14) when using Eq. (15).

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