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Climate change and economic analysis

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Abstract

Macroeconomic models have been extended to incorporate climate change, to analyze its implications, and to examine the costs and benefits of green transitions. This paper discusses some limitations of these models and the critical dependence of their implications on factors that are subject to great uncertainty. Instead of trying to derive optimal trajectories of mitigation and macroeconomic policy, economics may be useful primarily in the analysis of the pervasive collective-action problems and distributional effects associated with a green transition and in the design of economic incentives to ensure a successful implementation of the transition. The analysis, moreover, must move beyond the 'brown'-'green' dichotomy and analyze different mitigation strategies, their scalability and their systemic effects.

JEL: Q43, Q54, O44

Key words: Integrated assessment models, Keynesian climate models, welfare criteria, damage functions, transition strategies, free-rider problem, distributional conflict.

1 Introduction

Economic activities generate CO2 and other greenhouse gasses, while climate change affects social and economic conditions in multiple ways. A large and rapidly expanding literature has been trying to include these interactions in macroeconomic models.

Following Nordhaus (1977, 1992), one strand of 'integrated assessment models' (IAMs) employs a Ramsey-type growth model with continuous full employment and a representative agent, adds a module to describe the connection

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between production, the flow of emissions and climate change, a damage function to capture the negative impact of climate change, and a specification of the costs of mitigation. A socially optimal path of mitigation is then derived by maximizing the utility function of the representative agent, taking into account the links between emissions and climate change.

The supply-driven macroeconomic model is replaced in (post-) Keynesian climate models by specifications that give the leading role to aggregate demand and abandon the optimizing representative agent. Damage functions and transition costs of mitigation remain the key building blocks of the interface between the macroeconomic model and climate change, but with policies evaluated based on their effects on GDP (e.g. Rezai et al., 2018) or, in some cases, by looking at an array of different objectives (e.g. Dafermos and Nikolaidi, 2022).

The details of the macroeconomic setting clearly matter for the analysis, but the crucial elements often lie elsewhere. The most serious damage from climate change will come in the future, and the damage has to be set against the current and future costs of mitigation. Not surprisingly, therefore, the conclusions driving the models derive mainly from three elements: (i) welfare criteria, including the discount rate, (ii) assumptions about the sensitivity of climate change and its damages to emissions and (iii) assumptions about the costs of mitigation and a green transition. Unfortunately, economic theory provides no clear welfare criteria to evaluate outcomes, damage functions are highly uncertain, and the modeling of mitigation as a choice between 'brown' and 'green' technologies misses the systemic complexity of the choices surrounding a green transition.

Greenhouse gasses affect temperature, precipitation and wind patterns across different countries and regions, with these changes influencing the overall environment and economic conditions in different locations.[1] The uncertainty surrounding predictions of these meteorological and physical processes becomes exacerbated by potential thresholds and tipping points. Added to this, a different order of uncertainty comes from the potential political and social fallout from climate changes, including large-scale migration pressures, social strife, wars and other forms of international conflict. Smooth production functions with damages that depend continuously on CO_2 concentrations provide a misleading picture of the issues associated with climate change.

We cannot even outline all scenarios, never mind assign meaningful probabilities to all possibilities. Catastrophic outcomes cannot be ruled out, however, and any prudent policy adopts strong measures to limit the increase in greenhouse gasses.[2] From this perspective, economic analysis provides little guidance in determining 'optimal' trajectories of emissions. Instead, it becomes useful primarily in the analysis of the collective-action problems and distributional effects that may stand in the way of a green transition and in the design of economic incentives to ensure a successful implementation of the transition. The analysis, moreover, must move beyond the 'brown'-'green' dichotomy and analyze

[1] For simplicity, I shall focus on CO_2, ignoring other greenhouse gasses.

[2] Weitzman (2012) presents some numerical examples of the value of a low atmospheric concentration of greenhouse gasses as insurance against catastrophic outcomes.

different mitigation strategies, their scalability and their systemic effects.

Climate-related episodes will undoubtedly require future macroeconomic intervention. Financial turbulence and crises, for instance, may originate in bankruptcies and loss of collateral when fossil-fuel assets become 'stranded' during the transition or because of the increased incidence of natural disasters like flooding or hurricanes. Aggregate-demand shifts include the possibility of overheating, if transition leads to a surge in investment, or recessionary pressures if climate-induced uncertainty and collapsing animal spirits reduce aggregate demand. It is hard to predict the nature, timing and severity of these macroeconomic repercussions in advance. But this unpredictability is no different than the unpredictability of other disturbances that may call for intervention, and the required climate-related macroeconomic interventions are unlikely to be qualitatively different from the interventions that may be necessary following other economic shocks or technological shifts – the macroeconomic impact of AI, for instance.

Section 2 discusses the widely different conclusions from two well-known models: a supply-driven IAM model and a demand-driven post-Keynesian model. Section 3 focuses on the absence of 'objective' or 'neutral' welfare criteria and the biases and limitations of using GDP or the utility function of a representative agent as a social welfare function. Section 4 turns to collective-action problems, with a simple example illustrating some of the distributional implications of different green policies. Systemic issues associated with different green strategies are addressed in section 5. Section 6 offers a few concluding comments.

2 Drivers of macroeconomic climate models

Macroeconomic climate models have reached very different conclusions. Using supply-driven growth models, many IAMs find relatively low 'social costs of carbon', suggesting optimal trajectories with limited current abatement efforts (e.g. Nordhaus 2017, Barrage and Nordhaus 2023);[3] some demand-driven, Kaleckian specifications of the growth process, by contrast, have suggested that high levels of mitigation are essential to avoid catastrophic outcomes (e.g. Rezai et al. 2018). The difference between a demand-focused analysis and the supply-driven Nordhaus-type IAMs may not, however, be the source of the contrasting conclusions.

This point can be illustrated using a simple model with two closures, one supply-driven and the other demand-driven, but the same specification of the production function, the private saving propensity, the determination of emissions and atmospheric CO_2 concentration, the climate damage function, and the mitigation options; see Appendix A for a full description and analysis.

The demand-driven version of the model can be seen as a simplified version of the specification in Rezai et al. (2018).[4] Not surprisingly, therefore, it matches

[3] The estimated damage from CO_2 emissions has been gradually increased in the successive iterations of the Nordhaus model but remains relatively low.

[4] The specification was chosen deliberately in order to stay close to Rezai et al. (2018).

their conclusions. What may be surprising is that the supply-driven version yields strikingly similar conclusions with respect to the long-run implications of climate change. If the climate damage becomes severe as CO_2 concentrations rise, both supply- and demand-driven versions require complete mitigation in order for positive rates of steady growth to be possible; if the damages remain relatively mild as CO_2 concentrations rise, both models allow continued growth, even without full mitigation.[5] These crucial climate-related conclusions are driven by the damage function.

There are differences between the detailed implications of the two versions, of course. The precise values of the output level (in cases with a stationary state) and the growth rate (in cases with positive steady growth) are different, and with a utilization rate below one (and therefore a lower output-capital ratio), the conditions for steady growth are stricter in the demand-driven model. The comparative statics also differ. As in standard Kaleckian models without climate change, the demand-driven model generates an inverse relation between the saving rate and the rate of growth (if positive growth is possible) or the level of output (if no long-run growth is possible); the supply-driven model, by contrast, implies a positive relation between the saving rate and the growth rate or the level of output.

These are quantitative differences. Overall, the similarities between the results of the demand- and supply-driven models suggest that, although important in other respects, the significance of this aspect of the models for the analysis of climate change and the choice of mitigation policy may be limited, a conclusion that is reinforced by two simple observations.

Climate policy, first, involves interventions that affect market mechanisms and economic outcomes. There is no reason to exclude supplementary interventions if climate change or climate policy produces undesirable aggregate-demand effects, whether positive or negative. Monetary and fiscal instruments can address any such issues. The demand effects of climate change and climate policy, in other words, become largely irrelevant.

Assuming that policy keeps the economy on a (near-) full-employment trajectory, second, it matters little for climate issues whether near-full employment is due to policy intervention (as in Keynesian models) or ensured by automatic market mechanisms (as in neoclassical and new Keynesian models). The damage function, by contrast, is crucial for the determination and implications of climate policy.

The production function, the cost of mitigation, and the welfare criteria, including the weights attached to future outcomes, also play key roles, and some elements of the model in Appendix A differ from those in many climate models, including all IAMs in the Nordhaus tradition.

Like most post-Keynesian models, the production function in the appendix

The weaknesses of the Kaleckian specifications (Skott 2012, 2017) are irrelevant for present purposes.

[5] The possibility of steady growth under incomplete mitigation emerges because no functional form of the damage function is imposed in Appendix A. The specification of the damage function in Rezai et al. (2018) rules out positive long-run growth without full mitigation.

has fixed coefficients. This assumption affects the results: a smooth neoclassical production function – a standard element of mainstream models – may allow steady growth, even if the conditions for positive steady growth are not being met for the fixed-coefficient case. Strong substitutability between capital and labor and an exogenous growth rate of the labor force serve to reduce the damages from climate change: effectively, the negative impact of climate change can be mitigated by movements along the production towards less capital intensive methods; see Appendix B. As shown by the Cambridge capital controversy, however, there are good reasons to doubt the relevance of adjustments along a smooth aggregate production function; my own take on these issues is outlined in Skott (2023, chapter 9).

Mitigation costs do not appear in the model in Appendix A.[6] The main purpose of the model is merely to illustrate how the long-run implications of macroeconomic climate models are driven by forces that have little to do with the precise specification of the economic setting, here exemplified by the demand- and supply-driven closures. In this context, there is little harm in neutralizing any effects of changes in mitigation costs. The focus on long-run growth also explains the treatment of mitigation and saving rates as constant.

Saving rates and mitigation efforts need not be constant over time, however, and treating them as such short-circuits critical issues. Mitigation rates cannot be adjusted instantaneously – they increase during a green transition as a result of investment that gradually reduces the dependence on fossil fuels. More important, the pace at which a transition should be implemented is central to any transition strategy.

Integrated assessment models in the Nordhaus tradition address the timing issues, deriving the trajectory of saving and mitigation rates by solving the intertemporal optimization problem of the representative agent. Since the 'social cost of carbon' increases as the economy grows and CO_2 concentrations rise, the optimal current spending on mitigation can be low, even if mitigation becomes essential in later periods. These calculations of optimal trajectories are misguided, both because of the welfare criterion that is being used (see section 3) and because of the uncertainty surrounding the damage function and future mitigation costs. But the problems with these calculations does not imply that timing issues can be dismissed.[7]

3 Welfare assessments

Following standard practice in new Keynesian macroeconomics, Nordhaus built his DICE models on a macroeconomic foundation with the representative agent at the center and the utility function of the representative agent as the welfare

[6] Mitigation costs only influence the outcomes in Rezai et al. (2018) because of their effect on aggregate demand.

[7] Using a framework that is quite different from tradional IAMs, Coram and Katzner (2018) argue that if the aim is to keep the CO_2 concentration at or below a target value, an optimal strategy typically requires strong early mitigation.

criterion. This approach is widely seen as "correct" and "natural".[8] Specifically with respect to the modeling of climate change, Weitzman (2007) criticized Stern (2007) for picking a low discount rate, applauding Nordhaus's integrated assessment models for using the preferences of a descriptive representative agent to assess social welfare. Economists, he argued, "understand the difference between their own personal preferences for apples over oranges and the preferences of others for apples over oranges"; thus, Nordhaus's "careful pragmatic modeling throughout his DICE series of IAMs has long set the standard in this area" (Weitzman 2007, pp. 712-713).

The unquestioning use by macroeconomists of a descriptive representative agent to measure social welfare is surprising: it has been known since the work of Sonnenschen, Debreu and Mantel in the 1970s that preferences cannot be aggregated. Even if all agents have well-defined preferences that satisfy the standard assumptions, the associated aggregate excess demand functions cannot be derived – except under highly restrictive assumptions – as the outcome of optimization by a single representative agent.

Disregarding this existence problem and assuming for the sake of argument that a representative agent can be used to describe the aggregate excess demand functions, the use of the representative agent as the welfare criterion is far from "correct" and "natural": doing so involves an intrinsic bias in favor of the rich. The reasons for this bias are very intuitive. The representative agent is constructed to describe aggregate outcomes, and in a market economy people without money do not influence demand. Aggregate market outcomes, in other words, depend on income distribution: greater weight must be given to the preferences of the rich in order to describe these outcomes. This basic property of market-based economies necessarily implies an intrinsic bias in favor of the rich.

A simple example can be used to illustrate the issue. Suppose there are only two types of agents, with n agents of each type. Agents of type A only like apples, while B-types only like oranges. The composition of the initial endowments is the same for all agents, with each endowment having an equal number of apples and oranges, but type-A agents have endowments that are twice as large as those of the type-B agents. Independently of the relative price, the value of A's endowment is therefore always double the value of B's endowment.

Agents of type A spend all their resources on apples and type B spend theirs on oranges. If $p_a, p_b\, c_a$ and c_b denote the prices and demands for apples and oranges (goods a and b), it follows that $p_a c_a = 2 p_b c_b$ for any relative price. This demand structure can be derived from the utility maximization of a representative agent with a Cobb-Douglas utility function and parameters 2/3 and 1/3:

$$U(c_a, c_o) = c_a^{2/3} c_b^{1/3} \tag{1}$$

[8] The representative agent, according to Woodford (2003, p.12), is "the natural objective in terms of which alternative policies should be evaluated". Blanchard (2008, p. 8) refers to it as "the correct (within the model) welfare criterion".

Suppose it has become possible to convert apples to oranges one-for-one and *vice versa* and that a decision must now be made on how this option should be exercised to maximize social welfare. To find the optimal solution, the policy maker maximizes (1) subject to the constraint that $c_a + c_b = M$, where M is the sum of the original endowments of apples and oranges. The maximization implies that some apples should be converted to oranges: the optimal composition is to have twice as many apples as oranges.[9] This conversion increases the utility of the representative agent by taking from the poor and giving to the rich: type B agents will get to eat fewer oranges, while the A-agents will be able to increase their consumption of apples.[10] [11]

Using aggregate GDP as the objective is no better. Like the representative agent, a welfare criterion based on GDP will tell you, for instance, that curing a disease affecting affluent groups who are able to pay is preferable to interventions that improve the health of people without the ability to pay.

As an alternative to both GDP and a representative agent, one could look at multiple criteria. In a climate context, this approach has been advocated by Dafermos and Nikolaidi (2022, pp. 2-3) who suggest that the relevant welfare criteria include ecological, economic, financial and social elements like "inequality, financial stability, employment, and the intrinsic value of the ecosystem". In principle, they argue, "the higher the number of dimensions, the more holistic the perspective will be". But they also note that "it is not clear how many dimensions should be included in the analysis", that "the higher the number of dimensions, the more difficult it is to draw clear conclusions", and that "[i]nstead of having researchers arbitrarily assign weights to specific dimensions, it is best to leave it to policy makers to take such decisions".

I largely share this position but with some caveats. It would be a mistake, first, to try to develop macroeconomic models that include all potentially

[9] The Lagrange function is given by

$$\mathcal{L} = c_a^{2/3} c_b^{1/3} + \lambda(M - c_a - c_b)$$

The first-order conditions require that

$$\frac{2}{3}(\frac{c_b}{c_a})^{1/3} = \lambda = \frac{1}{3}(\frac{c_b}{c_a})^{2/3}$$

or

$$c_a = 2c_b$$

[10] The analysis, it may be noted, has a corollary: if the relative size of the endowments and thereby the relative income of the two types were to change, the utility function of the representative agent would have to be redefined. If instead of having twice the endowments of type-B agents, agents of type-A were to become richer, with endowments three times as large, the representative agent would have preferences described by a Cobb-Douglas function with parameters 3/4 and 1/4. Putting it differently, the 'Lucas solution' – using the representative agent to describe aggregate behavior – is subject to the same Lucas critique that it was supposed to address: since the preferences of the representative agent are contingent on the distribution of income, the specification will not be invariant to policy changes that influence this distribution.

[11] See Skott and Davis (2013) and Skott (2023, chapter 2) for a more detailed analysis of the existence and questionable use in macroeconomic models of the representative agent.

relevant variables. Large models can become unwieldy and sensitive to minor changes in specification. The drivers of the outcomes in such models easily become obscure, even to the model builder, while the results may gain a spurious scientific veneer and credibility among policy makers. The large integrated models, second, may be neither necessary nor helpful in light of the great uncertainty surrounding the precise effects of both climate change and policies to address the change.[12]

This skepticism with respect to large climate models may go against the trend. New and powerful computational techniques and the availability of more and better data have made it possible to analyze larger and more complex models.[13] Recent IAMs in the Nordhaus tradition, for instance, have generalized the DICE analysis by going beyond the single representative agent. But the new models suffer from many of the same weaknesses as the older generation.

Kotlikoff et al. (2024) is a case in point. They divide the world into 18 separate regions, each with a separate damage function determined by the regional climate effects; the regional climate changes in turn are derived by aggregating the estimated changes in temperature at a much finer grid within the region; each region is populated by finitely-lived overlapping generations rather than by an infinitely lived representative agent. These extensions of the macroeconomic component of traditional IAM models are impressive but do not address the fundamental problems.

All regions produce the same homogeneous output; energy can be ‘clean’ or ‘dirty’, leaving out questions about how to reduce emissions and the systemic effects of different possible strategies; clean energy is produced using a Cobb-Douglas production function with the same parameters in all regions; agents still optimize intertemporally subject to a single intertemporal budget constraint; all agents have the same CIES utility function; there is perfect foresight except for the introduction of a stochastic time of death (but hedging via a perfect annuities market nullifies the effects of the stochastic mortality and implies that there will be no bequests); intra-regional distributional conflicts and collective-action problems that complicate climate policy are largely eliminated by assuming that cohorts consist of identical agents and that full employment is maintained at all times.

The regional disaggregation offers an improvement on models with a single, global damage function. Regional damages are determined by an effect on regional total factor productivity of deviations of regional temperatures from an

[12] Arguing along similar lines, Pindyck (2013, p. 870) concludes that

> IAMs are of little or no value for evaluating alternative climate change policies and estimating the SCC [social cost of carbon; PS]. On the contrary, an IAM-based analysis suggests a level of knowledge and precision that is nonexistent, and allows the modeler to obtain almost any desired result because key inputs can be chosen arbitrarily.

[13] Fernandez-Villaverde et al. (2025) discuss the "evolution in the IAM landscape" with the "introduction of powerful computational techniques (e.g., from machine learning) for model solutions, richer datasets for better empirical parameterizations, and enhanced integration between natural science and economic models".

optimal level, but the optimal temperature is taken to be uniform across all regions, ignoring that not all regions produce the same output and that not all production is equally sensitive to variations in temperature or even has the same optimal temperature. Regions also differ with respect to geography (mountainous, coastal, soil conditions, etc.), while climate induced damages may be influenced by what happens in other regions (changes in rainfall may depend on temperatures in surrounding areas. And most important, the regional damage function ignores the possibility of (and profound uncertainty surrounding the effects of) transregional, climate-induced migration flows, social unrest and wars.

In the absence of a single representative agent, finally, policies are evaluated based on global GDP: the trajectory of global carbon taxes is set equal to a social cost of carbon that is calculated as the present value of the extra loss of future GDP stemming from an additional unit of emissions. The adverse effects of climate change are much stronger for low-income countries in Africa, Latin America and South Asia than for affluent countries in Europe, North America and northern Asia with colder climates, and by basing the policy recommendation on aggregate GDP, the suggested intervention generates the same distributional biases as the maximization of the utility of the representative agent; it becomes biased in favor of the rich and the transition is slowed down.

In principle, the bias could be offset by compensatory transfers, especially since Kotlikoff et al. push aside all collective-action problems by simply assuming the presence of an international body that is able to determine and impose taxes and transfers to address distributional concerns. As it happens, their suggested use of this hypothetical body aggravates the distributional bias: the redistribution, they argue, should be designed to ensure a Pareto improvement, with all agents getting the same improvement in lifetime utility relative to the outcome under business as usual. Since India would suffer heavily from climate change associated with business as usual, the calculations of optimal redistribution indicate that India should be taxed heavily, while transfers will be going to some rich countries that would have been affected less strongly by climate change and therefore also gain less from mitigation.

Both the distributional bias and the effects on overall global mitigation show up clearly in a simple hypothetical case. Suppose that rich countries benefit slightly from global warming along a business-as-usual trajectory (their GDP increases by a small percentage) while poor countries suffer large losses (their GDP falls by a large percentage). In this scenario the optimal carbon tax may turn out to be zero (the small proportional rise in the high GDP of rich countries offsetting the large percentage drop in poor countries). Business as usual becomes the optimal policy and there will be neither mitigation nor compensation.

4 Political-economy issues and collective-action problems

Suppose that a general consensus has been achieved on the severity of the consequences of climate change and the urgent need for a transition away from fossil fuels. This consensus may seem to clear the way for increased mitigation and a rapid, global shift from 'brown' to 'green' technologies. The transition may be derailed, however, by collective-action problems and political-economy issues associated with a green transition. People may agree that new power sources must be developed but oppose the construction of wind turbines, solar farms or nuclear power stations in their own neighborhood or region. Transition-related job losses in some industries and regions also create losers who will resist the transition or insist on compensation in some form.[14]

Assuming that intra-national conflicts of this kind can be addressed, the global (but regionally diverse) effects of CO_2 emissions imply that local $CO2$ emissions have a negligible impact on the local climate and local economic conditions. And if all countries have incentives to free ride, game theory predicts that, even having reached a consensus on the desirability of a green transition, the outcome of a one-shot interaction will be a unique Nash equilibrium with little or no mitigation. Countries engage in repeated interactions, however, and the interaction should not be modeled as a one-shot game.

Repeated interactions open a large space of new strategies, including the potential use of conditional strategies to punish non-cooperating countries. These strategies may allow equilibrium outcomes with a coordinated green transition. But other, less benign outcomes, including 'business as usual' without any mitigation, can also be sustained as equilibrium solutions. Treating countries as the decision makers, the 'folk theorem' implies that pretty much any distributional outcome that leaves all countries as least as well off as under 'business as usual' can be an equilibrium in a repeated prisoners' dilemma if the discount rate is sufficiently low.[15]

In practice, international power balances – both economic and military – will influence the allocation of emission targets across nations as well as the pressures on the different countries to meet their commitments.[16] It is far beyond the present paper (and my expertise) to address these issues in any detail. For present purposes, however, a simple example of distributional issues will suffice.

[14] Domestic distribution is central to programs for a 'green new deal'. Chomsky and Pollin (2020) discuss a 'global green new deal'.

[15] Nordhaus (2015) analyzes free-riding in climate policy, suggesting 'climate clubs' with tariffs on non-member countries as the most promising way to overcome the problem.

[16] An expected expansion of international markets for green technologies may give individual countries an incentive to develop new industries to service these markets; this development may be facilitated by a domestic transition that creates a home market for these industries. China and Denmark can be seen as examples.

Along similar lines, Mercure et al. (2021) question the continued relevance of the free-rider problem, arguing that the momentum of the ongoing global energy transformation creates strategic incentives for countries to expand their own green investment.

A uniform global emissions tax would be an obvious element if a global authority were to design an optimal package of interventions. The allocation of the proceeds of the tax would be contentious,[17] but disregarding administrative issues, it would be irrelevant whether the emission tax were levied on production or consumption if a global authority collects the emission taxes and distributes the revenue to achieve desired distributional outcomes.

The irrelevance of the tax base no longer holds if, absent a global authority, emissions taxes are imposed and retained at the country level. As a stylized example, suppose there are three countries and two goods and that (i) good A creates no emissions, while the energy-intensive good B is associated with production-related emissions, (ii) all production of good B takes place in countries 2 and 3, (iii) all consumption of good B takes place in country 1, and (iv) all three countries are equally affected by climate change.

Consider two scenarios. In the first one, there is no consumption tax, but countries 2 and/or 3 may levy a tax on production. Having two producers introduces a collective-action problem: assuming that demand is price elastic, each country will have an incentive to reduce taxes to increase its share of the market; the result is likely to be an outcome with very low or zero taxes. But suppose the two countries cooperate, abstain from abusing their monopoly position vis-a-vis country 1, and implement an emission tax that is in line with a desirable pace of the green transition. In this scenario, the two producer countries will collect the revenue, with the main burden of the emissions tax falling on country 1. The incidence is reversed under a consumption tax: if climate policy is implemented through a consumption tax in country 1, the revenues now go to country 1, and the main burden falls on country 2 and 3.

Although simple, the example illustrates the presence of both distributional and collective-action issues. A real-world transition clearly involves far more complex and difficult problems; ignoring these problems will impede the prospects of a successful green transition and increase the risk of potentially catastrophic outcomes.

5 Systemic effects

A green transition will have large systemic effects throughout the economy, both because it requires thoroughgoing electrification and because of shifts towards production processes that are less energy intensive. But questions also arise with respect to the source of electricity generation.

Most discussions of the green transition have focused on solar and wind as the main power sources. Dramatic improvements and rapidly declining costs have made these technologies attractive, while highly publicized accidents involving

[17] One reasonable option, arguably, would use some fraction of the revenues to finance green R&D and investment, with the remaining part distributed on a per-capita basis or perhaps skewed towards areas that experience heavy adverse effects of climate change.

Nordhaus (2015) argues against transfers among members of the 'climate club' to affect the distribution of benefits of membership. It may be noted also that simplfying assumptions of his model renders the distinction between production and consumption based taxes irrelevant.

nuclear power plants, most notably Chernobyl and Fukushima, have fostered a retreat from nuclear power, a development that has been reinforced by cost overruns and delays to the construction of new plants (e.g. the British Hinkley Point C nuclear power station).

Germany exemplifies the shift away from nuclear energy and towards power from wind and solar. Eight out of 17 operating German nuclear power plants were closed down in 2011 shortly after Fukushima, and the last of the remaining plants stopped operations in 2023.[18] Meanwhile, the share of renewables has increased and in 2024 accounted for about 57 percent of total German electricity production (AGEB 2024). The increase becomes less impressive, however, when calculated as a share of total energy consumption. Electricity makes up less than 25 percent of German total final energy consumption; Germany has gone from being a net exporter of electricity to becoming a net importer; renewables include other sources (with biomass as the most important). As a result, the share of solar and wind in German primary energy consumption is reduced to about 8 percent (AGEB 2024).[19]

At about 70 percent, the headline number for the share of solar and wind in electricity production is higher in Denmark. But, as in the case of Germany, this figure is deceptive: solar and wind power made up about 12 percent of total energy supply in 2022 (IEA 2023).[20] Outside Europe, in 2023 the share of solar and wind in total energy supply amounted to about 3.5 percent in the US[21] and less than 3 percent for the world as a whole.[22]

The low current share of solar and wind power in total energy supply may not, in itself, invalidate a transition strategy based on these sources. The intermittency of solar and wind, however, presents a serious problem: much of the power from solar and wind is being produced when there is little need for it, and the problem worsens as the share of solar and wind power increases. As Germany increased the share of solar and wind power, the annual number of hours with negative electricity prices increased from less than 150 in 2021 and 2022 to almost 350 in 2024 (IEA, Energy Policy Review Germany 2025, April 2025), with prices positive but very low for much longer periods.

[18] Other countries have also scaled down the amount of electricity from nuclear power. The total production of nuclear power in the EU dropped by 32.2% between 2006 and 2023, with significant declines in France, Belgium and Sweden as well as Germany (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Nuclear_energy._statistics)

[19] Estimated using input-equivalent measures the share increases to 16.5 percent of total consumption (https://ourworldindata.org/grapher/share-of-primary-energy-from-solar-and-wind?tab=table)

The distinction between the raw and 'input-equivalent' measures of the energy supply is outlined here: https://www.energyinst.org/__data/assets/pdf_file/0003/1055541/Methodology.pdf

[20] The share increases to about 31 percent of total energy consumption in 2024, using 'input-equivalent' measures of total consumption (https://ourworldindata.org/grapher/share-of-primary-energy-from-solar-and-wind?tab=table).

[21] US Energy Information Association; https://www.eia.gov/energyexplained/us-energy-facts/

[22] International Energy Agency; https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=WORLD&fuel=Energy%20supply&indicator=TESbySource

The flip side of intermittent gluts and low prices is periods with shortages and booming prices. In October and November 2024 the output from Germany's wind turbines was 25 percent below its average for these months, requiring a large increase in the production from gas-fueled power plants. Then, in mid-December, the average output of wind power was nearly 85 percent lower than normal for this time of the year, and wholesale prices soared. Germany imported significant amounts of electricity, and neighboring countries had also experienced unusually low wind speeds. Consequently, the price increase affected large part of Europe; electricity prices in Germany, Belgium, Netherlands, Denmark and the Czech Republic were all above €350, more than three times their normal level of about €100, and most European countries experienced elevated prices (https://euenergy.live/?date=2024-12-12).

Solar and wind power looks attractive as long as we have existing fossil backups. The intermittency becomes increasingly important, however, as the share of solar and wind power in total energy consumption increases and fossil fuels are phased out. Seemingly cost-effective investment in solar and wind may turn out to be extremely costly as the systemic costs of adding non-fossil backup capacity increase during a transition towards zero emissions. Conversely, other energy sources may look unattractive in the early stages of a transition if they have to compete against free-riding intermittent sources whose backup costs are shifted onto other suppliers or the public sector.

Consider a simple example with three sources of energy: fossil fuels, nuclear power, and power from solar and wind. Let mc_i and cc_i denote the marginal and average fixed costs of source i ($i = F, N, SW$); for simplicity, suppose that marginal cost is constant below full capacity. Now suppose that, leaving out backup costs and assuming optimal capacity utilization of each power source, the costs can be ranked as follows

$$\begin{aligned} mc_F &> mc_N > mc_{SW} \\ cc_N &> cc_F = cc_{SW} \end{aligned}$$

With these assumptions both fossil fuels and nuclear power are more costly than power from solar and wind. Investment flows towards solar and wind projects, and the intermittency of production is accommodated by existing fossil fuel plants which act as the buffer.[23] The average utilization rate of fossil plants declines as the share of solar and wind power expands, and their profitability suffers in the absence of a rise in electricity prices.

The incentives to invest in fossil energy recover when depreciation of existing capacity and/or increasing energy demand lead to prices and fossil profit margins that are sufficiently high during periods of low output from solar and wind to justify new plants, even if these plants will only be operating as a buffer. High fixed costs imply that nuclear will not be chosen as a backup if the expected utilization rates are low.

[23] The production form fossil-fuel plants cannot be scaled up and down instantaneously, and batteries or other backup sources are need to accomodate high-frequency volatility.

If fossil fuels must be phased out, alternative buffers will be needed. Battery storage is one option, or excess energy during periods of high output could be used to create hydrogen or pump water into higher altitude reservoirs. Since it is always sunny or windy somewhere, a sufficiently large and robust distribution network could also offer a solution, as could the creation of sufficient intermittent capacity to ensure that even calm and cloudy days produce what is needed.[24]

These solutions are expensive. Adding four-hour storage capacity almost doubles the cost estimate for solar and wind power (Lazard 2025), and four hours may be "well suited for hot summer days in the United States, when demand peaks are shorter and energy storage is complemented with lots of low-cost solar energy" according to the National Renewable Energy Laboratorium of the US Department of Energy.[25] , But four hours would be of little help in a prolonged period with output significantly below normal levels, such as the 'dunkelflaute' in 2024 that affected Germany and large parts of western Europe. Tong et al. (2021) estimate that to achieve fewer than 10 hours a year with a supply gap exceeding 50 percent, countries like Germany, New Zealand and South Korea would need a combination of 12 hour storage and a generation capacity of 3 times annual demand. And a much lower supply gap of 10 percent could cause havoc: if the economy has been electrified, essential services like hospitals and public transportation have to be served, and the shortfall will be larger for non-essential usage. With triple capacity and 12 hours of storage, the supply gap on average exceeds 10 percent for more than 50 hours a year.[26]

Returning to the simple example, nuclear power may turn out to be the cheap option if the need for backup capacity is taken into account. Formally, we may have

$$cc_N + mc_N < cc_{SW} + cc_B + mc_{SW} + mc_B$$

where cc_B and mc_B denote the fixed cost per unit of backup capacity and marginal cost per unit of actual backup. If this happens, the early expansion of solar and wind power will turn out to have been a costly detour; the prioritization of solar and wind will now appear myopic.

Investment decisions would not fail to consider the systemic effects of a reliance on intermittent sources if a representative agent with perfect foresight were planning the total energy supply. But the investment decisions are not made by a representative agent with perfect foresight. Investors in solar and wind projects do not consider the negative externalities that they impose on other producers (reduced utilization and profits) and/or the consumers of energy (higher prices to alleviate the profitability effects on other producers).

Political intervention, moreover, has accelerated the expansion of solar and

[24] Dynamic pricing may also help adjust the demand for electricity to variations in supply. The contribution of this mechanism is likely to be limited, however.

[25] https://www.nrel.gov/news/detail/program/2023/from-minor-player-to-major-league-moving-beyond-4-hour-energy-storage.

[26] The estimated supply gaps assume perfect transmission of ignore within each country but leave out the possibility of cross-border transmission; controlling for generation and storage capacity, large countries therefore typically achieve fewer and smaller supply gaps than small countries.

wind power by offering generous incentives, including subsidies and public support of necessary infrastructure. These policies may have been sensible as a transitional and relatively inexpensive way to achieve a rapid reduction of emissions while using existing fossil fuel plants (with fixed sunk costs) as buffers. But this transitional use of solar and wind power would not justify a near-exclusive focus on investment in infrastructure and R&D related to solar and wind power. Nor does it seem wise to rely on optimistic expectations about sufficient future improvements in battery or other, completely new storage technologies to solve the problems.

While the benefits of solar and wind energy tend to be exaggerated, those of nuclear power have been underestimated. Common claims that nuclear power is too slow, too expensive and too dangerous are unconvincing. It is correct that nuclear projects have experienced long delays in many western countries.[27] But France built up its nuclear capacity from zero to 75 percent of total generation and more than 80 percent of domestic electricity use in less than 15 years from 1975 to 1988, and China routinely builds nuclear power plants in 5-6 years.

Cost comparisons are tricky, partly because of the systemic issues discussed above. Construction costs in real terms have increased by a factor 10 over the last 50 years in the US but, like the delays during construction, the cost increases have been due to "a lack of standardized designs, rising material and labour costs, evolving regulations and technical complexities" (Liu et al. 2025). Financing costs have also hampered nuclear power in the US. Nuclear power plants have high fixed costs and long life spans, which makes private finance expensive in a risky environment with a complex and unstable regulatory process. Regulatory delays in construction and the risk that large long-term investment in nuclear plants could become the victim of changing political regulatory winds raise the costs of finance.

In China, by contrast, cost reductions and short production times have been achieved through standardization, the creation of strong domestic nuclear-power supply chains, and a stable regularity framework, while "a consistent, state-backed industrial policy has provided stable electricity tariffs and low-cost financing" (Liu et al. 2025). Like wind and solar technologies, nuclear power benefits from learning by doing.

The safety concerns, finally, should be taken seriously but have arguably been greatly exaggerated. We now have a long history of data, and the death rate from accidents and air pollution per unit of electricity production is lower for nuclear power than for wind or hydro, never mind big killers like coal, oil and biomass.[28] Looking at the two most prominent accidents, the Chernobyl

[27] It may be noted that other energy projects have also been subject to long delays. The integration of intermittent power sources into the grid requires significant investment in new infrastructure, and the "UK renewable energy sector is currently grappling with a significant bottleneck: over 1,100 wind, solar, and other green energy projects are delayed due to long grid connection wait times", with some projects "waiting up to 8-10 years for grid connection" (https://haush.co.uk/1100-renewable-energy-projects-stuck-in-grid-queue-breaking-down-the-delays-in-the-uk/).

[28] Estimated death rates per terawatt-hour are about 20 for oil and coal power compared to about 0.04 for wind power, 0.03 for nuclear power and 0.02 for solar power

disaster has caused an estimated long-term excess death toll from radiation of about 4000, with fewer than 50 people dying in the immediate aftermath of the accident (WHO, 2006). The Fukushima accident, the other large accident, has caused one death from lung cancer as a result of radiation exposure and led to 2,313 deaths as a result of the physical and mental stress of evacuation (World Nuclear Association (2024), citing Japanese government estimates from September 2020).

Overall, there may be no obvious 'perfect strategy'. The systemic implications of different strategies need to be analyzed, however, and it would seem reckless to rely mainly on intermittent power sources like solar and wind. Different energy sources will undoubtedly be part of any sensible green transition, both for precautionary reasons (to create a robust energy system) and because of the option value of possible technological advances within the different ways of meeting the energy needs. Thus, the 'pragmatic' Chinese approach with strong expansion of both nuclear energy and solar and wind systems may be strategically wise. The European emphasis on solar and wind power, by contrast, seems risky.

6 Conclusions

Large integrated assessment models of interactions between the economic sphere and climate change have posited a well-defined welfare function, played down fundamental uncertainty, and treated climate policy as a simple choice of the welfare maximizing level of 'mitigation'. This approach can be questioned. The choice of welfare criteria is contentious, and the uncertainty surrounding the effects of climate change makes any calculation of an optimal trajectory of emissions illusory. Rather than attempt any such precise calculation, the very uncertainty and the disastrous worst-case scenarios make a strong case for urgent action: if the potential damages are sufficiently large, they should dominate our decisions, even if no calculation of precise probabilities and potential damages is possible.[29]

In short, large integrated climate models may have some role to play, but it is likely to be fairly limited. Instead of trying to derive optimal trajectories of mitigation and macroeconomic policy, it may be more fruitful to try to identify

(https://ourworldindata.org/safest-sources-of-energy).

[29] This position has close affinities with the Pindyck's (2013) statement quoted in footnote 10 as well as with Stern's (2021, p. 25) conclusion that

> "Standard utility or welfare functions at the heart of the IAMs cannot capture adequately the nature and scale of the risks from climate change, and the challenges of immense risk to life itself for many, points towards the need for alternative strategies for building theories and models. ... The policy challenge, as we have seen, involves generating rapid and major change in key complex systems .... Simple "cost" functions for emissions reductions, even if made more realistic, do not get to grips with the real policy challenges of how to make these changes.

and analyze ways of achieving given green transition targets. A reorientation of economic research on climate change should prioritize (i) the collective-action problems that would complicate policy implementation, even if everyone were to agree that a rapid transition is needed, (ii) intra-national and international distributional effects and how to address them, (iii) power balances and other political-economy issues that shape energy policies, (iv) the systemic effects of different potential sources of energy and (v) the design of public investment, taxes and subsidies, and financial interventions to guide the transition, counteract undesirable distributional effects and provide incentives for the shift away from fossil fuels. Clearly, work has been done on these issues. But the macroeconomic literature has shown a bias in favor large-scale integrated models that make strong assumptions and ignore most of the thorny issues.

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Appendix A

The dynamics of CO_2 concentrations is specified as

$$\dot{B} = H_0 + (1 - \theta)Y - \omega B \tag{2}$$

where, $B, H_0, Y, \theta, \omega$ are the CO_2 concentration in the atmosphere, natural emissions of CO_2, output, the degree of mitigation, and the rate of dissipation; a 'dot' over a variable denotes a rate of change.

Following standard post-Keynesian assumptions, the production function has fixed coefficients,

$$Y = \psi(B) \min\{K, L\}; \qquad \psi' < 0 \tag{3}$$

The ψ-function captures the effect of damage associated with increasing CO_2 concentrations; Y, K and L are the total output, capital stock and employment. To simplify, it is assumed that all spending on mitigation is financed by the government and that the government maintains a balanced budget and a constant tax rate. Formally,

$$G + M = tY \tag{4}$$

where M, G and t are mitigation expenditure, other government spending on goods and services, and the tax rate. The spending on mitigation depends on the degree of mitigation, $M = M(\theta)$, but equation (4) implies that the pure aggregate demand effects of mitigation policies are neutralized by the contraction of other spending.[30]

Private saving is taken as proportional to income,

$$S = sY \tag{5}$$

The saving rate s incorporates the effects of income distribution and taxation. If, for instance, saving rates are higher out of profits, and a constant, uniform tax rate applies to all income, we have $s = (1-t)[s_w(1-\pi) + s_\pi \pi]$. The reduced-form saving rate s is taken to be constant.

A supply-driven version In this version of the model, there is always 'full employment' of capital or labor. Thus, if N is the total labor supply, we have

$$Y = \psi(B)\min\{K, N\}; \qquad \psi' < 0 \tag{6}$$

$$L = \begin{cases} N & \text{if } N \leq K \\ K & \text{if } N > K \end{cases} \tag{7}$$

Private investment is identically equal to private saving,

$$I = sY \tag{8}$$

Using equations (5)-(9), the growth rate of the capital stock is given by

$$\hat{K} = \begin{cases} s\psi(B)\frac{N}{K} - \delta & \text{if } N \leq K \\ s\psi(B) - \delta & \text{if } N > K \end{cases} \tag{9}$$

The labor force grows at a constant rate n, with $n > 0$.

Several distinct cases emerge from this model:

1. If there is **incomplete mitigation**, $\theta < 1$, then

   (a) If $s\psi(B^\infty) - \delta < 0 < s\psi(H_0/\omega) - \delta$, where $\psi(B^\infty) = \lim_{B\to\infty}\psi(B)$, there are no steady growth paths with $\hat{Y} = \hat{K} \neq 0$. Instead, there is a locally stable stationary state with a finite CO_2 concentration, $\hat{Y} = \hat{K} = 0$ and $N/K > 1$.

   Intuitively, the first inequality, $s\psi(B^\infty) - \delta < 0$, precludes positive steady growth rates: if output increases without bound then emissions and the atmospheric CO_2 concentration must also grow without limit, and as $B \to \infty$ the net accumulation rate would fall below zero;

[30] The balanced-budget assumption avoids issues of government debt accumulation and its effects on demand. More importantly, it also neutralizes any direct influence of mitigation on aggregate demand. Effects of mitigation that derive purely from changes in aggregation government spending could presumably be replicated by other kinds of spending.

Rezai et al. (2018) also assume that mitigation costs are covered by the government and that these costs are proportional to income. Unlike the present specification, however, they treat mitigation spending as uncovered by taxation, yielding a positive relation between the short-run multiplier and the degree of mitigation. As it happens, however, the long-run qualitative results do not depend on the magnitude of the short-run multiplier.

thus positive growth leads to a contradiction. The second inequality requires that saving be sufficient to cover depreciation when the CO_2 concentration is at the lowest possible stationary level (that is, the level associated with the absence of any production-related emissions). If both inequalities are satisfied, a level of B exists such that $\hat{K} = 0$; the stationary solution for Y can be found by substituting this value of B into the dynamic equation for B, equation (2).

(b) If $0 < s\psi(B^{\infty}) - \delta$, the system converges to a steady growth path with $\hat{Y} = \hat{K} = \min\{s\psi(B^{\infty}) - \delta, n\} > 0$.

Since the ψ-function is decreasing in B, the inequality condition, $0 < s\psi(B^{\infty}) - \delta$, implies that $\hat{K}$ is bounded above zero for all values of B. With both K and N growing without limit, output Y will also go to infinity. It follows that $B \to \infty$ and, using equations (2), (6) and (9), both $\hat{K}$ and $\hat{Y}$ converge to $\min\{s\psi(B^{\infty}) - \delta, n\}$.

2. Under **complete mitigation**, the economy converges to a steady growth path with $\hat{Y} = \hat{K} = \min\{s\psi(B^{*}) - \delta, n\}$ where $B^{*} = H_0/\omega$.

   The dynamic equation for B now describes an autonomous differential equation, $\dot{B} = H_0 - \omega B$ with H_0/ω as the stable stationary solution. The asymptotic results for $\hat{K}$ and $\hat{Y}$ follow by substituting the stationary solution for B into equations (6) and (9)

A demand-driven version As a simple specification, investment depends on current output and full capacity output

$$I = g_0 Y^{\max} + g_1 Y \tag{10}$$

where $Y^{\max} = \psi(B)K$ is the level of output associated with the full utilization of capital. This functional form aligns with benchmark Kaleckian specifications if it is assumed that $g_1 < s$ (the 'Kaleckian stability condition') and $g_0 > 0$.[31]

Instead of equation (8), with output determined by (6), we now have an equilibrium condition for the goods market,

$$S = sY = g_0 Y^{\max} + g_1 Y = I \tag{11}$$

By assumption, there are no binding supply constraints in the demand-driven model, and equation (11) determines the level of output,

$$Y = \frac{g_0 Y^{\max}}{s - g_1} = \psi(B)K \frac{g_0}{s - g_1} \tag{12}$$

[31] Equation (10) implies that

$$\frac{I}{K} = \frac{Y^{\max}}{K}[g_0 + g_1 \frac{Y}{Y^{\max}}] = \tilde{g}_0 + \tilde{g}_1 u$$

where $\tilde{g}_0 = \frac{Y^{\max}}{K} g_0, \tilde{g}_1 = \frac{Y^{\max}}{K} g_1$ and u is the utilization rate of capital. The Kaleckian models typically assume a constant technical output-capital ratio $Y^{\max}/K$.

Employment is proportional to output, $Y = \psi(B)L$, and the rates of capital utilization and employment are given by

$$\begin{aligned} u &= \frac{Y}{Y^{\max}} = \frac{L}{K} = \frac{g_0}{s - g_1} && (13) \\ e &= \frac{L}{K}\frac{K}{N} = \frac{g_0}{s - g_1}\frac{K}{N} && (14) \end{aligned}$$

By assumption, there are no binding supply-side constraints in the demand-driven model; thus it is assumed that $u < 1$ and $e < 1$.

Like the supply-driven version, this demand-driven specification generates several cases (with the proof following steps that are completely analogous to those for the supply-driven model):

1. With **incomplete mitigation**, $\theta < 1$, there are, as in the supply-driven version, two scenarios:
   (a) If $s\psi(B^\infty)\frac{g_0}{s-g_1} - \delta < 0 < s\psi(H_0/\omega)g_0/(s - g_1) - \delta$, there are no steady growth paths with $\hat{K} = \hat{L} \neq 0$. Instead, there is a locally stable stationary state with a finite CO_2 concentration, $\hat{Y} = \hat{K} = 0$ and $N/K > 1$.
   (b) If $0 < s\psi(B^\infty)\frac{g_0}{s-g_1} - \delta$, the CO_2 concentration goes to infinity, $B \to \infty$, and (assuming that labor constraints will never be binding in this demand-driven version) the steady growth rate will be equal to $s\psi(B^\infty)\frac{g_0}{s-g_1} - \delta$.[32]
2. With **complete mitigation**, $\theta = 1$, the economy converges to a steady growth path with $\hat{Y} = \hat{K} = s\psi(B^*)\frac{g_0}{s-g_1} - \delta$ where $B^* = H_0/\omega$.

Appendix B

Consider a simple model with full employment, passive investment and a smooth neoclassical production function:

$$\begin{aligned} Y &= \psi(B)F(K, L); \quad \psi' < 0, \psi \to 0 \text{ for } B \to \infty \\ \hat{K} &= s\frac{Y}{K} - \delta && (15) \\ \hat{L} &= n > 0 \\ \dot{B} &= H_0 + (1 - \theta)Y - \omega B \end{aligned}$$

Depending on the precise specification of the different functions, there may be a steady growth path with a constant capital-output ratio.

[32] The specification of the damage function in Rezai et al. (2018) implies that $s\psi(B^\infty) - \delta < 0$. Case 1.b. therefore does not arise in their model.

To see this, suppose the production function takes the Cobb-Douglas form,

$$Y = B^{-\eta} K^{\alpha} L^{1-\alpha}$$

We then have

$$\hat{Y} = -\eta \hat{B} + \alpha \hat{K} + (1-\alpha) n \tag{16}$$

and a stationary solution for Y/K implies that

$$\hat{Y} = n - \eta \hat{B}/(1-\alpha) \tag{17}$$

If $B \to \infty$, the dynamic equation for B implies that $H_0/B \to 0$, and asymptotically we have

$$\hat{B} = (1-\theta)\frac{Y}{B} - \omega \tag{18}$$

Combining equations (17) and (18) and assuming that a steady growth path exists with $\hat{K} = \hat{Y} = \hat{B} > 0$, the asymptotic dynamics of the Y/B ratio can be written

$$\widehat{\frac{Y}{B}} = \hat{Y} - \hat{B} = n - (1 + \frac{\eta}{1-\alpha})[(1-\theta)\frac{Y}{B} - \omega]$$

This differential equation has a (stable) stationary solution:

$$\frac{Y}{B} = \frac{n + (1 + \frac{\eta}{1-\alpha})\omega}{(1 + \frac{\eta}{1-\alpha})(1-\theta)} \tag{19}$$

Using equations (17)-(19), it now follows that, asymptotically, we have

$$\begin{aligned} \hat{K} &= \hat{Y} = \hat{B} = (1-\theta)\frac{n + (1 + \frac{\eta}{1-\alpha})\omega}{(1 + \frac{\eta}{1-\alpha})(1-\theta)} - \omega \\ &= \frac{n}{1 + \frac{\eta}{1-\alpha}} > 0 \end{aligned} \tag{20}$$

The solution in equation (20) meets the condition that $\hat{B} > 0$ and, using (19) and setting $Y/K = n/[s(1 + \frac{\eta}{1-\alpha})]$, it it readily seen that the dynamic equations $(15) - (18)$ are satisfied.