WILL THE PARIS ACCORD ACCELERATE CLIMATE CHANGE?

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Abstract
The 2015 Paris climate accord (Paris Agreement) is meant to control our planet's rising temperature to limit climate change. But it may be doing the opposite in permitting a slow phase-in of CO_2 emission mitigation. The accord asks its 195 national signatories to specify their emission reductions and to raise those contributions over time. However, there is no mechanism to enforce these pledges. This said, the accord puts dirty energy producers on notice that their days are numbered. Unfortunately, this "use it or lose it" message may accelerate the extraction and sale of fossil fuels and, thereby, permanently worsen climate change. Our paper uses a simple OLG model to illustrate this long-noted, highly troubling Green Paradox. Its framework properly treats climate damage as a negative externality imposed by today's generations on tomorrow's—an externality that is, in part, irreversible and, if large enough, can tip the climate to a permanently bad state. Our paper shows that delaying abatement can be worse than doing nothing. Indeed, it can make all generations worse off. In contrast, immediate policy action can make all generations better off. Finally, we question the standard use of infinitely lived, single-agent models to determine optimal abatement policy. Intergenerational altruism underlies such models. But its assumption lacks empirical support. Moreover, were such altruism widespread, effective limits on CO_2 emissions would, presumably, already be in place. Unfortunately, optimal abatement prescriptions derived from such models can differ, potentially dramatically, from those actually needed to correct the negative climate externality that today's generations are imposing on tomorrow's.
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Introduction

In the 2015 Paris climate accord (Paris Agreement), 195 countries agreed to limit the planet's temperature rise to 2°C above pre-industrial levels. The accord calls for moderate measures through 2025 and tougher measures thereafter. Unfortunately, the accord includes neither an enforcement mechanism nor any compliance deadlines. Consequently, the accord represents a voluntary arrangement that countries may fail to honor until they have been identified and called to account, both of which can take time. The accord did accomplish one thing. It sent dirty energy producers a clear message that their days are number.

This *use it or lose it* message—that reserves of oil, natural gas, and coal will become stranded assets—may be accelerating fossil fuel extraction and CO_2 emissions. Since 2010, global oil production has risen by 10 percent[1], global coal production by 9 percent[2], and global natural gas production by 11 percent[3]. Yet slower, not quicker, release of CO_2 is critical to limiting the planet's temperature rise. Thus, the Paris accord, in not mandating immediate emission limitation policy, may actually be accelerating climate change. This is the well-known Green Paradox [Sinn, 2008].

This paper illustrates the Green Paradox, arising from delaying climate change policy. Our vehicle is a two-period OLG model featuring dirty and clean energy. Dirty energy, referenced as oil, is exhaustible and in inelastic supply. Clean energy, referenced as solar, eventually supplies all energy needs—but, depending on policy, this outcome may, paradoxically, occur too soon to prevent irreversible climate damage. Indeed, the earlier solar takes over, the worse matters can be for the climate.

The life-cycle model is the appropriate framework for studying climate policy since it captures the negative externality that current generations impose on future generations in using fossil fuels. Climate policy's natural objective is to achieve an abatement path that makes no generation worse off and at least some generations better off. The search for such efficient abatement policies moves the climate policy debate from the realm of ethics to that of economic efficiency.

Our reference here to ethics alludes to the use of infinite-horizon models in which optimal climate policy is set based on the infinitely lived, representative agent's time preference factor. The recent paper by [Golosov et al., 2014] is an example. Its optimal carbon tax formula de-

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[1] https://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=5&pid=53&aid=1&cid=regions&syid=2010&eyid=2015&unit=TBPD.

[2] http://www.indexmundi.com/energy.aspx?product=coal&graph=production.

[3] http://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2015/bp-statistical-review-of-world-energy-2015-natural-gas-section.pdf.

pends critically on the representative agent's time preference rate[4]. But [Altonji et al.], and other studies, particularly [Population Aging and the Generational Economy.., 2011] analyses of the postwar change in the shape of the age-consumption profile, provide strong evidence against the intergenerational altruism required by single-agent models.

Indeed, were such intergenerational altruism ubiquitous, there would be no reason to analyze climate change policy. Agents with such preferences would set optimal climate policy to protect their progeny. This is true even if one considers different clans within a single country or in different countries. As shown in [Bernheim, Bagwell, 1988], the assumption of intergenerational altruism combined with the assumption that agents from different clans become altruistically linked with one another implies effective altruistic linkages across essentially everyone on the planet. In this case, there is global agreement on enacting first-best dirty energy policy. Stated differently, a climate change policy problem cannot arise in models with infinitely lived agents because such agents would automatically internalize the externality.

This said, were intergenerational altruism ubiquitous and operational, [Golosov et al., 2014] elegant and impressive paper would provide an excellent guide to the planet's single dynasty for setting abatement policy. But since this appears not to be the case, their model and similar models must be viewed as entailing the optimization of social welfare functions in which the time preference rate becomes a central parameter for optimal carbon policy. Since there is no economic basis for choosing the preferences of social planners, "optimal" carbon policy devolves into a matter of ethical conviction.

If one leaves ethics aside and focuses on economics in the context of selfish life-cycle agents, optimal policy analysis becomes a matter of determining the set of policies that produce Pareto improvements. Once that set is determined, the job of the economist is finished and it is up to policymakers to determine what policies, if any, to undertake.

The natural means of achieving an efficient climate policy is levying a time-varying carbon tax rate, but using, as needed, generation-specific redistribution to achieve a Pareto improvement. Unfortunately, as we show, climate accords that permit delayed limitation of emissions encourage a fast rather than a slow fossil fuel burn, which may be economically inefficient; i.e., they can be worse than doing nothing, producing a Pareto loss.

The same is true of policies that accelerate technical improvement in clean energy. Telling dirty energy producers that they will face much

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[4] The formula also depends critically on the assumption of a fixed saving rate. Life-cycle models, in the presence of active generational policy, deliver net national saving rates that can vary dramatically through time. The U.S. net national saving rate was 15 percent in 1950. It is just 4 percent today. The net national saving rate is defined here as net national income measured at producer prices less economy-wide consumption, also measured at producer prices divided by net national income.

stiffer competition from clean energy sources in the relatively near term sends the same "use it or lose it" message and, unfortunately, also leads to a faster burn.

To be clear, our model was designed solely to extend lessons about exhaustible resource extraction first taught by [Hotelling, 1931]. It is far too simple to provide precise policy prescriptions. Its use of two periods, rather than annual periods, limits its ability to accurately capture annual climate change processes. Furthermore, using a two-period, rather than an annual-period, model constrains the potential for dynamic policy adjustment through time stressed by [Cai et al., 2013] and others. The choice of long time periods can also, as [Cai et al., 2013] stress, both affect policy prescriptions and overlook stochastic changes to the economy and to climate damage.

Still, our models' main message would surely carry over to far more detailed models, including models with more complex preferences, uncertainty, and state-dependent policies. The reason is that our model is about the expected time path of policy and the point that getting the policy timing wrong can be worse than running no policy whatsoever. To be sure, our point that optimal policy requires immediate action can be seen in the optimal tax policies computed by [Cai et al., 2013; Golosov et al., 2014] and others. But the literature seems devoid of, or at least short on, studies examining the cost of policy delay.

Section 1 proceeds with a limited literature review. Section 2 lays out our model, its equilibrium conditions, and its steady-state properties. Section 3 explains in general terms how we compute the model's transition path solution. Appendix A provides the computation details. Section 4 describes our model's calibration. Section 5 presents simulations of the economy's transition path a) in the no-policy baseline; b) with a carbon tax, but introduced only after one period (roughly 30 years); and c) with a carbon tax which is introduced immediately. In each of the latter two simulations, the absolute carbon tax is the same and remains fixed through time. Our final simulation examines the impact of faster technological growth in green energy technology, whether stimulated by private discovery or government investment. Section 6 summarizes and concludes.

1. Literature Review

There is a large and growing literature on exhaustible resources and climate change, much of it emanating from seminal contributions by [Hoteling, 1931; Nordhaus, 1979; Sinn, 1982; Solow, 1974a, 1974b]. The literature includes theoretical models, optimal tax models, and simulation models, including [Gurgel et al., 2011; Manne et al., 1995; Metcalf, 2010, 2014; Nordhaus, 1994, 2008, 2010; Nordhaus, Boyer, 2000; Nordhaus, Yang, 1996; Ortiz et al., 2011; Plambeck et al., 1997; Rausch et al., 2011; Sinn, 2007, 2008; Stern, 2007; Tol, 1997, 2002; Tol et al., 2003]. The latest literature incorporates stochastic elements, e.g., [Cai et al., 2013; Golosov et al., 2014]; endogenous economic growth, e.g., [Acemoglu et al., 2012; Popp, 2004; van der Zwaan et al., 2002]; and problems of coalition formation, e.g., [Bréchet et al., 2011; Nordhaus, 2015; Yang, 2008].

The [Cai et al., 2013; Golosov et al., 2014] papers are particularly important additions to the literature showing that optimal carbon tax rates can be considerably higher if the extent of future carbon damage is uncertain. This is particularly the case if the climate tips. Potential tipping mechanisms include the near-total loss of the Amazon rain forest, faster onset of El Niño, the reversal of the Gulf Stream and other ocean circulatory systems, the melting of Greenland's ice sheet, and the collapse of the West Antarctic ice shelf. Key scientific articles on climate tipping include [Kriegler et al., 2009; Lenton et al., 2008]. The inclusion of uncertainty reminds us that optimal climate policy is a dynamic process, which responds to the economy's state of nature.

Our paper is related to a component of the literature that considers resource extraction and global warming within overlapping generation models. Early papers in this area include [Burton, 1993; Howarth, Norgaard, 1990, 1992; John et al., 1995; Marini, Scaramozzino, 1995; Pecchenino, John, 1994]. [Burton, 1993; Howarth, 1991a, 1991b; Howarth, Norgaard, 1990] ignore environmental externalities. The other papers incorporate environmental degradation.

[Howarth, Norgaard, 1990], using a pure exchange OLG model, and [Howarth, 1991b], using a standard OLG model with capital, demonstrate that policymakers can choose among an infinite number of Pareto efficient paths in the process of correcting negative environmental externalities. Clearly, social judgments will matter in deciding which, if any, of such paths to adopt[5]. [Howarth, 1991a] extended his important work to consider, in general terms, how to analyze economic efficiency in OLG models in the context of technological shocks. [Howarth, Norgaard, 1992] introduced damages to the production function from environmental degradation and studied the problem of sustainable development[6]. [Rasmussen, 2003; Wendner, 2001] examine the impact of the Kyoto Protocol on the future course of the energy sector. [Wendner,

[5] [Gerlagh, Keyzer, 2001; Gerlagh, van der Zwaan, 2001] consider the choice among Pareto paths and the potential use of trust fund policies that provide future generations with a share of the income derived from the exploitation of the natural resource. [Gerlagh, van der Zwaan, 2001] point out that demographics can influence the set of efficient policy paths through their impact on the economy's general equilibrium.

[6] An alternative approach to incorporating a negative environmental externality is including environmental quality directly in the utility function. [John et al., 1995; Pecchenino, John, 1994] make this assumption in a discrete time OLG models. [Marini, Scaramozzino, 1995] do the same, but in a continuous time OLG framework. The problem of generational equity and sustainable development is also discussed by [Batina, Krautkraemer, 1999; Mourmouras, 1991, 1993] in a model where energy is renewable.

2001] also considers the extent to which carbon taxes can be used to shore up Austria's state pension system. Their papers feature large-scale, perfect foresight, single-country models. But they omit climate damage per se.

The fact that OLG models do not admit unique solutions when it comes to allocating efficiency gains across agents, including agents born at different dates, has led some economists to introduce social welfare weights. Papers in this genre include [Ansuategi, Escapa, 2002; Burton, 1993; Calvo, Obstfeld, 1988; Endress et al., 2014; Howarth, 1998; Lugovoy, Polbin, 2016; Marini, Scaramozzino, 1995; Schneider et al., 2012]. In these papers the level of the social time preference rate plays a critical role in influencing the choice of abatement policy.

Our paper is closely related to [Bovenberg, Heijdra, 1998, 2002; Heijdra et al., 2006; Karp, Rezai, 2014]. Their studies consider the use of debt policy to achieve Pareto improvements in the context of adverse climate change[7]. But their model differs from ours in three important ways. First, they confine environmental damage to the utility function. Second, they do not model clean as well as dirty energy, with dirty energy exhausting in the future based on the speed of technological change in the clean energy sector as well as climate change policy. Third, their focus is not on the Green Paradox, which we view as being of central importance for analyzing climate change policy.

In addition to explicating the paradoxical effects of phasing in emissions controls or carbon taxes and accelerating technological improvements in the production of green energy, our paper makes clear that social welfare valuations bear no fundamental connection to the derivation of Pareto efficient emissions policies. Introducing the preferences of a social planner does not impact the range of Pareto efficient solutions available to correct the negative externalities imposed on future generations by the burning of fossil fuels by current generations. Instead, it simply prevents society from understanding the full set of policies that are economically efficient, and potentially turns a win-win policy debate into one in which winners are pitted against losers.

2. Model

Firms

Final goods production is given by

$$Y_t = A_t K_{y,t}^{\alpha} L_{y,t}^{\beta} E_t^{1-\alpha-\beta}, \tag{1}$$

[7] [Karp, Rezai, 2014] also consider a life-cycle model, but explore the degree to which policy-induced general equilibrium changes in factor and asset prices could affect a Pareto improvement with no direct redistribution across generations.

where Y_t is final output and A_t, $K_{y,t}$, $L_{y,t}$, E_t reference total factor productivity and the three inputs used to produce this output, namely capital, labor, and energy[8]. Profit maximization requires

$$\alpha A_t K_{y,t}^{\alpha-1} L_{y,t}^{\beta} E_t^{1-\alpha-\beta} = r_t + \delta, \tag{2}$$

$$\beta A_t K_{y,t}^{\alpha} L_{y,t}^{\beta-1} E_t^{1-\alpha-\beta} = w_t, \tag{3}$$

and

$$(1-\alpha-\beta) A_t K_{y,t}^{\alpha} L_{y,t}^{\beta} E_t^{-\alpha-\beta} = p_t, \tag{4}$$

where r_t, δ, w_t and p_t reference the real interest rate, the capital depreciation rate, the real wage rate, and the price of energy, respectively.

We assume that clean and dirty energy, S_t and O_t, substitute perfectly in producing energy, hence

$$E_t = S_t + O_t. \tag{5}$$

Production of clean energy obeys

$$S_t = B_t K_{s,t}^{\theta} L_{s,t}^{\varphi} H_t^{1-\theta-\varphi}, \tag{6}$$

where B_t, $K_{s,t}$, $L_{s,t}$, H_t reference, respectively, the clean energy sector's productivity level and its demands for capital, labor, and land. For simplicity we assume that both labor and land are fixed in supply.

Profit maximization in the clean energy sector implies

$$p_t \theta B_t K_{s,t}^{\theta-1} L_{s,t}^{\varphi} H_t^{1-\theta-\varphi} = r_t + \delta, \tag{7}$$

$$p_t \varphi B_t K_{s,t}^{\theta} L_{s,t}^{\varphi-1} H_t^{1-\theta-\varphi} = w_t, \tag{8}$$

and

$$p_t (1-\theta-\varphi) B_t K_{s,t}^{\theta} L_{s,t}^{\varphi} H_t^{-\theta-\varphi} = n_t, \tag{9}$$

where n_t is the rental price of land.

Oil firms face no costs in extracting and supplying their reserves, R_{t-1}, which they do to maximize market value, V_t, given by

$$V_t = \sum_{s=0}^{\infty} (p_{t+s} - \tau_{t+s})\, O_{t+s} \left(\prod_{i=0}^{s} \frac{1}{1+r_{t+i}} \right), \tag{10}$$

where

$$R_t = R_{t-1} - O_t,\ R_t \geq 0. \tag{11}$$

[8] One can argue over the appropriate form of this production function. Take the production of transportation. Miles driven by a car at a fixed speed are clearly subject to fixed coefficient technology between capital and energy. On the other hand, if the price of energy rises, people can use public transportation and collectively consume transportation with more capital relative to labor. Based on examples like this, we believe our Cobb–Douglas formulation is appropriate. This said, we had simulated our model treating capital and energy as perfect complements in production, i.e., we had assumed $Y_t = A_t(\min(K_{y,t}, \kappa E_t))^{1-\beta} L_{y,t}^{\beta}$. The results proved quite different from those presented here. In particular, the Green Paradox no longer arises. Intuitively, since capital is fixed in the short run, the short-run demand for energy, in general, and oil, in particular, is not greatly impacted by announcements of future oil taxation.

Let T stand for the date of dirty energy exhaustion[9]. Prior to period $T+1$, as Rule dictates [Hotelling, 1931], oil producers must be indifferent, at the margin, as to when they supply oil. This requires equality in the present value of net extraction prices,

$$p_t - \tau_t = \frac{p_{t+1} - \tau_{t+1}}{1 + r_{t+1}},\ t \le T - 1, \tag{12}$$

where τ_t is the absolute tax per unit of oil levied at time t. The condition for exhaustion at T is

$$p_T - \tau_T \ge \frac{p_{T+1} - \tau_{T+1}}{1 + r_{T+1}}. \tag{13}$$

The value of land, Q_t, satisfies

$$Q_t = \sum_{s=0}^{\infty} n_{t+s} H_{t+s} \left(\prod_{i=0}^{s} \frac{1}{1 + r_{t+i}} \right). \tag{14}$$

Modeling Climate Change's Negative Externality

Following [Nordhaus, 1994, 2008, 2010; Nordhaus, Yang, 1996] and the associated climate change literature, we assume that productivity in final goods production depends negatively on CO_2 concentration. Specifically, we modify [Golosov et al., 2014] formulation, which represents a reduced form for the temperature-based, CO_2 concentration damage mechanism posited in [Nordhaus, 1994] seminal paper.

[Golosov et al., 2014] assume that CO_2 concentration has permanent and temporary components, with the permanent component depending solely on cumulative CO_2 emissions. In our model, this is simply the sum of initial, time-0 CO_2 concentration plus the additional concentration arising from exhausting, over time, R_0—the time-0 stock of oil reserves[10]. We modify the [Golosov et al., 2014] formulation by making climate damage the sum of two components. The first one is a function of the maximum past CO_2 concentration level. The second one captures tipping point damage, which is triggered if CO_2 concentration exceeds a critical threshold.

To be precise, we define the damage to output's productivity at time t, D_t, as

$$D_t = 1 - \exp(-\gamma \max_{s \le t}([J_s - \bar{J}])) + gG, \tag{15}$$

where $g=0$ for $J_s < J^*$ and $g=1$ for $J_s \ge J^*$. The term J_t references CO_2 concentration at time t, $\bar{J}$ is the pre-industrial CO_2 concentration level, and J^* is the critical tipping point value of CO_2 concentration[11]. In (15)

[9] We assume that exhaustion occurs at the end of period T.

[10] [Golosov et al., 2014] model has no steady state. Instead, it potentially features permanently increasing climate change damage arising from the ongoing use of coal, which is assumed to be in infinite supply.

[11] This is [Golosov et al., 2014] damage function apart from the maximum operator.

the highest past level of CO_2 emissions determines the first component of damages. The second component, which entails a potential damage level of G, is triggered for all future periods if the current concentration level exceeds J^*. Climate change damages output productivity according to

$$A_t = (1 - D_t)Z_t. \tag{16}$$

CO_2 concentration at time t, J_t, is the sum of the permanent and temporary components, $J_{1,t}$ and $J_{2,t}$, i.e.,

$$J_t = J_{1,t} + J_{2,t}. \tag{17}$$

The permanent carbon concentration component, $J_{1,t}$, evolves according to

$$J_{1,t} = J_{1,t-1} + d_L O_t. \tag{18}$$

The temporary concentration component, $J_{2,t}$, depreciates at rate d with additions to the temporary stock of carbon depending on the share, $1 - d_L$, absorbed by the oceans and other carbon sinks, and d_0, the extent to which non-absorbed carbon reaches the atmosphere:

$$J_{2,t} = (1-d)J_{2,t-1} + d_0(1 - d_L)O_t. \tag{19}$$

Technical Change

We assume that technology improves according to

$$Z_t = Z_0 \exp(g_Z t), \tag{20}$$

and

$$B_t = B_0 \exp(g_B t). \tag{21}$$

As shown below, g_Z can differ from g_B without preventing long-run balanced growth. Indeed, our model admits many different long-run balanced growth paths. These include steady states in which output grows faster or slower than energy supply. If energy supply grows at a slower rate than output, its price must fall through time.

Households

Households born at time t maximize utility defined over the logarithm of consumption when young, c_t^y, and consumption when old, c_{t+1}^o:

$$U = (1 - m)\log c_t^y + m \log c_{t+1}^o. \tag{22}$$

Households work only when young. Oil revenues, $\tau_t O_t$, in period t, are transferred to the contemporaneous elderly. Since the elderly collectively own time-t oil reserves, this use of oil revenues limits the economic impact of carbon taxation to its direct effect on dirty energy production[12].

Maximization of (22) is subject to

$$c_t^y + \frac{c_{t+1}^o}{1+r_{t+1}} = w_t L_t + \frac{\tau_{t+1} O_{t+1}}{1+r_{t+1}}. \tag{23}$$

Since generations consume a fixed share, $1-m$, of their lifetime resources when young,

$$c_t^y = (1-m)\left(w_t L_t + \frac{\tau_{t+1} O_{t+1}}{1+r_{t+1}} \right), \tag{24}$$

and the savings of the young satisfies

$$K_{t+1} + V_{t+1} + Q_{t+1} = m w_t L_t - (1-m)\frac{\tau_{t+1} O_{t+1}}{1+r_{t+1}}. \tag{25}$$

Sectoral Allocation of Inputs

When $t > T$ the distribution of capital and labor in the output and energy sectors satisfies

$$K_{y,t} = \frac{\alpha}{\theta(1-\beta) + \alpha(1-\theta)} K_t, \tag{26}$$

$$K_{s,t} = \frac{(1-\alpha-\beta)\,\theta}{\theta(1-\beta) + \alpha(1-\theta)} K_t, \tag{27}$$

$$L_{y,t} = \frac{\beta}{\varphi(1-\alpha) + \beta(1-\varphi)} L, \tag{28}$$

and

$$L_{s,t} = \frac{\varphi(1-\alpha-\beta)}{\varphi(1-\alpha) + \beta(1-\varphi)} L. \tag{29}$$

When $t \leq T$, factor allocation across sectors is more complex. However, the system of factor supply and demand equations can be reduced to the following four equations in sector-specific capital and labor demands. These demands can be solved non-linearly for a given price of energy.

$$L_{s,t} = \left(\begin{matrix} A_t (1-\alpha-\beta)^{1-\alpha-\beta} \alpha^{\alpha} \beta^{\beta} \theta^{-\alpha} \varphi^{-\beta} \\ B_t^{-\alpha-\beta} H^{(\alpha+\beta)(\varphi+\theta-1)} p_{t-1} K_{s,t}^{\alpha-\theta(\alpha+\beta)} \end{matrix} \right)^{\frac{1}{\varphi(\alpha+\beta)-\beta)}}, \tag{30}$$

$$L_{y,t} = L - L_{s,t}, \tag{31}$$

[12] I.e., it rules out intergenerational redistribution or changes in government consumption, which would have independent impacts on the economy's transition.

$$K_{y,t} = \frac{\alpha\varphi}{\beta\theta}\frac{L_{y,t}}{L_{s,t}}K_{s,t}, \qquad (32)$$

and

$$K_t = K_{y,t} + K_{s,t}. \qquad (33)$$

Long-Run Balanced Growth

In the long run, after all oil reserves have been extracted and climate change damage has stabilized, output and clean energy grow at rates g_Y and g_S determined by

$$g_Y = \frac{g_Z + (1-\alpha-\beta)\,g_B}{1-\alpha-\theta(1-\alpha-\beta)}, \qquad (34)$$

and

$$g_S = g_B + \theta\frac{g_Z + (1-\alpha-\beta)\,g_B}{1-\alpha-\theta(1-\alpha-\beta)}. \qquad (35)$$

In addition, the prices of energy and land grow at rates g_P and g_N determined by

$$g_P = \frac{g_Z(1-\theta) - g_B\beta}{1-\alpha-\theta(1-\alpha-\beta)}, \qquad (36)$$

and

$$g_N = \frac{g_Z + (1-\alpha-\beta)\,g_B}{1-\alpha-\theta(1-\alpha-\beta)} \equiv g_Y. \qquad (37)$$

It is easy to show that, along the economy's balanced growth path, the wage rate grows at g_Y and that the return to capital is constant.

These equations admit a range of long-run dynamics. To illustrate, Figure 1 presents long-run growth rates in the supply and price of solar energy for a) alternative values of the parameters g_B, the rate of technical change in solar energy, θ, the share of capital in producing solar energy, and b) empirically reasonable values of the parameters α, β, and g_Y, respectively[13].

Since our model excludes population growth, we set g_Y to 0.01, which comports with annual per capita GDP growth of 1 percent. This is in line with recent experience in developed countries. We also set capital's share in the production of output at 30 percent and labor's share at 65 percent, hence $\alpha = 0.30$ and $\beta = 0.65$. This makes energy's output share 5 percent[14].

Figure 1 shows different implied annual growth rates of solar production and the price of solar for different combinations of θ and g_B. The light plane, which is flat with a height of zero for all combinations

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[13] Note that given these parameter values, q_Z is determined by (34).

[14] These values are very close to those in [Golosov et al., 2014].

of the two parameters, clarifies that growth in solar output is never negative and is highest when the price of solar is falling most rapidly. Since output is assumed to be growing at a 1 percent annual rate, our model can produce much more rapid growth in solar energy than in output. It can also produce slower growth.

In the case that θ, like α, equals 0.30 and g_B equals 0.01 (i.e., 1 percent technical change in solar per year), g_Z, the underlying annual rate of technical change in producing output, Y, is 0.006. That is, output grows annually about two thirds faster than its rate of technical change. For these parameters, solar energy grows at 1.3 percent per year and its price falls at 0.3 percent per year. However, the higher growth rate in output than in energy is not primarily due to the faster growth in solar energy, but to the growth rate in the stock of capital, which is also 1 percent each year.

If θ is 0.30, but technical growth in solar, g_B, is quite rapid—say, 2 percent per year—solar energy will grow at 2.3 percent annual. Its price will fall by 1.3 percent. Since these are permanent growth rates, our economy's long-run price of energy will asymptotically approach zero.

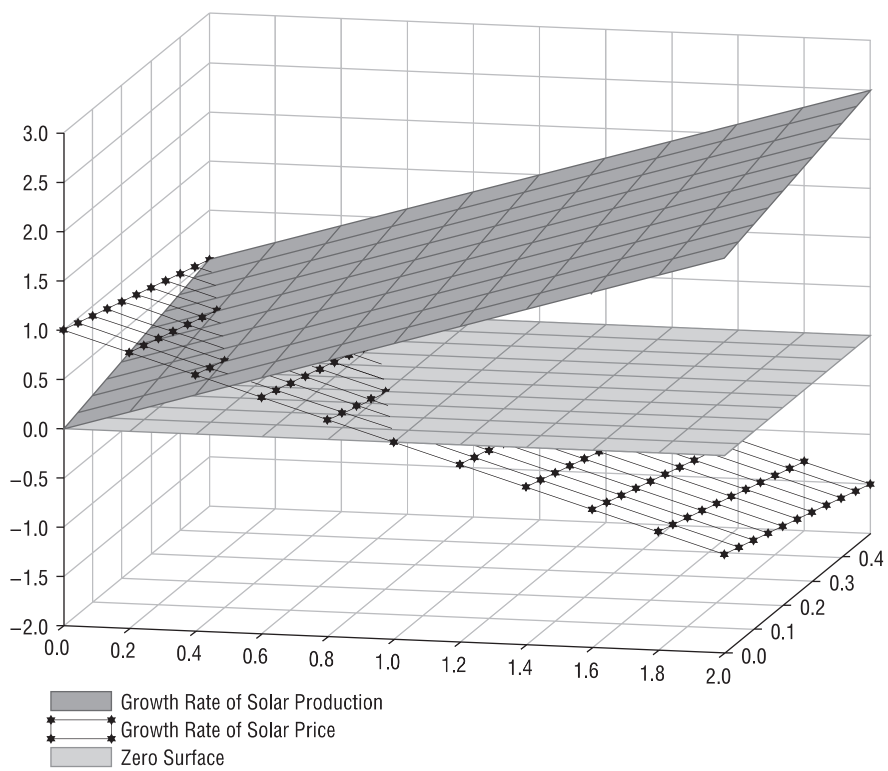

Figure 1. **Growth Rates per Year** (percentage points, vertical axis), **Rate of Technical Change in Solar Energy per Year** (percentage points, x-axis) **and Share of Capital in Producing Solar Energy** (y-axis)

Note that we have been discussing long-run growth rates. But it is important to bear in mind that the absolute levels of output, wages, and consumption will, at any point in time, including any time along the economy's balance growth path, be smaller based on the degree to which the transition to balance growth has involved higher concentration of CO_2. Stated differently, given that climate change's damage depends on the highest past level of CO_2 emissions, all future generations will be negatively impacted by earlier generations that let carbon levels reach new heights, however temporarily.

3. Solving the Transition

To solve the model's transition, we first normalize the time-t levels of all variables, X_t, by their specific cumulative long-run growth factors, $e^{g_X t}$. I.e., we define

$$\hat{X}_t = \frac{X_t}{e^{g_X t}}, \tag{38}$$

and rewrite all equations of our model in terms of these transformed variables.

For example, the transformed equation for final output production is

$$\hat{Y}_t = (1 - D_t)\, \hat{Z}_t \hat{K}^{\alpha}_{y,t} L^{\beta}_{y,t} \hat{S}^{1-\alpha-\beta}_t. \tag{39}$$

For a second example, the transformed equation for equilibrium in the final goods market is

$$\hat{Y}_t = e^{g_Y} \hat{K}_{t+1} - (1 - \delta)\, \hat{K}_t + \hat{c}^{y}_t + \hat{c}^{o}_t. \tag{40}$$

The transformed system of equations has a well-defined stationary state (i.e., all transformed variables are constant). This means, of course, that the model's original variables grow in the long run at the rate used in their normalization. Note, in this regard, than in (39) the value of D_t will vary through time along the transition path, but be constant along the economy's balanced growth path.

We provide an informal description of our solution method here and provide details in Appendix. In solving the normalized model's transition we use the initial conditions for capital, oil reserves, and temporary and permanent levels of CO_2 emissions, K_0, R_{-1}, $J_{1,-1}$ and $J_{2,-1}$, respectively.

We assume (but subsequently verify) that the economy reaches its balanced growth path by date M. Next we guess a path of damages, D_t, from $t = 1$ through M. We solve the entire transition conditional on this guessed path of damages and then update the guessed path of damages and resolve the model. In the final solution to the model, the guessed path of damages is consistent with the model's actual path of damages.

For any assumed path of damages, we start with a guess of $T=0$. In step 2, we guess the path for $\hat{K}_t$ for $t=1$ through $T+1$. In step 3, we use our guessed value of $\hat{K}_{T+1}$ to solve for the economy's transition from T onward using the method in [Auerbach, Kotlikoff, 1987].

The solution for the post-T economy's transition yields, among other things, a value for p_{T+1}. In step 4, we use this value to guess the path of p_t for $0 \leq t \leq T$. Specifically, we backcast the values for p_t by assuming that their path obeys (13) with equality. To do this, we first assume that the path of returns from $t=0$ to $t=T$ is constant and equals the long-run value of r found in step 3.

In step 5 we iterate over our guessed path of $\hat{K}_t$ through $t=T+1$ and all other of the models' variables for periods up through T. I.e., we solve for factor allocations, wage rates, and returns. In each iteration, we use the updated rate of return series to update our backcast of p_t.

In step 6 we check if oil reserves exhaust at our guessed value of T, i.e., if cumulative oil consumption through T exceeds R_0. If they do not, we raise T to $T+1$ and return to step 3. Once we find a time T^* such that cumulative oil consumption oil exceeds initial reserves, we set $T=T^*$ and repeat step 5 but base our backcasting off of a guessed value of p_T that is larger than $\tau_T + \frac{p_{T+1} - \tau_{T+1}}{1 + r_{T+1}}$. In this inner loop we adjust the value of p_T upward until we find the lowest value which is consistent with cumulative oil consumption through time T equaling initial reserves. This condition is simply that the oil market clears on an intertemporal basis. Note that any higher price would entail less demand for oil through T and would not, therefore, be consistent with exhaustion at T.

Once we have found paths of the economy through period T and beyond that are consistent with market clearing in the intertemporal oil market, we use the path of oil production to update our guess of D_t and repeat the entire analysis starting at step 1 until the guessed path of D_t equals the assumed path of D_t.

4. Calibration

We chose the following parameters for our baseline calculations. The share of wages saved by the young, m, is set to 0.5. The capital, labor, and energy shares in (1) (the coefficients α, β, and $(1-\alpha-\beta)$ in the production function for output) are set to 0.3, 0.65, and 0.05, respectively. The capital, labor, and land shares in (6) (the coefficients θ, φ, and $(1-\theta-\varphi)$ in the production function for clean energy) are set to 0.2, 0.2, and 0.6, respectively. The depreciation rate, δ, is set to 1.0. The technology coefficients, A and B, are set to 12 and 15, respectively. If the climate is not tipped, the long-run damage to output productivity, absent policy, is

30 percent. The trigger point concentration level, J^*, equals 45. We set G such that steady-state damages, if the tipping point is triggered, equal 50 percent of output productivity.

The initial stocks of reserves, R_0, and capital, K_0, are set to 50 and 3, respectively. The quantity of land, H, is normalized to 1. The climate change damage parameters, γ, d_L, d_0, and d, are set to 0.009, 0.2, 1, and 0.2. Our total factor productivity growth rates, g_z and g_B, are set to 0.67 percent and 0.82 percent[15].

These parameters were chosen to generate the following realistic macroeconomic relationships. Dirty energy initially constitutes 95 percent of total energy supply. This no-policy baseline economy's real return to capital, measured on an annual basis, is 1.5 percent, initially, and 2 percent in the long run. The long-run growth rate of output is 1.03 percent, the long-run growth rate of clean energy is also 1.03 percent, and the long-run growth rate of the price of energy is zero.

5. Simulation Findings

The Baseline, No Carbon Tax Transition Path

Our baseline simulation, which features no policy, is depicted in Figure 2. All variables are detrended by their long-run growth rate. The initial value of capital is taken from the economy's steady state in the absence of any climate damage.

As can be seen, the depletion of oil occurs at the end of the fourth period, roughly 120 years in real time, although most of the depletion occurs in the first two periods, roughly 60 years. Carbon concentration, J_t, rises through time, but never passes the tipping point. At time 0, the level of carbon damage, D_t, is close to 0.2, i.e., 20 percent. In the long run, D_t equals 0.3. This increase in damages and the induced decline in capital as well as the long-run reduction in energy produces a roughly one third decline in output compared to its level at time 0.

As oil is depleted, the price of energy rises as does the supply of clean energy. The damage inflicted on the economy lowers real wages, which limits the ability of young workers to save. Consequently, the capital stock falls relative to its initial value. So too does consumption of the young and old. The charts also show a reallocation of capital between the output and clean energy sectors. As expected, the rental rate and price of land both rise reflecting the higher demand for clean energy. The relative scarcity of capital leads to a higher real interest rate. The value of oil reserves naturally declines to zero as the reserves are depleted. Interestingly, the economy becomes less energy-intensive in the long run.

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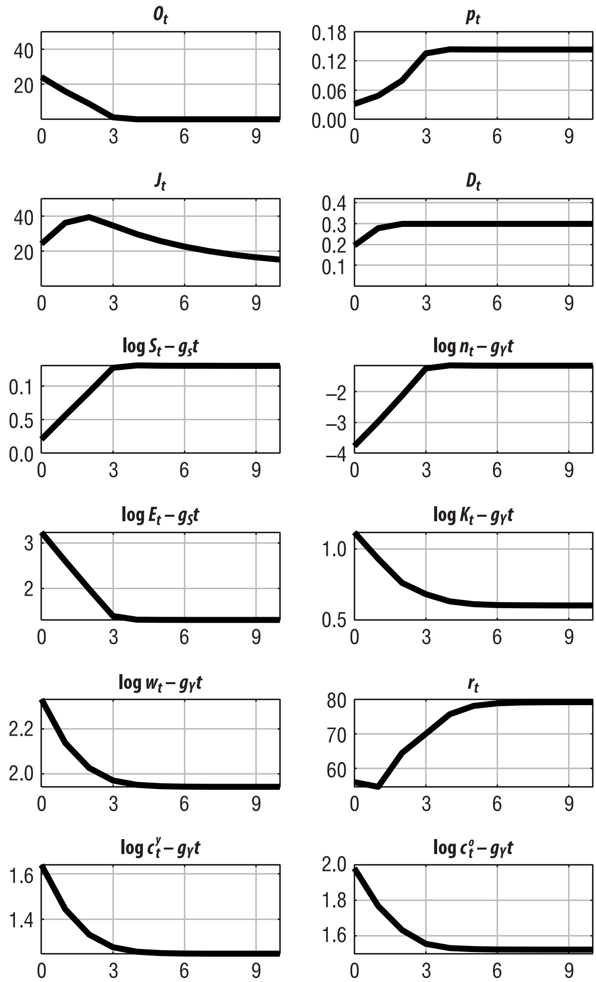
[15] These are annual growth rates.



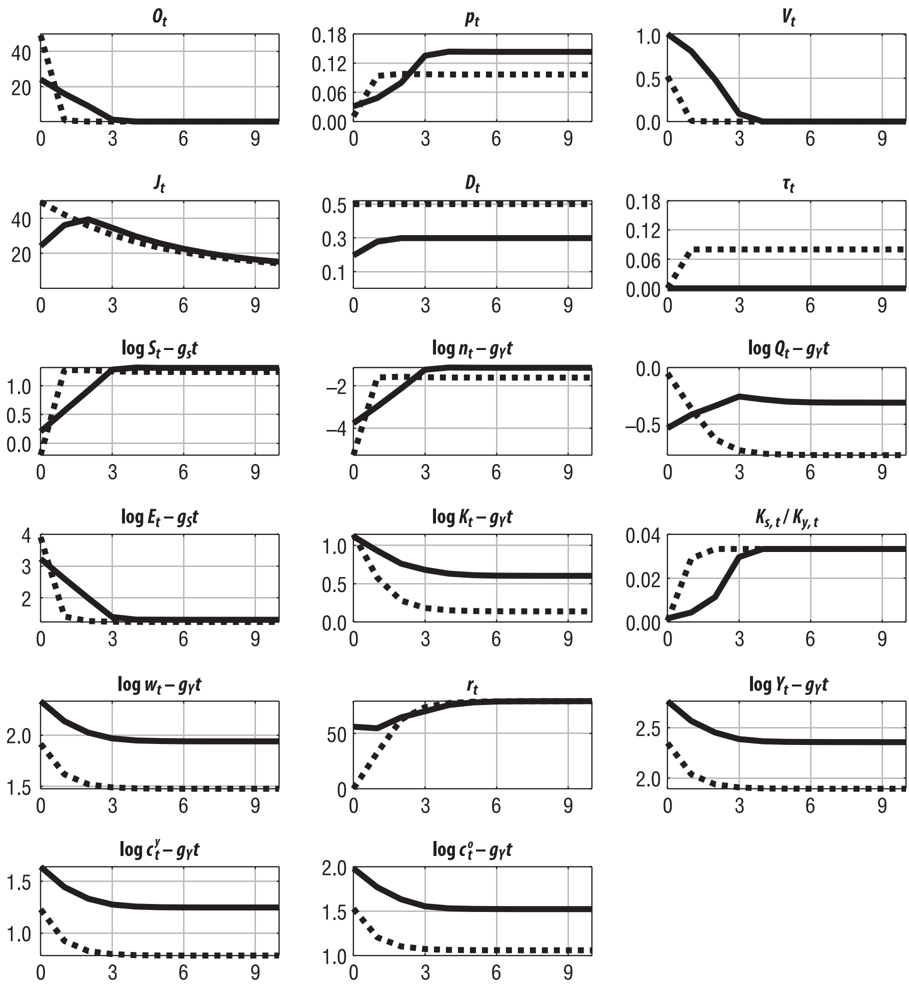
Note: O_t — oil, p_t — price of energy, V_t — value of oil company, J_t — CO_2 concentration, D_t — damages, τ_t — absolute tax per unit of oil, S_t — clean energy production, n_t — rental price of land, Q_t — value of land, E_t — total energy consumption, K_t — total capital, $K_{s,t}$ — clean energy sector's capital, $K_{y,t}$ — final goods production sector's capital, w_t — real wage rate, r_t — real interest rate, Y_t — final output, c_t^y — consumption of young households, c_t^o — consumption of old households, g_Y — steady state growth rate of output, g_S — steady state growth rate of clean energy.

Figure 2. **Baseline Simulation**

The Delayed Carbon Tax Transition Path

Figure 3 considers the introduction of a permanent absolute tax equal to 0.08 starting in period 1. The solid curves reference the baseline transition. The dotted curves reference the transition under the period-1 (i.e., delayed) carbon tax. Dirty energy producers respond to this "use it or lose it" policy by exhausting all oil reserves in the initial, time-0, period. This faster fossil fuel burn produces both earlier and larger damages. Indeed, carbon concentration becomes sufficiently high to tip the climate.

As a result, initial as well as all future generations end up consuming less, both when young and when old. Consequently, the delayed carbon tax policy produces a Pareto loss. The loss is substantial. All generations suffer declines in remaining lifetime consumption of roughly 40 percent.

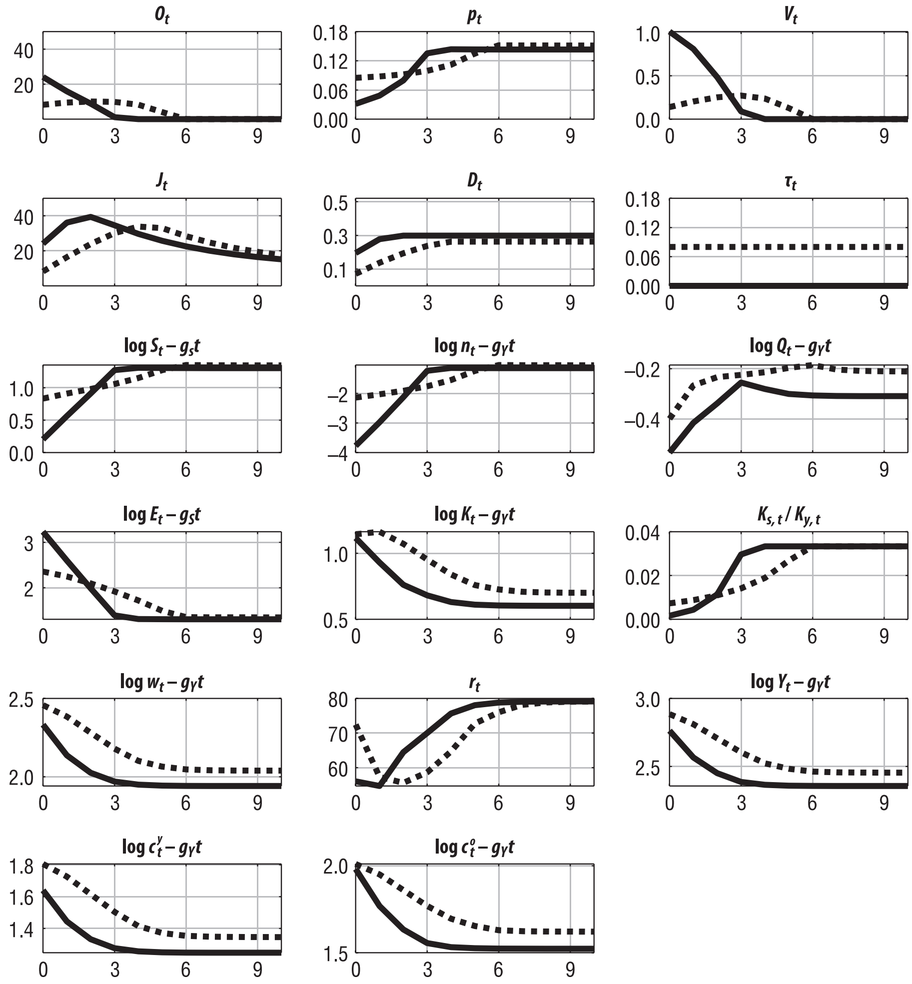


Note: Solid line indicates baseline. Dotted line indicates tax policy. O_t — oil, p_t — price of energy, V_t — value of oil company, J_t — CO_2 concentration, D_t — damages, τ_t — absolute tax per unit of oil, S_t — clean energy production, n_t — rental price of land, Q_t — value of land, E_t — total energy consumption, K_t — total capital, $K_{s,t}$ — clean energy sector's capital, $K_{y,t}$ — final goods production sector's capital, w_t — real wage rate, r_t — real interest rate, Y_t — final output, c_t^y — consumption of young households, c_t^o — consumption of old households, g_Y — steady state growth rate of output, g_S — steady state growth rate of clean energy.

Figure 3. **Tax Introduced in Period 1**

The Immediate Carbon Tax Transition Path

Figure 4 shows the impact of implementing the same carbon tax, but starting in period 0. The solid curves, again, reference the no-policy transition and the dotted curves reference the transition with an immediate carbon tax. This alternative policy gives dirty energy producers a strong incentive to delay production. Indeed, rather than exhaust after one period (30 years), exhaustion occurs by in six (approximately 180 years). This much slower fossil fuel burn reduces damages in both the short and long runs. It also produces higher levels of consumption of all generations in all periods of life alive at time 0 and thereafter. I.e., it produces a Pareto gain.



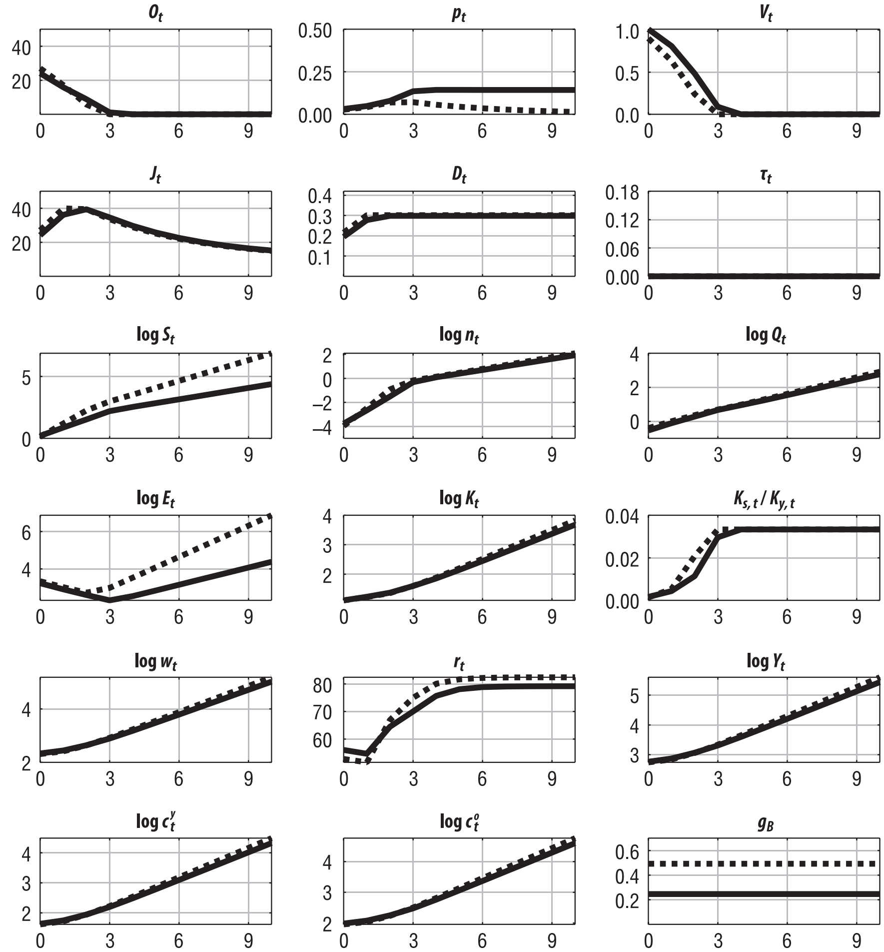
Note: Solid line indicates baseline. Dotted line indicates tax policy. O_t — oil, p_t — price of energy, V_t — value of oil company, J_t — CO_2 concentration, D_t — damages, τ_t — absolute tax per unit of oil, S_t — clean energy production, n_t — rental price of land, Q_t — value of land, E_t — total energy consumption, K_t — total capital, $K_{s,t}$ — clean energy sector's capital, $K_{y,t}$ — final goods production sector's capital, w_t — real wage rate, r_t — real interest rate, Y_t — final output, c_t^y — consumption of young households, c_t^o — consumption of old households, g_Y — steady state growth rate of output, g_S — steady state growth rate of clean energy.

Figure 4. **Tax Introduced in Period 0**

The Impact of Technological Change on the Transition

This simulation uses the same initial conditions as in the baseline scenario. It differs solely in positing a faster rate of technological change in clean energy production[16]. Specially, we double the growth rate of B_t, g_B, from 0.82 to 1.64 percent on an annual basis.

Figure 5 shows the variables without detrending to make clear what happens to absolute values[17]. There is, as one would expect, a lower price



Note: Solid line indicates baseline. Dotted line indicates transition with the double growth rate g_B. O_t — oil, p_t — price of energy, V_t — value of oil company, J_t — CO_2 concentration, D_t — damages, τ_t — absolute tax per unit of oil, S_t — clean energy production, n_t — rental price of land, Q_t — value of land, E_t — total energy consumption, K_t — total capital, $K_{s,t}$ — clean energy sector's capital, $K_{y,t}$ — final goods production sector's capital, w_t — real wage rate, r_t — real interest rate, Y_t — final output, c_t^y — consumption of young households, c_t^o — consumption of old households, g_Y — steady state growth rate of output, g_S — steady state growth rate of clean energy.

Figure 5. **The Transition with Faster Technical Progress in Clean Energy**

[16] We assume that this shock to technology was not known prior to period 0.

[17] Figure B1 in Appendix B show detrended variables.

path of energy, even in period 0. This produces more and thus faster use of dirty energy, but, actually, less short-run use of clean energy. Consequently, there is little impact on the economy in time 0.

Our next simulation considers a major, but one-time jump in the level of clean energy technology, B_t, occurring in the second period ($t=1$). We assume that in subsequent periods B_t grows at the baseline growth rate. We calibrate the size of the jump to produce the same long-run after-tax price of energy as in the delayed carbon tax scenario (Figure 3).

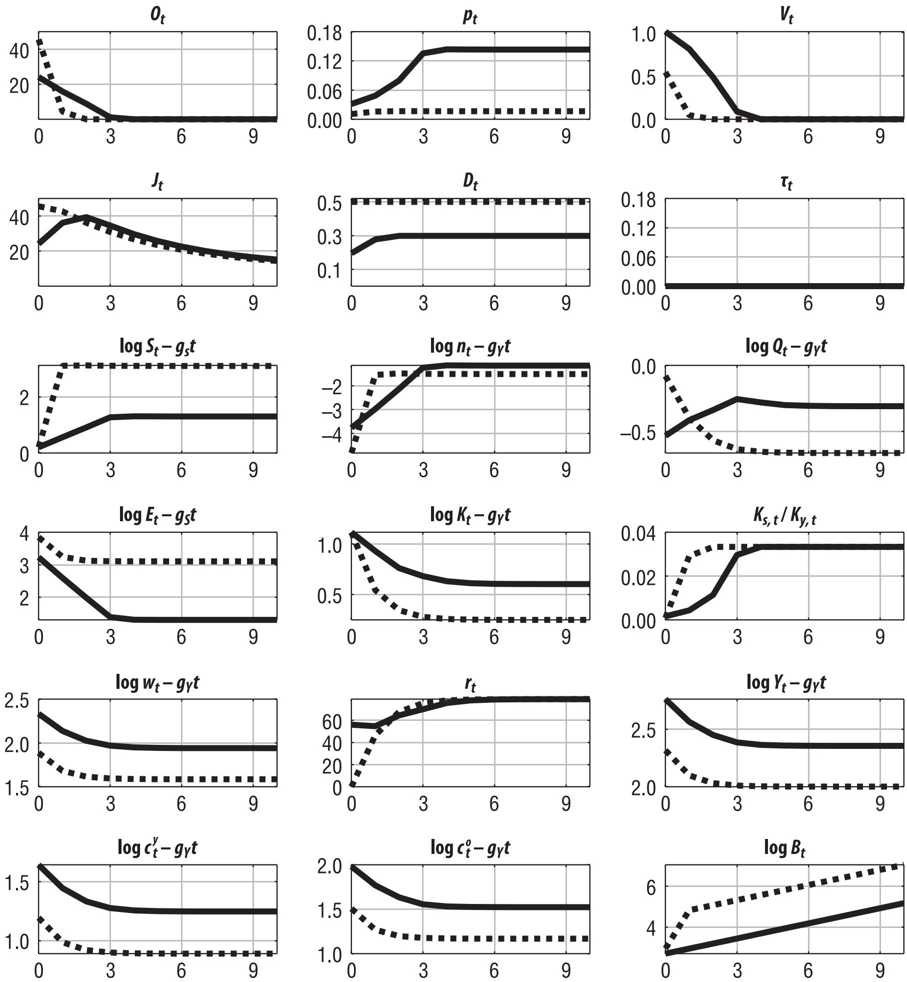
As Figure 6 shows, if the market perceives that clean energy technology will improve significantly in the not-too-distant future, the price of energy will fall dramatically and most of the economy's existing oil reserves will immediately be extracted. Like delaying the imposition of a significant carbon tax, this path of emissions tips the climate, dramatically and permanently exacerbating carbon damage. This, in turn, significantly reduces both output and capital formation, producing a substantial Pareto loss for all generations. The price of land first rises and then falls during the transition relative to the baseline. This reflects the near-term higher level of technology and thus marginal productivity of land, and the lower short-run interest rates. Over time, though, the environmental damage reduces the marginal productivity of all inputs, including energy, and this, in turn, lowers the discounted present value of future land rents.

A comparison of 5 and 6 indicates that exactly how clean energy is expected to evolve can make a major difference to whether we have a fast or slow burn and whether the planet's climate tips or not. In Figure 6, the near-term technical advance leads dirty energy producers to exploit their reserves at a much faster rate, producing considerable external damage. Therefore, good news about clean energy technology improvements can spell bad news for the planet and for both current and future generations.

Figure 7 depicts the variables without trend elimination[18]. It shows the impact of a faster rate of technical progress in the final goods production sector. Specifically, we double the growth rate of Z_t from 0.67 to 1.34 percent on annual basis. All variables that grow, in the long run, at rate g_Y are shown without the g_Y offset to make clear how the level of the variable has changed in the baseline, where g_Y has a smaller value.

This raises the demand for energy and its price, relative to the baseline scenario, continues growing in the long run. On the other hand, the more rapid technical change increases the growth rate and level of interest rates. This leaves oil producers with no reason to exhaust their reserves at a quicker pace than in the baseline.

[18] Figure B2 in Appendix B shows the detrended variables.

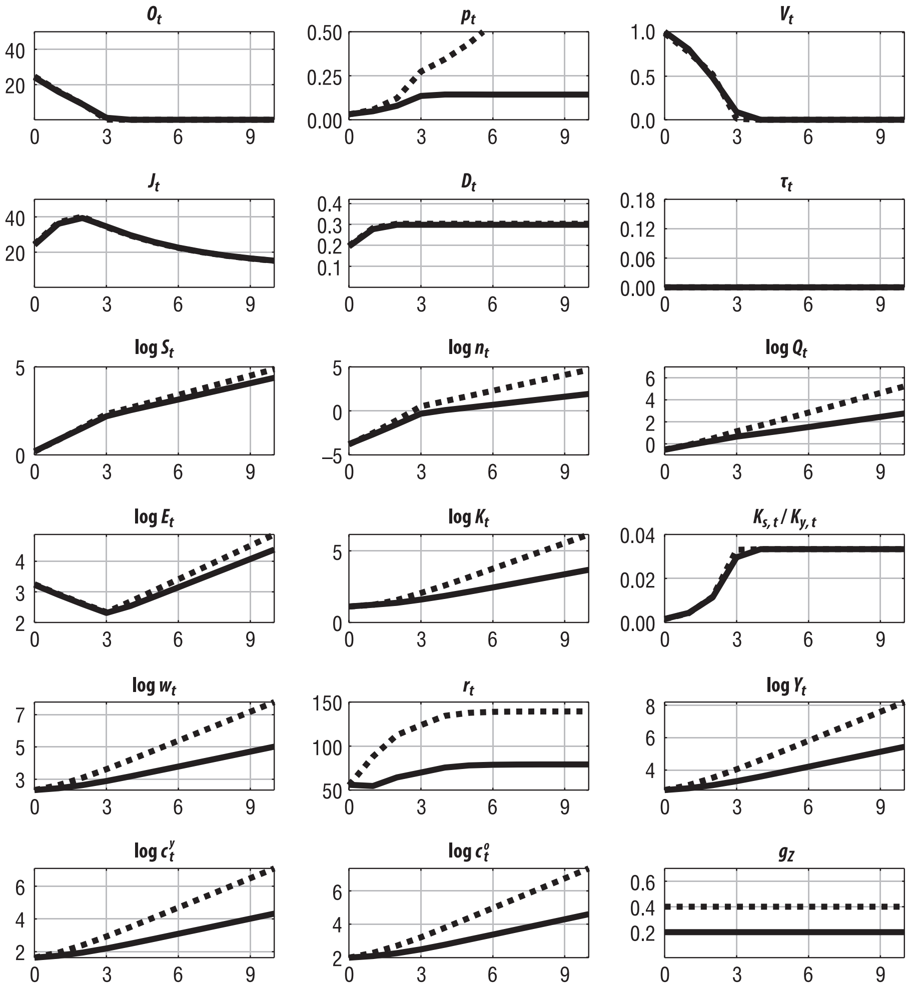


Note: Solid line indicates baseline. Dotted line indicates transition with the jump in clean energy productivity B_t. O_t — oil, p_t — price of energy, V_t — value of oil company, J_t — CO_2 concentration, D_t — damages, τ_t — absolute tax per unit of oil, S_t — clean energy production, n_t — rental price of land, Q_t — value of land, E_t — total energy consumption, K_t — total capital, $K_{s,t}$ — clean energy sector's capital, $K_{y,t}$ — final goods production sector's capital, w_t — real wage rate, r_t — real interest rate, Y_t — final output, c_t^y — consumption of young households, c_t^o — consumption of old households, g_Y — steady state growth rate of output, g_S — steady state growth rate of clean energy.

Figure 6. **The Transition with an Anticipated Major Jump in Clean Energy Technology in Period 1**

Figure 8 also shows results without controlling for trend[19]. It simulates a permanent doubling of both growth rates, g_B and g_Z. Thus g_Y also doubles and increases from 1.03 to 2.06 percent on annual basis. This experiment leads to a short-run decline in energy prices, but a much

[19] Figure B3 in Appendix B shows the detrended variables.

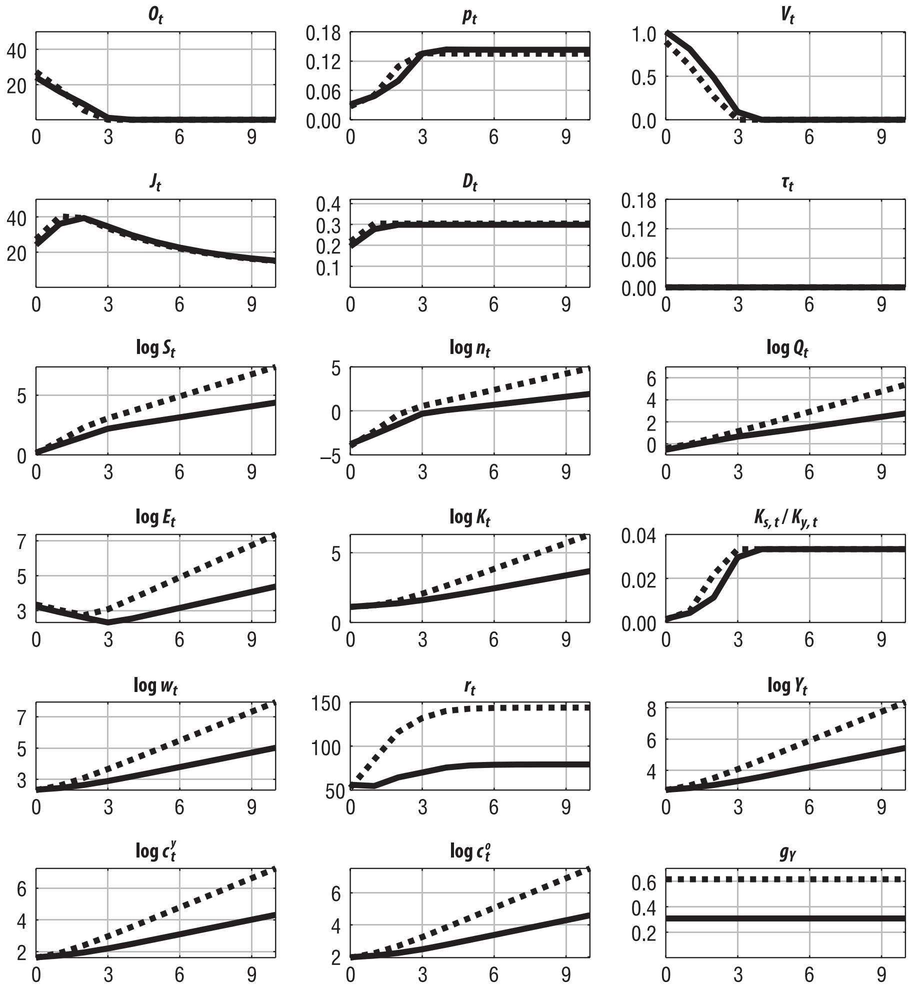


Note: Solid line indicates baseline. Dotted line indicates transition with the double growth rate g_Z. O_t — oil, p_t — price of energy, V_t — value of oil company, J_t — CO_2 concentration, D_t — damages, τ_t — absolute tax per unit of oil, S_t — clean energy production, n_t — rental price of land, Q_t — value of land, E_t — total energy consumption, K_t — total capital, $K_{s,t}$ — clean energy sector's capital, $K_{y,t}$ — final goods production sector's capital, w_t — real wage rate, r_t — real interest rate, Y_t — final output, c_t^y — consumption of young households, c_t^o — consumption of old households, g_Y — steady state growth rate of output, g_S — steady state growth rate of clean energy.

Figure 7. **Transition with Faster Technical Progress in the Final Goods Sector**

higher path of interest rates. The equilibrium response is faster exhaustion of oil and higher initial and permanent damages.

There are a number of offsetting factors underlying Figure 8. Clean energy technology is growing at a faster pace. This puts downward pressure on energy prices, but the higher growth rate of final goods technology exerts upward energy price pressure.



Note: Solid line indicates baseline. Dotted line indicates transition with the double growth rates g_B, and g_Z, and thus g_Y. O_t — oil, p_t — price of energy, V_t — value of oil company, J_t — CO_2 concentration, D_t — damages, τ_t — absolute tax per unit of oil, S_t — clean energy production, n_t — rental price of land, Q_t — value of land, E_t — total energy consumption, K_t — total capital, $K_{s,t}$ — clean energy sector's capital, $K_{y,t}$ — final goods production sector's capital, w_t — real wage rate, r_t — real interest rate, Y_t — final output, c_t^y — consumption of young households, c_t^o — consumption of old households, g_Y — steady state growth rate of output, g_S — steady state growth rate of clean energy.

Figure 8. **The Transition with Faster Economy-Wide Technical Progress**

Conclusion

This paper uses a bare bones model to make a simple but important point. The world's supply of dirty energy is, to a large extent, fixed in supply. This means that short of prohibiting its production and sale, most of the world's dirty energy will be used. The only question is when.

If it is used quickly, we will have a fast burn and the damage to the planet will, according to some estimates, be massive and irreversible. If it is used slowly, we will have a slow burn and the damage will be mitigated.

Unfortunately, delaying the implementation of carbon abatement policy, which we model as the delayed imposition of a carbon tax, gives dirty energy producers strong incentives to "use it or lose it." As our model shows, this can significantly accelerate the production and sale of carbon, leaving current and future generations worse off than in the absence of any abatement policy. In contrast, immediately implementing the same size carbon tax can materially limit climate damage and leave all generations better off. Our paper also shows that announcing a near-term, but one-time, improvement in clean energy technology can also lead dirty energy producers to use it before they lose it. Thus, we have the prospect of wonderful news of near-term clean energy technological improvements triggering terrible reactions by dirty energy producers, which make matters far worse than had there been no such good news.

Therefore, paradoxically, the Paris accord could be making climate change worse. So could certain incentives to improve green energy technology that will pay off only through time. This said, our findings make a strong case for climate policy provided that it occurs immediately.

Appendix A: Solution Algorithm

Step A. Find the Economy's Steady State

Guess $\hat{K}_i^e$, compute the supply of capital K^S, update $\hat{K}_{i+1}^e = 0.8\hat{K}_i^e + 0.2K^S$, and iterate until $|\hat{K}_{i+1}^e - \hat{K}_i^e| < \varepsilon$.

Step B. Find T

The price of energy at T satisfies

$$p_T - \tau_T \geq \frac{p_{T+1} - \tau_{T+1}}{1 + r_{T+1}} \quad \text{(A1)}$$

or

$$p_T - \tau_T = \chi \frac{p_{T+1} - \tau_{T+1}}{1 + r_{T+1}},\ \chi \in [1, \infty]. \quad \text{(A2)}$$

Let us set χ at 1 and find a date T at which cumulative oil consumption exceeds oil reserves, but at date $T - 1$ cumulative oil consumption is less than oil reserves. Then in step C we iterate on χ to equalize cumulative oil consumption and oil reserves at time T. We also define some large value, M, by which time the model converges to its steady state.

Step B1. Set $T = 0$.

Step B2. Set $\chi = 1$.

Step B3. Guess K_t^i, $t \in [1, T+1]$.

Step B4. Given the value of K_{T+1}^i in the non-oil regime, find a transition path from $T+1$ to the steady state by iterating over the path of capital. Guess K_t^j, $t \in [T+2, M-1]$, update $K_t^{j+1} = 0.8K_t^j + 0.2K_t^S$, $t \in [T+2, M-1]$, iterate until $\| K_t^{j+1} - K_t^j \|_\infty < \varepsilon$, $t \in [T+2, M-1]$. The converged solution provides paths for all variables at $t \in [T+2, M-1]$.

Step B5. Guess $p_T^0 = \tau_T + \chi \dfrac{p_{T+1} - \tau_{T+1}}{1+r^e}$, $p_t^0 = \tau_t + \dfrac{p_{t+1}^0 - \tau_{t+1}}{1+r^e}$, $t < T$.

Step B6. For $t \leq T$ and given the path for price of energy, determine the allocation of total capital and labor between clean energy and final goods production sectors using the bisection method to solve the nonlinear system of equations (30)–(33). Compute r_t and update the guess of the price path for energy: $p_T^i = \tau_T + \chi \dfrac{p_{T+1} - \tau_{T+1}}{1 + r_{T+1}}$, $p_t^i = \tau_t + \dfrac{p_{t+1}^i - \tau_{t+1}}{1 + r_{t+1}}$, $t < T$.

Step B7. Fixed point iterations on price of energy. Repeat step B6 until $\| p_t^{i+1} - p_t^i \|_\infty < \varepsilon$, $t \in [0, T]$.

Step B8. Compute capital supply K_t^S, $t \in [1, T+1]$. Update the path of capital $K_t^{i+1} = 0.8K_t^i + 0.2K_t^S$, $t \in [1, T+1]$.

Step B9. Repeat steps B4–B8 until $\| K_t^{i+1} - K_t^i \|_\infty < \varepsilon$, $t \in [1, T+1]$.

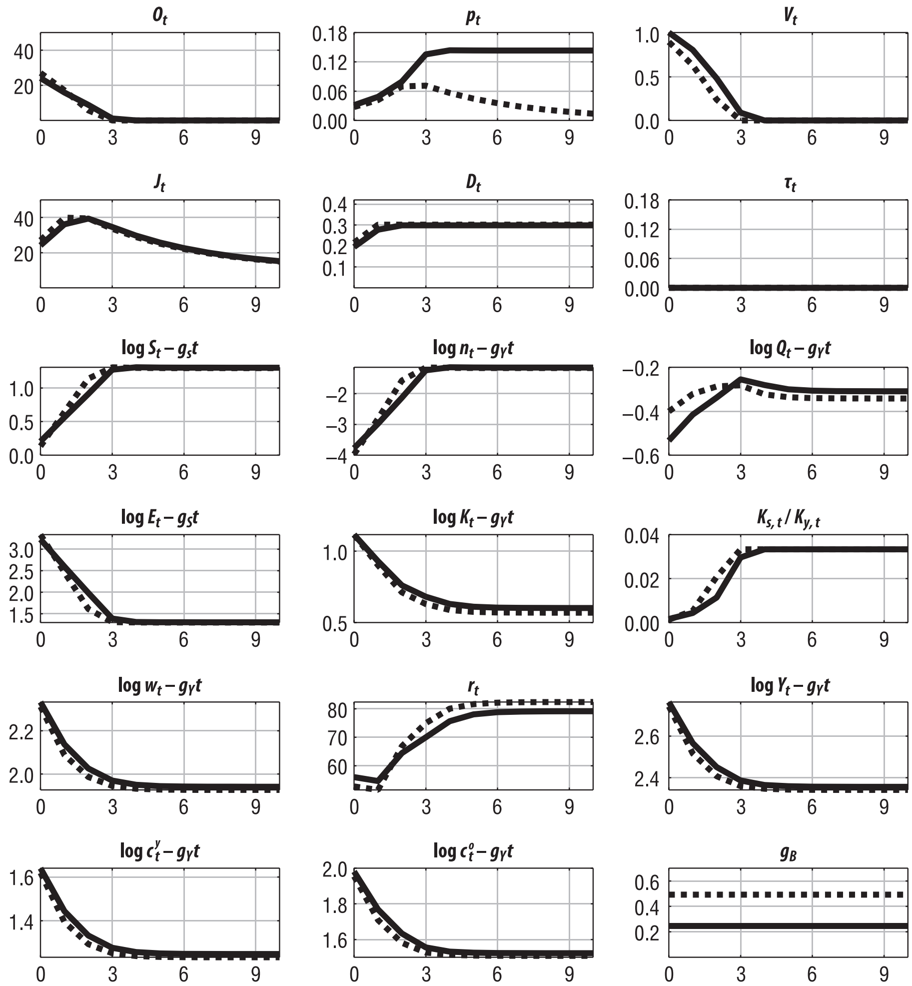
Step B10. Compute $\sum_{t=1}^{T} O_t$.

Step B11. If $\sum_{t=1}^{T} O_t < R_0$ set $T = T+1$ and repeat steps B2–B10, else stop.

Step C. Find Transition Path

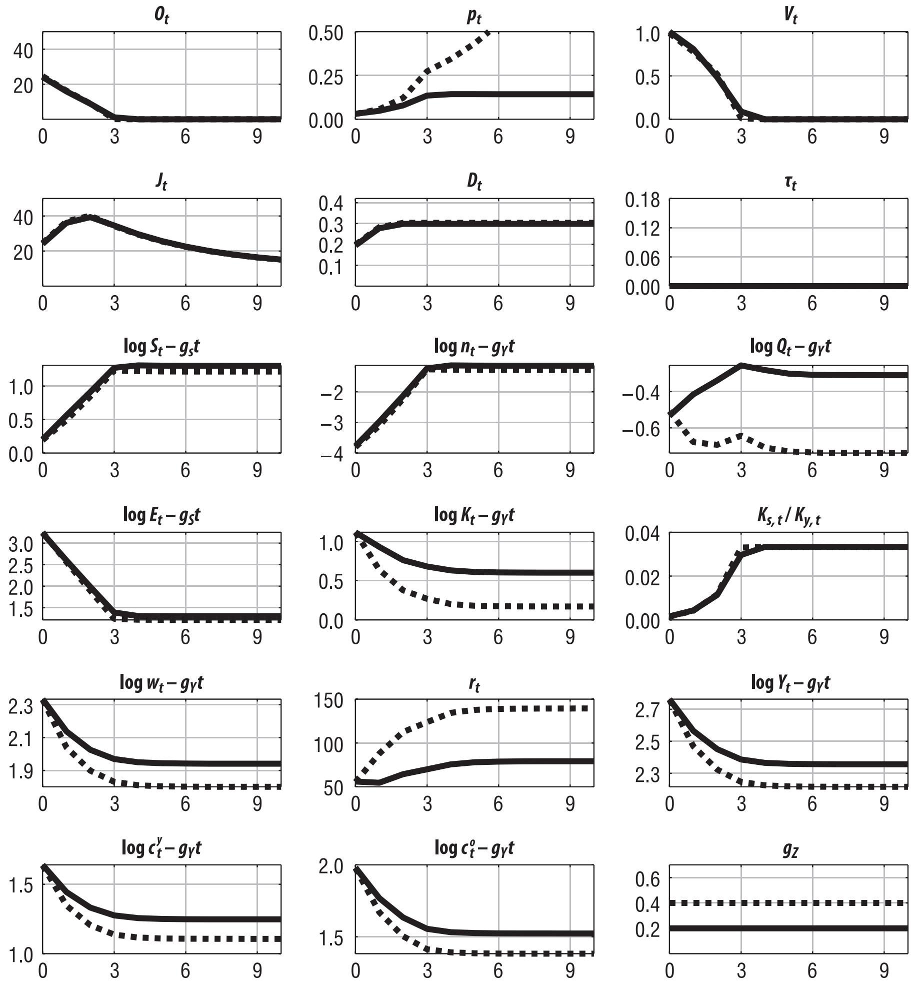
We have found date T at which cumulative oil consumption exceeds oil reserves. But at date $T-1$ cumulative oil consumption is less than oil reserves. Now we will solve for the transition path that entails equalization of cumulative oil consumption and oil reserves at T. At steps B3–B10 we have a mapping $G : \chi \rightarrow \sum_{t=1}^{T} O_t$. Define a function $g(\chi) = G(\chi) - R_0$. Solve the equation $g(\chi) = 0$, $[1, \bar{\chi}]$ using the bisection method, where $\bar{\chi}$ is some upper bound for χ. For each χ^i we need to iterate on steps B3–B10.

Appendix B: Supplementary Figures



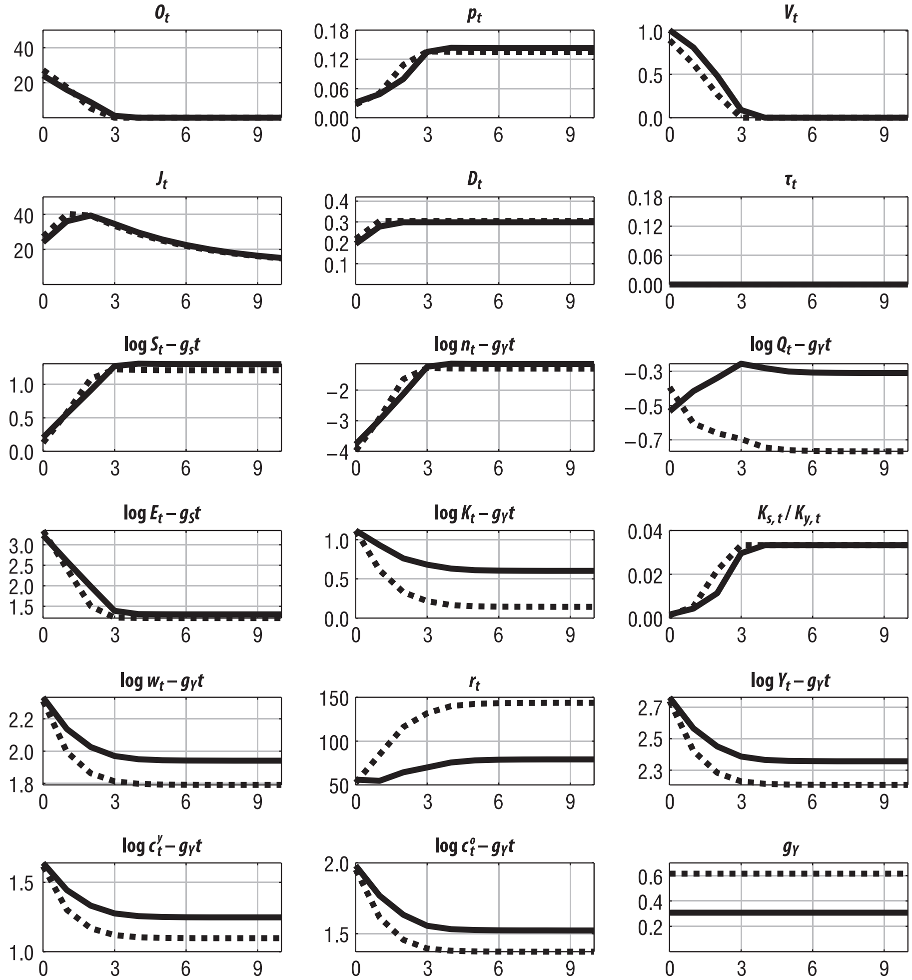
Note. Solid line indicates baseline. Dotted line indicates transition with the double growth rate g_B. O_t — oil, p_t — price of energy, V_t — value of oil company, J_t — CO_2 concentration, D_t — damages, τ_t — absolute tax per unit of oil, S_t — clean energy production, n_t — rental price of land, Q_t — value of land, E_t — total energy consumption, K_t — total capital, $K_{s,t}$ — clean energy sector's capital, $K_{y,t}$ — final goods production sector's capital, w_t — real wage rate, r_t — real interest rate, Y_t — final output, c_t^y — consumption of young households, c_t^o — consumption of old households, g_Y — steady state growth rate of output, g_S — steady state growth rate of clean energy.

Figure B1. **The Transition with Faster Technical Progress in Clean Energy (Detrended Variables)**



Note. Solid line indicates baseline. Dotted line indicates transition with the double growth rate g_Z. O_t — oil, p_t — price of energy, V_t — value of oil company, J_t — CO_2 concentration, D_t — damages, τ_t — absolute tax per unit of oil, S_t — clean energy production, n_t — rental price of land, Q_t — value of land, E_t — total energy consumption, K_t — total capital, $K_{s,t}$ — clean energy sector's capital, $K_{y,t}$ — final goods production sector's capital, w_t — real wage rate, r_t — real interest rate, Y_t — final output, c_t^y — consumption of young households, c_t^o — consumption of old households, g_Y — steady state growth rate of output, g_S — steady state growth rate of clean energy.

Figure B2. **Transition with Faster Technical Progress in the Final Goods Sector (Detrended Variables)**



Note. Solid line indicates baseline. Dotted line indicates transition with the double growth rates g_B and g_Z, and thus g_Y. O_t — oil, p_t — price of energy, V_t — value of oil company, J_t — CO_2 concentration, D_t — damages, τ_t — absolute tax per unit of oil, S_t — clean energy production, n_t — rental price of land, Q_t — value of land, E_t — total energy consumption, K_t — total capital, $K_{s,t}$ — clean energy sector's capital, $K_{y,t}$ — final goods production sector's capital, w_t — real wage rate, r_t — real interest rate, Y_t — final output, c_t^y — consumption of young households, c_t^o — consumption of old households, g_Y — steady state growth rate of output, g_S — steady state growth rate of clean energy.

Figure B3. **The Transition with Faster Economy Wide Technical Progress (Detrended Variables)**

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