# Why Green Growth is Possible

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In the past decades, a canonical type of economic growth models has emerged. It is often dubbed the neoclassical growth model, and it provides the backbone of much research in climate economics. An excellent presentation is given by Barro and Sala-i-Martin (2003), the best application in climate economics is due to Nordhaus (2008).

This model type has its problems, and there are strong reasons to look for models of a different kind, especially in light of the recent financial crisis (Farmer and Foley 2009). However, existing models embody considerable empirical knowledge about past patterns of economic growth and provide a common language currently used by most analysts and policy makers. Therefore, we take the neoclassical growth model as our starting point. The starting point, however, is what we will leave behind step by step.

Neoclassical models express the familiar view of a market economy as organized by an 'invisible hand' in such a way as to achieve a unique equilibrium. In growth theory, this is a unique growth path. In climate economics, this path is then seen as causing massive damages in the future because of greenhouse gases emitted now. In order to avoid these damages, present emissions must be reduced, leading to lower GDP now. The problem of climate policy then is to find some mechanism of sharing that burden among the various relevant actors. More climate protection then means lower growth: the idea of green growth as a way to protect the environment while enhancing economic growth would be an illusion.

We start by rehearsing a model of this type. Then we introduce three modifications that lead to the possibility of green growth.

## 1 A Single Growth Path

### 1.1 Time and agents

There is a single representative household and a single representative firm operating through a finite number of moments in time. Despite being only one of its kind, both agents mimic a situation of perfect competition in the sense that they react to price signals over which they have no influence. It is customary to assume that the firm only takes decisions about the present moment while all inter-temporal decisions are taken by the household.

If one lets the number of moments in time grow very large, one may approximate decisions over infinite time (in numerical simulations, when considering a period of a decade one may run the program for a century - longer runs usually do not yield different results anymore). If one lets the number of moments in time be small, say two or three, one can build overlapping generations models (see Gerlagh and van der Zwaan 2000 and Michel and de la Croix 2000, for a discussion in view of climate economics).

We use the following notation:

$$\begin{aligned} t &= 0, 1, .., T \\ i &: \text{firm} \\ h &: \text{household} \end{aligned} \tag{1}$$

The time index will be written as superscript, the agent index as subscript (exponents will be put outside of brackets).

## 2 Firm

At each moment in time, the representative firm produces output of a single good $q_i^t$ by using capital $k_i^t$, labor $l_i^t$ and an emissions generating resource $e_i^t$. The firm's technological production possibilities are represented by a CES production function with exogenous technical progress (represented by the variable $\pi^t$). The parameters of the function are chosen so as to roughly match the most recent estimates for the U.S. (Raval 2009). The firm chooses its (non-negative) inputs so as to maximize the difference between revenues and costs, where costs include interest $i^t$ and depreciation $\delta$ on the capital stock, wages $w^t$ for labor, and a price $p_e^t$ for the emissions generating resource. To keep things simple, we assume that the resource is imported from the outside world and paid for by exporting the good produced by the representative firm. We treat the price of the resource as set exogenously, so as to be able to analyze the impact of climate policies via changes in that price. These changes may result from technical standards, taxes, tradable permits, etc.

$$\begin{aligned} \max_{k_i^t, l_i^t, e_i^t} \quad & q_i^t - k_i^t \cdot (i^t + \delta) - l_i^t \cdot w^t - ei_i^t \cdot p_e^t \\ \text{s.t.} \quad & q_i^t = \left(0.3 \cdot (k_i^t)^{-1}, 0.65 \cdot (l_i^t \cdot \pi^t)^{-1}, 0.05 \cdot (e_i^t)^{-1}\right)^{-1} \\ & k_i^t, l_i^t, e_i^t \in I\!R_{>0} \end{aligned} \tag{2}$$

## 3 Household

At each moment in time, the representative household earns an income $y_h^t$ composed of the wage $w^t$ for its labor $l_h^t$ and the interest $i^t$ on its assets $s_h^t$. The household consumes a fraction $c_h^t$ of its income and saves the rest by lending it to the firm as credit and keeping one unit of financial asset per unit of good lent. The initial endowment of financial assets $s_h^0$ is given. At each moment, the household is capable of delivering at most one unit of labor. The labor it actually supplies then is a number between 0 and 1. The household chooses sequences of consumption fractions and fractions of labor units so as to satisfy its preferences. These can be represented by a standard utility function with a discount factor and a bequest function for the final moment $T$.

$$\begin{aligned}
\max_{c_h, l_h} \quad & \sum_{t=0}^{T} (0.97)^t \cdot \left( \text{Log}\,(y_h^t \cdot c_h^t) + \frac{1}{l_h^t - 1} - (s_h^{T+1} - \alpha_h \cdot y_h^T)^2 \right) \\
\text{s.t.} \quad & y_h^t = l_h^t \cdot w^t + s_h^t * i^t \\
& s_h^{t+1} = s_h^t + y_h^t \cdot (1 - c_h^t) \\
& s_h^0 = \bar{s}_h \\
& \alpha_h = \bar{\alpha}_h \\
& c_h, l_h : I\!N \rightarrow [0,1] \times [0,1]
\end{aligned} \tag{3}$$

## 4 System Properties

It is well known that in neoclassical models the accumulation of capital is insufficient to explain actual growth rates. The problem is that labor in industrialized countries shows only little growth and sometimes none at all. To explain growth rates of 2% and more in a neoclassical framework, capital would need to grow much faster than that, which it does not. The missing residual, which is in the order of half of total growth, is then explained by invoking technical progress. The long-term dynamics of industrialized countries can be described quite well by assuming an exogenous rate of growth for labor productivity in the order of 2% as well.

$$\begin{aligned}
\pi^{t+1} &= \pi^0 \cdot \exp(0.02 \cdot t) \\
\pi^0 &= \bar{\pi}^0 \\
p_e^t &: I\!N \rightarrow I\!R_{>0}
\end{aligned} \tag{4}$$

For our present purposes, the price on emissions generating resources is exogenous as well. One may then consider price increases due to increasingly stringent climate policies.

## 5 Equilibrium Conditions

In the neoclassical tradition, the invisible hand of the market is assumed to balance supply and demand so smoothly that one can focus on the situations where they are equal. This is the economic concept of equilibrium. It is quite important to distinguish this notion from other equilibrium concepts like critical point of dynamical systems of Nash equilibria in game theory. In specific situations, such notions may or may not coincide. In the present case, we simply require that supply and demand match at each moment in time. This means that the output of the firm minus the depreciation of capital is equal to the income of the household, labor demanded by the firm is equal to labor supplied by the household, capital used by the firm is equal to the assets owned by the household and the tax raised on emissions generating resources is equal to the subsidy handed out to the household. Other incentive schemes to avoid emissions can be investigated, but for our present purposes this one will suffice:

$$\begin{aligned} q_i^t - k_i^t \cdot \delta &= y_h^t \\ l_i^t &= l_h^t \\ k_i^t &= s_h^t \end{aligned} \tag{5}$$

## 6 The Critical Property

Because the representative firm solves only a static optimization problem at each moment in time, it can be incorporated into the intertemporal optimization problem of the household. The optimization problem of the household then involves a goal function – call it $U$ for utility – and a domain over which it is to be maximized – call it $A$ for action space. We can define:

$$A = \{(c_h^0, l_h^0, .., c_h^T, l_h^T) \mid c, l \in [0,1] \subset I\!R\} \tag{6}$$

This set is bounded, convex, and closed. If the goal function is continuous, it will assume a maximum at least once over $A$, so the economy under consideration has at least one equilibrium. If the goal function is strictly concave, the problem will have exactly one solution. Otherwise, a set of equilibria may result. To check concavity of the goal function, it is useful to rewrite it as a function of total consumption $C_h^t = c_h^t \cdot y_h^t$:

$$U(C_h^0, l_h^0, ..., c_h^T, l_h^T, s_h^{T+1}) = \sum_{t=0}^{T} \beta^t \cdot (u_c(C_h^t) + u_l(1 - l_h^t)) + \beta^{T+1} \cdot U_T(s_h^{T+1}) \tag{7}$$

where

$$\begin{aligned} u_c(C_h^t) &= \begin{cases} \log(C_h^t) & \text{for } C_h^t > 0 \\ -\infty & \text{for } C_h^t = 0 \end{cases} \\ u_l(l_h^t) &= \begin{cases} \frac{1}{l_h^t - 1} & \text{for } l_h^t > 0 \\ -\infty & \text{for } l_h^t = 0 \end{cases} \\ u_T(s_h^{T+1}) &= -(s_h^{T+1} - \alpha_h \cdot y_h^T)^2 \\ \beta &= 0.97 \end{aligned}$$

Each of the three functions is continuous and strictly concave. $U$ is additively separable into time steps. Notice that the value of $\beta$ is irrelevant here, because multiplication with a constant does not alter the concavity of a function. At each time step $0, .., T$, the goal function is additively separable into $u_c$ and $u_l$, at time $T + 1$ it just involves $u_T$. So, $U$ is strictly concave except where it converges towards $-\infty$ because either $c_h^t = 0$ or $l_h^t = 0$ or both. Values of $-\infty$ can be disregarded when looking for maxima. For our purposes, then, strict concavity of $U$ can be taken for granted.

However, the transformation of the goal function transforms the action space, too. Using the equilibrium condition $k_i^t = s_h^t$, the new action space can be parametrized on given sequences $\hat{e}_i$, i.e. sequences of emissions generating resources as follows:

$$\begin{aligned} A^*(\hat{e}_i) \quad = \quad & \{ \, (C_h^0, l_h^0, .., C_h^T, l_h^T, s_h^{T+1}) \mid \\ & \quad l_h^t \in [0,1] \subset I\!R, \\ & \quad C_h^t \in [0, f(l_h^t \cdot \pi^t, k_i^t)], \\ & \quad s_h^{T+1} = f(l_h^T \cdot \pi^T, k_i^T) - C_h^T \\ & \} \end{aligned} \quad (8)$$

where

$$\begin{aligned} k_i^{t+1} &= f(l_h^t \cdot \pi^t, k_i^t, \hat{e}_i^t) - C_h^t, \\ \pi^{t+1} &= \pi^0 \cdot \exp(0.02 \cdot t), \\ k^0 &= \bar{s}_h^0 \\ \pi^0 &= \bar{\pi}^0, \\ f &: I\!R_{\geq 0} \times I\!R_{\geq 0} \times I\!R_{\geq 0} \to I\!R_{\geq 0}, \\ f & \quad \text{differentiable, strictly concave} \end{aligned}$$

The values for $l_h^t$ stay within $[0,1]$, but the upper bound of $C_h^{t+1}$ now depends on $(l_h^t, C_h^t, s_h^t)$ via production at time $t$. Moreover, the action space is enlarged by the variable $s_h^{T+1}$. However, $A^*(\hat{e}_i^t)$ is still closed and bounded, because given the situation at time $t$ there is always a maximal value of output that can be reached at time $t+1$. As the goal function is continuous, the optimization problem has a solution and the economy has at least one equilibrium.

To show convexity of $A^*(\hat{e}_i^t)$, and thereby uniqueness, one must show that if $\tilde{x} = (C_h^0, \tilde{l}_h^0, ..., \tilde{c}_h^T, \tilde{l}_h^T, \tilde{s}_h^{T+1})$ and $\bar{x} = (\bar{C}_h^0, \bar{l}_h^0, ..., \bar{c}_h^T, \bar{l}_h^T, \bar{s}_h^{T+1})$ both belong to $A^*(\hat{e}_i^t)$, any convex combination $\lambda \cdot \tilde{x} + (1-\lambda) \cdot \bar{x}$ (with $0 < \lambda < 1$) also belongs to $A^*(\hat{e}_i^t)$.

Let $t^*$ be the first moment in time where the two differ. If they differ in $C_h^{t^*}$ only, any convex combination of $\tilde{C}_h^{t^*}$ and $\bar{C}_h^{t^*}$ will also be feasible. If they differ in $l_h^{t^*}$, any convex combination of $\tilde{l}_h^{t^*}$ and $\bar{l}_h^{t^*}$ will be feasible. Because of the strict concavity of $f$, any such convex combination will lead to an output $q_i^{t*}$ that will be higher than the corresponding convex combination of $\tilde{q}_i^{t*}$ and $\bar{q}_i^{t*}$. Therefore, whatever consumption levels $\tilde{C}_h^{t*}$ and $\bar{C}_h^{t*}$ may occur at time $t^*$, their convex combination will be feasible as well.

If $\tilde{s}_h^{t^*+1} = \bar{s}_h^{t^*+1}$, the same reasoning applies for time $t^*+1$. Now suppose $\tilde{s}_h^{t^*+1} \neq \bar{s}_h^{t^*+1}$. *Because* $\pi^{t^*+1}$ *does not depend on the choices of the agents*, this is the only way decisions at time $t^*$ can affect $\tilde{x}$ and $\bar{x}$ at time $t^*+1$ . The strict concavity of $f$ then implies that any convex combination of $\tilde{s}_h^{t^*+1}$ and $\bar{s}_h^{t^*+1}$ will allow for a maximal output (i.e. with $l^{t^*+1} = 1$) that will be higher than the corresponding convex combination of the maximal outputs of $\tilde{x}$ and $\bar{x}$ at time $t^* + 1$. The strict convexity of $f$ so ensures that step by step convex combinations of $\tilde{x}$ and $\bar{x}$ are elements of $A^*(\hat{e}_i^t)$. This reasoning can be iterated up to time $T$, and it holds for $s_h^{T+1}$ as well.

The strict concavity of $U$ also ensures that there is a one-to-one correspondence between sequences of quantities $\hat{e}_i^t$, $t = 0, .., T$, and sequences of prices $p_e^t$: any optimal solution must fulfill the central tenet of neoclassical thinking, $p_e^t = \frac{\partial U_i^t}{\partial \hat{e}_i^t}$, and strict concavity implies a monotonic relation between the quantity $\hat{e}_i^t$ and its marginal utility.

If the neoclassical growth model captures the key features of the actual economy that matter for climate policy, it has severe consequences. The problem that climate policy seeks to address is a situation where emissions in the present lead to suffering in the future. Reducing present emissions in this model type, however, means reducing present incomes, and thereby either returns on investment or wages or both. It is obvious that this makes the implementation of an effective climate policy an arduous task. The task becomes even harder when different governments have to find a way to allocate those income reductions among themselves.

## 7 Alternative Growth Paths

Taking the neoclassical model as our starting point, we now introduce some features that are relevant to think about European climate policy. The European economy is charactized by persistent unemployment and less than spectacular growth, and under these conditions proposals for climate policy that imply reductions in income are likely to receive more rhetorical than practical support. Recent advances in economic modeling suggest that there are better possibilities, however. Moreover, the recent financial crisis provides strong reasons for an overhaul of existing models. In this spirit, we now introduce a few amendments to the neoclassical model.

## 8 Time and agents

We consider a number $N_i$ of firms and a number $N_h$ of households:

$$\begin{aligned} t &= 0, 1, .., T \\ i &= 1, .., N_i \\ h &= 1, .., N_h \end{aligned} \tag{9}$$

Once the implications of heterogeneous agents and their interaction networks have been investigated, their aggregate behavior may sometimes still be approximated by representative agent models. There can be little doubt, however, that this cannot be done in general (Kirman 1992).

## 9 Firms

We leave the firm nearly unaltered, except for the important fact that now there is more than one. The one change is the introduction of a sales tax $\zeta$ in order to finance unemployment benefits. The sales tax is just a simple way of doing so, other tax schemes can be introduced without changing the main finding.

$$\max_{k_i^t, l_i^t, e_i^t} \quad q_i^t \cdot (1-\zeta^t) - k_i^t \cdot (i^t + \delta) - l_i^t \cdot w^t - e_i^t \cdot p_e^t \tag{10}$$
$$\text{s.t.} \quad q_i^t = \left(0.3 \cdot (k_i^t)^{-1}, 0.65 \cdot (l_i^t \cdot \nu_i^t \cdot \pi^t)^{-1}, 0.05 \cdot (e_i^t)^{-1}\right)^{-1}$$
$$k_i^t, l_i^t, e_i^t \in I\!R_{>0}$$

## 10 Households

We keep many features of households unchanged (again except for having more than one). However, households now must reckon with the possibility of a stochastic shock, namely finding themselves unemployed. This means that expectations become crucial for economic dynamics, as present decisions now depend on what economic agents expect from an uncertain future.

In the past years, the prevalent style to model such situations has been shaped by the rational expectations hypothesis, according to which all agents are assumed to have common expectations, corresponding to the probabilities implied by the economists model. As with the neoclassical growth model, there is much to be said against this hypothesis (Evans and Honkapohja 2001). For our present purposes, however, it is sufficient. The model implies that households get unemployed with probabilities $m^t$ (introduced below) and that they share expectations based on these probabilities. Employment status is represented by a random variable: $\mu_h^t = 1$ for employed, $\mu_h^t = 0$ for unemployed. When a household is unemployed, it gets unemployment benefits $z^t$.

Because the intertemporal optimization problem now involves stochastic shocks, its solution cannot be a sequence of consumption demands and labor supply - deciding today whether to carry an umbrella two months in advance is an inferior strategy to choosing a decision rule and taking the actual decision in two months on the basis of additional information that will be available then. Therefore, the households search for a decision rule $\psi$ that yields the fraction of income to be consumed and the amount of labor to be offered as a function of their financial assets and their employment status.

$$
\begin{aligned}
\max_{\psi_i} \quad & \mathrm{E}\left[\sum_{t=0}^{T}(0.97)^t \cdot \left(\mathrm{Log}\,(y_h^t \cdot c_h^t) + \frac{1}{l_h^t \cdot \mu_h^t - 1} \right.\right. \\
& \left.\left. \qquad\qquad -(s_h^{T+1} - \alpha_i \cdot y_h^T)^2\right)\right] \qquad (11) \\
\text{s.t.} \quad & y_h^t = l_h^t \cdot w^t \cdot \mu_h^t + z^t \cdot (1-\mu_h^t) + s_h^t * i^t \\
& s_h^{t+1} = s_h^t + y_h^t \cdot (1 - c_h^t) \\
& s_h^0 = \bar{s}_h \\
& \psi_i : \mathbb{R}_{\geq 0} \times \{0,1\} \rightarrow [0,1] \times [0,1] \\
& \psi_i(s_h^t, \mu_h^t) = (c_h^t, l_h^t)
\end{aligned}
$$

## 11 System Properties

A major advance in climate economic modeling has been the introduction of endogenous technical change (Edenhofer et al. 2006). It is a well-established fact that productivity increases with production thanks to learning by doing, and to some extent it is possible to quantify this link. Careful empirical research (e.g. Alberth 2008, Nagy et al. 2011) provides strong evidence to the effect that unit costs fall, and labor productivity increases, in line with the expansion of cumulative production. We therefore replace the exogenous dynamics of (4) with the endogenous dynamics of (12).

The endogenous productivity dynamics matters for the probability of unemployment, $m^t$, too. The debate about how much unemployment is voluntary, how much an inevitable consequence of time-consuming search processes on the labor market, and how much due to various departures from the neoclassical idea of market equilibrium will hardly be settled anytime soon. But it is widely accepted that unemployment can rise to levels where deflationary processes set in, and that it can fall to levels where runaway inflation becomes a serious danger. Somewhere in between lies a rate of unemployment that is sometimes emphatically called "natural", sometimes labelled more technically as the non-accelerating inflation rate of unemployment, aka NAIRU. However, empirical research has shown that the NAIRU itself moves in the course of time, and a major factor affecting its dynamics is the rate of productivity growth (Ball and Mankiw 2002).

Ormerod, Rosewell and Phelps (2009) provide evidence suggesting that since more than a century industrialized economies move back and forth between two kinds of equilibria, one characterized by higher one by lower unemployment. The differences in inflation between the equilibria are remarkably small, while the historical record shows that differences in productivity growth are substantial. A third constellation of very high unemployment seems relevant mainly for the years of the great depression after 1929, and the world came dangerously close to it again in the financial crisis of 2007-2008. In view of the possibility of green growth this hypothesis may become quite important. For our present purposes we stick to a weaker hypothesis that remains agnostic about the number of possible equilibria by simply letting the probability of unemployment decrease with productivity growth in a way that is consistent with broad patterns of growth in industrialized countries.

The price of the emissions generating resource stays exogenous as before, and the unemployment benefits are set exogenously, too.

$$\begin{aligned}
\pi^{t+1} &= \pi^t \cdot (1 + \frac{q^t}{Q^t}) \qquad (12)\\
q^t &= \sum_{i=1}^{N_i} q_i^t \\
Q^t &= Q^0 + \sum_{i=0}^{t} \sum_{i=1}^{N_i} q_i^t \\
\pi^0 &= \bar{\pi}^0 \\
m^t &= \text{Prob}(\mu_h^t = 1),\ \forall h \\
m^{t+1} &= 0.0012 \cdot \left( \frac{\pi^{t+1} - \pi^t}{\pi^t} \right)^{-1} \\
m^0 &= \frac{\sum_{h=1}^{N_h} \mu_h^0}{N_h} \\
p_e^t, z^t &: I\!N \rightarrow I\!R_{>0}
\end{aligned}$$

## 12 Equilibrium Conditions

The equilibrium conditions need only two amendments, both needed to deal with unemployment. First, the labor actually employed is equal to the labor offered on the market minus the unemployed. A more sophisticated treatment could represent vacancies, too, but it would not change the argument. Second, the sales tax is set at the level needed to finance unemployment benefits.

$$\begin{aligned} \sum_{i=1}^{N_i}(q_i^t - k_i^t \cdot \delta) &= \sum_{h=1}^{N_h} y_h^t \\ \sum_{i=1}^{N_i} l_i^t &= \sum_{h=1}^{N_h} l_h^t \cdot \mu_h^t \\ \sum_{i=1}^{N_i} k_i^t &= \sum_{h=1}^{N_h} s_h^t \\ \sum_{i=1}^{N_i} \zeta \cdot q_i^t &= \sum_{h=1}^{N_h} (1-\mu^t) \cdot z^t \end{aligned} \tag{13}$$

## 13 Sunspots with Externalities

At each moment in time, the household is faced with two possibilities. The application of the decision function then can be analyzed as a binary tree (see Olson and Roy 2006 for a related analysis of policies as sequences of conditional probabilities). As in (7), the goal function for the economy as a whole can be rewritten in separately additive form and shown to be continuous and strictly concave. The action space is again a bounded closed set, so the problem has at least one solution and the economy at least one equilibrium.

The proof of convexity, however, breaks down because of endogenous productivity dynamics. Financial assets are no more the only way for decisions at time $t^*$ to influence the decision problem at time $t^* + 1$. If in period $t^*$ policy $\phi$ leads to higher growth than policy $\psi$, in period $t^* + 1$ policy $\phi$ can take advantage of a higher level of labor productivity. As a result, at time $t^* + 1$, the maximal output that can be generated by a convex combination of $\phi$ and $\psi$ – call it $\chi$ – may be smaller than the corresponding convex combination of maximal outputs from $\phi$ and $\psi$ at time $t^* + 1$. In this case, the convex combination of the consumption and investment decisions implied by $\phi$ and $\psi$ at time $t^* + 1$ is impossible for $\chi$ if the latter is to fulfill the specification of the action space. So, $\chi$ does not belong to the action space and the latter is not convex.

Non-convexity of the action space means that there may be several equilibria. In view of endogenous technical progress, this possibility has been analyzed by Benhabib and Farmer (1999), who notice: "An interesting feature of endogenous models is their ability to generate multiple balanced growth paths in conjunction with indeterminacy" (p.424, see also Mino 2001). Multiple equilibria are a pervasive property of economic models with more than two goods (remember that in dynamic models with only one sector the output of each period counts as a different good). In particular, rational expectations are possible for an arbitrary large set of equilibria (Driskill 2006).

In the present case, an individual household can only form expectations about the future by assuming what the other households will expect. If all expect low productivity growth with the associated high NAIRU, that is what they will get. Of course, not any conceivable set of expectations leads to a possible equilibrium, but there is definitely more than one possibility. As a result, economic agents may be trapped in a situation of low productivity growth and high unemplyoment, and they can only overcome this situation if they find some way to jointly shift their expectations. This is what a well designed green growth strategy can achieve.

In the presence of several possible equilibria, neither rationality nor the forces of supply and demand can explain equilibrium selection. This has led to the concept of sunspot equilibrium and the vast literature that has grown around it (Shell 2008). A sunspot equilibrium is selected by coordination of expectations via events taking place outside of the market place, like sunspots.

Sunspot equilibria can arise in models that fulfill all the conditions of a general equilibrium of the Arrow-Debreu type. In the present case, they are linked to a double externality: the one of productivity increase and the related one of high unemployment linked to low productivity growth. This means two things: first, not all possible equilibria are Pareto optimal. And second: a Pareto improvement can be reached by coordinating expectations towards a new growth path. Such is the historical opportunity of green growth.

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