Green Transformation and Economic Growth

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Motivation

- Variability of greenhouse gas (GHG) emissions among countries.
- The relationship between economic growth and pollution: is there a trade-off?
- Exploring the possibility of achieving higher economic growth with controlled emissions.
- Identifying key mechanisms that influence this dynamic.

GDP and CO2 emissions of major advanced economies

Source: Global Carbon Budget (2023). The values of the year 1981 are normalized to one.

What we do

- We propose a model incorporating the endogenous green transformation of heterogeneous firms.
- "Green transformation" refers to an endogenous choice of technology aimed at abating CO2 emissions.
- We calibrate the theoretical model to empirical data and perform a counterfactual analysis.
- Our findings indicate a significant benefit from green transformation, reducing significantly the growth of CO2 stock.
- Moreover, the green transformation potentially positively impacts output growth by mitigating negative externalities.

Literature

- DSGE with firm dynamics: Bilbiie et al. (2012), Ghironi and Melitz (2005), Hamano and Zanetti (2017)
- Real business cycle: Heutel (2012), Fischer and Springborn (2011), Annicchiarico and Di Dio (2015), Dissou and Karnizova (2016)
- Directed technical change: Acemoglu et al. (2012), Hassler and Krusell (2012a), Hassler and Krusell (2012b), Golosov et al. (2014a), Acemoglu et al. (2016), Aghion et al. (2016), Golosov et al. (2014b)
- Integrated assessment model: Nordhaus (1991), Nordhaus (1992) Nordhaus (1993), Nordhaus (2008),

Theoretical Model

- We model a decentralized economy that facilitates a green transformation within firms.
- Firms operate under monopolistic competition and vary in their idiosyncratic productivities.
- Firms endogenously choose between "brown" technology (no abatement) and "green" technology (with abatement).
- The distribution of green and brown firms within the economy is endogenous.
- Firms do not internalize the negative externalities of emissions, which ultimately reduces aggregate labor productivity.
- Investment manifests as firm creation.

Production and pricing: Brown firms

The amount of emission of the brown firm with productivity z is given by

$$e_{b,t}(z) = \frac{y_{b,t}(z)}{z}$$

where $e_{b,t}(z)$ stands for the level of CO2 emission and $y_{b,t}(z)$ is the level of production of the firm. The output of the brown firm z is given by

$$l_{b,t}(z) = \frac{y_{b,t}(z)}{A_t z} + \tau_t \frac{e_{b,t}(z)}{A_t}$$

We interpret $\tau_t \geq 0$ as a policy instrument that also captures various types of social pressure on a cleaner economy.

The real profits of the brown firm which is denoted with $d_{b,t}(z)$ is given by

$$d_{b,t}(z) = \rho_{b,t}(z)\, y_{b,t}(z) - w_t l_{b,t}(z)$$

The brown firm maximizes the profits given the demand addressed to them under the monopolistic competition. This yields the following optimal price:

$$\rho_{b,t}(z) = \frac{\sigma}{\sigma - 1} \frac{w_t}{A_t z} (1 + \tau_t)$$

Production and pricing: Green firms

Green firms emit also CO2 but they abate by a fraction $\Omega_t(z)$ of the original emission as follows:

$$e_{g,t}(z) = (1 - \Omega_t(z)) \frac{y_{g,t}(z)}{z}$$

However, this abatement technology requires additional costs in terms of effective labor:

$$l_{g,t}(z) = \frac{y_{g,t}(z)}{A_t z}(1 + g(\Omega_t(z))) + \frac{\tau_t e_{g,t}(z)}{A_t} + \frac{f_{a,t}}{A_t}$$

- The green firms optimally choose the fraction abated $\Omega_t(z)$ and abatement rate is related to a fraction $g(\Omega_t(z))$ of costs in terms of labor units necessary for output.
- We assume this "abatement cost function" such that

$$g(\Omega_t(z)) = \theta_{1,t}\Omega_t(z)^{\theta_2}$$

with $\theta_{1,t} > 0$ and $\theta_2 > 0$ following Nordhaus (2008) and Heutel (2012). Importantly, we assume that $\theta_{1,t}$ represents the technology level for abatement and it is time-varying whose gross growth rate is denoted with g_{θ_1}.

The real profits of the green firm which is denoted with $d_{g,t}(z)$ is given by

$$d_{g,t}(z) = \rho_{g,t}(z)\, y_{g,t}(z) - w_t l_{g,t}(z)$$

The profit maximization yields the following optimal price:

$$\rho_{g,t}(z) = \frac{\sigma}{\sigma - 1} \frac{w_t}{A_t z} \left[1 + \tau_t (1 - \Omega_t(z)) + \theta_1 \Omega_t(z)^{\theta_2}\right]$$

Further, the green firm optimally chooses the fraction abated. Given the above optimal price, this is

$$\Omega_t(z) = \Omega_t = \left(\frac{\tau_t}{\theta_1 \theta_2}\right)^{\frac{1}{\theta_2 - 1}}$$

All firms choose the same amount of investment for the abatement respectively of their specific productivity level.

Abatement decision

Proposition

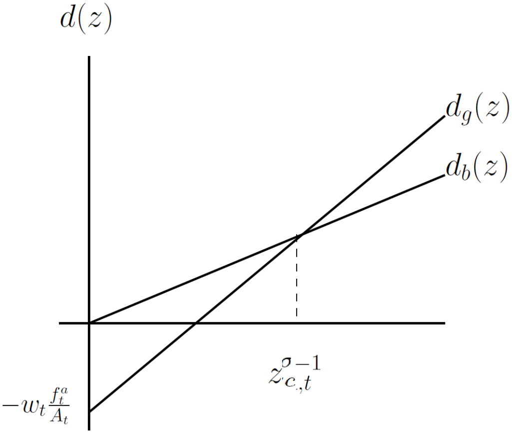
Under the assumption of $\theta_2 > 1$, there exists a cutoff level firm productivity $z_{c,t}$ with which firms are indifferent to choose between green and brown technology as

$$d_{g,t}\left(z_{c,t}\right) = d_{b,t}\left(z_{c,t}\right)$$

Corollary 1: When $\theta_2 < 1$, there is no such abatement cutoff level productivity and all firms become brown.

Corollary 2: When, $\tau_t = 0$, there is no such abatement cutoff level productivity and all firms become brown.

Determination of the abatement cutoff level productivity



Pollution and negative externalities

The flow of total emission at time t, e_t is given by

$$e_t = N_{b,t}\tilde{e}_{b,t} + N_{g,t}\tilde{e}_{g,t}$$

We assume that the emission in each period accumulates over time as follow.

$$s_t = (1 - \delta_s)\, s_{t-1} + e_t + e^{row}$$

The stock of emissions induces negative externalities in the aggregate productivity of labor:

$$A_t = (1 - d\,(s_t))\, a_t$$

where a_t is an exogenous process whose gross growth rate is denoted with g_a. $d(s_t)$ is a damage function.

System of Equations

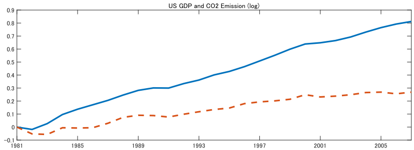
Average pricing	$\tilde{\rho}_{b,t} = \frac{\sigma}{\sigma-1}\frac{w_t}{A_t\tilde{z}_{b,t}}(1+\tau_t)$, $\tilde{\rho}_{g,t} = \frac{\sigma}{\sigma-1}\frac{w_t}{A_t\tilde{z}_{g,t}}\left[1+\tau_t(1-\Omega_t)+\theta_1\Omega_t^{\theta_2}\right]$
Real price	$1 = N_{b,t}\tilde{\rho}_{b,t}^{1-\sigma} + N_{g,t}\tilde{\rho}_{g,t}^{1-\sigma}$
Average profits	$\tilde{d}_{b,t} = \frac{1}{\sigma}\tilde{\rho}_{b.t}{}^{1-\sigma}C_t, \quad \tilde{d}_{g,t} = \frac{1}{\sigma}\tilde{\rho}_{g,t}^{1-\sigma}C_t - w_t\frac{f_{a,t}}{A_t}$
Average sales	$\tilde{d}_{b,t} = \frac{1}{\sigma}\tilde{\rho}_{b.t}\tilde{y}_{b,t}, \quad \tilde{d}_{g,t} = \frac{1}{\sigma}\tilde{\rho}_{g,t}\tilde{y}_{g,t} - w_t\frac{f_{a,t}}{A_t}$
Average profits	$\tilde{d}_t = \frac{N_{b,t}}{N_t}\tilde{d}_{b,t} + \frac{N_{g,t}}{N_t}\tilde{d}_{g,t}$
Zero Abatement cutoff	$\tilde{d}_{g,t} = \frac{\kappa}{\kappa-(\sigma-1)}\left(\frac{\tilde{z}_{b,t}}{z_{c,t}}\right)^{1-\sigma}\tilde{d}_{b,t} + \left[\frac{\sigma-1}{\kappa-(\sigma-1)}\right]w_t\frac{f_{a,t}}{A_t}$
Av. brown productivity	$\tilde{z}_{b,t} = \left(\frac{\kappa}{\kappa-(\sigma-1)}\right)^{\frac{1}{\sigma-1}} z_{min}\left[\frac{1-\left(\frac{N_{g,t}}{N_t}\right)^{1-\frac{\sigma-1}{\kappa}}}{\frac{N_{b,t}}{N_t}}\right]^{\frac{1}{\sigma-1}}$
Av. green productivity	$\frac{N_{g,t}}{N_t} = z_{min}^{\kappa}\left[\frac{\kappa}{\kappa-(\sigma-1)}\right]^{\frac{\kappa}{\sigma-1}}\tilde{z}_{g,t}^{-\kappa}$
Surviving rate	$\frac{N_{g,t}}{N_t} = 1 - \left(\frac{z_{min}}{z_{c,t}}\right)^{\kappa}$
	$\frac{N_{b,t}}{N_t} = 1 - \frac{N_{g,t}}{N_t}$
Free entry condition	$v_t = \frac{w_t f_{E,t}}{A_{,t}}$
Motion of products	$N_{t+1} = (1-\delta)(N_t + H_t)$
Euler equity	$v_t = \beta(1-\delta)E_t\left(\frac{C_{t+1}}{C_t}\right)^{-1}\left(v_{t+1} + \tilde{d}_{t+1}\right)$
Optimal labor supply	$\chi L_t^{\psi} = w_t C_t^{-1}$
Labor market clearing	$L_t = N_{b,t}(\sigma-1)\frac{\tilde{d}_{b,t}}{w_t} + N_{g,t}\left((\sigma-1)\frac{\tilde{d}_{g,t}}{w_t} + \sigma\frac{f_{a,t}}{A_t}\right) + H_t\frac{v_t}{w_t}$
Emission	$\tilde{e}_{b,t} = \frac{\tilde{y}_{b,t}}{\tilde{z}_{b,t}}, \quad \tilde{e}_{g,t} = (1-\Omega_t)\frac{\tilde{y}_{g,t}}{\tilde{z}_{g,t}}$
Total emission	$\mathrm{e}_t = N_{b,t}\tilde{e}_{b,t} + N_{g,t}\tilde{e}_{g,t}$
The stock of emissions	$\mathrm{s}_t = (1-\delta_s)s_{t-1} + e_t + e^{row}$
Externalities	$A_t = \left[1 - \left(d_0 + d_1 s_t + d_2 s_t^2\right)\right]a_t$
Abatement	$\Omega_t = \left(\frac{\tau_t}{\theta_1\theta_2}\right)^{\frac{1}{\theta_2-1}}$
Real GDP	$Y_t \equiv L_t w_t + N_t\widetilde{d}_t$

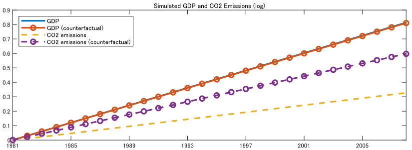
Calibration

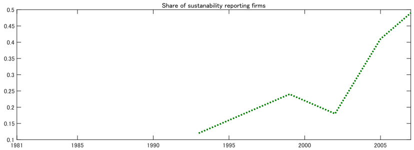
- The calibrations of the theoretical model is annual basis.
- Specifically, we align the model to match historical data on GDP growth rates, CO2 emissions, and the rate of green transformation in the US economy from 1981 to 2007.
- We use the share of firms reporting sustainability (KPMG data) as a proxy for the proportion of green firms, assuming a steady state share of 10 percent.
- The steady state abatement rate is set at 20 percent.
- The damage function is modeled as $d(s_t) = d_0 + d_1 s_t$, following the approach in Heutel (2012).

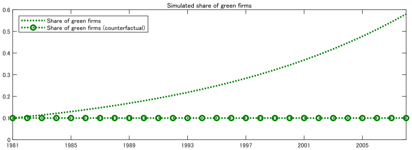
	Name	Steady state value	Gross growh rate
β	Discount factor of workers	0.96	1
φ	Inverse of Frisch elasticity of labor supply	0.5	1
σ	Elasticity of substitution among varieties	3.8	1
δ	Exogenous exit shock	0.1	1
κ	Pareto shape	3.4	1
a	Exogenous technology	1	1.0224
χ	disutility for working	0.9320	
f_E	Fixed cost for entry	1	1
f_a	Fixed cost for abatement	3.2458e-04	1
τ	Emission tax rate	0.0042	1
δ_s	Exogenous CO2 depreciation rate	0.0084	1
θ_1	Abatement technology	0.0272	0.9080
θ_2	Abatement technology	2.8	1
$erow$	Emissions from ROW	3.2138	1
d_0	damage function parameter (annual)	1.3950e-3*4	1
d_1	damage function parameter (annual)	-6.6722e-6*4	
d_2	damage function parameter (annual)	1.4647e-8*4	1

Data, simulated model, and the counterfactual with $g_{\theta_1} = 0$: 1981-2007

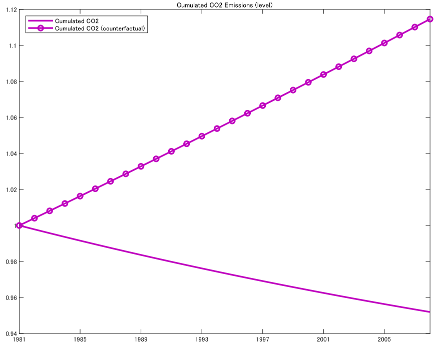








Cumulated CO2 emissions



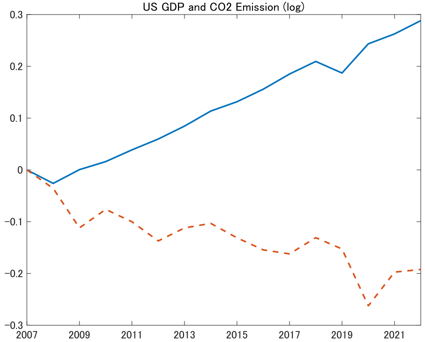
Summary of the Results

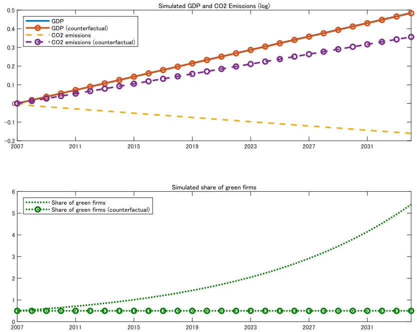
- The benchmark theoretical model successfully replicates the growth trends of US GDP and CO2 emissions.
- It also accurately models the green transformation.
- In a counterfactual scenario without improvements in abatement technology ($g_{\theta_1} = 0$), emissions are higher.
- Output growth is modestly higher in the benchmark model, which includes a greener economy.

Further Green Transformation

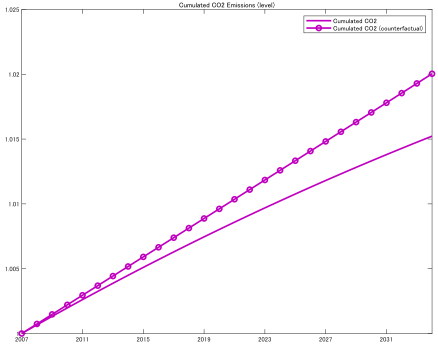
- Emphasizing the importance of reducing GHG emissions while sustaining economic growth.
- Does reducing emissions necessitate a trade-off? Our theoretical model explores this question.
- We now extend our model calibration to include US data from the more recent period of 2007-2022.
- For this period, we calibrate the model with $g_a = 1.0134$ and $g_{\theta_1} = 0.8775$.
- We assume that the steady state share of green firms reaches approximately 50 percent.

Data, simulated model, and the counterfactual with $g_{\theta_1} = 0$: 2007-2022





Cumulated CO2 emissions



Conclusion

- This paper provides a framework to understand the green transformation and its impacts on economic dynamics.
- While the quantitative impacts require careful estimation, our findings indicate that managing negative externalities from CO_2 emissions would not prevent the economy from growing.
- Possible extensions of this research could include:
  - Stochastic simulations
  - A planner's solution to explore outcomes in a centralized economy.
  - Incorporation into a New Keynesian framework to examine interactions with monetary policy.
  - Investigation of regime switching to understand transitions between economic states concerning preferences.

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Appendix

Firm averages

Given the distribution $G(z)$, the share of brown and green firms are defined as $N_{b,t} = G(z_{c,t})\,N_t$ and $N_{g,t} = [1 - G(z_{c,t})]\,N_t$, respectively. Further, we define the two average productivity levels as

$$\tilde{z}_{b,t} \equiv \left[\frac{1}{G(z_{c,t})}\int_{z_{min}}^{z_{c,t}} z^{\sigma-1} dG(z)\right]^{\frac{1}{\sigma-1}}, \quad \tilde{z}_{g,t} \equiv \left[\frac{1}{1 - G(z_{c,t})}\int_{z_{c,t}}^{\infty} z^{\sigma-1} dG(z)\right]^{\frac{1}{\sigma-1}}.$$

where stands for the average productivity of brown and green firms respectively. With these averages, the average real price, and the average real profits, of both brown and green firms are defined accordingly.

Firm entry and exit

New entry (whose number is denoted with H_t) in the market takes place by comparing the value of entry and sunk costs for entry. This implies the following free entry condition that holds in equilibrium.

$$v_t = \frac{w_t f_{E,t}}{A_t}$$

The value of firm is defined as the discounted expected sum of future stream of dividends:
$v_t = E_t \sum_{i=t+1}^{\infty} \left[\beta\left(1-\delta\right)\right]^{i-t} \left(\frac{C_i}{C_t}\right)^{-1} \widetilde{d}_i$.
The motion of the total number of firms N_t is given by the following equation:

$$N_t = \left(1-\delta\right)\left(N_{t-1} + H_{t-1}\right)$$

where δ stands for the depreciation rate of the number of firms.

Prametrization and productivity draw

Following Meltiz (2003) and Ghironi and Melitz (2005), we assume the following Pareto distribution for $G(z)$:

$$G(z) = 1 - \left(\frac{z_{min}}{z}\right)^{\kappa}$$

Accordingly, we have the following expressions of the average productivities:

$$\tilde{z}_{b,t} = \left[\frac{\kappa}{\kappa - (\sigma - 1)}\right]^{\frac{1}{\sigma - 1}} z_{min} z_{c,t} \left(\frac{z_{c,t} - z_{min}^{\kappa - (\sigma - 1)}}{z_{c,t} - z_{min}^{\kappa}}\right)^{\frac{1}{\sigma - 1}}, \quad \tilde{z}_{g,t} = \left[\frac{\kappa}{\kappa - (\sigma - 1)}\right]^{\frac{1}{\sigma - 1}} z_{c,t}$$

The share of brown firm is $\frac{N_{b,t}}{N_t} = 1 - \frac{N_{g,t}}{N_t}$. Also the share of green firm is given by $\frac{N_{g,t}}{N_t} = z_{min}^{\kappa} \left[\frac{\kappa}{\kappa-(\sigma-1)}\right]^{\frac{\kappa}{\sigma-1}} \tilde{z}_{g,t}^{-\kappa}$.
Also, the cutoff abatement condition is rewritten as

$$\tilde{d}_{g,t} = \frac{\kappa}{\kappa - (\sigma - 1)} \left(\frac{\tilde{z}_{b,t}}{z_{c,t}}\right)^{1-\sigma} \tilde{d}_{b,t} + \left[\frac{\sigma - 1}{\kappa - (\sigma - 1)}\right] w_t \frac{f_{a,t}}{A_t}$$

We can define the total average profits as $\tilde{d}_t = \frac{N_{b,t}}{N_t}\tilde{d}_{b,t} + \frac{N_{g,t}}{N_t}\tilde{d}_{g,t}$

Intertemporal optimization

Households maximize the expected sum of utility under the following budget constraints.

$$C_t + x_{t+1} v_t \left(N_t + H_t\right) = L_t w_t + x_t N_t \left(v_t + \tilde{d}_t\right)$$

where x_{t+1} stand for share holdings into $t+1$.

The first-order conditions concerning consumption and labor supply yield the standard labor supply equation as follows:

$$\chi L_t^{\psi} = w_t C_t^{-1}.$$

The first-order condition with respect to the shareholdings yield the following Euler equations:

$$v_t = \beta \left(1 - \delta\right) E_t \left(\frac{C_{t+1}}{C_t}\right)^{-1} \left(v_{t+1} + \tilde{d}_{t+1}\right).$$

General equilibrium condition

To complete the model, we use the following labor market clearing conditions: $L_t = N_{b,t}\tilde{l}_{b,t} + N_{g,t}\tilde{l}_{g,t} + H_t \frac{v_t}{w_t}$. The left-hand side shows the labor used in production for both brown and green firms and the creation of entrants. The condition is rewritten as

$$L_t = N_{b,t} (\sigma - 1) \frac{\tilde{d}_{b,t}}{w_t} + N_{g,t} \left((\sigma - 1) \frac{\tilde{d}_{g,t}}{w_t} + \sigma \frac{f_{a,t}}{A_t} \right) + H_t \frac{v_t}{w_t}$$

Calibration

The calibration is annual baisis and for the two subsequent time periods of the US economy that show a different pattern for CO2 emissions, namely from 1981 to 2007 and 2007 to 2022. The first time period is characterized with an increasing GDP and CO2 emissions while the second period is characterized by a "decoupling", i.e., a decreasing CO2 emissions while having a posive economic growth. The parameter values of subjective discount factor and the inverse of the Frisch elasticity of labor supply, are set to 9.6 and 0.5, respectively. These are the standard values in the literature. The elasticity of subtsitution among varieties, firm exit inducing shock, Paret shape parameter are set as 3.8, 0.1, and 3.4 according to Ghironi and Melitz (2005) and Hamano and Zanetti (2012, 2022). These values are assumed to be the same over time and thus for both subsequent time periods. Also, we set the disutiliy for working so that the labor supply is normalized to unity in each period.

Calibration

Heutel (2012) assumes a quadratic damage function such that $D(s_t) = d_0 + d_1 s_t + d_2 s_t^2$ where s is the stock of atmorphistic CO2 (expressed in giga ton) and we use his estimation for the value of d_0, d_1, and d_2 for our annual baisis calibration. The cumulative CO2 in 1981 is found to be 621 GtC and that in 2007 is doubled to 12462. We set the value of *erow* so that these values realize the observed stock of emissions at the initial steady states.

Calibration

Further, we assume the abatement cost function such that $g\left(\Omega_t\right) = \theta_{1,t}\Omega_t^{\theta_2}$ with $\theta_{1,t} > 0$ and $\theta_2 > 0$ following Nordhous (2008) and Heutel (2012). We assume that green firms use 0.03 % and 0.015% share of workers in the average prodution of green frims for the first and the second period, respectively to realize the steady state abatement rate Ω_t of 0.2. The values of $\theta_{1,t}$ is thus pin down accordingly as 0.0272 for the first period and as 0.0136 for the second period. In the abatement cost function, θ_2 is set to 2.8 following Nordhous (2008). With these values, the steady state tariffs are found to be 0.42 % for the first period and 0.21 % for the second period, respectively

Calibration

The difficulty is to pin down the steady state greeness (browness) in the economy.

Whether a firm is classified as green or brown depends on its position within the distribution of firms by their total tonnes of CO2-equivalent GHG emissions attributed to $1 million of revenue at a point in time. This scaled-GHG variable is referred to as GHG emissions intensity (Drempetic et al. 2020, Ilhan et al. 2021).9

Calibration

We set the steady state value of fixed cost for abatemet f_a so that it gives the steady state share of green firms as 0.1, for the steady state of the first period and 0.5 for the steady state of the second period. These values are based on the suttanability reporting rate by world large 100 copaneis provided by KPMG. The value increases from 0.12 in 1993 to 0.53 in 2008. While it is a crude estimate of the greeness of the economy, we assume that it can be an indirect measure of the share of green firms who engange in abatement in our theoretical model.

Calibration

Finally, there are two parameters that change overtime: exogenous componet of technology a_t and that represents abatement technology $\theta_{1,t}$. These values are set whose gross growth rate matche to the observed growth rate of GDP and emissions in the two subsequent periods. For the first period, US economy shows a stronger growth at the same of increasing emissions whose growth rates are 1.0305 and 1.0100, respectively. For the second period, after around the global financial crisis, it shows a lower growth rate in GDP and reducing emissions such that 1.0182 and 0.9880.