Création d'un PIB durable micro-fondé

Remise en cause du système capitaliste et de l'idéal de croissance

Jeremy Dyens et Pr Kenza Benhima

Think Tank Cronos 2020

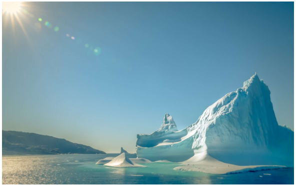
1er septembre 2020

UNIL | Université de Lausanne
HEC Lausanne

CRONOS FINANCE

Motivation

Motivation



Motivation

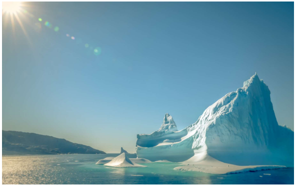
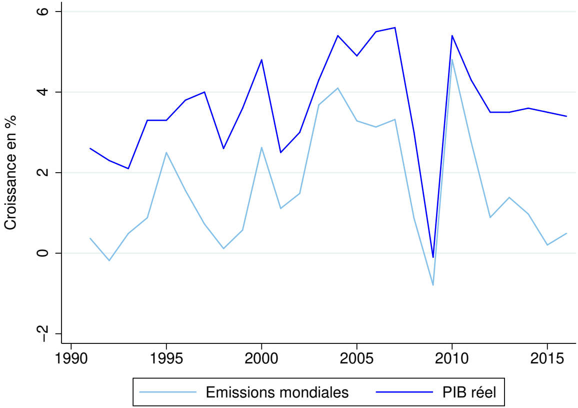
  

Figure: Croissance du PIB mondial vs croissance des émissions mondiales



Source : l'Agence Néerlandaise de l'Environnement pour les émissions mondiales et le FMI pour la croissance du PIB mondial.

Objectif

- Création d'un PIB durable (PIB vert) en se basant sur un modèle économique et sur les émissions de gaz à effet de serre (GES).
- Utilisation du concept du bien-être des individus.

Objectif

- Création d'un PIB durable (PIB vert) en se basant sur un modèle économique et sur les émissions de gaz à effet de serre (GES).
- Utilisation du concept du bien-être des individus.

Externalité négative

L'impact des actions d'un individu sur d'autres individus sans qu'il n'y ait de contrepartie monétaire.

Objectif

- Création d'un PIB durable (PIB vert) en se basant sur un modèle économique et sur les émissions de gaz à effet de serre (GES).
- Utilisation du concept du bien-être des individus.

Externalité négative

L'impact des actions d'un individu sur d'autres individus sans qu'il n'y ait de contrepartie monétaire.

- Production

Objectif

- Création d'un PIB durable (PIB vert) en se basant sur un modèle économique et sur les émissions de gaz à effet de serre (GES).
- Utilisation du concept du bien-être des individus.

Externalité négative

L'impact des actions d'un individu sur d'autres individus sans qu'il n'y ait de contrepartie monétaire.

- Production $\Rightarrow$ Emissions GES

Objectif

- Création d'un PIB durable (PIB vert) en se basant sur un modèle économique et sur les émissions de gaz à effet de serre (GES).
- Utilisation du concept du bien-être des individus.

Externalité négative

L'impact des actions d'un individu sur d'autres individus sans qu'il n'y ait de contrepartie monétaire.

- Production $\Rightarrow$ Emissions GES $\Rightarrow$ Dégâts futurs

Objectif

- Création d'un PIB durable (PIB vert) en se basant sur un modèle économique et sur les émissions de gaz à effet de serre (GES).
- Utilisation du concept du bien-être des individus.

Externalité négative

L'impact des actions d'un individu sur d'autres individus sans qu'il n'y ait de contrepartie monétaire.

- Production $\Rightarrow$ Emissions GES $\Rightarrow$ Dégâts futurs $\Rightarrow$ Bien-être des individus

Objectif

- Création d'un PIB durable (PIB vert) en se basant sur un modèle économique et sur les émissions de gaz à effet de serre (GES).
- Utilisation du concept du bien-être des individus.

Externalité négative

L'impact des actions d'un individu sur d'autres individus sans qu'il n'y ait de contrepartie monétaire.

- Production $\Rightarrow$ Emissions GES $\Rightarrow$ Dégâts futurs $\Rightarrow$ Bien-être des individus $\Rightarrow$ Rôle pour un PIB durable

Structure de la présentation

1. Un tour d'horizon des émissions de gaz à effet de serre
2. Pourquoi un PIB durable ?
3. Modèle théorique
4. Résultats empiriques
5. Cas pratique : évaluation financière d'une entreprise

Stock de carbone dans l'atmosphère

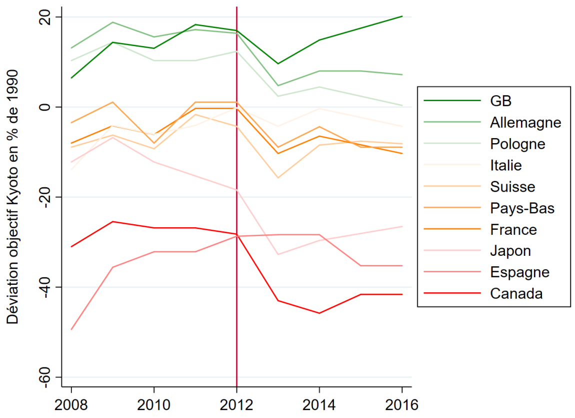
- Selon Stern (2007) : stock de carbone dans l'atmosphère entre 950 et 1'200 Gigatonnes de Carbone (GtC - 10^9 tonnes) $\Longleftrightarrow$ réchauffement climatique de 2 à 3°C.
- Niveau actuel : 960 GtC (+5,3 GtC par année).

Coopération Internationale

- Protocole de Kyoto (2005) : objectif moyen de réduction de 5% des émissions par rapport à 1990 pour 2008-2012.
- Amendement de Doha (jamais entré en vigueur) : objectif moyen de réduction de 18% par rapport à 1990 pour 2013-2020.
- Accord de Paris (2016) : objectif de limiter le réchauffement climatique à 1,5°C avec des cibles individuelles différentes. Obligation de formuler des objectifs.

Coopération Internationale

Figure: Déviation objectif de Kyoto en % de 1990



Source: l'Agence Néerlandaise de l'Environnement pour les émissions et les Nations Unies pour les objectifs.

Pourquoi un PIB durable ?

- PIB standard : valeur ajoutée $\Rightarrow$ bénéfice $\Rightarrow$ salaire des individus $\Rightarrow$ ☺

Cependant :

- Crises actuelles montrent que la croissance ne rime pas toujours avec bien-être.
- La croissance génère énormément d'émissions nocives pour notre environnement.
- Cette croissance "vole" les ressources des futurs générations.

Modèle théorique - justification

- Un modèle permet d'enlever le côté arbitraire des PIB verts.
- Un modèle utilise des hypothèses reconnues par la communauté scientifique et leur utilisation est plus que répandue.
- Modèle d'équilibre général dynamique stochastique (EGDS) avec une externalité liée au changement climatique de Golosov et al (2014).
- Objectif : lier PIB et externalité du climat au bien-être.

Hypothèses

- Une période (l'indice t) représente 10 ans.
- Chaque variable est calculée à l'échelle mondiale (agrégée à travers tous les pays du monde).
- La satisation du consommateur ou le bien-être s'écrit :

$$U(C_t) = \log(C_t)$$

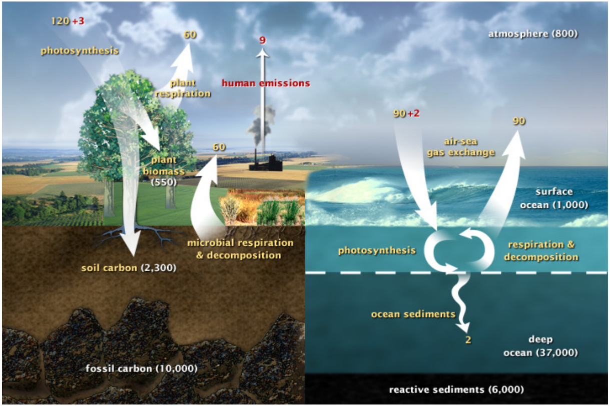
Hypothèses (bis)

- La production du bien de consommation, Y_t, s'écrit :

$$Y_t = (1 - D(S_t))E_t = \underbrace{e^{-\gamma_t(S_t - \bar{S})}}_{<1} E_t$$

- Le stock de carbone dans l'atmosphère évolue de la manière suivante :

$$S_t - \bar{S} = \sum_{s=0}^{t+T} (1 - d_s) E_{t-s} \quad \text{avec} \quad (1 - d_s) = \varphi_L + (1 - \varphi_L)\varphi_0(1 - \varphi)^s$$


120 +3
photosynthesis
60
plant respiration
9
human emissions
atmosphere (800)
90+2
air-sea gas exchange
90
60
plant biomass (550)
surface ocean (1,000)
microbial respiration & decomposition
photosynthesis
respiration & decomposition
soil carbon (2,300)
ocean sediments
2
deep ocean (37,000)
fossil carbon (10,000)
reactive sediments (6,000)

L'utilité indirecte et l'externalité du climat

- Pour amener de la durabilité, il faut s'intéresser à la satisfaction future des individus.
- En économie, on utilise le concept d'utilité indirecte.

Utilité indirecte

Représente le maximum de la satisfaction totale (à travers toutes les périodes) obtenu par un agent et actualisé à aujourd'hui. Elle ne dépend que des variables de stock du modèle.

Utilité indirecte

$$V_t(S_{t-1}) \equiv \max \quad \log(C_t) + \beta\, \mathbb{E}_t V_{t+1}(S_t)$$

- Prend en compte la satisfaction (utilité) actuelle : $\log(C_t)$.
- Prend en compte toutes les satisfactions futures : $\mathbb{E}_t V_{t+1}(S_t)$.
- Le facteur β représente le poids que les agents donnent au futur (patience des individus).

PIB durable

$$\text{Variation bien-être} \begin{cases} \dfrac{\partial V_t(S_{t-1})}{\partial t} = \underbrace{\dfrac{1}{Y_t}\dfrac{\partial Y_t}{\partial t}}_{\text{Croissance PIB}} + \underbrace{\beta\,\mathbb{E}_t \dfrac{\partial V_{t+1}(S_t)}{\partial S_t}\dfrac{\partial S_t}{\partial t}}_{\text{Externalité du climat}} \end{cases}$$

Résultats principaux

Pour la période allant de 2007 à 2016:

- Externalité du climat : 0,8 point de pourcentage (avec le facteur d'escompte bas) et 8,7 points de pourcentage (avec le facteur d'escompte élevé) pour 10 ans.

- Externalité du climat: 0,1 point de pourcentage (avec le facteur d'escompte bas) et 1,1 points de pourcentage (avec le facteur d'escompte haut) chaque année.

Annualisation

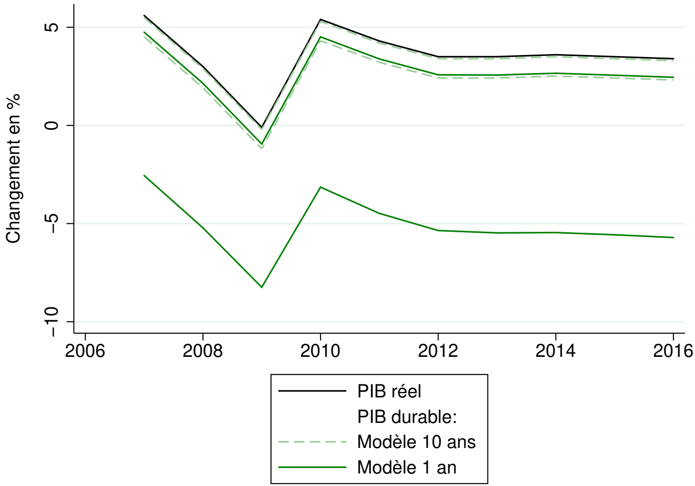
Résultats empiriques

Table: Croissances moyennes du PIB en % pour la période 2007-2016

	PIB durable - 10 ans			
PIB	β_L & $\bar{\gamma}$	β_H & $\bar{\gamma}$	β_L & γ^H	β_H & γ^H
3,57	3,47	2,46	2,67	-9,53
	PIB durable - 1 an			
	β_L & $\bar{\gamma}$	β_H & $\bar{\gamma}$	β_L & γ^H	β_H & γ^H
	2,67	-5,12	-4,21	-71,17

Représentation graphique

Figure: Croissance PIB mondial vs PIB durable : modèle 1 et 10 ans



Contributions par pays

Table: Contribution 2016 à l'ajustement lié à l'externalité du climat en milliards de dollars Calculs

Pays	β_L & $\bar{\gamma}$	β_H & $\bar{\gamma}$	β_L & γ^H	β_H & γ^H
Chine	196	1'842	1'690	15'837
Etats-Unis	99	935	858	8'047
Allemagne	15	138	127	1'187
GB	8	75	69	645
France	7	65	59	556
Italie	7	61	56	529
Espagne	5	47	44	408
Belgique	2	16	15	141
Autriche	1	10	9	88
Suisse	0,8	7	7	64

Evaluation financière d'une entreprise

- Inclure de la durabilité dans notre mesure la rend plus fiable pour prédire les futurs taux de croissance.
- En finance, il existe la méthode d'actualisation des flux de trésorerie pour évaluer la valeur d'une entreprise.
- Des cash-flows sont estimés jusqu'à un certain horizon. Au delà de cette horizon, la valeur terminale est calculée. L'approche la plus courante est celle de Gordon-Shapiro qui se base sur un taux de croissance perpétuel (g) :

$$\text{Valeur Terminale} = \frac{F_0 * (1+g)}{t-g}$$

Evaluation financière d'une entreprise

Cash-flows libres estimés				Valeur terminale		
millions USD	2020	2021	2022	Variante 1	Variante 2	Variante 3
CFL estimé	6'000	6'500	7'100	7'353	7'346	7'275
Croissance en %		8,3%	9,2%	3,6%	3,46%	2,47%
				PIB réel	PIB durable 1	PIB durable 2

Evaluation financière d'une entreprise

Taux de croissance	3,6%	3,46%	2,47%
Valeur entreprise	182'757	178'563	148'326
Valeur nette de la dette	20'000	20'000	20'000
Valeur fonds propres	162'757	158'563	128'326
Valeur estimée des actions	162,76	158,56	128,33
Nombres d'actions (millions)	1'000		

Conclusion

- Création d'un PIB durable basé sur un modèle micro-fondé. Approche novatrice qui réduit le côté arbitraire.
- Le PIB durable représente mieux le potentiel de croissance et peut donc impacter les décisions d'investissement.
- Ajustement pour tenir compte de l'externalité du climat de 0,1 point de pourcentage et 1,1 points de pourcentage selon le facteur d'escompte.
- D'autres ajustements suivant la même méthodologie pourraient être ajoutés par la suite.

What is next ?

- Adresser le débat autour du facteur d'escompte.
- Comment augmenter la transparence du modèle ?
- Comment développer un modèle spécifique à chaque pays ?

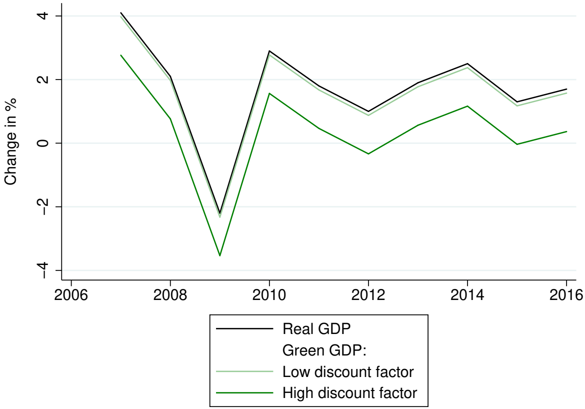
$\Rightarrow$ Un consensus international sur ces mesures se fera que si les mesures sont aussi transparentes et intuitives que possible.

Merci pour votre attention!

Annexes

- Robustness Check
- Constant Profit and Equilibrium
- Climate Externality
- Complete Characterisation
- Data
- Parameter Selection
- Annualising
- A Country-Specific Model
- Global Emissions
- Green GDP for two β's
- Green GDP for different β's
- Green GDP for different γ's 1
- Green GDP for different γ's 2
- Climate externality evolution
- 2016 country contributions 1
- 2016 country contributions 2
- 2016 country contributions 3

PIB durable suisse



Sélection des paramètres

Table: Résumé de la calibration

φ	φ_L	φ_0	β_L	β_H	$10^4\bar{\gamma}$	$10^4\gamma^H$	$10^4\gamma^L$	$S_0(S_{1,0})$
0.0228	0.2	0.393	0.985^{10}	0.999^{10}	0.2379	0.106	2.046	844(717)

Détails Données Externalité au climat Modèle 1 an

Les données

- Croissance PIB réel : FMI
- PIB nominal : Banque Mondiale
- Emissions mondiales, chinoises et américaines : Olivier et al. (2017) de l'Agence Néerlandaise de l'Environnement
- Emissions pour les autres pays : OCDE

The Production Function

$$Y_t = (1 - D(S_t))E_t = e^{-\gamma_t(S_t - \bar{S})}E_t$$

- Damages, represented by $D(S_t)$, are multiplicative and therefore measure the economic costs of the climate change as a percent of final-good output.

The Production Function

$$Y_t = (1 - D(S_t))E_t = e^{-\gamma_t(S_t - \bar{S})}E_t$$

- Damages, represented by $D(S_t)$, are multiplicative and therefore measure the economic costs of the climate change as a percent of final-good output.
- The parameter γ_t is the damage semi-elasticity, that is, a percentage change in output from one unit change in the amount of carbon in the atmosphere, S_t, caused by emitting one unit of carbon today, E_t.

The Carbon Cycle

$$S_t - \bar{S} = \sum_{s=0}^{t+T} (1 - d_s) E_{t-s}$$

$$\textit{with} \quad (1 - d_s) = \varphi_L + (1 - \varphi_L)\varphi_0(1 - \varphi)^s$$

- A share φ_L of the carbon emitted stays for ever in the atmosphere.

The Carbon Cycle

$$S_t - \bar{S} = \sum_{s=0}^{t+T} (1 - d_s) E_{t-s}$$

$$with \quad (1 - d_s) = \varphi_L + (1 - \varphi_L)\varphi_0(1 - \varphi)^s$$

- A share φ_L of the carbon emitted stays for ever in the atmosphere.
- A share $(1 - \varphi_L)(1 - \varphi_0)$ exits the atmosphere into the biosphere and the surface oceans within a decade.

The Carbon Cycle

$$S_t - \bar{S} = \sum_{s=0}^{t+T} (1 - d_s) E_{t-s}$$

$$\textit{with} \quad (1 - d_s) = \varphi_L + (1 - \varphi_L)\varphi_0(1 - \varphi)^s$$

- A share φ_L of the carbon emitted stays for ever in the atmosphere.
- A share $(1 - \varphi_L)(1 - \varphi_0)$ exits the atmosphere into the biosphere and the surface oceans within a decade.
- The remaining share decays at a geometric rate φ because only a small fraction of atmospheric GHG falls down into the deep oceans every decade.

Additional Information

- $C_t = Y_t$ See proof
- Recursive form for the carbon stock:

$$
\begin{aligned}
S_t &= S_{1,t} + S_{2,t} \\
S_{1,t} &= S_{1,t-1} + \varphi_L E_t \\
S_{2,t} &= (1-\varphi) S_{2,t-1} + (1-\varphi_L)\varphi_0 E_t
\end{aligned}
$$

The Indirect Utility and the Climate Externality

$$V_t(S_{1,t-1}, S_{2,t-1}) \equiv \max_{E_t} \quad \log(Y_t) + \beta\, \mathbb{E}_t V_{t+1}(S_{1,t}, S_{2,t})$$

$$Y_t = \exp\left(-\gamma_t (\overbrace{S_{1,t-1} + \varphi_L E_t}^{S_{1,t}} + \overbrace{(1-\varphi) S_{2,t-1} + (1-\varphi_L)\varphi_0 E_t}^{S_{2,t}} - \bar{S}) \right) E_t$$

Welfare change or Green GDP growth

$$\frac{\partial V_t(S_{t-1})}{\partial t} = \underbrace{\frac{1}{Y_t}\frac{\partial Y_t}{\partial t}}_{\text{Real GDP growth}} + \underbrace{\beta\,\mathbb{E}_t \frac{\partial V_{t+1}(S_t)}{\partial S_t}\frac{\partial S_t}{\partial t}}_{\text{Climate Externality}}$$

with $$\frac{\partial V_{t+1}(S_t)}{\partial S_t}\frac{\partial S_t}{\partial t} = \frac{\partial V_{t+1}(S_{1,t}, S_{2,t})}{\partial S_{1,t}}\frac{\partial S_{1,t}}{\partial t} + \frac{\partial V_{t+1}(S_{1,t}, S_{2,t})}{\partial S_{2,t}}\frac{\partial S_{2,t}}{\partial t}$$

The Climate Externality

Looking at the climate externality using the Envelope Theorem and by first looking at one period before:

$$\frac{\partial V_t(S_{1,t-1},S_{2,t-1})}{\partial S_{1,t-1}} = -\gamma_t + \beta \mathbb{E}_t \frac{\partial V_{t+1}(S_{1,t},S_{2,t})}{\partial S_{1,t}} \overbrace{\frac{\partial S_{1,t}}{\partial S_{1,t-1}}}^{=1}$$

$$= -\gamma_t - \beta \mathbb{E}_t \gamma_{t+1} - \beta^2 \mathbb{E}_t \gamma_{t+2} - \dots$$

$$= -\sum_{s=0}^{\infty} \beta^s \mathbb{E}_t \gamma_{t+s}$$

$$\frac{\partial V_t(S_{1,t-1},S_{2,t-1})}{\partial S_{2,t-1}} = -\gamma_t(1-\varphi) + \beta \mathbb{E}_t \frac{\partial V_{t+1}(S_{1,t},S_{2,t})}{\partial S_{2,t}} \overbrace{\frac{\partial S_{2,t}}{\partial S_{2,t-1}}}^{1-\varphi}$$

$$= -\gamma_t(1-\varphi) - \beta \mathbb{E}_t \gamma_{t+1}(1-\varphi)^2 - \dots$$

$$= -\sum_{s=0}^{\infty} \beta^s \mathbb{E}_t \gamma_{t+s}(1-\varphi)^{s+1}$$

Carbon Stock Evolution and Additional Assumption

$$\frac{\partial S_{1,t}}{\partial t} \approx S_{1,t} - S_{1,t-1} = \varphi_L E_t$$

$$\frac{\partial S_{2,t}}{\partial t} \approx S_{2,t} - S_{2,t-1} = (1 - \varphi_L)\varphi_0 E_t - \varphi S_{2,t-1}$$

$\mathbb{E}_t \gamma_{t+j} = \bar{\gamma}_t$ for all j

The expected time path for the damage parameter is constant.

The Climate Externality

All the steps

$$\beta \frac{\partial V_{t+1}(S_t)}{\partial S_t} \frac{\partial S_t}{\partial t} = -\left(\sum_{s=0}^{\infty} \beta^{s+1} \bar{\gamma}_t (1 - d_{s+1}) \right) E_t + \left(\sum_{s=0}^{\infty} \beta^{s+1} \bar{\gamma}_t (1 - \varphi)^{s+1} \right) \varphi S_{2,t-1}$$

$$= -\bar{\gamma}_t \left(\frac{\varphi_L \beta}{1 - \beta} + \frac{(1 - \varphi_L)\varphi_0 \beta (1 - \varphi)}{1 - \beta(1 - \varphi)} \right) E_t + \bar{\gamma}_t \left(\frac{\beta(1 - \varphi)}{1 - \beta(1 - \varphi)} \right) \varphi S_{2,t-1}$$

Complete Characterisation The table

Intuitions

- The first term is global emissions multiplied by the marginal externality cost of emissions defined in GHKT and forwarded one period ahead.

Intuitions

- The first term is global emissions multiplied by the marginal externality cost of emissions defined in GHKT and forwarded one period ahead.
- The marginal cost is a discounted sum of expected future damage semi-elasticities. It is discounted by the time preference and the carbon cycle.

Intuitions

- The first term is global emissions multiplied by the marginal externality cost of emissions defined in GHKT and forwarded one period ahead.
- The marginal cost is a discounted sum of expected future damage semi-elasticities. It is discounted by the time preference and the carbon cycle.
- The second term is $S_{2,t-1}$ multiplied by the marginal value of the carbon leaving the atmosphere.

Intuitions

- The first term is global emissions multiplied by the marginal externality cost of emissions defined in GHKT and forwarded one period ahead.
- The marginal cost is a discounted sum of expected future damage semi-elasticities. It is discounted by the time preference and the carbon cycle.
- The second term is $S_{2,t-1}$ multiplied by the marginal value of the carbon leaving the atmosphere.
- The formula is very simple.

Robustness Check

Appendix

- Depreciation Rate Assumption
- Power Utility
- Production Function Assumption
- Damages in Utility
- Technology for Carbon Capture and Damages
- Carbon Stock Calibration

Depreciation Rate Assumption

Back

According to GHKT, lowering the depreciation rate only impacts the tax through the evolution of the saving rate. Let's take the complete characterisation of the model and $C_t = (1 - s_t) Y_t$. The indirect utility change writes now as follows:

$$\frac{\partial V_t(S_{t-1}, K_t, R_{1,t})}{\partial t} = \underbrace{\frac{1}{Y_t}\frac{\partial Y_t}{\partial t}}_{\text{Real GDP growth}} + \underbrace{\frac{1}{1 - s_t}\frac{\partial s_t}{\partial t}}_{\text{Saving rate change}}$$

$$+ \underbrace{\beta \, \frac{\mathbb{E}_t \partial V_{t+1}(S_t)}{\partial S_t}\frac{\partial S_t}{\partial t}}_{\text{Climate Externality}} + \quad \ldots$$

Power Utility

Back

Similarly to GHKT, we consider the more general power-function class of utility (with constant relative risk aversion/elasticity of intertemporal substitution):

$$U(C_t) = \frac{C_t^{1-\sigma} - 1}{1 - \sigma}$$

with σ, the coefficient of relative risk aversion (curvature increases in σ). We move back to the simple model with no capital and $C_t = Y_t$.

Power Utility

Back

$$V_t(S_{1,t-1}, S_{2,t-1}) \equiv \max_{E_t} \quad \frac{Y_t^{1-\sigma} - 1}{1-\sigma} + \beta\, \mathbb{E}_t V_{t+1}(S_{1,t}, S_{2,t})$$

$$\equiv \max_{E_t} \left(\left[\exp\left(-\gamma_t (\overbrace{S_{1,t-1} + \varphi_L E_t}^{S_{1,t}} + \overbrace{(1-\varphi)S_{2,t-1} + (1-\varphi_L)\varphi_0 E_t}^{S_{2,t}} - \bar{S}) \right) E_t \right]^{1-\sigma} - 1 \right) \frac{1}{1-\sigma}$$

$$+ \beta\, \mathbb{E}_t V_{t+1}(S_{1,t}, S_{2,t})$$

and compute the indirect utility change:

$$\frac{\partial V_t(S_{t-1})}{\partial t} = Y_t^{-\sigma} \frac{\partial Y_t}{\partial t} + \underbrace{\beta\, \mathbb{E}_t \frac{\partial V_{t+1}(S_t)}{\partial S_t} \frac{\partial S_t}{\partial t}}_{\text{Climate Externality}}$$

Power Utility

Back

$$\frac{\partial V_t(S_{1,t-1}, S_{2,t-1})}{\partial S_{1,t-1}} = Y_t^{-\sigma}(-\gamma_t)Y_t + \beta\mathbb{E}_t \frac{\partial V_{t+1}(S_{1,t}, S_{2,t})}{\partial S_{1,t}} \overbrace{\frac{\partial S_{1,t}}{\partial S_{1,t-1}}}^{=1}$$

$$= Y_t^{-\sigma}(-\gamma_t)Y_t + \beta\mathbb{E}_t Y_{t+1}^{-\sigma}(-\gamma_{t+1})Y_{t+1} + \ \dots$$

$$= -\sum_{s=0}^{\infty} \beta^s \mathbb{E}_t \gamma_{t+s} Y_{t+s}^{1-\sigma}$$

$$\frac{\partial V_t(S_{1,t-1}, S_{2,t-1})}{\partial S_{2,t-1}} = Y_t^{-\sigma}(-\gamma_t)(1-\varphi)Y_t + \beta\mathbb{E}_t \frac{\partial V_{t+1}(S_{1,t}, S_{2,t})}{\partial S_{2,t}} \overbrace{\frac{\partial S_{2,t}}{\partial S_{2,t-1}}}^{1-\varphi}$$

$$= Y_t^{-\sigma}(-\gamma_t)(1-\varphi)Y_t + \beta\mathbb{E}_t Y_{t+1}^{-\sigma}(-\gamma_{t+1})(1-\varphi)^2 Y_{t+1} + \ \dots$$

$$= -\sum_{s=0}^{\infty} \beta^s \mathbb{E}_t \gamma_{t+s}(1-\varphi)^{s+1} Y_{t+s}^{1-\sigma}$$

Power Utility

Back

Like in GHKT, we use the simplification in Barrage (2014), that is a constant consumption growth (output growth) at net rate g:

$$\frac{\partial V_t(S_{1,t-1}, S_{2,t-1})}{\partial S_{1,t-1}} = -\sum_{s=0}^{\infty} \beta^s \mathbb{E}_t \gamma_{t+s} (1+g)^{s(1-\sigma)} Y_t^{1-\sigma}$$

$$\frac{\partial V_t(S_{1,t-1}, S_{2,t-1})}{\partial S_{2,t-1}} = -\sum_{s=0}^{\infty} \beta^s \mathbb{E}_t \gamma_{t+s} (1-\varphi)^{s+1} (1+g)^{s(1-\sigma)} Y_t^{1-\sigma}$$

Power Utility

Back

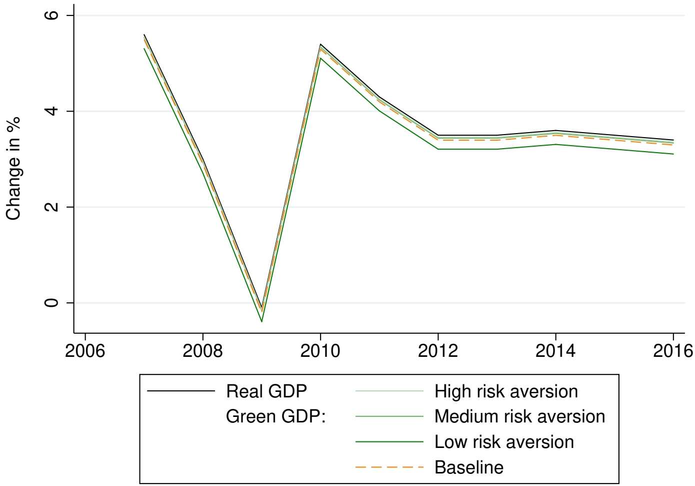
$$\frac{\partial V_t(S_{t-1})}{\partial t} = Y_t^{1-\sigma} \quad (\quad \underbrace{\frac{1}{Y_t}\frac{\partial Y_t}{\partial t}}_{\text{Real GDP growth}}$$

$$\left.\begin{aligned} -E_t\bar{\gamma}_t \left(\tfrac{\varphi_L\beta(1+g)^{1-\sigma}}{1-\beta(1+g)^{1-\sigma}} + \tfrac{\varphi_0(1-\varphi_L)\beta(1+g)^{1-\sigma}(1-\varphi)}{1-\beta(1+g)^{1-\sigma}(1-\varphi)}\right) \\ S_{2,t-1}\bar{\gamma}_t\left(\tfrac{\varphi\beta(1+g)^{1-\sigma}(1-\varphi)}{1-\beta(1+g)^{1-\sigma}(1-\varphi)}\right) \quad) \end{aligned}\right\} \text{Climate Externality}$$

Power Utility

Back

Figure: World real GDP and Green GDP growth for different σ values



Production Function Assumption

Back

- Even in an extreme case where output is Leontief in $AK^{\alpha}N^{1-\alpha}$ and E (extreme complementarity), GHKT argue that it is unlikely to obtain very different optimal-taxation results.
- This certainly implies the same conclusion in our model. In addition, we would need to find a way to derive the indirect utility with respect to the carbon stock.

Damages in utility

Back

We can use a specification in which damages occur directly in the utility function: $U(C_t, S_t) = \log(C_t) - D(S_t)$. Using the simple model again and $C_t = Y_t$, the indirect utility writes as follows:

$$V_t(S_{1,t-1}, S_{2,t-1}) = \max_{E_t} \quad \log(Y_t) - D(\overbrace{S_{1,t-1} + \varphi_L E_t}^{S_{1,t}} + \overbrace{(1-\varphi)S_{2,t-1} + (1-\varphi_L)\varphi_0 E_t}^{S_{2,t}})$$
$$+ \beta \mathbb{E}_t V_{t+1}(S_{1,t}, S_{2,t})$$

Damages in utility

Back

$$\frac{\partial V_t(S_{1,t-1}, S_{2,t-1})}{\partial S_{1,t-1}} = -D'(S_t) - \beta \mathbb{E}_t D'(S_{t+1}) - \dots$$
$$= -\sum_{s=0}^{\infty} \beta^s \mathbb{E}_t D'(S_{t+s})$$

$$\frac{\partial V_t(S_{1,t-1}, S_{2,t-1})}{\partial S_{2,t-1}} = -D'(S_t)(1-\varphi) - \beta \mathbb{E}_t D'(S_{t+1})(1-\varphi)^2 - \dots$$
$$= -\sum_{s=0}^{\infty} \beta^s \mathbb{E}_t D'(S_{t+1})(1-\varphi)^{s+1}$$

It is straightforward to see that if $D(S_t) = \gamma_t S_t$, these last two expressions exactly coincide with the derivation of the simple model.

Technology for Carbon Capture and Damages

Back

- If technology for carbon capture are used at the source of emissions, this should be reflected in the data emissions, E_t in the model, and no adjustment would be necessary in the formula.

- If we can capture carbon directly from the atmosphere, we would have to adjust our calibration of the carbon stock by changing some parameters (for example, the decaying rate φ) or by adding a term related to carbon capture.

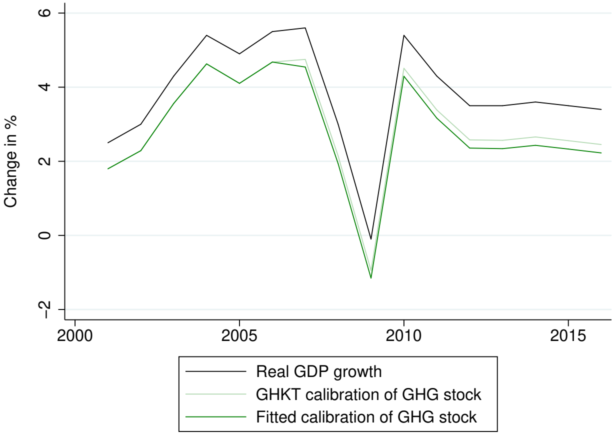
- Technical progress that would reduce the negative effect of carbon emissions would be taken into account with a different calibration of the parameter.

Carbon Stock Calibration

Back

We conduct a second analysis in which we increase φ^0 from 0.393 to 0.55 from 2007 onwards in order to better match the carbon stock in the data.

Figure: World real GDP and Green GDP for different φ_0 values.



Constant Profits and Equilibrium Condition

Back Appendix

The energy sector maximises the following profit function:

$$\max_{N_t} \quad \pi_{t,E} = P_{t,E} E_t - W_t N_t$$

subject to the production constraint, $E_t = A_t N_t$. The optimality solution is $W_t = P_{t,E} A_t$, which implies:

$$\pi_{t,E} = P_{t,E} E_t - P_{t,E} A_t N_t = P_{t,E} E_t - P_{t,E} E_t = 0.$$

Constant Profits and Equilibrium Condition

Back Appendix

The final-good sector maximises the following profit function:

$$\max_{E_t} \quad \pi_t = P_t Y_t - P_{t,E} E_t$$

subject to the production constraint, $Y_t = e^{-\gamma_t (S_t - \bar{S})} E_t$. The optimality solution is $P_{t,E} = P_t e^{-\gamma_t (S_t - \bar{S})}$, which implies:

$$\pi_t = P_t Y_t - P_t e^{-\gamma_t (S_t - \bar{S})} E_t = P_t Y_t - P_t Y_t = 0.$$

The consumer's budget constraint is $P_t C_t = W_t N_t$. Using the results above, it becomes $P_t C_t = P_{t,E} A_t N_t = P_t e^{-\gamma_t (S_t - \bar{S})} E_t = P_t Y_t$. Hence:

$$C_t = Y_t$$

Climate Externality Computations Back Appendix

$$\frac{\partial V_{t+1}(S_t)}{\partial S_t}\frac{\partial S_t}{\partial t} = \frac{\partial V_{t+1}(S_{1,t}, S_{2,t})}{\partial S_{1,t}}\frac{\partial S_{1,t}}{\partial t} + \frac{\partial V_{t+1}(S_{1,t}, S_{2,t})}{\partial S_{2,t}}\frac{\partial S_{2,t}}{\partial t}$$

$$\frac{\partial V_{t+1}(S_{1,t}, S_{2,t})}{\partial S_{1,t}} = -\sum_{s=0}^{\infty}\beta^s \mathbb{E}_t \gamma_{t+s+1}$$

$$\frac{\partial V_{t+1}(S_{1,t}, S_{2,t})}{\partial S_{2,t}} = -\sum_{s=0}^{\infty}\beta^s \mathbb{E}_t \gamma_{t+s+1}(1-\varphi)^{s+1}$$

$$\frac{\partial S_{1,t}}{\partial t} \approx S_{1,t} - S_{1,t-1} = \varphi_L E_t$$

$$\frac{\partial S_{2,t}}{\partial t} \approx S_{2,t} - S_{2,t-1} = (1-\varphi_L)\varphi_0 E_t - \varphi S_{2,t-1}$$

Climate Externality Computations

Back Appendix

$$
\begin{aligned}
\frac{\partial V_{t+1}(S_t)}{\partial S_t}\frac{\partial S_t}{\partial t} &= -\sum_{s=0}^{\infty}\beta^s \mathbb{E}_t \gamma_{t+s+1}\ \varphi_L E_t \\
&\quad - \sum_{s=0}^{\infty}\beta^s \mathbb{E}_t \gamma_{t+s+1}(1-\varphi)^{s+1}\ \left((1-\varphi_L)\varphi_0 E_t - \varphi S_{2,t-1}\right) \\
&= -\left(\sum_{s=0}^{\infty}\beta^s \mathbb{E}_t \gamma_{t+s+1}\underbrace{\left(\varphi_L + (1-\varphi_L)\varphi_0(1-\varphi)^{s+1}\right)}_{1-d_{s+1}}\right)E_t \\
&\quad + \left(\sum_{s=0}^{\infty}\beta^s \mathbb{E}_t \gamma_{t+s+1}(1-\varphi)^{s+1}\right)\varphi S_{2,t-1} \\
&= -\left(\sum_{s=0}^{\infty}\beta^s \mathbb{E}_t \gamma_{t+s+1}(1-d_{s+1})\right)E_t \\
&\quad + \left(\sum_{s=0}^{\infty}\beta^s \mathbb{E}_t \gamma_{t+s+1}(1-\varphi)^{s+1}\right)\varphi S_{2,t-1}
\end{aligned}
$$

The Complete Characterisation

Back Appendix

- We add capital, K_t, with $\delta = 1$ (full depreciation).
- There are three energy sectors: oil, coal, and green energy.
  - Oil is in finite supply.
  - Carbon and green energy are produced using $E_{i,t} = A_{i,t} N_{i,t}$.
  - $E_{i,t}$ represents emissions and is transformed into energy with $E_t = \left(\kappa_1 E_{0,1,t}^{\rho} + \kappa_2 E_{0,2,t}^{\rho} + \kappa_3 E_{0,3,t}^{\rho} \right)^{\frac{1}{\rho}}$.

$\Rightarrow$ The resulting Climate Externality is similar to the simple model.

The Complete Characterisation

Appendix

- Households
- Energy Sectors
- The Final-Good Sector
- Equilibrium
- Constant Saving Rate
- The Indirect Utility
- The Climate Externality

Households

Back

$$\max_{\{C_t, K_{t+1}\}_{t=0}^{\infty}} \quad \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t U(C_t)$$

$$\text{s.t} \quad \mathbb{E}_0 \sum_{t=0}^{\infty} q_t(C_t + K_{t+1}) = \mathbb{E}_0 \sum_{t=0}^{\infty} q_t[(1 + r_t - \delta)K_t + w_t N_t + T_t] + \Pi_E$$

- q_t denotes Arrow-Debreu prices.
- r_t is the rental rate of capital.
- $\delta = 1$ and is the depreciation rate of capital.
- w_t is the wage paid for working, N_t.
- $T_t = 0$ and is governmental transfer.
- $\Pi_E = \sum_{i=1}^{3} \Pi_i$ and is the sum of the profits of the energy firms.

Energy Sectors Back

$$\Pi_i \equiv \max_{\{E_{i,t},K_{i,t},N_{i,t},\mathbf{E_{i,t}},R_{i,t+1}\}_{t=0}^{\infty}} \mathbb{E}_0 \sum_{t=0}^{\infty} q_t [(p_{i,t} - \tau_{i,t}) E_{i,t}$$
$$- r_t K_{i,t} - w_t N_{i,t} - \sum_{j=1}^{3} p_{j,t} E_{i,j,t}] \quad i = 1, 2, 3$$

- $p_{i,t}$ is the price of fuel of type i.
- $\tau_{i,t} = 0$ and is a per-unit tax on the resource.
- $\mathbf{E_{i,t}} = \{E_{i,j,t}\}_{j=1}^{3} = 0$ and is the energy source j used for producing energy i.
- $K_{i,t} = 0$.
- $R_{1,t+1} = R_{1,t} - E_{1,t}$.
- $E_{i,t} = A_i N_{i,t}$, for $i = 2, 3$.
- $\Pi_1 = \mathbb{E}_0 \sum_{t=0}^{\infty} q_t \, p_{1,t} E_{1,t}$ and $\Pi_2 = \Pi_3 = 0$.

The Final-Good Sector Back

$$\Pi_0 \equiv \max_{\{K_{0,t}, N_{0,t}, \mathbf{E_{0,t}}\}_{t=0}^{\infty}} \quad \mathbb{E}_0 \sum_{t=0}^{\infty} q_t \left[Y_t - r_t K_{0,t} - w_t N_{0,t} - \sum_{i=1}^{3} p_{i,t} E_{0,i,t} \right]$$

$$\text{with} \quad Y_t = e^{-\gamma_t (S_t - \bar{S})} A_{0,t} K_{0,t}^{\alpha} N_{0,t}^{1-\alpha-\nu} E_t^{\nu}$$

Optimality solutions (lead to zero profit):

- $r_t = \alpha \frac{Y_t}{K_t}$
- $w_t = (1 - \alpha - \nu) \frac{Y_t}{N_{0,t}}$
- $p_{i,t} = \nu \frac{Y_t}{E_t} E_t^{1-\rho} \kappa_i E_{0,i,t}^{\rho-1} = \nu Y_t E_t^{-\rho} \kappa_i E_{0,i,t}^{\rho-1} \qquad i = 1, 2, 3$

Equilibrium Back

$$\mathbb{E}_0 \sum_{t=0}^{\infty} q_t (C_t + K_{t+1}) = \mathbb{E}_0 \sum_{t=0}^{\infty} q_t [r_t K_t + w_t N_t] + \sum_{t=0}^{\infty} q_t p_{1,t} E_{1,t}$$

$$\begin{aligned} \textit{with} \quad w_t N_t + p_{1,t} E_{1,t} &= w_t (N_{0,t} + N_{2,t} + N_{3,t}) + p_{1,t} E_{1,t} \\ &= wtN_{0,t} + p_{2,t} E_{2,t} + p_{3,t} E_{3,t} + p_{1,t} E_{1,t} \\ &= (1-\alpha-\nu) Y_t + v Y_t E_t^{-\rho} \underbrace{\sum_{i=1}^{3} \kappa_i E_{i,t}^{\rho}}_{E_t^{\rho}} = (1-\alpha) Y_t \end{aligned}$$

$$\Rightarrow \mathbb{E}_0 \sum_{t=0}^{\infty} q_t (C_t + K_{t+1}) = \mathbb{E}_0 \sum_{t=0}^{\infty} q_t [\alpha Y_t + (1-\alpha) Y_t] = \mathbb{E}_0 \sum_{t=0}^{\infty} q_t Y_t$$

$$\begin{aligned} \Rightarrow K_{t+1} &= \alpha\beta Y_t \\ C_t &= (1-\alpha\beta) Y_t \end{aligned}$$

Constant Saving rate Back

"This result comes from logarithmic utility, Cobb-Douglas production, and 100% depreciation of capital, presuming that energy is produced either for free (oil) or at a constant returns to labor (coal/green energy)"
The traditional Euler equation, when $\delta = 1$, is:

$$U'(C_t) = \beta \mathbb{E}_t \, U'(C_{t+1})(r_{t+1})$$

Using $U(C_t) = \log(C_t)$ and $r_t = \alpha \frac{Y_t}{K_t}$:

$$\frac{1}{C_t} = \beta \mathbb{E}_t \, \frac{1}{C_{t+1}} \alpha \frac{Y_{t+1}}{K_{t+1}}$$
$$\Rightarrow C_t = \frac{1}{\beta} \mathbb{E}_t \, C_{t+1} \frac{1}{\alpha} \frac{K_{t+1}}{Y_{t+1}}$$

Constant Saving rate

Back

Substituting C_t into the feasibility constraint, $Y_t = C_t + K_{t+1}$:

$$\frac{1}{\beta}\mathbb{E}_t\ C_{t+1}\frac{1}{\alpha}\frac{K_{t+1}}{Y_{t+1}} + K_{t+1} = Y_t$$

$$\Rightarrow K_{t+1}\left(\frac{1}{\beta}\mathbb{E}_t\ C_{t+1}\frac{1}{\alpha}\frac{1}{Y_{t+1}} + 1\right) = Y_t$$

Using $C_t = (1 - s_t)Y_t$ and $K_{t+1} = s_t Y_t$:

$$s_t Y_t\left(\frac{1}{\beta}\mathbb{E}_t\ (1 - s_{t+1})Y_{t+1}\frac{1}{\alpha}\frac{1}{Y_{t+1}} + 1\right) = Y_t$$

$$\Rightarrow \frac{1}{\alpha\beta}\mathbb{E}_t\ (1 - s_{t+1}) = \frac{1}{s_t} - 1 = \frac{1 - s_t}{s_t}$$

$$\Rightarrow \mathbb{E}_t\ (1 - s_{t+1})\frac{s_t}{1 - s_t} = \alpha\beta$$

This equation admits one well-behaved solution if and only if the saving rate is constant and therefore equal to $s_t = \bar{s} = \alpha\beta$.

The Indirect Utility

Back

$$
\begin{aligned}
V_t(S_{1,t-1}, S_{2,t-1}, K_t, R_{1,t}) &= \max_{\mathbf{E_t}} \quad \log((1-\alpha\beta)Y_t) + \beta \mathbb{E}_t V_{t+1}(S_{1,t}, S_{2,t}, K_{t+1}, R_{1,t+1}) \\
&= \max_{\mathbf{E_t}} \quad \log(\quad (1-\alpha\beta)\ exp[-\gamma_t(\underbrace{S_{1,t-1} + \varphi_L E_t^f}_{S_{1,t}} \\
&+ \underbrace{(1-\varphi)S_{2,t-1} + (1-\varphi_L)\varphi_0 E_t^f}_{S_{2,t}} - \bar{S}] \quad A_{0,t} K_t^{\alpha} N_{0,t}^{1-\alpha-\nu} E_t^{\nu} \quad) \\
&+ \beta \mathbb{E}_t V_{t+1}(S_{1,t}, S_{2,t}, K_{t+1}, R_{1,t+1})
\end{aligned}
$$

The Climate Externality Back

$$\frac{\partial V_t(S_{t-1}, K_t, R_{1,t})}{\partial t} =$$

$$\frac{1}{Y_t}\frac{\partial Y_t}{\partial t}$$ Real GDP growth

$$+ \beta\,\mathbb{E}_t \frac{\partial V_{t+1}(S_t, K_{t+1}, R_{1,t+1})}{\partial S_t}\frac{\partial S_t}{\partial t}$$ Climate Externality

$$+ \beta\,\mathbb{E}_t \frac{\partial V_{t+1}(S_t, K_{t+1}, R_{1,t+1})}{\partial K_{t+1}}\frac{\partial K_{t+1}}{\partial t}$$ Capital Accumulation

$$+ \beta\,\mathbb{E}_t \frac{\partial V_{t+1}(S_t, K_{t+1}, R_{1,t+1})}{\partial R_{1,t+1}}\frac{\partial R_{1,t+1}}{\partial t}$$ Finite resource stock Externality

The climate externality is the same as in the simple model.

Data

Back Appendix

- World real GDP growth: IMF
- Global GHG emissions: Olivier et al. (2017)
- Total emissions per country: OECD
- The carbon stock: European Environment Agency
- Nominal GDP: World Bank

Parameter Selection

Back Appendix

- The Discount factor β
- The Carbon Cycle
- The Carbon Stock
- The Damage Semi-elasticity
- The One-year Model

The Discount factor β Back

- 0.985^{10} (discount rate of 1.5%) as in Nordhaus (2008).
- 0.999^{10} (discount rate of 0.1%) as in Stern (2007).
- The correct value is still a debate nowadays.

The Carbon Cycle

Back

- $\varphi_L = 0.2$
  From the 2007 Intergovernmental Panel on Climate Change (IPCC) report: 20% of any emissions stay in the atmosphere almost for ever.

- $\varphi = 0.0228$
  From Archer (2005): the remaining emissions, the share slowly trickling down into the deep oceans, have a mean lifetime of 300 years, implying $(1 - \varphi)^3 = 0.5$.

- $\varphi_0 = 0.393$
  From the 2007 IPCC report: half of all GHG emissions disappear after 30 years, implying that $d_2 = 0.5$ and
  $(1 - d_2) = 1 - 0.5 = 0.2 + 0.8\varphi_0(1 - 0.0228)^2$.

The Carbon Stock

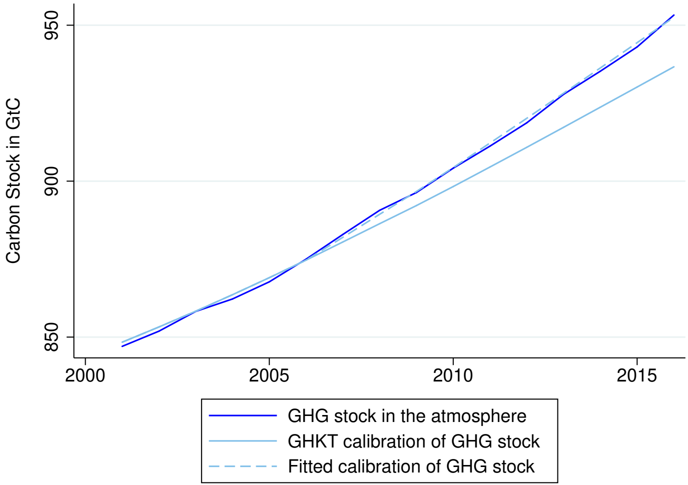
Back

- We set $S_0 = 844$ GtC in 2000 from the data on the carbon stock.
- We take GHKT proportion for S_1 (85%) and S_2 (15%) which lead to $S_1 = 717$ and $S_2 = 127$.
- We use the recursive form to generate the full path.
- Underestimation of the carbon stock by only 17 GtC out of 953 GtC in 2016.

The Carbon Stock

Back Fitted Calibration

Figure: Real carbon stock and calibrated version



The Damage Semi-elasticity

Back

- $\bar{\gamma} \equiv p\gamma^H + (1-p)\gamma^L$, with p, the ex ante probability of the high value and with $\gamma^H > \gamma^L$.

- $\gamma^L = 1.060 \times 10^{-5}$
  From Nordhaus (2008): a 2.5 degrees Celsius heating ($S_t = 1,035$ GtC)[1] leads to a global loss of 0.48% of GDP, implying $e^{-\gamma^L(1{,}035-581)} = 1 - 0.0048 = 0.9952$.

- $\gamma^H = 2.046 \times 10^{-4}$
  From Nordhaus (2008): with a probability of 6.8%, a 6 degrees Celsius heating ($S_t = 2,234$ GtC) has catastrophic effects, defined as a loss of 30% of GDP, implying $e^{-\gamma^H(2{,}324-581)} = 1 - 0.3 = 0.7$.

- $\bar{\gamma}_t = 2.379 \times 10^{-5}$

[1] The standard function in the literature for the mapping from S to T is: $T_t = T(S_t) = \lambda \log(\frac{S_t}{\bar{S}})/\log(2)$, with $\lambda = 3.0$ degrees Celsius.

One-year model

Back Parameter Selection

Two parameters need to be adjusted:

- β is set to 0.985 (Nordhaus) and 0.999 (Stern)
- $\varphi = 0.00231$
  From Archer (2005): the remaining emissions, the share slowly trickling down to the deep oceans, have a mean lifetime of 300 years, implying $(1 - \varphi)^{300} = 0.5$.

Annualising

Back Appendix

We first compute the indexes as follows:

$$Index_t = Index_{t-1} * (1 + realGDPgrowth_t)$$

Then, we sum the indexes for the period from 1997 to 2006 (sum1) and from 2007 to 2016 (sum2). We compute the following adjusted sum:

$$adjsum = sum2 - ClimateExternality * \text{sum1}$$

After that, we compute the adjusted indexes as follows:

$$Index^a_t = Index^a_{t-1} * (1 + realGDPgrowth_t - Annual\ Adjustment)$$

sum theses indexes and use a solver program to find an annual adjustment that gives the exact same sum as the adjusted sum.

A Country-Specific Model Appendix

The intertemporal budget constraint of the household is (taking into account the transversality condition):

$$\sum_{s=0}^{\infty}\left(\frac{1}{1+r_{t+s}}\right)^{s}(C_{t+s}+I_{t+s})=\sum_{s=0}^{\infty}\left(\frac{1}{1+r_{t+s}}\right)^{s}Y_{t+s}+(1+r_t)B_t$$

Compared to the model at the world level, it is harder to relate C_t to Y_t since countries can borrow and lend from one another. Therefore, we need the following additional assumptions:

- $B_{t+s}=0$, for $s=0$: initial debt is equal to zero.
- $\beta=\frac{1}{1+r}$ which implies that $C_{t+s}=C$, $\forall s$ and $r_{t+s}=r$, $\forall s$.
- $Y_{t+s}=(1+g)^s Y_t$, $\forall s$ with $g<r$.
- $I_{t+s}=I$, $\forall s$.

A Country-Specific Model

Appendix

This gives:

$$\frac{1+r}{r}(C+I) = \frac{1+r}{r-g}Y$$
$$C+I = \frac{r}{r-g}Y$$
$$\Rightarrow C = (1-s)\frac{r}{r-g}Y$$

- Consumption is higher than the fraction of output not saved for investment as this specific country can borrow from abroad.
- If there are countries that borrow, there must be countries that lend.
- The main problem with this specification is that we do not let the GDP grow at different rates over time and that consumption does not change at all over time.

A Country-Specific Model Appendix

$$\frac{\partial V_t^1(S_{t-1}^1, S_{t-1}^2)}{\partial t} =$$

$$\frac{1}{Y_t}\frac{\partial Y_t}{\partial t}$$ Real GDP growth of one country

$$+\beta\,\mathbb{E}_t \frac{\partial V_{t+1}(S_t^1, S_t^2)}{\partial S_t^1}\frac{\partial S_t^1}{\partial t}$$ Own Emissions

$$+\beta\,\mathbb{E}_t \frac{\partial V_{t+1}(S_t^1, S_t^2)}{\partial S_t^2}\frac{\partial S_t^2}{\partial t}$$ Foreign Emissions

A Country-Specific Model

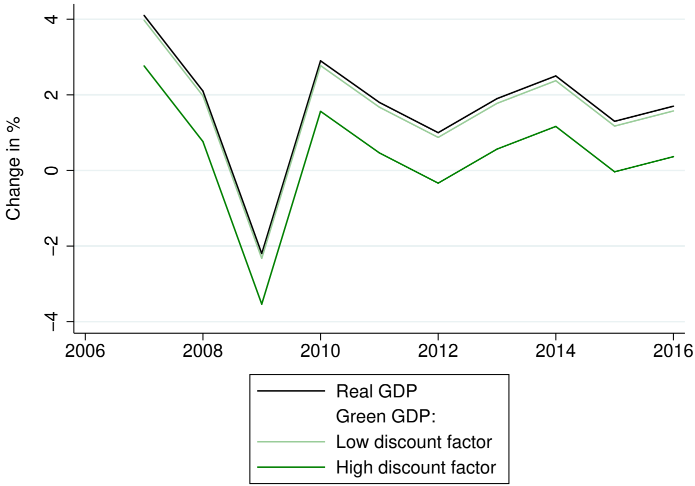
Appendix

- The total adjustment per country is not different than in the model at the world level.
- A different adjustment between countries can only happen if the damage parameter, γ, or the discount factor, β, is different.
- If we want to adjust the GDP of each country only with its own emissions, it would lead to very small adjustments that we can easily omit.
- The national contributions in the world climate externality would lead to relatively important adjustments but our model does not allow to adjust the national GDP for damages that impact other countries.

The Swiss Green GDP Growth

Appendix

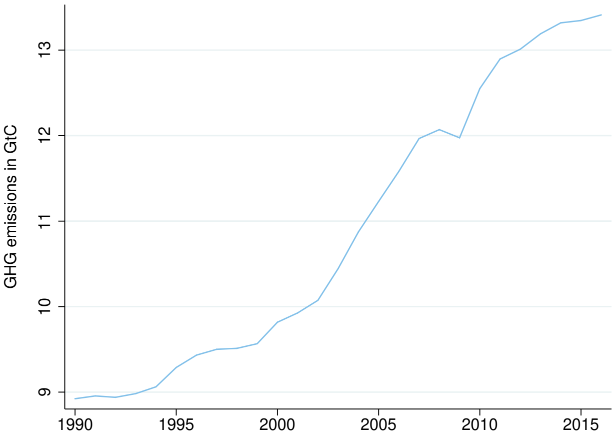
Figure: Real GDP and Green GDP growth for Switzerland



Global Emissions

Appendix

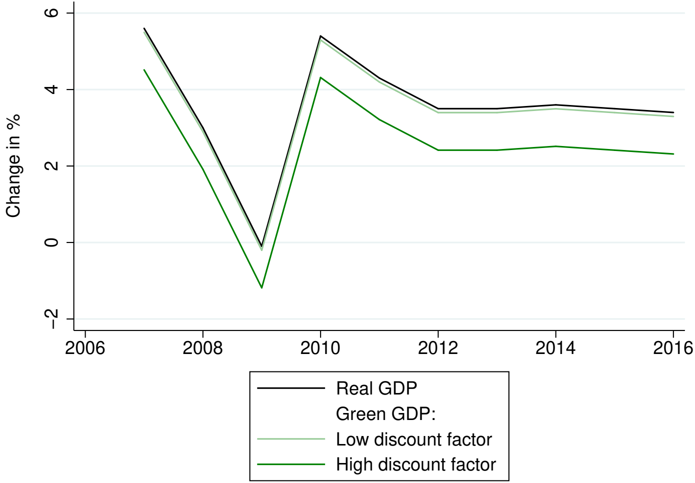
Figure: Global emissions in GtC



Source: Olivier et al. (2017).

Green GDP Growth Appendix

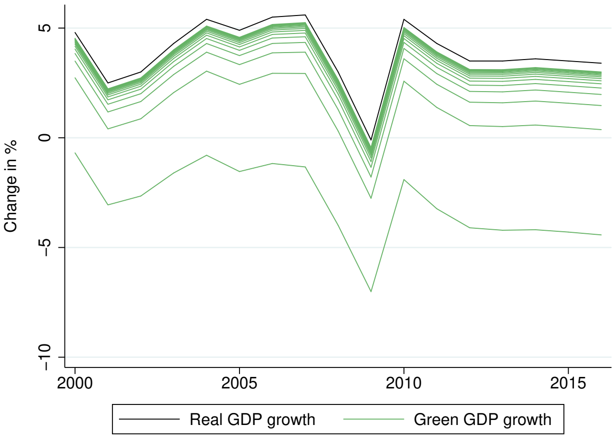
Figure: Real GDP and Green GDP growth for two β values



Green GDP Growth

Appendix

Figure: Real GDP and Green GDP growth for different β values

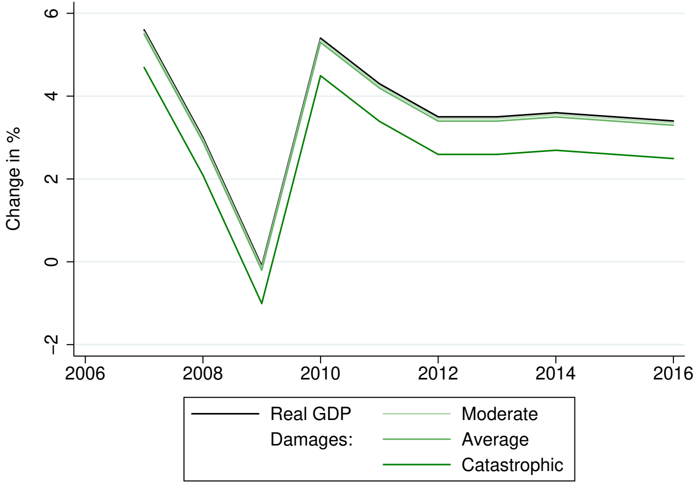


For the green curves from the top down, the discount rate goes from 2.7% to 0.1% (in increments of 0.2).

Green GDP Growth

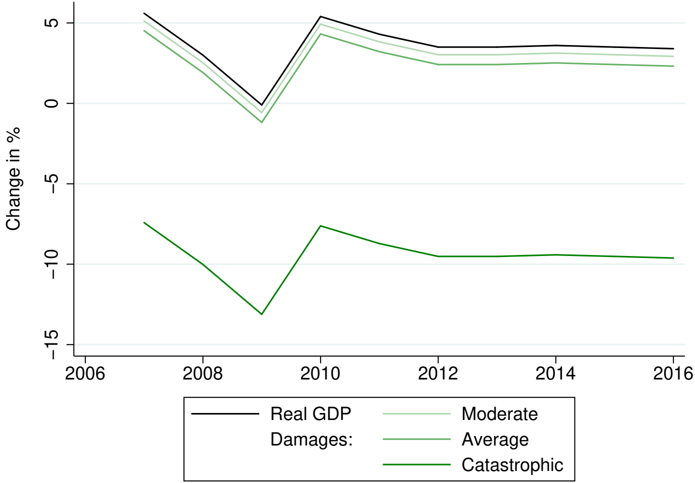
Appendix

Figure: Real GDP and Green GDP growth for different γ values (low β)



Green GDP Growth Appendix

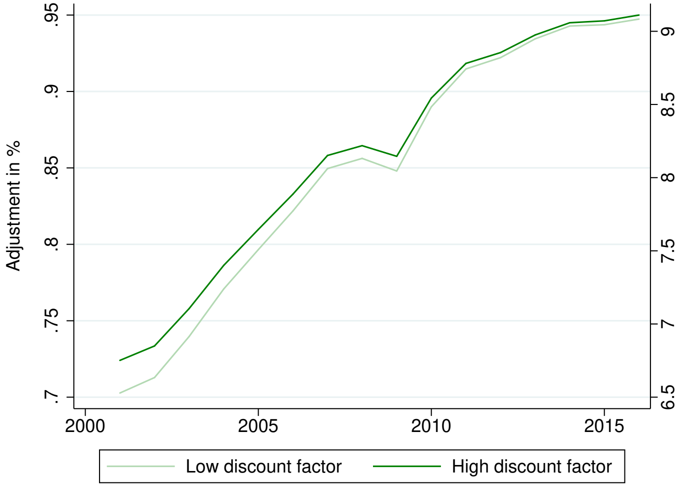
Figure: Real GDP and Green GDP growth for different γ values (high β)



Climate Externality Evolution

Appendix

Figure: Evolution over time of the climate externality in %



National Contribution - One-year Model Appendix

Table: Contribution 2016 à l'ajustement lié à l'externalité du climat en milliards de dollars Calculs

Pays	β_L & $\bar{\gamma}$	β_H & $\bar{\gamma}$	β_L & γ^H	β_H & γ^H
Chine	196	1'842	1'690	15'837
Etats-Unis	99	935	858	8'047
Allemagne	15	138	127	1'187
GB	8	75	69	645
France	7	65	59	556
Italie	7	61	56	529
Espagne	5	47	44	408
Belgique	2	16	15	141
Autriche	1	10	9	88
Suisse	0,8	7	7	64

National Contributions Appendix

Table: 2016 country contributions in the global climate externality in billions of US dollars

Country	β_L & $\bar{\gamma}$	β_H & $\bar{\gamma}$	β_L & γ^H	β_H & γ^H	2016 GDP
China	196	1,842	1,690	15,837	11,138
US	99	935	858	8,047	18,700
Germany	15	138	127	1,187	3,466
Canada	11	107	99	924	1,526
Australia	8	78	72	674	1,208
UK	8	75	69	645	2,694
France	7	65	59	556	2,471
Italy	7	61	56	529	1,875
Spain	5	47	44	408	1,232
Netherlands	3	31	28	265	783
Belgium	2	16	15	141	476
Austria	1	10	9	88	395
Switzerland	0.8	7	7	64	671

Notes: These results are obtained by multiplying each country's own emissions in 2016 with the marginal value computed in equation (**??**) and with the nominal world GDP of 2015 evaluated in billions of current US dollars. It represents the contributions of each country in the world GDP adjustment necessary to account for the climate externality. β_L corresponds to a value of 0.985 (discount rate of 1.5%) while β_H to a value of 0.999 (discount rate of 0.1%). γ^H is a scenario in which damages in the future are catastrophic. Scenarios with moderate damages, γ^L, are not reported as they are very similar to the baseline case. $\bar{\gamma}$ is simply the weighted average of the two scenarios : $\bar{\gamma} = (1-p)\gamma^L + p\gamma^H$. 2016 GDP corresponds to the nominal GDP per country in 2016 evaluated in billions of current US dollars.

National Contributions

Appendix

Table: 2016 country contributions in the global climate externality in percentage of their own GDP

Country	β_L & $\bar{\gamma}$	β_H & $\bar{\gamma}$	β_L & γ^H	β_H & γ^H
China	1.8	17	15	142
US	0.5	5	5	43
Germany	0.4	4	4	34
Canada	0.7	7	6	61
Australia	0.7	6	6	56
UK	0.3	3	3	24
France	0.3	3	2	23
Italy	0.4	3	3	28
Spain	0.4	4	4	33
Netherlands	0.4	4	4	34
Belgium	0.4	3	3	30
Austria	0.3	3	2	22
Switzerland	0.1	1	1	10

Notes: The results are obtained by dividing the results in Table 5 by the nominal GDP in 2016.