Integrated Assessment in a Multi-region World with Multiple Energy Sources and Endogenous Technical Change

(Hassler et al., 2019)

Soo Kim and Guillermo Verduzco

Department of Economics

University of Notre Dame

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1. Introduction
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Introduction: Motivation

- The problem of climate change and its policy implication is based on:
  - the quantification of greenhouse effect (Arrhenius, 1896)
  - the externality of climate change (Pigou, 1920)
- However, precise value for the policy implementation is often uncertain, since we need to know the following and their feedback mechanism:
  1. how much climate change emissions induce;
  2. how long carbon stays in the atmosphere;
  3. how large the economic consequences are.
- In addition, the economic impacts of climate change differ significantly by geographic location.

Introduction: Key Results

- Comparison between optimal carbon tax policy and suboptimal taxes.
  - Only Europe introduces carbon tax while others do not $\Rightarrow$ effects in mitigating global warming is very limited.
  - Europe adopts high tax while others uses taxes lower than optimal tax $\Rightarrow$ the effect is significant.
- Importance of taxation of all fossil fuels.
- Effect of the reduction of energy production cost.

Introduction: Key Results

- Comparison between optimal carbon tax policy and suboptimal taxes.
- Importance of taxation of all fossil fuels.
    - It is important to tax coal, however the effect of taxing conventional oil was limited.
    - Carbon tax should also be implemented on the shale gas.
- Effect of the reduction of energy production cost.

Introduction: Key Results

- Comparison between optimal carbon tax policy and suboptimal taxes.
- Importance of taxation of all fossil fuels.
- Effect of the reduction of energy production cost.
  - If coal-extracting technological progress is slow enough, it will work similarly to the optimal tax on coal.
  - Technological progress in green energy itself is not sufficient for mitigating global warming.
  - Directed technological progress can effectively nullify the effect of proportional tax. (per-unit tax is still effective)

Model: Overview

- This paper extends Nordhaus (1977, 1994, 2011), Nordhaus and Boyer (2000), Hassler and Krusell (2012), and Golosov et al. (2014).
- Key features
  - Geographical regions: United States, Europe, China, India, and Africa.
  - Imperfectly substitutable energy sources: gasoline, coal, green energy, and shale gas.
  - Hydraulic fracturing ("fracking").
  - (directed) Technological change of energy-producing firms.

Model: Overview

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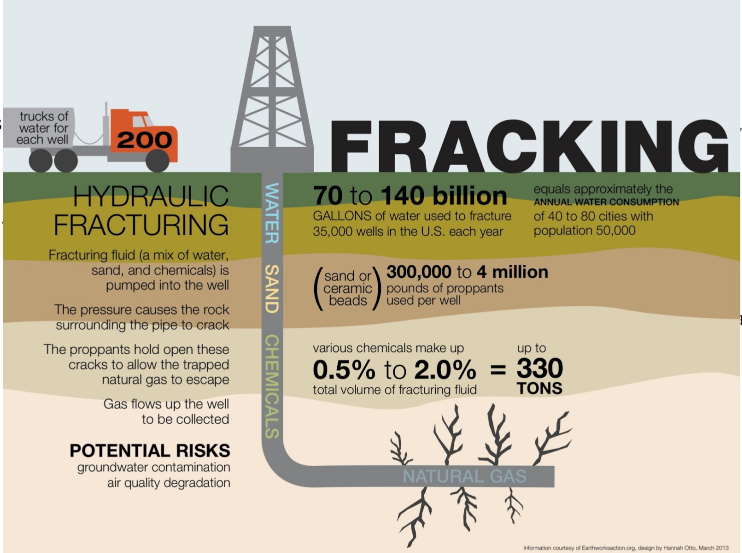


Model: Economy

Each region $i \in \{1, 2, \cdots, r\}$ has a representative consumer with preferences:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \log C_{it}$$

Each oil consuming region $i \in \{2, \cdots, r\}$ has an acess to an aggregate production function for the final good Y_{it}.

$$Y_{it} = A_{it} L_{it}^{1-\alpha-\nu} K_{it}^{\alpha} E_{it}^{\nu}$$

Energy services E_{it} are provided by competitive firms with n difference energy inputs:

$$E_{it} = \mathcal{E}\left(e_{1it}, \cdots, e_{nit}\right) = \left(\sum_{k=1}^{n} \lambda_k e_{kit}^{\rho}\right)^{\frac{1}{\rho}}$$

, where e_{1it} is region i's import of oil in period t.

Model: Economy

Resource constraint for the final good is:

$$C_{it} + K_{it+1} = Y_{it} - p_{1t}e_{1it} - \sum_{k=2}^{n} p_{kit}e_{kit}$$

Note that capital depreciates fully between periods.

Region 1 produces oils without resource cost, and the total stock of oil is R_t. With extraction $\sum_{i=2}^{r} e_{1it}$:

$$R_{t+1} = R_t - \sum_{i=2}^{r} e_{1it}$$

, where $R_t \geq 0 \, \forall t$. Oil producer have no access to the production technology hence its budget constraint is:

$$C_{1t} = p_{1t}(R_t - R_{t+1})$$

Model: Carbon Circulation

Total emission M_{it} from region i at t is given by:

$$M_{it} = \sum_{k=1}^{n} g_k e_{kit}$$

,where $g_k = 1$ for fossil energy sources and $g_k = 0$ for purely green energy sources.

The law of motion for the atmospheric excess stock of carbon S_t is given by:

$$S_t = \sum_{s=0}^{\infty}(1 - d_s) \sum_{i=2}^{r} M_{it-s}$$

, where $1 - d_s = \phi_L + (1 - \phi_L)\phi_0(1 - \phi)^s$.

- The share of emission that remains forever is ϕ_L.
- The share that leaves within a period is $(1 - \phi_L)(1 - \phi_0)$.
- The remainder depreciates at a rate ϕ is $(1 - \phi_L)\phi_0$.

Model: Climate and Damages

The effect of CO_2 concentration on productivity is well captured by log-linear specification (Golosov et al., 2014):

$$A_{it} = \exp\left(z_{it} - \gamma_{it} S_{t-1}\right)$$

, where z_{it} is stochastic productivity trend and γ_{it} is region-specific parameter that determines the potential damage caused by climate change.

γ_{it} is affected by:

- the sensitivity of the global mean temperature to changes in the CO_2 concentration;
- the sensitivity of the regional climate to global mean temperature;
- the sensitivity of the regional economy to climate change.

Model: Climate and Damages

The climate system is borrowed from the DICE/RICE:

$$T_t = T_{t-1} + \sigma_1 \left(\frac{\eta}{\ln 2} \ln \frac{S_{t-1}}{S_0} - \kappa T_{t-1} - \sigma_2 \left(T_{t-1} - T^L_{t-1} \right) \right)$$

$$T_t = T^L_{t-1} + \sigma_3 \left(T_{t-1} + T^L_{t-1} \right)$$

, where T_t is the global mean temperature in the atmosphere, and T^L_t is the temperature in the deep oceans.

Model: Government

Each region $i \in \{2, \cdots, r\}$ is allowed to set a carbon tax τ_{it}. The government budget with *ad valorem* taxes:

$$\Gamma_{it}\left(w_{it}L_{it} + r_{it}K_{it}\right) = \tau_{it}\sum_{k=1}^{n} p_{kit}(g_k e_{kit})$$

The government budget with *per unit* taxes:

$$\Gamma_{it}\left(w_{it}L_{it} + r_{it}K_{it}\right) = \tau_{it}\sum_{k=1}^{n} g_k e_{kit}$$

Hence, tax inclusive price $\hat{p}_{kit}$ is $(1 + \tau_{it}g_k)p_{kit}$ in the case of *ad valorem* taxes and $\tau_{it}g_k + p_{kit}$ for per-unit taxes.

Model: Equilibrium

Proposition 1

In each period, the equilibrium allocation is determined by state variables $\{K_{it}, R_t, S_{t-1}\}$ *such that:*

1. *the capital savings rate is constant at* $\frac{\alpha\beta}{1-\nu}$*;*
2. *oil supply is given by* $(1-\beta)R_t$*;*
3. *energy prices are* $P_{it} = \left(\sum_{k=1}^{n} \lambda_k^{\frac{1}{\rho-1}} \hat{p}_{kit}^{\frac{\rho}{\rho-1}}\right)^{\frac{\rho-1}{\rho}}$*;*
4. *energy-service demand is* $E_{it} = \left(\nu \frac{\exp^{z_{it}-\gamma_{it}S_{t-1}} L_{it}^{1-\alpha-\nu} K_{it}^{\alpha}}{P_{it}}\right)^{\frac{1}{1-\nu}}$*;*
5. *domestic energy demand is* $e_{kit} = E_{it}\left(\frac{P_{it}\lambda_k}{\hat{p}_{kit}}\right)^{\frac{1}{1-\rho}}$
6. *output net of energy expenses is* $\hat{Y}_{it} = (1-\nu)A_{it}L_{it}^{1-\alpha-\nu}K_{it}^{\alpha}E_{it}^{\nu}$

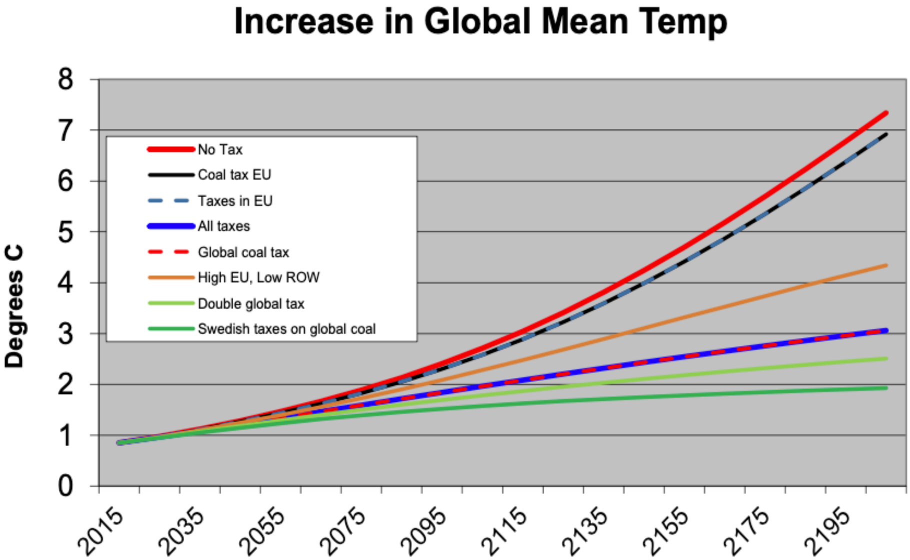
▸ Calibration

Results: Taxes

In this section we are going to present the simulation results for a set of different policies. The different policy scenarios differ in terms of coverage and in the level of the tax:

- The first scenario imposes a global Pigouvian tax, that increases by 2.2% per year, i.e., approximately at the growth rate of GDP.
- The second assumes that only Europe implements the fossil-fuel tax.
- The third scenario feature a global tax, but only on coal.
- The fourth scenario considers a unilateral European coal tax only.
- The fifth scenario, considers a case when Europe implements the Pigouvian tax while the rest of the world is less ambitious and chooses a coal tax that is only a quarter of the optimal.
- Finally, the authors consider two more ambitious tax policies:
  - One in which a global carbon tax that is twice as large as the Pigouvian tax is introduced.
  - One where the current Swedish carbon tax is introduced (x7 the Pigouvian tax).

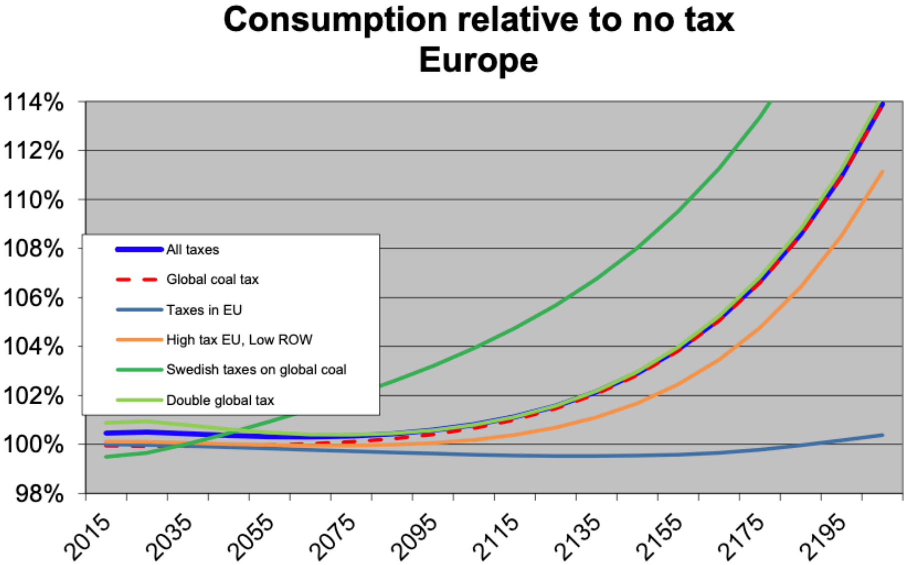
Results: Taxes



Main highlights

- Global fossil-fuel taxes are effective in mitigating climate change.
- A global Swedish tax would stop global warming almost completely and keep the global mean temperature just above 1.5 degrees Celsius.
- It is not effective to impose taxes only in EU.
- What matters for the resulting change in the temperature is taxes on coal.
- Also an asymmetric coal tax where most of the world implements a quite low tax has important effects on climate change.

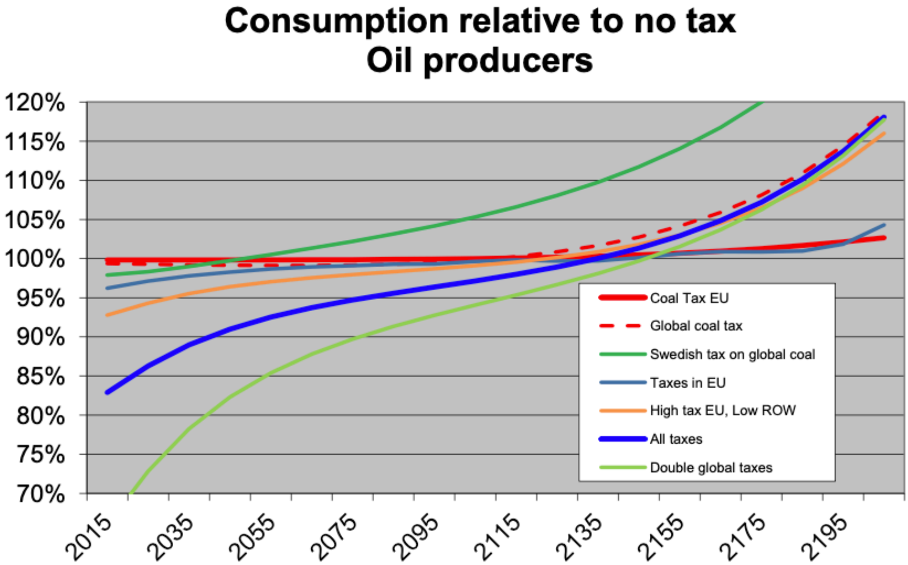
Results: Taxes



Main highlights

- Consumption is expressed relative to the consumption that is generated in the *laissez faire*.
- A global carbon tax increases welfare for EU consumers: consumption is always higher and substantially so far into the future.
- The effects are, however, relatively small in the current century.
- A global coal tax improves European welfare by less than as if the tax also includes oil.
- The effects of having taxes only in EU are very small.
- A carbon tax increases consumption marginally more due to its redistributional consequences.
- A global coal tax at the very high Swedish levels has a negative, but not very large effect in the current century.
- The long run is positive.

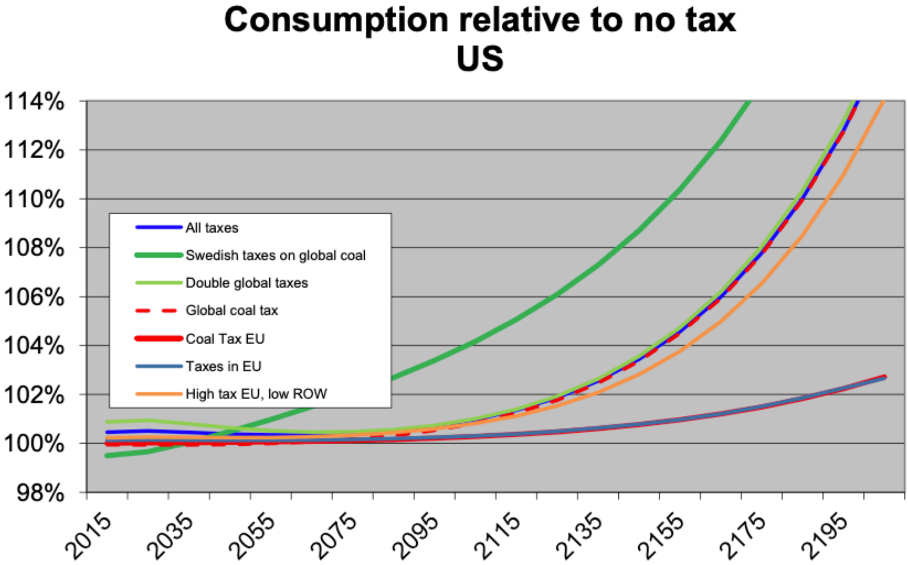
Results: Taxes



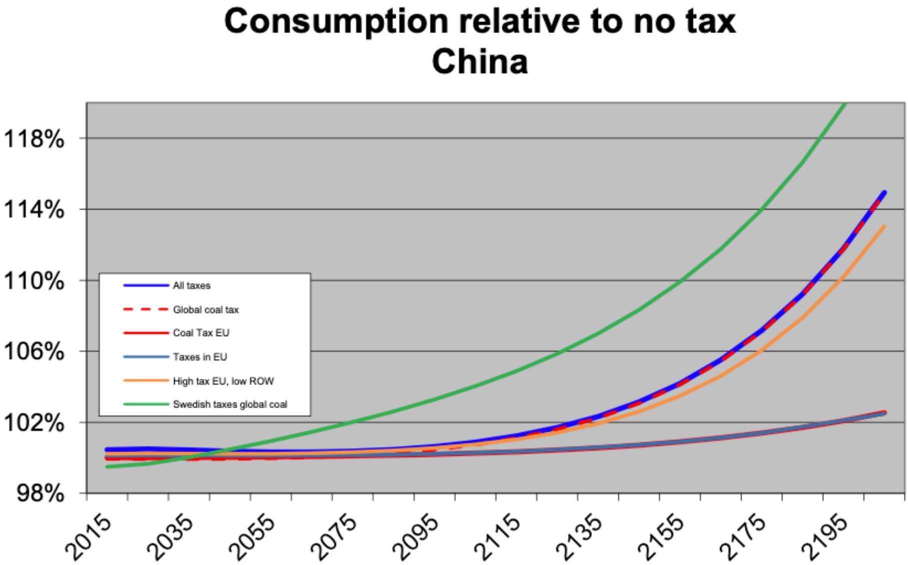
Main highlights

- A tax that includes oil reduces consumption over most of the considered time period.
- A tax on coal has a positive impact on the consumption of the oil producers towards the end of the simulation period.
- The reason for this is that the coal tax increases output through lower climate damages, and this leads to higher oil demand.

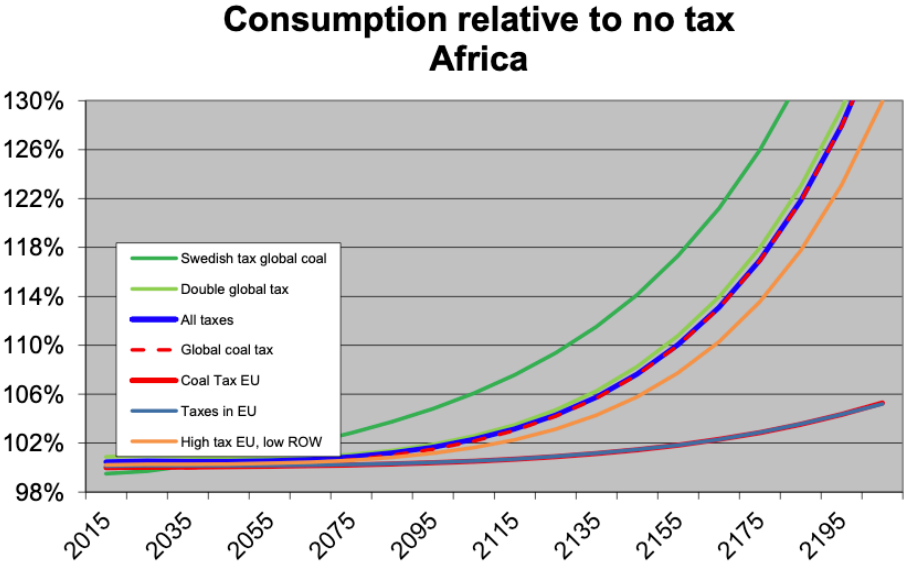
Results: Taxes



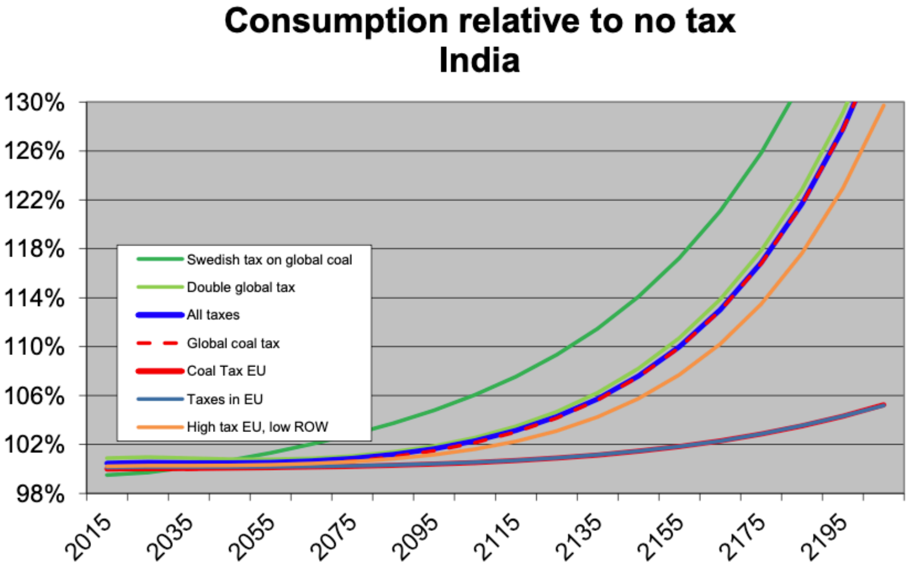
Results: Taxes



Results: Taxes



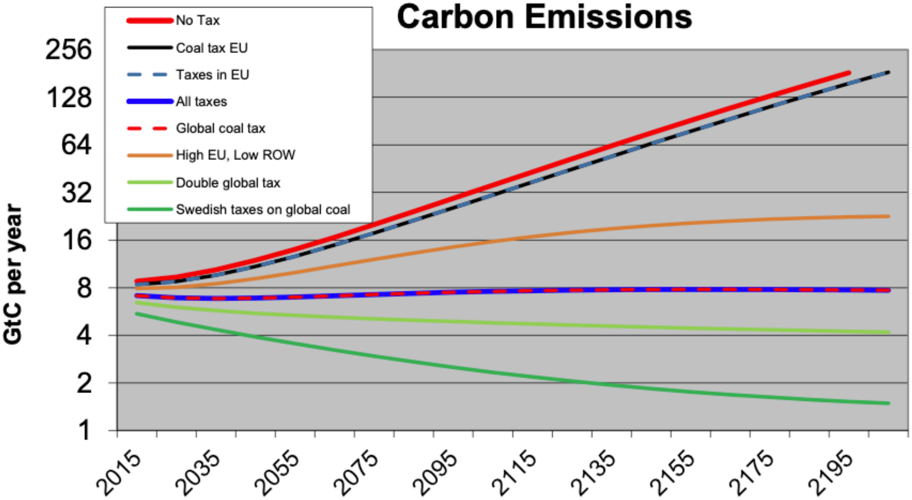
Results: Taxes



Results: Technical change

- The previous section revealed that a global coal tax is an efficient way of mitigating climate change.
- Specifically, while coal use increases by a factor of 40 over the coming 200 years in the *laissez faire* economy, a coal tax that increases by 2% per year reduces the increase in coal use to a factor of two.
- Total emissions then fall over time as is shown in next figure.
- Higher taxes than the Pigouvian leads to a substantial reduction in emissions.
- The growth rate of green energy is, however, largely unaffected in the different scenarios.

Results: Technical change



Results: Technical change

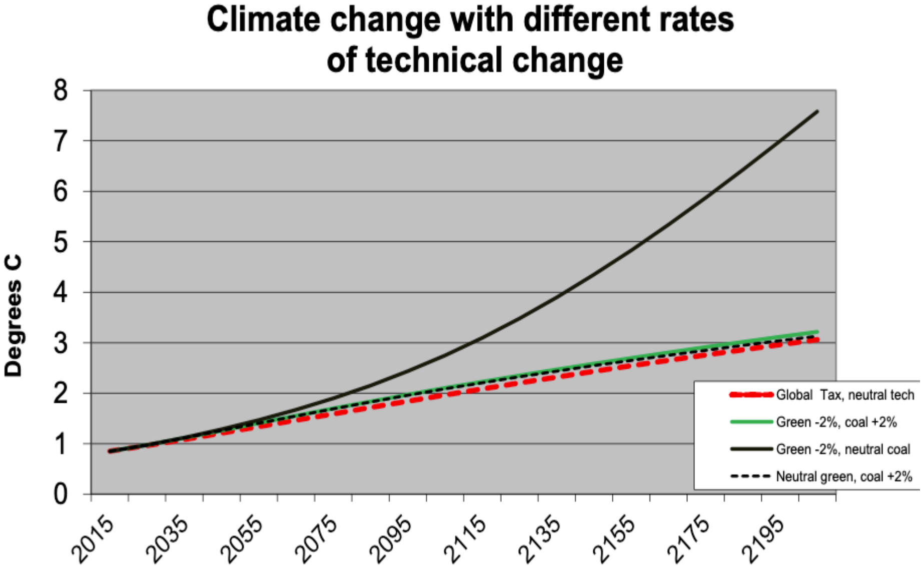
If we use equation (7) to c we get:

$$\frac{e_{2,i,t}}{e_{3,i,t}} = \left(\frac{\lambda_2}{\lambda_3}\frac{p_{3,i,t}}{(1+\tau_{i,t})\,p_{2,i,t}}\right)^{\frac{1}{1-\rho}}$$

The above equation shows that the relative usage of coal and green fuel is driven by the relative price including taxes. It also suggests that if technology were to develop in a way that increases the relative price of coal, this would have similar effects as a tax on coal. The authors consider two more scenarios:

1. One where green energy becomes 2% cheaper per year to produce (i.e., $p_{3,i,t}$ falls by 2% per year in all regions)
2. Second, one that adds to the first scenario that coal becomes more expensive over time (i.e., $p_{2,i,t}$ increases over time).

Results: Technical change



Main highlights

- The fact that the price of green energy falls over time by 2% is completely ineffective in mitigating global warming.
- Indeed, emissions are even larger in this scenario than in the base line *laissez faire* case.
- The reason is that lower green-energy prices implies lower energy prices in general, which increases the demand for all energy services, also for coal.
- The Figure also shows that the second scenario, where $p_{2,i,t}$ increases and $p_{3,i,t}$ falls produces a path of the global mean temperature that is virtually indistinguishable from that with global Pigouvian taxes.
- The finding that directing technical change away from the production of fossil fuel is a powerful means of overcoming the problems associated with climate change suggests that we need to analyze the determinants of technical change.

Energy sources with higher degree of substitutability

- So far, the authors imposed a moderate degree of substitutability between coal and oil, and they did not allow oil to be produced outside of the oil-producing region.
- In recent years, however, hydraulic fracturing (fracking) has made it possible to produce oil and gas in substantial quantities in the United States, as well as in some other regions.
- The output from these sources is highly substitutable with conventional oil and gas, but it has fairly high production costs, thus implying that it can be considered to be something of a hybrid between oil and coal.
- The fact that the “fracking revolution” has had important implications for the world oil market motivates an extension of the model that includes fossil fuels that are costly to produce, and that are good substitutes for conventional fossil fuels.

Energy sources with higher degree of substitutability

To achieve this, we generalize the production function for energy services to a nested CES:

$$E_{i,t} = \mathcal{E}(e_{1,i,t}, \ldots, e_{n,i,t}) = \left(\lambda_1 l \left(\sum_{k=1}^{l} \lambda_{1,k} \left(e_{1,k,i,t}\right)^{\rho_h} \right)^{\frac{\rho}{\rho_h}} + \sum_{2}^{n} \lambda_k \left(e_{k,i,t}\right)^{\rho} \right)^{\frac{1}{\rho}}$$

where $\sum_{k=1}^{n} \lambda_k = \sum_{k=1}^{l} \lambda_{1,k} = 1$. In the above specification, the l fuels $e_{1,k,i,t}$ can be allowed to be more substitutable with each other by setting $\rho_h > \rho$. We define the oil composite

$$O_{i,t} \equiv l \left(\sum_{k=1}^{l} \lambda_{1,k} \left(e_{1,k,i,t}\right)^{\rho_h} \right)^{\frac{1}{\rho_h}},$$

and interpret $e_{1,k,i,t}$ as conventional oil imports to region i in period t. The other components, $e_{1,k,i,t}$, $k > 1$, are locally produced close substitutes of oil, i.e., output from fracking. Hence, this specification allows for both locally produced substitutes to conventional fossil fuels, as well as a higher elasticity of substitution between these objects.

Energy sources with higher degree of substitutability

The regional demand of the different components of the oil composite can be determined from the following problem

$$\min_{e_{1,k,i,t}} \sum_{k=1}^{l} \hat{p}_{1,k,i,t} e_{1,k,i,t} - P_{i,t}^{O} \left(l \left(\sum_{k=1}^{l} \lambda_{1,k} \left(e_{1,k,i,t} \right)^{\rho_h} \right)^{\frac{1}{\rho_h}} - O_{i,t} \right) \tag{14}$$

where $\hat{p}_{1,k,i,t}$ denotes the different fuel prices, and $\hat{p}_{1,1,i,t}$ is the global market price of conventional oil including the region-specific tax. As for coal, the authors assume that the other components of the oil composite are determined from the regional cost side.

Energy sources with higher degree of substitutability

The first-order condition to the problem defined by (14) yields

$$e^{*}_{1,k,i,t} = \frac{O_{i,t}}{l}\left(\frac{\lambda_{1,k} l P^{O}_{i,t}}{\hat{p}_{1,k,i,t}}\right)^{\frac{1}{1-\rho_h}}, \quad k \in \{1, l\}.$$

Following the procedure in Section 2.5, the price index for the oil composite can be shown to be given by

$$P^{O}_{i,t} = l^{-1}\left(\sum_{k=1}^{l} \left(\lambda_{1,k}\right)^{\frac{1}{1-\rho_h}} \left(\hat{p}_{1,k,i,t}\right)^{\frac{\rho_h}{\rho_h-1}}\right)^{\frac{\rho_h-1}{\rho_h}}.$$

Energy sources with higher degree of substitutability

It then follows that the price of energy services and the demand for the oil composite, respectively, are given by

$$P_{t,i} = \left((\lambda_1)^{\frac{1}{1-\rho}} \left(P^O_{i,t}\right)^{\frac{\rho}{\rho-1}} + \sum_{k=2}^{n} (\lambda_k)^{\frac{1}{1-\rho}} \left(\hat{p}_{k,i,t}\right)^{\frac{\rho}{\rho-1}} \right)^{\frac{\rho-1}{\rho}},$$

and

$$O^*_{i,t} = \left(\frac{\lambda_1 P_{i,t}}{P^O_{i,t}} \right)^{\frac{1}{1-\rho}} E_{i,t},$$

where $E_{i,t}$ is still given by (10).

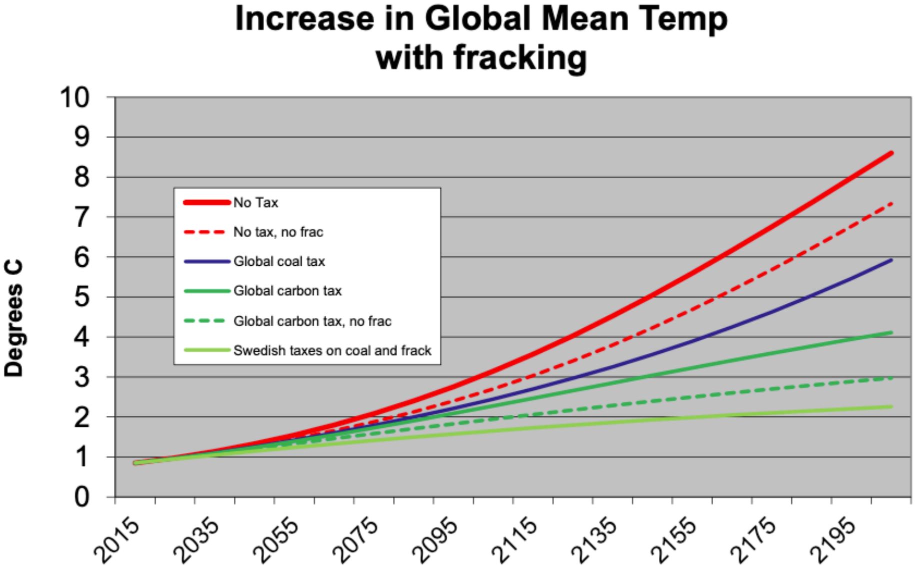
Finally, the demand for other energy sources are determined by the following equations

$$e^*_{k,i,t} = E_{i,t} \left(\frac{\lambda_k P_{i,t}}{\hat{p}_{k,i,t}} \right)^{\frac{1}{1-\rho}}, k \in \{2, n\}.$$

Calibration with fracking

- The amount of non-conventional reserves of fossil fuel extractable by fracking and other existing or future technologies is obviously hard to assess.
- The calibration in this section should therefore be seen as illustrative, and a more worked through calibration is left for future work.
- With these caveats in mind, we set $l = 2$ and assume that fracking costs in the U.S. are US $40 per barrel, corresponding to US $347 per ton carbon.
- Also China is assumed to be able to produce fracked oil at a cost that is 50 percent higher than that for the United States, while the other regions cannot or abstain from fracking.
- Finally, the authors impose a high degree of substitutability between the output from fracking and conventional fossil fuels.

Results with fracking



Results with fracking

- The addition of a fossil fuel that is a good substitute for conventional oil, but is provided without scarcity rents makes the problem of climate change substantially more severe.
- The good news is that taxes remain to be an effective way of dealing with climate change.
- Compared to the case without fracking, however, there is more global warning under the comprehensive tax scheme.
- An important difference compared to the case in the previous section is that a tax only on coal now results in substantially more global warning than a global carbon tax.
- The intuition for this is that the supply of the oil composite is highly elastic, implying that it responds strongly to a tax.
- A global tax on coal and fracking, however, results in global warning almost identical to the one under a global carbon tax.
- As in the case without fracking, a zero tax on conventional oil leads to substantially higher welfare for the region that is producing the conventional oil.

Endogenous technical change

- The purpose of this section is to provide a simple framework for endogenizing the cost of producing the different sources of energy.
- The authors here, again, abstract from fracking and maintain the assumption that oil is imported, whereas the other energy sources are domestically produced at costs $p_{k,i,t}$
- They allow a tax $\tau_{k,i,t}$ on each fuel.
- As in the previous sections, there is an energy-producing representative firm selling energy services on a competitive market.
- The important difference is that the energy producer now also has the possibility to improve the technologies for producing the different domestic energy inputs.
- Spec. all energy inputs except oil can be reduced at a costs that is determined by the constraint $RD_{i,t}(p_{2,i,t}, \ldots, p_{n,i,t}) \geq 0$.

Endogenous technical change

The problem of the representative energy-service provider with *ad-valorem* taxes is then given by

$$\min_{\{e_{k,i,t}\}_1^n,\{p_{k,i,t}\}_2^n} \sum_{k=1}^{n} (1+\tau_{k,i,t})\, p_{k,i,t} e_{k,i,t} \tag{15}$$
$$-P_{i,t}\left(\mathcal{E}(e_{1,i,t},\ldots,e_{n,i,t}) - E_{i,t}\right) - \Lambda_{i,t} RD_{i,t}\left(p_{2,i,t},...,p_{n,i,t}\right).$$

The problem defined by (15) differs from that in (6) in that the former problem includes a set of new choice variables $\{p_{k,i,t}\}_2^n$, as well as a new constraint $RD_{i,t}\left(p_{2,i,t},...,p_{n,i,t}\right)$ with a Lagrange multiplier $\Lambda_{i,t}$. Hence, the energy-producer takes the oil price, $p_{1,i,t}$ as given, but can affect $p_{k,i,t}$ for $k \neq 1$. It is straightforward to verify that all features of Proposition 1 still hold up.

Endogenous technical change

The first-order conditions with respect to $e_{k,i,t}$ and $p_{k,i,t}$, $k \neq 1$ are, respectively, given by

$$e^*_{k,i,t} = E_{i,t}\left(\frac{P_{t,i}\lambda_k}{(1+\tau_{k,i,t})\,p_{k,i,t}}\right)^{\frac{1}{1-\rho}}, \tag{16}$$

and

$$(1+\tau_{k,i,t})\,e^*_{k,i,t} = \Lambda_{i,t}\frac{\partial RD_{i,t}\,(p_{2,i,t},\ldots,p_{n,i,t})}{\partial p_{k,i,t}}. \tag{17}$$

Note that (16) is identical to (7) in Section (2.5.2).

With per-unit taxes imposed on the energy sources, the objective function (15) of the energy-service provider becomes

$$\sum_{k=1}^{n}(\tau_{k,i,t}+p_{k,i,t})\,e_{k,i,t}.$$

Endogenous technical change

The resulting first-order conditions are then given by

$$e^*_{k,i,t} = E_{i,t}\left(\frac{P_{t,i}\lambda_k}{\tau_{k,i,t} + p_{k,i,t}}\right)^{\frac{1}{1-\rho}}$$

and

$$e^*_{k,i,t} = \Lambda_{i,t}\frac{\partial RD_{i,t}\left(p_{2,i,t}, \ldots, p_{n,i,t}\right)}{\partial p_{k,i,t}}. \tag{18}$$

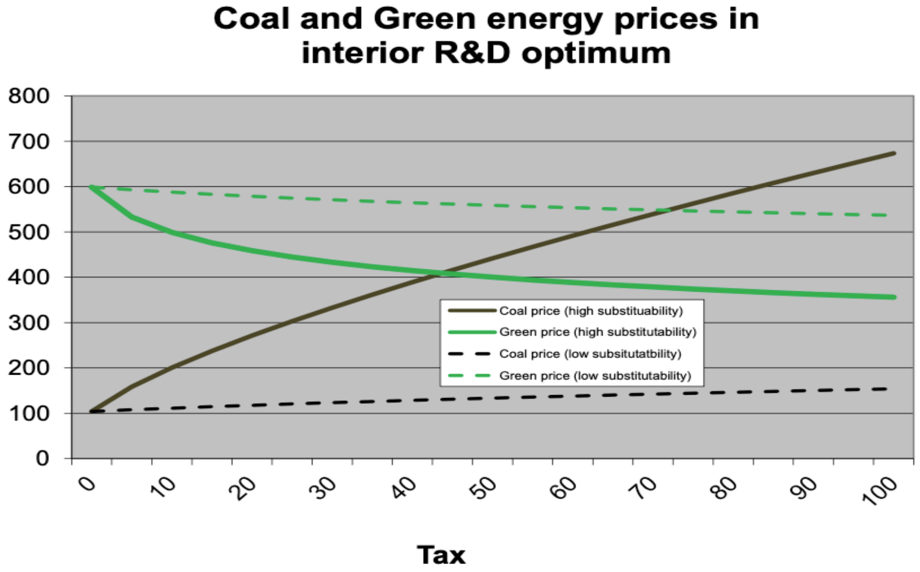
Comparing (17) and (18), we find an important difference. The left-hand side of both equations represents the value of reducing costs of producing a particular fuel. In the case of *ad-valorem* taxes, this value increases in the tax for given quantity $e^*_{k,i,t}$. This is not the case with taxes per unit. We will return to this feature below.

Specializing R&D technology

- The authors now make specific assumptions on the technology that is available to the energy-service producers.
- As with exogenous technologies, we still consider three different energy sources, i.e., oil, coal, and green energy.
- Now, however, production and extraction costs of coal and green fuel can be reduced subject to a constraint on the weighted average of the relative improvements.

Details

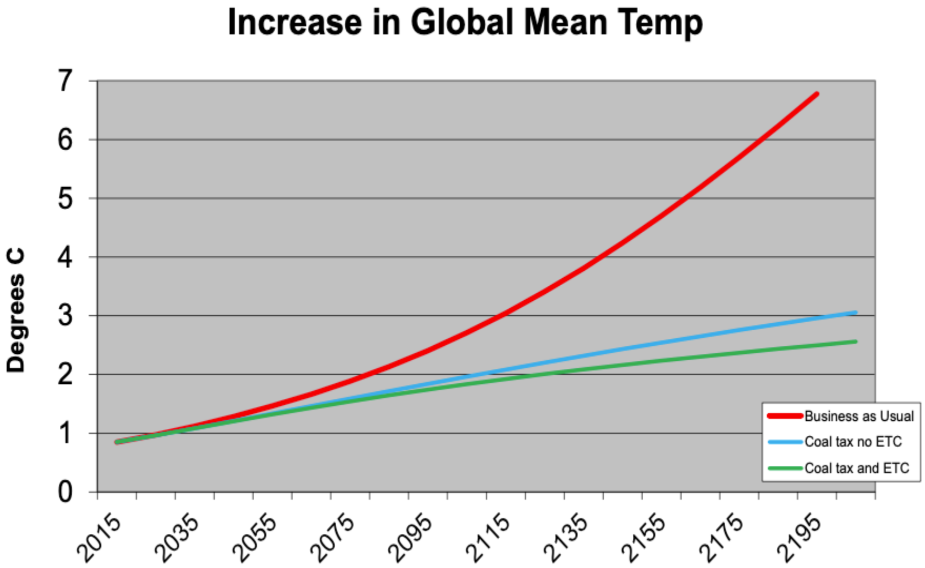
Results with endogenous technical change



Results with endogenous technical change

- The solid curves in the previous figure depicts the resulting relations between taxes and prices in an interior solution.
- The coal price is an increasing function of the tax, whereas the green-energy price is a decreasing function.
- Thus, R&D strongly amplifies the effect of a tax.
- The authors calibrated the elasticity of substitution above 1/2, which implies that it requires more R&D resources to reduce the cost of producing green energy than reducing the cost of producing coal.
- Both curves are, however, quite steep.
- Already for a coal tax of around US $35 per ton carbon, the coal price becomes as high as the price of green energy.
- The large effect of taxes on equilibrium prices is due to the fairly high elasticity of

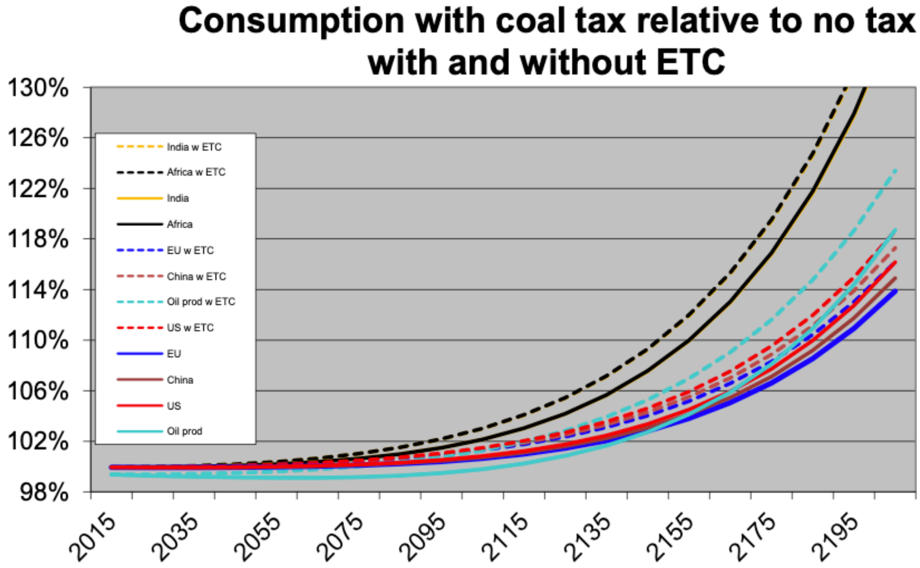
Results with endogenous technical change



Results with endogenous technical change

- The figure shows the paths for the global mean temperature with taxes and endogenous technical change, as well as the laissez faire scenario (which, by assumption, remains identical to the case with exogenous technical change).
- The temperature rises substantially less with endogenous technical change due to the fact that coal use immediately starts falling.
- Recall that with exogenous technical change and a global coal tax, coal use increased over the coming century and peaked around 2090.

Results with endogenous technical change



Results with endogenous technical change

- The figure plots the paths for consumption with a global coal tax and endogenous technical change relative to the laissez faire, where we assume neutral technological change (i.e., no change in relative prices).
- In comparison to the case of exogenous technical change, Europe and Africa now gains even more by the introduction of the global coal tax, while the consumption of all other regions remains largely unaffected.

Concluding remarks

- The authors set up an integrated assessment model with multiple imperfectly substitutable energy sources and multiple world regions to study the effects of sub-optimal taxation.
- The model also incorporates hydraulic fracturing - fracking - of nonconventional oil, and endogenous technical change directed at reducing the production costs for the different energy sources.
- The considered energy inputs include conventional oil, coal, green (renewable) energy, and the output from fracking that is highly substitutable with conventional oil.
- Despite this relatively rich model structure, all variables except the oil price have closed-form solutions.

Concluding remarks

The main findings can be summarized as follows:

- First, they find that optimal taxes that only are implemented in Europe are insufficient in mitigating global warming. Consequently, it is necessary that the other regions also impose, at least some, carbon taxes to reduce global warming.
- Second, the fracking technology has the potential to dramatically increase the stock of nonconventional oil which, in the absence of policy, can be expected to generate substantial global warming. It is therefore crucial that an effective carbon tax also is implemented on the nonconventional oil that is produced with the fracking technology.

Concluding remarks

The main findings can be summarized as follows:

- Third, taxes that are proportional to the price of a specific energy good are completely impotent in reducing the demand for this good. The intuition for this potentially surprising result comes from the fact that a proportional tax generates two effects with different signs. On the one hand, a proportional tax increases the marginal value of cost reductions. On the other hand, the proportional tax reduces the demand for the energy good, which also reduces the marginal value of cost reductions.
- Per-unit taxes, in fact, are effective in mitigating global warming. In this case, endogenous technical change actually reinforces the effectiveness of carbon taxes.

Thank You!

Appendix TOC

Appendix: Calibration

Parameters	Values	Parameters	Values	Parameters	Values
r	6	λ_1	0.543	$10^5\gamma_{US}$	2.395
n	3	λ_2	0.102	$10^5\gamma_{EU}$	2.698
d_s	0.985	λ_3	0.356	$10^5\gamma_{China}$	2.514
α	0.3	Δz_{it}	0.015	$10^5\gamma_{India}$	5.058
ν	0.055	ϕ_L	0.2	$10^5\gamma_{Africa}$	5.031
ρ	-0.058	ϕ_0	0.393	ϕ	0.0228

Table 1: Parameters used for calibration.

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improvements. Formally, the constraint is given by

$$RD_{i,t}\left(p_{2,i,t}, p_{3,i,t}\right) = \min\left(\varepsilon_{2,i} \ln \frac{p_{2,i,t}}{\bar{p}_{2,i,t-1}}, 0\right) + \min\left(\varepsilon_{3,i} \ln \frac{p_{3,i,t}}{\bar{p}_{3,i,t-1}}, 0\right) + a \geq 0, \quad (19)$$

$$\sum_k \varepsilon_{k,i} = 1, \quad (20)$$

where $\bar{p}_{k,i,t-1}$ denotes costs if no cost-reductions occur. These costs are determined by aggregate innovation decisions in the previous period, either in the region or globally. Cost-reductions then spill over with a one-period lag, which implies that firms are myopic in their choices of technology. It is natural to think that $\bar{p}_{k,i,t-1}$ is higher than average costs in the previous period in line with the discussion in the previous section. However, it appears natural to assume that $p_{k,i,t}$ cannot be increased by making $p_{j,i,t}$ larger than the cost when no cost-reductions occur. This motivates the min operator in (19).

Appendix

The R&D production technology defined by (19) can be thought of as an interesting starting point in the spirit of Romer (1986), where the number of researchers that are active in R&D determines the rate of technological change. Our specification can then be seen as an extension to directed technical change where the number of R&D workers is fixed, and the productivity in improving the technology differs between the energy sources.

The specification in (19) now reads for $k = 2, 3$

$$\frac{\partial RD_{i,t}\left(p_{2,i,t}, ..., p_{n,i,t}\right)}{\partial p_{k,i,t}} = \frac{\varepsilon_k}{p_{k,i,t}},$$

which, in turn, implies

$$\left(1 + \tau_{k,i,t}\right) p^*_{k,i,t} e^*_{k,i,t} = \varepsilon_k \Lambda_{i,t}. \tag{21}$$

Appendix

Proposition 2 *When first-order conditions for the technology choice are satisfied, and taxes are* ad-valorem, *spending on green energy is a fixed fraction of all spending on domestically produces energy sources, i.e.,*

$$\frac{(1+\tau_{3,i,t})\, p^*_{3,i,t} e^*_{3,i,t}}{P_{t,i} E_{i,t} - (1+\tau_{1,i,t})\, p_{1,i,t} e^*_{1,i,t}} = \varepsilon_3.$$

Proof. Follows directly from noting that $(1+\tau_{1,i,t})\, p_{1,i,t} e^*_{1,i,t} + \sum_{k=2}^{3} (1+\tau_{k,i,t})\, p^*_{k,i,t} e^*_{k,i,t} = P_{i,t} E_{i,t}$ and using (21). ■

Appendix

Furthermore, using the expression (16) in (21) for $k = 2$ and 3, yields the following two conditions

$$(1+\tau_{k,i,t})\, p^{*}_{k,i,t} = \left(\frac{\varepsilon_k \Lambda_{i,t}}{E_{i,t}}\right)^{\frac{\rho-1}{\rho}} (P_{t,i}\lambda_k)^{\frac{1}{\rho}}\,, \tag{22}$$

and

$$\frac{(1+\tau_{2,i,t})\, p^{*}_{2,i,t}}{(1+\tau_{3,i,t})\, p^{*}_{3,i,t}} = \left(\frac{\varepsilon_2}{\varepsilon_3}\right)^{\frac{\rho-1}{\rho}} \left(\frac{\lambda_2}{\lambda_3}\right)^{\frac{1}{\rho}}. \tag{23}$$

Since the right-hand-side of (23) only contains technological constants, it follows that taxes are unable to change the after-tax relative price of domestic fuels - provided that the solutions to the first-order conditions all are interior. Furthermore, the growth rates of the two production costs are identical.

Appendix

With both prices and spending being independent of taxes, also volumes are independent of taxes, i.e.,

$$\frac{e^*_{2,i,t}}{e^*_{3,i,t}} = \left(\frac{\lambda_3}{\lambda_2} \frac{\varepsilon_2}{\varepsilon_3} \right)^{\frac{1}{\rho}}.$$

We can get an intuition for this result by considering the first-order condition for the choice $p_k, k \neq 1$ given by (17). The left-hand side of the equation represents the marginal value of cost reductions. As can be seen, this value is increasing in the tax rate $\tau_{k,i,t}$ for a given quantity $e^*_{k,i,t}$. The fact that taxes are proportional to the cost of production implies that costs reductions are worth more the higher is the tax, *ceteris paribus.* However, an increased tax also reduces $e^*_{k,i,t}$ and this reduces the value of cost reductions. With the log-linear specification of R&D costs, the two effects exactly balances. Hence, R&D effectively nullifies the effect of taxes on after-tax prices.

Appendix

This intuition also suggests that per-unit taxes should, in fact, lead to higher costs simply because the positive effect of taxes on the value of cost reductions just described disappears. Let us now turn to the formal analysis on the effects of per-unit taxes.

In this case, the first-order condition are given by

$$p_{k,i,t}e^*_{k,i,t} = \Lambda_{i,t}\varepsilon_k,$$

where

$$e^*_{k,i,t} = E_{i,t}\left(\frac{P_{t,i}\lambda_k}{\tau_{k,i,t} + p_{k,i,t}}\right)^{\frac{1}{1-\rho}}.$$

Combining the conditions for $k = 2$ and 3, we get the following condition

$$\frac{p_{2,i,t}\left(\tau_{2,i,t} + p_{2,i,t}\right)^{\frac{-1}{1-\rho}}}{p_{3,i,t}\left(\tau_{3,i,t} + p_{3,i,t}\right)^{\frac{-1}{1-\rho}}} = \frac{1-\varepsilon_3}{\varepsilon_3}\left(\frac{\lambda_2}{\lambda_3}\right)^{\frac{1}{\rho-1}}. \tag{24}$$

Appendix

We can now consider the effects of changes in the coal tax. Total differentiation of the previous expression, noting that the R&D constraint implies $\frac{dp_{3,i,t}}{dp_{2,i,t}} = -\frac{1-\varepsilon_3}{\varepsilon_3}\frac{p_{3,i,t}}{p_{2,i,t}}$, and evaluating at both taxes being zero, yields

$$\left.\frac{dp_{2,i,t}}{d\tau_{2,i,t}}\right|_{\tau_{3,i,t}=\tau_{2,i,t}=0} = -\frac{\varepsilon_3}{\rho}.$$

Hence, when ρ is negative but close to zero, an increase in coal taxes leads to a large increase in the relative price of coal.

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