More Gas to Reduce CO_2 Emissions?

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Abstract

Shale gas is hoped to effectively help gas producing regions meet their emission reduction commitments. We examine an open economy that produces both shale gas and another, more carbon intensive fuel like coal. We find that imposing a domestic emission cap may in fact contribute to increase global emissions. This may happen if the emission commitment, implemented through a cap and trade system or a carbon tax, leads to increase domestic gas extraction. Indeed, gas releases coal that is exported instead of being consumed domestically, increasing emissions in the rest of the world. Our two-resource setting thus contradicts the standard analysis of emissions' leakage with a single resource. We establish testable conditions under which (1) governmental emission commitments warrant the domestic exploitation of gas, and (2) imposing a cap on domestic emissions increases global emissions.

1 Introduction and Detailed Description

The use of shale gas notoriously releases less carbon emissions than regular fuels. Now more than ever, it is hoped that a large substitution of regular, very carbon intensive fuels by gas can help reduce carbon emissions, mitigating a climate problem labeled "the ultimate commons problem of the twenty-first century" (Stavins (2011)).

On this basis, an increasing number of top CO_2 emitting countries that are endowed with large shale gas deposits plan to meet their emission reduction governmental commitments by promoting the shale gas resource; among them, the US, Russia and China. For example, shale gas promotion seems at the heart of the current US Administration's energy strategy. As President Obama puts it, the US "position as the top natural gas producer (...) not only can provide (...) cheap power, but it can also help reduce [US] carbon emissions." (Remarks by the President on Climate Change, June 25, 2013). Not so surprisingly, this view is supported by the gas industry.[1] The hope that natural gas can play a major role in national climate and energy policy strategies has also been substantiated by academic experts (see the MIT report of Jacoby, O'Sullivan and Paltsev, 2011, on the US),[2] but remains controversial (see the recent projections of Chakravorty et al. (2015), for China).

Figure 1 shows US consumption of coal and natural gas from electricity generation from 2001 to 2014, and Figure 2 shows US energy related CO_2 emissions on the same period. The progressive substitution of coal by gas is clearly apparent. It is expected to continue in the near future. The downward trend is also clear: emissions have been reduced by 10% between 2007 and 2013. However, this reduction may be explained by many other factors besides coal to gas substitution. Feng et al. (2015) for instance decompose the decline in CO_2 emissions according to different factors, including donsumption volume, energy intensity and fuel mix. They find that the economic slowdown has been an important driver of the decrease in CO_2 emissions but the fuel mix played a significant positive role in this decrease. Knittel et al. (2015) find that the drop in the price of natural gas between June 2008 and the end of 2012 translates to a large reduction in CO_2 emissions from the electricity sector.

Regardless of whether the substitution of regular fuels by natural gas is desirable for an economy concerned by its CO_2 emissions, the global effect of this strategy is limited by a leakage phenomenon: substitution by gas releases amounts of tradable fuels like coal; the resulting supply meets the foreign energy demand of regions that do not have emissions target, contributing to increase emissions in those regions. For example, empirical evidence shows that the recent US shale gas boom has been accompanied by a severe rise in US exports of coal between 2007 and 2012 (see Figure 3). Of course, this upward trend in US exports may be explained by other factors.

However, the standard analysis of CO_2 leakage delivers a relatively optimistic message: domestic efforts to reduce CO_2 emissions are compensated by leakage only partially but not completely (e.g. Eichner and Pethig (2011) and Fischer and Salant (2012)), to an extent that depends on the elasticities of supply and demand of the CO_2 containing commodity

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[1] BP, BG Group, Eni, Statoil and Total recently declared: "We urge governments to take decisive action at December's UN summit. We are also united in believing such action should recognize the vital roles of natural gas and carbon pricing in helping to meet the world's demand for energy more sustainably." Letter on the role of gas and carbon pricing to media, June 1, 2015.

[2] According to the report (see Jacoby et al. (2011)), "the emergence of shale gas supplies is a boon to the US economy and an aid to potential climate policy."

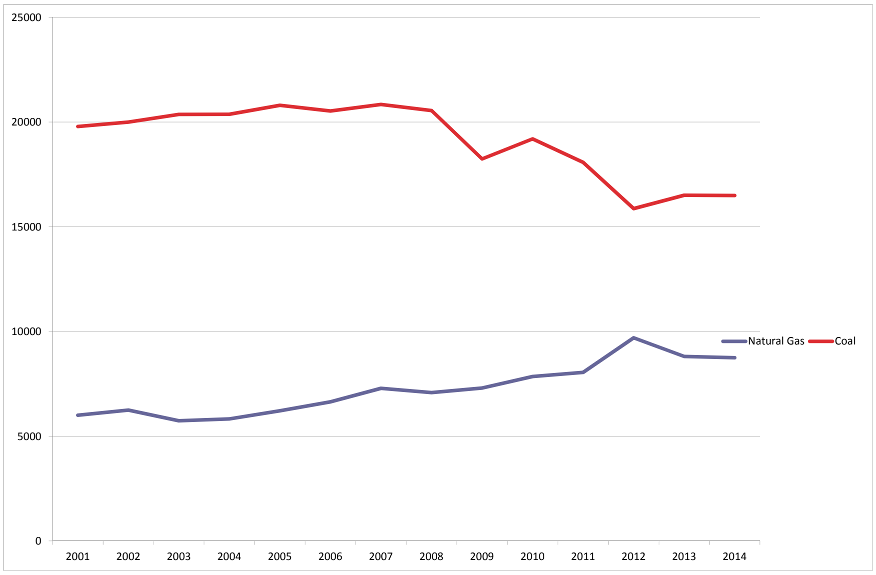

Figure 1: US consumption of natural gas and coal for electricity generation (MMBtu)

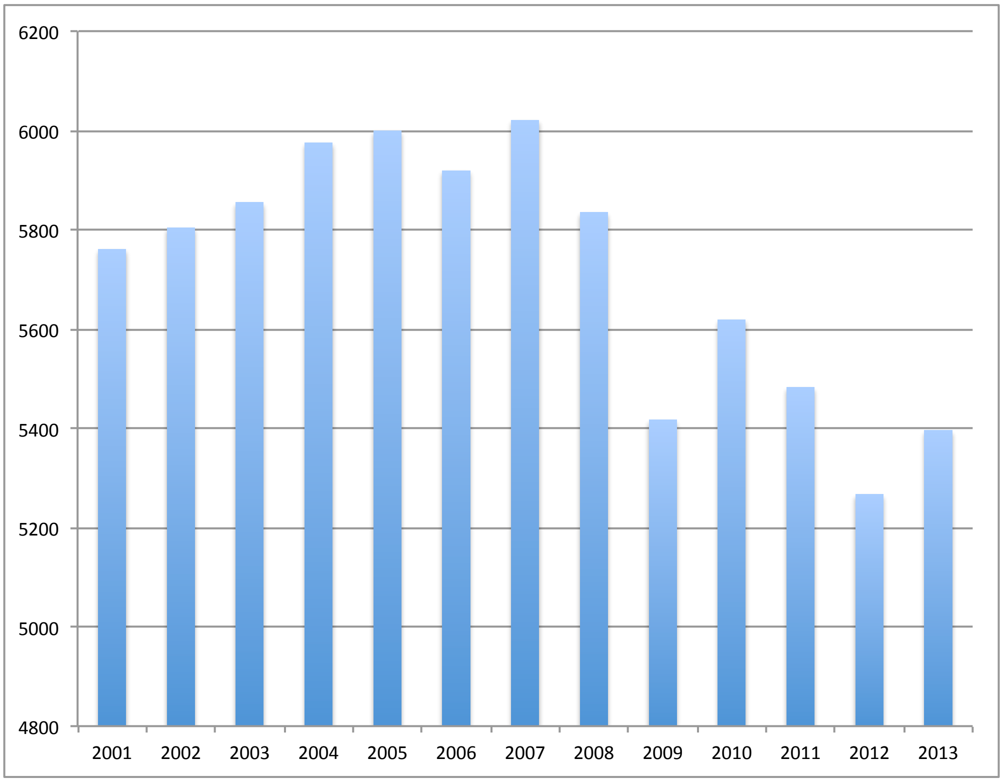

Figure 2: US energy related CO2 emissions (millions of tons)

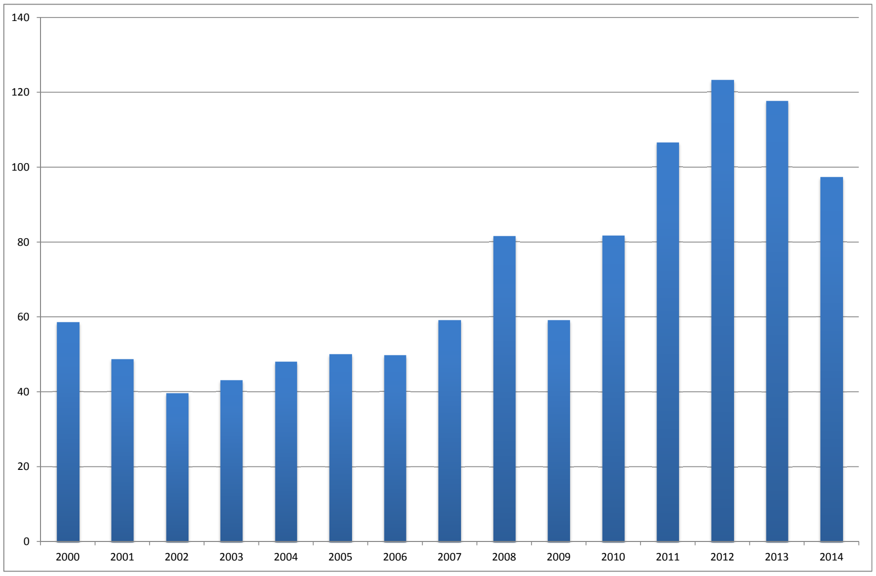

Figure 3: US coal exports (Thousand Short Tons)

and of the market share of the CO_2 reducing economy. Carbon leakage has been extensively studied in various settings, e.g. Ritter and Schopf (2013) or Quentin Grafton et al. (2012). Yet there exists no theoretical study where carbon leakage arises as a result of the substitution of one polluting resource by another (less) polluting resource. We extend the leakage literature to take into account the multiplicity and heterogeneity of resources that actually compete for the energy demand, in the spirit, for example, of Chakravorty et al. (2008). The optimistic message of a less than 100% leakage conveyed by the standard analysis with a single resource does not carry over to our novel two-resource setup: an economy that relies on domestic natural gas to meet its emission commitment may in fact contribute to increase global emissions. Burniaux and Oliveira Martins (2012) study carbon leakage in a general equilibrium framework with multiple fossil fuels, but they group natural gas with carbon-free energy. The paper also relates to the "green paradox" litterature (see for instance, Sinn (2008), van der Ploeg and Withagen (2012)) as an environmental policy, here a domestic cap on emissions, could lead to an adverse effect: the increase of world emissions.

In this project, we examine an open economy that produces both natural gas and another, more carbon intensive fuel – thereafter, coal.

There are three mains channels of carbon leakage:[3] i) International energy markets;

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[3] see Dröge et al. (2009) for a typology,

ii) firm's production costs, investments decisons and relocalisation; iii) the dynamics of technological innovation and policy diffusion. In this paper, we only focus on leakage through international energy markets.

Optimal resource extraction with various pollution contents and/or costs has been studied by Herfindahl (1967), Heal (1976), van der Ploeg and Withagen (2012) and Coulomb and Henriet (2013), among others. Recently, Henriet and Schubert (2015) has studied the optimal exploration and exploitation of shale gas and a renewable backstop in an economy initially producing its electricity with coal-fired power plants. However, the closed economy setup prevents it from studying carbon leakage issues.

Natural gas domestic production is consumed domestically. Coal domestic production may be exported to the rest of the world. We address the following questions. (1) Faced with an emission reduction objective, should a natural gas producing economy increase its domestic gas production? (2) Does this strategy decrease global emissions? The analysis involves the minimal elements needed to address those questions. That is, all sectors are competitive. There is a single policy, that sets a cap on domestic emissions. This cap is implemented in a cost-effective manner, for example by use of a tradable permits system. There is no impediment to the perfect substitution of one resource by another, as should be the case in a medium to long run perspective over which resource-using technologies can be adapted.

We establish testable conditions under which (1) a more stringent governmental emission commitment warrants more domestic exploitation of gas, and (2) this strategy increases global emissions. Combining those conditions, we characterize situations where domestic policy is strongly counter-effective: even when an economy finds optimal from a domestic perspective to rely on its natural gas to meet its own emission commitments, this strategy may effectively contribute to increase global emissions. That is this result that contradicts the standard analysis of less than 100 percent leakage. With several resources, the novelty is that an emission cap not only penalizes the most polluting resources, but also encourages the least polluting ones. Thus, despite leakages, less coal is produced in the aggregate, as one should expect from the standard leakage analysis; but this reduction can be more than compensated because the rise of natural gas makes energy more abundant. The conditions that we establish bring up new insights. They involve measurable economic notions such as the elasticities of gas and coal supply and demand, and the market shares of the emission-reducing economy in the two sectors respectively. They can easily be used to assess the role that natural gas should play in any country: that is, for each country, whether domestic gas promotion is desirable from a domestic perspective and whether such policy helps to meet global efforts to reduce CO_2 emissions. Our systematic examination and the formulas we obtain are therefore critical for the design of effective policies against the global climate problem that are acceptable at the national level.

The first part of the analysis follows Hoel (1994)'s and Harstad (2012)'s static picture of the energy market. In fact, the exploitation of natural gas and other resources introduces a dynamic dimension. Exploitable resources are developed first and are then exploited over time. Thus in a second part, we also build on the literature on intertemporal extraction of natural resources (see Quyen (1991), Arrow and Chang (1982), Pindyck (1978), Gaudet and Lasserre (1988)). We show how the analysis accommodates this intertemporal extension. This extension highlights the role of the ultimately exploited resource quantities. Yet those cumulative quantities behave in the same way as their instantaneous flow counterparts in the static analysis; that is, the conditions obtained in the first static setup qualitatively follow through in the long run.

Section 2 presents the model. In section 3, we derive the effect of a more stringent domestic emission cap on gas extraction and world emissions. Extensions are presented in section 4.

2 Model and Sketch of Analysis

We examine an open economy in which a country H (Home) produces natural gas in quantity x_g^H and another, more carbon intensive fuel – thereafter, coal, in quantity x_c^H. Gas is not traded and is produced by country H alone. Coal is also produced and consumed in the rest of the world F. The quantity of coal extracted in the rest of the world is denoted x_c^F. Home consumes the quantity x_g^H of gas and a quantity y_c^H of coal, whereas the rest of the world consumes a quantity y_c^F of coal. The two fossil resources are perfect substitutes in electricity generation. Burning one unit of natural gas (resp. coal) increases emissions by θ_g (resp. θ_c).

Coal supply There is a competitive world market where coal can be sold to electricity producers at price p_c. The cost of supplying x units of coal in the Home country is given by $C_c^H(x)$, where $C_c^H(.)$ is an increasing and strictly convex function. The Home coal producers take the world coal market price p_c as given and maximize: $p_c x_c^H - C_c^H(x_c^H)$. Similarly, the Foreign coal producers face an increasing and convex supply cost function denoted $C_c^F(.)$. They take the world coal market price as given and maximize $p_c x_c^F - C_c^F(x_c^F)$. At the equilibrium:

$$p_c = C_c^{H\prime}(x_c^H) \tag{1}$$

$$p_c = C_c^{F\prime}(x_c^F) \tag{2}$$

Alternatively, we denote the supply of coal $x_c^H = S_c^H(p_c) \equiv C_c^{H\prime^{-1}}(p_c)$, $x_c^F = S_c^F(p_c) \equiv C_c^{F\prime^{-1}}(p_c)$, $x_c^H + x_c^F = S_c(p_c)$.

Gas supply Gas is only produced and consumed in the Home country. It is sold to electricity utilities by gas producers in a competitive market at price p_g. The cost of supplying x_g^H units of gas is represented by a convex and increasing function $C_g^H(x_g^H)$. The Home gas producers take the market price p_g as given and maximize: $p_g x_g^H - C_g^H(x_g^H)$. At the equilibrium:

$$p_g = C_g^{H\prime}(x_g^H) \tag{3}$$

Alternatively, we denote the supply of gas $x_g^H = S_g(p_g) \equiv C_g^{H\prime^{-1}}(p_g)$.

Climate policy There is a single policy, in country H, that sets a cap on domestic emissions $\overline{e}$. This cap is implemented in a cost-effective manner, for example by use of a tradable permits system or a carbon tax. This tax or the permits price is denoted τ. The revenues from the tax or the quotas are redistributed lump sum to consumers. At the equilibrium:

$$\overline{e} = \theta_g x_g^H + \theta_c y_c^H \tag{4}$$

Market for electricity in the Home country Consumers have a quasi-linear utility function. When one consumes y unit of electricity, bought at price q, one gets utility: $B(y) - qy$. Electricity is produced with a one-for-one technology using coal or shale gas, which are perfect substitutes. Electricity producers must pay a tax (or the permit price) on emissions. At the equilibrium, the final energy price in the Home country is:

$$q = p_g + \theta_g \tau = p_c + \theta_c \tau \tag{5}$$

and demand in the Home country is given by:

$$B'(x_g^H + y_c^H) = q \tag{6}$$

Alternatively, we denote the domestic demand of electricity $x_g^H + y_c^H = D^H(q) \equiv B'^{-1}(q)$.

Market clearing In the rest of the world, electricity is produced with a one-for-one technology using only coal. There is no climate policy. Consumers have a quasi-linear utility function, which yields a demand for coal $y_c^F = D^F(p_c)$. The equilibrium of the coal market reads:

$$y_c^H + y_c^F = x_c^H + x_c^F \tag{7}$$

Equilibrium The equilibrium values of $(p_c, p_g, x_c^H, x_c^F, x_g^H, y_c^H, y_c^F, \tau)$ are given by the system of equations (1) to (7). Eliminating $p_g, x_c^H, x_c^F, y_c^H, y_c^F$ and τ between these equations yields the following system in (p_c, x_g^H):

$$\begin{aligned} \frac{\theta_c - \theta_s}{\theta_c} B' \left(\frac{\overline{e} + (\theta_c - \theta_g) x_g^H}{\theta_c} \right) - {C_g^H}'(x_g^H) + p_c \frac{\theta_g}{\theta_c} &= 0 && (8) \\ S_c^H(p_c) + S_c^F(p_c) - D^F(p_c) &= \frac{\overline{e} - \theta_g x_g^H}{\theta_c} && (9) \end{aligned}$$

3 Effects of a more stringent domestic emission cap

In this section, we look at the effect of strenghtening the cap on domestic emissions on natural gas extraction. We assume a marginal change $d\overline{e}$ in the cap $\overline{e}$.

Proposition 1. *Faced with a lower cap $\overline{e}$ on its emissions, the Home country increases gas domestic use x_g^H if and only if:*

$$\frac{\theta_c - \theta_g}{\theta_g} > \frac{{D^H}'(q)}{{D^F}'(p_c) - S_c'(p_c)} \qquad (10)$$

Proof. See Appendix. □

To understand this proposition, note that, using the definition of domestic electricity demand $D^H(q) = x_g^H + y_c^H$, the market clearing condition (7) can be rewritten as:

$$S_g(p_g) = \underbrace{D^H(q)}_{\text{domestic electricity demand}} - \underbrace{\left[S_c(p_c) - D^F(p_c)\right]}_{\text{residual coal supply}}$$

It is straightforward that the tax τ has two effects playing in opposite directions on the gas producer price p_g:

- On the one hand, the tax decreases the coal producer price compared to the natural gas producer price: $p_c = p_g - (\theta_c - \theta_g)\tau$. Following an increase in τ, the residual supply curve of coal for the domestic market $S_c(p_c) - D^F(p_c)$ is shifted to the right in the (gas producer price, quantity) space. If domestic demand $D^H(q)$ was unchanged, the residual demand curve $D^H(q) - \left[S_c(p_c) - D^F(p_c)\right]$ would be shifted to the right and would cross the gas supply curve at a higher gas producer price, implying that more gas is developed. That would be the only effect were domestic demand totally inelastic.

The magnitude of this effect is:

$$S_g'(p_g)d_1p_g = (\theta_c - \theta_g)\left[S_c'(p_c) - D^{F\prime}(p_c)\right]d\tau$$

- In general, there is another effect playing in the opposite direction: the tax increases the domestic energy price $q = p_g + \theta_g\tau$, and thus shifts the domestic demand $D^H(q)$ to the left in the (price, quantity) space. If the residual supply of coal for the domestic market was unchanged by the tax, the supply curve of gas and the residual demand for gas would cross at a lower gas producer price, implying a lower gas supply. The magnitude of this effect is:

$$S_g'(p_g)d_2p_g = \theta_g D^{H\prime}(q)d\tau$$

To sum up, the effect of the tax on gas extraction is ambiguous. On the one hand, the tax decreases the coal producer price compared to the gas producer price, leading to a lower supply of coal on the domestic market, and thus leaving more room for natural gas. On the other hand, the tax reduces domestic demand, reducing the demand for gas as well. The overall effect is given by:

$$S_g'(p_g)dp_g = \left\{\theta_g D^{H\prime}(q) + (\theta_c - \theta_g)\left[S_c'(p_c) - D^{F\prime}(p_c)\right]\right\}d\tau$$

Let us define the elasticities of electricity demand in Home and Foreign countries:

$$\epsilon_D^H = -\frac{D^{H\prime}(q)q}{D^H(q)}, \quad \epsilon_D^F = -\frac{D^{F\prime}(p_c)p_c}{D^F(p_c)}$$

and the elasticity of world coal supply:

$$\epsilon_{Sc} = \frac{S_c'(p_c)p_c}{S_c(p_c)}$$

Let us look at condition (10). For a marginal increase in τ from $\tau = 0$, it can be rewritten as:

$$\frac{\theta_c - \theta_g}{\theta_g} > \frac{\epsilon_D^H}{\epsilon_D^F}\frac{D^H}{D^F}\frac{1}{1 + \frac{\epsilon_{Sc}}{\epsilon_D^F}\frac{S_c}{D^F}} \tag{11}$$

This condition is more likely to be satisfied, i.e. a cap on emissions is more likely to lead the Home country to increase natural gas extraction, if the difference in pollution contents of coal and gas is high; the Home country is small in front of the rest of the world ($D^H \ll D^F$);

the price elasticity of the world coal supply is large; the price elasticity of electricity demand is small.

In particular, if demand in the Home country is totally inelastic or if the world supply of coal is very elastic, a more stingent cap on emissions in the Home country leads to increase natural gas extraction. The intuition is the following: if demand is very inelastic, increasing the quantity of gas extracted decreases exactly by the same amount the quantity of coal consumed domestically, thus reducing emissions; if the world coal supply is very elastic, an increase in gas extraction reduces coal production and reduces domestic emissions.

Let us calibrate roughly the model to the US case, to get insights on how likely the increase of natural gas extraction is.

EIA (2012) gives that the US coal consumption is 12% of world total coal consumption. We assume that gas represents half of electricity consumption, so that $D^H/D^F \simeq 0.24$ and $S_c/D^F \simeq 1.12$.

The empirical literature gives price elasticity of energy demand between 0.05 and 1 (see Bentzen and Engsted (1993), Masih and Masih (1996), Truby and Paulus (2012)). We make the assumption $\epsilon_D^H = \epsilon_D^F \simeq 0.5$.

Condition (11) may be written as:

$$\epsilon_{Sc} > \epsilon_D^F \frac{D^F}{S_c} \left(\frac{1}{\frac{\theta_c - \theta_g}{\theta_g}} \frac{\epsilon_D^H}{\epsilon_D^F} \frac{D^H}{D^F} - 1 \right)$$

i.e., with our calibration:

$$\epsilon_{Sc} > 0.264 \left(\frac{0.24}{\frac{\theta_c - \theta_g}{\theta_g}} - 1 \right)$$

The condition is satisfied for all values of ϵ_{Sc} as soon as $\theta_c/\theta_g \geq 1.24$. Most estimates of the CO_2 emissions coefficient of coal relative to natural gas yield figures around 2 (Heath et al. (2014), Jenner and Lamadrid (2013), Alvarez et al. (2012)). Things are more controversial regarding the relative global warming potential of the two fossil fuels, mainly because of the methane leakage associated to shale gas exploitation (see Howarth et al. (2011)). Anyway, $\theta_c/\theta_g \geq 1.12$ appears as quite plausible. Hence it is very likely that the increase of shale gas extraction will reduce emissions in the Home country.

The question that arises next is whether this leads to increase or decrease world CO_2 emissions. Of course, a necessary condition for an increase in world emissions is an increase in natural gas extraction. Let us look now at the effect on world emissions $E = \overline{e} + \theta_c D^F(p_c)$. We have:

$$dE = d\overline{e} + \theta_c D^{F\prime}(p_c) dp_c$$

so that:

Proposition 2. *If the Home country imposes a unilateral cap on its emissions, world emissions are increased if and only if:*

$$\frac{\theta_c - \theta_g}{\theta_g} > \frac{D^{H\prime}(q)}{D^{F\prime}(p_c) - S_c{}'(p_c)} \left[1 + \frac{\theta_c}{\theta_g} S_c^{\prime}(p_c) \left(\frac{\theta_c}{\theta_g} \frac{1}{S_g^{\prime}(p_g)} - \frac{\theta_c - \theta_g}{\theta_g} \frac{1}{D^{H\prime}(q)} \right) \right] \tag{12}$$

Proof. See Appendix. □

A necessary condition for world emissions to increase is that the Home country increases gas extraction in order to comply with the domestic emission cap. For a marginal decrease in domestic emissions compared to business as usual (i.e. a change from $\tau = 0$ to $d\tau$), the sign of the change in world emissions is a second degree equation in $\frac{\theta_g}{\theta_c}$ (see Appendix), which reaches its maximum for:

$$\left(\frac{\theta_g}{\theta_c} \right)^* = \frac{S_c^{\prime} - D^{F\prime}/2}{S_c^{\prime} - D^{F\prime} - D^{H\prime}}$$

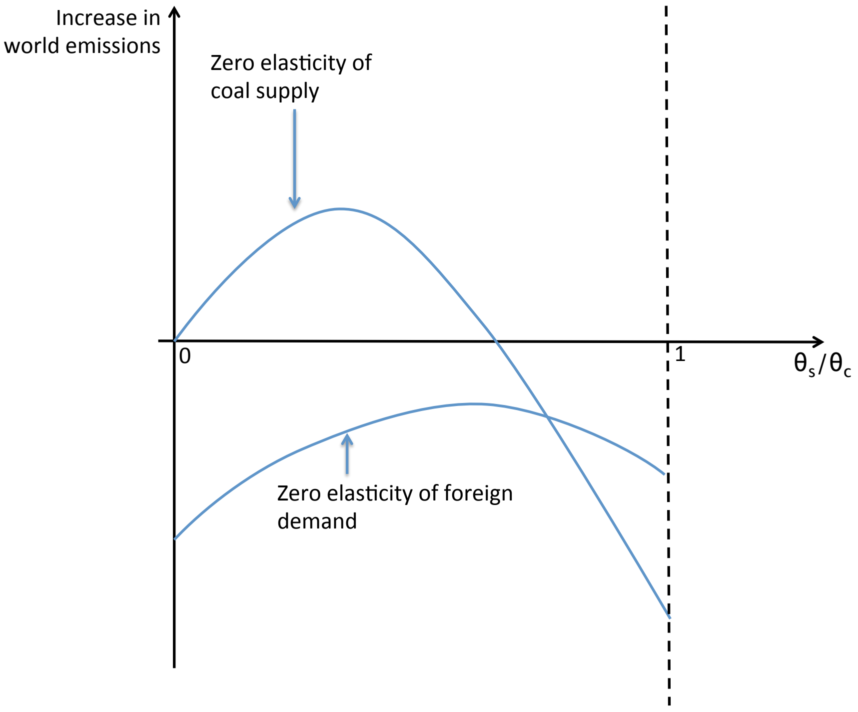
It is straightforward that $0 < \left(\frac{\theta_g}{\theta_c} \right)^* < 1$. For $\left(\frac{\theta_g}{\theta_c} \right)^* = 0$ and $\left(\frac{\theta_g}{\theta_c} \right)^* = 1$, world emissions are decreased thanks to the emission cap in the Home country. But for $0 < \left(\frac{\theta_g}{\theta_c} \right)^* < 1$, it may well be the case that emissions are increased because of the domestic emission cap. Let us look at the conditions for this to occur. The maximum change in emissions, obtained for a ratio of the emission coefficients of $\left(\frac{\theta_g}{\theta_c} \right)^*$, has the sign of:

$$D^{F\prime 2} + 4 D^{H\prime} \frac{S_c^{\prime}}{S_g^{\prime}} (S_c^{\prime} + S_g^{\prime} - D^{F\prime} - D^{H\prime})$$

Corollary 3. *For a marginal decrease in domestic emissions compared to business as usual (i.e a change from $\tau = 0$ to $d\tau$), there exists some values of the ratio of the emission coefficients $\frac{\theta_g}{\theta_c}$ such that world emissions are increased because of the domestic cap on emissions, if and only if:*

$$\left(\epsilon_D^F \right)^2 - 4 \epsilon_D^H \frac{\epsilon_{Sc}}{\epsilon_{Ss}} \frac{S_c}{D^F} \frac{D^H}{S_g} \left(\epsilon_{Sc} \frac{S_c}{D^F} + \epsilon_{Sg} \frac{S_g}{D^F} + \epsilon_D^F + \epsilon_D^H \frac{D^H}{D^F} \right) > 0$$

Elasticity of natural gas supply between 0.76 and 1.6 Brown and Krupnick (2010). There are hardly any estimate of coal and gas supply in the literature, however the order of magnitude are between 0.11 (but issues with the econometrics, see Dahl and Duggan (1996)) and 7.9 for coal production. Between years 1970 and 2000, coal production has been steadily increasing while the real price of coal has declined. Beck et al. (1991) found a supply elasticity for Australian mines between 0.4 and 1.9 but Light (1999) and Light et al. (1999) find a



supply elasticity of 0.3. Dahl and Duggan (1996) found reserve elasticities between 0.4 and 7.9. Labys et al. (1979) found supply elasticities of 0.11. We take equal elasticities of supply for gas and coal supply and we consider that half of the domestic demand is met with gas, i.e. $\frac{D_H}{S_g} = 2$. We find that the LHS of Eq. **??** is negative. As a result, the world emissions are likely to decrease thanks to the domestic emission cap, if this is done in a cost effective manner.

We next compute the leakage rate associated with a domestic cap:

$$\frac{dE}{de} - 1 = \frac{D^{F\prime}\left[\left(\frac{\theta_c - \theta_g}{\theta_c}\right)\frac{1}{D^{H\prime}} - \frac{1}{S_g'}\right]}{\left[\left(\frac{\theta_c - \theta_g}{\theta_c}\right)^2 \frac{1}{D^{H\prime}} - \frac{1}{S_g'}\right](S_c^{F\prime}) - \left(\frac{\theta_g}{\theta_c}\right)^2}$$

Considering a marginal domestic cap, this can be rewritten:

$$\frac{dE}{de} - 1 = \frac{\epsilon_D^F}{\epsilon_D^H}\frac{D^F}{D^H}\frac{\frac{\theta_c - \theta_g}{\theta_c} + \frac{\epsilon_D^H D^H}{\epsilon_{Sg} S_g}}{\frac{\epsilon_D^F}{\epsilon_D^H}\frac{D^F}{D^H}\left[\left(\frac{\theta_c - \theta_g}{\theta_c}\right)^2 + \frac{\epsilon_D^H D^H}{\epsilon_{Sg} S_g}\right]\left(-\frac{\epsilon_{Sc} S_c}{\epsilon_D^F D^F} - 1\right) - \left(\frac{\theta_g}{\theta_c}\right)^2}$$

So that the leakage rate is approximatively equal to:

$$\frac{dE}{de} - 1 \simeq -37\%$$

In comparison, the leakage rate in our model if gas was a carbon free resource would be around 30% and with only one polluting resource, i.e. if gas is as polluting as coal, the leakage rate in our model is approximatively 28%. These estimates are in line with the litterature, see Burniaux and Oliveira Martins (2012) for a review. The leakage rate may be underestimated by considering an homogenous polluting resource, or that gas is a carbon free resource.

4 Extensions

4.1 Imperfect competition

Assume now that the Home country maximizes its welfare under the constraint that its own emissions remain below the threshold $\bar{e}$, but takes into account the effect of its climate policy on the coal world market price. Denoting the exports elasticity

$$\eta_{exp} = -\frac{(D^{F\prime}(p) - S_c^{F\prime}(p))p}{D^F(p) - S_c^{F\prime}(p)}$$

This elasticity is positive as long as the Home country is a net exporter. The solution is given by:

$$\begin{aligned}
B'(y^H) &= p\left(1 - \frac{1}{\eta_{exp}}\right) + \mu\theta_c \\
C_c^{H\prime}(x_c^H) &= p\left(1 - \frac{1}{\eta_{exp}}\right) \\
C_g^{H\prime}(x_g^H) &= p\left(1 - \frac{1}{\eta_{exp}}\right) + \mu(\theta_c - \theta_g) \\
\theta_g x_g^H + \theta_c(y^H - x_g^H) &= \bar{e} \\
x_g^H + x_c^H - y^H &= D^F(p) - S_c^F(p)
\end{aligned}$$

The solution can be decentralized with three instruments:

- A tariff $\tau = \mu\theta_c - \frac{p}{\eta_{exp}}$ (or an export tax $-\mu\theta_c + \frac{p}{\eta_{exp}}$)
- A pigovian production tax on gas: $\mu\theta_g$

- A pigovian production tax on coal: $\mu\theta_c$

This result is in line with Hoel (1991). Let us compare the result with a perfect competition result, denoting p_c the competitive world coal price of the previous section.[4] It is straightforward that, for all values of the cap $\overline{e}$:

$$p\left(1-\frac{1}{\eta_{exp}}\right) < p^c < p$$

As a result, for a given e the leakage is always less important with imperfect competition because the Home country is a net exporter of coal, thus preferring a high price for coal.

A corollary of this result is that, if the objective of the home country is to reach the cap $\overline{e}$ without increasing world emissions, this can be done by imposing a tax on CO_2 emissions, together with a carefully chosen export tax.

4.2 A cap on coal use

As a result of new Environmental Protection Agency (EPA) rules regulating air pollution, many coal-fired power plants will be forced to shut down. Let us look now at what would happen if there was a cap on coal use in the Home country, $\overline{y}_c^H$. Then, the quantity of natural gas extracted always increases. When the cap is tightened, we get:

$$\frac{dy_g}{d\overline{y}_c^H} = \frac{S_g'(p_g)}{D^{H\prime}(q) - S_g'(p_g)}$$

So that whenever the cap on coal use decreases, natural gas use increases. It is straightforward that domestic emissions decrease, as $-\frac{dy_g}{d\overline{y}_c^H} < 1$.

The effect on world emissions is the following:

$$\frac{dE}{d\overline{y}_c^H} = \theta_c \frac{S_c'}{S_c' - D^{F\prime}} - \theta_g \frac{S_g'}{S_g' - D^{H\prime}}$$

which can be rewritten as:

$$\frac{dE}{d\overline{y}_c^H} = \theta_c \frac{\epsilon_{Sc}}{\epsilon_{Sc} + \epsilon_D^F \frac{S_c}{D^F}} - \theta_g \frac{\epsilon_{Sg}}{\epsilon_{Sg} + \epsilon_D^H \frac{S_g}{D^H}}$$

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[4] The FOC of the competitive solution are rewritten in appendix B

World emissions increase if and only if:

$$\frac{\theta_g}{\theta_c} > \frac{\epsilon_{Sc}}{\epsilon_{Sg}} \frac{\epsilon_{Sg} + \epsilon_D^H \frac{S_g}{D^H}}{\epsilon_{Sc} + \epsilon_D^F \frac{S_c}{D^F}}$$

The leakage rate can be written:

$$\frac{dE}{de} - 1 = - \frac{\epsilon_D^F \left(\epsilon_{Sg} \frac{S_g}{D^H} + \epsilon_D^H \right)}{\left(\epsilon_{Sc} \frac{S_c}{D^F} + \epsilon_D^F \right) \left(\epsilon_{Sg} \frac{S_g}{D^H} \frac{\theta_c - \theta_g}{\theta_c} + \epsilon_D^H \right)}$$

A numerical application for the US gives a leakage rate around 42%.

4.3 Dynamic Extension

In this part, we extend the previous model into a dynamic model. Exploration and development at date 0 allow to build reserves that will be extracted (Gaudet and Lasserre, 1988). These extraction costs are denoted $C_g^H(X_g)$, where X_g is the total amount of natural gas extracted in the Home country, $C_c^H(X_c^H)$, where X_c^H is the total amount of coal extracted in the Home country, and $C_c^F(X_c^F)$, where X_c^F is the total amount of coal extracted elsewhere. There is a ceiling E on the stock of pollution. We denote $p(t)$ the coal world price at date t. As coal producers are in perfect competition and extraction costs are paid at date 0, this price rises at the rate of interest. In the rest of the world, the supply of coal is given by:

$$p(0) = C_c^{F\prime}(X_c^F)$$

and demand at date t :

$$p(t) = B^{F\prime}(y^F(t))$$

We rewrite $y^F(t) = D(p(t)) \equiv B^{F\prime(-1)}(p(t))$ and $Y^F(t) = \int_0^\infty B^{F\prime(-1)}(p(t))dt$. As extraction is performed at date 0, only the overall demand over time is relevant for equilibrium.

The problem amounts to solve:

$$\max \int_0^\infty \left[B^H(y^H(t)) + p(t) \left(x_g^H(t) + x_c^H(t) - y^H(t) \right) \right] e^{-rt} dt - C_g^H(X_g) - C_c^H(X_c^H) \quad (13)$$

under the constraints:

$$\theta_g \int_0^\infty x_g^H(t)dt + \theta_c \left(\int_0^\infty (y^H(t) - x_g^H(t))dt \right) \leq E \qquad (\mu(t)) \tag{14}$$

$$\int_0^\infty x_g^H(t)dt \leq X_g^H \qquad (\lambda_g^H(t)) \tag{15}$$

$$\int_0^\infty x_c^H(t)dt \leq X_c^H \qquad (\lambda_c^H(t)) \tag{16}$$

Let us write the Hamiltonian of the problem:

$$\begin{aligned} \mathcal{H} &= \left[B^H(y^H(t)) + p(t) \left(x_g^H(t) + x_c^H(t) - y^H(t) \right) \right] \\ &\quad -\mu(t) \left(\theta_g x_g^H(t) + \theta_c \left((y^H(t) - x_g^H(t)) \right) \right) - \lambda_g^H(t) x_g^H(t) - \lambda_c^H(t) x_c^H(t) \end{aligned}$$

The optimality conditions are given by:

$$B^{H\prime}(y^H(t)) = p(t) + \theta_c \mu e^{rt} \tag{17}$$

$$p(t) + \theta_c \mu e^{rt} = \theta_g \mu e^{rt} + \lambda_g^H e^{rt} \tag{18}$$

$$p(t) = \lambda_c^H e^{rt} \tag{19}$$

where λ_g^H and λ_c^H are the initial values of the scarcity rent on natural gas and coal respectively, and μ is the initial carbon value in the Home country. The enveloppe theorem yields:

$$C_g^{H\prime}(X_g^H) = \lambda_g^H \tag{20}$$

$$C_c^{H\prime}(X_c^H) = \lambda_c^H \tag{21}$$

The solution of the dynamic problem is thus given by:

$$p(0) = \lambda_c^H \tag{22}$$

$$Y^H = \int_0^\infty B^{H\prime^{-1}}((p(0)+\theta_c\mu)e^{rt})dt \tag{23}$$

$$\theta_g\mu + \lambda_g^H = \theta_c\mu + \lambda_c^H \tag{24}$$

$$C_g^{H\prime}(X_g^H) = \lambda_g^H \tag{25}$$

$$C_c^{H\prime}(X_c^H) = \lambda_c^H \tag{26}$$

$$E = \theta_g X_g^H + \theta_c(Y^H - X_g^H) \tag{27}$$

$$C'(X_c^F) = \lambda_c^H \tag{28}$$

$$Y^F = \int_0^\infty B^{F\prime^{-1}}((\lambda_c^H)e^{rt})dt \tag{29}$$

$$Y^F + Y^H = X_g^H + X_c^H + X_c^F \tag{30}$$

The system of equation is the same as in the static case, provided that we define for both countries the cumulated demand as $D(p) = \int_0^\infty B'^{-1}(pe^{rt})dt$ (instead of $D(p) = B'^{-1}(p)dt$ in the static case). All the previous results remain unchanged, as far as aggregate variables are concerned.

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A Emissions

Differentiating system (8)-(9) yields:

$$\begin{pmatrix} A_1 & \frac{\theta_g}{\theta_c} \\ \frac{\theta_g}{\theta_c} & A_2 \end{pmatrix} \begin{pmatrix} dx_g \\ dp_c \end{pmatrix} = \begin{pmatrix} -\frac{\theta_c-\theta_g}{(\theta_c)^2}\frac{1}{D^{H\prime}} \\ \frac{1}{\theta_c} \end{pmatrix} d\overline{e}$$

with

$$\begin{aligned} A_1 &= \left(\frac{\theta_c-\theta_g}{\theta_c}\right)^2 \frac{1}{D^{H\prime}} - \frac{1}{S_g'} < 0 \\ A_2 &= S_c^{W\prime} - D^{F\prime} > 0 \end{aligned}$$

Hence:

$$\begin{pmatrix} dx_g \\ dp_c \end{pmatrix} = \frac{1}{A_1A_2 - \left(\frac{\theta_g}{\theta_c}\right)^2} \begin{pmatrix} A_2 & -\frac{\theta_g}{\theta^c} \\ -\frac{\theta_g}{\theta_c} & A_1 \end{pmatrix} \begin{pmatrix} -\frac{\theta_c-\theta_g}{{\theta_c}^2}\frac{1}{D^{H\prime}} \\ \frac{1}{\theta_c} \end{pmatrix} d\overline{e}$$

i.e.

$$\begin{aligned}
\begin{pmatrix} \frac{dx_g}{d\overline{e}} \\ \frac{dp_c}{d\overline{e}} \end{pmatrix} &= \frac{1}{A_1A_2 - \left(\frac{\theta_g}{\theta_c}\right)^2} \begin{pmatrix} -\frac{\theta_c-\theta_g}{{\theta_c}^2}\frac{1}{D^{H\prime}}A_2 - \frac{\theta_g}{\theta_c^2} \\ \frac{\theta_g}{\theta_c}\frac{\theta_c-\theta_g}{{\theta_c}^2}\frac{1}{D^{H\prime}} + \frac{1}{\theta_c}A_1 \end{pmatrix} \\
&= \frac{1}{A_1A_2 - \left(\frac{\theta_g}{\theta_c}\right)^2} \begin{pmatrix} -\frac{\theta_g}{{\theta_c}^2}\left[-\frac{\theta_c-\theta_g}{\theta_g}\frac{D^{F\prime}-S_c^{W\prime}}{D^{H\prime}} + 1\right] \\ \frac{1}{\theta_c}\left[\frac{\theta_c-\theta_g}{\theta_c}\frac{1}{D^{H\prime}} - \frac{1}{S_g^{\prime}}\right] \end{pmatrix}
\end{aligned}$$

As $A_1A_2 - \left(\frac{\theta_g}{\theta_c}\right)^2 < 0$,

$$\begin{aligned}
\frac{dx_g}{d\overline{e}} &< 0 \Longleftrightarrow -\frac{\theta_c - \theta_g}{\theta_g}\frac{D^{F\prime} - S_c^{W\prime}}{D^{H\prime}} + 1 < 0 \\
\frac{dp_c}{d\overline{e}} &> 0
\end{aligned}$$

Total emissions:

$$\begin{aligned}
\frac{dE}{d\overline{e}} &= 1 + \theta_c D^{F\prime}\frac{dp_c}{d\overline{e}} \\
&= \frac{1}{A_1A_2 - \left(\frac{\theta_g}{\theta_c}\right)^2}\left[A_1A_2 - \left(\frac{\theta_g}{\theta_c}\right)^2 + D^{F\prime}\left(\frac{\theta_c - \theta_g}{\theta_c}\frac{1}{D^{H\prime}} - \frac{1}{S_g^{\prime}}\right)\right] \\
&= \frac{1}{A_1A_2 - \left(\frac{\theta_g}{\theta_c}\right)^2}\left[\left(\left(\frac{\theta_c - \theta_g}{\theta_c}\right)^2\frac{1}{D^{H\prime}} - \frac{1}{S_g^{\prime}}\right)S_c^{W\prime} - \left(\frac{\theta_g}{\theta_c}\right)^2 + \frac{\theta_c - \theta_g}{\theta_c}\frac{\theta_g}{\theta_c}\frac{D^{F\prime}}{D^{H\prime}}\right] \\
&= \frac{\left(\frac{\theta_g}{\theta_c}\right)^2}{A_1A_2 - \left(\frac{\theta_g}{\theta_c}\right)^2}\left[\frac{\theta_c}{\theta_g}\left(\left(\frac{\theta_c - \theta_g}{\theta_g}\right)\frac{S_c^{W\prime}}{D^{H\prime}} - \frac{\theta_c}{\theta_g}\frac{S_c^{W\prime}}{S_g^{\prime}}\right) + \frac{\theta_c - \theta_g}{\theta_g}\frac{D^{F\prime} - S_c^{W\prime}}{D^{H\prime}} - 1\right]
\end{aligned}$$

Hence

$$\frac{dE}{d\overline{e}} < 0 \Longleftrightarrow \frac{\theta_c - \theta_g}{\theta_g}\frac{D^{F\prime} - S_c^{W\prime}}{D^{H\prime}} > 1 + \frac{\theta_c}{\theta_g}S_c^{W\prime}\left(\frac{\theta_c}{\theta_g}\frac{1}{S_g^{\prime}} - \left(\frac{\theta_c - \theta_g}{\theta_g}\right)\frac{1}{D^{H\prime}}\right)$$

or equivalently:

$$\frac{dE}{d\overline{e}} < 0 \Longleftrightarrow -\left(S_c^{W\prime} - D^{H\prime} - D^{F\prime}\right)\left(\frac{\theta_g}{\theta_c}\right)^2 + \left(2S_c^{W\prime} - D^{F\prime}\right)\frac{\theta_g}{\theta_c} - S_c^{W\prime}\left(1 - \frac{D^{H\prime}}{S_g^{\prime}}\right) > 0$$

B FOC for the competitive case

The FOC were:

$$\begin{array}{rcl} B'(y^H) & = & p_c + \mu\theta_c \\ C_c^{H\prime}(x_c^H) & = & p_c \\ C_g^{H\prime}(x_g^H) & = & p_c + \mu(\theta_c - \theta_g) \\ \theta_g x_g^H + \theta_c(y^H - x_g^H) & = & \overline{e} \\ x_g^H + x_c^H - y^H & = & D^F(p_c) - S_c^F(p_c) \end{array}$$