More Gas, Less Coal, and Less CO2? Unilateral CO2 Reduction Policy with More than One Carbon Energy Source*

by

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Abstract

We examine an open economy's strategy to reduce its carbon emissions by replacing its consumption of coal—very carbon intensive—with gas—less so. Unlike the standard analysis of carbon leakage, unilateral carbon-reduction policies with more than one carbon energy source may turn counter-productive, ultimately increasing world emissions. We establish testable conditions as to whether a governmental emission-reduction commitment warrants the exploitation of gas, and whether such a strategy increases global emissions. We also characterize this strategy's implications for climate policy in the rest of the world. Finally, we present an illustrative application of our results to the US.

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I. Introduction

Natural gas is the fossil fuel that releases the least CO2 when burned. Now more than ever, it is hoped that a large replacement of very carbon intensive fuels by shale gas can help reduce carbon emissions and, therefore, significantly mitigate a climate problem labeled "the ultimate commons problem of the twenty-first century" (Stavins, 2011). For example, an increasing number of top CO2 emitting countries that are endowed with substantial shale gas deposits plan to meet their emission reduction commitments by promoting this resource; among them, the US, Russia, China, the UK and, more recently, Japan. This substitution is mostly manifest in the power generation sector in which electricity can be economically produced from both steam coal and natural gas. In a sufficiently long-run perspective, over which the appropriate infrastructure can be built, gas can virtually replace coal and other traditional fuels for all uses.

The hope that shale gas can play a major role in national climate policy strategies has been substantiated by academic experts—e.g., the MIT report of Jacoby, O'Sullivan, and Paltsev (2011). Not surprisingly, this option is also supported by the industry, which is an evident implementation advantage over traditional climate mitigation strategies.[1]

However, two important aspects of the rise of shale gas have raised serious questions about its climate impact. The first—and most obvious—one concerns the net relative contribution of gas to global warming, once the leakage of methane at the production level is taken into account. This first aspect has been addressed in the field of natural sciences and raises specific regulatory challenges.[2] Although our results will connect with the relative climate impact of gas,[3] our analysis deals more directly with the second concerning aspect of the rise of gas: international coal leakage. For example, according

[1]BP, BG Group, Eni, Statoil and Total recently declared in a joint letter to media (June 1, 2015): "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."

[2]For a synthetic review on this aspect and on the perspective of regulating the leakage of methane due to fracking, see, for example, https://www.scientificamerican.com/article/epa-will-regulate-methane-emissions-from-oil-and-gas-wells/.

[3]Our application will consider the absence of scientific consensus around this parameter.

to Light, Kolstad, and Rutherford (1999), the international competitive market for coal implies a particularly high leakage potential. By contrast, the transport of gas—in particular, its shipment—is highly more challenging, which explains that gas is still virtually all consumed where it is produced. As a consequence, the domestic replacement of coal by shale gas releases amounts of tradable coal, whose supply meets the foreign energy demand, and, therefore, contributes to increase emissions in the rest of the world. For example, the empirical evidence reported in Section II suggests a relationship between the recent boom of shale gas, the reduction in US CO2 emissions, and the peak in US coal exports. See also the recent projections by Chakravorty, Fischer, and Hubert (2015) on the development of shale gas in China.

There are two main reasons why this problem deserves a particular attention in the context of the current energy landscape. First, in the aftermath of the Paris Climate Agreement, governments will have to rely on unilateral initiatives to meet their respective emission reduction commitments. Indeed, in the light of both the agreement and the preceding COP21 talks, the project of penalizing carbon at the global level in a coordinated manner seems unrealistic.

The second reason motivates our research more specifically: It is that the rise of gas as an intermediate (less carbon containing) energy source fundamentally modifies the analysis of unilateral climate policy. Indeed, with more than one carbon energy source, our results highlight that a large country's unilateral emission reduction may ultimately increase global carbon emissions if it is achieved by promoting an intermediate source of energy like gas. This theoretical possibility sharply differs from the standard analysis with a single source of carbon, which predicts that leakage cannot exceed 100%. The difference may be explained as follows. With a single source of carbon, any carbon penalty—be it unilateral—causes its total supply to contract; leakage, in that case, reallocates the consumption of a smaller total carbon quantity. With multiple carbon-generating energy sources, things are not so simple: A unilateral carbon penalty not only reduces the total production of the most polluting sources, it may also boost—under some condition that we establish—the domestic production of intermediate sources like gas to replace the domestic consumption of the former. This boost—under another condition that we establish—may be of such an extent that it compensate, at the global level, the carbon reduction due to the global contraction in the most polluting sources; in this case, the total quantity of carbon is increased and, therefore, carbon leakage from the carbon reducing economy is augmented to more than 100% by this economy's exports of the most carbon intensive energy sources.

To our knowledge, however, there exists no analysis of unilateral emission reduction policies with more than one carbon energy source addressing the possibility that such policies turn counter-productive due to carbon leakage. This is so despite the fact that the large replacement of coal by gas is a relevant option in several top-emitting regions.

To analyze this new situation, we examine a highly stylized open economy, purposely considering the minimal set of ingredients involved. There are two regions: the home country and the rest of the world. The home country relies on two substitutable carbon energy inputs: coal—more carbon intensive—and gas—less so. By contrast, the rest of the world cannot use the home country's gas, but may trade coal with the latter. In each region, there is a single representative energy consumer and a single firm representative of the sector supplying carbon energies; their demands and supplies depend on prices only. The model features policy-induced leakage of carbon emissions; this leakage results from both changes in the production of carbon energy inputs, and the reallocation of their consumption from one region to another.[4] In this setup, we address the question whether the domestic rise of gas can help reduce domestic and global CO2 emissions, and how this rise affects foreign regions' ability to meet their own carbon emission commitments. Our analysis rests on a simple static representation of the energy market, in the spirit,

[4]That is, our analysis does not rely on other forms of carbon leakage. In principle, the supply and demand functions of representative producers and consumers can be interpreted as reflecting various economic decisions (including relocation) by a continuum of individual agents, each ultimately choosing whether to consume or produce an infinitesimal quantity in each region. That being said, our model would need to be modified to represent in a more realistic fashion leakage induced by agents' decisions to relocate their activity.

for example, of Hoel (1994) and Harstad (2012). Accordingly, in Section VI, we explain how our results carry over to more complex—also dynamic—environments, stressing the following aspects that, although not central to the theory, deserve attention: (*ı*) technical progress in the production of gas, (*ıı*) carbon resources' scarcity and their dynamic exploitation, (*ııı*) the development of non-carbon energy sources, and (*ıv*) the international trade of gas.

This paper lies at the intersection of mainly two strands of literature. On the one hand, it is complementary with recent papers on the leakage effect that limits the effectiveness of unilateral climate policies—see, among other important contributions, Eichner and Pethig (2011), and Ritter and Schopf (2014). In general, leakage only limits, but does not more than compensate, the effect of the unilateral policy. Indeed, the above studies have focused on the simplifying case in which there is a single polluting energy source. We extend this literature to the case of more than one polluting source, which gives rise to the possibility that leakage exceed 100%, so that a unilateral well-intentioned policy may turn counter-productive. Such a possibility can be interpreted as the leakage counterpart of the "green paradox" (Sinn, 2008).

On the other hand, this article is complementary with the resource economics literature that has dealt with the coexistence of several polluting energy sources—see, among other papers, Chakravorty, Moreaux, and Tidball (2008), Henriet and Schubert (2015), and Coulomb and Henriet (2017), which examine closed economy situations, as when policies are implemented at the world level. We extend this literature to the case in which an open economy implements a climate policy unilaterally.

At the intersection of these two strands of literature, Golombek, Hagem, and Hoel (1995), and Fischer and Salant (2017), for example, study unilateral climate policies in presence of various carbon energy sources. The possibility that, in that context, leakage exceed 100% and policies turn counter-productive, however, has remained overlooked; our paper fills the gap.

The rest of the article is structured as follows. In Section II, we discuss an important example: the US climate strategy, the rise of shale gas, and the concomitant peak in US coal exports. Section III presents our model. First, Section IV examines the relationship between a unilateral CO2 reduction commitment and the increase in gas production. Second, it assesses the effect of more gas on world CO2 emissions. Third, it draws implications for the adjustment of climate policy in the rest of the world. The analysis yields testable conditions establishing in which contexts the promotion of natural gas is justified from the perspective of an individual country's emissions objective and from a global perspective, and the extent to which this promotion undermines the rest of the world's efforts to meet its own CO2 emission commitment. In Section V, we illustrate our previously obtained formulas with a numerical application to the case of the US. In Section VI, we discuss a few aspects that, although relevant empirically, are not central to—and, thus, purposely omitted from—our theory.

II. An Important Example: The US Climate Strategy, the Shale Gas Boom, and the Peak of US Coal Exports

The issue addressed in this paper is particularly well illustrated by recent developments in both the US energy sector and the US climate policy project: namely, the rise of shale gas, the US climate policy plan to rely on gas supply, the replacement of coal by gas in the US power sector, and the recent peak of US coal exports. These developments, because of their magnitude, are likely to have an impact on the world energy policy landscape. Indeed, the US is the second biggest carbon emitting economy. It is also the most important gas producer, the second biggest coal producer and coal consumer, and, last but not least, the top coal reserve holder.

Since 2011, the US CO2 emissions have been regulated by the EPA under the Clean Air Act Federal law. As a matter of fact, the ratification of the Paris Climate Agreement by President Obama commits—at least for the next four years—the US Federal Government to a $26-28\%$ reduction in CO2 emissions by 2025 with respect to their 2005 level. To meet this commitment, the previous US Administration's plan has been to rely on the rapid development of gas production—which was already manifest in the aftermath of the early 2000s' "fracking" revolution—and to support this development. For example, in his June 25, 2013 Speech on Climate Change, President Obama put things this way:

> My administration pledged to reduce America's greenhouse gas emissions . . . And today, we produce more natural gas than anybody else. So we are producing energy. And these advances have grown our economy, they have created new jobs, they can't be shipped overseas—and, by the way, they have also helped drive our carbon pollution to its lowest levels in nearly twenty years. Since 2006, no country on Earth has reduced its total carbon pollution by as much as the US . . . In fact, many power companies have already begun modernizing their plants, and creating new jobs in the process. Others have shifted to burning cleaner natural gas instead of dirtier fuel sources . . . Today, we use more clean energy . . . which is supporting hundreds of thousands of good jobs. We waste less energy, which saves you money at the pump and in your pocketbooks. And guess what—our economy is 60% bigger than it was twenty years ago, while our carbon emissions are roughly back to where they were twenty years ago.

Two years after this statement, the US policy project of replacing the steam coal input by natural gas in the US power generation sector was strengthened by the proposal of the Clean Power Plan to command this transition.[5]

Although the rise of gas became reality already before the regulation of the US CO2 emissions, the latter has explicitly supported the former. In any case, Figure 1 shows that the replacement of coal by gas has been effective for the past few years, and that this movement has gone hand in hand with the development of gas. It also indicates that the policy promotion of gas has accelerated this transition in recent years.[6]

Given the large CO2 impact of the US power sector, this coal-gas substitution has

[5] Officially, the enforcement of the plan has been temporarily halted by the Supreme Court. Meanwhile, in practice, an increasing number of States—including Republican-held ones—are taking initiatives

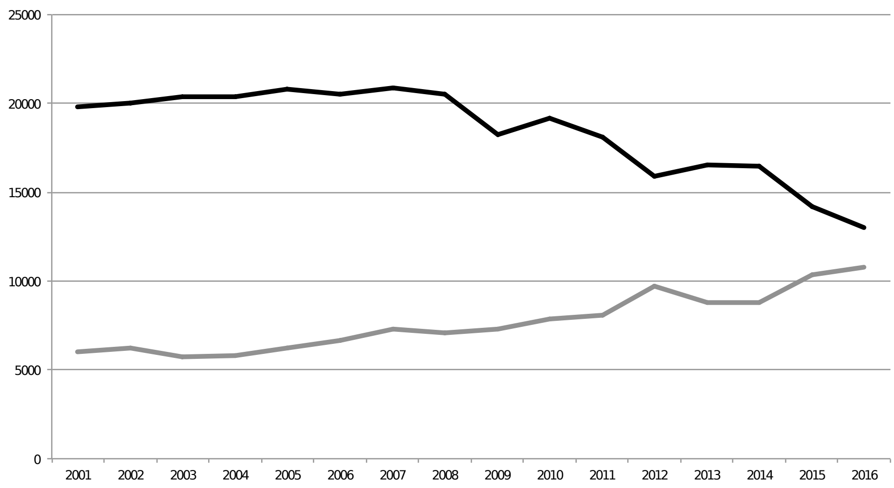

Figure 1: Consumption of coal—black curve—and gas—grey curve—by the US power generation sector in million MMBtu (Source: US Energy Information Administration)

indeed contributed—of course, among other factors—to the reduction of the US CO2 emissions (Feng, Davis, Sun, and Hubacek, 2015, and Kotchen and Mansur, 2016). For example, Figure 2 shows the fall in CO2 emissions generated by energy consumption in the US.

As President Obama emphasized in his 2015 speech, the economic success surrounding the gas boom has entailed domestic benefits, despite the reduction in CO2 emissions that it has induced. However, the gas boom and, then, its policy promotion, caused—again, among other factors[7]—large amounts of coal to be released that ultimately met the foreign demand for cheap energy. Figure 3 shows the peak in net US coal exports that has been concomitant with the replacement of coal by gas in the US power sector.

The above developments are likely to persist under the recently elected US Administration. First, despite President Trump's plan that the US not be party any longer to the Paris agreement after 2020—and irrespective of the ultimate decision of the next US

so as to meet the plan's requirements.

[6]Figure 1 shows yearly consumption. Gas use has notoriously overtaken coal in the US power generation sector for some months in 2015 for the first time in history. See, for example, `http://www.nytimes.com/2015/07/14/business/natural-gas-overtakes-coal-in-us-electric-generation.html`.

[7]For example, in 2011, massive flooding in Australia prevented Australian coal to be delivered to China, which was compensated by US coal. Besides, the US coal exports in the past few years have served less distant markets, in South America and Europe.

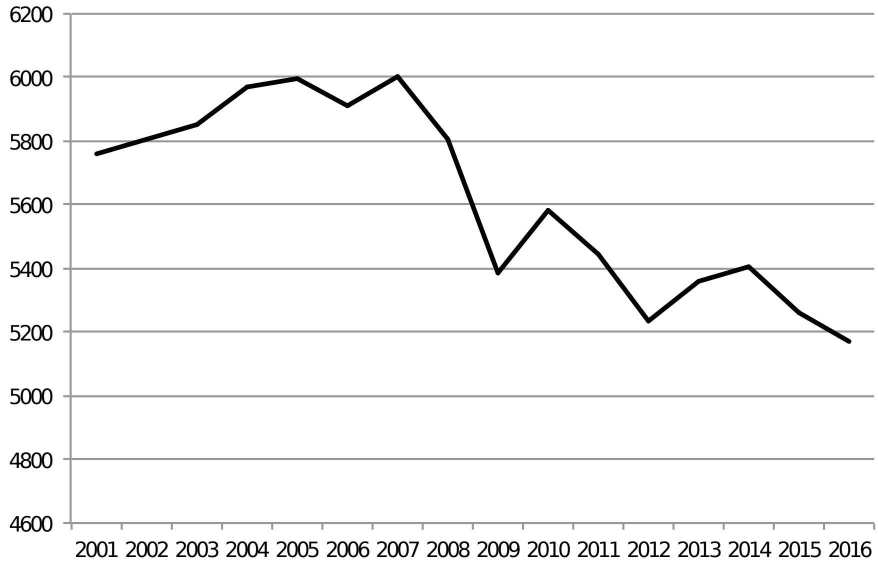

Figure 2: CO2 emissions (million metric tons) from energy consumption in the US (Source: US Energy Information Administration)

Administration on this matter—the pressure towards a decrease in US CO2 emissions is likely to be continued by the public actions of US states and by the self-regulation of companies—see, for example, *The Economist*, June 5, 2017. Second, the rise of natural gas will continue to be publicly supported, as confirmed by President Trump on June 29, 2017, thus accompanying the decreasing trend in US CO2 emissions.

Third, and most importantly, US coal exports are likely to continue increasing. On the one hand, according to specialists, the ongoing replacement of coal by gas will generate a potential for US coal exports to keep rising in the future.[8] The realization of this potential has been limited, under the Obama Administration, by the successful opposition of environmental groups to the building of new coal-export terminals needed to meet the growing coal demand in Asia.[9] However, as the newly elected US Administration notoriously supports the coal industry, it is to be anticipated that these projects will

[8]See, for example, a summary of Wolak's simulations at `http://news.stanford.edu/news/2013/january/coal-asia-environment-011513.html`. See, moreover, the most recent EIA short-run projections at `https://www.eia.gov/outlooks/steo/report/coal.cfm`.

[9]See, for example, `https://www.bloomberg.com/news/articles/2014-11-21/gulf-coast-embraces-u-s-coal-shippers-rejected-by-west-freight`.

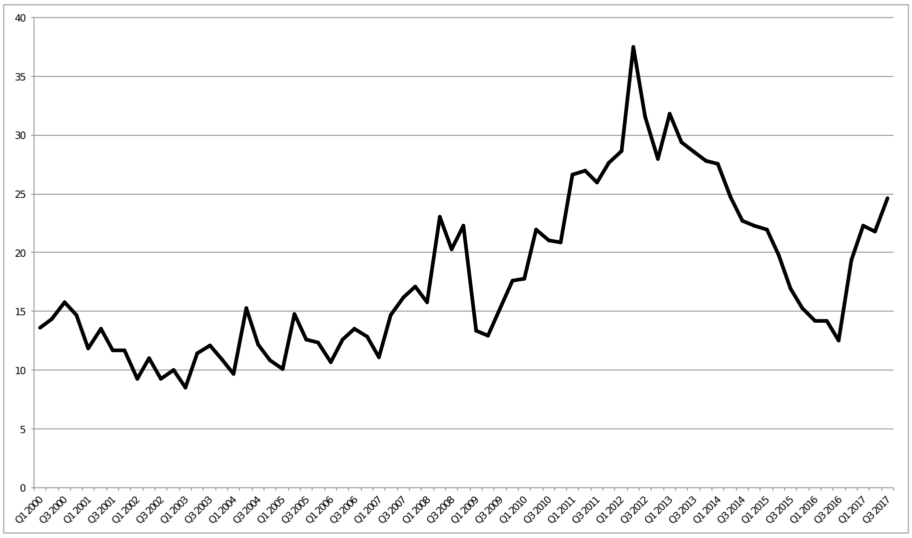

Figure 3: Net exports of coal (short tons) from the US to the rest of the world (Source: US Energy Information Administration)

receive a more favorable regulatory treatment. On the other hand, the rise in US coal exports has become an objective in itself of the Trump Administration. For example, in his recent speech at the "Unleashing American Energy Event" on June 29, 2017, President Trump made the following announcement:

> The Department of the Treasury will address barriers to the financing of highly efficient, overseas coal energy plants. Ukraine already tells us they need millions and millions of metric tons right now. There are many other places that need it, too. And we want to sell it to them, and to everyone else all over the globe who need it.

The perspective of rising US coal exports has caused growing concerns both in the academic sphere—e.g., Meredith Fowlie's contribution to the blog of the Energy Institute at Haas, Berkeley,[10] and Knittel, Metaxoglou, and Trindade (2016)—and in the NGO sector, and will continue to do so under the current US administration. This paper seeks to substantiate these concerns. Indeed, existing studies about the coal-gas policy-induced

[10] Available at `https://energyathaas.wordpress.com/2014/07/28/will-coal-exports-abroad-offset-hard-won-carbon-reductions-at-home/`.

substitution have mostly focused on the changes within the US economy—e.g., Burtraw et al. (2014), Knittel, Metaxoglou, and Trindade (2015), and Cullen and Mansur (2017). A recent interesting addition to this literature is due to Wolak (2016) who presents simulations relating the coal-gas substitution in the US and the global coal market, assuming a zero price-elasticity of the foreign demand for coal. According to very recent elasticity estimations for coal exports and imports by Knittel, Metaxoglou, Soderbery, and Trindade (2017), the latter assumption is justified in a short-term perspective. Accordingly, both studies imply that US coal exports do not contribute to increase the rest of the world's CO2 emissions in the short run.

There exists no theoretical analysis that integrates the US policy objective of reducing domestic CO2 emissions, the coal-gas substitution that this objective induces, and the resulting change in coal exports. Therefore, our paper is complementary with Wolak (2016) and Knittel et al. (2017) because it brings up new theoretical insights as to the logic—at work in their studies—of policy-induced CO2 leakage in presence of more than one carbon energy source. Compared with these papers, we adopt a longer-run perspective and, accordingly, we do away with the assumption that the foreign demand for coal is perfectly price inelastic—see, for example, Burke and Liao (2015) for recent medium-run empirical estimates. In that context, our results indicate—and our application illustrates—that the medium-run leakage induced by the US climate policy may exceed a rate of 100%, unlike the standard logic. Our theory, therefore, points out that the zero coal-demand elasticity assumption is critical, requiring that a relevant policy prescription regarding the policy support to the development of gas in the US be examined in a longer-run perspective over which the foreign demand for coal effectively responds to energy prices.

III. A Simple Model of an Open Economy Using Coal and Gas

A. Basics

Regions. There are two regions. The domestic open economy of interest will be called "Home," and variables related to this country will accordingly be denoted by the superscript "H." The rest of the world will be treated as a single open economy which will be called "Foreign," and variables related to it will be denoted by the superscript "F."

Coal supply. In each of the two regions, there is a price-taking representative firm supplying coal. Coal being tradable across regions, competitive markets will establish a single international coal price p_c. The Home and Foreign coal supplying firms respectively produce amounts s_c^H and s_c^F—expressed in energy units—which are determined by the following supply functions of the coal price p_c:

$$s_c^H = S_c^H(p_c)$$

and

$$s_c^F = S_c^F(p_c),$$

which are both assumed non negative, differentiable and strictly increasing for all $p_c \geq 0$.

Gas supply. For simplicity, gas is only produced in the Home country by a price-taking representative firm, which does not export it.[11] Its production s_g^H—expressed in energy units—is given by the supply function of the domestic price of gas p_g

$$s_g^H = S_g^H(p_g),$$

which is assumed non negative, differentiable and strictly increasing for all $p_g \geq 0$.

Energy demand by the Foreign country. For simplicity, the rest of the world does only rely on the coal energy source:[12] There is a price-taking representative consumer of

[11] In Section VI, we explain how the analysis accommodates the possibility that gas be exported.

[12] The foreign coal demand function D^F may be interpreted as a residual demand after other locally produced non-carbon energy sources have been consumed, with no implications on our analysis. As far as the presence of gas in the Foreign country is concerned, see the discussion of Subsection VI.C—with technical details in the Appendix—highlighting that the analysis' extension to foreign gas leads to similar qualitative conclusions.

electric energy in the Foreign country, and electricity is solely produced from coal through a linear technology which, in energy units, is "one-for-one." Therefore, the Foreign country's coal consumption x_c^F is determined by the energy demand function

$$x_c^F = D^F(p_c),$$

which is assumed non negative, differentiable and strictly decreasing for all $p_c \geq 0$.

Energy demand by the Home country. The domestic economy relies on both coal and gas: There is a competitive representative consumer of electric energy in the Home country, and electricity can be produced equivalently from coal or gas through a one-for-one energy transformation technology. Since coal and gas are perfectly substitutable, competitive markets will establish a single final energy price, irrespective of the source of energy. We will denote this final price by p. Therefore, the Home country's consumption x^H of coal and gas is determined by the energy demand function

$$x^H = D^H(p),$$

which is assumed non negative, continuous and strictly decreasing for all $p \geq 0$.[13] The domestic consumption x^H corresponds to the consumption of the domestically produced gas s_g^H and a residual consumption of coal x_c^H:

$$x^H = x_c^H + s_g^H.$$

B. *Laissez-Faire Equilibrium*

By assumption, the energy market is competitive. In this subsection, we assume away any policy intervention. Public policy will be introduced in the next section.

As will be clear shortly below, our analysis will focus on the empirically relevant equilibria in which the Home economy produces electricity from coal and gas at the same time. Since the latter are assumed perfectly substitutable, such interior equilibria are

[13]This demand function may be interpreted as the residual energy demand after other—e.g., alternative—energies have been used.

characterized by the following no-arbitrage equality,[14] relating the equilibrium domestic final energy price to the equilibrium domestic producer prices of coal and gas:

$$\tilde{p} = \tilde{p}_c = \tilde{p}_g; \tag{1}$$

a "~" on top of a variable or function will be used to indicate that this variable or function is evaluated at the market equilibrium.

In this context, the equilibrium price $\tilde{p}$ is characterized by the balance between energy demand and supply at the world level:

$$D^H(\tilde{p}) + D^F(\tilde{p}) = S_c^H(\tilde{p}) + S_c^F(\tilde{p}) + S_g^H(\tilde{p}), \tag{2}$$

where we assume that $D^H(0)+D^F(0) > S_c^H(0)+S_c^F(0)+S_g^H(0)$ and $\lim_{p \mapsto +\infty} \left[D^H(p) + D^F(p)\right] < \lim_{p \mapsto +\infty} \left[S_c^H(p) + S_c^F(p) + S_g^H(p)\right]$, so as to eliminate the uninteresting situation in which there exists no equilibrium with non-zero energy consumption. Since the left-hand side and right-hand side of (2) are respectively strictly decreasing and increasing, $\tilde{p} > 0$ is uniquely defined.

The equilibrium condition (2) may be written in the following way, highlighting the equality between the (residual) demand for coal by the Home country, on the left-hand side, and the world coal supply net of the rest of the world's demand, on the right-hand side:

$$D^H(\tilde{p}) - S_g^H(\tilde{p}) = S_c^H(\tilde{p}) + S_c^F(\tilde{p}) - D^F(\tilde{p}). \tag{3}$$

We make the following assumption:

$$D^H(\tilde{p}) > S_g^H(\tilde{p}) > 0, \tag{4}$$

[14] In practice, coal and gas inputs are not perfectly substitutable at the plant level because power plants are typically fuel specific. Instead, they are substitutable at the industry level in a sufficiently-long-term perspective that allows the building of new coal- and gas-fired power plants. That is why, despite the fact that the US power generation sector has been investing in new coal- and gas-fired plants simultaneously in the past few years, the equality between the price of coal and the price of gas for an equivalent amount of power was not exactly observed. It is important to note, nevertheless, that the respective costs of using these two fuels have been rapidly converging since 2005, whether or not other operating expenses are integrated—see, e.g., http://www.eia.gov/electricity/annual/html/epa_08_04.html. This convergence reflects that the short-run arbitrage between the two substitutable energies tends to vanish in the long run.

which implies that there exists a non-zero residual demand $D^H(\tilde{p}) - S_g^H(\tilde{p}) > 0$ for coal in the Home country in the equilibrium. Assumption (4) formally validates our earlier-mentioned focus on situations in which coal and gas are used simultaneously in the Home country.

The equilibrium price of energy $\tilde{p}$ defined by (2) determines all other variables: domestic gas production $\tilde{s}_g^H = S_g^H(\tilde{p})$; domestic and foreign coal production $\tilde{s}_c^H = S_c^H(\tilde{p})$ and $\tilde{s}_c^F = S_c^F(\tilde{p})$; domestic electricity consumption from coal and gas $\tilde{x}^H = D^H(\tilde{p})$, and, therefore, domestic coal consumption $\tilde{x}_c^H = \tilde{x}^H - \tilde{s}_g^H$; rest-of-the-world coal consumption $\tilde{x}_c^F = D^F(\tilde{p})$.

It follows that the equilibrium also determines the Home country's *net* exports of coal, on the left-hand side, which meet the Foreign country's net imports, on the right-hand side:

$$\tilde{s}_c^H - \left(\tilde{x}^H - \tilde{s}_g^H\right) = \tilde{s}_c^F - \tilde{x}_c^F; \tag{5}$$

net exports may be positive or negative—that is, the Home country may be a net exporter or importer of coal—with no consequence on our results.

IV. Domestic CO2 Reduction and Gas Promotion

In this section, we examine a policy aiming to reduce the CO2 emissions that are generated by the use of coal and gas in the Home country.

A. CO2 Emissions

We assume that, per unit of energy, coal consumption and gas consumption generate respectively θ_c and θ_g units of CO2. We further assume that coal is more CO2 intensive than gas:

$$\theta_c \geq \theta_g > 0.$$

Therefore, domestic CO2 emissions amount to

$$e^H = \theta_c x_c^H + \theta_g s_g^H. \tag{6}$$

B. *Domestic CO2 Commitment and Implementation*

Assume now that the Home country is committed to limit its CO2 emissions e^H, so that it remains below the exogenous cap $\bar{e}^H$:

$$\theta_c x_c^H + \theta_g s_g^H \leq \bar{e}^H. \tag{7}$$

However this commitment is implemented, it necessarily translates into a penalty for using CO2 that augments the market price of coal and gas, whether this penalty is explicit or implicit.[15] Consider, for simplicity, that this penalty is explicit: For example, (7) is implemented by a carbon tax or by a competitive market for emission rights, giving rise, in either case, to an explicit CO2 price, which we denote by the variable $\tau^H \geq 0$. In equilibrium, this variable is endogenously determined in such a way that the emission commitment is met. If the implementation system is a carbon tax, the domestic government establishes the tax level $\tilde{\tau}^H$ so that (7) is satisfied. If there is a tradable permit system, $\tilde{\tau}^H$ is the equilibrium price of a right to emit one CO2 unit out of the quota $\bar{e}^H$. Obviously, if the cap $\bar{e}^H$ is soft in the sense that it exceeds the equilibrium emissions $\theta_c \tilde{x}_c^H + \theta_g \tilde{s}_g^H$ realized in absence of policy, as described in the previous section, then $\tilde{\tau}^H = 0$, and the analysis of the previous section applies; otherwise, the cap is strong, constraint (7) will be active and $\tilde{\tau}^H > 0$.

In turn, the CO2 price τ^H amounts to varying taxes on coal and gas, proportional to their CO2 intensity. That is, under the commitment (7), the additional unit cost of using coal is $\theta_c \tau^H$ and the additional unit cost of using gas is $\theta_g \tau^H$. Therefore, the user prices of coal and gas in the Home country become respectively $p_c + \theta_c \tau^H$ and $p_g + \theta_g \tau^H$ and the no-arbitrage condition (1) which must prevail in equilibrium should be adjusted as follows:

$$\tilde{p} = \tilde{p}_c + \theta_c \tilde{\tau}^H = \tilde{p}_g + \theta_g \tilde{\tau}^H. \tag{8}$$

This condition relates the equilibrium producer prices for coal $\tilde{p}_c$ and gas $\tilde{p}_g$ to the

[15] In practice, for example in the US, regulatory standards are often used, imposing tighter constraints to the biggest sources of CO2 emissions.

equilibrium domestic price for energy $\tilde{p}$ and the equilibrium domestic price of CO2, $\tilde{\tau}^H$. Therefore, the former producer prices are given by

$$\tilde{p}_c = \tilde{p} - \theta_c \tilde{\tau}^H \tag{9}$$

and

$$\tilde{p}_g = \tilde{p} - \theta_g \tilde{\tau}^H. \tag{10}$$

Like in Section III, equilibrium prices must balance supply and demand on the world energy market; using expressions (9) and (10), the equilibrium condition (2) becomes

$$D^H(\tilde{p}) + D^F(\tilde{p} - \theta_c \tilde{\tau}^H) = S_c^H(\tilde{p} - \theta_c \tilde{\tau}^H) + S_c^F(\tilde{p} - \theta_c \tilde{\tau}^H) + S_g^H(\tilde{p} - \theta_g \tilde{\tau}^H). \tag{11}$$

Equilibrium prices must further satisfy the commitment (7):

$$\theta_c \left[D^H(\tilde{p}) - S_g^H(\tilde{p} - \theta_g \tilde{\tau}^H) \right] + \theta_g S_g^H(\tilde{p} - \theta_g \tilde{\tau}^H) = \bar{e}^H, \tag{12}$$

which is considered binding to avoid the uninteresting case in which the domestic cap is soft and leaves the laissez-faire equilibrium unaffected.

We make the two following assumptions, which justify our focus on a binding commitment (12). First, the emission cap $\bar{e}^H$ falls short of the level of emissions generated by the laissez-faire equilibrium of the previous section. Second, $\lim_{p \mapsto +\infty} \left[\theta_c D^H(p) - (\theta_c - \theta_g) S_g^H(p) \right] < \bar{e}^H$, which means that sufficiently high energy prices can reduce domestic emissions to the $\bar{e}^H$ limit.

Appendix A shows the following property.

Proposition 1 (Existence and uniqueness of the equilibrium) *Under our assumptions, the system (11)-(12) has a unique solution $(\tilde{p}, \tilde{\tau}^H)$, which determines producer prices $\tilde{p}_c$ and $\tilde{p}_g$ by (9) and (10), and, therefore, all equilibrium quantities.*

In particular, the equilibrium domestic gas production

$$\tilde{s}_g^H = S_g^H(\tilde{p}_g) = S_g^H(\tilde{p} - \theta_g \tilde{\tau}^H)$$

will be examined in the next subsection.

C. Effect of Domestic CO2 Reduction on Domestic Gas Production

We now turn to the effects of a reduction in the domestic CO2 cap $\bar{e}^H$. In this subsection, we focus on the reaction of the domestic production of gas; the effect on world CO2 emissions will be examined thereafter.

For simplicity, we consider an infinitesimal change $d\bar{e}^H < 0$, starting from the equilibrium level of emissions $\theta_c \tilde{x}_c^H + \theta_g \tilde{s}_g^H$ in absence of emission commitment, as in the previous section. That means that, by assumption, prior to the change in $\bar{e}^H$, the constraint (7) is not active so that $\tilde{\tau}^H = 0$ and the equilibrium is the one characterized in Section III.

Intuition suggests—and Appendix B confirms—that the change $d\bar{e}^H < 0$ causes $\tilde{\tau}^H$ to become strictly positive, thus introducing penalties on both coal and gas used in the Home country. Accordingly, the domestic final price of energy $\tilde{p}$ increases, so that domestic energy consumption $\tilde{x}^H$ decreases, as expected.

According to (9) and (10), it follows that the producer prices $\tilde{p}_c$ and $\tilde{p}_g$ for coal and gas are each affected in two opposite directions: On the one hand, they are pushed upwards by the rise in the final energy price $\tilde{p}$, and, on the other hand, they are impacted negatively by the increase in the carbon penalty $\tilde{\tau}^H$, to the extent of their respective CO2 intensities $\theta_c \geq \theta_g$. As far as coal is concerned, Appendix B verifies that the reduction in the domestic emission cap systematically induces the producer price $\tilde{p}_c$ to decrease, thus reducing coal production $\tilde{s}_c^H$; this intuitive reaction is the same as in standard models with a single polluting energy.

As far as gas is concerned, things are not so simple. Gas is polluting, but less so than coal. For such an intermediate energy, the rise in the final energy price $\tilde{p}$ may more than compensate the increase in the carbon penalty $\tilde{\tau}^H$, so that the producer price of gas $\tilde{p}_g = \tilde{p} - \theta_g \tilde{\tau}^H$ and, therefore, domestic gas production $\tilde{s}_g^H = S_g(\tilde{p}_g)$, may increase as a result of the emission cap reduction $d\bar{e}^H < 0$.

In Appendix B, the analysis of the total differentiation of (11)-(12) with respect to $\bar{e}^H$, $\tilde{\tau}^H$ and $\tilde{p}$ shows the following result.[16]

[16] Were the production of gas increased exogenously—perhaps due to technical progress as, for example,

Proposition 2 (Effect of domestic CO2 reduction on gas production) *A reduction of CO2 emissions in the Home country warrants a higher production of gas if and only if*

$$\frac{\theta_c - \theta_g}{\theta_g} > \tilde{r}_0 \equiv \frac{\tilde{\xi}_{D^H}}{\frac{\tilde{x}_c^F}{\tilde{x}^H}\tilde{\xi}_{D^F} + \frac{\tilde{s}_c}{\tilde{x}^H}\tilde{\xi}_{S_c}}. \tag{13}$$

We have used the following notations: $\xi_{D^H} \equiv -D^{H\prime}(p)p/x^H > 0$ is the price elasticity of the domestic energy demand, $\xi_{D^F} \equiv -D^{F\prime}(p_c)p_c/x^F > 0$, the price elasticity of coal demand in the rest of the world, and $\xi_{S_c} \equiv S_c'(p_c)p_c/s_c > 0$ the price elasticity of the world coal supply, where $s_c = S_c(p_c) \equiv S_c^H(p_c) + S_c^F(p_c)$ is the world supply of coal.

Proposition 2 provides a testable condition according to which the reduction of domestic emissions in a gas-producing country justifies that more gas be produced. This condition relates, on the one hand, the rate of increase in pollution $(\theta_c - \theta_g)/\theta_g \geq 0$ from gas to coal with, on the other hand, demand and supply price elasticities and market shares evaluated in equilibrium.

For any observed elasticities and market shares, the proposition tells that more gas should be produced when coal is sufficiently more CO2 intensive than gas. For example, in the limit case in which gas would tend to be CO2 free ($\theta_g \mapsto 0$), the left-hand side of (13) would tend to be infinitely high, so that the condition would be systematically satisfied. Indeed, in the standard model in which only one of two perfectly substitutable energy sources is polluting, the reduction of pollution commands to increase the production of the non-carbon substitute. Also for example, if coal and gas were equally polluting ($\theta_c - \theta_g = 0$), the fact that the right-hand side of (13) is non negative implies that the condition would never be satisfied. Indeed, in this limit case, there would be a single homogeneously polluting energy source with no substitute, requiring that its production be reduced to decrease pollution.

However, for sensible values of CO2 intensities θ_c and θ_g, whether condition (13) is

during the US "fracking" revolution—the same condition (13) would indicate whether this rise would induce the Home country's CO2 emissions to increase or not. In other words, under condition (13), the Home economy's development of gas and its reduction of CO2 emissions go hand in hand, irrespective of whether the latter or the former is the cause of the change.

satisfied and, therefore, gas production should be increased depends on the properties of the emission-reducing open economy, which are reflected in the right-hand side $\tilde{r}_0$ of the condition. The analysis of this term indicates that relying on gas to reduce CO2 emissions is most likely to be justified if $\tilde{x}^H$ is low, if $\tilde{x}_c^F$ and $\tilde{s}_c$ are high, and if $\tilde{\xi}_{S_c}$ is low, that is, for small energy-consuming open economies, in a world in which coal has a large market share, especially in the rest of the world, and in which the price of coal will have little impact on coal supply. Therefore, this formula may be satisfied for some gas-producing countries and not for others, implying different policy recommendations about the promotion of gas.

For example, in Section V, we will examine how Proposition 2 applies to the case of the US.

D. Effect of Domestic CO2 Reduction on Coal Exports and World Emissions

We now examine the impact of reducing the domestic CO2 cap $\bar{e}^H$ on world CO2 emissions. In our model, total CO2 emissions e^W not only consist of the domestic emissions e^H defined in (6), but also of emissions e^F released by the rest of the world:

$$e^W = e^H + e^F. \tag{14}$$

By assumption, the former are set to the binding limit $\tilde{e}^H = \bar{e}^H$ as per (7) and are, therefore, reduced accordingly. At the same time, the Foreign country's use of coal releases equilibrium CO2 emissions

$$\tilde{e}^F = \theta_c \tilde{x}_c^F, \tag{15}$$

where $\tilde{x}_c^F = D^F(\tilde{p}_c)$.

Were the foreign coal demand D^F perfectly price inelastic, as it might be in the short run, the rest of the world's CO2 emissions would never increase.[17] In a medium- to long-term perspective over which coal demand becomes elastic, however, emissions

[17] For example, this is the assumption that Wolak (2016) makes and that Knittel et al.'s (2017) short-run estimation supports.

$\tilde{e}^F$ are systematically increased as a result of the domestic CO2 reduction.[18] In this context, as mentioned above—and shown in Appendix A—the domestic CO2 reduction policy necessarily reduces the producer price $\tilde{p}_c$ of the most carbon intensive coal energy, inducing a rise in the equilibrium use of coal $\tilde{x}_c^F$ in the rest of the world. This is so despite the fact that the decreased coal producer price $\tilde{p}_c$ induces a reduction in coal production $\tilde{s}_c^H$ and $\tilde{s}_c^F$ in both regions. This is the effect highlighted by the standard leakage analysis focusing on a single carbon energy source. It follows that the net coal imports $\tilde{s}_c^F - \tilde{x}_c^F$ of the Foreign country, and, by (5), the net coal exports of the Home country in direction of the rest of the world, increase systematically as a result of the domestic CO2 emission reduction. This stresses the central role of the latter, identified in Section II in the case of the US.

Therefore, the policy-induced reduction in domestic CO2 emissions is, at least partly, compensated by the increase in emissions in the rest of the world due to increased domestic coal exports. In fact, our next result indicates that this compensation may more than offset the domestic CO2 reduction, ultimately causing world CO2 emissions to rise. In other words, unlike the standard leakage analysis with a single carbon energy source, the rate of CO2 leakage associated with the domestic CO2 reduction—see Appendix C for details—

$$\frac{d\tilde{e}^F}{-d\bar{e}^H} = \frac{\left[\frac{\tilde{\xi}_{D^H}\tilde{x}^H}{\tilde{\xi}_{S_g}\tilde{s}_g^H}\left(\frac{\theta_c-\theta_g}{\theta_g}+1\right)+\frac{\theta_c-\theta_g}{\theta_g}\right]\left(\frac{\theta_c-\theta_g}{\theta_g}+1\right)}{\frac{\tilde{\xi}_{D^H}\tilde{x}^H}{\tilde{\xi}_{D^F}\tilde{x}_c^F}+\left[\left(\frac{\theta_c-\theta_g}{\theta_g}\right)^2+\left(\frac{\theta_c-\theta_g}{\theta_g}+1\right)^2\frac{\tilde{\xi}_{D^H}\tilde{x}^H}{\tilde{\xi}_{S_g}\tilde{s}_g^H}\right]\left(\frac{\tilde{\xi}_{S_c}\tilde{s}_c}{\tilde{\xi}_{D^F}\tilde{x}_c^F}+1\right)} \tag{16}$$

may exceed 100%. Accordingly, in this subsection, we address the question of the effectiveness of the domestic unilateral CO2 reduction policy: Under which circumstances does this policy remain less than compensated by the concomitant increase in emissions in the rest of the world? In other words, under which circumstances does the emission

[18] Although coal demand in the Foreign country can be interpreted as the residual demand for coal after some other local energies have been used, our simplifying formulation implies that CO2 emissions from these other energies are omitted, as if they were all non-carbon energies. Taking into account the CO2 emissions generated by other carbon energies in the Foreign country would slightly modify the model, with no implications on our qualitative results.

leakage rate remain less than 100%?

In Appendix C, the analysis of the total differentiation of world emissions $\tilde{e}^W = \bar{e}^H + \tilde{e}^F$ and of the leakage rate (16) with respect to $\bar{e}^H$ shows the following result.

Proposition 3 (Leakage from domestic CO2 reduction and effect on world CO2) *A reduction of CO2 emissions in the Home country effectively contributes to reduce world CO2 emissions—i.e., the leakage rate is less than* 100%*—if and only if*

$$\frac{\theta_c - \theta_g}{\theta_g} < \frac{\tilde{\xi}_{D^H}}{\frac{\tilde{x}_c^F}{\tilde{x}^H}\tilde{\xi}_{D^F} + \frac{\tilde{s}_c}{\tilde{x}^H}\tilde{\xi}_{S_c}} \left[1 + \left(\frac{\theta_c - \theta_g}{\theta_g} + 1 \right) \tilde{\xi}_{S_c} \left(\frac{\frac{\theta_c - \theta_g}{\theta_g} + 1}{\frac{\tilde{s}_g^H}{\tilde{s}_c}\tilde{\xi}_{S_g}} + \frac{\frac{\theta_c - \theta_g}{\theta_g}}{\frac{\tilde{x}^H}{\tilde{s}_c}\tilde{\xi}_{D^H}} \right) \right]. \tag{17}$$

Proposition 3 provides a testable condition according to which the reduction of domestic emissions in a gas-producing country effectively contributes to reduce world emissions. Like (13), condition (17) relates, on the one hand, the rate of increase in pollution $(\theta_c - \theta_g)/\theta_g \geq 0$ from gas to coal with, on the other hand, demand and supply price elasticities and market shares.

Comparing (17) with (13), one can immediately see that their left-hand sides are identical, equal to the rate of increase in pollution from gas to coal. The comparison further reveals that the first fraction on their right-hand sides are similar, equal to $\tilde{r}_0$ as defined in (13). Moreover, by definition of the elasticity variables, the term between brackets on the right-hand side of (17) happens to be more than one—rather than equal to one in (13).

Condition (17), therefore, can only be violated if condition (13) is satisfied: It means that the domestic CO2 reduction policy may only be counter-productive—and the leakage rate be more than 100%—if it is accompanied by a development of gas as per Proposition 2.[19] In particular, in the extreme situation in which coal supply is perfectly inelastic, as when $\tilde{\xi}_{S_c} = 0$, the right-hand sides of (17) and (13) become identical to each other, so that the two conditions are complementary. In this example, obviously, a domestic CO2

[19]Following footnote 16, that means that an exogenous increase in gas production induces world CO2 emissions to decrease if condition (17) is satisfied and, vice versa, causes a rise in world CO2 emissions if (17) is violated.

reduction policy accompanied by a development of gas does not induce a reduction of coal use at all, thus systematically leading to a more-than-100% leakage rate. Otherwise, when the domestic CO_2 reduction justifies to limit both coal and gas use in the Home country, world emissions will never increase.

Everything else being held constant, the intervention of $\tilde{s}_g^H$ on the right-hand sides of (16) and (17) shows that as the price elasticity of gas becomes larger, the leakage rate increases, and the domestic CO_2 reduction policy is more likely to be counter-productive. For example, according to Newell, Prest, and Vissing (2016), the price responsiveness of shale gas production is three times larger than that of conventional forms of gas. Therefore, the possibility that a unilateral CO_2 reduction policy relying on gas be counter-productive is even more concerning when gas is produced from shale resources.

Besides, condition (17) cannot be merely interpreted as an inequality condition for the rate of pollution increase $(\theta_c - \theta_g)/\theta_g$ from gas to coal. Indeed, unlike condition (13), the rate $(\theta_c - \theta_g)/\theta_g$ is not only involved in the left-hand side of (17) but also in its right-hand side. For any observed equilibrium elasticities and market shares, for which values $(\theta_c - \theta_g)/\theta_g$ is inequality (17) satisfied, the leakage rate (16) less than 100%, and, therefore, the domestic CO_2 reduction policy effective? To start with, we examine the two limit cases. First, one can easily verify that if gas tended to be CO_2 free ($\theta_g \mapsto 0$), the right-hand side of (17) would tend to infinity more rapidly than its left-hand side. In this case, therefore, the condition would always be satisfied so that the domestic CO_2 reduction would always lead to less CO_2 at the world level, like in the standard model in which only one energy source is polluting. Second, if gas and coal were equally CO_2 intensive ($\theta_c - \theta_g = 0$), the left-hand side would be zero and would always be strictly less than the right-hand non-negative side. Therefore, in this case, the condition would also be systematically satisfied so that the domestic reduction policy would be effective, like in the standard model in which there is a homogenous carbon energy source.

For intermediate values of the rate of pollution increase from gas to coal, nevertheless, the domestic CO_2 reduction may be more than compensated by a more-than-100% leakage rate. More precisely, Appendix C shows that condition (17) is satisfied if and only if the function of $r = (\theta_c - \theta_g)/\theta_g$

$$P(r) = S_c'(\tilde{p}_c)\left(1 - \frac{D^{H\prime}(\tilde{p})}{S_g^{H\prime}(\tilde{p}_g)}\right) r^2 + \left(D^{F\prime}(\tilde{p}_c) - \frac{S_c'(\tilde{p}_c) D^{H\prime}(\tilde{p})}{S_g^{H\prime}(\tilde{p}_g)}\right) r - D^{H\prime}(\tilde{p})\left(1 + \frac{S_c'(\tilde{p}_c)}{S_g^{H\prime}(\tilde{p}_g)}\right) \tag{18}$$

is strictly positive. This function is a polynomial of degree two, which is represented by the U-shaped curve of Figure 4. Its analysis in Appendix C yields the following corollary of Proposition 3.

Corollary 1 (Counter-productive domestic CO2 reduction) *A reduction of CO2 emissions in the Home country induces a rise in world CO2 emissions—i.e., the leakage rate is more than* 100%—

1. *Only if*

$$\left(\frac{\tilde{x}_c^F}{\tilde{x}^H}\tilde{\xi}_{D^F}\right)^2 - 4\left(\frac{\tilde{s}_c}{\tilde{x}^H}\tilde{\xi}_{S_c} + \frac{\tilde{s}_g^H}{\tilde{x}^H}\tilde{\xi}_{S_g} + \frac{\tilde{x}^F}{\tilde{x}^H}\tilde{\xi}_{D^F} + \tilde{\xi}_{D^H}\right)\frac{\tilde{\xi}_{D^H}\tilde{\xi}_{S_c}}{\tilde{\xi}_{S_g}}\frac{\tilde{s}_c}{\tilde{s}_g} > 0, \tag{19}$$

   which guarantees that function $P(r)$ in (18) admits two real roots $\underline{\tilde{r}} < \tilde{\tilde{r}}$;

2. *And, provided that (19) is satisfied, if and only if,*

$$\underline{\tilde{r}} < \frac{\theta_c - \theta_g}{\theta_g} < \tilde{\tilde{r}}. \tag{20}$$

Corollary 1 helps summarize the conditions under which the domestic CO2 reduction policy happens to be counter-productive.

E. Summary

Assuming that condition (19) is satisfied, Corollary 1 tells that the domestic CO2 reduction policy turns out to be counter-productive when the rate of pollution increase from gas to coal $(\theta_c - \theta_g)/\theta_g$ takes intermediate values, in between the two thresholds $\underline{\tilde{r}}$ and $\tilde{\tilde{r}}$ represented in Figure 4. At the same time, the analysis of Proposition 3 already revealed that the domestic policy may only be counter-productive when the policy warrants the production of more gas, implying that $\tilde{r}_0 \leq \underline{\tilde{r}}$.

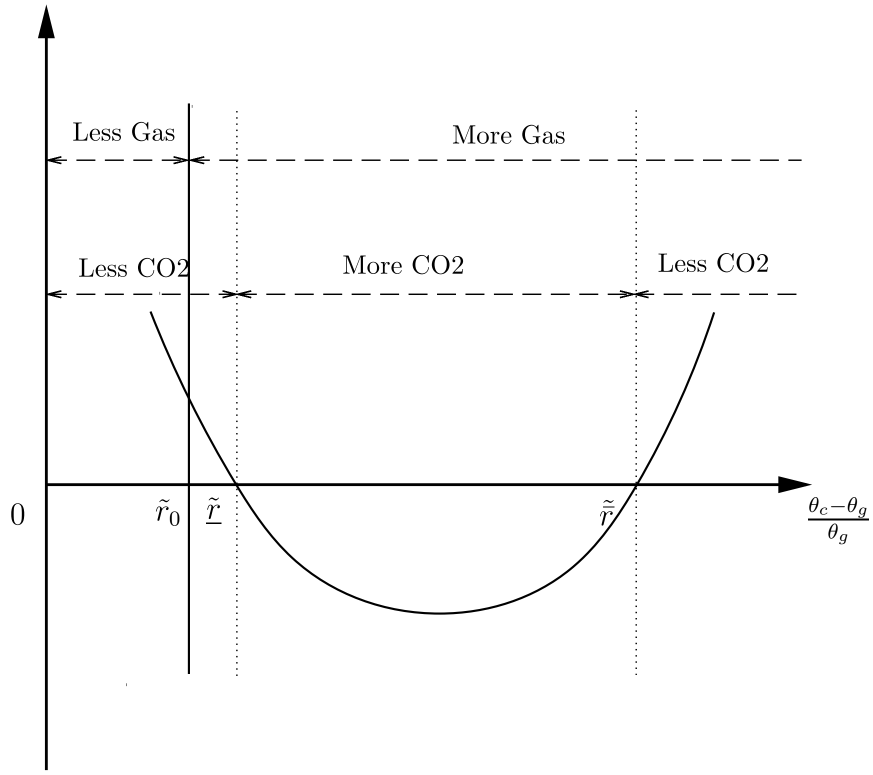

Figure 4: Domestic CO2 reduction policy, occurrence of gas boom and increase in world CO2 emissions

To sum up, for low values of the rate of pollution increase from gas to coal $(\theta_c-\theta_g)/\theta_g \leq \tilde{r}_0$, as when coal and gas are not so different as far their CO2 intensity is concerned, the domestic CO2 reduction objective does not call for a rise in gas production. For sufficiently high values $(\theta_c-\theta_g)/\theta_g > \tilde{r}_0$, as when gas is significantly less CO2 intensive than coal, the domestic CO2 reduction policy does warrant that more gas be produced. Despite the fact that the promotion of gas induces more coal to be exported from the Home country to the rest of the world, this does not necessarily mean that world emissions are increased. In fact, only for intermediate values of the rate pollution increase in the range $\tilde{r}_0 \leq \underline{\tilde{r}} < (\theta_c-\theta_g)/\theta_g < \tilde{\tilde{r}}$, if any, the domestic policy is counter-productive, inducing ultimately more CO2 emissions at the world level. For $\tilde{\tilde{r}} \leq (\theta_c-\theta_g)/\theta_g$, as when gas has a sufficiently low carbon intensity, the policy does command more gas to be produced and more coal to be exported, yet ultimately contributing to reduce world CO2 emissions.

Last but not least, these various possibilities do not only depend on the rate of pollution increase $(\theta_c - \theta_g)/\theta_g$, but also on the values of the thresholds $\tilde{r}_0$, $\underline{\tilde{r}}$ and $\tilde{\tilde{r}}$, which all reflect the observed equilibrium characteristics of the gas-rich Home country committed to reduce its CO2 emissions. This motivates, for example, the application of Section V to the case of the US.

F. CO2 Commitment and Implementation in the Rest of the World

We have hitherto considered that the rest of the world was not committed to any CO2 limitation when examining the domestic CO2 reduction policy. In that case, we have established the conditions under which this policy increases excessively the emissions of the Foreign country so that it may become counter-productive at the world level. In fact, in the aftermath of the Paris agreement, it is interesting to examine the case in which the rest of the world is also committed to a CO2 emission cap. That is what we do in this subsection: We assume that the Foreign country's CO2 emissions are limited to the exogenous level $\bar{e}^F$. With our simplifying assumption that the Foreign country only relies on the coal energy, that means

$$\theta_c \tilde{x}_c^F = \bar{e}^F. \tag{21}$$

In a way similar to the Home country, consider that this limitation is implemented by means of an explicit carbon price $\tilde{\tau}^F > 0$, whether it is a carbon tax or the price of carbon permits. It implies a carbon penalty $\theta_c \tau^F$ on the Foreign country's use of coal. Accordingly, the coal consumer price in the rest of the world should be adjusted to become, instead of $\tilde{p}_c = \tilde{p} - \theta_c \tilde{\tau}^H$ as per equation (9),

$$\tilde{p}_c = \tilde{p} - \theta_c \tilde{\tau}^H + \theta_c \tilde{\tau}^F, \tag{22}$$

where, following our previous formulation, $\tilde{p} - \theta_c \tilde{\tau}^H$ remains the international price of the coal energy. Consequently, the world energy balance condition (11) should be adjusted to become

$$D^H(\tilde{p}) + D^F\left(\tilde{p} - \theta_c \tilde{\tau}^H + \theta_c \tilde{\tau}^F\right) = S_c^H(\tilde{p} - \theta_c \tilde{\tau}^H) + S_c^F(\tilde{p} - \theta_c \tilde{\tau}^H) + S_g^H(\tilde{p} - \theta_g \tilde{\tau}^H). \tag{23}$$

In the context of this subsection, compared with the previous setting in absence of CO2 emission cap in the rest of the world, equilibrium prices $\tilde{p}$, $\tilde{\tau}^H$ and $\tilde{\tau}^F$ are determined so as to satisfy the new world energy market equilibrium condition (23), the Home country's commitment (12), as well as the new Foreign country's commitment

$$\theta_c D^F(\tilde{p} - \theta_c \tilde{\tau}^H + \theta_c \tilde{\tau}^F) = \bar{e}^F. \tag{24}$$

In this new setting, Appendix D shows that the domestic CO2 reduction policy still induces a lower coal price $\tilde{p}_c$ and more coal exports $\tilde{s}_c^H - \tilde{x}_c^H$ from the Home country to the rest of the world. Although, by assumption, CO2 emissions in the latter are not increased, the carbon equilibrium penalty $\tilde{\tau}^F$ should be raised to ensure that the cap (21) is satisfied: It means that the domestic CO2 reduction policy makes it more difficult for the rest of the world to meet its own commitment.

The following proposition—proved in Appendix D—establishes the extent to which the rest of the world should increase its carbon price in response to the domestic CO2 reduction policy, so as to meet its emission limit $\bar{e}^F$.

Proposition 4 (Domestic CO2 reduction and policy in the rest of the world) *In the face of a reduction of CO2 emissions in the Home country, satisfying the Foreign country's CO2 commitment requires that the latter raises its carbon penalty relatively to the Home country's one to an extent given by*

$$\frac{d\tilde{\tau}^F}{d\tilde{\tau}^H} = \frac{\tilde{\xi}_{D^H} + \left(\frac{\theta_c - \theta_g}{\theta_c}\right) \frac{\tilde{x}_g^H}{\tilde{x}^H} \tilde{\xi}_{S_g}}{\tilde{\xi}_{D^H} + \frac{\tilde{s}_c}{\tilde{x}^H} \tilde{\xi}_{S_c} + \frac{\tilde{x}_g^H}{\tilde{x}^H} \tilde{\xi}_{S_g}}. \tag{25}$$

Interestingly, expression (25) of the relative carbon-price rise in the rest of the world is increasing with the rate $\frac{\theta_c - \theta_g}{\theta_c}$, all other things being equal. This suggests that, in reaction to the domestic CO2 reduction policy, the rest of the world should increase its carbon penalty even more when gas is less CO2 intensive relative to coal.

V. Numerical Application to the US

Section II stressed the relevance of the US example by documenting the following developments: The US administration's commitment to reduce the country's CO2 emissions, and the effective reduction in the US CO2 emissions, have gone hand in hand with the rise in the production of gas and its substitution for coal in the US power sector; moreover, this replacement has been concomitant with a peak in the US exports of coal. The predictions of our model are in line with these developments, indicating the relevance of our theory for the case of the US.

In this section, we apply the theoretical results of Section IV to the case of the US. The stylized nature of our model can only provide a limited approximation of the actual policy relevance and effectiveness of the coal-gas substitution occurring in the US. Accordingly, our application should not be used to draw definitive policy lessons.

That being said, it is of interest to estimate our results with empirically-estimated values of the parameters. Besides an approximative estimation of the effectiveness of the US' climate policy project to reduce its CO2 emissions by relying on the rise of gas, our application provides an illustration of our results, that allows to highlight not only the particular role of some parameters but also the critical assumptions made in existing related studies.

We will use the following sensible approximations of market shares, as well as empirical estimates collected from the existing literature on energy demand and supply elasticities.

A. Empirical Estimates of Parameters and Equilibrium Values

Coal and gas relative CO2 intensity. Following the Intergovernmental Panel on Climate Change (IPCC, 2014, Annex 3, Table A.3.2), the relative CO2 pollution intensity of coal is approximately $\theta_c/\theta_g = 2$, implying that the rate in pollution increase from gas to coal is $(\theta_c - \theta_g)/\theta_g = 1$. Although the use of this ratio is standard, it is also controversial for mainly two reasons. One is the heterogeneity of the coal resource as far as its carbon content is concerned. Another one, already mentioned in the Introduction, is that gas does not only contribute to climate change by releasing CO2 when burnt but also by potentially releasing methane when extracted—see, e.g., Howarth et al. (2011). To take this controversy into account, we will examine how our application is sensitive to changes in $(\theta_c - \theta_g)/\theta_g$.

Market shares. Data from the US Energy Information Administration (EIA)[20] suggest the following approximation: Were the current world production/consumption of coal and the US gas production/consumption normalized to $\tilde{s}_c + \tilde{s}_g^H = 8$ units of energy, it would be decomposed as $\tilde{s}_c = 7$ units of coal production, $\tilde{s}_g^H = 1$ unit of US gas production, and $\tilde{x}^H = 2$ units of US energy consumption. It follows that $\tilde{x}_c^F = 6$ units of the $\tilde{s}_c = 7$ units of world coal production would be consumed in the rest of the world, while the US coal consumption would be of $\tilde{x}_c^H = 1$ unit. Also, the US energy consumption $\tilde{x}^H = 2$ would consist of about $\tilde{x}_c^H = 1$ unit of coal consumption and $\tilde{x}_g^H = 1$ unit of gas consumption.

US electricity demand price elasticity. Various studies estimate the price elasticity of the demand for electricity in the US. Maddala et al. (1997) focus on the residential demand; their average estimates across 49 US States are 0.16 and 0.24 for the short and long run respectively. These orders of magnitude are confirmed by Garcia-Cerrutti (2000), and Bernstein and Griffin (2006). The former studies the residential sector in Californian counties and finds mean elasticity estimates of 0.17 for the short run and 0.19 for the lung run. The latter find 0.24 and 0.32 for the short and long run respectively. For the US commercial sector, Paul et al. (2009) find average price elasticities of the electricity demand of 0.11 and 0.29 in the short and long run. In the industrial sector, their estimates are 0.16 in the short run and 0.4 in the long run. Recently, Deryugina et al. (2017) find the one-year average price elasticity to be 0.14 and the three-year price elasticity to be 0.29 in the residential and small commercial sector.

For their recent simulation, Chakravorty et al. (2015) assume a 0.3 price elasticity of the US final demand for energy, which is in line with the above long-run estimates.

[20] The data used here are available at `https://www.eia.gov/electricity/data.php#consumption` and `https://www.eia.gov/outlooks/ieo/coal.php`.

In our model, price elasticities are medium-run responses, i.e., evaluated over periods of time that allow the replacement of coal-fired power stations by gas-fired ones. In reality, the elasticity of the demand for coal and gas induced by the demand for the electricity produced from these energies may differ from the elasticity of the final electricity demand because there are other, alternative ways of producing electricity. However, alternative sources play a minor role in electricity generation.

Therefore, our numerical application will assume the intermediate value of 0.2 for the price elasticity $\tilde{\xi}_{D^H}$ of the US demand of coal and gas for electricity generation purposes.

Non-US coal demand price elasticity. The non-US demand for coal—especially in the top coal-consuming Chinese economy—is often considered to be very inelastic in the short run. This assumption has been recently questioned by Burke and Liao (2015). They estimate the price elasticity of the demand for coal in China using a panel of province-level data over the 1998-2012 period. They find a range 0.3 to 0.7 when responses are considered over a two years period of time.

For their simulation, Chakravorty et al. (2015) assume a price elasticity of the energy demand of 0.4 for the industrial sector and of 0.5 for the commercial and residential sectors.

Accordingly, our numerical application will assume the intermediate value of 0.5 for the price elasticity $\tilde{\xi}_{D^F}$ of the demand for coal in the rest of the world.

Coal and gas supply price elasticity. The price elasticity of fossil fuels' supply is usually low, even in the long run; it reflects the scarcity of economically exploitable resources. As far as natural gas is concerned, Brown and Krupnick's (2010) estimates of the long-run price elasticity of supply range from 0.9 to 1.4. The empirical literature on the price elasticity of coal supply is characterized by a large variety of estimates, ranging from 0.1 to 7.9—see, e.g., Labys et al. (1979), Beck et al. (1991), Dahl and Duggan (1996), Light (1999), Light et al. (1999), and Truby and Paulus (2012).

In our numerical application, we proceed in two basic steps. First, we assume the sensible, but arbitrary, value of 1 for both the price elasticity $\tilde{\xi}_{S_c}$ of coal supply and the price elasticity $\tilde{\xi}_{S_g}$ of gas supply. Second, we examine how our results are sensitive to changes in these two elasticities.

B. Results of the Application and Sensitivity Analyses

CO2 reduction policy in the US and domestic gas production. According to Proposition 2, condition (13) tells whether the Home country CO2 reduction commitment justifies a rise in gas production. In the case of the US, the values given by the previous subsection yields $\tilde{r}_0 = 0.04$ for left-hand-side threshold of condition (13), which largely falls short of the value of 1 for the rate of pollution increase $(\theta_c - \theta_g)/\theta_g$. This application of Proposition 2, therefore, suggests that a reduction of CO2 emissions in the US justifies that this reduction be met by increasing the US production of gas.

CO2 reduction policy in the US and world CO2 emissions. Proposition 3 and its analysis point out that a rise in US gas induced by a reduction of CO2 emissions in the US may be accompanied by a more-than-100% leakage rate causing an ultimate increase in world CO2 emissions.

With the above chosen values, however, we find that the value in (19) is negative, implying by Corollary 1 that a US CO2 reduction reached by means of a domestic rise in gas cannot induce world CO2 emissions to increase, irrespective of the rate $(\theta_c - \theta_g)/\theta_c$ of pollution increase from gas to coal. That means that, in the case of the US with our chosen values, function (18) has no real roots, so that, in Figure 4, the U-shaped curve lies above the horizontal axis. Accordingly, the associated leakage rate as expressed in (16) takes the value of

$$\frac{d\tilde{e}^F}{-d\bar{e}^H} = 41\%.$$

This number, although relatively high, significantly falls short of the 100% counter-effectiveness threshold. This result, nevertheless, happens to change dramatically when other values of supply elasticities are considered.

Variations in supply price elasticities. The leakage rate of 41% just obtained is highly sensitive to small changes in the price elasticities $\tilde{\xi}_{S_c}$ and $\tilde{\xi}_{S_g}$ of coal and gas supply.

This is illustrated by the iso-leakage-rate curves of Figure 5 in the coal- and gas-supply elasticities' space. These curves reflect that, for any given price elasticity of coal supply, the leakage rate becomes larger with the elasticity of gas supply, making the US CO2 reduction policy more likely to be counter-productive. This is especially concerning since the US shale gas resource exhibits a particularly high supply elasticity (Newell et al., 2016). In particular, Figure 5 shows that the leakage rate may exceed 100% for elasticity values that fall into the range of values that are admitted by the empirical literature, as, for example, with $\tilde{\xi}_{S_c} = 0.1$ and $\tilde{\xi}_{S_g} = 1$.

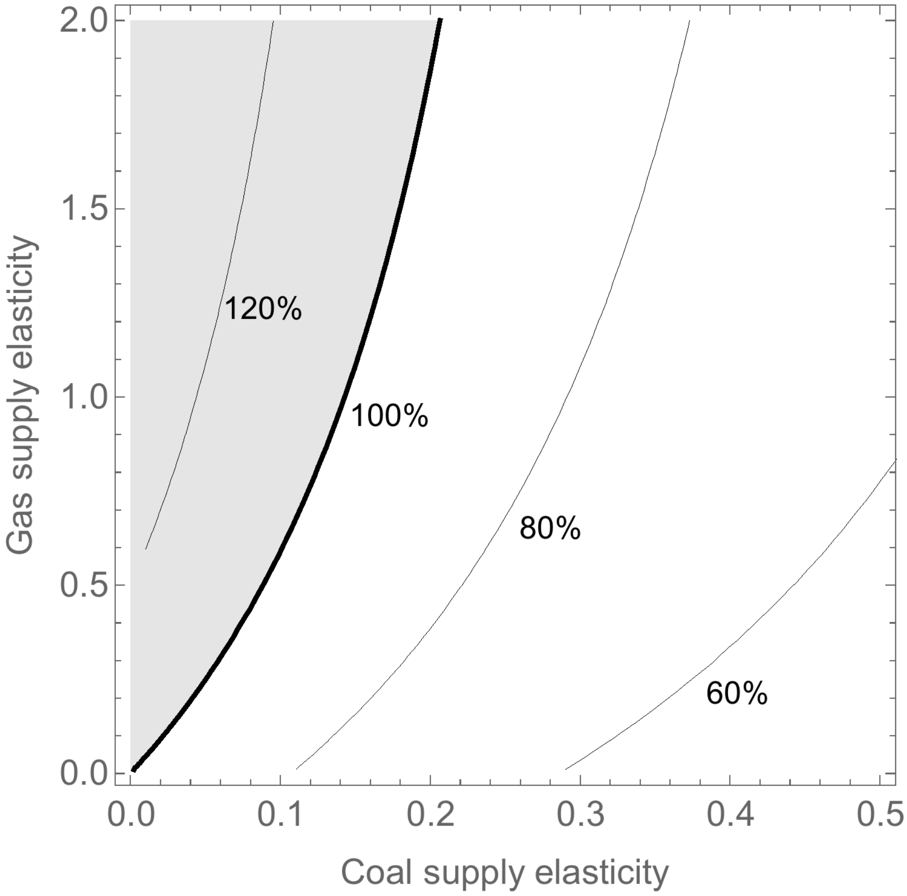

Figure 5: Curves of iso-leakage-rate and supply elasticities

Variations in relative CO2 intensities. By contrast, Figure 6 shows that sensible changes in the rate of pollution increase $(\theta_c - \theta_g)/\theta_g$ around the standard—but controversial—value of 1 does not modify significantly the rate of leakage. For example, the leakage rate is maximum at 42% when coal is 62% more polluting than gas.

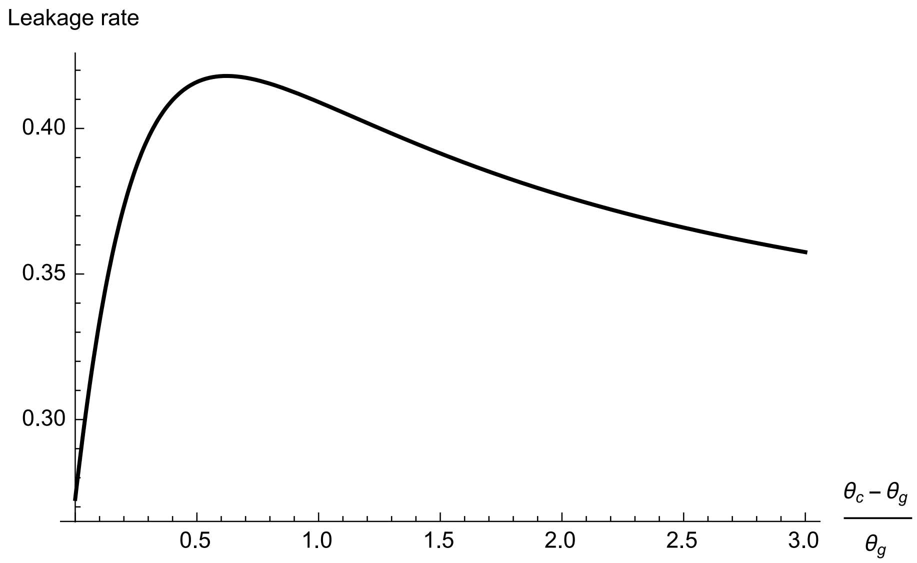

Figure 6: Leakage rate and the rate of increase of pollution from gas to coal

At the same time, Figure 6 shows that the often-made simplifying assumption of a single polluting energy may lead to importantly underestimate the leakage rate. For example, if gas were considered as polluting as coal—i.e., $(\theta_c - \theta_g)/\theta_g = 0$—as if there were no intermediate energy source, the obtained leakage rate would be of 27%, rather than 41%.

CO2 reduction policy in the US and policy in the rest of the world. According to Proposition 4, formula (25) indicates the relative carbon penalty increase that the rest of the world must implement to ensure that its CO2 commitment remains satisfied in the face of the domestic CO2 reduction. With the values chosen in the previous subsection, the application of this formula tells us that, were the US policy raising the US price of carbon by \$10, the rest of the world should react by raising its carbon price by \$1.7. With a single resource ($\theta_g = \theta_c$)—as when the presence of gas as an intermediate energy is ignored—the same increase in the US price of carbon would be offset by a rise in rest-of-the-world carbon price by only \$0.48.

VI. Concluding Remarks

Our analysis stresses that, with an intermediate carbon energy source like gas, a well-intentioned unilateral CO2 reduction policy may be more than offset by a more-than-100% leakage rate, making the policy counter-productive at the world level. This sharply contrasts with the standard analysis of unilateral policies with a single carbon energy source, in which the leakage rate is always less than 100%. In this new context, an examination was needed of the circumstances under which a unilateral policy relying on gas turns counter-productive. We have established simple and testable conditions ($\imath$) under which a domestic CO2 reduction warrants that gas production be increased and ($\imath\imath$) under which such an increase effectively helps reduce CO2 emissions at the world level.

Our results look simple. However, they are new and they shed light on a currently important policy option. Indeed, in the aftermath of the Paris Climate Agreement, countries will rely on unilateral initiatives to meet their CO2 reduction targets, and, in this context, a number of large gas-rich economies hope to do so by increasing their gas production.

Our formulas can be applied to any such gas-rich region to approximately evaluate whether the option of relying on gas effectively contributes to reducing CO2 emissions at the world level. For example, our application to the most important US case with sensible empirical estimates suggests that the rise of gas in the US might not only be justified from the perspective of the national current CO2 commitment, but also from the perspective of a need to reduce CO2 emissions at the world level. This is in line with the conclusion of Wolak (2016) and Knittel et al. (2017), obtained under the extreme assumption that the foreign demand for coal is perfectly inelastic. At the same time, our model is too stylized to draw definitive policy conclusions. Instead, our theory and its application indicate that Wolak's short-run assumption of inelastic foreign coal demand is critical: In presence of more than one carbon energy source, doing away with this assumption, in a medium to long run perspective, gives rise to the possibility that the US climate policy be counter-productive. Accordingly, our analysis calls for examining more carefully the global impact of relying on gas to reduce domestic emissions, not only in the US but also wherever this is a relevant policy option. Moreover, our application indicates the critical importance of the coal and gas supply elasticities, and calls for more empirical research on their estimation.

The stylized nature of our model is a methodological and pedagogical choice of focusing on the most fundamental aspects of our theory: an open-economy relying on carbon-generating coal and gas, using its gas domestically and trading coal with the rest of the world. Consequently, our results have been obtained under simplifying conditions and one may question whether they survive more complex settings. Five main aspects are omitted in our analysis, which deserve further discussion. For the sake of clarity, we discuss each of them in isolation.

A. Dynamic Coal and Gas Supplies

Our analysis may be extended to dynamic coal and gas supply in the following standard and straightforward manner. Assume that both energy sources are costlessly produced over some time horizon by Hotelling-style (Hotelling, 1931) competitive sectors seeking to maximize long-term profits. Moreover, consider that these sectors develop exploitable reserves prior to extracting them at some convex exploration and development costs, in the fashion first proposed by Gaudet and Lasserre (1988). Under these assumptions, as is widely known in the field of non-renewable-resource economics, the formulation of the model in terms of cumulative quantities over the time horizon is isomorphic to the static model of Sections III and IV; it follows that the analysis of a reduction in long-term total emissions in the Home country yields the same results as Propositions 2, 3 and 4, and Corollary 1. The formulas only differ by the notion of supply elasticities involved, which emerge as elasticities of the long-run production of reserves, rather than static supply elasticities; this difference highlights that the elasticity notion that is relevant for our analysis should reflect sufficiently long-run supply responses.

B. International Gas Trade

The second aspect that needs to be discussed is the possibility that natural gas be traded. As already mentioned in the Introduction, the international trade of gas is highly challenging in comparison with coal. However, the former is progressively becoming reality. For example, following a wave of investment in Liquefied Natural Gas export terminals, the US has shipped natural gas since February 2017.

In fact, our analysis extends in a relatively straightforward way to the possibility that the rest of the world may import some gas produced in the Home country. There are two basic cases.

First, assume that coal and gas are perfectly substitutable not only in the Home country but also in the Foreign region. If coal and gas are used simultaneously in the Home country, as in our main analysis, the no-arbitrage condition $\tilde{p}_c + \theta_c \tilde{\tau}^H = \tilde{p}_g + \theta_g \tilde{\tau}^H$ prevails as per (8), and implies that $\tilde{p}_c < \tilde{p}_g$: In this case, no gas will ultimately be used in the rest of the world and the analysis of the main text applies. If instead coal and gas are used simultaneously in the rest of the world, the counterpart of (8) for the Foreign country $\tilde{p}_c = \tilde{p}_g$ must hold, contradicting (8): $\tilde{p}_c + \theta_c \tilde{\tau}^H > \tilde{p}_g + \theta_g \tilde{\tau}^H$. In this case, no coal is used in the Home country, and the analysis reduces to the standard leakage model in which a unilateral CO2 reduction never increases world CO2 emissions.

Second, assume that coal and gas are imperfect substitutes in the rest of the world. For simplicity, consider that there is an independent demand for gas $D_g^F(p_g)$ in the Foreign country. This allows gas to be used at the same time as coal not only in the Home country but also in the rest of world. In this case, our analysis survives, provided that the domestic supply of gas is reinterpreted as a residual supply, after the rest-of-the-world demand has been served.

C. Gas Supply in the Rest of the World

As a matter of fact, natural gas is produced in various gas-rich regions. That being said, as already mentioned in the Introduction and reminded in the previous subsection, regional gas markets are hardly integrated, despite the fact that the international trade of gas is progressively becoming reality—see, for example, Li, Joyeux, and Ripple (2014).

The extension of our theory to the presence of non-internationally-tradable gas, not only in the domestic economy, but also in the rest of the world has an obvious implication: As the domestic CO2 reduction policy negatively impacts the international price of coal, it induces a reduction in the foreign gas production. This effect mitigates the carbon leakage and, therefore, the potential rise of CO2 emissions at the world level.

Appendix E presents the extension of our model to this situation: It stresses that, besides the quantitative adjustment just explained, the extension's analysis follows the same steps as the analysis of the main text, implying similar qualitative conclusions, including the possibility of more-than-100% leakage, as summarized in Subsection IV.E and illustrated in Figure 4.

D. Additional Non-Tradable Non-Carbon Energy Sources

As already explained in the main text, the extension of the model to the case in which other non-tradable non-carbon energy sources can be used to produce electricity is straightforward once energy demand functions are reinterpreted as residual demands after other energies have been used. Therefore, the extension of our model to the presence of such alternative energy sources does not imply any qualitative nor quantitative adjustments.

E. Technical Progress in the Production of Gas, and Development of Non-Carbon Energy Sources

Our comparative-statics results are to be interpreted as effects taking place over time. With time, however, other phenomena take place that, although theoretically orthogonal to our model, may in practice play an important role. These phenomena include, for example, technical improvements in the technology of domestic gas production and the deployment of alternative non-carbon energy sources. The former amounts to a positive shift in the domestic gas supply function; the latter, in light of the above discussions, can be characterized by a negative shift in the (domestic and foreign) demand for carbon energy sources.

As a complement to the main text's analysis of changes in the domestic CO2 emissions' governmental commitment, Appendix F examines, in absence of public policy, the effect of shifting both the domestic gas supply and the demand for carbon energy sources. It shows that technical improvements in the production of gas affects world CO2 emissions in a way comparable with a domestic CO2 reduction policy relying on the replacement of coal by gas.[21] The analysis of the appendix further shows that the development of non-carbon energy production systematically contributes to the reduction of CO2 emissions worldwide. The policy promotion of non-carbon energy sources is, clearly, a way of reducing world CO2 emissions that is less hazardous than the unilateral promotion of the gas intermediate energy source.

[21] In particular, Appendix F substantiates the claim of footnote 16 on the impact of an exogenous increase in domestic gas production on domestic CO2 emissions.

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Online Appendix to "More Gas, Less Coal, and Less CO2? Unilateral CO2 Reduction Policy with More than One Carbon Energy Source"

by

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A Proof of Proposition 1

In order to alleviate notations, variables' functions will be omitted throughout the following appendices, as long as it does not cause ambiguity.

Replacing the final energy price variable $\tilde{p}$ by the producer price of coal $\tilde{p}_c = \tilde{p} - \theta_c \tilde{\tau}^H$ as per (9), and using the simplifying notation $S_c \equiv S_c^H + S_c^F$, the system (11)-(12) rewrites as follows:

$$D^H\left(\tilde{p}_c + \theta_c \tilde{\tau}^H\right) + D^F\left(\tilde{p}_c\right) = S_c\left(\tilde{p}_c\right) + S_g^H\left(\tilde{p}_c + (\theta_c - \theta_g)\tilde{\tau}^H\right) \tag{A.1}$$

and

$$\theta_c D^H\left(\tilde{p}_c + \theta_c \tilde{\tau}^H\right) - (\theta_c - \theta_g) S_g^H\left(\tilde{p}_c + (\theta_c - \theta_g)\tilde{\tau}^H\right) = \bar{e}^H. \tag{A.2}$$

Each of equations (A.1) and (A.2) defines a relationship between $\tilde{p}_c$ and $\tilde{\tau}^H$. Let us examine the latter first.

Totally differentiating (A.2) with respect to $\tilde{p}_c$ and $\tilde{\tau}^H$, one obtains the derivative

$$\left.\frac{d\tilde{\tau}^H}{d\tilde{p}_c}\right|_{(A.2)} = \frac{\theta_c D^{H\prime} - (\theta_c - \theta_g) S_g^{H\prime}}{(\theta_c - \theta_g)^2 S_g^{H\prime} - \theta_c^2 D^{H\prime}}, \tag{A.3}$$

which appears to be strictly negative. (A.2) characterizes a continuous and strictly decreasing relationship between $\tilde{p}_c$ and $\tilde{\tau}^H$, which we denote by the function

$$\tilde{\tau}^H = \tau_2\left(\tilde{p}_c\right),\ \tilde{p}_c \geq 0, \tag{A.4}$$

illustrated in Figure 7 in the $(\tilde{p}_c, \tilde{\tau}^H)$ plane.

In the rest of this appendix, it will be useful to refer to the price of both coal and gas in the laissez-faire equilibrium presented in Section III. We denote this laissez-faire energy price by

$$\tilde{p}^* > 0.$$

As explained in Section III, this price is uniquely characterized by (2). That means, in other words, that $\tilde{p}^*$ is uniquely characterized by (A.1) once $\tilde{\tau}^H$ is set equal to zero.

Our formulation of the binding commitment (A.2) relies on our assumption that the emission cap $\bar{e}^H$ falls short of the emission level in the laissez-faire equilibrium. Therefore, if the coal price was the laissez-faire price $\tilde{p}^*$, (A.2) would be satisfied by the strictly positive tax

$$\tilde{\tau}^H = \tau_2\left(\tilde{p}^*\right) > 0.$$

If the coal price was $\tilde{p}_c = 0$, the tax satisfying the emission commitment (A.2) would be the unique

$$\tilde{\tau}^H = \tau_2(0),$$

defined by $\theta_c D^H(\theta_c \tilde{\tau}^H) - (\theta_c - \theta_g) S_g^H((\theta_c - \theta_g)\tilde{\tau}^H) = \bar{e}^H$

Figure 7 depicts the two points of function τ_2 that we just established: $(0, \tau_2(0))$ and $(\tilde{p}^*, \tau_2(\tilde{p}^*))$.

Let us now examine the relationship defined by (A.1). Totally differentiating (A.1) with respect to $\tilde{p}_c$ and $\tilde{\tau}^H$, one obtains the derivative

$$\left.\frac{d\tilde{\tau}^H}{d\tilde{p}_c}\right|_{(A.1)} = \frac{(S_c' + S_g^{H\prime}) - (D^{H\prime} + D^{F\prime})}{\theta_c D^{H\prime} - (\theta_c - \theta_g) S_g^{H\prime}}, \tag{A.5}$$

which appears to be strictly negative. (A.1) characterizes a continuous and strictly decreasing relationship between $\tilde{p}_c$ and $\tilde{\tau}^H$, which we denote by the function

$$\tilde{\tau}^H = \tau_1\left(\tilde{p}_c\right),\ \tilde{p}_c \geq 0, \tag{A.6}$$

illustrated in Figure 7.

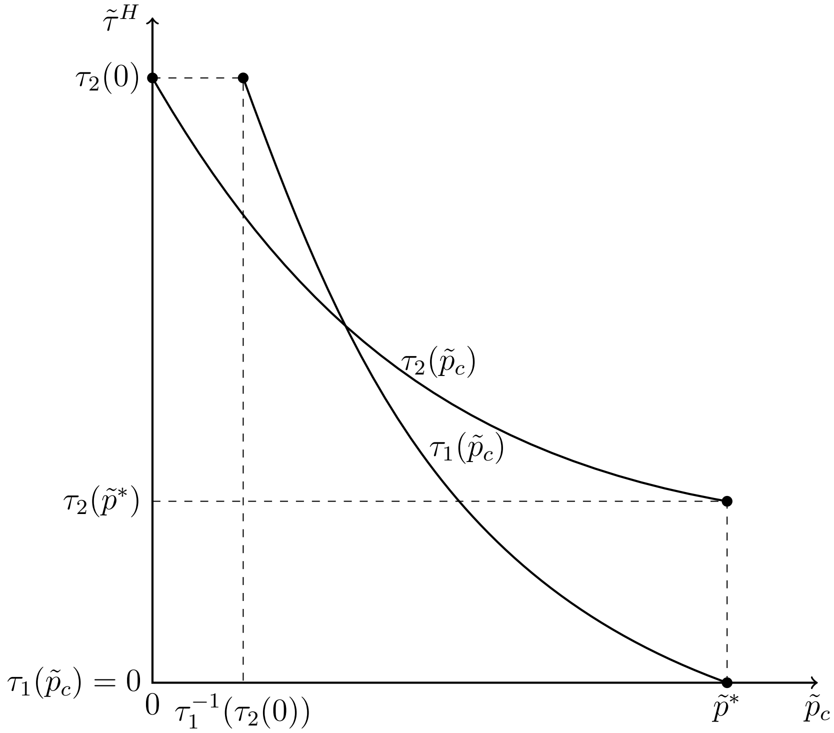

Figure 7: Functions $\tau_1(\tilde{p}_c)$ and $\tau_2(\tilde{p}_c)$

We now compare function τ_1 with function τ_2 around the two points of the latter that we already established. By definition, the laissez-faire energy price $\tilde{p}^*$ satisfies the equilibrium condition (A.1) when $\tilde{\tau}^H = 0$. In other words,

$$\tau_1(\tilde{p}^*) = 0.$$

Finally, we will characterize the price $\tilde{p}_c$ that would balance the energy market as per (A.1), if the tax $\tau_2(0)$ defined above was implemented. Treating $\tau_2(0)$ as a parameter, this price $\tilde{p}_c = \tau_1^{-1}(\tau_2(0))$ is uniquely given by the condition

$$D^H(\tilde{p}_c + \theta_c \tau_2(0)) + D^F(\tilde{p}_c) - S_c(\tilde{p}_c) - S_g^H(\tilde{p}_c + (\theta_c - \theta_g)\tau_2(0)) = 0, \tag{A.7}$$

where the left-hand side is a continuous and strictly decreasing function of $\tilde{p}_c$. On the one hand, for $\tilde{p}_c = 0$, this function's value is $D^H(\theta_c \tau_2(0)) + D^F(0) - S_c(0) - S_g^H((\theta_c - \theta_g)\tau_2(0))$, which can be shown to be strictly negative as follows. First, by definition of $\tilde{p}^*$ and $\tau_2(0)$,

$$\theta_c D^H(\tilde{p}^*) - (\theta_c - \theta_g) S_g^H(\tilde{p}^*) > \bar{e}^H = \theta_c D^H(\theta_c \tau_2(0)) - (\theta_c - \theta_g) S_g^H((\theta_c - \theta_g)\tau_2(0)).$$

Second, we have the obvious inequality

$$\theta_c D^H(\theta_c \tau_2(0)) - (\theta_c - \theta_g) S_g^H((\theta_c - \theta_g)\tau_2(0)) > \theta_c D^H(\theta_c \tau_2(0)) - (\theta_c - \theta_g) S_g^H(\theta_c \tau_2(0)).$$

Combining the last two inequalities, one obtains

$$\theta_c D^H(\tilde{p}^*) - (\theta_c - \theta_g) S_g^H(\tilde{p}^*) > \theta_c D^H(\theta_c \tau_2(0)) - (\theta_c - \theta_g) S_g^H(\theta_c \tau_2(0)),$$

which implies $\theta_c \tau_2(0) < \tilde{p}^*$ and, therefore, $(\theta_c - \theta_g)\tau_2(0) < \tilde{p}^*$. In turn, the last two inequalities imply

$$D^H(\theta_c \tau_2(0)) + D^F(0) - S_c(0) - S_g^H((\theta_c - \theta_g)\tau_2(0)) > D^H(\tilde{p}^*) + D^F(0) - S_c(0) - S_g^H(\tilde{p}^*),$$

where the right-hand side is strictly positive since

$$D^H(\tilde{p}^*) + D^F(0) - S_c(0) - S_g^H(\tilde{p}^*) > D^H(\tilde{p}^*) + D^F(\tilde{p}^*) - S_c(\tilde{p}^*) - S_g^H(\tilde{p}^*) = 0.$$

One can, therefore, conclude

$$D^H(\theta_c \tau_2(0)) + D^F(0) - S_c(0) - S_g^H((\theta_c - \theta_g)\tau_2(0)) > 0.$$

On the other hand, by assumption, $\lim_{p \mapsto +\infty} D^H(p) + D^F(p) - S_c(p) - S_g^H(p) < 0$. The last two inequalities imply that the unique $\tilde{p}_c$ that satisfies the market equilibrium condition (A.1) under the tax $\tau_2(0)$ previously established is strictly positive:

$$\tau_1^{-1}(\tau_2(0)) > 0.$$

This is depicted in Figure 7.

Having shown that

$$\tau_2(p_c^*) > 0 \text{ and } \tau_1^{-1}(\tau_2(0)) > 0,$$

as illustrated in Figure 7, the last step of the proof consists in showing that the continuous functions τ_1 and τ_2 characterized respectively by equations (A.1) and (A.2) intersect for a single value of $\tilde{p}_c$. Using the simplifying notation $r \equiv \frac{\theta_c - \theta_g}{\theta_c}$, (A.5) and (A.3) imply that, over $\tilde{p}_c \geq 0$, the ratio of their derivatives is

$$\frac{\tau_1'(\tilde{p}_c)}{\tau_2'(\tilde{p}_c)} \equiv \frac{\left.\frac{d\tilde{\tau}^H}{d\tilde{p}_c}\right|_{(A.1)}}{\left.\frac{d\tilde{\tau}^H}{d\tilde{p}_c}\right|_{(A.2)}} = \frac{[(S_c' + S_g^{H\prime}) - (D^{H\prime} + D^{F\prime})][(\theta_c - \theta_g)^2 S_g^{H\prime} - \theta_c^2 D^{H\prime}]}{(\theta_c D^{H\prime} - (\theta_c - \theta_g) S_g^{H\prime})^2}$$
$$= \frac{[(S_c' + S_g^{H\prime}) - (D^{H\prime} + D^{F\prime})][r^2 S_g^{H\prime} - D^{H\prime}]}{(D^{H\prime} - r S_g^{H\prime})^2},$$

from which the following inequality is easily obtained:

$$\frac{\tau_1'(\tilde{p}_c)}{\tau_2'(\tilde{p}_c)} > \frac{[S_g^{H\prime} - D^{H\prime}][r^2 S_g^{H\prime} - D^{H\prime}]}{(D^{H\prime} - r S_g^{H\prime})^2},$$

which is strictly more than one since $(1 - r)^2 > 0$.

One can conclude that functions τ_1 and τ_2 characterized respectively by equations (A.1) and (A.2) intersect for one and only one value of $\tilde{p}_c$, which is strictly positive, completing the proof.

B Proof of Proposition 2

Final energy price and domestic C02 price

Totally differentiating the system (11)-(12) with respect to $\bar{e}^H$, $\tilde{p}$ and $\tilde{\tau}^H$ yields two linear equations which can be written as the following matrix equation:

$$\begin{pmatrix} A_1 & A_2 \\ A_3 & A_4 \end{pmatrix} \begin{pmatrix} d\tilde{p} \\ d\tilde{\tau}^H \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} d\bar{e}^H,$$

where, using the simplifying notation $S_c \equiv S_c^H + S_c^F$,

$$\begin{aligned} A_1 &= D^{H\prime} + D^{F\prime} - (S_c^{\prime} + S_g^{H\prime}) < 0, \\ A_2 &= -\theta_c D^{F\prime} + \theta_c S_c^{\prime} + \theta_g S_g^{H\prime} > 0, \\ A_3 &= \theta_c D^{H\prime} - (\theta_c - \theta_g) S_g^{H\prime} < 0, \\ A_4 &= \theta_g(\theta_c - \theta_g) S_g^{H\prime} > 0. \end{aligned} \tag{B.1}$$

The signs of terms A_1, A_2, A_3 and A_4 follow from our assumptions.

Inverting the matrix, one obtains

$$\begin{pmatrix} d\tilde{p} \\ d\tilde{\tau}^H \end{pmatrix} = \frac{1}{A_1 A_4 - A_2 A_3} \begin{pmatrix} A_4 & -A_2 \\ -A_3 & A_1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} d\bar{e}^H$$

or, equivalently,

$$\begin{pmatrix} \frac{d\tilde{p}}{d\bar{e}^H} \\ \frac{d\tilde{\tau}^H}{d\bar{e}^H} \end{pmatrix} = \frac{1}{A_1 A_4 - A_2 A_3} \begin{pmatrix} -A_2 \\ A_1 \end{pmatrix}. \tag{B.2}$$

By (B.1), $A_1 < 0$, $-A_2 < 0$, while $A_1 A_4 - A_2 A_3$ can easily be reduced as follows and, therefore, shown to be positive:

$$A_1 A_4 - A_2 A_3 = -\theta_g^2 D^{H\prime} S_g^{H\prime} + (\theta_c - \theta_g)^2 S_g^{H\prime} \left(S_c^{\prime} - D^{F\prime}\right) - \theta_c^2 D^{H\prime} \left(S_c^{\prime} - D^{F\prime}\right) > 0. \tag{B.3}$$

One can conclude

$$\frac{d\tilde{p}}{d\bar{e}^H} < 0 \quad \text{and} \quad \frac{d\tilde{\tau}^H}{d\bar{e}^H} < 0. \tag{B.4}$$

Coal price on the international market

By (9), the equilibrium coal price is $\tilde{p}_c = \tilde{p} - \theta_c \tilde{\tau}^H$. Differentiating this equation with respect to $\bar{e}^H$ and using (B.2), one obtains:

$$\frac{d\tilde{p}_c}{d\bar{e}^H} = -\frac{1}{A_1 A_4 - A_2 A_3} \left(A_2 + \theta_c A_1\right),$$

where $A_1 A_4 - A_2 A_3 > 0$ by (B.3), and where, by (B.1), $A_2 + \theta_c A_1$ can easily be shown to be negative:

$$A_2 + \theta_c A_1 = \theta_c D^{H\prime} - (\theta_c - \theta_g) S_g^{H\prime} < 0.$$

One can conclude

$$\frac{d\tilde{p}_c}{d\bar{e}^H} > 0. \tag{B.5}$$

Home country energy consumption and coal and gas supplies

The equilibrium energy consumption in the Home country is $\tilde{x}^H = D^H(\tilde{p})$. Differentiating with respect to $\bar{e}^H$ and using (B.4), one obtains

$$\frac{d\tilde{x}^H}{d\bar{e}^H} = D^{H\prime}\frac{d\tilde{p}}{d\bar{e}^H} > 0.$$

The domestic supply of coal is $\tilde{s}_c^H = S_c^H(\tilde{p}_c)$. Differentiating with respect to $\bar{e}^H$ and using (B.5), one obtains

$$\frac{d\tilde{s}_g^H}{d\bar{e}^H} = S_c^{H\prime}\frac{d\tilde{p}_c}{d\bar{e}^H} > 0.$$

By (10), the domestic supply of gas is $\tilde{s}_g^H = S_g^H(\tilde{p}-\theta_g\tilde{\tau}^H)$. Differentiating with respect to $\bar{e}^H$, one obtains $d\tilde{s}_g^H/d\bar{e}^H = S_g^{H\prime}\left(d\tilde{p}/d\bar{e}^H - \theta_g d\tilde{\tau}^H/d\bar{e}^H\right)$, which, using the expressions in (B.2), becomes

$$\frac{d\tilde{s}_g^H}{d\bar{e}^H} = \frac{-S_g^{H\prime}\left(A_2 + \theta_g A_1\right)}{A_1A_4 - A_2A_3}.$$

In this expression, (B.1) allows to rewrite $A_2 + \theta_g A_1$ as follows:

$$A_2 + \theta_g A_1 = (\theta_c - \theta_g)\left(S_c' - D^{F\prime}\right) + \theta_g D^{H\prime}.$$

Since, by (B.3), $A_1A_4 - A_2A_3 > 0$, and, by assumption, $S_g^{H\prime} > 0$, it follows that $d\tilde{s}_g^H/d\bar{e}^H$ and $(\theta_c - \theta_g)\left(S_c' - D^{F\prime}\right)+\theta_g D^{H\prime}$ have opposite signs. Therefore, $d\tilde{s}_g^H/d\bar{e}^H < 0$—as when a reduction in $\bar{e}^H$ causes an increase in gas production $\tilde{s}_g^H$—is equivalent to $(\theta_c - \theta_g)\left(S_c' - D^{F\prime}\right) + \theta_g D^{H\prime} > 0$, which is also

$$\frac{\theta_c - \theta_g}{\theta_g} > \frac{-D^{H\prime}}{S_c' - D^{F\prime}},$$

from which condition (13) is obtained after using the elasticity notations presented in the main text immediately after Proposition 2. This proves the proposition.

C Proof of Proposition 3 and Corollary 1

(14) and (15), together with the expression of $\tilde{p}_c$ in (9), imply the following expression of the world CO2 emissions:

$$\tilde{e}^W = \bar{e}^H + \theta_c D^F(\tilde{p} - \theta_c\tilde{\tau}^H).$$

Differentiating with respect to $\bar{e}^H$, one obtains $d\tilde{e}^W/d\bar{e}^H = 1+\theta_c D^{F\prime}\left(d\tilde{p}/d\bar{e}^H - \theta_c d\tilde{\tau}^H/d\bar{e}^H\right)$, which, after using the expressions in (B.2), becomes

$$\frac{de^W}{d\bar{e}^H} = 1 - \frac{\theta_c D^{F\prime}\left(A_2 + \theta_c A_1\right)}{A_1A_4 - A_2A_3}.$$

After replacing the terms given in (B.1), and using the simplifying notation $r \equiv (\theta_c - \theta_g)/\theta_g$, simple manipulations allow to obtain

$$\frac{d\tilde{e}^W}{d\bar{e}^H} = \frac{\theta_c^2 S_g^{H\prime}}{A_1A_4 - A_2A_3}\frac{1}{(1+r)^2}P(r) \tag{C.1}$$

with

$$P(r) = S_c' \left(1 - \frac{D^{H\prime}}{S_g^{H\prime}}\right) r^2 + \left(D^{F\prime} - 2\frac{S_c' D^{H\prime}}{S_g^{H\prime}}\right) r - D^{H\prime}\left(1 + \frac{S_c'}{S_g^{H\prime}}\right), \tag{C.2}$$

which has been reported in (18). In (C.1), $A_1A_4 - A_2A_3 > 0$ by (B.3), and, by assumption, $S_g^{H\prime} > 0$. Therefore, $d\tilde{e}^W/d\bar{e}^H$ and $P(r)$ as expressed in (C.2) have the same sign. After simple manipulations using the elasticity notations of the main text, it follows that $d\tilde{e}^W/d\bar{e}^H > 0$ is equivalent to condition (17). This proves Proposition 3.

The leakage rate, as expressed in (16), can be obtained in a similar way since, by (14),

$$\frac{d\tilde{e}^F}{d\bar{e}^H} = \frac{d\tilde{e}^W}{d\bar{e}^H} - 1;$$

clearly, this rate is less than 100% when $d\tilde{e}^W/d\bar{e}^H > 0$ and more than 100% otherwise.

$P(r)$ in (C.2) is a polynomial of degree two. Since its second degree coefficient $S_c'\left(1 - D^{H\prime}/S_g^{H\prime}\right)$ is positive, it satisfies $\lim_{r\mapsto+\infty} P(r) = +\infty$. Moreover, it satisfies $P(0) = -D^{H\prime}\left(1 + S_c'/S_g^{H\prime}\right) > 0$.

It follows that $P(r)$—and, equivalently $d\tilde{e}^W/d\bar{e}^H$—can only be negative if it admits two real roots; in this case, it will be negative for values of r in between these roots. It is the case if and only if the polynomial's determinant

$$\Delta = D^{F\prime 2} + 4\left(S_c' + S_g^{H'} - D^{F\prime} - D^{H\prime}\right)\frac{S_c' D^{H\prime}}{S_g^{H\prime}} \tag{C.3}$$

is strictly positive. This positivity condition is expressed in (19). It is clearly a necessary condition for the possibility that $d\tilde{e}^W/d\bar{e}^H$ be negative, as when the domestic CO2 reduction is counter-productive at the world level, proving the first part of Corollary 1.

If this condition $\Delta > 0$ is satisfied, the two roots $\underline{\tilde{r}} < \tilde{\tilde{r}}$ of $P(r)$ as labelled in the main text are

$$\underline{\tilde{r}} \equiv \frac{2\frac{S_c' D^{H\prime}}{S_g^{H\prime}} - D^{F\prime} - \sqrt{\Delta}}{2S_c'\left(1 - \frac{D^{H\prime}}{S_g^{H\prime}}\right)} \tag{C.4}$$

and

$$\tilde{\tilde{r}} \equiv \frac{2\frac{S_c' D^{H\prime}}{S_g^{H\prime}} - D^{F\prime} + \sqrt{\Delta}}{2S_c'\left(1 - \frac{D^{H\prime}}{S_g^{H\prime}}\right)}, \tag{C.5}$$

where $\Delta > 0$ is given by (C.3).

These two roots, assuming that they exist so that $\Delta > 0$ in (C.3), can be shown to be positive as follows. First, following a famous property of second degree polynomials, the roots' product is

$$\underline{\tilde{r}}\tilde{\tilde{r}} = \frac{-D^{H\prime}\left(1 + \frac{S_c'}{S_g^{H\prime}}\right)}{S_c'\left(1 - \frac{D^{H\prime}}{S_g^{H\prime}}\right)},$$

which is positive, implying that the two roots have the same sign. Second, following another famous property of second degree polynomials, the roots' sum is

$$\underline{\tilde{r}} + \tilde{\tilde{r}} = \frac{2\frac{S_c' D^{H\prime}}{S_g^{H\prime}} - D^{F\prime}}{S_c'\left(1 - \frac{D^{H\prime}}{S_g^{H\prime}}\right)}. \tag{C.6}$$

In the latter fraction, the denominator is positive by our assumptions. At the same time, the positivity of Δ in (C.3) can easily be shown to imply the inequality $D^{F\prime} < 4\frac{S_c' D^{H\prime}}{S_g^{H\prime}}\left(1 + \frac{D^{H\prime}}{D^{F\prime}} - \frac{S_c' + S_g'}{S_{gc}^{H\prime}}\right)$, where the fact that the term between parentheses is less than one implies, in turn, $D^{F\prime} < 4\frac{S_c' D^{H\prime}}{S_g^{H\prime}} < 2\frac{S_c' D^{H\prime}}{S_g^{H\prime}}$. It follows that the fraction's numerator in (C.6) and, therefore, the roots' sum are positive. Having already established that the roots have the same sign, one can conclude that this sign is positive.

In fact, the analysis and comparison of Propositions 2 and 3 in the main text revealed that $0 < \tilde{r}_0 < \underline{\tilde{r}}$.

To sum up, provided $\Delta > 0$—and, therefore, condition (19) in Corollary 1—$P(r)$ is strictly negative—and, therefore, so is $d\tilde{e}^W/d\bar{e}^H$—for and only for all rates of pollution increase $r = (\theta_c - \theta_g)/\theta_g$ within the non-empty positive interval $(\underline{\tilde{r}}, \tilde{\tilde{r}})$. This proves the second point of Corollary 1.

D Proof of Proposition 4

Totally differentiating the equilibrium condition (23) with respect to $\tilde{p}$, $\tilde{\tau}^H$ and $\tilde{\tau}^F$, and rearranging terms, one obtains

$$A_1 d\tilde{p} + A_2 d\tilde{\tau}^H + \theta_c D^{F\prime} d\tilde{\tau}^F = 0, \tag{D.1}$$

where the notations defined in (B.1) have been used.

Proposition 4 assumes that the Foreign country's emissions are limited as per (24), which implies that the coal price $\tilde{p}_c = \tilde{p} - \theta_c\tilde{\tau}^H + \theta_c\tilde{\tau}^F$ therein, as given in (22), is held unchanged. Its total derivative with respect to $\tilde{p}$, $\tilde{\tau}^H$ and $\tilde{\tau}^F$ is, therefore, zero:

$$d\tilde{p} - \theta_c d\tilde{\tau}^H + \theta_c d\tilde{\tau}^F = 0. \tag{D.2}$$

Combining equations (D.1) and (D.2) by substituting $d\tilde{p}$, one obtains

$$\frac{d\tilde{\tau}^F}{d\tilde{\tau}^H} = \frac{-D^{H\prime} + \frac{\theta_c - \theta_g}{\theta_c} S_g^{H\prime}}{-D^{H\prime} + S_c' + S_g^{H\prime}},$$

from which equation (25) is derived after using the elasticity notations of the main text. This proves Proposition 4.

E Gas Supply in the Rest of the World

In this appendix, we reexamine the basic model of the main text, used in Section IV from Subsections IV.A to IV.E—that is assuming that the rest of the world is not committed to any CO2 limitation—with the single following modification: Gas is produced not only in the Home country but also in the Foreign country. Like in the former, it is produced in the latter by a price-taking representative firm, which does not export it. Gas production in the rest of the world s_g^F—expressed in energy units—is given by the supply function of the foreign gas price

$$s_g^F = S_g^F(p_g^F),$$

which is assumed non negative, differentiable and strictly increasing for all p_g^F. In the same way as for the Home country, coal and gas can equivalently be used to produced electricity energy, and jointly meet the foreign energy demand $D^F(p^F)$, where p^F denotes the final energy price in the Foreign country.

In the context of this extension, the interesting equilibria are those in which coal and gas are used at the same time in the rest of the world. To focus on these situations, we consider that the following no-arbitrage condition holds:

$$\tilde{p}^F = \tilde{p}_g^F = \tilde{p}_c.$$

It follows from our assumptions that (11) becomes

$$D^H(\tilde{p})+D^F(\tilde{p}-\theta_c\tilde{\tau}^H) = S_c^H(\tilde{p}-\theta_c\tilde{\tau}^H)+S_c^F(\tilde{p}-\theta_c\tilde{\tau}^H)+S_g^H(\tilde{p}-\theta_g\tilde{\tau}^H)+S_g^F(\tilde{p}-\theta_c\tilde{\tau}^H), \quad \text{(E.1)}$$

where the balance of the world energy market now also depends on the foreign supply of gas $S_g^H(\tilde{p}_c)$; the equality $\tilde{p}_c = \tilde{p} - \theta_c\tilde{\tau}^H$ still holds, as in the analysis of the main text.

With this adjustment, the system (E.1)-(12) determines completely the equilibrium, instead of (11)-(12), in the same way as in the main analysis.

The other implication of the production of gas in the Foreign country is that this gas generates CO2 emissions. The rest of the world's CO2 emissions, instead of (15), become

$$\tilde{e}^F = \theta_c\tilde{x}_c^F + \theta_g\tilde{s}_g^F, \quad \text{(E.2)}$$

including emissions due to the consumption of the local foreign gas.

Given these changes, the analysis is the same as in the absence of gas in the Foreign country. Following the same steps as in Appendices B and C, one obtains the following result: A reduction in domestic emissions $\bar{e}^H$ causes an increase in global emissions $\tilde{e}^W$ if and only if

$$\tilde{P}(r) = S_c'\left(1-\frac{D^{H\prime}}{S_g^{H\prime}}\right)r^2+\left(D^{F\prime}-2\frac{S_c'D^{H\prime}}{S_g^{H\prime}}-\frac{S_g^{F\prime}D^{H\prime}}{S_g^{H\prime}}\right)r-D^{H\prime}\left(1+\frac{S_c'+S_g^{F\prime}}{S_g^{H\prime}}\right) \quad \text{(E.3)}$$

is negative, instead of (C.2). The comparison of (E.3) with its counterpart (C.2) in the absence of foreign gas highlights that the two expressions only differ by the intervention of $S_g^{F\prime}$ in the former, making (E.3) less likely to be negative. That means that the domestic CO2 reduction policy is less likely to cause a more-than-100% leakage rate and is, equivalently, less likely to be counter-productive, in the presence of foreign gas.

Besides this adjustment, the analysis is not qualitatively modified by the presence of gas in the rest of the world. More precisely, (E.3) has positive roots and, therefore, there exist values of $(\theta_c - \theta_g)/\theta_c$ between these roots that induce a more-than-100% leakage rate, if and only if

$$\left(\frac{\tilde{x}^F}{\tilde{x}^H}\tilde{\xi}_{D^F} + \frac{\tilde{\xi}^F_g s^F_g}{\tilde{\xi}^H_g s^H_g}\right)^2 - 4\left(\frac{\tilde{s}_c}{\tilde{x}^H}\tilde{\xi}_{S_c} + \frac{\tilde{s}^H_g}{\tilde{x}^H}\tilde{\xi}_{S^H_g} + \frac{\tilde{s}^F_g}{\tilde{x}^H}\tilde{\xi}_{S^F_g} + \frac{\tilde{x}^F}{\tilde{x}^H}\tilde{\xi}_{D^F} + \tilde{\xi}_{D^H}\right)\tilde{\xi}_{D^H}\left(\frac{\tilde{\xi}_{S_c}}{\tilde{\xi}_{S_g}}\frac{\tilde{s}_c}{\tilde{s}^H_g} + \frac{\tilde{\xi}_{S^F_g}}{\tilde{\xi}_{S^H_g}}\frac{\tilde{s}^F_g}{\tilde{s}^H_g}\right) > 0. \tag{E.4}$$

The presence of foreign gas, therefore, yields results that can be summarized like in Subsection IV.E and illustrated like in Figure 4.

F Technical Progress in the Production of Gas, and Development of Non-Carbon Energy Sources

Technical progress in the production of gas may be captured as follows. Replace the gas supply function by

$$s^H_g = \alpha S^H_g(p_g),$$

where $\alpha \geq 0$ is a multiplicative technological parameter. An increase of α from its value $\alpha = 1$ in the analysis of the main text reflects, for any gas price p_g, an improvement in production conditions causing an increase in supply.

Similarly, the development of non-carbon energy sources may be represented as follows. Replace the (residual) demand functions for (coal and gas) carbon energy sources by

$$x^F_c = \beta D^F(p_c)$$

and

$$x^H = \beta D^H(p),$$

where $\beta \geq 0$ is a multiplicative parameter measuring the capacity of production from non-carbon energy sources. A decrease in β from its value $\beta = 1$ in the analysis of the main text reflects, for any price of coal and gas, an improvement in the production of non-carbon energy sources reducing the residual demand for carbon energy sources.

As explained in the main text, this appendix presents a complement to the paper's analysis of a unilateral CO2 reduction policy. Here, instead, we do away with the public policy so as to focus the analysis on the effect of both technical progress in gas production and the development of non-carbon energy sources.

In this new context, the final energy price $\tilde{p}$ is only determined by the balance of the world energy market:

$$\beta\left(D^H(\tilde{p}) + D^F(\tilde{p})\right) = S^H_c(\tilde{p}) + S^F_c(\tilde{p}) + \alpha S^H_g(\tilde{p}).$$

At the same time, the final energy price determines domestic CO2 emissions as per

$$\theta_c\beta\left[D^H(\tilde{p}) - \alpha S^H_g(\tilde{p})\right] + \theta_g\alpha S^H_g(\tilde{p}) = \tilde{e}^H,$$

where CO2 emissions are now endogenous, rather than exogenously given by public policy in the main text.

The total differentiation of the above system with respect to the new parameters α and β, evaluated in the neighborhood of the main text's case in which $\alpha = \beta = 1$, yields

$$\begin{pmatrix} A_3 & -1 \\ A_1 & 0 \end{pmatrix} \begin{pmatrix} d\tilde{p} \\ d\tilde{e}^H \end{pmatrix} = \begin{pmatrix} (\theta_c - \theta_g) S_g^H(\tilde{p}) & -\theta_c D^H(\tilde{p}) \\ S_g^H(\tilde{p}) & -\left(D^H(\tilde{p}) + D^F(\tilde{p})\right) \end{pmatrix} \begin{pmatrix} d\alpha \\ d\beta \end{pmatrix},$$

where notations A_1 and A_3 have been introduced in Appendix B.

Inverting, and dropping the price argument for simplicity, one obtains

$$\begin{pmatrix} d\tilde{p} \\ d\tilde{e}^H \end{pmatrix} = \frac{1}{A_1} \begin{pmatrix} S_g^H & -\left(D^H + D^F\right) \\ -A_1(\theta_c - \theta_g) S_g^H + A_3 S_g^H & A_1 \theta_c D^H - A_3\left(D^H + D^F\right) \end{pmatrix} \begin{pmatrix} d\alpha \\ d\beta \end{pmatrix}. \quad \text{(F.1)}$$

Since $A_1 < 0$, the first line of system (F.1) implies the following effects of α and β on the final energy price: $d\tilde{p}/d\alpha < 0$ and $d\tilde{p}/d\beta > 0$. That means that both technical progress in the production of gas ($d\alpha > 0$) and the development of non-carbon substitutes ($d\beta < 0$) induce a decrease in the world price for coal and gas.

Let us first examine the impact of technical progress in gas production. Given that $A_1 < 0$, it follows from (F.1) that a rise in α causes a decrease in domestic CO2 emissions if and only if $-A_1(\theta_c - \theta_g) + A_3 > 0$. Using the notations of Appendix B, and rearranging, the condition becomes

$$\frac{\theta_c - \theta_g}{\theta_g} > -\frac{D^{H\prime}}{S_c' - D^{F\prime}}. \quad \text{(F.2)}$$

In other words, technical improvements in the production of gas induce a reduction of domestic CO2 emissions if and only if the rate of pollution increase from gas to coal is sufficiently high, as when gas is sufficiently less carbon intensive than coal.

In fact, condition (F.2) appears to be formally the same as condition (13): In other words, a reduction of domestic CO2 emissions warrants to produce more gas if and only if an increase in gas supply contributes to reducing domestic CO2 emissions. This condition may write

$$\frac{\theta_c - \theta_g}{\theta_g} > \tilde{r}_0.$$

This formal, and intuitive, symmetry substantiates the claim of footnote 16.

By contrast, CO2 emissions in the rest of the world are always increased as a result of technical progress in gas production. Indeed, a rise in α contributes to decreasing the energy price $\tilde{p}$ and, therefore, the foreign consumption of coal $\beta D^F(\tilde{p})$ and the resulting emissions $\tilde{e}^F = \theta_c \beta D^F(\tilde{p})$.

As far as the world CO2 emissions are concerned, there are two basic cases. First, low values of the rate of pollution increase

$$\frac{\theta_c - \theta_g}{\theta_g} \leq \tilde{r}_0$$

imply that, as a consequence of technical progress in gas production, emissions increase both in the Home country and in the Foreign country, hence at the global level unambiguously.

Second, if $(\theta_c - \theta_g)/\theta_g > \tilde{r}_0$, gas-production technical improvements lead to a decrease in domestic emissions $\tilde{e}^H$ and a decrease in the world price $\tilde{p}$, causing foreign emissions $\tilde{e}^F = \theta_c \beta D^F(\tilde{p})$ to increase. Using system (F.1) to characterize the effect on $\tilde{e}^W = \tilde{e}^H + \tilde{e}^F$ allows to obtain the following: When domestic CO2 emissions are reduced by technical progress in gas production, i.e., when $-A_1(\theta_c - \theta_g) + A_3 > 0$, this reduction is accompanied by a leakage rate

$$-\frac{d\tilde{e}^F}{d\tilde{e}^H} = -\frac{\theta_c D^{F\prime}}{-A_1(\theta_c - \theta_g) + A_3} = \frac{-\theta_c D^{F\prime}}{-(\theta_c - \theta_g)(D^{F\prime} - S_c') + \theta_g D^{H\prime}},$$

which is more than 100% if and only if

$$-\theta_c D^{F\prime} > -(\theta_c - \theta_g)(D^{F\prime} - S_c') + \theta_g D^{H\prime}.$$

This condition may write as follows:

$$\frac{\theta_c - \theta_g}{\theta_g} < \frac{-\left(D^{F\prime} + D^{H\prime}\right)}{S_c'}. \tag{F.3}$$

The comparison of the threshold at the right-hand side of (F.3) with the $\tilde{r}_0$ threshold used above immediately shows that the latter is lower than the former. Therefore, for intermediate values of the rate $(\theta_c - \theta_g)/\theta_g$, such as

$$\tilde{r}_0 < \frac{\theta_c - \theta_g}{\theta_g} < \frac{-\left(D^{F\prime} + D^{H\prime}\right)}{S_c'},$$

technical progress in the production of gas, despite a decrease in domestic CO2 emissions, contributes to increasing world CO2 emissions. However, for sufficiently high values

$$\frac{\theta_c - \theta_g}{\theta_g} \geq \frac{-\left(D^{F\prime} + D^{H\prime}\right)}{S_c'},$$

as when gas is sufficiently less carbon intensive than coal, technical progress in gas production does induce domestic and world CO2 emissions to decrease. The above results are illustrated in Figure 8.

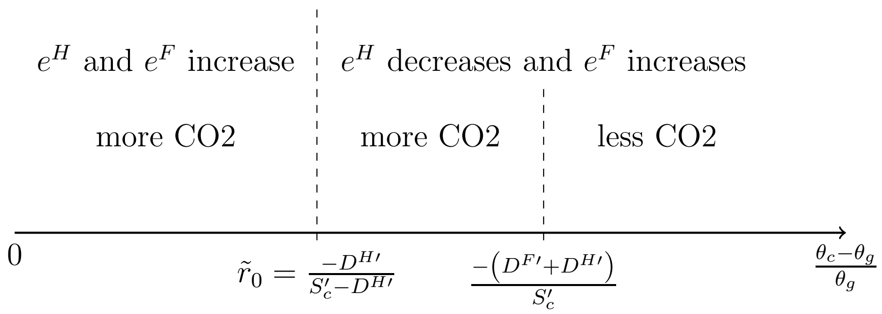

Figure 8: Technical progress in gas production, and domestic, foreign and world CO2 emissions

Let us now turn to the impact of the development of non-carbon energy sources. The system (F.1) tells how a change in β impacts domestic emissions $\tilde{e}^H$. As far as foreign emissions $\tilde{e}^F = \beta D^F(\tilde{p})$ are concerned, they are affected both directly via β, and indirectly via the price $\tilde{p}$; the effect of β on $\tilde{p}$ is also indicated by (F.1).

Formally, we obtain that

$$\begin{aligned}\frac{d\tilde{e}^W}{d\beta} &= \frac{d\tilde{e}^H}{d\beta} + \frac{d\tilde{e}^F}{d\beta} = \frac{1}{A_1}\left(A_1\theta_c D^H - A_3(D^H + D^F)\right) + \theta_c D^F + \theta_c D^{F\prime}\frac{d\tilde{p}}{d\beta} \\ &= \frac{\theta_c(D^{F\prime} - S_c') - \theta_g S_g^{H\prime}}{A_1}(D^H + D^F) + \theta_c D^{F\prime}\frac{d\tilde{p}}{d\beta}.\end{aligned}$$

Using (F.1) to replace $d\tilde{p}/d\beta$, and rearranging, we finally obtain

$$\frac{d\tilde{e}^W}{d\beta} = -\frac{1}{A_1}\left(\theta_c S_c' + \theta_g S_g^{H\prime}\right)(D^H + D^F),$$

which appears to be positive: The development of non-carbon energy sources never increases world CO2 emissions.