Working paper

WHEN CAN WE CENTRALIZE GLOBAL WARMING POLICIES AND HOW SHOULD WE DO IT?

January 31, 2019

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ABSTRACT. This paper studies how global warming, a worldwide *public bad* should be regulated, whether such a regulation can be centralized and how to do so. We impose several key constraints on the design of such a regulatory policy: heterogeneity of countries, two-tier private information both at a national and international level and full participation. We show that there is a trade-off between a better internalization of the externality under a centralized regulation, although informatively contracted at the national and international level, and a lesser internalization under a decentralized domestic regulations with a lesser informational problem. The centralized policy dominates decentralized policies, but the existence of double level of asymmetry of information may rule out the possibility of implementing the optimal regulation. When optimal regulation is not possible, second-best centralized regulations must take into account the double level of asymmetry of information.

Keywords. Asymmetric information, environmental policy, global warming, centralization.

JEL codes. Q54, D82, H23.

INTRODUCTION

Some countries refuse to join or even draw back from international agreements on the grounds that agreements are unfair to their workers and taxpayers. This argument can be contested in some cases, but cannot be ignored. What is exactly the room for maneuver of governments in front of their electors ? Many examples illustrate the lack of flexibility of domestic governments. In France, the movement *gilets jaunes*, yellow vests, gives a perfect illustration. Strikers were claiming that their purchasing power was too low to bear an increase in fuel tax. The tax increase has been suspended for at least one year. Concurrently, both politicians and citizens seem to understand the idea that global warming, as a worldwide *public bad*, should be regulated at the international level and that cooperation between countries is needed. Citizens' movement against climate change are flourishing. For instance, in 2018, ten families from Portugal, Germany, France, Italy, Romania, Kenya, Fiji, and the Saami Youth Association Sminuorra have brought a case against the EU in front of the European Court of Justice. These families, supported by NGOs, claim that the EU has failed, and continues to fail, to meet its urgent responsibilities to limit the emission of greenhouse gases (GHGs). These examples paint the deadlock in which countries are. Neither governments nor citizens want to pay for emission reduction but rather let the other countries or citizens bear the cost of ambitious reduction. Nevertheless, as every country adopts the same behavior, emissions do not reduce significantly and citizens increasingly suffer from pollution. It is the well-known free-riding problem.

The question of knowing how we can reach a ambitious centralized regulation through international agreement is still high in the agenda. According to economic theory, with perfect information, global warming should be solved by a centralized institution. The

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institution would implement a regulation that would fully internalize the global externality. In practice, countries are heterogeneous, and in particular, costs of reducing emission differ among countries. Only domestic governments know the cost information about their own country. The existence of information hidden between countries is a first issue when deciding for a centralized regulation. A second problem arises due to hidden information at domestic scale. The centralized institution cannot force countries to accept the regulation. Governments accept regulation only if they obtain citizens' approval. Citizens accept or not regulation depending on their valuation for emission reduction. Governments ignorant of these heterogeneous valuations may have difficulties to implement any regulation at domestic scale. The existence of country and citizens' heterogeneity, asymmetry of information at global and domestic scale, as well as countries' sovereignty are as many barriers to reach a centralized agreement. In this complicated context, the question of whether and how a centralized regulation can be implemented comes back on the forefront of the analysis.

Our broader motivation is to better understand the nuts and bolts of the architecture of environmental regulation in an imperfect information environment. In particular, we consider as necessary to take into account the different levels of governance in the study the possibility and the implementation of centralized regulation. In practice, global agreement does not regulate directly domestic firms and consumers. Global agreements rather enact which objectives to follow and domestic governments are in charge of implementing domestic regulations.

Our contribution. Taking into account the heterogeneity of countries and firms, private information at double-scale and constraints on participation, we derive conditions under which implementing first-best and second-best policies with a central regulator is possible. We find that the asymmetry of information may be too high for implementing first-best centralized regulations. At the first best, regulations will be the same in every country. In a second-best environment, optimal regulations depend on country-specific parameters and as such, differ in every country. This result goes against a global agreement that would consist in a unique price for carbon.

In our model, when countries do not compel to centralized regulation, they non-cooperatively implement domestic regulations. Countries' decisions to undertake such domestic policies depend on their domestic costs and benefits from pollution reduction. This outside option, that occurs in case of failure of the general agreement, differs from the business as usual scenario more commonly assumed in the literature. We believe that our assumption may be more realistic. In the current reality if countries take part in environmental agreement, their domestic policies aim at respecting the agreement. For countries which refuse the agreement, they still often implement, in a non-cooperative way, some -less ambitious-domestic regulations .

As a first pass, we study this *non-cooperative equilibrium in which countries implement their domestic regulations*. In each country, there is a continuum of firms which produce and sell their output on a competitive domestic market. Production generates emissions which contribute to a negative worldwide externality. By incurring quadratic abatement costs, a firm can reduce its emissions. These costs depend on a *firm-specific parameter*, capturing the fact that all the firms do not have access to the same technology. Importantly, this efficiency parameter is private information of the firms, it is the *first source of asymmetric information* in our model. To correct pollution, domestic regulators introduce domestic markets for firms to trade pollution permits and they compel firms either to abate or to buy permits for their emissions. Domestic governments not only have to take into account private information of heterogeneous firms but also participation constraints of firms and consumers. We find that at the first-best, domestic regulations are the same in every countries. First-best regulations correct domestic externalities but undesirable polluting emissions remain at a global scale. We find conditions under which costs of firms' private information is too high to implement first-best domestic regulations. When this happens, domestic regulators set up second-best domestic regulations. Such regulations are costly for regulators that give up rent to some firms in order to provide the good incentives and to respect the participation constraints. We derive domestic second-best prices for emission permits on domestic markets. Prices -being lower than in the first-best- correct less the externality. Of importance, domestic second-best prices depend on country-specific demand parameters. We find that second-best domestic regulations thus differ in each country.

Once derived what happens when countries do not sign the agreement, we study the *centralized regulation*. A central regulator, embodying an international institution, has the delegated power of implementing regulations in each country. Sovereign countries must find optimal to participate to the agreement. In other words, the regulation must raise greater payoffs than the non-cooperative domestic regulations scenario. To foster cooperation, the central regulator uses lump-sum inter-countries' transfers. Importantly, countries are *heterogeneous with respect to a domestic demand shock*. This shift parameter might embody fluctuations in domestic economic conditions, heterogeneity in consumer tastes across countries and the like. It constitutes *the second source of asymmetry of information* as the shock parameter is not known by the central regulator. Countries heterogeneity and private information, full participation and budget balance are key and stringent constraints. The global first-best is a unique market with a uniform price for emissions that fully internalizes the worldwide externality. We show that due to the participation and incentive constraints, first-best regulation might not be feasible. *We derive conditions under which informational costs are too high to implement the global first-best. We further study the central regulation in a second-best environment with two layers of asymmetry of information.* The central regulator must resort to give informational rents to countries and domestic firms. Interestingly, we find that the global second-best regulation cannot be implemented as a unique market for polluting permits but instead as nation-wide markets with different prices in each country. These prices are lower than the global first-best price and depend on the expected value of the domestic demand shock parameters.

The comparison between domestic and centralized regulation highlight an interesting trade-off. Centralized regulation allows more ambitious regulation even in second-best environment. In that sense, a central regulator is always preferred to non-cooperative domestic regulations. Nevertheless, implementability constraints are harder to satisfy. The central regulator faces two levels of asymmetry of information. In addition to rents distributed to firms at domestic scale, countries also receive rents. When informational costs outweigh benefits of pollution reduction, centralized regulation cannot be implemented. In this way, we show the existence of a *trade-off* between a better internalization of the externality under a centralized regulation with double level of asymmetric information and a smaller internalization under a domestic regulation with one level of asymmetric information.

Our model opens a discussion on the possibilities of implementing a centralized regulation that is budget-balanced, in a context where countries and domestic firms are heterogeneous, private information takes place at international and domestic scales and participation constraints of countries, firms and consumers are respected. Our model is, to our knowledge, the first to study global environmental agreement in such a rich environment.

A QUICK OVERVIEW OF THE LITERATURE.

The literature on the architecture of environmental agreement has being flourishing in the last decade. Among others, Aldy and Stavins (2007) discuss its main stakes and call for more research in this area. Our work goes in that direction and attempt to develop a theoretical tool to study and compare different architecture designs to solve the global warming problem. For that purpose, we use the mechanism design approach -as advocated by Baliga and Maskin (2003)-.[1]

In this field, Spulber (1988) studies the problem of domestic regulation in a context where domestic firms have private information about their cost of reducing pollution. He highlights the existence of a trade-off between benefits of pollution abatement and benefits from the economic activity which generates that pollution as an unwanted by-product. He shows that if the expected informational costs exceed net gains from trade in the product market net of external damages, then the full information optimum is not attainable by direct revelation mechanism. We follow Spulber (1988) in designing a model in which there is asymmetry of information between domestic firms and regulator and take it to the next step by integrating the main features of his model inside a global agreement model. By keeping the domestic scale, we manage to describe an economy with clear rational for polluting. The link between production and emissions is well specified. It differs from the assumption often met in the international agreement literature that emissions are taken as given.

The closest article of ours is Martimort and Sand-Zantman (2013). They study the feasibility and performances of simple mechanisms to implement international environmental agreements to reduce global warming in context of multilateral externalities between countries. They highlight that, in presence of asymmetric information, there is a trade-off between two central goals: participation to the central agreement and incentives to reduce significantly the level of emissions. In this context, market could fail to reach the first best and, in that case, second best mechanisms would need to be considered. Martimort and Sand-Zantman (2013) underline the one limit of their model is not to include a second level of analysis: the domestic scale. Starting from their work and the assessment that the domestic level is not integrated into the design of global agreement, we develop a model with two level of decisions: national and international. In each level we consider that there is some asymmetry of information. In doing so, we develop a more complete analysis of the design of environmental agreement architecture in incomplete information setting. This allows us to derive and compare regulations with two different levels of governance.

A part of literature in environment economics studies the different levels of governance. Many articles investigate characteristics of a given level of governance -in particular, international and domestic scales have been widely studied-. It is however not common that articles discuss explicitly the complexity arising from the superposition of these levels of governance. Shobe and Burtraw (2012) compare respective advantages and drawbacks of the domestic versus the national regulation in the US. Their arguments are numerous,

[1]They survey some of the main findings of this literature and recall the relevance of this approach for the economics of the environment.

very interesting and can easily be extrapolated to the case of national versus international governance. Their analytical work however does not present a theoretical model. We try to fill this gap, fully aware that we are only addressing some aspects of the intricate problem of multiple layers of governance.

Organization of the paper. Section 1 presents the model as well as three relevant benchmarks: 'business as usual', domestic first-best and global first-best. Section 2 analyzes the domestic regulation a government shall implement to maximize its own country's welfare. Section 3 investigates a centralized regulation set up by a central planer with asymmetry of information on domestic firms but complete information on countries' parameters. Finally, section 4 examines the case of a centralized regulation set up by a central planer in a double scale of asymmetry of information. Proofs are relegated to an Appendix.

1. MODEL AND RELEVANT BENCHMARKS

Our goal in this paper is to study how global warming, a worldwide *"public bad"* should be regulated, whether such regulation should be decentralized towards domestic governments and how it should be so. For that purpose, we consider an economy with n countries indexed by the subscript $i \in \{1, .., n\}$. Each country is viewed as an island, with consumers and firms trading only on the domestic market. The only interaction across countries comes from the worldwide externality that local productions in each country induce.

Firms. There is a continuum of firms of mass one in each country i. A firm which produces a quantity q (normalizing marginal cost at zero) sells this output on the domestic market at the competitive price r_i. One unit of output generates one unit of emissions which contributes to a negative worldwide externality. For simplicity, we normalize the firm's marginal costs at zero focusing only on abatement costs. Again for tractability, those abatement costs are supposed to be quadratic, $\frac{a^2}{2}$. firm which produces q units, and exerts abatements a, produces emissions e as given by

$$e = q - a + \theta$$

where the shock θ is a firm-specific parameter that reflects heterogeneity in abatement technologies. Those shock parameters are independently drawn from the same common knowledge cumulative distribution $F(\cdot)$ in each country. This distribution has compact support $\Theta = \left[\underline{\theta}, \overline{\theta}\right]$ and $\mathbb{E}_\theta(\theta) = \theta_e$.

To correct the negative pollution externality, firms in country i may trade pollution permits at price p_i on a domestic market. Beforehand, all firms are endowed with the same quantity of permits R_i.[2] Of course, at equilibrium on the market for permits, R_i should equal to total emissions E_i.

Taking into account the cost of abatements and the possibility of trading permits, the profit $U_i(\theta)$ of a type-θ firm in country i can be expressed in terms of its output and emissions as

$$U_i(\theta) = \max_{(q,e)} r_i q - \frac{1}{2}(q - e + \theta)^2 - p_i(e - R_i) + \tau_i. \tag{1.1}$$

[2]We follow Martimort and Sand-Zantman (2013) in assuming uniform distribution of rights.

τ_i is a lump-sum transfer paid to domestic firms by domestic consumers/taxpayers. Firms choose their production and emissions (in fact, their abatements) (q, e) so as to maximize profits on those competitive markets. The firm's competitive behavior on the market for permits implies that the marginal costs of abatement is equal to the price of permits while its competitive behavior on the output market i requires that price there is also equal to price of permits :

$$p_i = q - e + \theta \text{ and } r_i = p_i. \tag{1.2}$$

We also assume that abatement efforts remain non-negative under all circumstances below. From (1.2), and aggregating over the whole continuum of firms in country i, total emissions E_i in country i and aggregate production Q_i satisfy:

$$p_i = Q_i - E_i + \theta_e. \tag{1.3}$$

Consumers. In country i, the representative consumers' net surplus is defined as:

$$S(Q_i) - (r_i + \beta_i)Q_i - \frac{1}{n}\left(E_i + \sum_{j\neq i} E_j\right) - \tau_i \tag{1.4}$$

where Q_i is domestic consumption, β_i is a shift parameter which is country i-specific, E_j is aggregate emissions from country $j \neq i$ and τ_i is the lump-sum transfer from consumers to firms. We assume that S is increasing and strictly concave. Domestic demand writes as $D(r_i + \beta_i)$ where $D = S'^{-1}$ is decreasing.

The shock β_i might embody fluctuations in domestic economic conditions, heterogeneity in consumer tastes across countries and the like. Later, we will assume that firms, consumers and regulators in country i have private information on this parameter. The rest of the world remains ignorant of the realization of this shock.

The above expression makes clear that consumers in country i suffer not only from domestic pollution E_i, but also from emissions coming from elsewhere, namely $\sum_{j\neq i} E_j$. Consumers take these emissions as granted, meaning that they ignore the link between emissions, domestic production, and thus their own consumption.

Taking then into account (1.2) and (1.3) actually gives the expression of aggregate emissions E_i in terms of the price of permits p_i as:

$$E_i = D(\beta_i + p_i) - p_i + \theta_e. \tag{1.5}$$

Welfare in country i. Country i's welfare is the sum of consumer's surplus and the firms' overall profits. Expressed in terms of the price of permits, and inserting (1.2) into (1.1) and (1.5) to obtain the expression of those surplus and profits, welfare can be written as:

$$W_i(\boldsymbol{p}, \boldsymbol{\beta}) = \omega(p_i, \beta_i) - \frac{1}{n}\sum_{j\neq i}\left(D(\beta_j + p_j) - p_j + \theta_e\right)$$

where $\boldsymbol{p} = (p_1, ..., p_n)$, $\boldsymbol{\beta} = (\beta_1, ..., \beta_n)$ are respectively the vector of prices on permits in each country and the vector of their demand shocks. The function $\omega(p_i, \beta_i)$ stands for the welfare in country i in the hypothetical scenario where this country would be alone on earth as:

$$\omega(p_i, \beta_i) = S(D(\beta_i + p_i)) - \left(\beta_i + \frac{1}{n}\right) D(\beta_i + p_i) - \frac{1}{2}p_i^2 + \frac{1}{n}p_i - \frac{1}{n}\theta_e.$$

For technical reasons, we assume that this function is concave with respect to the price $\frac{\partial^2}{\partial p_i^2}\omega(p_i, \beta_i) \leq 0 \;\Leftrightarrow\; (D'(\beta_i + p_i) - 1) + \left(p_i - \frac{1}{n}\right) D''(\beta_i + p_i) \leq 0.$

The *BAU* scenario. Here, there is no public intervention. First, firms receive no lump-sum transfers from consumers, $\tau_i = 0$. Second, there is no market for permits and everything happens as if $p_i^B \equiv 0$. As a result, firms do not care about the impact of their emissions on others' welfare and abatements are zero, $a = 0$. The output price is equal to the marginal cost of production, $r_i^B = 0$. Emissions in country i are thus equal to $E_i^B = Q_i^B + \theta_e = D(\beta_i) + \theta_e$.

With these normalizations, firms make zero profit and welfare in country i writes as:

$$W_i(\boldsymbol{p}^B, \boldsymbol{\beta}) = \omega(0, \beta_i) - \frac{1}{n}\sum_{j \neq i} (D(\beta_j) + \theta_e).$$

Pigovian prices for domestic regulations. Under complete information on the domestic firms' technologies, welfare in country i would be maximized at the domestic Pigovian price that internalizes the pollution externality in country i. Each unit of pollution is paid at its domestic social value:

$$p_i^D = \frac{1}{n} \quad \forall i \in \{1, .., n\}$$

Although this price is the same in all countries, it only corrects for the externality problem at the domestic level and leaves uncorrected the externality exerted abroad.

Pigovian price for a worldwide regulation. Suppose now that lump-sum transfers across countries are feasible. Total welfare is thus defined as $\sum_{i=1}^n W_i(\boldsymbol{p}, \boldsymbol{\beta})$. A welfare-maximizing regulation could a priori specify different prices on each country-specific market for permits. In fact, since each unit of production wherever its origin contributes equally to the overall externality, all firms in all countries should pay the same price for permits. The Pigovian price for a worldwide regulation differs from the domestic Pigovian seen above because that price now corrects the worldwide negative externality:

$$p^G = 1.$$

This price is thus the same across all markets. Under complete information, Pigovian prices, whether targeted to domestic or global regulations, neither depend on the distribution of firms' efficiency parameters θ nor on the country-specific demand parameters $\boldsymbol{\beta}$. These prices are only determined by the level of externality they are supposed to correct; either locally or globally.

However, optimal emissions are not the same in all countries. Emissions in country i are given by, $E_i^D = D(\beta_i + \frac{1}{n}) - \frac{1}{n} + \theta_e$ and $E_i^G = D(\beta_i + 1) - 1 + \theta_e$, in the domestic and global optimum respectively. As at the optimum $E_i = R_i$, the number of rights allowed also differs in all countries both in domestic and global optimum. Optimal emissions depend on the size of the domestic demand shock, and in this way adapt to domestic economy. Emissions and number of distributed rights are lower in countries hit by less favorable demand shocks.

Under asymmetric information on costs and demand parameters; second-best prices, whether set at the local or at the global level, also depend on local cost and demand. We now turn to the characterization of those prices.

2. DOMESTIC REGULATION UNDER ASYMMETRIC INFORMATION

Consider the scenario where the government in country i is uninformed on both the cost parameters of domestic firms and demand parameters $\boldsymbol{\beta_{-i}} = (\beta_1, \ldots, \beta_{i-1}, \beta_{i+1}, \ldots, \beta_n)$. We thus look for a Bayesian-Nash equilibrium in which countries non-cooperatively choose their domestic regulations, namely a price p_i at which permits are traded on the domestic market, a quantity of allowed permits which of course will be equal to the total emissions $R_i = E_i$ and a lump-sum transfer τ_i, to maximize domestic welfare under those informational requirements.

Incentive and Participation Constraints. Firms are privately informed on their efficiency parameter θ. A firm whose abatement efficiency parameter is θ can pretend being slightly less efficient $\theta + d\theta$ (with $d\theta > 0$) and still emit the same quantity while buying less permits. This means that this firm with type θ saves $p_i d\theta$ and gets this extra amount in terms of information rent on the market for pollution permits. Formally, incentive compatibility thus requires

$$\dot{U}_i(\theta) = -p_i. \tag{2.1}$$

A domestic regulation (p_i, E_i, τ_i) must give firms a greater profit than what they get in the BAU scenario; i.e., 0 with our previous normalizations. From (2.1), this participation constraint is of course more stringent for the firm which is the least efficient in abating $\overline{\theta}$. Imposing participation of all firms thus requires:

$$U_i(\overline{\theta}) \geq 0.$$

Using the expressions of the number of equilibrium permits and the domestic price given in (1.2), (1.3) and (1.5), this condition becomes:

$$U_i(\overline{\theta}) \geq 0. \tag{2.2}$$

To be feasible, a domestic regulation (p_i, E_i, τ_i) must also give more surplus to consumers than what they get in the BAU scenario, which actually corresponds to a triplet $(0, D(\beta_i) + \theta_e, 0)$. This condition puts an upper bound on the lump-sum transfers that can be distributed to the firms, namely

$$S(D(\beta_i + p_i)) - (\beta_i + p_i)D(\beta_i + p_i) - \frac{1}{n}E_i - \frac{1}{n}\mathbb{E}_{\boldsymbol{\beta_{-i}}}\left(\sum_{j\neq i} E_j\right) - \tau_i$$

$$\geq S(D(\beta_i)) - \left(\beta_i + \frac{1}{n}\right)D(\beta_i) - \frac{1}{n}\theta_e - \frac{1}{n}\mathbb{E}_{\boldsymbol{\beta_{-i}}}\left(\sum_{j\neq i} E_j\right).$$

Thanks to the additive separability, we obtain the following simpler condition independent of foreign emissions:

$$S(D(\beta_i+p_i))-(\beta_i+p_i)D(\beta_i+p_i)-\frac{1}{n}E_i-\tau_i \geq S(D(\beta_i))-\beta_i D(\beta_i)-\frac{1}{n}(D(\beta_i)+\theta_e). \tag{2.3}$$

or expressing in terms of the local part of domestic welfare:

$$\omega(p_i,\beta_i)+\frac{1}{2}p_i^2-p_iD(\beta_i+p_i)-\tau_i \geq \omega(0,\beta_i). \tag{2.4}$$

Implementability Condition. Taking together (2.2) and (2.4) gives us a condition that must be satisfied by any implementable regulation (p_i, E_i, τ_i).

Lemma 1 *A domestic regulation (p_i, E_i, τ_i) is incentive-feasible if and only if:*

$$\omega(p_i,\beta_i)-\omega(0,\beta_i) \geq p_i\left(\overline{\theta}-\theta^e\right). \tag{2.5}$$

The feasibility constraint (2.5) is a fundamental requirement on any domestic regulation constrained by asymmetric information. A p_i is incentive-feasible if benefits from pollution reduction that it induces outweighs the informational costs of implementing such policy. In this way, asymmetric information may hinder the implementation of the domestic Pigovian price as we will see below.

More precisely, under complete information, the term $p_i\left(\overline{\theta}-\theta^e\right)$ would disappear and the so simplified condition $\omega(p_i,\beta_i) \geq \omega(0,\beta_i)$ would be trivially satisfied by the domestic Pigovian price. Under asymmetric information, incentive compatibility requires to give the same subsidy τ_i to all firms. This subsidy must be large enough to induce the least efficient firm $\overline{\theta}$ to participate. Firms with more efficient technologies would be ready to participate rather than opting for the *BAU* scenario even with lower subsidies. Those firms enjoy thus an information rent. The overall value of this rent taken over the whole distribution of firms is precisely the quantity $p_i\left(\overline{\theta}-\theta^e\right)$ on the right-hand side of (2.5).

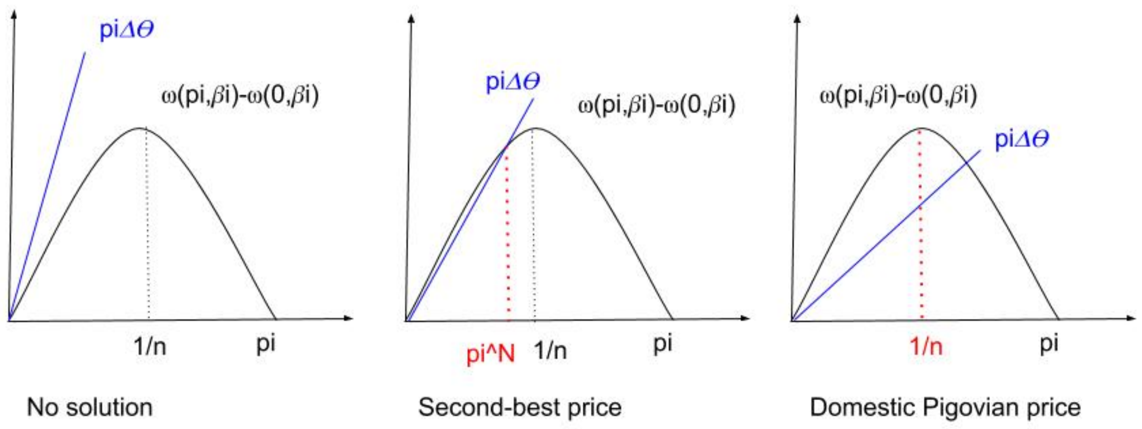
To better understand the importance of feasibility constraint (2.5), Figure 1 below represents on the set of feasible price under asymmetric information. As uncertainty on the firms' technologies diminishes, i.e., $\Delta\theta=\overline{\theta}-\theta^e$ decreases, the cost of information rent $p_i\Delta\theta$ turns clockwise. The expected gains of moving from the *BAU* scenario to a market for permits at price p_i can now be maximized at the domestic Pigovian price $p^D=\frac{1}{n}$. Otherwise, the highest feasible price is obtained when those two curves intersect at a lower price. Note from the figure that the feasible set has a non-empty interior only when

$$\frac{\partial}{\partial p_i}\left(\omega(p_i,\beta_i)-\omega(0,\beta_i)\right)|_{p_i=0} > \overline{\theta}-\theta^e \Leftrightarrow -\frac{1}{n}\left(D'(\beta_i)-1\right) > \overline{\theta}-\theta^e;$$

a condition that will be supposed to hold throughout.

Symmetric Bayesian-Nash equilibrium. A symmetric Bayesian-Nash equilibrium is a collection of mappings $\{(p(\cdot),E(\cdot),\tau(\cdot))\}$ that, for each country i, associate to each realization of the domestic demand parameter β_i an optimal regulation price $p(\beta_i)$, a quantity of permits $E(\beta_i)$ and a lump-sum transfer $\tau(\beta_i)$. These mappings must be an

FIGURE 1.— The feasibility set.



equilibrium fix point.[3] More precisely, expressing $E(\beta_i)$ from $p(\beta_i)$ by means of (1.5) and observing that transfers τ cancel out in the objectives, $p(\beta_i)$ must solve

$$(2.6) \qquad p(\beta_i) \in \arg\max_{p_i} \omega(p_i, \beta_i) - \frac{1}{n}\mathbb{E}_{\boldsymbol{\beta}_{-i}} \left(\sum_{j \neq i} (D(\beta_j + p(\beta_j)) - p(\beta_j) + \theta_e) \right)$$

subject to the incentive-feasibility condition (2.5).

Thanks to the additive separability of the regulator's objective function between domestic benefits and worldwide externality and the fact that the incentive-feasibility condition only depends on local instruments, this Bayesian-Nash equilibrium is actually achieved with dominant strategy. Moreover, the externality term coming from pollution elsewhere, $\frac{1}{n}\mathbb{E}_{\boldsymbol{\beta}_{-i}} \left(\sum_{j \neq i} (D(\beta_j + p(\beta_j)) - p(\beta_j) + \theta_e) \right)$, does not affect the optimal domestic regulation.

Equilibrium Characterization

Had domestic regulation taken place under complete information on the firms' technologies, the incentive-feasibility condition (2.5) would be absent of this optimization problem. The equilibrium price would then be equal to the domestic Pigovian price $p^D = \frac{1}{n}$ in all countries. Under asymmetric information, this local Pigovian price might not always be implementable because it may fail to satisfy the incentive-feasibility condition (2.5).

IMPLEMENTABILITY OF THE DOMESTIC PIGOVIAN PRICE. Condition (2.5) illustrates an important trade off between the domestic regulator's desire to correct externalities and the fact that doing so requires giving up information rents to domestic firms. Investigating

[3] Since countries are symmetric up to their demand shock parameters, we are able, for the sake of clarity, to drop the indexes i in the expressions of price, quantity of permits and transfers at the equilibrium. Remark, that in a more sophisticated version of our model, countries demand functions may differ, and in this case, countries' indexes would remain.

whether the Pigovian price can be implemented boils down to checking whether (2.5) holds for the domestic Pigovian price $p^D = \frac{1}{n}$. This condition writes as:

$$\omega\left(\frac{1}{n}, \beta_i\right) - \omega(0, \beta_i) \geq \frac{1}{n}\left(\overline{\theta} - \theta^e\right). \tag{2.7}$$

To illustrate, consider the case of a quadratic surplus $S(Q) = aQ - \frac{1}{2}Q^2$. Demand is linear, $D(\beta_i + p(\beta_i)) = a - \beta_i - p(\beta_i)$, and Equation (2.7) becomes:

$$\frac{1}{n} \geq \overline{\theta} - \theta^e. \tag{2.8}$$

The size of the domestic externality must be large enough compared to the information problem to ensure that domestic Pigovian prices can be implemented.[4]

Second-Best Domestic Regulation. When the Pigovian price does not respect the implementability constraint (2.5), the price of permits must be reduced to decrease information rent and relax (2.5).

Proposition 1 *In a Bayesian-Nash equilibrium, with the BAU scenario as fall-back option, the second-best domestic price $p^N(\beta_i)$ in country i is lower than the domestic Pigovian price:*

$$p^N(\beta_i) = \frac{1}{n} - \frac{\lambda_i}{1+\lambda_i}\frac{\left(\overline{\theta} - \theta^e\right)}{1 - D'(\beta_i + p^N(\beta_i))} \leq \frac{1}{n} \quad \forall i. \tag{2.9}$$

where $\lambda_i \geq 0$ is the Lagrangian multiplier for constraint (2.5).

Because of asymmetric information, the second-best domestic price is always lower than the domestic Pigovian price. The price is negatively distorted in order to limit the rents distributed to efficient firms. The size of the distortion may a priori depend on the distribution of the firms' efficiency parameters but also on the domestic demand shock β_i. It is an important point. While under complete information, the domestic Pigovian price only depends on the externality; the second-best price now depends on demand; a result that, of course bears some resemblance with the well-known Ramsey-pricing distortions familiar from public economics.

Importantly, in our context, this dependence on demand means that the domestic regulator's information on demand shock matters. Any centralized regulation that could be designed to improve on this Bayesian-Nash equilibrium may thus have to collect such information.

The domestic second-best prices (2.9) now depend on domestic demand shock parameters. They thus differ in each country. As we depart from the optimum regulation, countries adapt their second-best domestic regulations to the negative demand shock

[4]In the case of a linear demand, the implementability condition (2.8) is the same in all countries -as it does not depend on domestic shock β_i. With more general demand, the implementability condition (2.7) depends on β_i, and as such, differs among countries. There may be cases in which condition (2.7) is respected for some countries but not others. Countries hit by small demand shocks are able to implement the domestic first-best regulation, while countries hit by stronger shocks cannot.

they face. A direct consequence is that a unique worldwide market in which permits are traded is no longer possible. Independent and differentiated markets, in each country, are required to implement the second-best regulations. The only exception is the case of the linear demand considered before. With linear demand, second-best prices do not depend on the negative demand shocks. Only in this case, the price of carbon is the same in all countries in a second-best environment; constraint (2.5) is saturated and the second best-price with linear demand is given by :

$$p^N = \frac{2}{n} - \left(\overline{\theta} - \theta_e\right), \quad \forall i.$$

Transfers are used to compensate the least efficient firms whose cost of regulation would be too high to make a positive profit otherwise. Yet, transfers also reduce consumers' welfare who pay for it. Efficiency thus requires that the participation constraint of the least efficient firms (2.2) is saturated at the equilibrium. As transfers are uniform, the saturated constraint (2.2) gives the value of the transfers at the equilibrium, namely:

$$\tau^N(\beta_i) = \frac{1}{2}p^N(\beta_i)^2 + p^N(\beta_i)\left(\overline{\theta} - \theta_e\right) - p^N(\beta_i)D\left(\beta_i + p^N(\beta_i)\right). \tag{2.10}$$

The size of transfers depends on domestic second-best price, shock on domestic demand and firms' efficiency parameters. Transfers depend negatively on the demand as they compensate for the loss of demand suffered by domestic firms.

Countries are similar up to the negative demand shocks that affect them locally. Prices differ among countries depending on the strength of the domestic demand shocks. At the equilibrium, the feasibility constraint (2.5) is saturated and we have:

$$\omega\left(p^N(\beta_i), \beta_i\right) - \omega\left(0, \beta_i\right) = p^N(\beta_i)(\overline{\theta} - \theta_e).$$

Taking the derivative of this equation with respect to β_i and rearranging terms gives:

$$\dot{p}^N(\beta_i) = -\frac{\omega_{\beta_i}\left(p^N(\beta_i), \beta_i\right) - \omega_{\beta_i}\left(0, \beta_i\right)}{\omega_p\left(p^N(\beta_i), \beta_i\right) - \left(\overline{\theta} - \theta_e\right)}. \tag{2.11}$$

From the first-order condition of the domestic regulator's maximization problem :

$$\omega_p\left(p^N(\beta_i), \beta_i\right) = \frac{\lambda_i}{1+\lambda_i}(\overline{\theta} - \theta_e) \leq \overline{\theta} - \theta_e.$$

The denominator of (2.11) is thus negative, and the sign of (2.11) is the sign of the derivative of welfares' difference with respect to demand shock. This sign itself depends on whether demand is convex or concave.

Lemma 2 *When $D(\cdot)$ is convex (resp. concave), $\dot{p}^N(\beta_i) \leq 0$ (resp. ≥ 0).*

At the optimum, optimal domestic emissions are such that $E^N(\beta_i) = D\left(\beta_i + p^N(\beta_i)\right) - p^N(\beta_i) + \theta_e$. The derivative of the emissions with respect to domestic chock writes: $\dot{E}^N(\beta_i) = \left(1 + \dot{p}^N(\beta_i)\right) D'\left(\beta_i + p^N(\beta_i)\right) - \dot{p}^N(\beta_i)$. When $\dot{p}^N(\beta_i) \leq 0$, emissions are non-decreasing with the size of the negative demand shock β_i, i.e., $\dot{E}^N(\beta_i) \geq 0$. And when $\dot{p}^N(\beta_i) \geq 0$, emissions are non-increasing, i.e., $\dot{E}^N(\beta_i) \leq 0$.

3. CENTRALIZED REGULATION UNDER COMPLETE INFORMATION ON DOMESTIC DEMANDS

We now examine the design of a centralized regulation that would be run by a hypothetical central planer. This central planner stands as a metaphor for an international agreement. His objective is thus to maximize global welfare. Such a centralized regulation is viewed as a collection of n different domestic regulations cum a set of compensatory transfers between countries. More precisely, the central regulator supersedes domestic regulator in each country by recommending a domestic regulation $\{(p, E, \tau)\}$ and a set of international compensatory transfers across countries T. Of course, such scheme satisfies incentive compatibility and participation constraints so as each country complies with these suggestions. On top, compensatory payments must remain budget-balanced.

Such a regulation first consists of price p at which permits are traded on the domestic market, a quantity of allowed permits E, and as before a lump-sum transfer τ paid by domestic consumers and received by domestic firms. The novel instrument available to foster worldwide cooperation and make each country internalize the impact of its own emissions on others is a set of compensatory transfers *from* and *towards* this country. Payments given compensate other country for reducing their emissions. Payments received compensate country i for having reduced its own emissions. By construction, those payments are budget balanced.

In a first scenario, we assume that *both the central regulator and the countries* know the whole collection of demand shock parameters $\boldsymbol{\beta} = (\beta_1, \ldots, \beta_n)$ that affect countries. Of course, this regulator remains ignorant of the cost parameters of domestic firms. These informational assumptions have two consequences. First, any domestic regulation, even when suggested by this central regulator, is still bound to satisfy domestic incentive and participation constraints. Second, the planner can condition the domestic regulation in country i on demand shocks that affect emissions abroad to facilitate coordination if needed.

Compensatory Transfers. At the Bayesian-Nash equilibrium of domestic regulations, country i emits a quantity of pollution $E^N(\beta_i)$. This quantity takes into account the local negative externality suffered in country i, but does not take into account the negative externality suffered by other countries $j \neq i$. Those other countries would eventually be willing to pay for country i to reduce its emissions. At the centralized regulation, if country i emits the lower amount E instead of $E^N(\beta_i)$, country j's welfare (for $j \neq i$) increases by $\frac{1}{n}\left(E^N(\beta_i) - E\right)$. This is the amount that j is ready to pay i so as to have the latter reduce its emissions:

$$T(\beta_i) = \frac{1}{n}\left(E^N(\beta_i) - E\right). \tag{3.1}$$

Symmetrically, if a centralized regulation is adopted and all countries $j \neq i$ reduce their own emissions from $E^N(\beta_j)$ to E, the welfare gain for country i is $\frac{1}{n}\sum_{j\neq i}\left(E^N(\beta_j) - E\right)$. From this, it follows that country i pays to country $j \neq i$

$$T(\beta_j) = \frac{1}{n}\left(E^N(\beta_j) - E\right). \tag{3.2}$$

Of course, the set of bilateral transfers so constructed is budget balanced since

$$\sum_{(i,j), j\neq i} T(\beta_i) + T(\beta_j) = 0.$$

Domestic Incentive and Participation Constraints. For the sake of completeness, we now express how domestic regulation affects domestic consumers and firms' payoffs. The novelty here comes from the fact that, whenever the centralized regulation is found unattractive, by either domestic firms or domestic consumers, the next best outside option is to opt out for the Bayesian-Nash domestic regulation. Thanks to the additive separability of emissions in the expression of each country's welfare, we already noticed that this equilibrium strategy is in fact a dominant strategy. It is thus independent of the emissions of other countries. In addition, whenever a given country refuses the centralized regulation and opts for its Bayesian-Nash domestic regulation, the other countries will follow by adopting the same behavior. Implicit in this statement is the assumption that, the approval of all the countries is necessary to implement the centralized solution.

From these remarks, it follows that incentive compatibility requires that a type θ-firm in country i still receives an information rent as stipulated in (2.1). Turning to the condition for acceptance in country i, a centralized regulation $\{(p,E,\tau)\}_{i\in\{1,\dots,n\}}$ must give to domestic firms a greater profit that what they get at the Bayesian-Nash equilibrium with domestic regulations $\{\left(p^N(\beta_i),E^N(\beta_i),\tau^N(\beta_i)\right)\}_{i\in\{1,\dots,n\}}$. We define $U^N(\overline{\theta})$ as the profit of the least efficient firm in country i at the Bayesian-Nash equilibrium with domestic regulation $\left(p^N(\beta_i),E^N(\beta_i),\tau^N(\beta_i)\right)$. Imposing participation of all firms in country i requires:

$$U(\theta)\geq U^N(\theta)\quad \forall\theta\in\Theta.$$

When the centralized regulation induces a greater price than the Bayesian-Nash equilibrium domestic regulation, the incentive compatibility conditions (2.1) imply that $\dot{U}(\theta)=-p\leq -p^N(\beta_i)=\dot{U}^N(\theta)$ and thus the latter participation constraint holds for all types θ if it holds for the least efficient one $\overline{\theta}$. This leads us to rewrite the acceptance condition for domestic firms in a simpler form as:

$$U(\overline{\theta})\geq U^N(\overline{\theta}).$$

Using the expressions of the number of equilibrium permits and the domestic price given in (1.2), (1.3) and (1.5), this condition can again be simplified as:

$$pD(\beta_i+p)-\frac{1}{2}p^2-p(\overline{\theta}-\theta_e)+\tau_i\geq p^N(\beta_i)D(\beta_i+p^N(\beta_i))-\frac{1}{2}(p^N(\beta_i))^2-p^N(\beta_i)(\overline{\theta}-\theta_e)+\tau_i^N(\beta_i). \tag{3.3}$$

To be feasible, a centralized regulation $\{(p,E,\tau)\}_{i\in\{1,\dots,n\}}$ must also give more surplus to consumers in country i than what they get in the domestic regulation scenario $\left(p^N(\beta_i),E^N(\beta_i),\tau^N(\beta_i)\right)$:

$$S(D(\beta_i+p))-(\beta_i+p)D(\beta_i+p)-\frac{1}{n}E-\frac{1}{n}\left(\sum_{j\neq i}E_j\right)-\sum_{j\neq i}T(\beta_i)+\sum_{j\neq i}T(\beta_j)-\tau$$

$$\geq S\left(D\left(\beta_i+p^N(\beta_i)\right)\right)-\left(\beta_i+p^N(\beta_i)\right)D\left(\beta_i+p^N(\beta_i)\right)-\frac{1}{n}E^N(\beta_i)-\frac{1}{n}\left(\sum_{j\neq i}E^N(\beta_j)\right)-\tau^N(\beta_i).$$

This expression takes into account that all compensatory transfers from and to country i will end up being paid by or redistributed to domestic consumers. Simplifying the above expression, we obtain:

$$\omega(p,\beta_i)+\frac{1}{2}p^2-pD(\beta_i+p)-\frac{1}{n}\left(\sum_{j\neq i}E_j\right)-\sum_{j\neq i}T(\beta_i)+\sum_{j\neq i}T(\beta_j)-\tau \tag{3.4}$$

$$\geq \omega\left(p^N(\beta_i),\beta_i\right)+\frac{1}{2}\left(p^N(\beta_i)\right)^2-p^N(\beta_i)D\left(\beta_i+p^N(\beta_i)\right)-\frac{1}{n}\left(\sum_{j\neq i}E^N(\beta_j)\right)-\tau^N(\beta_i).$$

Now inserting the expressions of bilateral transfers from (3.1) and (3.2) into (3.4) and simplifying yields

$$\omega(p,\beta_i)+\frac{1}{2}p^2-pD(\beta_i+p)+\frac{n-1}{n}\left(E^N(\beta_i)-E\right)-\tau \tag{3.5}$$

$$\geq \omega\left(p^N(\beta_i),\beta_i\right)+\frac{1}{2}\left(p^N(\beta_i)\right)^2-p^N(\beta_i)D\left(\beta_i+p^N(\beta_i)\right)-\tau^N(\beta_i).$$

Implementability Condition. Taking together (3.3) and (3.5) yields a necessary and sufficient condition that must be satisfied by any implementable centralized regulation.

Lemma 3 *A centralized regulation $\{(p,E,\tau)\}$ is incentive-feasible if and only if, in every country i:*

$$\tilde{\omega}(p,\beta_i)-\tilde{\omega}\left(p^N(\beta_i),\beta_i\right)\geq\left(p-p^N(\beta_i)\right)\left(\overline{\theta}-\theta^e\right) \tag{3.6}$$

where

$$\tilde{\omega}\left(p,\beta_i\right)=\omega\left(p,\beta_i\right)-\frac{n-1}{n}E.$$

The feasibility constraint (3.6) is a fundamental requirement of any centralized regulation constrained by asymmetry of information. The central regulator faces n implementability constraints, one for each country $i\in\{1,\dots,n\}$. A price for permits p is incentive-feasible in country i if the benefits it gets from reducing pollution outweigh the informational cost of implementing such a policy. Moving from a Bayesian-Nash domestic regulation to a centralized mechanism affects both sides of this condition. On the one hand, the informational cost takes into account that increasing the price of permits also redistribute more information rents to domestic firms. It thus becomes *a priori* more difficult to move away from the Bayesian-Nash status quo. On the other hand, the existence of compensatory transfers with the rest of the world makes each country internalize the worldwide impact of adopting a greater price for permits than the Bayesian-Nash status quo.

To understand the magnitude of those effects, consider the hypothetical scenario where the central regulator would have perfect information on domestic firms. The right-hand side of (3.6) would be zero. The condition

$$\tilde{\omega}(p,\beta_i)-\tilde{\omega}\left(p^N(\beta_i),\beta_i\right)\geq 0$$

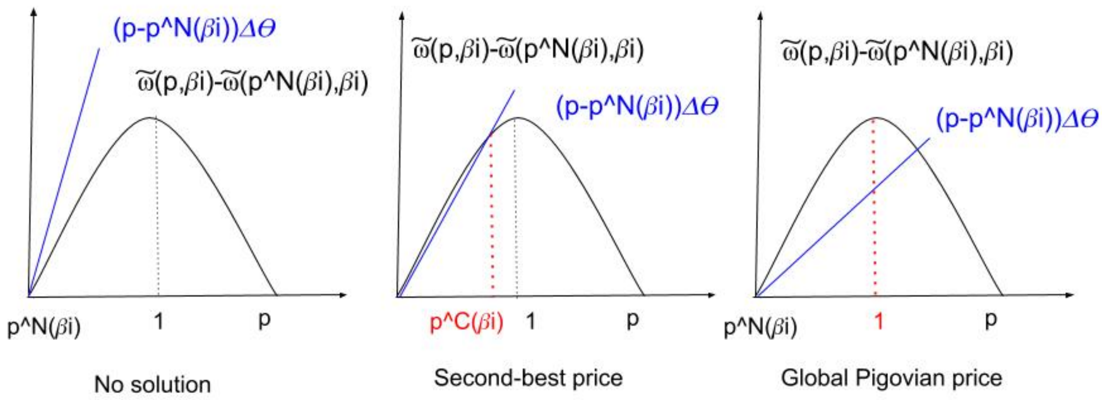
would obviously be satisfied by the Pigovian price $p^G = 1$ that maximizes worldwide welfare. Remaining ignorant on the firms' parameters, the central regulator is restricted to distribute the same subsidy τ_i to all the firms belonging to the same country i, whatever the realization of their cost parameter θ. The central regulator has thus to give up in every country i information rents that amount to $\left(p - p^N(\beta_i)\right)\left(\overline{\theta} - \theta^e\right)$ to induce acceptance of a higher price for permits than that arises under the Bayesian-Nash scenario.

To illustrate the importance of the feasibility constraint (3.6), Figure 2 below represents the set of feasible price in country i under asymmetry of information. As uncertainty on the firms' technologies diminishes, i.e., $\Delta\theta = \overline{\theta} - \theta^e$ decreases, the cost of information rent $p\Delta\theta$ turns clockwise. The expected gains of moving from a domestic regulation with a market price $p^N(\beta_i)$ to a centralized regulation with a market price p can now be maximized at the global Pigovian price $p^G = 1$. Otherwise, the highest feasible price is obtained when those two curves intersect at a lower price. Note from the figure that the feasible set has a non-empty interior in country i only when:

$$\frac{\partial}{\partial p}\left(\tilde{\omega}\left(p, \beta_i\right) - \tilde{\omega}\left(p^N(\beta_i), \beta_i\right)\right)|_{p=p^N(\beta_i)} \geq \overline{\theta} - \theta^e.$$

a condition that will be supposed to hold throughout.

Figure 2.— The feasibility set.



Optimal Regulation. The central regulator looks for a collection of mappings $\{(p(.), E(.), \tau(.))\}_{i\in\{1,\dots,n\}}$ that, for each country $i \in \{1, \dots, n\}$, associate to each realization of the domestic demand parameter β_i a regulation price $p(\beta_i)$, a quantity of permits $E(\beta_i)$ and a lump-sum transfer $\tau(\beta_i)$. These mappings must maximize the global welfare, namely:

$$\sum_{i=1}^{n}\left(\omega\left(p, \beta_i\right) - \frac{1}{n}\sum_{j\neq i} E_j\right) = \sum_{i=1}^{n}\tilde{\omega}\left(p, \beta_i\right) \tag{3.7}$$

Thanks to the additive separability of the domestic welfare between domestic benefits and worldwide externality and the fact that the incentive-feasibility condition (3.6) only depends on local instruments, the central regulator can maximize (3.7) point-wise so that for all $i \in \{1, \ldots, n\}$, $p(\beta_i)$ must solves

$$p(\beta_i) \in \arg\max \tilde{\omega}\,(p, \beta_i) \tag{3.8}$$

subject to the incentive-feasibility condition (3.6).

Central Regulation Characterization

If firm's technologies were known by the central regulator, the equilibrium prices would be equal to the global Pigovian price $p^G = 1$ for all countries. Under asymmetric information, this global Pigovian price may fail to satisfy the incentive-feasibility condition (3.6).

Implementability of the Global Pigovian Price. The central regulator faces the same trade-off as domestic regulators: correcting externalities without distributing too much rents to domestic firms. In this context, investigating whether the global Pigovian price can be implemented boils down to checking whether (3.6) holds for the global Pigovian price $p^G = 1$. This condition writes:

$$\tilde{w}\,(1, \beta_i) - \tilde{\omega}\left(p^N(\beta_i), \beta_i\right) \geq \left(1 - p^N(\beta_i)\right)\left(\overline{\theta} - \theta^e\right) \tag{3.9}$$

The global Pigovian price can be implemented worldwide only if this condition holds for all countries $i \in \{1, .., n\}$. The global Pigovian price is independent of the countries' demand shock parameters. However, interestingly enough, the central regulator must know these demand shock parameters to decide whether or not the global Pigovian price is implementable. Only then, the central regulator knows in which countries the global Pigovian price can be implemented or not.

Second-Best Centralized Regulation. When the global Pigovian price does not respect the incentive-feasibility constraint (3.6) in a country i, the price of permits must be reduced to cut down rents distributed to domestic firms and in this way, relax the constraint (3.6).

Proposition 2 *The optimal centralized regulation entails, in every country $i \in \{1, \ldots, n\}$, a second-best price $p^C(\beta_i)$ that is lower than the global Pigovian price:*

$$p^C(\beta_i) = 1 - \frac{\lambda_i^C}{1 + \lambda_i^C} \frac{(\overline{\theta} - \theta^e)}{(1 - D'\left(\beta_i + p^C(\beta_i)\right))} \leq 1 \tag{3.10}$$

where $\lambda_i^C \geq 0$ is the Lagrange multiplier associated to the incentive-constraint (3.6) of country i.

The second-best global prices of the centralized regulation are always lower than the global Pigovian price. The negative price distortion aims at cutting down the rent distributed to firms. Second-best prices of the centralized regulation correct better than domestic prices the worldwide negative externalities. Of importance, second-best prices depend on domestic demand shock parameters. As mentioned above, and as it was already the case in the domestic regulation, information on the demand shock parameters is crucial for the regulator to know whether first-best price can be implemented, and when it is not the case, derive second-best prices.

Taking together the saturation of the constraint of the least efficient firm (3.3) and the expression of the transfers at the Bayesian-Nash equilibrium (2.10) gives the expression of domestic transfers at the centralized regulation :

$$\tau^C(\beta_i) = \frac{1}{2}\left(p^C(\beta_i)\right)^2 + p^C(\beta_i)\left(\overline{\theta} - \theta^e\right) - p^C(\beta_i)D\left(\beta_i + p^C(\beta_i)\right).$$

4. CENTRAL REGULATION WITH DEMAND SHOCK PARAMETERS UNKNOWN.

We now consider the scenario in which the central planner not only is ignorant of domestic firms' abatement costs θ but also cannot observe demand shock parameters $\boldsymbol{\beta}$ that affect countries. To maximize global welfare the central planner has therefore less information than domestic governments who, even if they do not observe each other demand shock parameters' any more have, at least, private information over their own domestic demand shock parameters. These informational assumptions have two consequences. First, and as in the previous section, any regulation must satisfy domestic incentive and participation constraints. Second, the planner cannot directly implement domestic regulation that would be conditional on demand shocks. The central planner must instead propose different schemes of regulation and let countries decide which domestic regulation they want.

A regulation scheme consists of a price p at which duties are traded on the domestic market, a quantity of allowed permits E, and as before a lump-sum transfers τ paid by consumers and received by domestic firms. In addition, there is a set of compensatory transfers *from* and *towards* this country.

The central regulator recommends domestic regulations $\{(p(\beta_i), E(\beta_i), \tau(\beta_i))\}_{i\in\{1,\dots,n\}}$ and a set of international compensatory transfers that depends on the size of the negative demand shock. In theory, as $\boldsymbol{\beta}$ are not observed by the central planner, every country is free to choose any domestic regulation in the set, even if it is not the one targeted for its demand shock parameter. In practice, the regulatory schemes satisfy participation and incentive constraints such that every country prefers complying with the domestic regulation corresponding to its demand shock parameter. In addition, compensatory payments must remain budget-balanced.

COMPENSATORY TRANSFERS As in the previous section every country i is willing to pay all countries $j \neq i$ to reduce their emissions from $E^N(\beta_j)$ to $E(\beta_j)$ and *vice versa*. Transfers paid by i to the other countries $j \neq i$ thus remain unchanged up to the expected terms due to the fact demand shock parameters are now unknown:

$$\mathbb{E}_{\boldsymbol{\beta}_{-i}}\left(\sum_{j\neq i} T(\beta_j)\right) = \mathbb{E}_{\boldsymbol{\beta}_{-i}}\left(\frac{1}{n}\sum_{j\neq i}\left(E^N(\beta_j) - E_j(\beta_j)\right)\right). \tag{4.1}$$

We introduce a new notation $t(p(\beta_i))$ representing all transfers received by country i. This transfer depends on domestic price for duties p. Later on, this notation will be useful to interpret the central regulation as a simple non-linear transfer schedule.[5]

[5]See subsection REF.

COUNTRIES' INCENTIVE CONSTRAINTS. The expected equilibrium payoff of a country i that choose regulation $(p(\beta_i), E(\beta_i), \tau_i(\beta_i))$ is:

$$\mathcal{W}(\beta_i) - \mathbb{E}_{\boldsymbol{\beta_{-i}}}\left(\sum_{j\neq i} T(\beta_j)\right) - \frac{1}{n}\mathbb{E}_{\boldsymbol{\beta_{-i}}}\left(\sum_{j\neq i} E(\beta_j)\right). \tag{4.2}$$

where we define $\mathcal{W}(\beta_i) = \omega\left(p(\beta_i), \beta_i\right) + t_i(p(\beta_i))$.

Country i hit by a demand shock β_i selects the domestic regulatory scheme targeted for it, namely $(p(\beta_i), E(\beta_i), \tau_i(\beta_i))$, when the following incentive compatibility constraint is respected :

$$\mathcal{W}(\beta_i) = \max_{\hat{\beta}_i \in B} \omega\left(p(\hat{\beta}_i), \beta_i\right) + t_i\left(p(\hat{\beta}_i)\right) \tag{4.3}$$

If a country i hit by a domestic shock of β_i rather selects the domestic regulation targeted for those who have been hit by slightly stronger shock $\beta_i + d\beta_i$, country i can face the same price on the market for rights but at a lower welfare marginal cost. The marginal gains from doing so are approximately:

$$-\left(D'\left(\beta_i + p(\beta_i + d\beta_i, \boldsymbol{\beta_{-i}})\right)\left(p(\beta_i + d\beta_i, \boldsymbol{\beta_{-i}}) - \frac{1}{n}\right) - D\left(\beta_i + p(\beta_i + d\beta_i, \boldsymbol{\beta_{-i}})\right)\right) d\beta_i \approx -\dot{\mathcal{W}}(\beta_i) d\beta_i.$$

The central regulator has then no choice but to give a rent of $\mathcal{W}(\beta_i) - \mathcal{W}(\beta_i + d\beta_i) \approx -\dot{\mathcal{W}}(\beta_i) d\beta_i$ for countries to select their targeted domestic regulation. At the truthful equilibrium, countries have no incentive to select another scheme than the one targeted for them. The following lemma describes the set of incentive compatible allocations.

LEMMA 4 *When the demand is convex (respectively concave), an allocation $(p(\beta_i), E(\beta_i), t_i(\beta_i))$ is incentive compatible if and only if $p(\beta_i)$ is non-decreasing (respectively non-increasing) with respect to β_i, and $\mathcal{W}_i(\beta_i)$ is absolutely continuous with at each point of differentiability (i.e., almost everywhere)*

$$\dot{\mathcal{W}}(\beta_i) = \omega_{\beta_i}\left(p(\beta_i), \beta_i\right) = D'\left(\beta_i + p(\beta_i)\right)\left(p(\beta_i) - \frac{1}{n}\right) - D\left(\beta_i + p(\beta_i)\right) \ \forall i. \tag{4.4}$$

It is clear from (4.4) that pay-offs are decreasing with the size of the domestic demand shock. All countries, except the ones hit by the highest demand shock, obtain a positive informational rent.

PARTICIPATION CONSTRAINTS. We keep consistent with the assumptions that, first all countries must approve the central regulation for it to be implemented and, second that the next best outside option for all countries is the Bayesian-Nash domestic regulation. Under these assumptions, country i accepts the regulation if incentive and participation constraints of both domestic firms and domestic consumers are respected. Domestic firms accept the regulation if they receive a higher profit than under the Bayesian-Nash scenario, namely if condition (3.3) is fulfilled. For consumers, modifying condition (3.4) with the new notation for transfers $t(p(\beta_i))$ gives the following participation constraint:

(4.5)

$$\omega\left(p(\beta_i), \beta_i\right) + \frac{1}{2}\left(p(\beta_i)\right)^2 - p(\beta_i) D(\beta_i + p(\beta_i)) + t\left(p(\beta_i)\right) - \mathbb{E}_{\boldsymbol{\beta_{-i}}}\left(\sum_{j\neq i} T(\beta_j)\right) - \frac{1}{n}\mathbb{E}_{\boldsymbol{\beta_{-i}}}\left(\sum_{j\neq i} E_j(\beta_j)\right) - \tau$$

$$\geq \omega\left(p^N(\beta_i),\beta_i\right)+\frac{1}{2}\left(p^N(\beta_i)\right)^2-p^N(\beta_i)D\left(\beta_i+p^N(\beta_i)\right)-\frac{1}{n}\mathbb{E}_{\boldsymbol{\beta_{-i}}}\left(\sum_{j\neq i}E^N(\beta_j)\right)-\tau^N(\beta_i).$$

Now inserting the expressions of transfers paid by i, namely (4.1), into (4.5) and simplifying yields:

$$\omega(p(\beta_i),\beta_i)+\frac{1}{2}\left(p(\beta_i)\right)^2-p(\beta_i)D(\beta_i+p(\beta_i))+t_i\left(p(\beta_i)\right)-\tau \tag{4.6}$$

$$\geq \omega\left(p^N(\beta_i),\beta_i\right)+\frac{1}{2}\left(p^N(\beta_i)\right)^2-p^N(\beta_i)D\left(\beta_i+p^N(\beta_i)\right)-\tau^N(\beta_i).$$

Taking together (3.3) and (4.6) yields a necessary condition that must be satisfied by any implemented regulation.

Lemma 5 *A centralized regulation respects domestic firms and consumers' incentive and participation constraints if and only if, in every country i:*

$$\mathcal{W}(\beta_i)\geq \omega\left(p^N(\beta_i),\beta_i\right)+\left(p(\beta_i)-p^N(\beta_i)\right)\left(\overline{\theta}-\theta^e\right). \tag{4.7}$$

To illustrate this necessary constraint, Figure (3) below represents the set of feasible price in country hit by a shock β_i. In blue are the constraint the central planner face when he observe the demand shock parameter. In this particular case, the central planner cannot implement the global Pigovian price and implement a second-best price $p^C(\beta_i)$. With asymmetry of information, the feasibility constraint changes and is drawn in red. To implement the global Pigovian prices under asymmetric information, the central planner must give country i a transfer of the size $t(1)$.

Budget-balanced. We impose to international transfers to be budget-balanced. It implies that the on average money distributed to any country i is covered by contribution paid by the other countries $j\neq i$, that is to say:

$$\mathbb{E}_{\beta_i}\left(t\left(p(\beta_i)\right)\right)\leq \mathbb{E}_{\beta_i}\left(\sum_{j\neq i}T(\beta_i)\right)\Leftrightarrow \mathbb{E}_{\beta_i}\left(t\left(p(\beta_i)\right)\right)\leq \frac{(n-1)}{n}\mathbb{E}_{\beta_i}\left(E^N(\beta_i)-E(\beta_i)\right).$$

Using transfers' expression, it will be useful to rewrite this constraint as:

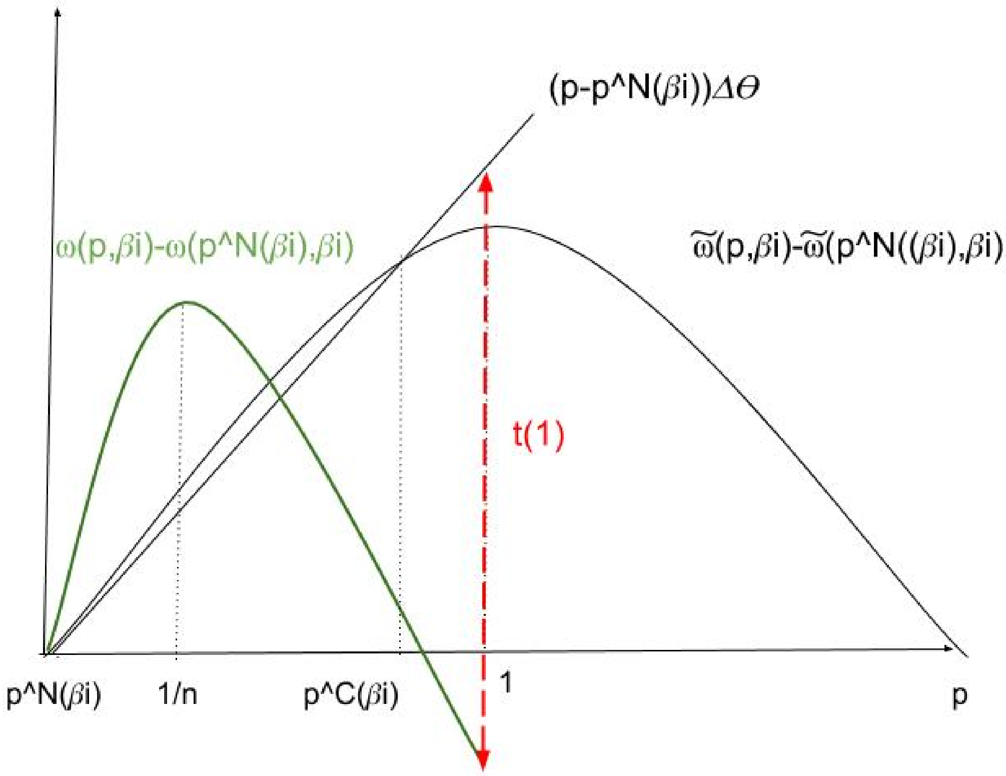
$$\mathbb{E}_{\beta_i}\left(\omega(p(\beta_i),\beta_i)-\frac{(n-1)}{n}E(\beta_i)\right)\geq \mathbb{E}_{\beta_i}\left(\mathcal{W}(\beta_i)-\frac{(n-1)}{n}E^N(\beta_i)\right). \tag{4.8}$$

Implementability of the Global Pigovian Price. Verifying whether the global Pigovian price $p^G=1$ can be implemented boils down to verify if the constraints of feasibility and budget-balanced are respected with that price.

First, the feasibility condition (4.7) is respected for every country if at the global Pigovian price the feasibility constraint of the country with highest negative demand shock $\overline{\beta}$ (4.7) is respected:

$$\omega\left(1,\overline{\beta}\right)-\omega(0,\overline{\beta})\geq\left(\overline{\theta}-\theta^e\right)-t(1). \tag{4.9}$$

FIGURE 3.— Feasibility constraint of the centralized policy with and without information about the countries demand shocks.



Second, we can look at the budget constraint (4.8) evaluated at the global Pigovian price.

$$\int_{\underline{\beta}}^{\overline{\beta}} \left[\omega\left(p,\beta_i\right) - \frac{n-1}{n}\left(D\left(p+\beta_i\right) - p + \theta^e\right)\right]_{p^N(\beta_i)}^{1} g(\beta_i)d\beta_i \tag{4.10}$$

$$\geq \left(\overline{\theta} - \theta^e\right) + \omega\left(0,\overline{\beta}\right) - \omega\left(1,\overline{\beta}\right) - \int_{\underline{\beta}}^{\overline{\beta}} \left(\dot{p}^N(\beta_i)\left(\overline{\theta} - \theta^e\right) + \omega_{\beta_i}\left(0,\beta_i\right) - \omega_{\beta_i}\left(1,\beta_i\right)\right) g(\beta_i)d\beta_i.$$

The central planer derives the second-best prices by maximizing the expected welfare subject to (4.4), (4.7) and (4.8), respectively incentive, participation and budget-balanced constraints. As a first pass we ignore the monotonicity conditions derived in Lemma (4) that will be verified ex-post.[6]

5. CONCLUSION

We have shown that asymmetry of information between domestic firms and central regulator can be an obstacle to the implementation of the global first-best regulation. As such, both asymmetry of information at domestic and international level should be consider to design global environmental agreement. Our results call for identifying how stringent can be the centralized regulation. First-best regulations are the same for all

[6]The maximization program solving is still work in process and, as such, do not figure in this version of the paper.

countries, but most probably costs of information asymmetry is too large to implement it. Second-best regulations take into account these costs and differ among countries. Prices for polluting permits adapt to countries' demand shocks so that countries and domestic citizens comply with the global agreement. A better understanding of informational obstacles at different levels of governance would eventually help to design environmental global regulation. The final goal being to correct global externality and to acquire adhesion of domestic citizens.

The limits of our model lie mainly in some of our assumptions. We first assume linear damages of pollution. A natural extension of our work can be to consider the robustness of our result with convex damages. We also consider that countries are homogeneously affected by pollution. That assumption does not hold in the current reality. Assuming heterogeneous damages of pollution will in the first place affect the first-best regulations. There will not be uniform any more. That can be an interesting alley for further research. At another level, we do not model any international trade. Finally, we assume that the central planer embodies the assembly of countries gathering to decide upon the policy. We put strong requirements on the regulatory mechanism (full participation, incentive and budget-balanced). However, we gloss over the negotiation process taking place between these countries before reaching an agreement.

APPENDIX

Proof of Lemma 1: Summing (2.2) and (2.4) and taking into (1.5) immediately yields (2.5). Reciprocally, suppose that (2.5) holds and define τ_i such that (2.4) is an equality. Then, (2.2) is satisfied .

Q.E.D.

Proof of Proposition 1: The price $p(\beta_i)$ must maximize (2.6) subject to the incentive-feasibility condition (2.5). With $\lambda_i \geq 0$ being the Lagrange multiplier of this maximization problem, the Lagrangian writes:

$$L(p, \lambda_i) = (1+\lambda_i)\omega(p, \beta_i) - \frac{1}{n}\mathbb{E}_{\boldsymbol{\beta}_{-i}}\left(\sum_{j\neq i}(D(\beta_j + p_j) - p_j + \theta_e)\right) - \lambda_i\left(\omega\left(0, \beta_i\right) + p(\overline{\theta} - \theta_e)\right)$$

Deriving the first-order conditions with respect to p and using the equilibrium condition gives:

$$(1+\lambda_i)\left(p - \frac{1}{n}\right)\left(D'(\beta_i + p) - 1\right) - \lambda_i(\overline{\theta} - \theta_e) = 0$$

Rearranging terms, you obtain the second-best domestic price (**??**). Because $\lambda_i \geq 0$, we have $p^N(\beta_i) \leq p^D = \frac{1}{n}$. *Q.E.D.*

Proof of Lemma 2: The sign of (2.11) is that of the following expression:

$$\frac{\partial \omega}{\partial \beta_i}\left(p^N(\beta_i), \beta_i\right) - \frac{\partial \omega}{\partial \beta_i}(0, \beta_i) = \left(p^N(\beta_i) - \frac{1}{n}\right) D'\left(\beta_i + p^N(\beta_i)\right) - D\left(\beta_i + p^N(\beta_i)\right) - \left(-\frac{1}{n}D'\left(\beta_i\right) - D(\beta_i)\right).$$

The right-hand side can be rewritten as:

$$\int_0^{p^N(\beta_i)}\left(p - \frac{1}{n}\right) D''(\beta_i + p)dp$$

whose sign is minus that of D'' when $p^N(\beta_i) \leq p^D = \frac{1}{n}$ as demonstrated in Proposition 1. *Q.E.D.*

Proof of Lemma 3: Summing (3.3) and (3.4) and taking into account compensatory transfers yields:

$$\omega(p, \beta_i) + \frac{n-1}{n}\left(E^N(\beta_i) - E_i\right) \geq \omega\left(p^N(\beta_i), \beta_i\right) + \left(p - p^N(\beta_i)\right)\left(\overline{\theta} - \theta^e\right)$$

Rearranging terms and using notations defined in (??) yields (3.6). Reciprocally, suppose that (3.6) holds and define τ such that (3.4) is an equality. Then, (3.3) is satisfied. *Q.E.D.*

Proof of Proposition 2: The price p must maximize (3.8) subject to the incentive-feasibility condition (3.6). With λ_i^C being the Lagrange multiplier of the maximization problem associated to country i, the Lagrangian writes:

$$\sum_i \left(\left(1 + \lambda_i^C\right)\tilde{\omega}\left(p, \beta_i\right) - \lambda_i^C \tilde{\omega}\left(p^N(\beta_i), \beta_i\right) - \lambda_i^C\left(p - p^N(\beta_i)\right)\left(\overline{\theta} - \theta^e\right)\right).$$

Maximizing point-wise with respect to p and using (??) gives the first-order condition with respect to p:

$$\left(1 + \lambda_i^C\right)\left(\omega_p\left(p, \beta_i\right) - \frac{(n-1)}{n}\left(D'\left(\beta_i + p\right) - 1\right)\right) = \lambda_i^C\left(\overline{\theta} - \theta^e\right)$$

Rearranging terms gives the expression of the second-best centralized regulation price for every country $i \in \{1, \dots, n\}$ (3.10). *Q.E.D.*

Proof of Lemma (4): A direct revelation mechanism is truthful in Bayesian Nash strategies if it is a Bayesian Nash equilibrium to truthfully reveal his type for each agent. It requires the following condition to be respected :

$$\mathcal{W}_i(\beta_i) = \max_{\widehat{\beta}_i} \; t_i(\widehat{\beta}_i) + \omega\left(p(\widehat{\beta}_i), \beta_i\right) - \frac{1}{n}\mathbb{E}_{\boldsymbol{\beta}_{-i}}\sum_{j \neq i} E_j(\beta_j) \;\forall i.$$

It implies that the following first-order condition for for country i to truthfully reveal its type is satisfied:

$$\dot{t}_i(\widehat{\beta}_i) + \dot{p}(\widehat{\beta}_i)\omega_p\left(p(\widehat{\beta}_i), \beta_i\right) = 0$$

For the truth to be an optimal response for all β_i, it must be the case that:

$$\text{(A.1)} \qquad \dot{t}_i(\beta_i) + \dot{p}(\beta_i)\omega_p\left(p(\beta_i), \beta_i\right) = 0,$$

and it must hold for all $\beta_i \in B$. It is also necessary to satisfy the local second-order condition:

$$\ddot{t}_i(\widehat{\beta}_i)|_{\widehat{\beta}_i = \beta_i} + \ddot{p}(\widehat{\beta}_i)\omega_p\left(p(\widehat{\beta}_i), \beta_i\right)|_{\widehat{\beta}_i = \beta_i} + \dot{p}(\widehat{\beta}_i)\omega_{pp}\left(p(\widehat{\beta}_i), \beta_i\right)|_{\widehat{\beta}_i = \beta_i} \leq 0$$

or

$$\text{(A.2)} \qquad \ddot{t}_i(\beta_i) + \ddot{p}(\beta_i)\omega_p\left(p(\beta_i), \beta_i\right) + \dot{p}(\beta_i)\omega_{pp}\left(p(\beta_i), \beta_i\right) \leq 0.$$

But differentiating (A.1):

$$\ddot{t}_i(\beta_i) + \ddot{p}(\beta_i)\omega_p\left(p(\beta_i), \beta_i\right) + \dot{p}(\beta_i)\omega_{pp}\left(p(\beta_i), \beta_i\right) + \dot{p}(\beta_i)\omega_{p\beta_i}\left(p(\beta_i), \beta_i\right) = 0,$$

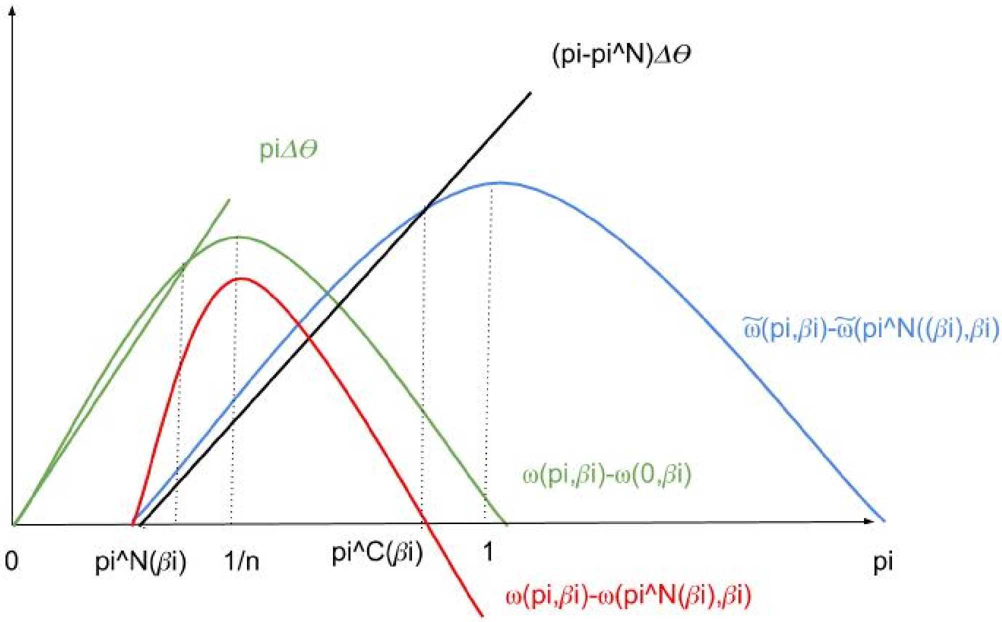
(A.2) can be written more simply as:

$$\dot{p}(\beta_i)\omega_{p\beta_i}\left(p(\beta_i),\beta_i\right) \geq 0 \Leftrightarrow \ \dot{p}(\beta_i)D''\left(\beta_i + p(\beta_i)\right)\left(p(\beta_i) - \frac{1}{n}\right) \geq 0.$$

We are interested in prices such that $p(\beta_i) \geq p^D(\beta_i) = \frac{1}{n}$. We can thus conclude that when the demand is convex (respectively concave), the price has to be non-decreasing (respectively non-increasing) to respect the second-order condition.

Q.E.D.

FIGURE 4.— Feasibility constraint of the three different policies for a country i. In green the decentralized domestic regulation, in blue the centralized regulation when the central planner is informed about the demand shock parameters, and in red the centralized regulation when the central planner cannot observe the demand shock parameter



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