



**Instrument Choice and Cost Uncertainty  
in the Electricity Market**

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# Instrument choice and cost uncertainty in the electricity market\*

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## Abstract

This paper deals with policies to boost the deployment of renewables for electricity generation as a means to curb pollution. We build a partial equilibrium model of the retail electricity market, in which production costs are the sum of generation, transmission and distribution costs. Electricity can be produced either with conventional energy sources (low-cost but polluting) or with renewable energy sources (high-cost and not polluting). A government wants to reach the socially optimal level of pollution, electricity consumption and renewable electricity production while facing uncertainty on the production costs of renewable electricity. Thus, it implements price-based or quantity-based incentives for renewable electricity on the basis of its estimated production costs. While it is well-known that implementing price or quantity instruments yields opposite deviations from the optimum under cost uncertainty, we show that all quantity instruments are not equivalent, and can be strictly ranked in terms of the distortions they generate when the government misestimates production costs. The most efficient quantity-based instrument is a conventional electricity quota, because it makes use of demand effects to smooth the impact of a cost estimation error. A less efficient instrument is a compulsory share of renewable electricity, and the least efficient is a renewable electricity quota.

**JEL codes:** D62, H23, Q42, Q48.

**Keywords:** prices vs. quantities, renewable energy sources, electricity.

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# 1 Introduction

This paper deals with policies to boost the deployment of renewables for electricity generation as a means to curb greenhouse gas emissions, in a context where the production costs of green technologies are uncertain. In particular, we focus on the divergence in market outcomes of implementing price-based versus quantity-based energy policies. Recognizing that quantity instruments can be designed in various ways and that there is no ex-ante reason to believe they are all equivalent, we rank them according to the distortions their implementation entails at the equilibrium when the policy maker misestimates the production costs.

It is now recognized that energy policy choices have to be influenced by climate change concerns given the dominating share of the energy sector in the generation of total emissions.<sup>1</sup> Greening electricity via its generation from renewable energy sources (RES-E) is seen by governments as a way to decarbonize the power sector.<sup>2</sup> This has prompted public intervention through the setup of incentive schemes for the deployment of RES-E, which are usually labeled as price-based or quantity-based.

However, the choice of the optimal form for incentive schemes is still drastically constrained by large uncertainties with respect to key dimensions. In fact, technologies for the generation of renewable electricity are still not financially competitive with conventional technologies and the future evolution of their capital costs is unpredictable; changes in the institutions, regulation and infrastructure necessary for the full integration of renewable sources into the market are still incomplete. These elements translate into uncertainty regarding the full production cost of green electricity.

Since Weitzman (1974), we have been able to rely on a formal assessment of the relevance of these sources of uncertainty for the optimal instrument choice. We better understand the circumstances under which the solution to an instrument choice problem is the use of prices, quantities, or a combination of both.<sup>3</sup>

Over time, however, pollution control policy has evolved. In the electricity sector, quantity instruments are implemented by either imposing a minimum share of renewable sources out of total energy generation, or a minimum level of reliance on renewables.<sup>4</sup>

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<sup>1</sup>In 2009, energy generated 76.5% of total greenhouse gas (GHG) emissions in the EU27, while in the US the same sector accounted for 85% of all domestic GHG emissions (World Resources Institute, 2014).

<sup>2</sup>Following the European Commission, we consider electricity from renewable energy sources as electricity generated from non-fossil renewable energy sources - more specifically, “wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases” (European Commission, 2009, art. 2). We refer to it as *renewable* or *green* electricity. Conversely, we talk of *conventional* or *fossil* electricity to label power generated from polluting energy sources such as fossil fuels.

<sup>3</sup>See Roberts and Spence (1976), or Mandell (2008), Muller and Mendelsohn (2009), Ambec and Coria (2013), and Wirl (2012) for recent contributions.

<sup>4</sup>The EU uses the former scheme, aiming at reaching at least a 27% share of renewable energy consumption within 2030 (European Commission, 2014). The US government mixes both: it uses the former for the long term 2035 target (generate 80% of electricity from clean energy sources,

The recognition of such differences in the implementation of quantity-based policies begs for a reassessment of the rationale suggested by Weitzman. In this paper, we show how taking a closer look at quantity-based policies allows to refine the classical model of instrument choice, thus yielding more precise policy advice.

We model the retail electricity market with a partial equilibrium approach. We assume the marginal cost of production of conventional electricity is constant, while the marginal cost of renewable electricity is marginally increasing and higher than the cost of the former.<sup>5</sup> When talking about the ‘marginal cost of production of electricity’, we mean in fact the marginal cost of bringing an extra ‘unit’ of electricity to the final consumer. That encompasses the several steps in the electricity production process: generation, transmission, distribution.

Within this specification of the power market, we assume that a government aims at maximizing the benefits of electricity consumption, net of its production costs and of the externality costs generated by pollution. The government has no information on the production costs of renewable electricity. For this reason, it sets up a policy supporting the deployment of renewables on the basis of costs estimations.

We consider four different policies: (i) a price-based tax on conventional electricity, (ii) a quantity-based renewable electricity quota, (iii) a quantity-based conventional electricity quota, (iv) an indirect quantity-based mandatory share of renewable electricity.

We first show that, as in Roberts and Spence (1976), in the presence of uncertainty on the production costs of renewable electricity, price and quantity instruments yield opposite market outcomes. When a government has overestimated the costs of green electricity, the equilibrium level of electricity consumption as well as pollution is lower than optimal when using a price instrument, and higher than optimal when using a quantity instrument.

We then show that, ranking quantity instruments by their capacity to approach the optimal level of the variables of interest (in particular, pollution and electricity consumption), a conventional electricity quota dominates a mandatory share of renewable electricity, which in turn dominates a renewable electricity quota. This is not due to the conventional electricity quota acting as a proxy for a ‘pollution quota’: under cost uncertainty, a cap on conventional electricity allows renewable electricity producers to capture the extra demand generated from the lower equilibrium price – what we call the ‘demand effect’. For instance, if the objective of the government were to attain the optimal quantity of renewable electricity (e.g., to create green jobs), a conventional electricity quota would still be a more efficient tool than a renewable electricity quota.

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including hydro, nuclear, natural gas and clean coal (Executive Office of the President, 2011)) but uses the latter for the 2020 target (doubling renewable electricity generation with respect to 2013 levels (Executive Office of the President, 2013)). These objectives match targets for reducing greenhouse gas emissions: in 2014 the EU has announced its plan to cut 40% of GHG emissions compared to 1990 levels (European Commission, 2014), while in 2009 the US government has committed to a 17% reduction of GHG emissions with respect to 2005 levels by year 2020 (Executive Office of the President, 2013).

<sup>5</sup>This matches, among others, the stylised facts reported in DB Climate Change Advisors (2012), based on Eurostat data and on data from the German Ministry of Energy.

The paper is organized as follows. We provide further information on how price and quantity tools are implemented in energy policy and relate our work to the relevant literature in Section 2. Section 3 describes the objective function of the government, and how differences in production cost affects the variables of interest. We introduce uncertainty in section 4, and study the impact of price and quantity instruments. We discuss those results in section 5 and conclude in section 6.

## 2 Background

In the power sector, the price instrument is applied through a system of taxes and subsidies (feed-in tariffs) to support electricity from renewable energy sources. The application of a quantity instrument is however more complex. Rather than setting quotas on the generation of conventional electricity, governments rely on objectives based on the desired level of electricity to be generated from renewable energy sources:

During the President's first term, the United States more than doubled generation of electricity from wind, solar, and geothermal sources. To ensure America's continued leadership position in clean energy, President Obama has set a goal to **double renewable electricity generation once again by 2020**. (Executive Office of the President, 2013, p. 6)

Instead of mandating a certain amount of electricity to be generated through renewables, the European Commission has set a proportional objective:

The Renewable Energy Directive 2009/28/EC [...] established a European framework for the promotion of renewable energy, setting mandatory national renewable energy targets for **achieving a 20% share of renewable energy in the final energy consumption [...] by 2020**. (European Commission, 2013b, p. 2)

However, objectives on renewable energy deployment cannot be set without further incentives for firms to act:<sup>6</sup> a first type of incentive scheme is the feed-in tariff system mentioned above; another one is a quota obligation associated to a tradable green certificates scheme.

*Feed-in tariffs* (FITs) are payment schemes in which a fixed financial support is provided per 'unit' of electricity generated, hence per kWh. The amount, normally guaranteed for a specified time span of 10-15 years, is generally the same regardless of the underlying cost structure borne by the producer or of the market price of electricity: this makes FITs the most reliable support scheme for a producer in terms of being shielded from market risk. Concretely, FITs require electricity utilities to

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<sup>6</sup>In this paper we focus on generation-based incentives as opposed to investment-based incentives. While the former provide support to electricity actually generated through renewable energy sources, the latter reward generating capacity installed, mostly in the form of capital grants and tax credits. We do not consider investment-based instruments as they represent a smaller slice of the overall RES-E 'subsidization pie' (European Commission, 2008), but also because they represent long-run incentives.

buy RES-E at the tariff fixed by the regulator. This scheme is generally financed through a tax on electricity consumption.

*Quota obligations* are often associated to *tradable green certificates*. The regulator sets a desired target of electricity to be produced through specific renewables and RES-E generators can directly sell electricity at the market price, or they can sell green certificates they issue on the designated ‘artificial’ market. The parties facing the obligation have to show compliance by the settlement date, proving that a share of their energy mix has been drawn from RES. Concretely, this can be done either by directly purchasing renewable energy or by purchasing green certificates, whose price is determined on the market. Non-compliance is punished through fines.

These two generation-based instruments are the most widely used in reality: according to 2013 EU data, 19 EU member states out of 28 have price-based feed-in tariffs in place (European Commission, 2013a);<sup>7</sup> at the beginning of 2010, 30 US states out of 50 had implemented a quantity-based quota obligation (Schmalensee, 2012).<sup>8</sup>

This kind of policy setting, in which the government has to choose between a price or a quantity instrument to shape an environmental policy aimed at curbing pollution emissions, has long interested scholars. In the baseline setting of the prices vs. quantities literature, the regulator has full information with regards to the elements needed to set an optimal environmental policy. As Hepburn puts it, “under idealized conditions, there is a one-to-one correspondence between price and quantity instruments” (Hepburn, 2006, p. 229). The implementation of a pure quantity/price regulatory measure<sup>9</sup> has the virtue of simplicity but the downside of inefficiency: hybrid schemes, combining prices and quantities can also be envisioned.<sup>10</sup> A more realistic question may be: when dealing with partial information, what is the second-best regulatory solution? More specifically, in our setting the regulator has partial information regarding the production costs of renewable electricity. Weitzman (1974) is the first to analyze the choice of quantity control over price setting from the perspective of a regulator with partial information. His main conclusion

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<sup>7</sup>The European Commission has recently underlined the importance that “support schemes are adjusted regularly and quickly enough to take account of falling technology costs and to ensure reforms make renewable energy producers part of the energy market (such as by moving from feed in tariffs to feed in premiums or quotas, and using tendering to avoid over compensation etc.); to ensure such market interventions are correcting market failures and not adding or maintaining market distortions.” (European Commission, 2013b, p. 9). In other words, having reckoned that some renewable energy sources are closer to grid parity than others, the Commission has focused on the need to reform incentive schemes for RES-E taking stock of technological improvements. The ongoing trend, strengthened by the Commission 2013 policy recommendation, is to phase out feed-in tariffs and substitute them with premiums, which are to allow higher market responsiveness of renewables generators: currently, 10 EU member states have opted for price-based feed-in premiums and 5 for quantity-based quotas (European Commission, 2013a).

<sup>8</sup>Quotas are referred to as ‘renewable portfolio standards’ in US policy and in US-related literature.

<sup>9</sup>Examples of quantity-based regulatory interventions are quotas, targets, tradable permit schemes, specific bans setting allowed quantity to zero, upper bounds on pollution. Price measures instead are normally applied through taxes, or more rarely through direct interventions on the price level.

<sup>10</sup>Examples are tradable permit schemes paired with a price ceiling or floor.

is that, under uncertainty, the outcome of both sorts of regulation differs from the first best solution. Thus, the choice between price or quantity regulation should be based on the coefficient of comparative advantage of prices over quantities, a function of the market’s supply and demand curve slopes. As summarized by Hepburn, in the presence of uncertainty: “using a price instrument is more (less) efficient than a quantity instrument when the marginal benefits of that good are relatively flat (steep) compared with the marginal costs. As a rough heuristic, this is because the instrument is intended to internalize the marginal benefit curve.” (Hepburn, 2006, p. 231) While Weitzman uses the magnitude of the deadweight loss at the second-best equilibrium as the main criterion to compare price and quantity instruments, we zoom onto their impact on the variable that drives the rationale behind renewable energy policy: which policy instrument allows the level of pollution caused by electricity generation to get closer to the optimum?

Roberts and Spence start from the observation that “effluent charges and license outcomes deviate from the optimum in opposite ways” (Roberts and Spence, 1976, p. 194) and propose a mixed price-quantity scheme<sup>11</sup> to reach a second-best level of pollution that yields a Pareto-improvement with respect to the implementation of either prices or quantities. We formally replicate their starting point observation and compare price-based and direct quantity-based instruments to an indirect quantity-based instrument: a mandatory share of renewable electricity.

Buchanan and Tullock (1975) compare a tax system to a proportional reduction of the polluting activity (which they label ‘direct regulation’) and analyse both the optimal choice for the regulator and for the regulated polluting agents. The proportional reduction resembles what we call a mandatory share, but while Buchanan and Tullock imagine a scenario in which there is no ‘clean’ technological alternative to the polluting process and thus apply the mandatory proportional reduction to the final polluting good, in our model the policy restriction is set in order to make sure the proportion of the ‘clean’ input reaches the optimal level.

A vast strand of research has followed this seminal literature on the prices vs. quantities dichotomy by considering the additional assumptions that characterize instrument choice for a regulator in charge of environmental, energy or climate change policy. Recent literature, reviewed by Nordhaus (2007) and Goulder and Parry (2008), has applied instrument choice between prices and quantities to climate change policy focusing on carbon prices vs. emission permit schemes aimed at tackling a global public good as global warming (Pizer, 1999, 2002) and extending the models to consider the stock, as opposed to flow, nature of GHGs (Hoel and Karp, 2001, 2002). Reviewing extensions to the prices vs. quantities framework, Rohling and Ohndorf (2012) enumerate incomplete enforcement (analyzed by Montero (2002)), fiscal cushioning (i.e. the situation in which governments can reduce actual incentives for pollution abatement through national policies, thus hindering the implementation of international price-based incentives), repeated interaction between regulators and firms, the role of fines for noncompliance, the importance of

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<sup>11</sup>Specifically, they build up a three-fold control mechanism in which the regulator issues transferable licences and gives a unit effluent subsidy to all those firms which pollute less than what allowed by their licence allocation. Finally, firms exceeding their allowances are fined with a per-unit penalty.

the attitude of firms towards risk. Considering these elements within an uncertain policy framework, they state, contributes to altering the setup delineated by Weitzman.

Focusing on the electricity market, the prices vs. quantities dichotomy has also been used to analyze the efficiency and effectiveness of RES-E incentive schemes, comparing price-based feed-in tariffs to quantity-based quotas of renewables. Menanteau et al. (2003) analyze the two most common renewable energy support schemes in the EU: feed-in tariffs versus quotas. They discuss the different implications of these two alternative policies regarding four different objectives: capacity to stimulate renewable electricity generation, net overall cost for the community, incentives to reduce costs and prices, incentives to innovate. Schmalensee (2012) compares the EU approach to supporting renewables to the US one, and evaluates their ex-post efficiency. Both papers focus on the capacity of public support to increase the weight of renewables in the energy mix, while in this paper we argue that the policy-maker should focus on reaching the optimal level of pollution generated by electricity generation, rather than maximizing the level of the cleaner, yet dearer generation technology.

### 3 The model

In this section we present a model of the retail electricity market. We derive the benchmark results from a setting in which there is no cost uncertainty, in which case all policies are equivalent. The objective is to identify the impact of a difference in the marginal production cost of renewable electricity on: (i) equilibrium prices and quantities, (ii) pollution level at the equilibrium, (iii) proportion of renewable and fossil electricity out of the total power generation.

#### 3.1 Supply side

We assume the production costs of renewable and fossil electricity are different. Generating fossil electricity has a constant private marginal cost of 1, while renewable electricity has an increasing private marginal cost (with  $c > 0$ ).

$$PMC_f = 1 \tag{1}$$

$$PMC_r = 1 + cq_r \tag{2}$$

The generation of fossil electricity generates marginally increasing convex pollution costs  $\gamma(q_f)$ , with  $\gamma' > 0$ ,  $\gamma'' > 0$ , hence its full social marginal cost is

$$SMC_f = 1 + \gamma'(q_f) \tag{3}$$

Since the production of green electricity does not cause pollution emissions (i.e.  $PMC_r = SMC_r$ ), it is considered as a means to decarbonize the electricity sector.

Given aggregate electricity produced is  $Q = q_r + q_f$ , the share of electricity produced with renewable energy is defined by  $s = \frac{q_r}{q_r + q_f}$ , such that

$$q_r = sQ \tag{4}$$

$$q_f = (1 - s)Q \tag{5}$$

## 3.2 Demand side

Consumers are interested in using electricity: we assume renewable and conventional energy are perfect substitutes for them, ruling out the possibility that some consumers may have a preference for renewable electricity. The representative consumer's utility function underlying electricity demand is given by  $U = B(Q) - P$ , with decreasing marginal utility of consumption:  $B'(Q) > 0$  and  $B''(Q) < 0$ . For the ease of presentation, we assume  $B'''(Q) = 0$ , so that the marginal utility of consumption is linear. The aggregate demand function is decreasing in price,  $\frac{dAD}{dP} < 0$ . The inverse demand function is  $P(Q)$ , where  $Q = AD(P)$ .

## 3.3 Objective Function

The objective of the government is to minimize the aggregate costs of electricity production including pollution costs, and to maximize consumers' utility. Rent creation is not the focus of this paper: we assume that it can be dealt with through other policy instruments.

$$\Pi(q_f, q_r) = B(Q) - (q_f + \gamma(q_f)) - \int_0^{q_r} (1 + cx)dx \quad (6)$$

The social optimum is therefore derived from the two following first order conditions.

$$MB_{q_f}(Q) = \frac{dB(q_r + q_f)}{dq_f} = 1 + \frac{d\gamma(q_f)}{dq_f} \quad (7)$$

$$MB_{q_r}(Q) = \frac{dB(q_r + q_f)}{dq_r} = 1 + cq_r \quad (8)$$

Condition 7 is the classic result of Pigouvian taxation. At the social optimum, the social marginal costs of fossil electricity (the production costs and marginal damage caused by pollution) should equate the marginal benefit from electricity consumption.

Condition 8 states that as the marginal private cost of renewable electricity corresponds to its social marginal cost, at the optimum the social marginal cost of renewable electricity should equate its marginal benefits.

Since, as stated in Section 3.2, consumers find that renewable and fossil electricity are perfect substitutes, the marginal private cost of renewable electricity should equate the social marginal cost of fossil electricity: they both correspond to the general marginal benefit of electricity consumption, i.e.  $MB_{q_r}(Q) = MB_{q_f}(Q) = MB_Q(Q)$ .

We represent the retail market for electricity in Figure 1. We use a linear representation for the ease of exposition. However, all the results and proofs are computed with the general functions described above. The downward-sloping demand is represented by the line  $AD$ . At the social optimum the electricity price reflects its full social marginal cost: the social marginal cost of fossil electricity is the sum of the private marginal cost and the pollution marginal damage, thus the optimal supply of fossil electricity is represented by the line  $SMC_f(q_f) = 1 + \gamma'(q_f)$ , independent of  $c$ .

If its slope is  $\hat{c}$ , the optimal supply curve of renewable electricity is  $\hat{SMC}_r = 1 + \hat{c}q_r$ . Compare this situation to a scenario in which the marginal cost of renewable electricity production is lower,  $c < \hat{c}$ : the optimal supply curve of renewable electricity then is  $SMC_r = 1 + cq_r$ .

We know from the first order conditions 7 and 8 that, for any level of aggregate electricity produced, the social marginal cost of production of renewable electricity should equate the social marginal cost of production of fossil electricity. Hence, the social marginal cost of aggregate electricity production is obtained by horizontally summing the two lines. This is how we obtain the supply curve of electricity  $SMC_Q(Q, \hat{c})$  which coincides with the expected social marginal cost of aggregate electricity production if the slope of the cost function for renewable electricity  $\hat{SMC}_r$  is  $\hat{c}$ . Likewise we obtain the supply curve of electricity  $SMC_Q(Q, c)$  relative to the scenario in which renewable electricity is less costly to produce, i.e.  $c < \hat{c}$ .

The social optimum for the scenario in which  $c$  drives green electricity production lies at the intersection of the aggregate electricity supply  $SMC_Q(Q, c)$  and the aggregate electricity demand  $AD$ . When renewable electricity is more expensive, with  $\hat{c} > c$ , the social optimum lies at the intersection of  $SMC_Q(Q, \hat{c})$  and  $AD$ . Reporting the price on the curve  $SMC_r(q_r, c)$  and  $SMC_f(q_f)$  (respectively  $\hat{SMC}_r(q_r, \hat{c})$  and  $SMC_f(q_f)$ ) we obtain the optimal quantities of renewable and fossil electricity when the former is driven by  $c$  (respectively by  $\hat{c}$ ).

Thus, when marginal costs of production of renewable electricity are high,  $\hat{SMC}_r(q_r, \hat{c})$ , the values at the social optimum (labeled with hats) differ from the situation in which renewable electricity production is cheaper,  $SMC_r(q_r, c)$  (where socially optimal values are labeled with stars):

$$q_r^* > \hat{q}_r \quad (9)$$

$$q_f^* < \hat{q}_f \quad (10)$$

$$P^* < \hat{P} \quad (11)$$

$$Q^* > \hat{Q} \quad (12)$$

$$\gamma(q_f^*) < \gamma(\hat{q}_f) \quad (13)$$

When the marginal cost of renewable electricity is low,  $c$ , the optimal aggregate power consumption  $Q^*$  is higher than when in the alternative scenario ( $\hat{c} > c$ ), with a substitution of fossil energy by renewable energy. Thus, the share of RES-E out of the total energy mix is higher than in the alternative scenario, i.e.  $s^* > \hat{s}$ .

## 4 Uncertainty

The main question of interest in this paper is to understand the impacts of instrument choice in the framework of energy policy when the government is uncertain regarding the production cost of renewable electricity.<sup>12</sup> Such uncertainty is mea-

<sup>12</sup>We assume there is no uncertainty regarding  $\gamma(q_f)$ , the marginal pollution damage caused by conventional electricity production nor regarding the value the policy-maker assigns to it (namely, the cost of cleanup). We believe this is a reasonable assumption when thinking about regulation at national level (e.g. within the US) or regional level (e.g. within the EU), while it could be challenged if it were applied in the context of international negotiations.

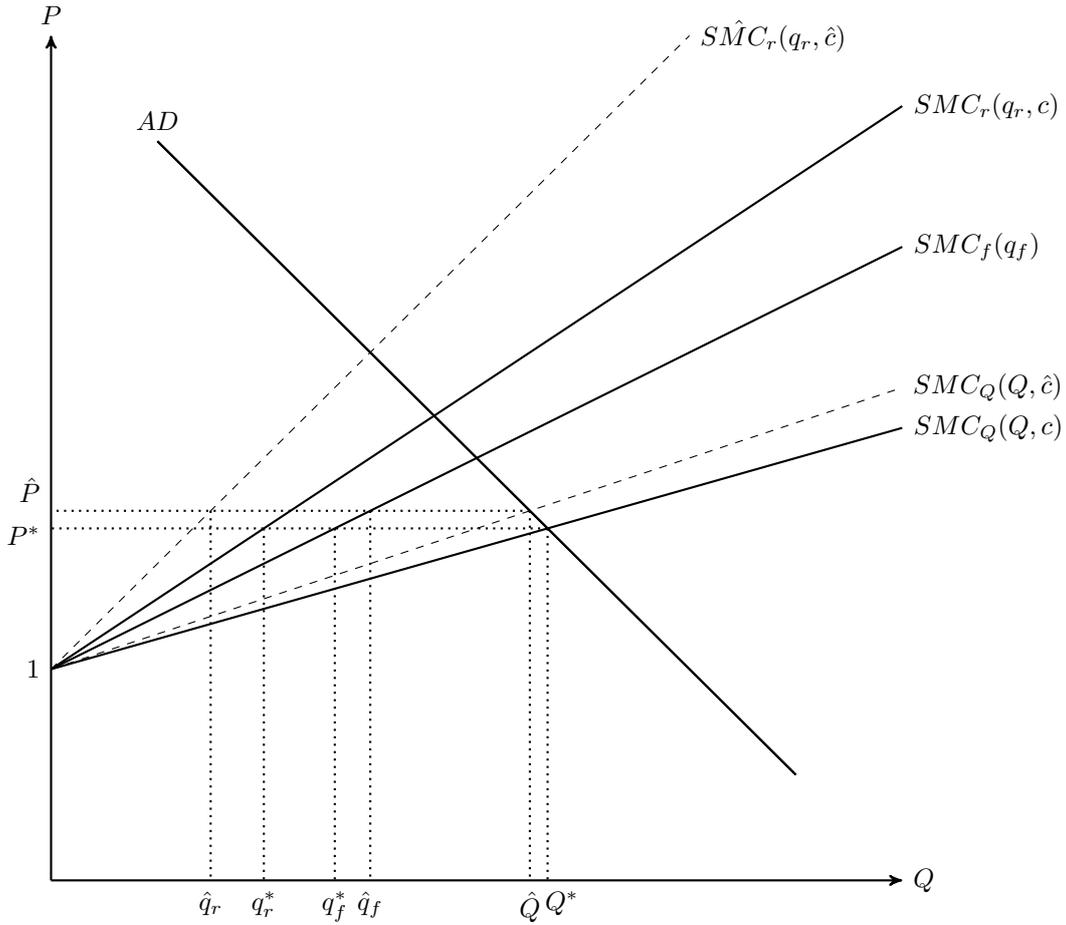


Figure 1: The electricity market under two alternative production cost scenarios for renewable electricity:  $c < \hat{c}$

sured by the discrepancy between what the government expects to be the slope of the marginal cost of renewable electricity,  $\hat{c}$ , and what the real slope is,  $c$ . The timeline of the problem is as follows:

- In  $t = 1$ , the government announces the implementation of an incentive scheme for renewable electricity, which can be price-based or quantity-based. At this time, the environment is uncertain for the government, because it does not know the marginal production costs of renewable electricity: the government expects  $\hat{MC}_r = 1 + \hat{c}q_r$ , but the actual value of  $c$  is observed only after the policy choice is realized. The environment is uncertain for producers because they do not know the marginal cost, nor the policy decision of the government.
- In  $t = 2$ , production costs are observed. Producers take their production decision given their marginal costs and given the mandatory share of renewables imposed by the government, which also influences their marginal costs. At the end of  $t = 2$ , equilibrium is attained.

Hatted variables  $\hat{x}$  represent the expectations agents have in  $t = 1$  when the environment is uncertain; starred variables  $x^*$  represent the social optimum (i.e. the

point at which the optimal level of fossil electricity is produced, thus generating the optimal amount of pollution), whereas a variable with no superscripts  $x$  describes what is the actual equilibrium at the end of  $t = 2$ .

We present here the results for the case of an overestimation of the costs. It can easily be shown that the results are symmetric in the case of an underestimation. The overestimation is such that the government chooses the policy instrument to use while believing the marginal cost of renewable electricity will depend on  $\hat{c}$ , but the realized costs turn out to be lower,  $c < \hat{c}$ . We observe how the results of the policy, denoted by  $Q$ ,  $q_f$ ,  $q_r$ ,  $P$  and  $s$ , deviate from the expectedly optimal values, denoted by  $\hat{Q}$ ,  $\hat{q}_f$ ,  $\hat{q}_r$ ,  $\hat{P}$  and  $\hat{s}$ , and the actual optimal values, denoted by  $Q^*$ ,  $q_f^*$ ,  $q_r^*$ ,  $P^*$  and  $s^*$ .

In this section, we explain the mechanisms at work, and recover one of the main results of Roberts and Spence (1976), showing that the errors created by a price instrument go in the opposite direction with respect to the errors generated by a quantity instrument. If the cost of renewable electricity is overestimated, with a quantity instrument, the level of pollution at the equilibrium is too high, whereas it is too low under a price instrument.

#### 4.1 A price-based instrument: a tax on conventional electricity

The most straightforward price-based instrument to tackle pollution problems is a Pigouvian tax, set equal to the marginal pollution damage caused by conventional electricity generation. By the first order conditions (7) and (8), the per-unit tax on conventional electricity consumption is set aiming at the expected optimal level of marginal pollution,  $T = \gamma'(\hat{q}_f) = \hat{c}\hat{q}_r$ . Thus, the supply of conventional electricity follows  $P = \hat{P} = 1 + T$ . The equilibrium quantity of green electricity is reached when the marginal production cost of renewable electricity is equal to the sum of the marginal cost of conventional electricity and the per-unit subsidy. With a price-based policy, the per-unit tax on conventional electricity is fixed by construction of the model, hence the sales price of electricity is not affected by the actual cost functions.

The intuition is represented in Figure 2 and formalized in the following proposition.<sup>13</sup>

**Proposition 1** *For a given tax on conventional electricity, if the government has overestimated the marginal cost of green electricity production: (i) the realized equilibrium price is higher than optimal, thus driving down electricity consumption with respect to the social optimum, (ii) the equilibrium level of renewable electricity is higher than optimal, while the level of conventional electricity produced at the equilibrium is lower than optimal, (iii) pollution emissions are lower than optimal.*

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<sup>13</sup>The bold line  $AS^*(c)$  represents the optimal supply curve of electricity; the dotted line  $\hat{AS}(\hat{c})$  represents the expected supply curve of electricity; the solid line  $AS(c)$  represents the realized supply curve of electricity. The same notation is used in all following figures.

**Proof.** The market price of electricity is determined by the level of the tax, fixed on the basis of the expectedly optimal quantity of conventional electricity. Thus it corresponds to the expected price,  $P = \hat{P} = 1 + T = 1 + \hat{c}q_r$ . Because the tax has been set on the basis of overestimated costs, the equilibrium price is too high with respect to the socially optimal price, i.e.  $P > P^*$ . The equilibrium level of renewable electricity corresponds to the point where  $P = 1 + cq_r$ . Hence, the production of renewable electricity is higher than expected,  $q_r > \hat{q}_r$ . As we have  $q_r > q_r^* > \hat{q}_r$ , it follows that the realized price is higher than optimal  $P = \hat{P} > P^*$  and consequently the aggregate quantity of electricity effectively produced is lower than optimal,  $Q = \hat{Q} < Q^*$ . As a consequence, it is straightforward that  $q_f < q_f^* < \hat{q}_f$ , and  $s > s^* > \hat{s}^*$ . It follows that pollution is lower than optimal, as  $\gamma(q_f) < \gamma(q_f^*) < \gamma(\hat{q}_f)$ . ■

If the tax has been set on the basis of overestimated marginal costs of renewable electricity, this tax is too high with respect to the optimum. As the level of the tax is what determines the equilibrium market price, this price is also too high. Hence, an insufficient amount of electricity is sold at the equilibrium price, and therefore the level of pollution is too low. Too high a quantity of total electricity production is generated with renewable energy sources, because the high tax on conventional electricity gives higher incentives to the production of renewable electricity.

An alternative price-based approach still yielding the same equilibrium consists in setting up subsidies for renewable electricity producers. In this setting, electricity is taxed regardless of the energy sources used to generate it, and then fiscal revenues rebated to renewable electricity producers. More specifically, the rebates are allocated as subsidies per each unit of renewable electricity produced, in order to bridge the cost difference between renewable and fossil electricity.

Feed-in tariffs are another widely used price-based incentive scheme: RES-E generators are guaranteed a fixed price, which concretely translates into being protected from market price fluctuations thus fully recovering costs. In the setup we delineate, implementing a fixed price yields the same equilibrium as a fixed subsidy. The important point is that electricity itself should still be taxed, so that the marginal pollution of conventional electricity is internalized.

While in our setup all three policies allow to reach the same equilibrium, as they translate into fixing the price of electricity, they differ in terms of their fiscal implications. With a Pigouvian tax on conventional electricity, the government accumulates tax revenues. On the other hand, with per-unit subsidies and feed-in tariffs, revenues from electricity taxation are rebated to renewable power producers. In the case of cost overestimation, the government raises more than necessary to fund subsidies for RES-E producers.

## 4.2 A quantity-based instrument: a conventional electricity quota

Assume the government sets a conventional electricity quota, by which the maximum level of conventional electricity allowed on the market corresponds to the expected

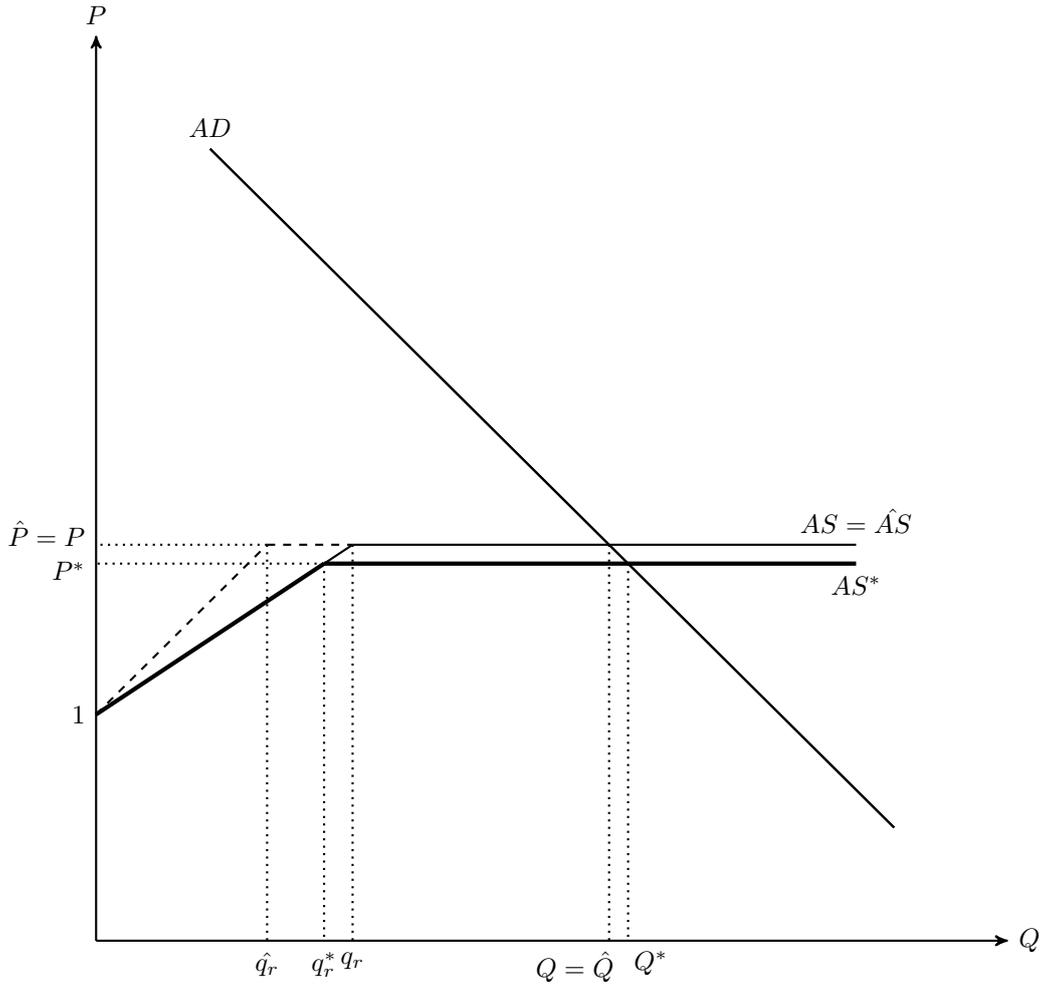


Figure 2: A price-based instrument: a tax on conventional electricity.

optimum  $\hat{q}_f$ . The market price of electricity is determined by the marginal cost of the last unit of renewable electricity. Hence, the market equilibrium is determined by the intersection between the demand curve and a supply curve of the form:

$$Q = \hat{q}_f + q_r(P). \quad (14)$$

Since the supply of renewable electricity  $q_r(P)$  is determined by the condition  $P = MC_r \Leftrightarrow P = 1 + cq_r$ , we can rewrite the equation above as

$$Q = \hat{q}_f + \frac{P - 1}{c}. \quad (15)$$

This has to be compared respectively with the expected supply curve and the optimal supply curve:

$$\hat{Q} = \hat{q}_f + \frac{\hat{P} - 1}{\hat{c}} \quad (16)$$

$$Q^* = q_f^* + \frac{P^* - 1}{c}, \quad (17)$$

where, by Proposition 1,  $q_f^* < \hat{q}_f$ . We represent these three conditions in Figure 3. The result is formalized in the following proposition.

**Proposition 2** *For a given conventional electricity quota, if the government has overestimated the marginal cost of renewable electricity production: (i) the realized equilibrium price is lower than optimal, consequently the realized aggregate quantity of electricity at the equilibrium is higher than optimal, (ii) the realized equilibrium quantity of conventional electricity is higher than optimal, while the realized equilibrium quantity of renewable electricity is lower than optimal, (iii) pollution is higher than optimal.*

**Proof.** The market price of electricity is lower than expected, given that the last unit of electricity produced (which is generated from renewable energy sources) is cheaper than expected, hence  $P < \hat{P}$ . Thus, marketed quantities are higher than expected,  $Q > \hat{Q}$ . The overestimation of  $c$  has led to fix a conventional electricity quota that is less ambitious than the optimal restriction: producers are forced to sell  $q_f = \hat{q}_f$ . Had the policy-maker known that renewable electricity was more convenient than expected, he would have set a stricter limit on fossil electricity, at  $q_f^* < q_f = \hat{q}_f$ , thus  $q_r^* > q_r > \hat{q}_r$ . Since the supply of electricity becomes elastic to prices at  $q_f > q_f^*$ , it follows that the realized equilibrium price is lower than optimal, hence the realized equilibrium quantity of aggregate electricity is lower than optimal. Because the expected slope of the price-elastic segment of the supply curve is higher than the realized slope (as  $\hat{c} > c$ ), it follows that  $Q > Q^* > \hat{Q}$  and  $P < P^* < \hat{P}$ . Finally, it follows that the realized share of renewable electricity is sub-optimal,  $s^* > s > \hat{s}$ . Realized pollution emissions are proportional to the quantity of conventional electricity produced at the equilibrium, hence  $\gamma(q_f^*) < \gamma(q_f) = \gamma(\hat{q}_f)$ . ■

If the conventional electricity quota has been estimated based on higher-than-realized marginal costs of renewable electricity, this quota is too high. Therefore, the market is flooded with too much conventional electricity, so that where the marginal cost of the last unit of renewable electricity equates the demand, the price is too low. Hence, there is excess demand for electricity and a higher than optimal fraction of this demand is directed towards conventional electricity producers. Consequently, there is too much pollution in equilibrium. This is partly counterbalanced as the producers of renewable electricity benefit from a demand effect: when the quantity of renewable electricity increases above the expected level, the equilibrium price also increases, allowing to smooth the estimation error.

### 4.3 A second quantity-based instrument: a renewable electricity quota

Assume the government sets a renewable electricity quota, corresponding to the expected optimum  $\hat{q}_r$ . Such a policy requires a guaranteed price for electricity corresponding to the marginal cost of renewable electricity to prevent conventional electricity generators from undercutting green electricity producers. This can be implemented through a tax levied on fossil electricity producers (aimed at extracting their rent). Hence, the market equilibrium price is determined by the marginal

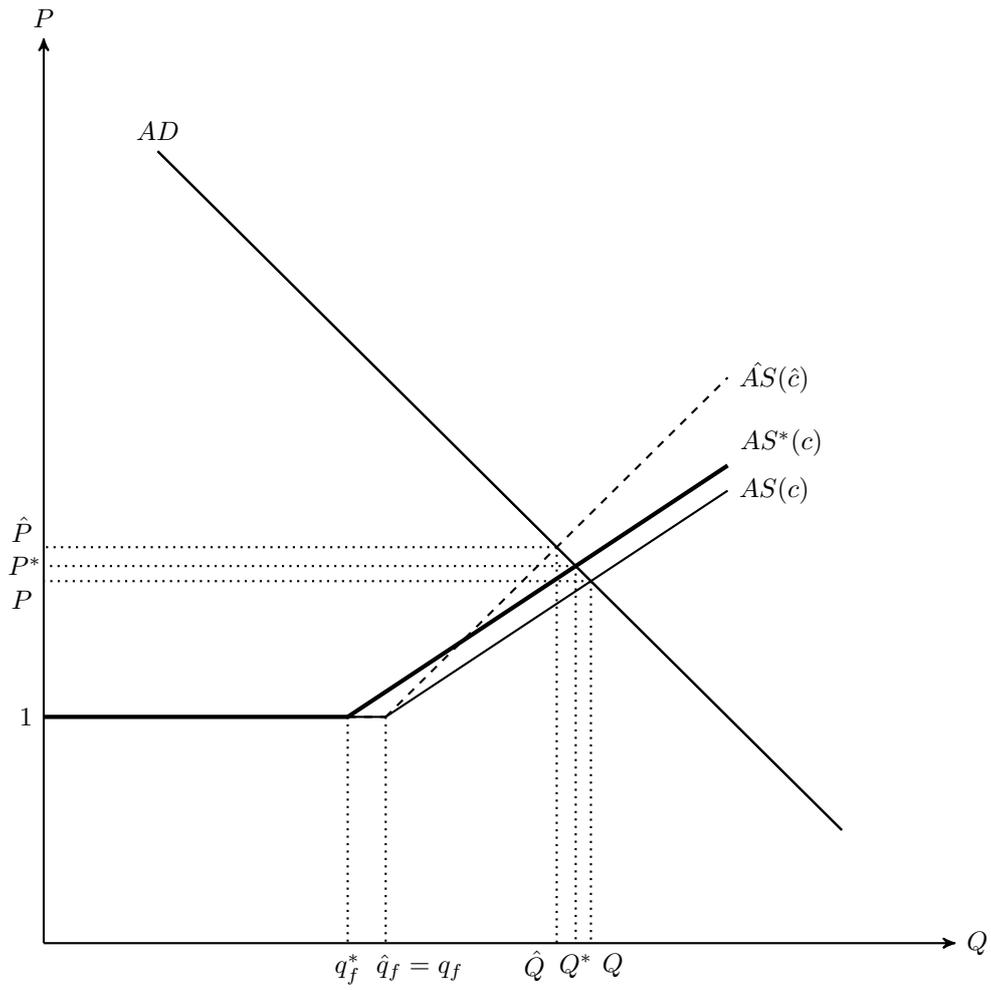


Figure 3: A first quantity instrument: a conventional energy quota

cost of the last unit of renewable electricity generated:

$$P = 1 + c\hat{q}_r \quad (18)$$

The realized equilibrium price has to be compared respectively with the expected equilibrium price and with the optimal equilibrium price:

$$\hat{P} = 1 + \hat{c}\hat{q}_r \quad (19)$$

$$P^* = 1 + cq_r^*. \quad (20)$$

We represent these three conditions in Figure 4. The result is formalized in the following proposition.

**Proposition 3** *For a given renewable electricity quota, if the government has overestimated the marginal cost of renewable electricity production: (i) the realized price of electricity is lower than optimal, consequently the equilibrium quantity of electricity is higher than optimal, (ii) the quantity of renewable electricity produced at the equilibrium is lower than optimal, thus the realized quantity of conventional electricity is higher than optimal, (iii) the equilibrium level of pollution is higher than optimal.*

**Proof.** By assumption, the quantity of renewable electricity actually produced at the equilibrium corresponds to the quota imposed by the government  $q_r = \hat{q}_r$ . Hence the realized equilibrium price is lower than expected,  $\hat{P} = 1 + \hat{c}\hat{q}_r > P = 1 + c\hat{q}_r$ . It follows from (19) and (20) that  $P < P^* < \hat{P}$ . Thus, aggregate equilibrium quantities are higher than optimal and than expected  $Q > Q^* > \hat{Q}$ . Because green electricity was considered to be more expensive than what it really is, we know that its imposed quota is less ambitious than needed, hence suboptimal:  $\hat{q}_r = q_r < q_r^*$ . The generation of conventional electricity is higher than optimal  $q_f > \hat{q}_f > q_f^*$ . Hence, pollution emissions are also higher than optimal,  $\gamma(q_f) > \gamma(\hat{q}_f) > \gamma(q_f^*)$ . Finally, the optimal share of RES-E out of total electricity generation is higher than realized and than expected,  $s^* > s > \hat{s}$ . ■

If the renewable electricity quota has been set on the basis of overestimated marginal costs of renewable electricity, this quota is too low. Therefore, there is not enough renewable electricity on the market and the equilibrium price is too low. The first consequence is that demand for electricity is too high and that the share of conventional electricity in the equilibrium mix is also too high. Consequently, this energy mix generates excessive pollution emissions. The second consequence is that, as opposed to the conventional electricity quota, demand being higher than optimal does not influence the price. Indeed, as the quantity of renewable electricity is fixed, all the additional capacity required to match the demand comes from conventional electricity producers, with constant marginal costs. Therefore, producing more does not increase the price and the estimation error is not smoothed as it is the case with a conventional electricity quota: the scope of misestimation is higher.

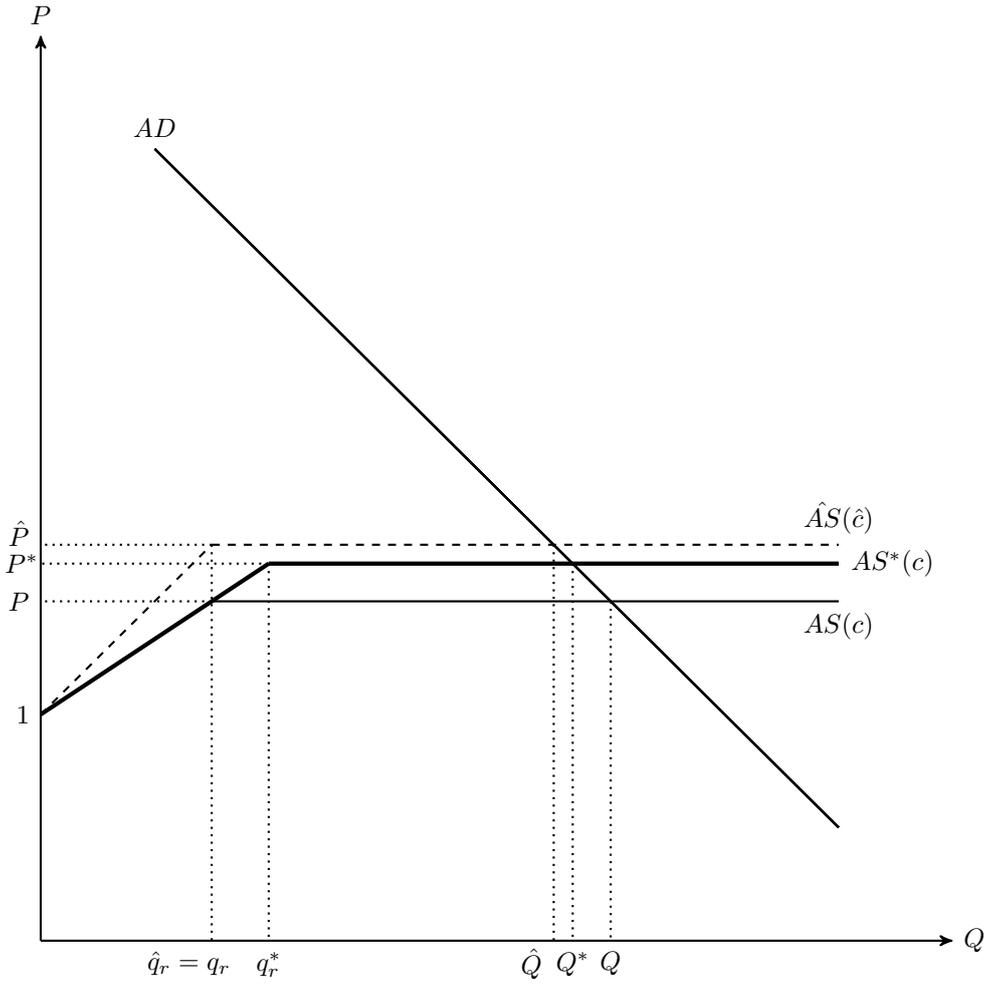


Figure 4: A second quantity instrument: a renewable electricity quota

#### 4.4 A third quantity-based instrument: a share of renewable electricity

Assume the government sets a compulsory share of renewable electricity out of the total aggregate electricity production, corresponding to the expected optimum  $\hat{s} = \frac{\hat{q}_r}{Q}$ . As in the previous case, since the optimal price is determined by the marginal cost of the last unit of renewable electricity, there must be a guaranteed price for electricity corresponding to this marginal cost.

The realized equilibrium price is given by

$$P = 1 + \hat{s}cQ \quad (21)$$

This has to be compared respectively with the expected equilibrium price and with the socially optimal price:

$$\hat{P} = 1 + \hat{s}\hat{c}\hat{Q} \quad (22)$$

$$P^* = 1 + s^*cQ^*, \quad (23)$$

We represent these three conditions in Figure 5, respectively as  $AS(\hat{s}, c)$ ,  $AS(\hat{s}, \hat{c})$  and  $AS(s^*, c)$ . The result is formalized in the following proposition.

**Proposition 4** *For a given share of renewable electricity, if the government has overestimated its cost: (i) the realized equilibrium price is lower than optimal, hence the realized equilibrium quantity of aggregate electricity is higher than optimal, (ii) the realized equilibrium quantity of renewable electricity is lower than optimal, hence the realized quantity of conventional electricity is higher than optimal, (iii) pollution emissions are higher than optimal.*

**Proof.** Because of cost overestimation, the mandated share of RES-E is suboptimal, i.e.  $s^* = \frac{q_r^*}{Q^*} > \hat{s}$ , since  $q_r^* > \hat{q}_r$  and  $Q^* > \hat{Q}$ . Since the optimal supply curve is steeper than the realized supply curve, it follows that equilibrium prices are not as high as they should be at the social optimum,  $P < P^* < \hat{P}$ . Thus equilibrium quantities of aggregate electricity are higher than optimal,  $Q > Q^* > \hat{Q}$ . As, by assumption, the mandated share of green electricity is based on the cost expectation of the government, we have that  $s = \hat{s}$ . The realized equilibrium quantity of aggregate electricity is higher than expected  $Q > \hat{Q}$ , where the extra quantity of electricity with respect to expectations has been provided through fossil energy sources,  $q_f > \hat{q}_f$ . We already know that  $\hat{q}_f > q_f^*$ , thus we find  $q_f > \hat{q}_f > q_f^*$ . Consequently, we can derive that  $sQ > \hat{s}\hat{Q}$ , hence  $q_r > \hat{q}_r$ . As the price is determined by the marginal cost of the last unit of renewable electricity, and as the optimal and realized costs are identical, it also follows that  $q_r^* > q_r$ . Hence,  $q_r^* > q_r > \hat{q}_r$ . Finally, because of higher than optimal fossil electricity production, pollution emissions are also higher than optimal,  $\gamma(q_f) > \gamma(\hat{q}_f) > \gamma(q_f^*)$ . ■

If the share of renewable electricity has been set on the basis of overestimated production costs, this share is too low. Therefore, the generation of renewable electricity in equilibrium is insufficient and the price is lower than optimal. As with other quantity instruments, this implies that production of conventional electricity is too high, and so is pollution. The mechanism at work is a combination of two elements. There is a demand effect that smooths the estimation error, whereby the price increases when demand is above expectations. However, the price increases at a slower pace than under a quota of conventional electricity, because only a certain share of the demand exceeding expectations is produced using renewable electricity.

## 5 Discussion

We now compare the results of the four analysed policy schemes in terms of equilibrium levels of conventional electricity (which drives the pollution level  $\gamma(q_f)$ ), renewable electricity and aggregate electricity. Our natural benchmark is the social optimum. We refer in what follows to the case in which the policy-maker overestimates the production costs of renewable electricity; all results symmetrically transpose to the case in which the policy-maker instead underestimates  $c$ .

The following proposition compares the effect of alternative policy instrument choices on the level of conventional electricity produced at the equilibrium.

**Proposition 5** *If the government has overestimated the cost of renewable electric-*

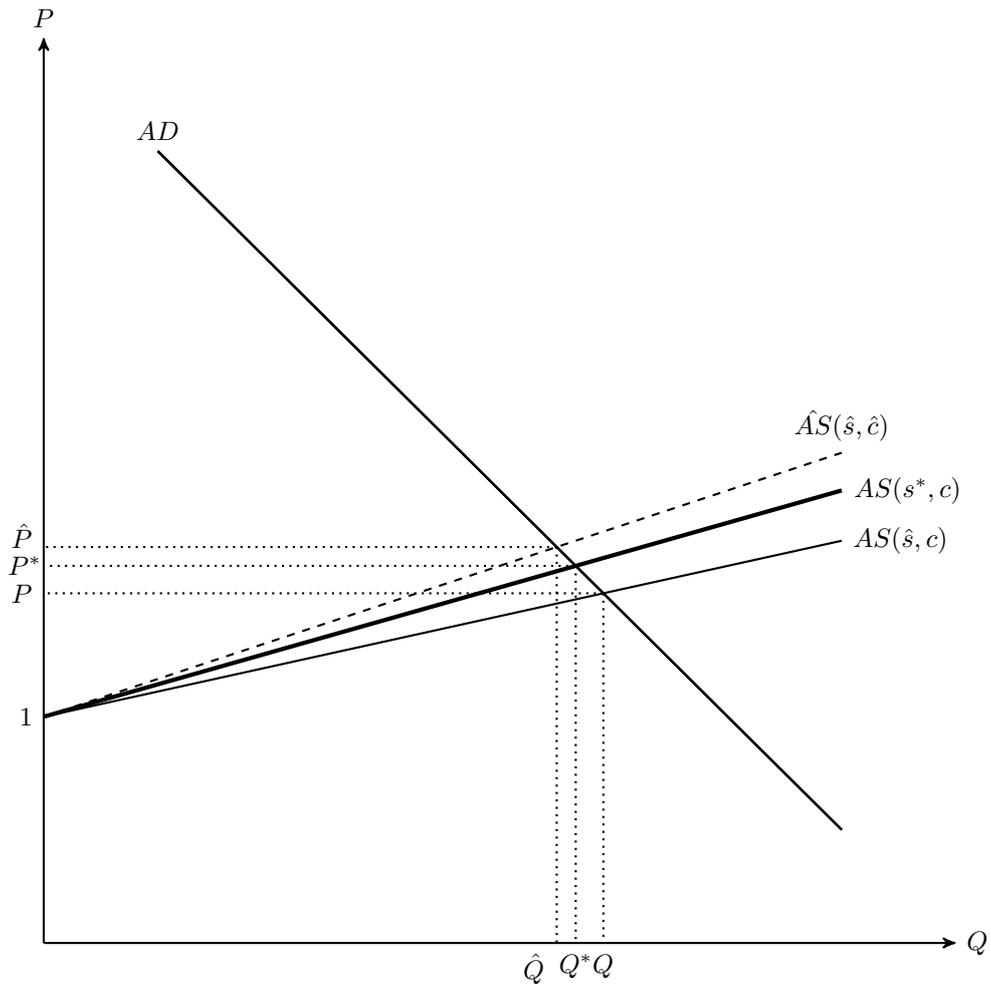


Figure 5: A third quantity instrument: a share of renewable electricity

Index	Instrument	Type of instrument
1	per-unit tax on conventional electricity consumption	price-based
2	conventional electricity quota	quantity-based
3	renewable electricity quota	quantity-based
4	mandatory share of renewable electricity	quantity-based

ity, the following is verified:

$$q_{f,1} < q_f^* < q_{f,2} = \hat{q}_f < q_{f,4} < q_{f,3} \quad (24)$$

More specifically, (i) the level of conventional electricity generated under a price-based instrument is lower than optimal, (ii) the level of conventional electricity generated under a quantity-based instrument is higher than optimal, (iii) among quantity-based instruments, a conventional electricity quota yields a level of conventional electricity generation that is closest to the optimum, followed by a mandatory share of renewable electricity and lastly by a renewable electricity quota.

The first five relationships follow straightforwardly from our previous section. The latter,  $q_{f,4} < q_{f,3}$  can be derived as follows:

**Proof.** By assumption, the quota of renewable electricity is based upon estimated costs, hence  $q_{r,3} = \hat{q}_r$ . Because of the government cost overestimation, it follows that  $q_{r,3} = \hat{q}_r < q_{r,4}$ , thus  $s_3 = \hat{s} < s_4$ . Hence, as  $q_{r,3} < q_{r,4}$  and as price is determined by the marginal cost of the last unit of renewable electricity, it follows that  $P_3 < P_4$  and therefore  $Q_3 > Q_4$ . Thus, as  $q_f = Q - q_r$ ,  $Q_3 > Q_4$  and  $q_{r,3} < q_{r,4}$ , it follows that  $q_{f,4} < q_{f,3}$  ■

The two other variables of interest, the equilibrium level of renewable electricity and the equilibrium aggregate power production behave the same way. We already know from part 2 that  $Q^* > \hat{Q}$ . We know by Proposition 1 that the price instrument yields  $Q_1 = \hat{Q}$ . We also know by Proposition 2, 3, 4 that the realized consumption of electricity is higher than optimal with a quantity instrument.

**Proposition 6** *If the government has overestimated the cost of renewable electricity, the following is verified:*

$$Q_3 > Q_4 > Q_2 > Q^* > Q_1 = \hat{Q} \quad (25)$$

More specifically, (i) the aggregate level of electricity generated under a price-based incentive scheme is lower than optimal, (ii) the aggregate level of electricity generated under a quantity-based incentive scheme is higher than optimal, (iii) among quantity-based instruments, a conventional electricity quota yields a level of aggregate production that is closest to the optimum, followed by a mandatory share of renewable electricity and lastly by a renewable electricity quota.

**Proof.** To find the different equilibrium quantities, it suffices to find the equilibrium prices corresponding to each different policy implementation. By the “demand

effect” argument, we know that  $P_3 < P_4 < P_2$ . Hence, we find  $Q_3 > Q_4 > Q_2 > Q^* > Q_1 = \hat{Q}$ . The errors following the implementation of a price-based instrument go in opposite directions with respect to the errors driven by the choice of a quantity-based instrument, and the error with a conventional electricity quota is lower than with a mandatory share of renewable electricity, which is lower than with a renewable electricity quota. ■

Finally, comparing the equilibrium levels of renewable electricity we find the following.

**Proposition 7** *If the government has overestimated the cost of renewable electricity, the following inequalities hold:*

$$q_{r,1} > q_r^* > q_{r,2} > q_{r,4} > q_{r,3} = \hat{q}_r \quad (26)$$

*More specifically, (i) the level of renewable electricity generated under a price-based incentive scheme is higher than optimal, (ii) the level of renewable electricity generated under a quantity-based incentive scheme is lower than optimal, (iii) among quantity-based instruments, a conventional electricity quota is the most efficient option, followed by a mandatory share of renewable electricity and lastly by a renewable electricity quota.*

**Proof.** By assumption, under a renewable electricity quota, the realized level of renewable electricity corresponds to its expectation,  $q_r = \hat{q}_r$ . Both under a conventional electricity quota and under a mandatory share of renewable electricity,  $q_r > \hat{q}_r$ : the difference between the two policies is that, with a share, part of the extra demand is taken by conventional power producers, hence the above equality holds. ■

This proves a fundamental point: the reason why the renewable electricity quota is the least efficient tool in achieving pollution objectives is not because it is an indirect tool, as opposed to setting a conventional electricity quota, thus directly controlling pollution levels. If the government were interested in reaching a certain level of renewable electricity as a primary objective, the best quantity instrument would still be a conventional electricity quota. The intuition behind this is that the conventional electricity quota is the quantity instrument that uses at best the demand effect to smooth the impact of an estimation error.

The following tables summarize the discussion.

Table 1: **Realized equilibrium vs. Optimum.** The consequences of overestimating the cost of renewable energy as compared to the outcomes of the perfect information setting.

Criteria	Tax on conventional electricity	Conventional electricity quota	Renewable electricity quota	Mandatory share
<i>Aggregate consumption of electricity <math>Q</math></i>	lower (-)	higher (+)	higher (+++)	higher (++)
<i>Market price <math>P</math></i>	higher (+)	lower (-)	lower (- - -)	lower (- -)
<i>Level of renewable electricity <math>q_r</math></i>	higher (+)	lower (-)	lower (- - -)	lower (- -)
<i>Level of conventional electricity <math>q_f</math></i>	lower (-)	higher (+)	higher (+++)	higher (++)
<i>Pollution <math>\gamma(q_f)</math></i>	lower (-)	higher (+)	higher (+++)	higher (++)
<i>Share <math>s</math> of RES-E out of aggregate consumption</i>	higher (+)	lower (-)	lower (- - -)	lower (- -)
<b>Ranking of quantity instruments by distance to the optimal pollution level</b>		1	3	2

*Note:* When marked as ‘lower’ (respectively ‘higher’), the *realized* equilibrium level of the corresponding variable is lower (respectively higher) than its *socially optimal* level. Pluses and minuses indicate the magnitude of this discrepancy.

Table 2: **Realized vs. expected equilibrium.** The consequences of overestimating the cost of renewable energy as compared to the expected outcomes.

Criteria	Tax on conventional electricity	Conventional electricity quota	Renewable electricity quota	Mandatory share
<i>Aggregate consumption of electricity <math>Q</math></i>	unaffected (=)	higher (+)	higher (+++)	higher (++)
<i>Market price <math>P</math></i>	unaffected (=)	lower (-)	lower (- - -)	lower (- -)
<i>Level of renewable electricity <math>q_r</math></i>	higher (+++)	higher (++)	unaffected (=)	higher (+)
<i>Level of conventional electricity <math>q_f</math></i>	lower (-)	unaffected (=)	higher (++)	higher (+)
<i>Pollution <math>\gamma(q_f)</math></i>	lower (-)	unaffected (=)	higher (++)	higher (+)
<i>Share <math>s</math> of RES-E out of aggregate consumption</i>	higher (+ +)	higher (+)	lower (-)	unaffected (=)

*Note:* When marked as ‘lower’ (respectively ‘higher’), the *realized* equilibrium level of the corresponding variable is lower (respectively higher) than *expected* on the basis of cost estimations. Pluses and minuses indicate the magnitude of this discrepancy.

## 6 Conclusion

Weitzman (1974) compares marginal cost and marginal benefit curves of cleanup of the pollution damage implied by a negative production externality. More precisely, he deals with the negative of this problem, as he calls it, by looking at uncertainty affecting costs and benefits of clean air. He compares a quantity-based target to a price-based policy aimed at striking the optimal quantity of clean air – symmetrically, that of air pollution. Given that we consider the generation of renewable electricity as a means for decarbonizing the power sector, a government will shape energy policy according to its expectations of the slope of the marginal cost of renewable electricity production, seen as ‘clean’ power generation.

This paper provides a three-fold contribution.

First, our approach differs from previous research on prices versus quantities: we do not focus on the relative difference in the slope of marginal benefits and marginal costs in our market of reference – what Weitzman calls the ‘coefficient of comparative advantage of prices over quantities’ (Weitzman, 1974, p. 483). Indeed, the choice between prices and quantities will also depend on relative elasticities, but we do not focus on this. Instead, we take as given the demand for electricity and compare the impact of alternative policy choices on the marginal cost curve, and thus on market outcomes, which allows us to rank quantity instruments. Furthermore, we

deal with cost uncertainty in a slightly different way, explicitly modeling uncertain production costs of renewable electricity through an unknown cost parameter that enters the electricity cost function. On the generation side, the uncertainty relative to renewable electricity is connected to the intermittency that characterises renewable resources (e.g. solar power or wind) as well as to the uncertain evolution of the technology required to transform such resources into power. On the transmission side, intermittency translates into the need of a profound (and costly) adaptation and upgrade of grid infrastructure.

Second, our analysis of renewable energy incentive schemes differs from previous research on the same policy interventions. While other scholars have focused on the objective of maximizing the quantity of renewable electricity on the power market, we argue the objective function of the government should be directed at bringing the pollution caused by conventional electricity production to its optimal level. In other words, we argue regulators should support renewables only as a means to ‘green’ electricity generation, using renewable energy sources as a substitute for fossil energy as long as their private marginal production cost is lower than the social marginal cost of conventional energy. In that sense, even if the objective of the government were to reach the socially optimal level of renewable electricity (instead of the optimal level of pollution), a conventional electricity quota would be the best quantity instrument to do so.

Third, on top of the choice between price-based and quantity-based policies, we show the fundamental difference between alternative quantity instruments. Setting a definite target in terms of *level* of renewable electricity to be produced as opposed to a *share* of RES-E, yields very different results in terms of market outcomes, when the policy-maker sets its policy not knowing renewable energy production costs. Indeed, mandating a certain share of total electricity to be produced with renewable energy sources does not guarantee a fixed aggregate quantity of renewable electricity will be produced. Hence, it does not guarantee that a fixed amount of GHG emissions will be abated. We show that price and quantity instruments have well-known asymmetries, and we provide a clear ranking of quantity-based policy instruments in terms of the level of pollution they entail at the equilibrium. The less distortionary is a conventional electricity quota. If this kind of policy constraint on fossil power producers is politically unfeasible, mandating a certain share of green electricity out of the total energy mix is better than setting a renewable electricity quota.

Our results provide policy guidance consistent with the European Union context, in which more and more member states are planning to shift away from price-based feed-in tariffs. It is easy to imagine that conventional energy quotas would attract the ire of fossil electricity producers. Within this politically constrained context, the choice of setting a policy target in terms of a (more flexible) mandatory share of RES-E rather than in terms of a green electricity quota proves to yield lower distortions, hence a closer-to-the optimum level of pollution.

Setting renewable energy policies in terms of levels of green electricity is definitely to be ruled out, as it is by far the least efficient policy approach – the approach

the United States seem to prefer within the President’s 2013 climate action plan (Executive Office of the President, 2013).

Our analysis provides the policy-maker with an overview of the consequences of alternative policy choices under uncertainty. Assuming the primary objective is decreasing pollution generated by electricity production to its socially optimal level, our model clearly shows the trade-offs one must be aware of when implementing this kind of policy.

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