Decarbonizing electricity generation with intermittent sources of energy

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Abstract

We examine the impact of public policies that aim to decarbonate electricity production by replacing fossil fuel energy by intermittent renewable sources, namely wind and solar power. We consider a model of energy investment and production with two sources of energy: one is clean but intermittent (e.g. wind), whereas the other one is reliable but polluting (e.g. coal). A carbon tax decreases electricity production while simultaneously increasing investment in wind power. This tax may however increase total capacity because the retailing price of electricity does not depend on energy availability, which means that windmill capacity must be backed-up by thermal power plants. Feed-in tariffs and renewable portfolio standards enhance investment into intermittent sources of energy. However, both are likely to boost electricity production beyond the efficient level, in which case they must be complemented with a tax on electricity consumption. We also determine the social value of two technologies to accommodate intermittency: energy storage and smart meters. Lastly, we consider the case of a monopoly thermal power producer. The entry of a competitive fringe of wind power producers makes the thermal power producer reduce further its production capacity, which increases the electricity price.

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1 Introduction

Electricity production from fossil energy sources is one of the main causes of anthropogenic greenhouse gas emissions. The electricity sector has therefore paid close attention to the debate about climate change mitigation. Public policies have been launched worldwide to decarbonate electricity production by substituting renewable sources of energy, such as wind and solar power, for fossil-fuel generated electricity. Various instruments have been adopted: while several countries tax their CO_2 emissions, the EU caps them with tradable allowances.

The type of support for renewables also differ. US states tend to opt for renewable portfolio standards (RPS) programs which generally require a minimum fraction of electricity demand to be met by renewable sources. Those programs are usually implemented on the basis of renewable energy certificates (RECs) issued by state-certified renewable generators. Electricity retailers are required to hold enough certificates to comply with the minimum standards.[1]

Most European countries have opted for a price instrument: the feed-in tariff (FIT). They have committed to purchasing renewable generated electricity at a price fixed well above the wholesale price. The price difference is generally covered by a tax charged to electricity consumers. FITs have been quite successful in fostering investment in wind and solar power in Europe during the past decade. The price paid for success is an increase in the consumers' bill to cover the cost of FIT.[2]

Integrating renewable energy such as wind or solar power into the electricity mix is not easy. One reason is that, unlike conventional power units, electricity produced from wind turbines and photovoltaic panels varies over time and weather conditions. The supply of electricity from these sources is out-of-control and highly unpredictable. It depends on weather conditions that are rarely forecasted more than five days ahead.[3] The intermittency of electricity supplied from windmills and solar photovoltaic panels makes power dispatching more challenging. Electricity

[1] Since 2007, the U.S. House of Representatives has twice passed bills to make a nationwide RPS program mandatory (Schmalensee 2012). Information about RPS requirements and renewable portfolio goals is available on the EPA website: http://www.epa.gov/agstar/tools/funding/renewable.html

[2] How much it costs to consumers depends on whether suppliers can pass-through the additional cost through to their customers. In France, where the entire FIT is billed to final customers, subsidies for green technologies represent 10% of the electricity bill, and are continuously increasing. See http://entreprises.edf.com/le-mag-de-l-energie/actualites-du-marche-de-l-energie/marche-de-l-energie-en-france/evolution-de-la-cspe-au-1er-janvier-2015-293096.html

[3] See for instance Newberry (2011) for empirical evidence.

must be produced at the very same time it is consumed. Supply must thus match demand in real time, whereas the price signals do not change so quickly. Even if wholesale electricity prices vary with electricity provision, the retail prices that consumers pay do not. Even if prices could vary with weather conditions to reflect the supply of intermittent sources of energy (e.g. with the use of “smart meters"), most consumers will not instantly react to price changes.

The aim of the paper is to analyze the impact of environmental and energy policies on electricity provision in an industry with intermittent source of energy and non-reactive consumers. The model afford us insight into how public policies affect investment in production capacity, energy use, electricity provision, environmental pollution and welfare. We obtain clear-cut recommendations on the design of public policies that can be estimated empirically.

Equipped with our model, we first characterize the efficient energy mix and discuss its decentralization in a competitive market (free entry and price-taker firms). Several ingredients are needed to achieve efficiency: first, a wholesale market in which electricity producers sell to retailers at prices that fluctuate with the weather conditions at production spots; second, a retail market in which risk-neutral retailers offer fixed price contracts to final consumers whose consumption cannot be adjusted to price fluctuations; and third, a tax on polluting emissions at the Pigou rate.

Next we analyze the impact of several policy instruments on the energy mix in a competitive electricity industry. We focus on three instruments: a carbon tax on fossil fuel, a feed-in tariff (FIT), and a renewable portfolio standard (RPS). By increasing both the operating cost and the price of electricity produced by thermal power, a carbon tax makes renewable energy more competitive and reduces electricity production from fossil fuel. It increases investment in wind power and decreases thermal power facilities. Yet the total production capacity from both sources of energy may increase with the carbon tax.

Both FIT and RPS enhance the penetration of renewables into the energy mix. When they are designed to target the efficient share of renewable sources of energy, they induce too much electricity production, investment in thermal power and environmental pollution. They should be complemented by a tax on electricity or fossil fuels to implement first-best. In particular, the tax on electricity that only finances the FIT is not high enough to obtain an efficient energy mix. Alternatively, the efficient FIT raises more money than what is strictly necessary to balance the industry costs.

We then consider technological solutions to better deal with intermittency. We consider energy storage and contingent electricity pricing with smart meters. We identify the marginal benefits of these solutions and the market-driven incentives to invest in these technologies.

Lastly, we analyze environmental policies in the presence of market power. We consider the case of one thermal-power producer facing a fringe of price-taking wind-power producers. We show that competition from wind power producers does not alter the ability of the thermal plant to exert its market power. Worse than that, the fossil fuel producer reduces capacity below the stand-alone level because thermal power plants run less often, which increases the cost of equipment per period of activity. As a consequence, the retailing price of electricity is higher than without the competitive fringe of wind-power producers. We also point out that the carbon tax should vary with wind power production to correct the exercise of market power that varies accordingly.

Our paper is not the first to introduce intermittency in an economic model of electricity provision. Ambec and Crampes (2012) analyze the optimal and/or market-based provision of electricity with intermittent sources of energy.[4] However, they do not consider public policies and environmental externalities. Rubin and Babcock (2013) rely on simulation to quantify the impact of various pricing mechanisms - including FIT - on wholesale electricity markets. We take a different approach here: we analytically solve the model and make a welfare comparison of several policy instruments. Garcia, Alzate and Barrera (2012) introduce RPS and FIT in a stylized model of electricity production with an intermittent source of energy. Yet they assume an inelastic demand and a regulated price cap. In contrast, price is endogenous in our paper. More precisely, we consider a standard increasing and concave consumer's surplus function which leads to a demand for electricity that smoothly decreases in price. Our framework is more appropriate for analyzing long-term decisions concerning investment in generation capacity since in the long run smart equipment will improve demand response. It furthermore allows for welfare comparisons in which consumers' surplus and environmental damage are included.

So far, the literature on public policies to decarbonate electricity provision has ignored the problem of intermittency. Papers have looked at pollution externalities and R& D spillovers in a dynamic framework (e.g. Fischer and Newell 2008, Acemoglu et al. 2012) or in general equilibrium (Fullerton and Heutel, 2010). They have considered two technologies - a clean and a dirty one- that are imperfect substitutes in electricity production. In our pa-

[4] See also Rouillon (2013) and Baranes et al. (2014) for similar analysis.

per, we are more specific about the degree of substitution: it depends on weather conditions. Consequently, capacity and production also vary with weather conditions. This introduces uncertainty in energy supply which has to be matched with a non-contingent demand. To the best of our knowledge, our paper is the first analytical assessment of public policies that deals with intermittency.

The rest of the paper is organized as follows. Section 2 introduces the model. Section 3 describes the first-best energy mix. Environmental policies are analyzed in Section 4: carbon tax (Section 4.1), FIT (Section 4.2) and RPS (Section 4.3). Section 5 investigates two technological solutions to intermittency: energy storage in Section 5.1 and smart meters with contingent pricing in Section 5.2. We consider the case of market power in the electricity sector in Section 6. Section 7 concludes.

2 The model

We consider a model of energy production and supply with intermittent energy.[5] On the demand side, consumers derive a gross utility $S(q)$ from the consumption of q kWh of electricity. It is a continuous derivable function with $S' > 0$ and $S'' < 0$. The inverse demand for electricity is therefore $P(q) = S'(q)$ and the direct demand is $D(p) = S'^{-1}(p)$ where p stands for the retail price.

On the supply side, electricity can be produced by means of two technologies. First a fully controlled but polluting technology (e.g. coal, oil, gas) makes it possible to produce q_f at unit operating cost c as long as production does not exceed the installed capacity, K_f. The unit cost of capacity is r_f. This source of electricity will be named the "fossil" source. It emits air pollutants (e.g. CO_2, SO_2, NOx) which causes damages to society estimated at $\delta > 0$ per unit of output. We assume that $S'(0) > c + r_f + \delta$; in other words, producing electricity from fossil energy is socially efficient when it is the only production source.

The second technology relies on an intermittent energy source such as solar power and wind. It makes it possible to produce q_i kWh at 0 cost as long as (i) q_i is smaller than the installed capacity K_i and, (ii) the primary energy is available. We assume two states of nature: “with" and “without" intermittent energy. The state of nature with (respectively without) intermittent energy occurs with probability ν (respectively $1 - \nu$) and is denoted

[5] The model is a generalization of Ambec and Crampes (2012), with pollution damage and heterogeneous production costs for wind or solar power.

by the superscript w (respectively $\overline{w}$). The total potential capacity that can be installed is $\bar{K}$. The cost of installing new capacity is r_i per kWh. It varies depending on technology and location (weather conditions, proximity to consumers, etc.) in the range $[\underline{r}_i, +\infty]$ according to the density function f and the cumulative function F. To keep the model simple, we assume that investing in new intermittent capacity has no effect on the probability of occurrence of state w, which depends only on the frequency of windy days. Investing only increases the amount of energy produced. This assumption can be relaxed by allowing for more states of nature, that is by changing the occurrence of intermittent energy from several sources.[6]

Importantly, we assume that consumers do not react to price changes due to weather conditions or states of nature affecting production plants. The reason is that they do not receive the price signal, or they are not equipped to react to it. This implies that prices and electricity supply on the retail market cannot be made contingent on states $w, \bar{w}$. Furthermore, electricity cannot be stored, transported or curtailed.[7] The only way to balance supply and demand is then to rely on production adjustment and/or price variation.

3 Optimal energy mix

We first characterize the first-best energy mix, which is defined by capacities for each source of energy K_i and K_f, and outputs in each state of nature for each source of energy. Denote by q_j^h electricity production in state $h \in \{w, \bar{w}\}$, for energy source $j \in \{f, i\}$. First, by definition, in state $\overline{w}$, no intermittent energy is produced: $q_i^{\bar{w}} = 0$. Second, the non-reactivity of consumers implies that their electricity consumption cannot be state dependent: $q = q_f^{\bar{w}} = q_i^w + q_f^w$. Third, the assumption $S'(0) > c + \delta + r_f$ implies $q_f^{\overline{w}} = K_f > 0$: fossil fuel capacity will be installed and fully used. Fourth, since intermittent energy has no operating cost, all the energy produced by windmills (if any) will obviously be supplied to consumers, $q_i^w = K_i$ as long as $S'(K_i) \geq 0$. Fifth, the more efficient spots for wind or solar power will be equipped first. Therefore, denoting by $\tilde{r}_i \geq \underline{r}_i$ the cost of the last installed wind turbine, the installed capacity of wind power is $K_i = \bar{K}F(\tilde{r}_i)$.

The decision variables K_f, $\tilde{r}_i$ and q_f^w must be chosen to maximize the expected social

[6] See Ambec and Crampes (2012), Section 4.

[7] This assumption is relaxed later on when we extend the model in Section 6.

surplus:

$$\nu\left[S(\bar{K}F(\tilde{r}_i)+q_f^w)-(c+\delta)q_f^w\right] \quad +(1-\nu)\left[S(K_f)-(c+\delta)K_f\right]-\bar{K}\int_{\underline{r}_i}^{\tilde{r}_i} r_i dF(r_i)-r_f K_f$$

subject to the constraints:

$$\bar{K}F(\tilde{r}_i)+q_f^w = K_f \quad (1)$$
$$q_f^w \geq 0 \quad (2)$$
$$q_f^w \leq K_f \quad (3)$$
$$\tilde{r}_i \geq \underline{r}_i \quad (4)$$

The first constraint is the non-reactivity constraint. It requires electricity consumption to be the same in the two states of nature. Second, electricity production from fossil fuel in state w should be non-negative. Third, it should not exceed production capacity. Fourth, the threshold capacity cost $\tilde{r}_i$ is bounded downward by the lowest cost $\underline{r}_i$.

Let $\widehat{\delta}$ be a threshold on environmental damages defined implicitly by the following relationship:

$$\bar{K}F\left(\nu\left(c+\widehat{\delta}\right)\right)=S'^{-1}\left(c+r_f+\widehat{\delta}\right). \quad (5)$$

Solving the above program, we obtain the following proposition (the proof is in the appendix).

Proposition 1 *The optimal levels of capacity and output are such that:*

(a) for $\delta<\frac{r_i}{\nu}-c$: no intermittent energy

$K_i=0$

$K_f=q_f^w=q_f^{\overline{w}}=S'^{-1}(c+r_f+\delta)$

(b) for $\frac{r_i}{\nu}-c\leq\delta\leq\widehat{\delta}$: both sources of energy are used in state w

$K_i=\bar{K}F(\tilde{r}_i^b)$ *with* $\tilde{r}_i^b=\nu\,(c+\delta)$

$K_f=q_f^{\overline{w}}=S'^{-1}(c+r_f+\delta)$

$q_f^w=K_f-K_i$

(c) for $\widehat{\delta}\leq\delta$: only intermittent energy is used in state w

$K_i=\bar{K}F(\tilde{r}_i^c)$ *with* $\tilde{r}_i^c$ *given by* $\bar{K}F(\tilde{r}_i^c)=S'^{-1}((1-\nu)\,(c+\delta)+r_f+\tilde{r}_i^c)$

$K_f=K_i=q_f^{\overline{w}}=S'^{-1}((1-\nu)\,(c+\delta)+r_f+\tilde{r}_i^c)$

$q_f^w=0.$

The above conditions and solutions have natural economic interpretations. The ratio $\underline{r}_i/\nu$ represents the marginal cost of producing one kWh of wind power in the most efficient windmill, discounted by the probability of availability. It must be compared to the marginal social cost of one kWh of thermal power once capacity is installed. The latter includes operating costs c and environmental costs δ.[8] If $\underline{r}_i/\nu$ is higher than $c+\delta$ (case a), no wind power should be installed. Electricity production should only come from the more socially efficient technology, that is thermal power. Installed thermal capacity should match consumers' preferences in the sense that the marginal utility of electricity consumed equals its marginal social cost: $S^{'}(K_f) = c + r_f + \delta$, which is constant whatever the state of nature.

In Figure 1 we graph investment in the two sources of energy and consumption as a function of the environmental damage δ.[9]

[8]Note that the cost of thermal power equipment r_f does not matter when comparing the cost of the two sources of energy. This is because, due to intermittency and non-reactivity, every kW of wind power installed must be backed-up with 1 kW of thermal power. Thus both sources of energy need the same thermal power equipment.

[9]As shown in the Appendix, the threshold damage $\widehat{\delta}$ is implicitly defined by $\bar{K}F\left(\nu\left(c+\widehat{\delta}\right)\right) = S^{'-1}(c+r_f+\widehat{\delta})$. Since F is increasing and $S^{'-1}$ decreasing, $\bar{K}F\left(\nu\left(c+\delta\right)\right) < S^{'-1}(c+r_f+\delta)$ when $\delta < \widehat{\delta}$ and $\bar{K}F\left(\nu\left(c+\delta\right)\right) > S^{'-1}(c+r_f+\delta)$ for $\delta > \widehat{\delta}$. Moreover assuming $\bar{K}F(\underline{r}_i) < S^{'-1}(c+r_f)$ (i.e. the demand absent environmental damage cannot be covered by the more productive windmills), there exists δ' with $\nu(c+\delta') = \tilde{r}_i^b < \underline{r}_i$ such that $\bar{K}F(\tilde{r}_i^b) < S^{'-1}(c+r_f+\delta')$. Hence $\widehat{\delta} > \delta' > \frac{\underline{r}_i}{\nu} - c$.

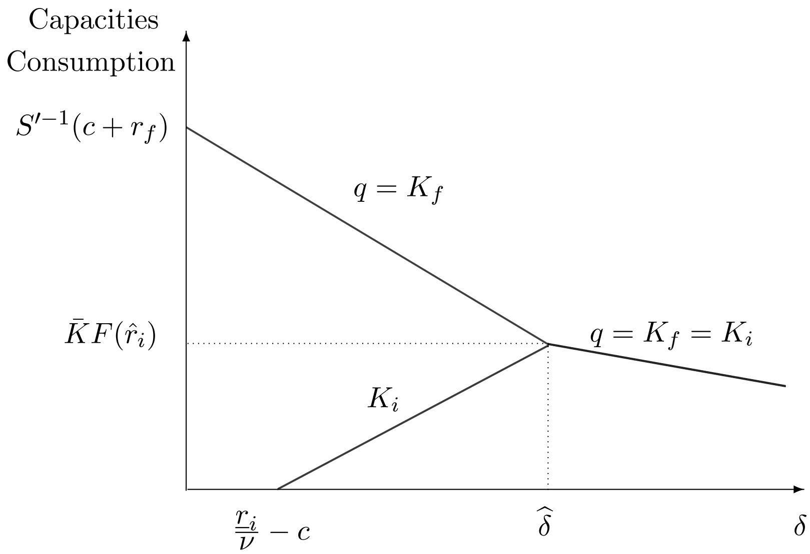

Figure 1: Investment and consumption when the environmental damage varies

In case (a) (left part of the graph), the environmental damage is too small to justify an investment in green technology.[10] An increase in δ results in a decrease in the investment and production in thermal power.

In case (b), wind power becomes attractive but not enough to cover all consumers' demand in state w. Both sources of energy are necessary.[11] Windmills are installed on the most efficient sites up to the marginal cost $\tilde{r}_i^b$. Total wind power capacity is $\bar{K}F\left(\tilde{r}_i^b\right)$. The threshold cost $\tilde{r}_i^b$ is such that the discounted marginal cost of providing one kWh of wind power $\tilde{r}_i^b/\nu$ matches the operating social cost of thermal power $c+\delta$ (productive efficiency). Since the same amount of electricity must be supplied in both states of nature (by the non-reactivity constraint), thermal power plants are used under full capacity in state $\overline{w}$ only (i.e. without wind). Electricity consumption is such that marginal utility is equal to the marginal social cost of one kWh under this energy mix, which can be written indifferently as $(1-\nu)(c+\delta)+r_f+\tilde{r}_i^b$ (in state w) or $c+\delta+r_f$ (in state $\overline{w}$). As displayed in the central part of Figure 1, when

[10] Note that this is true because we have assumed $\frac{\underline{r}_i}{\nu} > c$. Otherwise, given $\delta > 0$, there would be no case (a) : some investment in wind technology would always be profitable because of very low capacity costs $\underline{r}_i$, and/or very high wind probability ν, and/or very high fossil fuel costs c.

[11] Note that case (b) would not show up with homogenous costs r_i and unbounded capacity $\bar{K}$ for wind power like in Ambec and Crampes (2012) (see Proposition 3 and Figure 3 in the paper).

the environmental damage increases, consumption and fossil-fueled, capacity decrease, and investment in clean energy source progressively increases.[12]

In case (c), only one source of energy is used in a given state of nature. Wind power covers the whole demand in state w. Windmills are therefore installed to match consumers' demand. The threshold cost $\tilde{r}_i^c$ is given by a fixed point condition determined by demand in state w and the social cost of electricity. It is such that the marginal utility of electricity produced by windmills $S'\left(\bar{K}F(\tilde{r}_i^c)\right)$ equals the marginal social cost of one kWh $(1-\nu)(c+\delta)+r_f+\tilde{r}_i^c$. To supply the same quantity of electricity regardless of the state of nature, fossil fuel capacity matches wind power capacity: $K_f=\bar{K}F(\tilde{r}_i^c)$. Therefore thermal power capacity also equalizes the marginal utility of consumers $S'(K_f)$ with the social cost of one kWh $(1-\nu)(c+\delta)+r_f+\tilde{r}_i^c$. The investment in K_i that was increasing with δ in case (b) is now decreasing. This is due to the non-reactivity of consumers to state-contingent prices, which forces capacity to match $K_f=K_i$ in case (c). Therefore, as fossil-fueled energy becomes more harmful to the environment, less capacity of thermal power is installed, which in turn implies less wind mills. Electricity consumption has to be reduced, as does capacity and production from both the clean and dirty sources of energy.

We now turn to the decentralization of the efficient energy mix by alternative environmental policies.

4 Environmental policy

To analyze the efficiency of alternative energy and environmental policies, we suppose that intermittent energy is socially efficient but not privately efficient, that is

$$c<\frac{r_i}{\nu}<c+\delta. \tag{6}$$

This implies that windmills would not be installed by profit-maximizing firms whereas they must be installed from the social point of view. Without any regulation, electricity producers would install only thermal power plants, as in case (a) of Proposition 1. By contrast, the efficient energy mix is described by case (b) or (c) in Proposition 1 depending on the value of the parameters.

We successively consider the following policies:

[12] Formally, by differentiating fossil-fuel and clean energy capacities, we obtain $\frac{dK_f}{d\delta}=\frac{1}{S''(q)}<0$ and $\frac{dKi}{d\delta}=\overline{K}f\left(\tilde{r}_i^b\right)\nu>0$.

- A tax on pollution emissions from fossil fuel τ.
- A feed-in tariff (FIT) on wind power p^i financed by a tax t levied on electricity consumption.
- A renewable portfolio standard (RPS) setting a minimal share α of renewable energy sources in electricity generation.

We will now examine the impact of the above instruments on electricity production and welfare. We consider a market economy with free-entry and price-taker producers and retailers. At equilibrium, prices and quantities (production and capacity) should be such that no firms enter or exit the industry. The equilibrium is determined by a zero-profit condition for the thermal power plants and the less profitable wind power mills installed, as well as the electricity retailers. The question is whether one single policy instrument is sufficient to obtain the first-best outcome. If not, can we reach first best by adding a complementary instrument?

4.1 Carbon tax

4.1.1 The mechanism

We analyze the impact of a tax on pollutants emitted by thermal generators. Let τ denote the tax rate per kilowatt-hour of electricity that they produce. We call it a carbon tax even though it could be a tax on other sources of pollution from fossil fuel burning such as SO2 or NOx. In our decentralized economy, electricity has three different prices: the wholesale price on windy days p^w, the price on non-windy days $p^{\bar{w}}$, and the retail price p. Equilibrium prices are determined by the producers' and retailers' supply functions and zero-profit conditions, as well as by demand by retailers and consumers. As in Proposition 1, we analyze three cases: no windmills installed (case (a)), joint use of wind and thermal power on windy days (case (b)), and only wind power on windy days (case (c)).

* Case (a): When no windmill is installed, the thermal power plants are active under full capacity in both states of nature w and $\overline{w}$. The price of electricity in the wholesale market is state invariant. It matches the long run marginal cost (including the cost of regulation τ per kilowatt-hour) $p^w = p^{\overline{w}} = c + r_f + \tau$. It is lower than the cost per kilowatt-hour of the most efficient windmill $\frac{r_i}{\nu}$ to prevent entry by wind-power producers. The zero profit condition for the retailers set the consumers' price at the wholesale price: $p = p^w = p^{\overline{w}}$. Capacity is determined by demand at this price $p = S'(K_f)$ which yields $K_f = S'^{-1}(c + \tau + r_f)$.

* Case (b): Investing in wind power becomes profitable when the cost of the most efficient windmill (discounted by the probability of state w) is lower than the most competitive wholesale price in state w, which is the operating cost of thermal power gross of tax: $(\underline{r}_i/\nu) \leq c+\tau$. This condition sets a lower bound on the carbon tax:

$$\tau \geq \frac{\underline{r}_i}{\nu} - c.$$

When τ satisfies the above inequality, some wind turbines will be installed: $K_i = \bar{K}F(\tilde{r}_i)$ where $\tilde{r}_i > \underline{r}_i$ defines the capacity cost of the less efficient windmill installed. Investment in wind and thermal power is driven by electricity prices which are defined by the zero-profit conditions as follows:

$$p^w = \frac{\tilde{r}_i^\tau}{\nu}, \tag{7}$$

$$p^{\overline{w}} = c + \tau + \frac{r_f}{1-\nu}, \tag{8}$$

$$p = \nu p^w + (1-\nu)p^{\overline{w}} = (1-\nu)(c+\tau) + \tilde{r}_i^\tau + r_f. \tag{9}$$

where $\tilde{r}_i^\tau$ denotes the capacity cost of the least efficient wind turbine installed at market equilibrium when the tax on pollutants is τ.

First, the price of electricity in state w equals the discounted equipment cost of the least efficient wind power producers, which obtain zero profit. All other wind power producers ($\underline{r}_i \leq r_i < \tilde{r}_i^\tau$) obtain inframarginal profits. In the case where the two sources of energy are used in state w, the price of electricity also matches the operating costs (gross of tax) of the thermal power plants $p^w = c + \tau$. With $p^w > c + \tau$, new producers using thermal technology would enter, driving the price down to the operating cost. With a price below $c + \tau$, thermal producers would stop producing as they could not cover their operating costs.

Second, the price of electricity in state $\overline{w}$ equalizes the overall marginal cost of thermal powered electricity including the cost of equipment and taxes. Equipment is remunerated only in state $\overline{w}$ when used at full capacity.

Third, the retail price paid by consumers is the average of the two wholesale prices. It is equal to the average marginal cost of one kilowatthour from wind power supplied in state w and thermal power supplied in state $\overline{w}$.

With the joint use of wind and fossil fuel in state w, thermal power and wind power producers compete on the wholesale market on windy days. Thermal power producers run their utilities below capacity. Their zero-profit condition in state w leads to $p^w = c + \tau$.

Combined with (7), it yields the threshold cost of windmills entering the industry $\tilde{r}_i^\tau = \nu(c+\tau)$ so that investment in wind power is $K_i = \bar{K}F(\nu(c+\tau))$. Similarly, $\tilde{r}_i^\tau = \nu(c+\tau)$ substituted in (9) yields the retail electricity price $p = c + \tau + r_f$ which, through consumer's demand, defines investment in thermal power $K_f = S'^{-1}(c + \tau + r_f)$. It shows that, as τ increases, investment in wind power K_i also increases, whereas thermal power capacity K_f decreases.[13]

* Case (c): At some point, the two capacities meet $K_i = K_f$. The tax rate $\hat{\tau}$ for which capacity of both sources of energy match is found by substituting the equilibrium values of K_i and K_f in condition $K_i = K_f$, which yields:

$$\bar{K}F(\nu(c+\hat{\tau})) = S'^{-1}(c + \hat{\tau} + r_f). \tag{10}$$

Equation (10) defines the threshold tax rate $\hat{\tau}$ for which the energy supply switches from mixed sources of energy (case (b)) to only wind power on windy days (case (c)). When the tax rate exceeds $\hat{\tau}$, only wind power is used in state w. The non-reactivity constraint forces capacities to match: $K_i = K_f$. Furthermore, with the retail price defined in (9), electricity consumption is $q = K_f = S'^{-1}((1-\nu)(c+\tau) + \tilde{r}_i^\tau + r_f)$. The last two equalities determine wind power capacity $K_i = \bar{K}F(\tilde{r}^\tau) = S'^{-1}((1-\nu)(c+\tau) + \tilde{r}_i^\tau + r_f)$. Differentiating with respect to τ shows that $\frac{d\tilde{r}_i^\tau}{d\tau} < 0$ and, therefore, both K_i and K_f decrease when the carbon tax increases above $\hat{\tau}$. Proposition 2 below summarizes our results.

Proposition 2 *With a carbon tax τ per kilowatt-hour of thermal power, the competitive equilibrium for electricity markets is defined by the following prices, capacities and productions:*

a) for $\tau \leq \frac{r_i}{\nu} - c$, no intermittent energy

$$\begin{aligned} p^w &= p^{\overline{w}} = p = c + r_f + \tau \\ K_i &= 0 \\ K_f &= q_f^w = q_f^{\overline{w}} = S'^{-1}(c + \tau + r_f) \end{aligned}$$

[13] Formally, by differentiating wind and thermal power capacities with respect to τ, we obtain $\frac{dK_i}{d\tau} = \bar{K}f(\nu(c+\tau))\nu > 0$ and $\frac{dK_f}{d\tau} = S''^{-1}(c + \tau + r_f) < 0$.

(b) for $\frac{r_i}{\nu} - c < \tau < \hat{\tau}$*, both sources of energy are used in state* w

$$\begin{aligned} p^w &= \frac{\tilde{r}_i^\tau}{\nu} \text{ where } \tilde{r}_i^\tau \text{ is defined by } \tilde{r}_i^\tau = \nu(c+\tau) \\ p^{\overline{w}} &= c + \tau + \frac{r_f}{1-\nu} \\ p &= \nu p^w + (1-\nu)p^{\overline{w}} = c + \tau + r_f = (1-\nu)(c+\tau) + \tilde{r}_i^\tau + r_f \\ K_i &= \bar{K}F(\nu(c+\tau)) \\ K_f &= q_f^{\overline{w}} = S'^{-1}(c+\tau+r_f) \\ q_f^w &= K_f - K_i > 0 \end{aligned}$$

(c) for $\hat{\tau} \leq \tau$*, only intermittent energy is used in state* w

$$\begin{aligned} p^w &= \frac{\tilde{r}_i^\tau}{\nu} \leq c + \tau \text{ where } \tilde{r}_i^\tau \text{ is defined by } \bar{K}F(\tilde{r}_i^\tau) = S'^{-1}((1-\nu)(c+\tau) + r_f + \tilde{r}_i^\tau) \\ p^{\overline{w}} &= c + \tau + \frac{r_f}{1-\nu} \\ p &= \nu p^w + (1-\nu)p^{\overline{w}} = (1-\nu)(c+\tau) + \tilde{r}_i^\tau + r_f \\ K_i &= \bar{K}F(\tilde{r}_i^\tau) = K_f = S'^{-1}((1-\nu)(c+\tau) + r_f + \tilde{r}_i^\tau) \end{aligned}$$

Proposition 2 can be illustrated by Figure 1, in which the carbon tax τrather the environmental damage δ is plotted on the horizontal axis. If the cost of intermittent energy producers is not low enough, given the thermal plants' private cost (including tax) $c + \tau$ (case (a)), then an increase of τ reduces electricity production in the short run, as well as investment in thermal capacities in the long run. Yet an increase of the carbon tax can make the economy switch from case (a) to case (b) whereby intermittent energy becomes profitable compared to the cost of operating the installed thermal power plants. The threshold tax rate is $\frac{r_i}{\nu} - c$. Windmills are installed in the most profitable spots. Some thermal power is replaced by wind power in state w. The tax reduces consumption, and thermal power capacity decreases. The two sources of energy are thus substitutes in regime (b) as long as the wind is blowing. The maximal intermittent capacity is achieved at tax rate $\hat{\tau}$ defined in (10) where it matches the thermal power capacity. Above the threshold $\hat{\tau}$, the carbon tax reduces electricity consumption and equipment of both sources of energy. This is because the two types of equipment are complements (the thermal plant provides an insurance to wind turbines in state $\overline{w}$) but the energy they produce are perfect substitutes and the thermal production is excluded in state w of regime (c).

When the two sources of energy are substitutes (case (b)), even though thermal power capacity decreases when τ increases, total capacity $K_i + K_f$ may increase. Differentiating total capacity with respect to the carbon tax yields:

$$\frac{d(K_f + K_i)}{d\tau} = S''^{-1}(c + \tau + r_f) + \bar{K} f(\nu(c + \tau))\nu.$$

If the reduction of thermal power capacity (the first term on the right-hand side is negative) is more than compensated for by the increase in wind power capacity (the second term on the right-hand side is positive), then total equipment $K_f + K_i$ increases. The effect of an increase of the carbon tax on total capacity is ambiguous because it is determined by two unrelated features of the model: the decrease in K_f is due to consumers' demand for electricity (how they react to a change in the retail price) whereas the increase in K_i is due to the technological characterization of the intermittent energy (including the distribution of cost $F(.)$). The lower the elasticity of demand to changes in the retail price (very small $\left|S''^{-1}\right|$) the more likely total capacity will increase after an increase in the tax on pollutants. By contrast, with more elastic demand, one can expect a negative effect of the tax on total capacity.

4.1.2 First-best implementation

It is easy to show that the first-best can be decentralized by a Pigou tax.It is worth mentioning that the revenue from the tax should be redistributed to consumers in a way that does not impact their consumption of electricity, e.g. through lump-sum payments. Substituting τ by δ in Proposition 2 leads to first-best investment in capacity and production levels for both source of energy, as described in Proposition 1.

Proposition 3 *A carbon tax $\tau = \delta$ implements the first-best.*

Intermittency does not prevent achieving efficiency with Pigouvian taxation. The Pigou tax rate is easy to compute under our assumption of constant marginal damage due to pollution. It would be more complex under alternative assumptions on environmental damage such as increasing marginal damage. The Pigou tax rate would then vary with the state of nature (whether there is wind or not) or with pollution concentration.[14] Nevertheless our result would remain valid: a tax rate equals to marginal damages would implement the first-best energy mix.

[14] We thank Marc Baudry for pointing this out.

A particular feature of the above market equilibrium is that electricity retailers insure consumers at no cost against price volatility due to the intermittency of wind power. Whatever the environmental cost, as soon as $K_i > 0$, risk neutrality is necessary for firms to implement the first-best. Risk adverse retailers would include a risk premium in the electricity price, which would reduce electricity consumption and production below the first-best level.

4.2 Feed-in tariffs and price premium

4.2.1 The mechanism

Under feed-in tariffs (FIT), public authorities commit to purchasing wind power at a given price p^i per kilowatt hour, which is higher than the wholesale market price. The FIT p^i is financed by a tax on electricity consumption. Let us denote this tax per kilowatt hour as t. The unit price paid by consumers is thus $p + t$. We first examine the impact of FIT (as an instrument to enhance investment in intermittent sources of energy) on prices. Next we analyze the implementation of the first-best energy mix by FIT.

Although the FIT is set out of electricity markets, the introduction of FIT in an industry with thermal power impacts electricity prices. First, it induces price variability on the wholesale market. Starting from invariant prices $p = p^w = p^{\bar{w}} = c + r_f$, the price of electricity drops to $p^w = c < c + r_f$ on windy days, while simultaneously increasing to $p^{\bar{w}} = c + \dfrac{r_f}{1-\nu}$ in state $\bar{w}$. This is because thermal power plants are used below capacity during windy periods. Therefore the price in state w matches only the operating cost of thermal power plants, not the cost of capital. By contrast, when windmills are not spinning, thermal power plants are used at full capacity. The price must remunerate not only operating costs c but also the equipment cost which is $\dfrac{r_f}{1-\nu}$ per hour because capacity is fully used only during $1-\nu$ periods. Second, the FIT increases the energy billed to consumers. Even though the retail price of electricity is unchanged at $p = \nu p^w + (1-\nu)p^{\bar{w}} = c + r_f$, consumers pay $p + t$ per kilowatt-hour consumed because of the tax t that finances the FIT. Consequently consumers reduce their consumption after the introduction of a FIT. Thus production is also reduced, as is thermal power capacity K_f.

The FIT p^i and tax t are linked through a budget-balancing constraint. The tax revenue collected from consumers should cover the difference between the price paid to wind-power producers p^i and the wholesale price of electricity p^w in sate w. The expenditures by consumers are $(p+t)\,q$ and the revenues of producers are $(1-\nu)\,p^{\overline{w}}K_f + \nu p^w q_f^w + \nu p^i q_w^i$. Given that i)

electricity consumption matches with thermal power capacity $q = K_f$ in all states of nature, ii) wind power production is equal to wind power capacity $q_i^w = K_i$ in state w, and iii) thermal production in state w is the difference between the thermal capacity and the wind capacity $q_f^w = K_f - K_i$, the budget constraint writes $(p + t) K_f \geq (1 - \nu) p^{\overline{w}} K_f + \nu p^w (K_f - K_i) + \nu p^i K_i$ or, using the retail price formula $p = \nu p^w + (1 - \nu) p^{\overline{w}}$,

$$tK_f \geq \nu(p^i - p^w)K_i. \tag{11}$$

The FIT system is sustainable when (11) holds as an equality: the revenue from taxing consumers just finances the extra cost of purchases from the intermittent source.

A milder form of green reward is the feed-in premium (FIP) which is a subsidy on wind power production on top of the market price. With a subsidy ρ per kilowatt hour, wind power producers obtain $p^w + \rho$ per kWh produced. The financial constraint is then $(p + t^\rho) K_f \geq (1 - \nu) p^{\overline{w}} K_f + \nu p^w (K_f - K_i) + \nu (p^w + \rho) K_i$. The tax t^ρ on electricity that finances ρ must satisfy the financial constraint $t^\rho K_f \geq \nu \rho K_i$.

4.2.2 First-best implementation

- Feed-in tariff

We now examine the implementation of the first-best energy mix by a FIT. Let us consider case (b) in Proposition 1. Case (c) is derived in Appendix B. Compared to the unregulated outcome with only thermal power, i.e. case (a) in Proposition 2 with $\tau = 0$, investment in wind power must be increased while, at the same time, electricity consumption must be reduced. FIT does foster investment in wind power up to the efficient level. It reaches first-best investment $K_i = \bar{K} F(\tilde{r}_i^b)$ if it is set at the threshold marginal equipment cost $p^i = \tilde{r}_i^b / \nu = c + \delta$. On the other hand, the tax on electricity t must provide incentives to reduce electricity consumption down to $q = K_f = S'^{-1}(c + r_f + \delta)$. Hence the price paid by consumers should be $c + r_f + \delta$ per KWh. Since the zero profit condition of the electricity retailers defines the retail price of electricity $p = c + r_f$, the tax per kWh should be $t = \delta$.

Inserting into the financial constraint the FIT $p^i = c + \delta$ and the tax on consumption $t = \delta$ that implement first-best, we get a budget surplus: the money collected by taxing consumers $K_f \delta$ exceeds the FIT financial cost $\nu(p^i - p^w)K_i = \nu \delta K_i$ because $K_f \geq K_i$ and $\nu < 1$ The budget balance constraint (11) holds as a strict inequality.

Alternatively, if the tax rate is set to just balance the funds needed to finance the FIT $p^i = \tilde{r}_i^b/\nu = c + \delta$ that leads to the optimal penetration of intermittent energy, we obtain

$$tK_f = \nu\delta K_i \Longrightarrow t = \frac{\nu K_i}{K_f}\delta < \delta,$$

i.e. the unit price paid by consumers is too low, which induces over-consumption of electricity, and, therefore, too much fossil fuel burnt. Hence the tax on electricity consumption should be set not to finance the FIT only but rather with the aim of reducing electricity consumption at the first-best level.

Finally, if the budget constraint is binding and the tax charged to consumers is set at the environmental damage, we obtain

$$\delta K_f = \nu(p^i - c)K_i \Longrightarrow p^i = c + \frac{\delta K_f}{\nu K_i} > c + \delta. \quad (12)$$

Since the owners of wind turbines invest up to $\tilde{r}_i^b/\nu = p^i$, we have that $\tilde{r}_i^b/\nu > c + \delta$, so that there is too much investment in the intermittent source.

- Feed-in premium

FIP leads to similar conclusions. The subsidy ρ should cover the gap between the efficient price of electricity in state w, which is $\tilde{r}_i^b/\nu = c + \delta$ in case (b) of Proposition 1, and the wholesale market equilibrium price $p^w = c$. Therefore $\rho = \delta$. On the other hand, electricity should be taxed at rate $t = \delta$ to induce efficient consumption. The budget-balancing constraint becomes $\delta K_f \geq \nu\delta K_i$ which always holds with a strict inequality since $K_f \geq K_i$ and $\nu < 1$. Thus, too much money is levied compared to what is needed to finance the FIP. Setting the tax on electricity consumption at the minimum rate to finance the FIP therefore causes too much electricity to be produced from thermal power plants.

We summarize our results in the following proposition.

Proposition 4 *Introducing FIT or FIP to foster the development of intermittent energy increases price variability. To reach first-best, the tariff or premium must be complemented by a tax on electricity consumption that is not linked to the FIT or FIP through a budget balancing constraint.*

Without the carbon tax, two instruments are required to implement first-best: the FIT that subsidies wind power and a tax on electricity that reduces its consumption. Each of them influences one equipment investment choice. By increasing the price of electricity from wind power, the FIT can be chosen to obtain the efficient investment in wind power capacity K_i. By increasing the price paid by consumers for each kWh, the tax can be selected to reduce electricity consumption at the efficient level and therefore to ensure an efficient investment in thermal power K_f. The level of each of the two instruments that implements first-best is unique. Each of them achieves one goal.

We can thus conclude that linking the two instruments by a binding budget constraint fails to implement first-best. Even though the FIT or FIP is set efficiently to induce the optimal equipment in wind power, the constraint would result in electricity being under-taxed and consequently too much electricity being produced from fossil fuel.

4.3 Renewable portfolio standard

4.3.1 The mechanism

Another popular instrument to foster investment in renewable sources of energy is the Renewable Portfolio Standard (RPS), also called renewable energy obligation (Schmalensee, 2012). Under this regime, electricity retailers are obliged to purchase a share of electricity produced from renewable sources of energy. They are required to purchase Renewable Energy Credits (REC) or green certificates produced by state-certified renewable generators, which guarantees that this share is achieved. For each kWh sold, renewable energy producers issue a REC. Retailers and big consumers are required to buy enough credits to meet their target. In our model, a RPS defines a share $\alpha < 1$ of energy consumption that must be supplied with an intermittent source of energy. Wind producers issue RECs that they sell to electricity suppliers at price g. They thus obtain $p^w + g$ per kWh where p^w is the price of electricity in the wholesale market in state w. Retailers buy αq RECs in addition to electricity in the wholesale market when supplying q kWh to final consumers.

Under RPS, the zero-profit conditions per kilowatt-hour for the less efficient wind power producers (with cost $\tilde{r}_i$) and for electricity suppliers are respectively:

$$p^w + g = \frac{\tilde{r}_i}{\nu}, \tag{13}$$

$$p = \nu p^w + (1-\nu)p^{\bar{w}} + \alpha g. \tag{14}$$

Investment in production capacity by wind power producers is such that the return they get per kWh $p^w + g$ is equal to the long run marginal cost of the less efficient windmill $\tilde{r}_i/\nu$ as shown in (13). Retailers pass on the additional cost of producing electricity from renewable energy to consumers by increasing electricity prices by αg, that is, the price of RECs weighted by the share of renewable energy in the electricity mix.

Wholesale prices of electricity p^w and $p^{\bar{w}}$ are determined by the thermal power production costs. On windy days, thermal power plants are running below capacity so that the price of electricity matches their operating cost $p^w = c$. The equipment cost are covered absent wind with a wholesale market price of $p^{\bar{w}} = c + \frac{r_f}{1-\nu}$. Substituting wholesale prices into (13) and (14) yields:

$$g = \frac{\tilde{r}_i}{\nu} - c, \tag{15}$$

$$p = c + r_f + \alpha\left(\frac{\tilde{r}_i}{\nu} - c\right). \tag{16}$$

According to condition (15), the price of RECs should compensate for the difference between marginal costs of the two sources of energy, given that thermal power plants are used below capacity. It equals the opportunity cost of using wind power rather than thermal power to produce electricity on windy days. Condition (16) gives the price of electricity paid by consumers as a function of the RPS, α. The mark-up on the thermal power long-term marginal cost is equal to the opportunity cost of wind power for its mandatory share on electricity supply, α.

The above analysis shows that the RPS disentangles the value of each kWh of renewable source of energy from wholesale prices. By selling a REC, wind power producers obtain more than the price of electricity in the wholesale market. Competitive electricity retailers, who are obliged by law to buy green certificates, pass this mark-up on wholesale prices to consumers, by increasing the retail price. The premium paid by consumers depends on the RPS, both directly, through the quantity of green certificates per kWh α, and indirectly via the price of those certificates g which increases with α.

4.3.2 First-best implementation

We now turn to the decentralization of the first-best energy mix with RPS. Starting from an unregulated economy described in the Proposition 1 case (a), the RPS must meet two goals: (i) to increase investment in wind power and (ii) to reduce electricity consumption.

For instance, to reach the efficient outcome (b) in Proposition 1, investment in wind power should be increased up to $K_i^b \equiv \bar{K}F(\tilde{r}_i^b)$. It should also reduce electricity consumption to $q^b = K_f^b \equiv S^{'^{-1}}(c + r_f + \delta)$. Hereafter we show that the two goals cannot be met with a single instrument like a RPS. Indeed to obtain K_i^b, the cost of the less productive windmill should be $\tilde{r}_i^b = \nu(c + \delta)$ which, combined with (15), gives the unit price of REC, $g = \delta$, i.e., it should be equal to the environmental cost avoided by using wind instead of fossil fuel as the source of energy. By increasing the return per kWh of wind power from $p^w = c$ to $p^w + g = c + \delta$, RECs fill the gap between the private cost of electricity from thermal power c and its social cost $c + \delta$. Now under this price for RECs, the retail price of electricity defined in (16) becomes $p = c + r_f + \alpha\delta$. It is strictly lower than the one inducing first-best electricity consumption $p = c + r_f + \delta$ as $\alpha < 1$. Hence setting a RPS that induces first-best investment in renewables leads to a retail price of electricity which is too low. As a result, too much electricity using fossil fuel will be produced.

One way to implement the first-best energy mix is to complement the RPS with a carbon tax or a tax on electricity consumption $t = \delta\,(1 - \alpha)$. The equilibrium price paid by consumers per kWh is then $p + t = c + r_f + \alpha\delta + (1 - \alpha)\delta = c + r_f + \delta$, which is the price that induces them to consume at first-best. A similar argument derived in Appendix C shows that first-best cannot be achieved with RPS for case (c) in Proposition 2.

Proposition 5 *The first-best energy mix cannot be implemented with RPS. It should be complemented with a tax on electricity consumption.*

5 Technological solutions to intermittency

We now investigate several technological solutions to cope with intermittency in energy supply. We analyze the private and social benefits of those solutions when environmental damages are involved.

5.1 Energy storage

A natural technological solution to accommodate the intermittency of renewable sources is to store energy. The most efficient technology is pumped storage, constituting in filling up reservoirs supplying hydropower plants. The electricity produced on windy days −when windmills are spinning− can be used to pump water into upstream reservoirs. Stored water is then flowed down to produce electricity when wind speed is low while demand peaks.[15] Formally, in our model, storage allows some kilowatt-hours of electricity to be transfered state w to state $\overline{w}$. This requires investment (e.g. dams and hydropower plants) and it consumes energy, in particular for pumping water.

We derive the social marginal benefit of investing in storage facilities. We compare it to the private marginal benefit provided by a market economy where pollutants are taxed.

The social benefit from storage can be found by modifying the social welfare maximization program defined in Section 3. Let s be the quantity of electricity produced in state w that is stored for state $\overline{w}$ rather the consumed. For each kilowatthour of energy stored in state w, only λs with $0 < \lambda < 1$ can be consumed in state $\overline{w}$. The remaining fraction is lost because of the double conversion process. Abstracting from the cost of building and maintaining a storage facility, the expected social welfare when s kilowatts are stored is:

$$\nu\left[S(\bar{K}F(\tilde{r}_i) + q_f^w - s) - (c+\delta)q_f^w\right] + (1-\nu)\left[S(K_f + \lambda s) - (c+\delta)K_f\right]$$
$$-\bar{K}\int_{\underline{r}_i}^{\tilde{r}_i} r_i dF(r_i) - r_f K_f$$

while the non-reactivity constraint (1) becomes $\bar{K}F(\tilde{r}_i) + q_f^w - s = K_f + \lambda s$. Define the Lagrangian as in Appendix A after modifying for the above expected social welfare and non-reactivity constraint. Assuming an interior solution $0 < s < K_i$, differentiating this Lagrangian with respect to s yields the following first-order condition:

$$\lambda(1-\nu)S^{'}(K_f + \lambda s) - \nu S^{'}(\bar{K}F(\tilde{r}_i) + q_f^w - s) - (1+\lambda)\,\nu\gamma = 0, \tag{17}$$

where γ is the Lagrange multiplier associated to the non-reactivity constraint.

Similarly, differentiating the Lagrangian with respect to $\tilde{r}_i$ we obtain a first-order condition similar to (A3) in Appendix A:

$$\nu\left[S'(\bar{K}F(\tilde{r}_i) + q_f^w - s) + \underline{\mu}_i' + \gamma\right] - \tilde{r}_i = 0. \tag{18}$$

Besides, we know that in both cases (b) and (c) in Proposition 2, the social marginal value of electricity is $S'(K_f + \lambda s) = (1-\nu)(c+\delta) + r_f + \tilde{r}_i$.[16] Combined with (17) and (18) it leads

[15] For an economic analysis of water storage and pumping, see Crampes and Moreaux (2010). Ambec and Doucet (2003) study water storage under imperfect cometition.

[16] To see that in case (b), just replace $\tilde{r}_i^b = \nu(c+\delta)$ in $S'(K_f + \lambda s) = c + r_f + \delta = (1-\nu)(c+\delta) + \nu(c+\delta) + r_f$.

to the social value of energy storage:

$$\lambda\left[(1-\nu)(c+\delta)+r_f\right]-\tilde{r}_i. \tag{19}$$

The marginal value of one kilowatt of storage capacity is the cost difference of this kilowatt produced in state $\bar{w}$ (with fossil fuel) versus state w (with wind power) weighted by the loss of energy λ with the storage technology.

A firm that invests in storage capacity can expect to obtain a return $(1-\nu)\lambda p^{\bar{w}} - \nu p^{w}$ by buying one kilowatt-hour in state w and selling the remaining λ kilowatt-hour stored in state $\bar{w}$. Given the equilibrium prices $p^w = \frac{\tilde{r}_i}{\nu}$ and $p^{\bar{w}} = c + \tau + \frac{r_f}{1-\nu}$ from the wholesale market as defined in cases b and c of Proposition 2, and a Pigouvian tax $\tau = \delta$, we obtain the social marginal benefit of storage. Hence, private and social interests in operating the storage facility are aligned. However, firms would invest the socially optimal storage capacity only if (19) is large enough to cover the equipment cost, which requires a high profitability of the intermittent source (low $\tilde{r}_i$), high costs of the fossil fueled plants (high c, δ and r_f), few periods with intermittent energy (low ν), and a very efficient coupling of pumping and turbinating (λ close to 1).

5.2 Smart meters

Another technological solution to cope with energy intermittency would be to equip consumers with smart meters and demand response switches to make them reactive to variations in electricity prices. This would allows for a better match between electricity consumption with supply, and thereby, avoid the need to back-up windmills with thermal power facilities. Consumers would be charged the wholesale electricity price and, using automatic electricity storage and switching devices, they would be able to adapt their consumption to fluctuating prices. Such devices are however costly to install and maintain. Theses costs could be offset by the benefit of making consumers reactive. In our model we compute the marginal benefits of making consumers reactive to price changes.

Let β denote the share of "reactive" consumers. they are equipped with smart meters which charge wholesale electricity prices p^w and $p^{\bar{w}}$, and with switching devices that allow them to modify their consumption online with real-time price changes. Other consumers are "non-reactive": they pay a constant price for electricity p, which is the average wholesale price. Reactive consumers buy q_r^w kilowatt-hours in state w and $q_r^{\bar{w}}$ in state $\bar{w}$ where the "r" subscript stands for "reactive". We denote by $q_{\bar{r}}$ the electricity consumption of non-reactive consumers where the "$\bar{r}$" subscript stands for "not reactive". The supply of electricity being K_f in state $\bar{w}$ (full capacity of thermal power plants) and $\bar{K}F(\tilde{r}_i)$ from intermittent sources of energy and q_f^w from fossil fueled energy in state w, the market clearing conditions in state $\bar{w}$ and w are respectively:

$$K_f = \beta q_r^{\bar{w}} + (1-\beta) q_{\bar{r}}, \tag{20}$$

$$\bar{K}F(\tilde{r}_i) + q_f^w = \beta q_r^w + (1-\beta) q_{\bar{r}}. \tag{21}$$

The expected social welfare is:

$$\beta[\nu S(q_r^w) + (1-\nu) S(q_r^{\bar{w}})] + (1-\beta) S(q_{\bar{r}}) - \nu(c+\delta) q_f^w - (1-\nu)(c+\delta) K_f - \bar{K} \int_{\underline{r}_i}^{\tilde{r}_i} r_i dF(r_i) - r_f K_f.$$

By differentiating with respect to β, we obtain the marginal benefit of making consumers reactive:

$$\nu S(q_r^w) + (1-\nu) S(q_r^{\bar{w}}) - S(q_{\bar{r}}) - [(1-\nu)(c+\delta) + r_f] \frac{dK_f}{d\beta} - \bar{K}\tilde{r}_i f(\tilde{r}_i) \frac{d\tilde{r}_i}{d\beta},$$

where $\frac{dK_f}{d\beta} = q_r^{\bar{w}} - q_r$ and $\frac{d\tilde{r}_i}{d\beta} = \frac{q_r^w - q_{\bar{r}}}{\bar{K} f(\tilde{r}_i)}$ can be found by differentiating (20) and (21) respectively. This leads to a marginal benefit of:

$$[\nu S(q_r^w) + (1-\nu) S(q_r^{\bar{w}}) - S(q_{\bar{r}})] + [(1-\nu)(c+\delta) + r_f](q_{\bar{r}} - q_r^{\bar{w}}) - \tilde{r}_i (q_r^w - q_{\bar{r}}). \tag{22}$$

The first term into brackets in (22) is the difference in expected utility (or surplus) from making consumers reactive. As long as consumers are risk averse ($S'' < 0$), this difference is negative: switching from a constant price to state-contingent prices reduces welfare. The stronger the risk aversion, the greater this utility loss will be. Since the constant retailing electricity price is equal to the expected wholesale (or state-contingent) prices, risk-averse consumers prefer to pay the constant retail price. The second term in (22) is the cost saved on thermal powered electricity by the consumption pattern of reactive consumers. Consumption in state $\bar{w}$ is reduced by $q_{\bar{r}} - q_r^{\bar{w}} > 0$, which allows for $(1-\nu)(c+\delta) + r_f$ in expected savings per kilowatt-hour by reducing thermal power capacity and burning less fossil fuel. The third term in (22) is the extra cost on wind power due to reactive consumers' higher demand in state w. Consumption is state w is increased by $q_r^w - q_{\bar{r}}$, of which the marginal cost is $\tilde{r}_i$.

It is beneficial to equip consumers with smart meters and load switching devices, if the expected utility loss is more than offset by the net production cost saved. But smart devices are costly: the total cost saved on thermal power- including savings on production capacity and externality costs- should outweigh the extra cost of installing new windmills. This means that c, δ and r_f should be relatively higher than $\tilde{r}_i$. Moreover, the change of consumption parttern matters: the difference in consumption from non-reactive to reactive consumers should make it worth exposing consumers to price volatility. This means that the reduction of consumption when the wind is not blowing $q_{\bar{r}} - q_r^{\bar{w}}$ should be substantial compared to the increase of consumption during windy periods $q_r^w - q_{\bar{r}}$. The social gains from smart devices depends on consumers' ability to spread their consumption out over time.

6 Market power and environmental policy

Almost everywhere, electricity production is a concentrated industry protected by technological and financial barriers to entry. In many countries a dominant producer or a few big players supply most of the market. The introduction of intermittent sources of energy modifies the market structure as many small producers can install and run windmills or photovoltaic solar panels. In this section we examine public policies with a dominant thermal power producer and a competitive fringe of producers of intermittent energy.

6.1 An adjusted Pigou tax

This section of the paper draws on the literature on environmental policy in industries with natural monopolies. A well-known message from this literature is that, without price regulation, taxes on pollution externality should be lower than the Pigou rate to mitigate the exercise of market power (see Requate (2005) for a survey). We investigate the extend to which this principle applies when competition comes only from intermittent sources of energy. Is competition from wind and solar power strong enough to mitigate the exercise of market power by a thermal plant producer?

Before starting our analysis, it is worth mentioning that, in our framework, a tax on fossil fuel emissions would be sufficient to implement first-best if there were no intermittent energy, *i.e.* in case (a) of Proposition 1. It would remedy both market failures: the environmental externality and the exercise of market power. This is because in our model pollution is linked to thermal power production: in the absent of renewable energy, the only way to reduce pollution is to reduce production. Hence, electricity production (and thus electricity prices) can be controlled by taxing or subsidizing pollution emissions. Following Requate (2005), one can easily show that efficiency is achieved in case (a) if fossil fuel is taxed at a rate:

$$\tau = \delta + \frac{p}{\epsilon}$$

where $\epsilon = \frac{\Delta q/q}{\Delta p/p} < 0$ is the price elasticity of the demand function $P(q) = S^{'}(q)$. The first right-hand term is the Pigou rate while the second one fixes for the exercise of market power. As it is negative, with the result that the tax should be reduced compared to perfect competition (i.e. the Pigou rate) to compensate for the monopoly's shortage of supply. It could lead to a negative tax rate, i.e. a subsidy, if this shortage is excessive compared to the efficient outcome, including environmental externality. In the next section we will see that a single tax (or more generally a single instrument) is not enough to implement first best when there is a competitive fringe of intermittent energy producers.

6.2 Thermal monopoly and fringe of wind turbines

To make the point, let us examine the capacity and production choices of a thermal power producer with a monopoly position in state $\overline{w}$ facing a competitive fringe of wind power producers in state w. Assume that the thermal power firm is Stackelberg leader: it chooses capacity and production before wind power producers. We consider state-contingent taxes on fossil fuel τ^w and $\tau^{\overline{w}}$.[17] As before, the price of electricity in the retail market is the same in both states of nature due to the non-reactivity of consumers to short-term price changes. Therefore, production levels are the same in states $\overline{w}$ and w: $K_i + q_f^w = q_f^{\overline{w}}$. Since $K_i > 0$ (by assumption),[18] Production meets the thermal power plant capacity in state $\overline{w}$ but not in state w: $q_f^{\overline{w}} = K_f$ and $q_f^w < K_f$. Since the thermal power producer competes with wind power producers in state w, the price of electricity on windy days p^w is such that the less efficient wind power producer with cost $\tilde{r}_i$ makes zero expected profit: $\nu p^w - \tilde{r}_i = 0$. Given that $p^w = P\left(K_i + q_f^w\right)$ where $P(.) \equiv S^{'}(.)$ denotes the inverse demand function, we obtain the following equilibrium relationship between production levels from the two sources of energy

[17] This is without loss of generality since taxes could be uniform or even set to zero.

[18] We do not consider the case of limited pricing whereby the thermal power producer sets capacity and production levels high enough to deter entry of the most efficient wind-power producers (*i.e.* with equipment costs $\underline{r}_i$). Formally, the limit pricing production and equipment K_f^L is such that $P\left(K_f^L\right) = \frac{\underline{r}_i}{\nu}$. It is preferred by the monopoly thermal power producer to competition with wind power in state w if it induces higher profits. Limit pricing can easily be avoided by taxing more fossil fuels or by subsidizing wind power.

q_f^w and K_i :

$$P\left(K_i + q_f^w\right) = \frac{\tilde{r}_i}{\nu}, \tag{23}$$

with $K_i = \overline{K}F(\tilde{r}_i)$. The monopoly thermal power producer chooses q_f^w and K_f that maximize its expected profit:

$$\nu \left[P\left(K_i + q_f^w\right) - (c + \tau^w)\right] q_f^w + (1-\nu)\left[P\left(K_f\right) - \left(c + \tau^{\overline{w}}\right)\right] K_f - r_f K_f$$

with $P\left(K_i + q_f^w\right) = \frac{\tilde{r}_i}{\nu}$ and $K_i = \overline{K}F\left(\tilde{r}_i\right)$. The first order conditions yield

$$q_f^w \quad : \quad P\left(K_i + q_f^w\right) + P^{'}\left(K_i + q_f^w\right)\left(1 + \frac{dK_i}{dq_f^w}\right) q_f^w = c + \tau^w \tag{24}$$

$$K_f \quad : \quad P\left(K_f\right) + P^{'}\left(K_f\right) K_f = c + \tau^{\overline{w}} + \frac{r_f}{1-\nu} \tag{25}$$

We obtain adjusted versions of the standard equalization of marginal revenue to marginal cost (including regulation cost τ) for monopoly pricing. In state $\overline{w}$, the marginal cost includes the full cost of equipment on the right-hand side of (25) since it is used at full capacity. In state w, the marginal revenue is diminished by competition from wind power on the left-hand side of (24).

The thermal power producer obtains the benefit of a reduction in electricity supply through a higher price only on its market share q_f^w, which reduces the revenue by $P^{'}\left(K_i + q_f^w\right) q_f^w$. Furthermore, its market share is reduced by the entry of new wind-power producers. Market eviction is captured by $\frac{dK_i}{dq_f^w}$ in (24) which is the reaction by wind power producers to thermal power production. It is computed by differentiating the equilibrium condition (23):

$$\frac{dK_i}{dq_f^w} = \overline{K}f(\tilde{r}_i)\frac{d\tilde{r}_i}{dq_f^w} = \frac{\overline{K}f(\tilde{r}_i)}{\frac{D'(\tilde{r}_i/\nu)}{\nu} - \overline{K}f(\tilde{r}_i)}$$

where $D\left(.\right) \equiv P^{-1}\left(.\right)$ is the demand function. The variation in K_i is negative because $D^{'} < 0$: more thermal power in the grid reduces the entry of wind power producers.

6.3 Amplification of market power

From (24) and (25) we can conclude that competition from wind power producers does not reduce the price of electricity: in fact it increases it. Due to consumers' non-reactivity, the quantity of electricity consumed is determined by thermal power production capacity $q = K_f = K_i + q_f^w$. The thermal power firm fully controls the retailing price $p = P(K_f) = P(K_i + q_f^w)$

by fixing production capacity K_f. As shown by condition (25), capacity is chosen under the full exercise of monopoly power by equalizing marginal revenue to long-run marginal costs. The thermal producer is therefore able to restrict the supply of electricity as a monopolist. This full exercise of market power is amplified by the increase in costs due to competition from wind power on the right-hand side of (25). As seen above in the perfect competition case, since capacity costs are recovered only in state $\overline{w}$, the long-run marginal cost of each kWh of fossil-fuelled electricity increases from $c + \tau^{\overline{w}} + r_f$ to $c + \tau^{\overline{w}} + \frac{r_f}{1-\nu}$. Hence, apart from the environmental impact, the introduction of wind-power producers is bad news for consumers as it does not reduce the market power of the thermal power producer in state $\overline{w}$ (which determines production) and it increases marginal costs.

By comparing the first-order conditions (24) and (25) with the equilibrium prices in case (b) of Proposition 2 with $\tau = \delta$, we obtain the two tax rates that implement first-best when the two sources of energy co-exist on windy days:

$$\tau^w = \delta + \frac{p^w}{\epsilon^w}\left(1 + \frac{dK_i}{dq_f^w}\right) \tag{26}$$

$$\tau^{\overline{w}} = \delta + \frac{p^{\overline{w}}}{\epsilon^{\overline{w}}} \tag{27}$$

where p^w and $p^{\overline{w}}$ are the equilibrium state-contingent prices at the first-best energy mix, whereas ϵ^w and $\epsilon^{\overline{w}}$ are the corresponding price elasticities. The two taxes cover the environmental damage δ to mitigate the externality problem, in line with Pigouvian taxation. In addition, the taxes correct for the exercise of market power. This correction shows up in the second right-hand terms of (26) and (27) which are negative. Both taxes are lower than the Pigou rate δ. Yet this departure from the Pigou rate differs across states. It depends on the exercise of market power which is full in the absence of wind (state $\overline{w}$) but only partial on windy days. As a consequence, assuming constant price elasticity $\epsilon^w = \epsilon^{\overline{w}}$, the tax must be lower when there is no wind : $\tau^{\overline{w}} < \tau^w$.

Instead of using two tax rates, the first-best energy mix could be implemented with a price cap combined with a single tax on fossil fuel (or emissions from fossil fuel burning). If the monopolist cannot charge more than $p^{\overline{w}} = c + \tau^{\overline{w}} + \dfrac{r_f}{1-\nu}$ for electricity, it switches to the efficient production capacity. It therefore supplies electricity efficiently when it is the only supplier, i.e. in state $\overline{w}$. On the other hand, this price cap is not binding in state w when the thermal producer competes with wind-power producers. Yet the tax on fossil fuel τ^w ensures that it supplies the efficient amount of electricity during windy periods.[19] We summarize our findings in the following proposition.

Proposition 6 *The entry of a competitive fringe of wind-power producers does not mitigate the under-supply of electricity by a monopoly thermal power producer. The efficient energy mix is achieved with state-contingent carbon taxes or, alternatively, a price cap coupled with a single carbon tax.*

7 Concluding comments

Climate change mitigation requires the replacement of fossil-fuel energy with renewables such as wind and solar power. It has been fostered through diverse policies implemented worldwide, from carbon tax to feed-in tariffs and renewable portfolio standards. The intermittent nature of renewables, coupled with the non-reactivity of electricity consumers to short-term fluctuations in electricity provision, makes it necessary to back-up any new installation of intermittent energy facilities (e.g. new windmills) with reliable energy (e.g. coal-fueled power plants). As a result, the two sources of energy are not always substitute. They are indeed substitutes every time the wind is blowing. When there is no wind and consumers still want power, thermal technology is the obvious complement to wind turbines.

Because of the intermittency of renewables, the impact of environmental policies is by no means trivial. In particular, the support for renewables through feed-in tariffs (FIT) results in too much energy production. FIT should be complemented by a tax on electricity consumption to reduce the use of fossil fuel. Similarly, a renewable portfolio standard fails to implement the efficient energy mix. A complementary instrument which controls fossil fuel burning, such as a carbon tax, should be added to reach efficiency.

Technologies provide solutions to the intermittency of renewable sources of energy. Our model allows us to identify the social value of those technological solutions. Energy storage, in particular pumping water into upstream reservoirs, reduces the burden of intermittency.

[19] Significantly, when thermal power production is perfectly offset by wind power in state w, we get $\frac{dK_i}{dq_f^w} = -1$ so that the fossil fuel should be taxed at the Pigou rate in state w, *i.e.* $\tau^w = \delta$ in (26). This would occur for instance if all wind power producers had the same cost r_i and unlimited maximum capacity $\overline{K} = +\infty$ like in Ambec and Crampes (2012). Then thermal and wind power producers would then compete à la Bertrand in state w. The only market failure that the tax would have to solve in state w would be the pollution externality. Market power would still have to be mitigated but only in state $\overline{w}$ through a reduced tax rate or a price cap.

The marginal value of energy storage depends on the cost difference between intermittent and reliable sources of energy. It is reflected by the difference in electricity prices on the wholesale market. Smart meters with load-switch devices and batteries also help consumers to adapt their consumption to price changes. Although making consumers reactive reduces production costs − including the back-up equipment cost and the environmental cost of thermal power − it exposes risk-averse consumers to price fluctuations. Such risk exposure effects should be incorporated into the cost-benefit analysis of installing smart meters.

We also have established that competition from intermittent energy producers does not significantly alter the ability of a private monopolist using thermal technology to exert market power. The thermal power producer underinvests in production capacity to charge the monopoly price when windmills are not spinning. Since the capital cost must be charged only during no-wind periods, the monopoly decreases its production and equipment more than if there were no wind turbines available. Regulation is thus required to improve welfare even with a competitive fringe of wind power producers. The carbon tax that would fix the two market failures - the exercise of market power and the environmental externality- should be state-dependent, i.e. it should vary with the availability of the intermittent source of energy.

More can be done within our framework. First, other sources of intermittent energy can be considered. The diversification of energy sources is indeed a technological solution to mitigate intermittency. Windmills and solar panels can be spread out in different regions to take advantage of diverse weather conditions and thus increase the number of days with significant wind and solar power. Other intermittent sources such as tide or wave power can be used to increase the supply of energy, in particular its frequency. Our model can be extended to accommodate several intermittent sources of energy with heterogeneous costs and occurrence. Using a similar model, we have shown in Ambec and Crampes (2012) that it is optimal to invest in two different intermittent sources of energy that do not produce at the same time, even if one is more costly. Similarly, in this paper investing in wind or solar power at different locations, or in tide or wave power, would reduce the probability of relying only on thermal power. Yet as long as global intermittent production remains a random variable, our analysis remain qualitatively valid since intermittent energy capacity must be backed up with thermal power facilities.

Another question the model can address is the design of retailing contracts with state contingent prices or curtailment.[20] We have shown that risk-averse consumers prefer to sign a retail contract with a constant electricity price − which is the average of the wholesale electricity prices− rather than with spot prices even if they are equipped to react to price changes. To make it attractive for some consumers, particularly the biggest ones for whom it is worth investing in batteries and load-switching devices, the contract with state-contingent prices should compensate for the risk premium. This can be done for instance through a two-part tariff. A complete analysis of the design of the retail contract with two-part tariffs and heterogeneous consumers is beyond the scope of the present paper. It has been left for future research.

[20] On retail contracts with load-shedding clauses, see Crampes and Léautier (2015).

A Proof of Proposition 1

Denoting $\gamma, \underline{\mu}_f, \overline{\mu}_f$ and $\underline{\mu}_i$ the multipliers respectively associated with the constraints (1), (2), (3) and(4),the Lagrange function corresponding to the program can be written as

$$\begin{aligned}\mathcal{L} &= \nu\left[S(\overline{K}F(\widetilde{r}_i)+q_f^w)-(c+\delta)\,q_f^w+\underline{\mu}_f q_f^w+\overline{\mu}_f(K_f-q_f^w)+\underline{\mu}_i(\widetilde{r}_i-\underline{r}_i)+\gamma\left(\overline{K}F(\widetilde{r}_i)+q_f^w-K_f\right)\right] \\ &\quad +(1-\nu)\left[S(K_f)-(c+\delta)\,K_f\right]-r_fK_f-\overline{K}\int_{\underline{r}_i}^{\widetilde{r}_i} r_i dF(r_i)\end{aligned}$$

Given the linearity of technologies and the concavity of the surplus function, the following first-order conditions are sufficient to determine the optimal level of capacity and output:

$$q_f^w : \nu\left[S'(\overline{K}F(\widetilde{r}_i)+q_f^w)-(c+\delta)+\underline{\mu}_f-\overline{\mu}_f+\gamma\right]=0 \tag{A1}$$

$$K_f : \nu\left(\overline{\mu}_f-\gamma\right)+(1-\nu)\left[S'(K_f)-(c+\delta)\right]-r_f=0 \tag{A2}$$

$$\widetilde{r}_i : \nu\left[S'(\overline{K}F(\widetilde{r}_i)+q_f^w)+\underline{\mu}_i^{'}+\gamma\right]-\widetilde{r}_i=0 \tag{A3}$$

where $\underline{\mu}_i^{'} \equiv \underline{\mu}_i/\overline{K}f(\widetilde{r}_i)$, plus the complementary slackness conditions derived from the four constraints of the program.

Combining (A1) and (A3) yields:

$$\frac{\widetilde{r}_i}{\nu}=\overline{\mu}_f+\underline{\mu}_i^{'}-\underline{\mu}_f+c+\delta \tag{28}$$

* First, without intermittent energy (case a), $\widetilde{r}_i=\underline{r}_i$ and $\underline{\mu}_i^{'}\geq 0$. Moreover, since $\overline{K}F(\widetilde{r}_i)=0$, the non-reactivity condition (1) implies $q_f^w=K_f>0$ and therefore $\underline{\mu}_f=0$ and $\overline{\mu}_f\geq 0$. Hence, condition (28) implies

$$\frac{\widetilde{r}_i}{\nu}\geq c+\delta. \tag{29}$$

Substituting $q_f^w=K_f$ and $\overline{K}F(\widetilde{r}_i)=0$ into (A1) yields $\overline{\mu}_f-\gamma=S'(K_f)-(c+\delta)$ which, combined with (A2), leads to $K_f=S'^{-1}(c+\delta+r_f)$

* Second, with investment in intermittent energy (cases b and c), we have $\widetilde{r}_i>\underline{r}_i$ and $\underline{\mu}_i^{'}=0$. Since $\overline{K}F(\widetilde{r}_i)>0$ and $q_f^w=K_f-K_i$ by the non-reactivity constraint (1), then $q_f^w<K_f$ and therefore $\overline{\mu}_f=0$. Thus (28) becomes

$$\frac{\widetilde{r}_i}{\nu}=-\underline{\mu}_f+c+\delta. \tag{30}$$

Suppose first that $q_f^w > 0$ (case b). Then $\underline{\mu}_f = 0$ in (30) so that the threshold intermittent energy cost $\widetilde{r}_i$ is defined by $\widetilde{r}_i^{\,b} = \nu(c + \delta)$.

Combining (A1), (A2) and the non-reactivity constraint (1) yields the installed capacity of fossil energy $K_f = K_i + q_f^w = S'^{-1}(c + \delta + r_f)$ as well as the production of fossil energy in state w, $q_f^w = K_f - K_i = S'^{-1}(c + \delta + r_f) - \overline{K}F\left(\widetilde{r}_i^{\,b}\right)$.

Let $\Delta(\delta) \equiv S'^{-1}(c + \delta + r_f) - \overline{K}F(\nu(c + \delta)) > 0$. Since $\Delta'(\delta) < 0$ and $\Delta(0) = S'^{-1}(c + r_f) > 0$, we have that $\Delta(\delta) > 0$ for every $\delta < \widehat{\delta}$, where $\widehat{\delta}$ is uniquely defined by $\Delta(\widehat{\delta}) = 0$ which is condition (5) in the text. Hence $q_f^w > 0$ for $\delta < \widehat{\delta}$.

Suppose now that $q_f^w = 0$ (case c), which means that $\delta \geq \widehat{\delta}$. Then $\underline{\mu}_f \geq 0$ and (30) implies $\frac{\widetilde{r}_i}{\nu} \leq c + \delta$. Furthermore (1), (A1), (A2), and (30) imply:

$$S'(K_i) = S'(K_f) = (1 - \nu)(c + \delta) + \widetilde{r}_i + r_f,$$

with $K_i = \overline{K}F(\widetilde{r}_i) = K_f$. It leads to $\overline{K}F(\widetilde{r}_i^{\,c}) = K_f = S'^{-1}((1 - \nu)(c + \delta) + \widetilde{r}_i^{\,c} + r_f)$ which determines both K_f and $\widetilde{r}_i^{\,c}$, the latter being a fixed point in the relationship.

B Proof of Proposition 4 for case (c) in Proposition 1

In case (c) of Proposition 1, the FIT should be set to $p^i = \tilde{r}_i^c/\nu$ to induce first-best investment in wind power. On the other hand, the price paid by consumers should be $p + t = (1 - \nu)(c + \delta) + r_f + \tilde{r}_i^c$ per kWh to reduce consumption up to the optimal level $q = K_f = S'^{-1}((1 - \nu)(c + \delta) + r_f + \tilde{r}_i^c)$. Since thermal power is produced only in state $\bar{\omega}$, the zero-profit condition leads to a wholesale electricity price $p^{\bar{\omega}} = c + \frac{r_f}{1 - \nu}$ and a retailing price of electricity $p = (1 - \nu)c + r_f$. Therefore tax per kWh should be $t = (1 - \nu)(c + \delta) + r_f + \tilde{r}_i^c - p = (1 - \nu)\delta + \tilde{r}_i^c$ to induce first-best consumption. By substituting the above values for p^i, $p^{\bar{\omega}}$ and t into the financial constraint (11) we obtain a budget surplus of $K_f[(1 - \nu)\delta + \nu c + \frac{\nu}{1 - \nu} r_f] > 0$. If the tax is set to bind the financial constraint (11) with a FIT $p^i = \tilde{r}_i^c/\nu$ while the wholesale electricity price is $p^{\bar{\omega}} = c + \frac{r_f}{1 - \nu}$, the tax rate is then $t = \tilde{r}_i^c - \nu c - \frac{\nu}{1 - \nu} r_f < (1 - \nu)\delta + \tilde{r}_i^c$, i.e. lower than the rate that induces first-best electricity consumption. The argument for FIP is similar and has therefore been omitted.

C Proof of Proposition 5 for case (c) in Proposition 1

In case (c) of Proposition 1, the RPS must at the same time induce investment in wind power up to $K_i^c \equiv \bar{K}F(\tilde{r}_i^c)$ and a reduction of electricity consumption down to $K_f^c \equiv S'^{-1}((1-\nu)(c+\delta)+r_f+\tilde{r}_i^c)$. The threshold cost of the less productive windmill should be $\tilde{r}_i^c$ on the right-hand side of (16) while the retail price of electricity should be $(1-\nu)(c+\delta)+r_f+\tilde{r}_i^c$ on the left-hand side. It leads to a condition on $\tilde{r}_i^c$ which differs from the one which explicitly defines $\tilde{r}_i^c$ in Proposition 1. Hence it is unlikely to hold.

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