Decarbonizing electricity generation with intermittent sources of energy

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Abstract

We examine the impact of public policies and technical solutions 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). Intermittency increases the cost of renewables through two channels: less frequent production and the need to back-up production from renewable with thermal power, or develop storage and demand-response solutions. In competitive markets, the first-best energy mix is achieved with a pigouvian carbon tax but not with the most popular supports to renewables: feed-in tariffs and renewable portfolio standards. Both policies enhance investment into intermittent sources of energy. However, they boost electricity production beyond the efficient level. They must be complemented with a tax on electricity consumption. Next we determine the social value of two technologies to accommodate intermittency: energy storage that allows to smooth solar and wind variations among states of nature and smart meters aimed at making consumers price responsive.

Keywords: electricity, intermittency, tax, feed-in tariff, renewables, storage, smart consumer.
JEL codes: D24, D61, Q41, Q42, Q48.

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1 Introduction

1.1 Demand for reliable electricity and intermittent production

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 to support renewables. The US states have opted for quantitative commitments: renewable portfolio standards (RPS). RPS programs generally require a minimum fraction of electricity demand to be met by renewable sources.[1] By contrast, most European countries have opted for a price instrument, feed-in tariffs (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.[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 unpredictable as weather conditions 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 because electricity 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 every hour or half-an hour, the retail prices

[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 Environmental Protection Agency website: https://www.epa.gov/sites/production/files/2015-08/documents/guide_action_chapter5.pdf

[2]FITs have been quite successful in fostering investment in wind and solar power in the European Union during the past decade. The price paid for success is an increase in the consumers' bill to cover the cost of FIT. How much it costs to consumers depends on whether suppliers can pass 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://www.cre.fr/operateurs/service-public-de-l-electricite-cspe/montant

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

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 would not instantly react to price changes.

Surprisingly, the intermittent nature of renewable sources of energy has been largely ignored in the economic modeling of the transition to low-carbon energy. Seminal papers deal with a carbon-free technology that replaces polluting ones at a cost that deceases over time (Fischer and Newell, 2008, Acemoglu et al., 2012). In these models, carbon-free energy can be used anytime once production capacity is installed. In reality intermittency modifies the availability of windmills or solar panels. It changes the business model of the electricity sector as well as investment in equipment, production and consumption patterns which, in turn, should influence the design of public policy for decarbonating energy.

This paper fills the gap by analyzing the transition to a decarbonated energy mix in a model of electricity provision with both intermittent and non intermittent sources energy. The supply of electricity from the climate-dependent technology is environmental friendly whereas the reliable source emit pollutants. On the demand side, most consumers are not reactive to short-term price variations. Absent energy storage and assuming that power cuts are not acceptable, the non-reactiveness of consumers requires to back-up new equipment of renewables with polluting thermal sources of production. It therefore impacts investment in production capacity, energy use, electricity provision, environmental pollution and welfare. By explicitly modeling intermittency, we are able to analyze important features of the energy transition such as the need for backing up renewables with thermal power capacity, the role of demand response to volatile electricity prices and the social value of energy storage.

Even though our analysis can be applied to all intermittent sources with a known distribution of probability, from now on we will mainly refer to the wind resource.

With this model, we first characterize the efficient energy mix when consumers cannot react to real-time price changes. We also discuss its decentralization in competitive electricity markets by a pigouvian carbon tax. We highlight two effects of intermittency on the cost of introducing renewables in the energy mix. First, since each kilowatt of windmill capacity is supplied with primary energy only a fraction of the year, the average cost of a kilowatt hour must be weighted by the frequency of production. It means that if windmills are spinning say half of the year, the cost of a kilowatt hour is doubled. Second, the final bill should include the cost of thermal power equipment used as a back-up, because electricity consumption is determined not by wholesale prices but by retail prices which reflect the social cost of the reliable source of energy. From a policy perspective, the extra cost of intermittency and back-up should be included in the cost-benefit analysis of renewables mandates.

Next we analyze the impact of the two most popular renewables mandates on the energy mix in a competitive economy: feed-in tariffs (FIT) and renewable portfolio standards (RPS). 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 greenhouse gas emissions. They should be complemented by a tax on electricity consumption or fossil fuels to implement first-best. In particular, a tax on electricity consumption that only finances the FIT is not high enough to obtain the efficient energy mix. Alternatively, the FIT adapted to the efficient mix raises more money than what is strictly necessary to balance the industry costs. We pin down the tax on electricity that should complement FIT and RPS.

Lastly, we investigate two technological solutions to better deal with intermittency. We consider energy storage that allows to smooth wind variation among states of nature. We also look at contingent electricity pricing with smart meters. We identify the marginal benefits of these solutions and the market-driven incentives to invest in these technologies.

1.2 Intermittency modeling

Several papers have introduced intermittency in an economic model of electricity provision. Ambec and Crampes (2012) analyze the optimal and market-based provision of electricity with intermittent sources of energy. However, they do not consider public policies and environmental externalities.[4] In the same vein, Helm and Mier (2016) investigate optimal and market-based investment in several intermittent sources of energy. However, they assume that consumers adapt their consumption to real-time changes in electricity prices. As a consequence, they find that it is optimal to exit from fossil energy when renewables are competitive enough. In contrast, when consumers do not modify instantaneously their consumption pattern to react to wholesale electricity prices as assumed in our model, fossil energy is always used as a back-up, which increases the social cost of renewables.[5] Similarly, Green and

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

[5]Helm and Mier (2016) analyze the effect of smart-meters on the energy mix by "flattening" the inverse demand function for electricity. Here, by assuming a proportion of non-reactive consumers, we are able to better identify the impact of making consumers reactive to wholesale prices with smart meters.

Léautier (2015) ignore the problem of consumers's reactivity to wholesale electricity prices in their investigation on the impact of FIT on the energy mix. In their model, there is no need to back-up renewables with reliable sources, which eventually disappear when the FIT becomes high enough. The issue of consumers' sensitivity to real-time electricity prices has been addressed by Joskow and Tirole (2007). They introduce non-reactive consumers in a model of electricity provision with variable demand.[6] They examine pricing, investment in generation and load rationing rules. We also deal with the two types of consumers in one single model. However, in our model the source of variability is on the supply side and the degree of variability is endogenously determined by investment in wind power through the support to renewables.

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 flexibility. It furthermore allows for welfare comparisons in which consumers' surplus and environmental damage are included.

Another strand of literature relies on local solar and wind energy data to compute the social value of intermittent renewables. Cullen (2013) estimates the pollution emission offset by wind power in Texas. In the same vein, Gowrisankaran et al. (2016) quantify the cost of solar power in Arizona in an optimized energy mix. Our paper complements this literature by identifying the key ingredients that determine the social value of intermittent renewables, both in an optimized and in a market-based electricity sector with public policy. For instance, we show that the social value includes the cost saved from installing or maintaining fewer thermal power plants only when the share of renewables is high enough, i.e., above a threshold that we

[6] They use the terms of "price-sensitive" and "price-insensitive" consumers, which is somehow misleading as price-insensitive consumers do respond to retail prices. We prefer to talk about "reactivity" to real-time price changes.

characterize. Similarly, we are able to identify in our model the social value of energy storage and how it is related with the cost of wind power and thermal power.

So far, the literature on public policies to decarbonate electricity provision has ignored the problem of intermittency. Researchers 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 paper, 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 characterizes the first-best energy mix when consumers are not reactive to climate-dependent prices. It also identifies the market outcome prices and the impact of intermittency on investment into power generation, production and pollution. Public policies are analyzed in Section 4: feed-in tariff and feed-in premium (Section 4.2) and renewable portfolio standard (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. Section 6 concludes.

2 The model

We consider a model of energy production and supply with intermittent energy and non-price reactive demand.[7]

- *Supply side.* Electricity can be produced by means of two technologies.
  - One is a fully controlled but polluting technology (e.g. plants burning coal, oil or gas). It allows to produce q_f kilowatt each hour 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

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

pollutants which causes damages to society. We focus on greenhouse gases, mostly CO_2, even though our analysis could encompass other air pollutants such as SO_2, NOx or particulate matters. Let's denote by $\delta > 0$ the environmental marginal damage due to thermal power, i.e., the social damage from CO_2 emissions per kilowatt-hour of electricity generated.

– The second technology relies on an intermittent energy source such as wind. It makes it possible to produce q_i kilowatt per hour at zero 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 frequency ν (respectively $1 - \nu$) and is denoted 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.[8]

- *Demand side.* Consumers derive a gross utility $S(q)$ from the consumption of q kilowatts of electricity per hour. 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 function is $D(p) = S'^{-1}(p)$ where p stands for the retail price. For the main part of the paper, we assume that consumers are "non-reactive" and we introduce a subset of "reactive" customers in Section 5 to analyze the role of smart meters. Reactive consumers are equipped with smart meters and load-switching devices that allow them to modify their consumption in line with real-time price changes. They pay the wholesale electricity prices which depend on weather conditions: p^w and $p^{\bar{w}}$ will denote the price of one kilowatt-hour of electricity in the wholesale market in states w and $\bar{w}$ respectively. By

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

contrast, “non-reactive”consumers are not equipped to adapt their takes to price changes due to states of nature affecting production plants. They pay a non-state contingent retail price p. The retail and wholesale electricity prices are related by the zero profit condition for electricity retailers implied by the assumption of free entry in the retailing market. Neglecting the operation costs of retailers, the retail price of one kilowatt-hour (KWh) of electricity sold to non-reactive consumers is equal to its expected price in the wholesale market $p = \nu p^w + (1-\nu)p^{\bar{w}}$. In most of the paper, we assume that electricity cannot be stored, transported or curtailed. The only way to balance supply and demand is then to rely on production adjustment and/or price variation.[9] Lastly, 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.

In Section 3, we determine the optimal energy mix and in Section 4 we analyze the impact of public policy when *all* consumers are non-reactive. We relax this assumption by introducing a proportion β of reactive consumers in Section 5.2.

3 Optimal energy mix with non-reactive consumers

3.1 Capacity, production and prices

In this section, all consumers are non-reactive to price changes in the wholesale market. Assume that air pollution is taxed optimally at the Pigou rate so that δ is the environmental or carbon tax of thermal power per kWh produced. The optimal energy mix 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 $j \in \{f, i\}$.

We first state a series of intuitive results that do not necessitate a formal proof: (i) by definition, in state $\overline{w}$, no intermittent energy is produced: $q_i^{\bar{w}} = 0$; (ii) the non-reactivity of consumers implies that their electricity consumption cannot be state dependent: $q = q_f^{\bar{w}} = q_i^w + q_f^w$; iii) the assumption $S'(0) > c + \delta + r_f$ implies $q_f^{\bar{w}} = K_f > 0$: fossil fuel capacity will be installed and fully used; (iv) since intermittent energy has no operating cost, all the energy produced by windmills (if any) will be supplied to consumers, $q_i^w = K_i$ as long as

[9] This assumption is relaxed later on when we introduce storage and reactivity in Section 5.

$S'(K_i) \geq 0$; (v) the more efficient spots for wind 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 $K_i = \bar{K}F(\tilde{r}_i)$.

Given these five statements, we are left with three decision variables K_f, $\tilde{r}_i$ and q_f^w that must be chosen to maximize the expected social surplus:

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

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 reflects the non-reactivity of consumers and the prohibition of blackouts. It requires electricity consumption to be the same in the two states of nature. By the second constraint, electricity production from fossil fuel in state w must be non-negative and by the third, it cannot exceed production capacity. Finally constraint (4), states that the threshold capacity cost $\tilde{r}_i$ is bounded downward by the lowest cost $\underline{r}_i$.

In order to limit the number of propositions, we include into the definition of first best the prices that allow to decentralize the optimal allocation in a perfect competition framework with free entry. Prices are defined by the zero-profit condition for both types of producers (non polluting and thermal) as well as for electricity retailers.

Let δ^0 be the threshold value for the social cost of carbon defined implicitly by the following relationship:

$$\bar{K}F\left(\nu\left(c+\delta^0\right)\right)=D\left(c+r_f+\delta^0\right). \quad (5)$$

It is the social cost of carbon such that demand is entirely covered with wind power in state w in the optimal energy mix (i.e. $q_f^w = 0$).

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

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

(a) for $\delta < \frac{\underline{r}_i}{\nu} - c$ *: no intermittent energy*

$$K_i = 0,\ K_f = D(p) = q_f^w$$

$$p = p^w = p^{\bar{w}} = c + r_f + \delta$$

(b) for $\frac{\underline{r}_i}{\nu} - c \leq \delta \leq \delta^0$*: both sources of energy are used in state* w

$$K_i = \bar{K}F(\nu p^w),\ K_f = D(p),\ q_f^w = K_f - K_i > 0$$

$$p^w = c + \delta,\ p^{\bar{w}} = c + \frac{r_f}{1-\nu} + \delta,\ p = \nu p^w + (1-\nu)p^{\bar{w}} = c + r_f + \delta$$

(c) for $\delta^0 \leq \delta$*: only intermittent energy is used in state* w

$$K_i = K_f = D(p),\ q_f^w = 0,$$

$$p^w = \frac{\tilde{r}_i^0}{\nu},\ p^{\bar{w}} = c + \frac{r_f}{1-\nu} + \delta,\ p = \nu p^w + (1-\nu)p^{\bar{w}} = \tilde{r}_i^0 + (1-\nu)(c+\delta) + r_f,$$

with $\tilde{r}_i^0$ *given by:*

$$\bar{K}F\left(\tilde{r}_i^0\right) = D\left((1-\nu)(c+\delta) + r_f + \tilde{r}_i^0\right)$$

The above conditions and solutions have natural economic interpretations. The ratio $\underline{r}_i/\nu$ represents the marginal cost of producing one kilowatt-hour 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. If $\underline{r}_i/\nu$ is higher than $c + \delta$ (case a), no wind power should be installed. Electricity production comes from thermal plants because they are more socially efficient. If $\underline{r}_i/\nu$ is lower than $c+\delta$ (cases b and c), windmills are to be installed.

Remarkably, 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 kilowatt of wind power installed must be backed-up with one kilowatt of thermal power. Thus both sources of energy need the same thermal power equipment. Equipment cost determines total consumption and thermal power capacity K_f but not the choice of energy source.

3.2 Impact of the social value of carbon

In Figure 1 we graph investment in the two sources of energy and consumption as functions of the environmental damage or the social value of carbon δ.

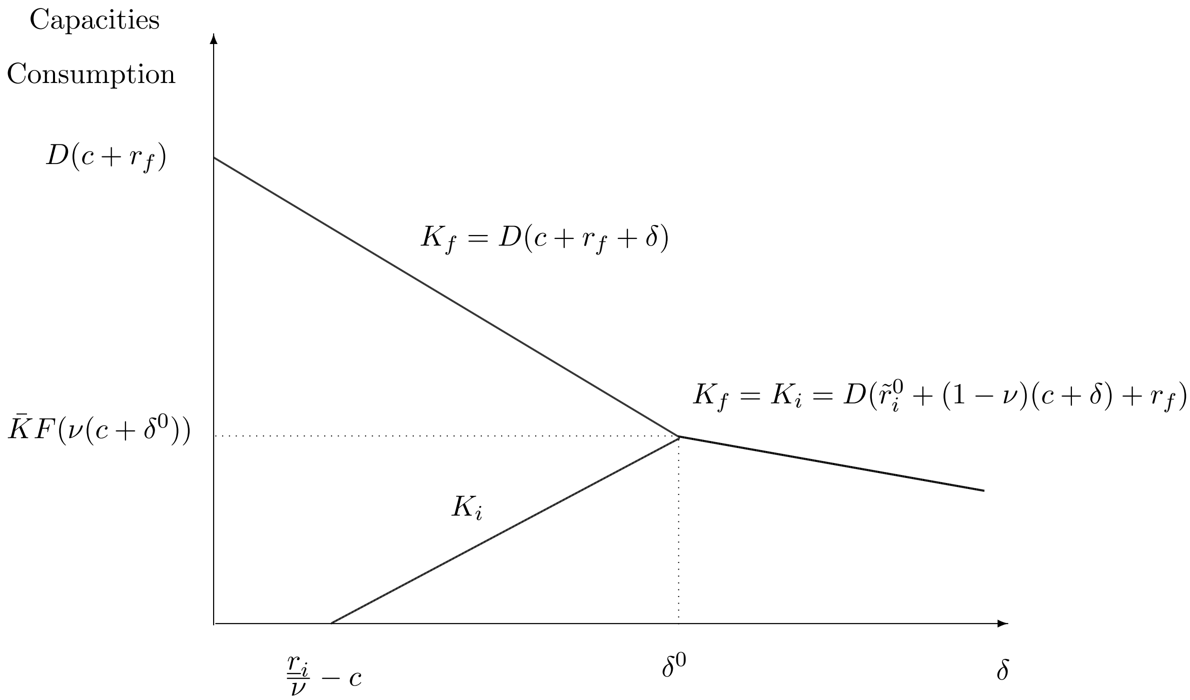

Figure 1: Investment and consumption when the social cost of carbon varies

In case (a) (left part of the graph), the environmental damage is too small to justify an investment in green technology.[10] Electricity should be priced at its long term marginal social cost $p = c + r_f + \delta$ which includes the operating and energy costs c, the capacity cost r_f and the environmental marginal damage δ. Installed thermal capacity should match consumers' demand at this optimal price $K_f = D(c + r_f + \delta)$. Electricity price in the wholesale market does not depend on the state of nature $p^w = p^{\bar{w}} = p$. 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

[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.

in state w. Both sources of energy are necessary.[11] Thermal power capacity K_f is determined by the demand for electricity at the socially efficient price, which is the social cost of thermal power: $p = c + r_f + \delta$. The efficient thermal power capacity is thus $K_f = D(c + r_f + \delta)$. Since the same amount of electricity must be supplied in both states of nature (by the non-reactivity constraint), thermal power plants are used at full capacity in state $\overline{w}$ (i.e. without wind) but not in state w (i.e. with wind). As a consequence, the price of electricity in the wholesale market covers capacity cost r_f only in state $\overline{w}$. It is set to $p^{\bar{w}} = c + \frac{r_f}{1-\nu} + \delta$, higher than the retailing price p. By contrast, in state w, the price of electricity reflects the social marginal cost of using the thermal power plants below capacity $p^w = c + \delta$ (i.e. the operating cost c plus the environmental cost δ) which is lower than the retailing price p.

Windmills are installed on the most efficient sites as long as the marginal cost of providing one kWh of wind power r_i/ν does not exceed p^w the price of electricity in state w. The marginal cost of the least profitable windmills is determined by its zero-profit condition which defines $\tilde{r}_i = \nu p^w = \nu(c + \delta)$. All other wind power producers ($\underline{r}_i \leq r_i < \tilde{r}_i$) obtain inframarginal profits. Total wind power capacity is thus $K_i = \bar{K}F(\tilde{r}_i) = \bar{K}F(\nu(c + \delta))$. As displayed in the central part of Figure 1, when 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. Thermal and wind power capacities match consumer's demand $K_f = K_i = D(p)$. The switch to case (c) arises when the social cost of carbon δ is high enough so that the supply of intermittent energy at wholesale market price in state w, that is $K_i = \bar{K}F(\nu(c + \delta)$, covers electricity demand at retail price $p = c + r_f + \delta$: it is δ^0 defined in (5). The wholesale electricity prices are given by the zero-profit conditions for each type of producer in each state of nature. In state w, wind power producers install capacity up to reach the threshold cost $\tilde{r}_i^0$ of the least profitable windmills which defines the price $p^w = \tilde{r}_i^0/\nu$. In state $\bar{w}$, thermal power plants are used at full capacity. The price of electricity $p^{\bar{w}} = c + \frac{r_f}{1-\nu} + \delta$ covers thermal power's capacity cost r_f even though the plants are running only a share $1 - \nu$ of the year. Those wholesale electricity prices yield a retail price $p = (1 - \nu)p^{\bar{w}} + \nu p^w = \tilde{r}_i^0 + (1 - \nu)(c + \delta) + r_f$, which is the social cost of the

[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).

[12] Formally, by differentiating fossil-fuel and clean energy capacities, we obtain $\frac{dK_f}{d\delta} = D'(c + r_f + \delta) < 0$ and $\frac{dKi}{d\delta} = \bar{K}f(\nu(c + \delta))\nu > 0$.

marginal kilowatt-hour on average over the year. It yields a demand for electricity in both states of nature equal to $D(\tilde{r}_i^0 + (1-\nu)(c+\delta) + r_f)$. The threshold cost $\tilde{r}_i^0$ is given by a fixed point condition determined by demand at retail price and the distribution of wind power capacity costs. It is such that profitable wind power capacity covers the demand at retail price $\bar{K}F\left(\tilde{r}_i^0\right) = D\left((1-\nu)(c+\delta) + r_f + \tilde{r}_i^0\right)$.

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 do capacity and production from both the clean and dirty sources of energy. Note that electricity consumption $D(p)$ decreases at a lower rate when δ increases in case (c) than in case (b) for a constant price-elasticity demand function.[13] It is because thermal power capacity is no longer substituted by investment in wind power in case (c) as the social cost of fossil energy increases. Rather production capacity from the two sources of energy decreases.

3.3 Impact of the carbon tax on investment

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

$$\frac{d(K_f + K_i)}{d\delta} = D'(c+\tau+r_f) + \bar{K}f(\nu(c+\tau))\nu.$$

If the reduction of thermal power capacity (the first term on the right-hand side is negative) is more than compensated 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 δ 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

[13] Formally, $\frac{dD(p)}{d\delta} = D'(p)$ in case (b) which is higher than $\frac{dD(p)}{d\delta} = D'(p)(1-\nu)$ in absolute value in case (c).

the elasticity of demand to changes in the retail price (very small $|D'|$) 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.

3.4 The effects of intermittency

To assess the impact of intermittency on the efficient energy mix, we consider the case of a renewable source of energy that is producing in all weather conditions as a benchmark. Suppose that power from renewables is produced in both states of nature w and $\bar{w}$. Electricity supply and demand being deterministic, energy production coincides with installed capacities from both sources of energy $q = K_i + K_f$ without any reference to the state of nature. The optimal energy mix is found by maximizing total welfare with respect to production capacities K_f and K_i. The problem is solved in Appendix B. Note that the solution cannot be obtained by simply considering the convergence of the results in Proposition 1 for $\nu \longrightarrow 1$. This is because constraint (1) is missing in the current problem so that the two problems are not directly comparable.

In Figure 2 we plot investment in both sources of energy and electricity consumption when renewables can be used in both states of nature (in dotted lines with superscript n) and when they are intermittent (in plain lines).

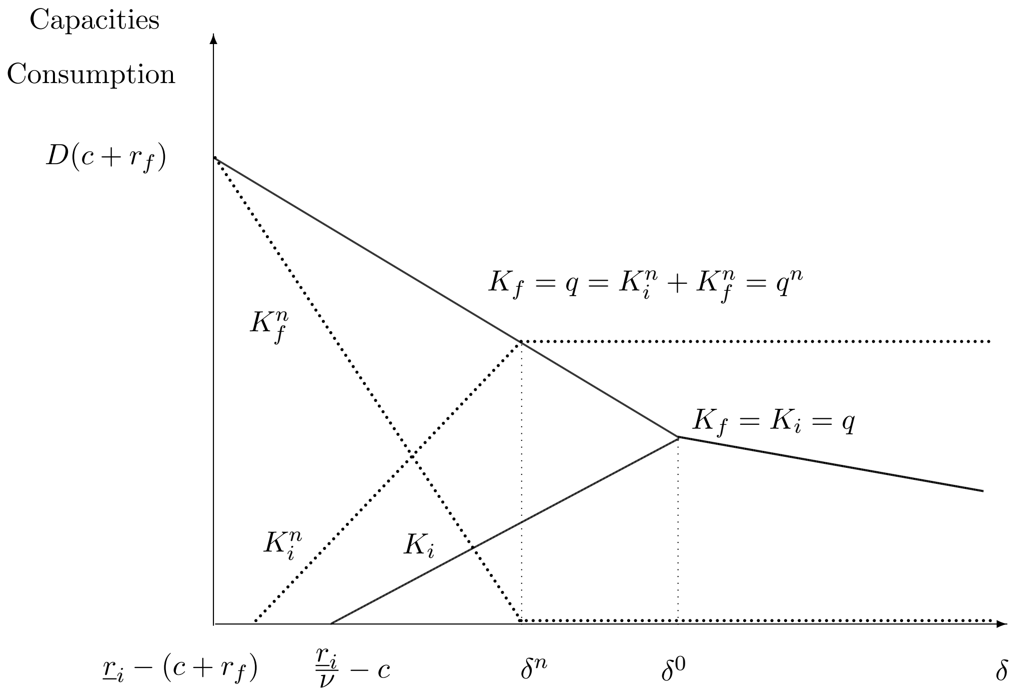

Figure 2: Investment and consumption with and without intermittency

Comparing the optimal energy mix with and without intermittency, we highlight two features.

First, everything else being equal, intermittency reduces the social value of green energy. This is because the minimal social cost of carbon for which green energy becomes socially efficient is higher. Formally, δ should be higher that $\underline{r}_i/\nu - c$ with intermittency (see case b in Proposition 1) as compared to $\underline{r}_i - (c + r_f)$ without intermittency. Two effects explain this difference. The *intermittency effect* increases the cost of one kilowatt-hour for the most efficient windmill from $\underline{r}_i$ to $\underline{r}_i/\nu$. In effect the windmill is producing only with frequency ν so that the cost of a kilowatt-hour must be discounted by ν. The *back-up effect* decreases the cost of using thermal power plants. Fossil-fueled energy capacity is tailored on demand without wind (in state $\bar{w}$) which creates overcapacity when windmills are spinning (in state w). Consequently, the social cost of using the thermal power plants in state w is $c+\delta$ as compared to $c + \delta + r_f$ if all capacity was used: it does not include the capacity cost r_f. When they are not intermittent, renewables are permanent substitutes to thermal power equipment and production. When intermittent, renewables are only substitutes of thermal production, not of thermal power capacity.[14] Both the intermittency and back-up effects make investment in green power less attractive. A higher carbon tax is required to induce investment in renewables when they are intermittent.

The second feature of intermittency is that it introduces climate-dependent price volatility in the wholesale electricity market. Without intermittency, when the two types of energy are profitable (cas b), the price would reflect the social cost of the two sources of energy $p = c + r_f + \delta = \tilde{r}_i$, where $\tilde{r}_i$ is the equipment cost of the less productive windmill installed, regardless of the state of nature. With intermittent source of energy, wholesale prices are lower during windy days $p^w = \tilde{r}_i \nu = c + \delta$ than absent wind $p^{\bar{w}} = c + \delta + r_f$. Electricity retailers are buying electricity at volatile prices and offer a constant retailing price. They insure consumers at no cost against price volatility due to the intermittency of wind power. Note that, whatever the social cost of carbon δ, 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.

We now turn to the decentralization of the efficient energy mix by alternative public policies when the clean technology is intermittent.

4 Public policy

To analyze the efficiency of existing public 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 because they do not internalize the social cost of carbon δ, whereas they must be installed from the social point of view. Without a carbon tax, electricity producers would install only thermal power plants,

[14] Note that the back-up effect creates a discontinuity in the threshold cost for which it is worth to invest in renewables. This is due to our assumption of no outage: as long as renewables are not producing during some weather events, power plant capacity must be increased to match renewables equipment even if those events occur with very low probability.

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. Coming back to Figure 1, while the market equilibrium outcome corresponds to the case $\delta = 0$, we investigate whether existing environmental policy tools can achieve the efficient mix corresponding to $\delta > \frac{r_i}{\nu} - c$. We successively consider a price and a quantity instrument:

- A feed-in tariff (FIT) paid to the production from 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.

In order to 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 firm enters or exits 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 Feed-in tariffs and price premium

Under feed-in premiums (FIP), green producers receive a fixed reward on top of the wholesale price. Hereafter, we rather focus on feed-in tariffs (FIT), a system where public authorities commit to purchasing wind power at a given price p^i per kilowatt hour, which is higher than the wholesale market price. FIT p^i is financed by a tax on electricity consumption that we will denote as t per kilowatt hour. 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.

4.1.1 The mechanism

Although the FIT is set out of electricity markets, its introduction in an industry with thermal power impacts electricity prices. First, by making production contingent to the state of nature, 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 price gained by electricity retailers 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 $(1-\nu)\,p^{\bar{w}}K_f + \nu p^w q_f^w + \nu p^i q_w^i$. Given that i) electricity consumption is equal to the thermal power capacity $q = K_f$ whatever the state 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 $(p+t)\,K_f \geq (1-\nu)\,p^{\bar{w}}K_f + \nu p^w\,(K_f - K_i) + \nu p^i K_i$ or, using the retail price formula $p = \nu p^w + (1-\nu)\,p^{\bar{w}}$,

$$tK_f \geq \nu(p^i - p^w)K_i. \tag{7}$$

The FIT system is sustainable when (7) 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 to 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 $(p+t^\rho)\,K_f \geq (1-\nu)\,p^{\bar{w}}K_f + \nu p^w\,(K_f - K_i) + \nu\,(p^w + \rho)\,K_i$. Therefore the tax t^ρ on electricity that finances ρ must satisfy the financial constraint $t^\rho K_f \geq \nu\rho K_i$.

4.1.2 First-best implementation

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 examined in Appendix C. Compared to the unregulated outcome with only thermal power, i.e. case (a) in Proposition 1 with $\delta = 0$, 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 $K_i = \bar{K}F(\nu(c + \delta))$ if it is set at the threshold marginal equipment cost $p^i = c + \delta$. 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 consumed should be equal to the environmental damage, $t = \delta$.

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 balancing constraint (7) holds as a strict inequality. We see that first-best is implemented with a budget surplus for the government.

Suppose the FIT is tailored to foster efficient investment in renewables $p^i = c + \delta$, while the tax on electricity consumption is set to just balance the budget constraint. Binding (7) with $p^i = c + \delta$ leads to $t = \frac{\nu K_i}{K_f}\delta < \delta$: 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.

It is easy to show that FIP leads to similar conclusions. The subsidy ρ should cover the gap between the efficient price of electricity in state w, which is $\tilde{r}_i/\nu = c + \delta$ 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 2 *A FIT or FIP should be set independently of the tax on electricity consumption to implement first-best. If the tax is fixed in order to just finance the FIT or FIP, then it is too low and, therefore, thermal power generation and pollution are larger than first-best.*

Without the carbon tax, two instruments are required to implement first-best: the FIT or FIP 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.

4.2 Renewable portfolio standard

4.2.1 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 K_f that must be supplied with an intermittent source of energy K_i, that is $\alpha = \dfrac{K_i}{K_f}$. 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:

$$p^w + g = \frac{\tilde{r}_i}{\nu}, \tag{8}$$

$$p = \nu \left(p^w + \frac{K_i}{K_f} g \right) + (1-\nu) p^{\bar{w}}. \tag{9}$$

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 (8). Retailers pass on the additional cost of producing electricity from renewable energy to consumers by increasing electricity prices by $\nu \frac{K_i}{K_f} g = \nu\alpha g$.

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 (8) and (9) yields:

$$g = \frac{\tilde{r}_i}{\nu} - c, \tag{10}$$

$$p = c + r_f + \nu\alpha \left(\frac{\tilde{r}_i}{\nu} - c \right). \tag{11}$$

According to condition (10), 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 (11) 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.

4.2.2 First-best implementation

We now turn to the decentralization of the first-best energy mix with RPS. Starting from an unregulated economy described in 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 $K_i = \bar{K}F(\nu(c+\delta))$. It should also reduce electricity consumption to $K_f = D(c+r_f+\delta)$. Hereafter we show that the two goals cannot be met by only using a RPS. Indeed to obtain $K_i = \bar{K}F(\nu(c+\delta))$, the cost of the less productive windmill should be $\tilde{r}_i = \nu(c+\delta)$ which, combined with (10), gives the unit price of REC, $g = \delta$, i.e., it should be equal to the social 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 (11) 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, equivalently, a tax on electricity consumption set at the level $t = \delta(1-\alpha)$. 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 D shows that first-best cannot be achieved with RPS for case (c) in Proposition 1.

Proposition 3 *The RPS alone cannot implement the first-best. It should be complemented by another instrument that influences investment in thermal power or electricity consumption.*

Controlling the share of renewables $\frac{\nu K_i}{K_f}$ in the energy mix is not enough to implement first-best. Even if it is targeted at the first-best share, fossil fuel remains the cheapest source of energy in the market, which induces too much thermal power investment K_f and, thus, too much electricity consumption and pollution. One need to control either investment in thermal power or, equivalently, electricity consumption to implement the optimal K_f. Any taxation that reduces fossil fuel use, investment in thermal power or electricity consumption would do the job.

5 Technological solutions to intermittency

We now investigate two technological solutions to cope with intermittency in energy supply: storage and demand-response.[15] We begin with energy storage, a technology strongly pushed by some car manufacturers. Then we consider demand response, i.e. the possibility that electricity consumers could react to spot prices, a long-dreamed solution now permitted by the development of ICT applied to energy consumption

5.1 Energy storage

5.1.1 The technology

A natural technological solution to accommodate the intermittency of renewable sources is to store the energy they produce. Car manufacturers invest massively in the design of more performing batteries, which could help to develop big fixed batteries installed in basement or farms of batteries able to absorb the variations in wind and solar inflows. The most efficient large-scale technology is pumped storage, an indirect storage method consisting in filling up water reservoirs that supply hydropower plants. A fraction of the electricity produced 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.[16] Formally, storage allows some kilowatt-hours of electricity to be transferred from one state of nature to the other. In our framework, it will be from state w where production is cheap to state $\bar{w}$ where it is costly. This requires investment (dams and hydropower plants, batteries, boilers for heat storage, and so on) and it consumes energy, whatever its source.[17]

Storage is a dynamic process whereas the model we use in this paper is static. However, we

[15]There are other solutions that we do not examine here. One consists of multiple plants producing from intermittent sources that are negatively correlated, for example PV pannels and wind turbines if the wind begins to blow at sunset. This possibility is examined in Ambec and Crampes (2012). Imports from and exports to interconnected regions fall unser the same principle. Another is non-price rationing protocols. On the normative analysis of blackouts, see Joskow and Tirole (2007). One can also consider prosuming: if we install electricity generators (in particular PV panels) at the consumption location, the demand function becomes dependent on the states of nature that determine production.

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

[17]See the website of eco2mix for figures on pumped energy in France: http://www.rte-france.com/en/eco2mix/eco2mix-mix-energetique-en.

can obtain enlightening results by reframing our framework as follows: electricity consumption is defined for a unit of time equal to a cycle of energy storage/release rather than for one hour. For example, in the case of solar power from PV panels, energy is stored during daytime and released during the night. Therefore the unit of time for consumption is the day (24 hours).[18] The parameters ν and $(1-\nu)$ are observed frequencies (rather than probabilities) of states w and $\bar{w}$ respectively. Let s^{w} be the power used to store energy in kilowatts in state w, i.e. during daytime. It is constant in all occurences of state w. The storage facility leads to $s^{\bar{w}}$ more power supplied in state $\bar{w}$, i.e. during night. With energy storage, the non-reactivity constraint (1) becomes

$$K_i + q_f^w - s^w = K_f + s^{\bar{w}} \tag{12}$$

The relationship between these two flows and between them and the storage capacity depends on the type of storage technology. We choose to measure the storage capacity K_s in terms of saved energy (inflow).[19] Then we have that

$$\nu s^w \leq K_s$$

A fraction $1-\lambda$ of the energy injected into the storage plant is lost[20], so that outflow and inflow are related by

$$(1-\nu)\, s^{\overline{w}} \leq \lambda \nu s^w$$

Since there is no randomness in the storage activity and building a storage plant is costly, it would be inefficient to install an oversized plant and to waste the energy stored. Therefore, we can set that so that the three variables K_s, s^w and $s^{\bar{w}}$ are linked by:

$$\lambda^{-1}(1-\nu)\, s^{\bar{w}} = \nu s^w = K_s \tag{13}$$

Substituting (13) in (12), leads to the non-reactivity constraint:

$$K_i + q_f^w - \frac{K_s}{\nu} = K_f + \frac{\lambda K_s}{1-\nu} \tag{14}$$

[18]The length of the cycle varies with weather conditions and forecasts. For wind power, it is a matter of weeks or even seasons.

[19]Alternatively, capacity could be measured in terms of energy for final consumption (outflow), i.e. after substracting energy losses.

[20]For pumped storage, $\lambda \simeq .75$. More general assumptions on storage costs could be considered, e.g. convex (quadratic) costs. We make the linear assumption to be able to pin down easily the benefit and cost of storage.

Multiplying the left-hand side by ν and the right-hand side by $1-\nu$, then summing the two terms, we obtain the total quantity available for consumption: $\nu\left(K_i+q_f^w\right)+(1-\nu)\,K_f-(1-\lambda)\,K_s$. This clearly shows that storage is a costly activity on physical grounds. It makes sense on economic grounds because it allows to transfer energy from low-value to high-value states of nature.

5.1.2 Social value of storage

Hereafter, we derive the marginal social benefit and cost of storing energy. We compare it to the private marginal benefit and costs in a market economy with a carbon tax. Using (14), the expected social welfare when capacity K_s is installed is:

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

Let us define the Lagrange function as in Appendix A after modifying for the above expected social welfare and non-reactivity constraint and assume an interior solution for storage: $K_s>0$.[21] If we denote by $S^{'}(.)$ the common value $S^{'}\left(\bar{K}F(\tilde{r}_i)+q_f^w-\frac{K_s}{\nu}\right)=S^{'}(K_f+\frac{\lambda K_s}{(1-\nu)})$, the first-order conditions with respect to K_f, $\tilde{r}_i$ and K_s are, respectively:

$$K_f:(1-\nu)\left[S'(.)-(c+\delta)\right]-r_f-\nu\gamma=0 \tag{15}$$

$$\tilde{r}_i:\nu S'(.)+\nu\gamma-\tilde{r}_i=0 \tag{16}$$

$$K_s:-S^{'}(.)\,(1-\lambda)-\gamma\left(1+\frac{\lambda\nu}{1-\nu}\right)=r_s \tag{17}$$

where γ is the Lagrange multiplier associated with the non-reactivity constraint (14).

First, it is easy to show that we cannot have $q_f^w>0$ if $K_s>0$: thermal power plants are never running when intermittent energy is active and partially stored. To see that, observe that the first-order condition with respect to q_f^w for an interior solution is $S^{'}(.)+\gamma=c+\delta$. It is not compatible with the above three first-order conditions because we have only three unknowns that are the marginal surplus $S^{'}(.)$, the Lagrange multiplier γ and the marginal

[21] Positive storage capacity obviously implies an interior solution for the intermittent source of energy: $K_i>0$.

cost of intermittency $\tilde{r}_i$. Therefore, except for very specific values of the coefficients λ, r_s, r_f, c and δ that would allow to eliminate one redundant equation, the system of four equations with three unknown parameters has no solution. Practically, it means that $q_f^w = 0$ if $K_s > 0$. This is quite intuitive: to consume one kWh in state $\bar{w}$, if it is produced from the fossil-fueled plant in state $\bar{w}$ its operating cost is $c+\delta$ instead of $\lambda^{-1}(c+\delta)$ if it comes from the same plant used in state w and transfered to state $\bar{w}$ by storage. Since the thermal plant is available in the two states of nature under totally identical conditions, it is inefficient to combine it with storage. If energy has to be stored, it must be from intermittent sources. Formally, it implies that case (b) of Proposition 1 disappears in the optimal energy mix.[22]

Second, using (16) to substitute γ into (17) and (15) defines two expressions for $S'(.)$, which combined lead to:

$$c + \delta + \frac{r_f}{1-\nu} = \lambda^{-1}\left(r_s + \frac{\tilde{r}_i}{\nu}\right) \tag{18}$$

that is the equality between social benefits and social costs of storage. The left-hand side of (18) is the social benefit of substituting fossil-fueled electricity is state $\bar{w}$ with wind or solar power produced and stored in state w. It allows to save the long term social cost of one kilowatt of thermal power, which includes the cost of energy c, the cost of capacity $r_f/(1-\nu)$ and the social cost of carbon δ. On the right-hand side, one kilowatt transferred to state $\bar{w}$ requires λ^{-1} kilowatts to be produced (at cost $\tilde{r}_i/\nu$) and stored (at cost r_s) in state w.

Before examining the private incentives to invest in energy storage devices, it is worth to notice that condition (18) emphasizes the complementarity between PV panels (or wind turbines) and storage capacity. A less expensive storage facility increases investment in renewables: any decrease in r_s pushes $\tilde{r}_i$ up and thus increases K_i. Similarly, a more efficient energy storage technology increases λ which also pushes $\tilde{r}_i$ up. Hence a more competitive storage technology foster investment in renewables by making this source of energy more attractive.

Note also that if the costs of the thermal plant are very high and the costs of the storage technology very low in a region with cheap and frequent intermittent energy, the thermal technology can be pushed out of the industry. Specifically, given (18) to determine the size of the intermittent plants $K_i = \bar{K}F(\tilde{r}_i)$, injecting (17) into (15), we have that $K_f = 0$ if

[22] Remember that the demand function does not depend on the state of nature. In many countries with pumped storage facilities, pumping occurs at night using thermal or nuclear energy because demand is low at night. This is the case examined in Crampes and Moreaux (2010).

$$S^{'}\left(K_i - \frac{K_s}{\nu}\right) = S^{'}\left(\frac{\lambda K_s}{(1-\nu)}\right) \leq \left(c + \delta + \frac{r_f}{(1-\nu)}\right)((1-\nu) + \lambda\nu) - \nu r_s. \tag{19}$$

From the non-reactivity constraint (12) where $q_f^w = K_f = 0$, with a storage facility of size $K_s = K_i \frac{\nu(1-\nu)}{1-\nu+\nu\lambda}$ there is no operating cost nor polluting emissions, only building costs.

5.1.3 Private incentives

What are the private incentives to invest in storage facilities? A firm involved in energy storage buys electricity during day time (in state w) and sells at night (in state $\bar{w}$). In order to sell 1kWday at price $p^{\bar{w}} = c + \delta + \frac{r_f}{1-\nu}$ in state $\bar{w}$, the firm must invest $r_s \lambda^{-1}$ (in terms of outflow) and buy λ^{-1} kilowatts-day at price $p^w = \frac{\tilde{r}_i}{\nu}$.[23] These are the prices in case (c) of Proposition 1. The profit of storage operators per kilowatt-day is

$$p^{\bar{w}} - \lambda^{-1}(r_s + p^w) = c + \delta + \frac{r_f}{1-\nu} - \lambda^{-1}\left(\frac{\tilde{r}_i}{\nu} + r_s\right)$$

Competitions among storage operators pushes the above profit down to zero, which leads to the efficiency condition (18). Hence, private and social interests in operating the storage facility are aligned.

Notice that the storage parameters λ and r_s do not explicitly appear as arguments of the competitive prices p^w and $p^{\bar{w}}$. Actually, storage is a technology for electricity transfer, not for production. Nevertheless, as we can see in (18), the storage possibility increases $\tilde{r}_i$, the marginal investment cost of the intermittent source. Consequently, $p^w = \tilde{r}_i/\nu$ is impacted by storage because $\tilde{r}_i$ increases when storage is introduced. It is an additional (indirect) demand in state w.

To sum up our results, we can state the following.

Proposition 4 *Competitive energy storage increases investment into intermittent renewables. It allows to cut on thermal power capacity and to save greenhouse gas emissions. Thermal power plants are never active when renewables are producing and energy is stored. The private and social incentives to invest in energy storage are aligned when carbon emissions are taxed efficiently.*

[23] Alternatively, the firm is buying λ^{-1}/ν kilowatts during the fraction ν of day time at price p^w so that the purchase price per day is $\nu p^w \times \lambda^{-1}/\nu = p^w \lambda^{-1}$.

5.2 Demand response

Another technological solution to cope with energy intermittency consists in equipping consumers with smart meters and demand response switches to make them reactive to variations in electricity prices. This allows for a better match between electricity consumption and supply, and thereby, avoids the need to back-up windmills with thermal power facilities or storage capacity. Reactive consumers are charged the wholesale electricity price and they are able to adapt their consumption to fluctuating prices in real-time or using automatic switching devices. Such devices are still costly to install, maintain and operate. But thanks to the development of ICT, their costs will progressively be offset by the benefit of making consumers reactive, as it is already the case for big consumers.

We first determine what the energy mix would be if a given proportion of consumers were price reactive. Then we analyze the effects of a policy aimed at increasing the number of the price sensitive consumers.

5.2.1 Optimal energy mix with reactive consumers

We generalize our analysis of the efficient energy mix by assuming that a proportion β of consumers react to price variations in the electricity wholesale market ($1 > \beta > 0$). 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".

As before, several variables are straightforwardly found: $q_i^{\bar{w}} = 0$, $q_f^{\bar{w}} = K_f$ and $q_i^w = K_i = \bar{K}F(\tilde{r}_i)$ where $\tilde{r}_i \geq \underline{r}_i$.

The remaining variables K_f, $\tilde{r}_i$, q_f^w, q_r^w, $q_r^{\bar{w}}$ and $q_{\bar{r}}$ are chosen to maximize the expected social surplus:

$$\beta[\nu S(q_r^w) + (1-\nu)S(q_r^{\bar{w}})] + (1-\beta)S(q_{\bar{r}}) - \nu(c+\delta)q_f^w \\ -(1-\nu)(c+\delta)K_f - \bar{K}\int_{\underline{r}_i}^{\tilde{r}_i} r_i dF(r_i) - r_f K_f. \tag{20}$$

subject to the constraints:

$$\begin{aligned} K_f &= \beta q_r^{\bar{w}} + (1-\beta) q_{\bar{r}} && (21) \\ \bar{K} F(\tilde{r}_i) + q_f^w &= \beta q_r^w + (1-\beta) q_{\bar{r}} && (22) \\ q_f^w &\geq 0 && (23) \\ q_f^w &\leq K_f && (24) \\ \tilde{r}_i &\geq \underline{r}_i && (25) \end{aligned}$$

The two first constraints (21) and (22) are the market clearing conditions in states of nature $\bar{w}$ and w respectively. Each condition equalizes electricity supply with demand from both types of consumers. The three remaining constraints are the same as in Section 3.

The solution to this problem is detailed in Appendix E. Like in the no-demand response case (Proposition 1), the solution varies with the parameter values, but in a more complex way. Let $\delta_1(\beta)$ denote the solution to

$$\beta \left[D(c+\delta_1) - D\left(c + \delta_1 + \frac{r_f}{1-\nu} \right) \right] = \bar{K} F(\nu(c+\delta_1)),$$

and $\delta_2(\beta)$ the solution to

$$\beta D(c+\delta_2) + (1-\beta) D(c+\delta_2+r_f) = \bar{K} F(\nu(c+\delta_2)).$$

The first equation corresponds to the implicit function $q_f^w = K_f$. It separates the solution where the fossil technology is used at full scale in state w (an outcome that did not occur in Proposition 1) and the solution with partial use. The second equation is given by $q_f^w = 0$. It separates the solution where the fossil technology is used in state w and the solution where all production comes from the intermittent technology. The threshold $\delta_2(\beta)$ generalizes δ^0 defined in (5) to the case $\beta > 0$: $\delta^0 = \delta_2(0)$.

Solving the above program and characterizing the equilibrium prices in the wholesale and retailing markets, we obtain the following proposition.[24] The proof is in Appendix E.

Proposition 5 *The optimal levels of capacity, output and price are such that:*

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

$K_i = 0,\ K_f = q_f^w = D(p)$

[24] As shown in Appendix E, Proposition 5 is valid if ν is below a critical value $\widehat{\nu}$. Otherwise, case *b.2* vanishes for large values of β.

$p = p^w = p^{\bar{w}} = c + r_f + \delta$

(b) for $\frac{r_i}{\nu} - (c + r_f) \leq \delta \leq \delta_2(\beta)$*: both sources of energy are used in state w*

(b.1) for $\frac{r_i}{\nu} - (c + r_f) \leq \delta \leq \delta_1(\beta)$*: thermal power used at full capacity in state w*

$K_i = \bar{K}F(\nu p^w)$, $K_f = \beta D(p^{\bar{w}}) + (1-\beta)D(p)$, $q_f^w = K_f$

$p^w = \frac{\tilde{r}_i}{\nu}$, $p^{\bar{w}} = \dfrac{c + \delta + r_f - \tilde{r}_i}{1-\nu}$, $p = c + r_f + \delta$

with $\tilde{r}_i$ *given by* $\bar{K}F(\tilde{r}_i) = \beta\left[D\left(\frac{\tilde{r}_i}{\nu}\right) - D\left(\dfrac{c + \delta + r_f - \tilde{r}_i}{1-\nu}\right)\right]$

(b.2) for $\delta_1(\beta) \leq \delta \leq \delta_2(\beta)$*: thermal power is used below capacity in state w*

$K_i = \bar{K}F(\nu p^w)$, $K_f = \beta D(p^{\bar{w}}) + (1-\beta)D(p)$, $q_f^w = K_f - K_i > 0$

$p^w = c + \delta = \frac{\tilde{r}_i}{\nu}$, $p^{\bar{w}} = c + \delta + \dfrac{r_f}{1-\nu}$, $p = c + r_f + \delta$

(c) for $\delta_2(\beta) < \delta$*: only intermittent energy is used in state w*

$K_i = \bar{K}F(\nu p^w)$, $K_f = \beta D(p^{\bar{w}}) + (1-\beta)D(p)$, $q_f^w = 0$

$p^w = \frac{\tilde{r}_i}{\nu}$, $p^{\bar{w}} = c + \dfrac{r_f}{1-\nu} + \delta$, $p = \tilde{r}_i + (1-\nu)(c+\delta) + r_f$

with $\tilde{r}_i$ *given by* $\bar{K}F(\tilde{r}_i) = \beta D\left(\frac{\tilde{r}_i}{\nu}\right) + (1-\beta)D\left((1-\nu)(c+\delta) + r_f + \tilde{r}_i\right)$.

Proposition 5 is illustrated in Figure 3.

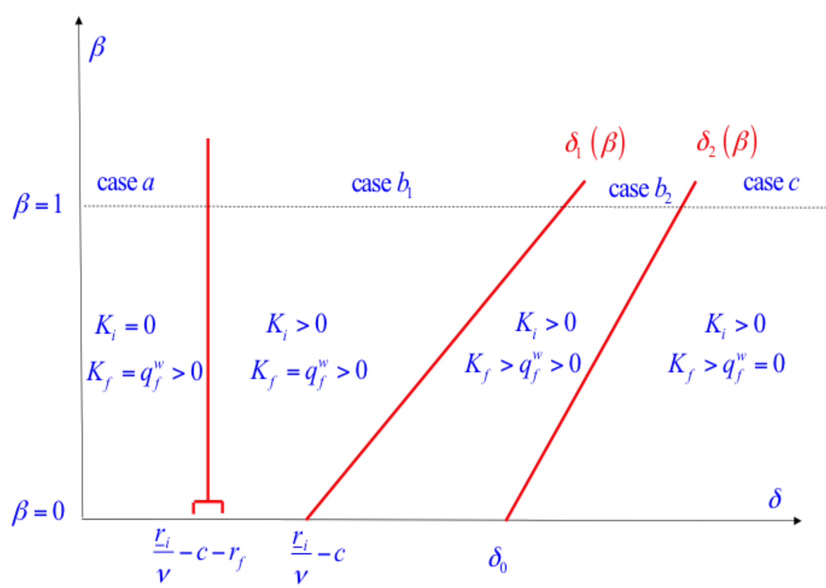

Figure 3: Different types of optimal energy mix with reactive consumers

Comparing Propositions 1 and 5, we can explain how reactive consumers modify the energy mix and market prices. First, their presence induces a new zone in the energy mix in which thermal power plants are running at full capacity in both states of natures w and $\bar{w}$: case $b.1$. With only non-reactive consumers, the non-reactive constraint that maintains the equality between the two states of nature $q_f^w + K_i = K_f$ obliges to decrease fossil fuel in state w, namely q_f^w, when introducing wind production K_i. As a consequence, the thermal power plants were thus running below capacity in state w: $q_f^w < K_f$. In contrast, with reactive consumers, thermal power plants can be used under full capacity in both states of natures, then including during windy days.

Second, introducing some reactive consumers changes the threshold social value of carbon above which wind power becomes socially beneficial: this threshold was $\underline{r}_i/\nu - c$ for $\beta = 0$. The reason was that thermal power plants where used below full capacity in state w when windmills are active (in case b of Proposition 1). Therefore the opportunity benefit to take into consideration was only the *operating cost* of fossil plants $c + \delta$. With flexible consumers ($\beta > 0$) the threshold becomes $\frac{\underline{r}_i}{\nu} - (c + r_f)$. That results in the emergence of the new zone (case *b.1*) where the thermal power plants are fully used in state w. The trade-off is between more capacity of the intermittent source and more *capacity* of the fossil source. Therefore the opportunity benefit is the full cost of the fossil technology $c + \delta + r_f$. Indeed there is a discontinuity in the threshold from $\beta = 0$ to $\beta > 0$.[25]

Third, reactive consumers affect the threshold social value of carbon $\delta_2(\beta)$ for which wind power capacity is sufficient to supply demand during windy days (case c). It also modifies investment in both sources of energy K_f and K_i.

Note that, since reactive consumers respond to state-dependent prices p^w and $p^{\bar{w}}$ instead of retail price p, their consumption is state-dependent. They indeed consume less than the non-reactive consumers when the price is higher (in state $\bar{w}$) and more when the price in lower (in state w). They substitute consumption across states of nature: consumption from reactive consumers is $q_r^w = \beta D(p^w)$ and $q_r^{\bar{w}} = \beta D(p^{\bar{w}})$ in states w and $\bar{w}$ respectively, while non-reactive consumers are consuming $q_{\bar{r}} = (1-\beta)D(p)$ kilowatts per hour is both states of nature. Such adaptation of prices from reactive consumers facing temporary price increased has been documented empirically by Jessoe and Rapson (2014).[26]

[25] This discontinuity confirms that the introduction of reactive consumers cannot be analyzed by just increasing ν (i.e. being able to use use wind power more often) in the case of non-reactive consumers only.

[26] Jessoe and Rapson (2014) found that households who are able to view in real time the quantity of power

How much reactive consumers' total consumption $\nu q_r^w + (1-\nu) q_r^{\bar{w}}$ compares with the one of the non-reactive consumers $q_{\bar{r}}$ depends on the curvature of the demand function $D(p)$. They consume the same if the demand function is linear. However, reactive consumers consume less than non-reactive ones if $D(p)$ is concave and more if it is convex.

5.2.2 Increasing the number of reactive consumers

We evaluate the marginal social benefit of making consumers reactive by differentiating the expected social welfare defined in (20) with respect to the share of reactive consumers β. Using the market-clearing conditions (21) and (22) and the envelop theorem, we show in Appendix F that the marginal expected social surplus due to an increase in β is given by:

$$[\nu S(q_r^w) + (1-\nu) S(q_r^{\bar{w}}) - S(q_{\bar{r}})] + [(1-\nu)(c+\delta) + r_f](q_{\bar{r}} - q_r^{\bar{w}}) - \tilde{r}_i (q_r^w - q_{\bar{r}}). \qquad (26)$$

The first term into brackets in (26) is the variation in expected surplus or utility from making consumers reactive. As shown in Appendix F, if the demand function is concave or linear, and even if it is not "too convex",[27] $S(q_{\bar{r}}) > \nu S(q_r^w) + (1-\nu) S(q_r^{\bar{w}})$ where $q_{\bar{r}} = D(p)$, $q_r^w = D(p^w)$, and $q_r^{\bar{w}} = D(p^{\bar{w}})$ with $p = \nu p^w + (1-\nu) p^{\bar{w}}$. Therefore the first term into brackets in (26) is negative. Switching from a constant price to state-contingent prices reduces welfare as it obliges consumers to modify their consumption of electricity across time depending on the states of nature. They prefer a constant price p which is the average of climate dependent prices p^w and $p^{\bar{w}}$ because, with a concave S, they are adverse to state-dependent consumption. The stronger the coefficient of risk aversion, the greater this utility loss.[28]

The second term in (26) 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 emitting less pollutants.

being consumed via an in-home display reduce their consumption during the window of price increase which lasts 2 or 4 hours. They also increase their consumption just after this period compared to the household with fix price contract.

[27]Intuitively, a very convex demand means a huge variation of price-elasticity along the curve. At the limit, demand is inelastic for high price $p^{\bar{w}}$ and very elastic for low price p^w. Such a consumer would benefit a lot from the reduction of the price of electricity from thermal powered plants $p^{\bar{w}}$ without being hurt too much from a higher price of wind power with the installation of more windmills.

[28]Notice that $S(q_r^w) + (1-\nu) S(q_r^{\bar{w}}) - S(q_{\bar{r}}) < 0$ cannot be directly infered from the concavity of $S(.)$ because $q_{\bar{r}} \neq \nu q_r^w + (1-\nu) q_r^{\bar{w}}$, except if the demand function is linear.

The third term in (26) is the extra cost on wind power due to reactive consumers' higher demand in state w. Consumption in state w is increased by $q_r^w - q_{\bar{r}}$, of which the marginal cost is $\tilde{r}_i$.

With negative and positive terms, the sign of (26) seems ambiguous. To be able to sign (26), remark that by replacing marginal costs by prices from Proposition 5, we can express (26) as a variation of consumers' net expected welfare:

$$\nu \left(S(q_r^w) - p^w q_r^w\right) + (1-\nu)\left(S(q_r^{\bar{w}}) - p^{\bar{w}} q_r^{\bar{w}}\right) - \left(S(q_{\bar{r}}) - p q_{\bar{r}}\right). \tag{27}$$

As shown in Appendix F, the net social surplus $S(D(p)) - pD(p)$ turns out to be a convex function of the power price p. It means that the social surplus is higher with state-contingent prices p^w and $p^{\bar{w}}$ than with the average of those price p. Hence, (27) is negative. We summarize our findings in the following proposition.

Proposition 6 *Demand response increases consumers' welfare by reducing the use of fossil-fueled electricity. The social cost saved exceeds the loss of welfare due to price volatility and increased wind power capacity.*

We conclude our study of demand response as a solution to intermittence with two remarks.

First, so far we have ignored the cost of installing smart meters and consumption appliances. Such cost should be compared with the aforementioned benefit of increasing demand response. In Appendix F, we show that the expected marginal social welfare (27) is generally decreasing with the share of reactive consumers β. It implies that, with a constant marginal cost of increasing β, we end up with an interior solution: not all consumers should be equipped with smart meters. It might be surprising in our model as consumers are homogenous. Despite having same demand for electricity, some consumers should be equipped and others should not.

Second, our results are determined at the margin. However, changes of public policies such as massive deployment of smart appliances and meters or the taxation of carbon might be not just marginal. Large variations in β and δ can have unexpected consequences due to switches from one energy mix to another one. For example, referring to Figure 3, assume we are in zone b.1. with the use of thermal power plants at full capacity even when the windmills are spinning. First, a drastic increase of the carbon tax δ might drive the energy mix into zone b.2. where thermal power plant are now used below capacity during windy days. If then price responsiveness is strongly encouraged with a big push on β, we can be driven back into the energy mix of type $b.1$: the thermal power plants are running again at full capacity during windy days.

6 Conclusion

Climate change mitigation requires the replacement of fossil-fuel energy with renewables such as wind power. It has been fostered through diverse policies implemented world-wide, from carbon tax to feed-in tariffs and renewable portfolio standards. The intermittent nature of renewables, coupled with the lack of responsiveness 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 substitutes in all states of nature. 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.

Technological innovations provide solutions to the intermittency of renewable sources of energy. Our model allows to identify the social value of those technological solutions. Energy storage, in batteries or by pumping water into upstream reservoirs, reduces the burden of intermittency. 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 which force them to adjust their consumption across time. Such risk exposure effects should be incorporated into the cost-benefit analysis of installing smart meters.[29]

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 can be spread out in different regions to take advantage of diverse weather conditions and thus increase the number of days with significant wind 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, Ambec and Crampes (2012) have shown 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 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 or complemented with storage and demand response.

Another question the model can address is the design of retailing contracts with state contingent prices or curtailment.[30] 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.[31] 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 when the energy mix includes intermittent sources of energy is beyond the scope of the present paper. It has been left for future research.

[29] This effect is in line with the empirical finding by Qiu et al. (2017) that risk-averse consumers are less likely to enroll into time-of-use electricity pricing programs in the U.S.

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

[31] This refusal of time-varying prices is quite common in electricity retail markets where competition authorities unsuccessfully try to enforce more price flexibility in the demand side (Crampes and Waddams, 2017).

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

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

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:

$$q_f^w : \nu\left[S'(\bar{K}F(\widetilde{r}_i)+q_f^w)-(c+\delta)+\underline{\mu}_f-\bar{\mu}_f+\gamma\right]=0 \tag{28}$$

$$K_f : \nu(\bar{\mu}_f-\gamma)+(1-\nu)\left[S'(K_f)-(c+\delta)\right]-r_f=0 \tag{29}$$

$$\tilde{r}_i : \nu\left[S'(\bar{K}F(\tilde{r}_i)+q_f^w)+\underline{\mu}_i^{'}+\gamma\right]-\tilde{r}_i=0 \tag{30}$$

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 (28) and (30) yields:

$$\frac{\tilde{r}_i}{\nu}=\overline{\mu}_f+\underline{\mu}_i^{'}-\underline{\mu}_f+c+\delta. \tag{31}$$

• First, without intermittent energy (case a), $\tilde{r}_i=\underline{r}_i$ and $\underline{\mu}_i^{'}\geq 0$. Moreover, since $\bar{K}F(\tilde{r}_i)=0$, the non-reactivity condition (1) implies $q_f^w=K_f>0$ and therefore $\underline{\mu}_f=0$ and $\bar{\mu}_f\geq 0$. Hence, condition (31) implies

$$\frac{\tilde{r}_i}{\nu}\geq c+\delta. \tag{32}$$

Substituting $q_f^w=K_f$ and $\bar{K}F(\widetilde{r}_i)=0$ into (28) yields $\overline{\mu}_f-\gamma=S'(K_f)-(c+\delta)$ which, combined with (29), leads to $K_f=S'^{-1}(c+\delta+r_f)=D(c+\delta+r_f)$ where the last equality is due to the definition of $D(.)$.

• Second, with investment in intermittent energy (cases b and c), we have $\tilde{r}_i>\underline{r}_i$ and $\underline{\mu}_i^{'}=0$. Since $\bar{K}F(\tilde{r}_i)>0$ and $q_f^w=K_f-K_i$ by the non-reactivity constraint (1), then $q_f^w<K_f$ and therefore $\bar{\mu}_f=0$. Thus (31) becomes

$$\frac{\widetilde{r}_i}{\nu}=-\underline{\mu}_f+c+\delta. \tag{33}$$

• Suppose first that $q_f^w > 0$ (case b). Then $\underline{\mu}_f = 0$ in (33) so that the threshold intermittent energy cost $\widetilde{r_i}$ is defined by $\widetilde{r_i}^b = \nu(c+\delta)$. Combined with (4), it defines the minimal damage δ for which investing in renewables is efficient: $\delta \geq \frac{r_i}{\nu} - c$.

Combining (28), (29) and the non-reactivity constraint (1) yields the installed capacity of fossil energy $K_f = K_i + q_f^w = S'^{-1}(c+\delta+r_f) = D(c+\delta+r_f)$as well as the production of fossil energy in state w, $q_f^w = K_f - K_i = D(c+\delta+r_f) - \bar{K}F\left(\tilde{r_i}^b\right) = D(c+\delta+r_f) - \bar{K}F(\nu(c+\delta))$, where the last equality is due to the definition of $\tilde{r}_i^b$.

Let $\Delta_0(\delta) \equiv D(c+\delta+r_f) - \bar{K}F(\nu(c+\delta)) > 0$.Since $\Delta_0^{'}(\delta) < 0$ and $\Delta_0(0) = D(c+r_f) > 0$,we have that $\Delta_0(\delta) > 0$ for every $\delta < \delta^0$, where $\delta^0$is uniquely defined by $\Delta(\delta^0) = 0$which is condition (5) in the text. Hence $q_f^w > 0$for $\delta < \delta^0$.

•Suppose now that $q_f^w = 0$(case c), which means that $\delta \geq \delta^0$. Then $\underline{\mu}_f \geq 0$ and (33) implies $\frac{\tilde{r}_i}{\nu} \leq c+\delta$.Furthermore (1), (28), (29), and (33) imply:

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

with $K_i = \bar{K}F(\tilde{r}_i) = K_f$. It leads to $\bar{K}F\left(\tilde{r_i}^0\right) = K_f = D\left((1-\nu)(c+\delta) + \tilde{r_i}^0 + r_f\right)$ which determines both K_f and $\tilde{r_i}^0$, the latter being a fixed point in the relationship.

Equilibrium prices p, p^w and $p^{\bar{w}}$ are now determined by the producers' and retailers' supply functions and zero-profit conditions, as well as by demand by retailers and consumers.

• 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 δ per kilowatt-hour) $p^w = p^{\overline{w}} = c + r_f + \delta$. 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 $K_f = D(c+\tau+r_f)$.

• Case (b): When wind and thermal power plants are running 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. The zero-profit condition for the less efficient wind power producer with capacity cost denoted by $\tilde{r}_i$ writes $\nu p^w - \tilde{r}_i = 0$ per kilowatt-hour produced. Thermal power are operating below capacity if the return per kilowatt-hour p^w compensates the cost $c+\delta$ (operating cost plus the carbon tax). Hence the zero-profit conditions for both types of producers in state w lead an equilibrium price of:

$$p^w = \frac{\tilde{r}_i}{\nu} = c + \delta$$

Given p^w, the zero-profit condition for thermal power producers in expectation yields:

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

Lastly, the zero-profit condition for electricity retailers leads to:

$$p = \nu p^w + (1-\nu)p^{\overline{w}} = c + r_f + \delta. \tag{34}$$

Given the threshold cost of windmills entering the industry $\tilde{r}_i = \nu(c+\delta)$, investment in wind power is $K_i = \bar{K}F(\nu(c+\delta))$. Investment in thermal power adjusts to demand $D(p)$ with retail prices defined in (34), which yields $K_f = D(c+\tau+r_f)$. It shows that, as δ increases, investment in wind power K_i also increases, whereas thermal power capacity K_f decreases.[32]

• Case (c): When only wind power is used in state w, the zero-profit condition for the less efficient windmill $\tilde{r}_i^0$ per kilowatt-hour yields:

$$p^w = \frac{\tilde{r}_i}{\nu}. \tag{35}$$

Thermal power producers are producing only in state $\bar{w}$. Their zero-profit condition per kilowatt-hour writes $(1-\nu)p^{\bar{w}} = (1-\nu)(c+\delta) + r_f$ leads to:

$$p^{\bar{w}} = c + \delta + \frac{r_f}{1-\nu}. \tag{36}$$

The zero-profit condition per kilowatt-hour for electricity retailers $p = \nu p^w + (1-\nu)p^{\bar{w}}$ with wholesale electricity prices p^w and $p^{\bar{w}}$ defined in (35) and (36) respectively yields a retail price of:

$$p = \tilde{r}_i + (1-\nu)(c+\delta) + r_f$$

Investment in both source of energy are driver by the above retail price: $K_i = K_f = D(p) = D(\tilde{r}_i + (1-\nu)(c+\delta) + r_f)$ which defines $\tilde{r}_i = \tilde{r}_i^0$. Both investments K_i and K_F decrease when δ increases.

[32]Formally, by differentiating wind and thermal power capacities with respect to δ, we obtain $\frac{dK_i}{d\delta} = \bar{K}f(\nu(c+\delta))\nu > 0$ and $\frac{dK_f}{d\delta} = D'(c+\delta+r_f) < 0$.

B Optimal energy mix without intermittency

We derive the optimal energy mix if wind power capacity can be used in both states of nature w and $\bar{w}$. Both sources of energy are used under full capacity K_f and K_i. Electricity production and consumption is $q = K_f + K_i$. For wind power capacity K_i, the more efficient spots for wind 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 optimal energy mix is characterized by K_f and $\tilde{r}_i$ that maximizes:

$$S(K_f + \bar{K}F(\tilde{r}_i)) - (c + r_f + \delta)K_f - \bar{K}\int_{\underline{r}_i}^{\tilde{r}_i} r_i dF(r_i).$$

subject to the constraints $K_f \geq 0$ and $\tilde{r}_i \geq \underline{r}_i$.

Let δ^n be a threshold on environmental damages defined implicitly by the following relationship:

$$\bar{K}F\left(c + r_f + \delta^n\right) = D\left(c + r_f + \delta^n\right). \tag{37}$$

Solving the above program as in Appendix A, we obtain the following capacity, output and price depending on the environmental damage /tax δ :

(a) for $\delta < \underline{r}_i - (c + r_f)$: no wind power

$K_i = 0$

$K_f = D(p)$ *with* $p = c + r_f + \delta$

(b) for $\underline{r}_i - (c + r_f) \leq \delta \leq \delta^n$: both sources of energy

$K_i = \bar{K}F(p)$ *with* $p = c + r_f + \delta$

$K_f = D(p) - K_i$

(c) for $\delta^n \leq \delta$: no thermal power

$K_i = \bar{K}F(\tilde{r}_i^n)$ *with* $\tilde{r}_i^n$ *given by* $\bar{K}F(\tilde{r}_i^n) = D(p)$ and $p = \tilde{r}_i^n$

$K_f = 0$.

C Proof of Proposition 2 for case (c) in Proposition 1

In case (c) of Proposition 1, the FIT should be set to $p^i = \tilde{r}_i^0/\nu$ to induce first-best investment in wind power. On the other hand, the price paid by consumers should be $p + t = (1 - \nu)(c + \delta) + r_f + \tilde{r}_i^0$ per kWh to reduce consumption up to the optimal level $q = K_f = S'^{-1}((1-\nu)(c+\delta) + r_f + \tilde{r}_i^0)$. Since thermal power is produced only in state $\bar{w}$, the zero-profit condition leads to a wholesale electricity price $p^{\bar{w}} = c + \frac{r_f}{1-\nu}$ and a retailing price of electricity $p = (1-\nu)c + r_f$. Therefore tax per kWh should be $t = (1-\nu)(c+\delta) + r_f + \tilde{r}_i^0 - p = (1-\nu)\delta + \tilde{r}_i^c$ to induce first-best consumption. By substituting the above values for p^i, $p^{\bar{w}}$ and t into the financial constraint (7) 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 (7) with a FIT $p^i = \tilde{r}_i^0/\nu$ while the wholesale electricity price is $p^{\bar{w}} = c + \frac{r_f}{1-\nu}$, the tax rate is then $t = \tilde{r}_i^0 - \nu c - \frac{\nu}{1-\nu} r_f < (1-\nu)\delta + \tilde{r}_i^0$, i.e. lower than the rate that induces first-best electricity consumption. The argument for FIP is similar and has therefore been omitted.

D Proof of Proposition 3 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 $K_i = \bar{K}F(\tilde{r}_i^0)$ and a reduction of electricity consumption down to $K_f = D((1-\nu)(c+\delta) + r_f + \tilde{r}_i^c)$. The threshold cost of the less productive windmill should be $\tilde{r}_i^0$ on the right-hand side of (11) while the retail price of electricity should be $(1-\nu)(c+\delta) + r_f + \tilde{r}_i^0$ on the left-hand side. It leads to a condition on $\tilde{r}_i^0$ which differs from the one which explicitly defines $\tilde{r}_i^0$ in Proposition 1. Hence it is unlikely to hold.

E Proof of Proposition 5

E.1 Solution

Denoting $\gamma_{\bar{w}}$,γ_w, $\underline{\mu}_f$,$\overline{\mu}_f$ and $\underline{\mu}_i$ the multipliers respectively associated with the constraints (21), (22), (3) and(4) respectively, the Lagrange function corresponding to the program can be written as

$$\begin{aligned}
\mathcal{L} \;=\;& \beta[\nu S(q_r^w) + (1-\nu)S(q_r^{\bar{w}})] + (1-\beta)S(q_{\bar{r}}) - \nu(c+\delta)q_f^w - (1-\nu)(c+\delta)K_f \\
&+ \nu\gamma_w[\bar{K}F(\tilde{r}_i) + q_f^w - \beta q_r^w - (1-\beta)q_{\bar{r}}] + (1-\nu)\gamma_{\bar{w}}[K_f - \beta q_r^{\bar{w}} - (1-\beta)q_{\bar{r}}] \\
&+ \nu\left[\underline{\mu}_f q_f^w + \bar{\mu}_f(K_f - q_f^w) + \underline{\mu}_i(\tilde{r}_i - \underline{r}_i)\right] - \bar{K}\int_{\underline{r}_i}^{\tilde{r}_i} r_i dF(r_i) - r_f K_f
\end{aligned}$$

Given the linearity of technologies and the concavity of the surplus function, the solution is determined by the following first-order conditions:

$$q_r^w : S'(q_r^w) = \gamma_w \tag{38}$$

$$q_r^{\overline{w}} : S'(q_r^{\bar{w}}) = \gamma_{\bar{w}} \tag{39}$$

$$q_{\bar{r}} : S'(q_{\bar{r}}) = \nu\gamma_w + (1-\nu)\gamma_{\bar{w}} \tag{40}$$

$$q_f^w : -(c+\delta) + \gamma_w - \bar{\mu}_f + \underline{\mu}_f = 0 \tag{41}$$

$$K_f : -(1-\nu)(c+\delta) - r_f + (1-\nu)\gamma_{\bar{w}} + \nu\bar{\mu}_f = 0 \tag{42}$$

$$\tilde{r}_i : -\tilde{r}_i + \nu\gamma_w + \nu\underline{\mu}_i' = 0 \tag{43}$$

where $\underline{\mu}_i' \equiv \underline{\mu}_i / \bar{K} f(\widetilde{r}_i)$, plus the complementary slackness conditions derived from the constraints of the program. Rearranging terms, we obtain:

$$S'(q_r^w) = c + \delta + \bar{\mu}_f - \underline{\mu}_f \tag{44}$$

$$S'(q_r^{\bar{w}}) = c + \delta + \frac{r_f - \nu\bar{\mu}_f}{1-\nu} \tag{45}$$

$$S'(q_{\bar{r}}) = \nu S'(q_r^w) + (1-\nu)S'(q_r^{\bar{w}}) \tag{46}$$

$$S'(q_r^w) = \frac{\tilde{r}_i}{\nu} - \underline{\mu}_i' \tag{47}$$

Combining (44) and (47) yields

$$\frac{\widetilde{r}_i}{\nu} = c + \delta + \bar{\mu}_f - \underline{\mu}_f + \underline{\mu}_i'. \tag{48}$$

• (case a) Without intermittent energy , $\tilde{r}_i = \underline{r}_i$ and $\underline{\mu}_i' \geq 0$. Moreover, since $\bar{K}F(\widetilde{r}_i) = 0$, the market-clearing conditions (21) and (22) imply

$$K_f - q_f^w = \beta(q_r^{\bar{w}} - q_r^w). \tag{49}$$

We show by contradiction that $q_f^w = K_f$. Suppose $q_f^w < K_f$. It entails that $\bar{\mu}_f = 0$ (because the constraint is not binding) and $q_r^{\bar{w}} > q_r^w$ by (49), which combined with (44) and (45), leads to $\frac{r_f}{1-\nu} < -\underline{\mu}_f$ a contradiction since $\underline{\mu}_f \geq 0$. Hence, $q_f^w = K_f$. It implies $\bar{\mu}_f \geq 0$ and $\underline{\mu}_f = 0$ which, in (48) yields $\frac{\widetilde{r}_i}{\nu} \geq c + \delta$.

Now $q_f^w = K_f$ in (49) implies $q_r^w = q_r^{\bar{w}}$ which, combined with $\underline{\mu}_f = 0$ in (44) and (45), leads to $\bar{\mu}_f = r_f$. In (44), (45) and (46), it yields $q_r^w = q_r^{\bar{w}} = q_{\bar{r}} = D(c + \delta + r_f)$ given the definition of $D(.) = S'^{-1}(.)$. The zero-profit condition of the thermal power determines prices $p = p^w = p^{\bar{w}} = c + \delta + r_f$.

• Second, with investment in intermittent energy (cases b and c), we have $\tilde{r}_i > \underline{r}_i$ and $\underline{\mu}_i' = 0$. In cases $b1$ and $b2$, we have $q_f^w > 0$, then $\underline{\mu}_f = 0$.

• (case $b1$) Assume first that $\bar{\mu}_f > 0$ and $q_f^w = K_f$. By equation (48), $\bar{\mu}_f = \frac{\tilde{r}_i}{\nu} - (c+\delta)$ which, combined with (44) and (45) leads to $q_r^w = D\left(\frac{\tilde{r}_i}{\nu}\right)$ and $q_r^{\bar{w}} = D\left(\frac{c+\delta+r_f-\tilde{r}_i}{1-\nu}\right)$. State-dependent prices are therefore $p^w = \frac{\tilde{r}_i}{\nu}$ and $p^{\bar{w}} = \dfrac{c+\delta+r_f-\tilde{r}_i}{1-\nu}$. Combined with (46), it leads to $q_{\bar{r}} = D(c+\delta+r_f)$ and $p = \nu p^w + (1-\nu)p^{\bar{w}} = c+\delta+r_f$. The threshold cost of wind power $\tilde{r}_i$ is defined by combining the market clearing conditions (21) and (22) with $q_f^w = K_f$. It is the solution $\tilde{r}_i$ of the following equation:

$$\bar{K}F(\tilde{r}_i) = \beta\left[D\left(\frac{\tilde{r}_i}{\nu}\right) - D\left(\frac{c+\delta+r_f-\tilde{r}_i}{1-\nu}\right)\right] \tag{50}$$

The switch from case a to case $b1$ is when $\bar{K}F(\underline{r}_i) \geq 0 \implies \frac{\underline{r}_i}{\nu} \leq \dfrac{c+\delta+r_f-\underline{r}_i}{1-\nu}$ (if $\beta \neq 0$) that is $\delta \geq \frac{\underline{r}_i}{\nu} - (c+r_f)$.

• (case $b2$) Suppose now that $\overline{\mu}_f = 0$ which holds for $q_f^w < K_f$. Conditions (44) and (45) become $S'(q_r^w) = c+\delta$ and $S'(q_r^{\bar{w}}) = c+\delta+\frac{r_f}{1-\nu}$ respectively, which combined with (46) yields state-dependent consumption levels for reactive consumers: $q_r^w = D(c+\delta)$, $q_r^{\bar{w}} = D(c+\delta+\frac{r_f}{1-\nu})$ and non-state dependent level for the otrhers $q_{\bar{r}} = D(c+\delta+r_f)$. They are consistent with state-dependent market prices $p^w = c+\delta$ and $p^{\bar{w}} = c+\delta+\frac{r_f}{1-\nu}$ and retail price $p = c+\delta+r_f$. These prices satisfy the zero-profit condition for thermal power producers and electricity retailers. Conditions (44) and (47) yield the threshold cost of windmills $\tilde{r}_i = \nu(c+\delta)$ and, therefore, wind power capacity is $K_i = \bar{K}F(\tilde{r}_i) = \bar{K}F(\nu(c+\delta))$. Thermal power capacity is determined by the market-clearing condition in state $\bar{w}$ (21), that is:

$$K_f = \beta q_r^{\bar{w}} + (1-\beta)q_{\bar{r}} = \beta D\left(c+\delta+\frac{r_f}{1-\nu}\right) + (1-\beta)D\left(c+\delta+r_f\right). \tag{51}$$

The market clearing condition in state w (22) yields:

$$q_f^w = \beta D(c+\delta) + (1-\beta)D(c+\delta+r_f) - \bar{K}F(\nu(c+\delta)) \tag{52}$$

The switch from case $b1$ to case $b2$ arises when $q_f^w \leq K_f \implies \beta D(c+\delta) - \bar{K}F(\nu(c+\delta)) \leq \beta D\left(c+\delta+\dfrac{r_f}{1-\nu}\right)$. Let $\delta_1(\beta)$ denote the solution to:

$$\beta\left[D(c+\delta_1) - D\left(c+\delta_1+\frac{r_f}{1-\nu}\right)\right] = \bar{K}F(\nu(c+\delta_1)) \tag{53}$$

Then case $b2$ begins when $\delta \geq \delta_1(\beta)$. Since we have that $q_f^w > 0$, the right-hand side of (52) must be positive. Since it is decreasing in δ, $q_f^w > 0$ holds for $\delta < \delta_2(\beta)$ where $\delta_2(\beta)$ is the root of $q_f^w = 0$ in (52). Then case $b2$ ends when $\delta \geq \delta_2(\beta)$.

Observe that q_f^w increases with β. This is because in state w reactive consumers pay less than non-reactive ones ($p^w = c+\delta < p = c+\delta+r_f$). Then, the former consume more than the latter. Consequently, for a given installed capacity, a larger β corresponds to a larger total consumption that can be satisfied only by an increase in the controlled source of energy: $\frac{\partial q_f^w}{\partial \beta} > 0$.

• (case c) Third, consider the case $q_f^w = 0$ with all energy coming from the intermittent source in state w. Then $\underline{\mu}_f \geq 0$, $\bar{\mu}_f = 0$ and $\mu_i' = 0$ which, in (45) and (47), leads to $S'(q_r^{\bar{w}}) = c+\delta+\frac{r_f}{1-\nu}$ and $S'(q_r^w) = \frac{\tilde{r}_i}{\nu}$. Inserting the last two equalities into (46) yields $q_{\bar{r}} = D(\tilde{r}_i+(1-\nu)(c+\delta)+r_f)$. In (45) and (47), those equalities show $q_r^{\bar{w}} = D\left(c+\delta+\frac{r_f}{1-\nu}\right)$ and $q_r^w = D\left(\frac{\tilde{r}_i}{\nu}\right)$. The market-clearing condition in state $\bar{w}$ (21) gives $K_f = \beta D\left(c+\delta+\frac{r_f}{1-\nu}\right)+ (1-\beta)D(\tilde{r}_i+(1-\nu)(c+\delta)+r_f)$, whereas the one is state w (22) defines $\tilde{r}_i$ uniquely as

$$\bar{K}F(\tilde{r}_i) = \beta D\left(\frac{\tilde{r}_i}{\nu}\right) + (1-\beta)D(\tilde{r}_i + (1-\nu)(c+\delta) + r_f). \tag{54}$$

Lastly, the prices $p^{\bar{w}} = c+\delta+\frac{r_f}{1-\nu}$, $p^w = \frac{\tilde{r}_i}{\nu}$ and $p = \tilde{r}_i + (1-\nu)(c+\delta) + r_f$ decentralize this solution under free entry.

E.2 Zoning

• First define

$$\beta_1(\delta,\nu) = \frac{\bar{K}F(\nu(c+\delta))}{D(c+\delta) - D\left(c+\delta+\frac{r_f}{1-\nu}\right)} \tag{55}$$

representing the frontier between the sets of parameters where $K_f \geq q_f^w$, respectively defined in (51) and (52). Its derivative with respect to δ is

$$\frac{\partial \beta_1(\delta,\nu)}{\partial \delta} = \frac{\bar{K}\nu f(\nu(c+\delta)) - \beta_1(\delta)\left[D'(c+\delta) - D'\left(c+\delta+\frac{r_f}{1-\nu}\right)\right]}{D(c+\delta) - D\left(c+\delta+\frac{r_f}{1-\nu}\right)}$$

The denominator is positive. A weakly convex demand function is sufficient for the numerator also being positive. Then under this convexity condition, $\beta_1(\delta,\nu)$ is increasing in δ. Note that when $\beta_1(\delta,\nu) = 0$, $\nu(c+\delta) = \underline{r}_i$.

• Second define

$$\beta_2(\delta,\nu) = \frac{\bar{K}F(\nu(c+\delta)) - D(c+\delta+r_f)}{D(c+\delta) - D(c+\delta+r_f)} \tag{56}$$

representing the frontier between the sets of parameters where $q_f^w \geq 0$, the function q_f^w being defined in (52) . Its derivative is

$$\frac{\partial\beta_2(\delta,\nu)}{\partial\delta} = \frac{\bar{K}\nu f(\nu(c+\delta)) - \beta_2(\delta) D^{'}(c+\delta) - (1-\beta_2(\delta))D^{'}(c+\delta+r_f)}{D(c+\delta) - D(c+\delta+r_f)} > 0$$

Then $\beta_2(\delta,\nu)$ is increasing in δ. Note that when $\beta_2(\delta,\nu) = 0$, $\bar{K}F(\nu(c+\delta)) - D(c+\delta+r_f) = 0$ which corresponds to the definition of δ^0 in (5).

• How do $\beta_1(\delta,\nu)$ and $\beta_2(\delta,\nu)$ compare? The numerator is obviously larger in $\beta_1(\delta,\nu)$ but the same is true for the denominator because of $\nu > 0$. Let denote

$$\widehat{\nu} = \min\{1, \arg_\nu[\beta_1(\delta,\nu) = \beta_2(\delta,\nu)]\} \tag{57}$$

- For $\nu < \widehat{\nu}$, $\beta_1(\delta,\nu) > \beta_2(\delta,\nu)$ whatever δ.

- Otherwise, there exists $\widehat{\delta}$ such that $\beta_1(\delta,\nu) > \beta_2(\delta,\nu)$ as $\delta < \widehat{\delta}$ and vice-versa.

• Figure 3 represents the different types of optimal energy mix depending on the values of β and δ when $\nu < \widehat{\nu}$. If $\nu > \widehat{\nu}$, $\beta_1(\delta,\nu)$ and $\beta_2(\delta,\nu)$ intersects at $\widehat{\delta}$. The consequence is that case $b.2$ vanishes for high values of β. To facilitate the reading of Proposition 5, in Figure 3 the two functions $\beta_1(\delta,\nu)$ and $\beta_2(\delta,\nu)$ are respectively labeled $\delta_1(\beta)$ and $\delta_2(\beta)$.

F Proof of Proposition 6

F.1 Proof of Condition (26)

Let EW denote the expected social surplus defined in (20). It is the difference between the expected gross surplus $ES = \beta[\nu S(q_r^w) + (1-\nu)S(q_r^{\bar{w}})] + (1-\beta)S(q_{\bar{r}})$ and the expected cost

$$EC = \nu(c+\delta)q_f^w + [(1-\nu)(c+\delta) + r_f]\, K_f + \tilde{r}_i\bar{K}F(\tilde{r}_i) - \bar{K}\int_{\underline{r}_i}^{\tilde{r}_i} F(r_i)dr_i.$$

where we have performed the integration by parts $\bar{K}\int_{\underline{r}_i}^{\tilde{r}_i} r_i dF(r_i) = \tilde{r}_i\bar{K}F(\tilde{r}_i) - \bar{K}\int_{\underline{r}_i}^{\tilde{r}_i} F(r_i)dr_i$. Using the market-clearing conditions (21) and (22), we write the expected cost as a function of β:

$$EC = \nu(c+\delta)q_f^w + [(1-\nu)(c+\delta) + r_f]\,(\beta q_r^{\bar{w}} + (1-\beta)q_{\underline{r}}) + \tilde{r}_i[\beta q_r^w + (1-\beta)q_{\underline{r}} - q_f^w] - \bar{K}F(\tilde{r}_i).$$

The expected social surplus is a function $EW(x,\beta)$ where x stands for the vector of control variables $q_r^w, q_r^{\bar{w}}, q_{\bar{r}}, q_f^w, K_f, \tilde{r}_i$. Differentiating wrt β, we obtain:

$$\frac{dEW(x,\beta)}{d\beta} = \frac{\partial EW(x,\beta)}{\partial x}\frac{dx}{d\beta} + \frac{\partial EW(x,\beta)}{\partial \beta} = \frac{\partial EW(x,\beta)}{\partial \beta}$$

by the envelop theorem. Consequently, in all cases, we have that

$$\begin{aligned}\frac{dEW(x,\beta)}{d\beta} &= \frac{\partial[ES(x,\beta) - EC(x,\beta)]}{\partial \beta}. \\ &= [\nu S(q_r^w) + (1-\nu)S(q_r^{\bar{w}}) - S(q_{\bar{r}})] + [(1-\nu)(c+\delta) + r_f](q_{\bar{r}} - q_r^{\bar{w}}) - \tilde{r}_i(q_r^w - q_{\bar{r}}).\end{aligned}$$

F.2 Expected social surplus

Let $g(p) \equiv S(D(p))$ be the social surplus as a function of power price. We have $g'(p) = S'(D(p))D'(p) < 0$ and $g''(p) = S''(D(p))[D'(p)]^2 + S'(D(p))D''(p)$. Therefore $g(p)$ is concave if $g''(p) \leq 0$, that is if:

$$D''(p) \leq -\frac{S''(D(p))[D'(p)]^2}{S'(D(p))}. \tag{58}$$

Since $S'(.) > 0$ $S''(.) < 0$, the right-hand side is positive. Condition (58) holds if $D''(p)$ is negative or nil, that is if $D(p)$ is concave or linear. It also holds if $D''(p)$ is positive and low, that is if $D(p)$ is not too convex.

With $g(p)$ concave, by Jensen inequality, $g(E[p_r]) > E[g(p_r)]$ where p_r is the price charged to reactive consumers, which is p^w with probability ν and $1 - p^{\bar{w}}$ with probability $1-\nu$. Therefore $g(p_r)$ is equal to $g(p^w)$ with probability ν and $g(p^{\bar{w}})$ with probability $1-\nu$. Since $E[p_r] = \nu p^w + (1-\nu)p^{\bar{w}} = p$ by Proposition 5, the last inequality becomes $g(p) > \nu g(p^w) + (1-\nu)g(p^{\bar{w}})$ which, given the definition of $g(p)$, $q_{\underline{r}} = D(p)$, $q_r^w = D(p^w)$, and $q_r^{\bar{w}} = D(p^{\bar{w}})$, leads to $S(q_{\bar{r}}) > \nu S(q_r^w) + (1-\nu)S(q_r^{\bar{w}})$.

F.3 Expected net social surplus

Let $h(p) \equiv S(D(p)) - pD(p)$ be the net social surplus (including spending $pD(p)$) as a function of power price. We have $h'(p) = [S'(D(p)) - p]D'(p) - D(p) = -D(p) < 0$ where the last equality is due to the fact that demand $D(p)$ at any arbitrary price p is such that $S'(D(p)) = p$. Therefore $h''(p) = -D'(p) > 0$. Hence $h(p)$ is decreasing and convex. By Jensen inequality, since $h(p)$ is convex, $p = \nu p^w + (1-\nu)p^{\bar{w}}$ implies $h(p) < \nu h(p^w) + (1-\nu)h(p^{\bar{w}})$. Given the definition of h, $q_{\underline{r}} = D(p)$, $q_r^w = D(p^w)$, and $q_r^{\bar{w}} = D(p^{\bar{w}})$, the last inequality leads to:

$$S(q_{\underline{r}}) - pq_{\underline{r}} < \nu[S(q_r^w) - p^w q_r^w] + (1-\nu)[S(q_r^{\bar{w}}) - p^{\bar{w}} q_r^{\bar{w}}].$$

F.4 Second derivative of the expected welfare

Consider now the second derivative of the expected welfare $EW(x,\beta)$ with respect to β. Applying the envelop theorem again, it is just

$$\begin{aligned}\frac{d^2EW(x,\beta)}{d\beta^2} &= -\nu q_r^w \frac{dp^w}{d\beta} - (1-\nu) q_r^{\bar{w}} \frac{dp^{\overline{w}}}{d\beta} + q_{\bar{r}} \frac{dp}{d\beta} \\ &= -\nu \left(q_r^w - q_{\bar{r}}\right) \frac{dp^w}{d\beta} + (1-\nu)\left(q_{\bar{r}} - q_r^{\bar{w}}\right) \frac{dp^{\overline{w}}}{d\beta} \end{aligned} \quad (59)$$

In all cases we know that $q_r^w > q_{\bar{r}} > q_r^{\bar{w}}$

- In case *b1,* by differentiation of (50) ,we obtain,

$$\frac{d\tilde{r}_i}{d\beta} = \frac{q_r^w - q_r^{\bar{w}}}{\overline{K} f\left(\tilde{r}_i\right) - \beta\left[\frac{1}{\nu} D'\left(\frac{\tilde{r}_i}{\nu}\right) + \frac{1}{1-\nu} D'\left(\frac{c+\delta+r_f-\tilde{r}_i}{1-\nu}\right)\right]} > 0 \quad (60)$$

Knowing the prices, we can compute $\frac{dp^w}{d\beta} = \frac{1}{\nu}\frac{d\tilde{r}_i}{d\beta}$, $\frac{dp^{\bar{w}}}{d\beta} = -\frac{1}{1-\nu}\frac{d\tilde{r}_i}{d\beta}$ that we insert into (59) to obtain

$$\frac{d^2EW(x,\beta)}{d\beta^2} = -\left(q_r^w - q_r^{\bar{w}}\right)\frac{d\tilde{r}_i}{d\beta} < 0 \quad (61)$$

- In case *b2,* since both $p^w = c+\delta$ and $p^{\bar{w}} = c + \delta + \frac{r_f}{1-\nu}$ are independent from β, we obtain $\frac{d^2EW(x,\beta)}{d\beta^2} = 0$.

- In case c, by differentiation of (54) ,we obtain,

$$\frac{d\tilde{r}_i}{d\beta} = \frac{q_r^w - q_r^{\bar{w}}}{\bar{K} f\left(\tilde{r}_i\right) - \frac{\beta}{\nu} D'(\frac{\tilde{r}_i}{\nu}) - (1-\beta) D'\left(\tilde{r}_i + (1-\nu)(c+\delta) + r_f\right)} > 0. \quad (62)$$

With prices $p^w = \frac{\tilde{r}_i}{\nu}$, $p^{\bar{w}} = c + \delta + \frac{r_f}{1-\nu}$, we find

$$\frac{d^2EW(x,\beta)}{d\beta^2} = -\left(q_r^w - q_{\bar{r}}\right)\frac{d\tilde{r}_i}{d\beta} < 0 \quad (63)$$

Notice that $q_r^w - q_r^{\bar{w}} > q_r^w - q_{\bar{r}}$: the marginal expected surplus decreases more rapidly in case *b1* than in case *c*.

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