Decarbonizing Electricity Generation with Intermittent Sources of Energy

Stefan Ambec, Claude Crampes

Abstract: We examine policy instruments that aim to decarbonize electricity production by replacing fossil fuel energy with intermittent renewable sources, namely, wind and solar power. We consider a model of investment, production, and storage with two sources of energy: one is clean but intermittent (wind or solar), whereas the other one is reliable but polluting (thermal power). We first determine the first-best energy mix depending on the social cost of polluting emissions. We then show that, to implement the socially efficient energy mix without a carbon tax, feed-in tariffs and renewable portfolio standards must be complemented with a price cap and volume-limited capacity payments.

JEL Codes: D24, D61, Q41, Q42, Q48

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ELECTRICITY PRODUCTION FROM FOSSIL ENERGY SOURCES is one of the main causes of anthropogenic greenhouse gas emissions. The electricity sector plays a pivotal role in the debate about climate change mitigation. Public policies have been launched worldwide to decarbonize electricity production by switching to renewable

Stefan Ambec (corresponding author) is at the Toulouse School of Economics, INRA, University of Toulouse, France (stefan.ambec@inra.fr). Claude Crampes is at the Toulouse School of Economics, University of Toulouse, France. We thank the participants at various conferences (World Congress of Environmental and Resource Economists in Istanbul, CESifo conference on Energy and Climate Change, Toulouse Conference on the Economics of Energy and Climate Change) and seminars at Ecole Polytechnique, MinesParisTech, the Universities of Bordeaux, Montreal, Oslo, Ottawa, and Paris for useful comments and suggestions. We also thank two referees of the journal who have greatly contributed to improve an earlier version of the paper. This research was supported by the TSE Energy and Climate Center and the H2020-MSCA-RISE project GEMCLIME-2020 GA no. 681228.

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sources of energy, such as wind and solar power, instead of fossil fuels. Various instruments have been adopted to support renewables. Some states in the United States have opted for quantitative commitments, renewable portfolio standards (RPS) that require a given proportion 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), that consist in 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]

1. INTERMITTENT AND RELIABLE ENERGY SOURCES

Integrating renewable energy such as wind and solar power into the electricity mix is not easy. One reason is that, unlike conventional power units, electricity produced from wind turbines and photovoltaic (PV) panels varies over time and weather conditions. The supply of electricity from these sources is not controllable and is hard to predict as weather conditions are rarely forecast more than 5 days ahead.[3] The intermittency of electricity supplied from wind turbines 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 though wholesale electricity prices vary with electricity provision every hour or half hour, the retail prices that consumers pay do not. And 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"), consumers would not be able to quickly respond to price changes.

Surprisingly, a number of influential papers presenting economic models of the transition to low carbon energy ignore intermittency. Seminal papers deal with a carbon-free technology that replaces polluting ones at a cost that decreases over time (Fischer and Newell 2008; Fullerton and Heutel 2010; 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 energy from wind energy converters and solar

1. Since 2007, the US 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/statelocalenergy/energy-and-environment-guide-action.

2. FITs have been quite successful in fostering investment in wind and solar power in the European Union over the past decade. The price paid for success is an increase in the consumers' bill to cover the cost of FITs. How much it costs 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 account for 10% of the electricity bill and are continuously increasing.

3. See, e.g., Newbery (2011) for empirical evidence.

panels. It changes the business model of the electricity sector, production, and consumption patterns, as well as investment in all types of equipment. This, in turn, can be expected to influence the design of public policy for decarbonizing energy.

This paper fills the gap by analyzing the transition to a decarbonized energy mix in a model of electricity provision with both intermittent and reliable energy sources. The supply of electricity from the climate-dependent technology is environmentally friendly, whereas reliable sources emit pollutants. On the demand side, most consumers are not reactive to short-term price variations. Without energy storage, and assuming that power cuts are not acceptable, the nonreactiveness of consumers makes it necessary to back up energy supplies from renewable sources with energy from 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.[4]

With this model, we first characterize the efficient energy mix when consumers cannot react to real-time price changes and producers have the obligation to serve them.[5] We also discuss its decentralization in competitive electricity markets with a Pigouvian carbon tax. We highlight three effects of intermittency on electricity generation. First, since each kilowatt of turbine capacity is supplied with wind only a fraction of the year, the average cost of one more kilowatt is the unit capital cost divided by the frequency of production. This means that if wind turbines are spinning say half of the year, the cost of a kilowatt-hour from wind power is doubled. Second, decarbonating further electricity provision does not always mean substituting thermal power with renewables. It sometimes requires reducing both thermal and renewable production. As a consequence, a higher carbon tax might reduce the price of clean energy instead of increasing

4. Note that intermittency is both a matter of dates and one of states of nature. Solar photovoltaic panels produce during the day and not at night, and their diurnal production intensity varies with cloud cover. Wind power is seasonal in most regions, and the wind speed results from differences in pressure, themselves caused by differences in temperature. In our paper, we do not distinguish between dates (e.g., day/night) and states of nature (e.g., high/low temperature). Only one variable will be used to identify the time or randomness dimension of production from renewables. Dates and occurrences of availability obey a given frequency or probability distribution. For convenience, we will mainly refer to the wind resource and its randomness. However, when addressing the problem of storage, we will show that the model can be interpreted in terms of the frequency of periods, which better corresponds to solar production.

5. Note that rationing and disconnections are also a solution to intermittency. However, in developed countries, strict legal rules require "keeping the lights on," that is, security of supply with very large probability, e.g., only 3 hours a year of failure, which represents a probability of $8{,}757/8{,}760 = 99.96\%$ for matching demand.

it, thereby lowering investment in wind or solar power. Third, the final bill should include the cost of thermal power or storage equipment used as a back-up, because electricity consumption is determined not by wholesale prices but by retail prices that reflect the social cost of the reliable provision 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.[6]

Next, we analyze FIT and RPS as policy instruments to implement the efficient energy mix for a given decarbonization target. Both instruments enhance the penetration of renewables into the energy mix. However, they induce too much electricity production and investment in thermal power as compared to first-best, then excessive emissions of greenhouse gas. Thermal power production and capacity can be lowered by a tax on electricity consumption or fossil fuels to implement first-best.[7] Similarly, first-best can be implemented with FIT (or RPS) by capping electricity price and subsidizing thermal power production capacity (e.g., with capacity payments or markets). Storage facilities have also to be subsidized when efficient if thermal power plants are active. If not, excluding fossil fuel energy from the energy mix would induce efficient investment in storage with FIT (or RPS).

2. RELATED LITERATURE

Several papers have introduced intermittency in an economic model of electricity provision. Ambec and Crampes (2012) analyze the optimal and market-based electricity mix with intermittent sources of energy. However, they do not consider public policies and environmental externalities.[8] In the same vein, Helm and Mier (2016, 2018) investigate optimal and market-based investment in several intermittent sources of energy. 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 instantaneously modify 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. Similarly, in their investigation of the impact of FIT on the energy mix, Green and Léautier (2015) ignore the problem of consumers' reactivity to wholesale electricity prices. 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

6. The cost of intermittency has been estimated for renewable penetration of less than 20%; see Heptonstall et al. (2017) for a meta-analysis.

7. 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.

8. See also Rouillon (2015) and Baranes et al. (2017) for similar analysis.

by Joskow and Tirole (2007). They introduce nonreactive consumers in a model of electricity provision with variable demand. In contrast, in our model, the source of variability is on the supply side and the degree of variability is endogenously determined by investment in intermittent power through the support to renewables.[9]

Rubin and Babcock (2013) rely on simulations to quantify the impact of various pricing mechanisms—including FIT—on wholesale electricity markets. We take a different approach here: we analytically solve a normative model and make a welfare comparison of several policy instruments. Garcia et al. (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, in our paper price is endogenous. More precisely, we consider a standard increasing and concave consumers' 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 taking into account intermittency. Kaffine and McBee (2017) perform a similar estimation for CO_2 emissions using high-frequency generation data from the US Southwest Power Pool. 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 constrained by 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, that is, above a threshold that we characterize. Similarly, we are able to identify in our model the social value of energy storage and how it is related to the cost of wind or thermal power.

Our paper also contributes to the policy debate on capacity mechanisms. To mitigate the so-called "missing money" problem, several countries have started subsidizing generation capacity, either by setting a payment per mega-watt (capacity payments) or by auctioning the option to supply power capacity (capacity markets). Economists have rationalized capacity markets with the exercise of market power: if prices are capped to mitigate market power, producers may need to be subsidized to induce optimal investment (Cramton et al. 2013; Fabra 2018). Our paper provides another economic rationale for both price caps and capacity markets: combining the two instruments allows limiting thermal power production when intermittent renewables are

9. In the same vein, two studies have identified the social the value of making consumers reactive to real-time electricity prices: Léautier (2014) with variable demand and Ambec and Crampes (2017) with variable supply (i.e., intermittent renewables).

pushed by FIT or RPS. The two instruments are necessary: price cap to avoid overproduction and capacity mechanism to control investment in thermal power equipment.

The rest of the paper is organized as follows. Section 3 introduces the model. Section 4 characterizes the first-best energy mix when consumers are not reactive to climate-dependent prices and energy storage is not profitable (4.2) or is profitable (4.3). It also identifies the market outcome prices and the impact of intermittency on production, emissions, and investment in power generation. Public policies are analyzed in section 5: feed-in tariff alone in section 5.1 and FIT complemented by capacity mechanisms in sections 5.2 and 5.3. Section 6 concludes.

3. THE MODEL

We consider a model of energy production and supply with intermittent energy and non-price-reactive demand.[10] 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 has the capacity to produce q_f kilowatt-hours at a unit operating cost c as long as production does not exceed the installed capacity, K_f. The unit cost of capacity is r_f. This source of electricity will be named the "fossil" source. It emits air pollutants that cause 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 us denote by $\delta > 0$ the environmental marginal damage due to thermal power, that is, the social damage from CO_2 emissions per kilowatt-hour of electricity generated.

The second technology relies on an intermittent primary energy source, for example, wind. It makes it possible to produce q_i kWh at zero cost as long as (i) q_i is smaller than the installed capacity K_i and (ii) the primary energy is available, for example, wind is blowing. 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 state-dependent variables are identified by the superscript w (respectively $\bar{w}$). The total potential capacity that can be installed is $\bar{K}$. The cost of installing new capacity is r_i per kilowatt. 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 or sunny hours. Investing only increases the amount of energy produced in state w. This assumption can be relaxed by allowing for more states of nature, that is, by changing the occurrence of intermittent energy from several sources.[11]

10. The model is a generalization of Ambec and Crampes (2012), with heterogeneous production costs for wind or solar power, energy storage, and explicit pollution damage.

11. See Ambec and Crampes (2012, sec. 4).

A third technology, called "storage," does not produce electricity. It allows the storing of energy when production is cheap (in state w in our model) to supply electricity when it is expensive (in state $\bar{w}$).[12] Energy storage capacity K_s (measured in kilowatt-hours) is installed at unit cost r_s. Let s^w be the power used to store energy in state w. The storage facility leads to $s^{\bar{w}}$ more power supplied in state $\bar{w}$. The relationship between these two flows on one hand and between the flows and the storage capacity on the other hand depends on the type of storage technology.[13] We choose to measure the storage capacity K_s in terms of saved energy (inflow).[14] The parameters ν and $1 - \nu$ are observed frequencies (rather than probabilities) of states w and $\bar{w}$ respectively. We have that $\nu s^w \leq K_s$. A share $1 - \lambda$ of the energy injected into the storage plant is lost,[15] so that outflow and inflow are related by $(1 - \nu)s^{\bar{w}} \leq \lambda \nu s^w$. 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 stored energy. Therefore, we can set that the three variables K_s, s^w, and $s^{\bar{w}}$ are linked by the two equalities:

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

To keep in line with the current state of technologies, we assume that r_s is large compared with r_f and λ still too low, so that storage can be part of the optimal mix only when the environmental cost δ reaches very high levels.

Consumers derive a gross utility $S(q)$ from the consumption of q kilowatt-hour of electricity. Consumption is defined over a unit of time equal to the full cycle of energy storage, for example, a day for solar power. Utility is a continuous derivable function

12. Nowadays, storage is mainly done by using cheap electricity from coal or nuclear plants to pump water up into reservoirs. At periods of scarce energy, this water is turbinated to complement the expensive electricity produced by peaking units. In our model with one single type of plant burning fossil fuel at a constant operating cost, given conversion losses it would be inefficient to store energy produced by thermal plants. For an economic analysis of water storage and pumping, see Crampes and Moreaux (2010). Ambec and Doucet (2003) study water storage under imperfect competition.

13. Storage is a dynamic process, whereas the model we use in this paper is static. However, we can obtain enlightening results by reframing 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). The length of the cycle varies with weather conditions and forecasts. For wind power, it is a matter of weeks or even seasons. For an overview of electricity storage characteristics, see Crampes and Trochet (2019).

14. Alternatively, one can measure capacity in terms of energy for final consumption (outflow), i.e., after subtracting energy losses.

15. 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.

with $S' > 0$ and $S'' < 0$. The inverse demand for electricity is therefore $P(q) = S'(q)$ and the direct demand function is $D(p) = S'^{-1}(p)$ where p stands for the retail price. It does not vary with the states of nature. By contrast, wholesale electricity prices are weather dependent: 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. 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 retail market. Neglecting the operation costs of retailers, the retail price of one kilowatt-hour of electricity sold to nonreactive consumers is equal to its expected price in the wholesale market $p = \nu p^w + (1 - \nu)p^{\bar{w}}$. All through the paper, we assume that electricity cannot be transported or curtailed. The only way to balance supply and demand is then to rely on production adjustment, storage, and/or price variation. Finally, we assume that

$$S'(0) > c + r_f + \delta. \tag{2}$$

In words, producing electricity from fossil energy is socially efficient when it is the only production source.

In section 4, we determine the optimal energy mix, and in section 5 we analyze the impact of public policy.

4. OPTIMAL ENERGY MIX WITH NONREACTIVE CONSUMERS

4.1. Capacity, Production, and Prices

The optimal energy mix is defined by capacities for each energy source K_i and K_f, of storage K_s, and outputs in each state of nature for each energy source. We 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 $\bar{w}$, no intermittent energy is produced: $q_i^{\bar{w}} = 0$; (ii) since thermal power equipment is costly, it is used at full capacity if no wind $q_f^{\bar{w}} = K_f$; (iii) since intermittent energy has no operating cost, all the energy produced by renewables (if any) will be supplied to consumers, $q_i^w = K_i$; (iv) 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 energy converter, the installed capacity of wind power is $K_i = \bar{K}F(\tilde{r}_i)$.

Second, we set up an implication of the constant retail price. Since the price paid by consumers does not vary with the state of nature, electricity consumption is the same in states w and $\bar{w}$. Prohibiting blackouts, electricity supply should be the same, meaning that:

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

Using (1), we can express the above relationship in terms of storage capacity K_s:

$$K_i + q_f^w - \frac{K_s}{\nu} = K_f + \frac{\lambda K_s}{1 - \nu}. \tag{3}$$

We call (3) the *nonreactivity constraint* as it is an implication of the consumers' inability to react to the variations of wholesale electricity prices. Given (3) and the above statements (i)–(iv), we are left with four decision variables K_f, $\tilde{r}_i$, K_s, and q_f^w that must be chosen to maximize the expected social surplus:

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

$$-\bar{K}\int_{\underline{r}_i}^{\tilde{r}_i} r_i dF(r_i) - r_f K_f - r_s K_s,$$

subject to the constraints:

$$\bar{K}F(\tilde{r}_i) + q_f^w - \frac{K_s}{\nu} = K_f + \frac{\lambda K_s}{1-\nu}, \tag{4}$$

$$q_f^w \geq 0, \tag{5}$$

$$q_f^w \leq K_f, \tag{6}$$

$$\tilde{r}_i \geq \underline{r}_i, \tag{7}$$

$$K_f \geq 0, \tag{8}$$

$$K_s \geq 0. \tag{9}$$

The first constraint is the nonreactivity constraint, (3), expressed in terms of the remaining decision variables. It requires supplying the same quantity of electricity in the two states of nature. The second constraint requires that electricity production from fossil fuel in state w be nonnegative, and the third constraint precludes it from exceeding production capacity. The fourth constraint, (7), states that the threshold capacity cost $\tilde{r}_i$ is bounded downward by the lowest cost $\underline{r}_i$. Finally, the last two constraints, (8) and (9), state that thermal power and storage capacity cannot be negative.

In order to limit the number of propositions, we include in the definition of first-best the prices that decentralize the optimal energy mix in a perfect competition framework with free entry and a Pigouvian carbon tax δ per kilowatt-hour. Prices are defined by the zero-profit condition for the last entrant in both types of production technology (thermal and renewable), storage, and retailing. The revenues from the carbon tax paid by consumers are redistributed in a nondistortionary way among consumers and producers.

Solving the above program, we obtain the following proposition that relates the optimal energy mix and market prices to the social cost of carbon δ. There are four thresholds, δ^b, δ^c, δ^d, δ^e, defined in appendix A with the proof of the proposition.

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

(a) no intermittent energy: if $\delta < \delta^b$

$$K_i = 0,\ K_f = D\left(c + r_f + \delta\right) = q_f^w,\ K_s = 0,$$

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

(b) both renewables and fossil in state w: if $\delta^b \leq \delta \leq \delta^c$,

$$K_i = \bar{K}F\left(\tilde{r}_i^b\right),\ K_f = D\left(c + r_f + \delta\right),\ q_f^w = K_f - K_i > 0,\ K_s = 0,$$

with $\tilde{r}_i^b = \nu(c + \delta)$

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

(c) only intermittent energy in state w: if $\delta^c \leq \delta \leq \delta^d$,

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

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

(d) renewables in state w, storage and thermal power in state $\bar{w}$: if $\delta^d < \delta < \delta^e$

$$K_i = \bar{K}F\left(\tilde{r}_i^d\right),\ K_f = K_i - \left[\frac{1}{\nu} + \frac{\lambda}{1-\nu}\right]K_s,\ q_f^w = 0,$$

$$K_s = \frac{1}{\nu}\left[K_i - D\left((1-\nu(1-\lambda))\left[c + \delta + \frac{r_f}{1-\nu}\right] - \nu r_s\right)\right],$$

with $\tilde{r}_i^d = \lambda\nu[c + \delta + \frac{r_f}{1-\nu}] - \nu r_s$,

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

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

(e) mix of renewables and storage: if $\delta^e \leq \delta$,

$$K_i = \bar{K}F(\tilde{r}_i^e),\ K_f = 0 = q_f^w,\ K_s = K_i\frac{\nu(1-\nu)}{1-\nu+\lambda\nu},$$

with $\tilde{r}_i^e$ given by

$$\bar{K}F(\tilde{r}_i^e) = \left[1 + \frac{1-\nu}{\lambda\nu}\right]D\left(\tilde{r}_i^e\left(1 + \frac{1-\nu}{\lambda\nu}\right) + \frac{1-\nu}{\lambda}r_s\right),$$

$$p^w = \frac{\tilde{r}_i^e}{\nu},\ p^{\bar{w}} = \lambda^{-1}\left[\frac{\tilde{r}_i^e}{\nu} + r_s\right],\ p = \tilde{r}_i^e + (1-\nu)\lambda^{-1}\left[\frac{\tilde{r}_i^e}{\nu} + r_s\right].$$

Proposition 1 is illustrated in figures 1 and 2.[16] We now comment proposition 1 and figures 1 and 2 by considering successively the energy mix without and with energy storage.

4.2. Energy Mix without Storage

4.2.1. Optimal Quantities

Given our hypothesis of high r_s compared with r_f and $\underline{r}_i$, storage is not socially profitable for low values of δ.

In case *a*, (left part of fig. 1), since $c + \delta < (\underline{r}_i/\nu)$ the cost of carbon is too small to justify an investment in renewables.[17] In both states of nature, thermal plants are the only providers of energy. The optimal capacity is the one that equates the marginal surplus $S'(K_f)$ with the full marginal cost $c + r_f + \delta$. A small increase in the environmental cost δ provokes a decrease in investment, production, and consumption.

For higher values of δ, we switch to case *b*, where windmill operators become competitive since now $c + \delta > (\underline{r}_i/\nu)$. However, entry is limited because the cost r_i is increasing with K_i.[18] Then the merit order in state w begins with renewables, up to the point where $(\tilde{r}_i/\nu) = c + \delta$, followed by fossil-fueled electricity q_f^w. To meet the nonreactivity requirement $q_f^w + K_i = K_f$, in period w the thermal plants are not fully used: $q_f^w = K_f - K_i < K_f$. Again, the installed capacity is determined by $S'(K_f) = c + r_f + \delta$. It is decreasing with δ, while K_i is increasing (recall that $(\tilde{r}_i/\nu) = c + \delta$). It results that q_f^w decreases more rapidly than K_f. As displayed in figure 1, in case *b*, thermal and wind power capacities substitute each other when the social cost of carbon increases: K_f decreases and K_i increases with δ.

With an additional increase in δ we reach case *c*, where only one source of energy is used in a given state of nature: wind power covers the whole demand in state w and fossil-fueled power in state $\bar{w}$. Thermal power is forced out of dispatching in state w. Capacities result from a fixed-point relationship between the marginal surplus $S'(.)$ and the marginal cost of green energy. Marginal surplus must be the same in both states of nature because of the nonreactivity constraint $K_i = K_f$. It equates the marginal

16. All the lines in figs. 1 and 2 are drawn as straight whereas in some of the cases the functions depicted are not linear.

17. This is because we have assumed $\underline{r}_i/\nu > c$. 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 variable cost c.

18. Note that case *b* would not show up with homogeneous costs r_i and unbounded capacity $\bar{K}$ for wind power, as in Ambec and Crampes (2012, proposition 3 and fig. 3).

costs of providing energy: $\tilde{r}_i/\nu$ in state w and $c + \delta + (r_f/[1 - \nu])$ in state $\bar{w}$, which is $(1 - \nu)(c + \delta) + r_f + \tilde{r}_i$ on average. The fixed-point condition is $\bar{K}F(\tilde{r}_i) = D((1 - \nu)(c + \delta) + r_f + \tilde{r}_i)$ to determine $\tilde{r}_i$, then K_i, then K_f. The investment in K_i that was increasing with the social cost of carbon in case b is now decreasing. This is due to the nonreactivity of consumers to states of nature, which forces capacity to match $K_f = K_i$ in case c. The two sources of energy are not anymore substitute but rather complement. Therefore, as thermal power becomes more harmful to the environment, less capacity of thermal power is installed, which in turn implies less equipment producing from renewables. Electricity consumption has to be reduced, as do capacity and production from both the clean and dirty sources of energy.

As a concluding remark, an important feature of intermittency with nonreactive consumers is that the cost of thermal power equipment r_f does not matter when comparing the cost of the two sources of energy: investing in wind power is socially efficient if $\underline{r}_i/\nu < c + \delta$ (see case b in proposition 1). This is because every kilowatt of wind power installed must be backed up with one kilowatt of thermal power. Thus, without storage, both sources of energy need the same thermal power equipment. Equipment cost determines total consumption and thermal power capacity K_f. If the output of converters were not intermittent, that is, if they were able to produce at full capacity anytime, the condition for investing in wind power would be $\underline{r}_i < c + \delta + r_f$.[19] The cost r_f would be saved for each kilowatt-hour by avoiding duplicating production capacity.

4.2.2. Market Outcome

In cases a and b, competitive wholesale prices are $p^w = c + \delta$, $p^{\bar{w}} = c + \delta + (r_f/[1 - \nu])$. In case a, since all production comes from thermal power, we could have expected a noncontingent price $p^w = p^w = c + \delta + r_f$. However, at this price the green operators with cost $(\tilde{r}_i/\nu) < p^w = c + \delta + r_f$ would enter. Actually, thermal plants can compete on the basis of their marginal operating cost in state w, that is $c + \delta$, since they have installed capacity to meet demand in state $\bar{w}$ where they do not suffer from the competition of renewables. Then competition drives p^w down to $c + \delta$ so that thermal power plants just balance their operating costs. In state $\bar{w}$, that occurs with probability $1 - \nu$, the peak price $p^{\bar{w}} = c + \delta + (r_f/[1 - \nu])$ allows thermal producers to recoup their full costs. Finally, competition between suppliers cancels the margin they could obtain from buying at prices p^w and $p^{\bar{w}}$ and selling at price p: $p = \nu p^w + (1 - \nu)p^{\bar{w}}$. It results $p = c + \delta + r_f$, so that the demand by consumers $D(p)$ just matches the optimal supply $K_f = S'^{-1}(c + r_f + \delta)$. The three

19. See Ambec and Crampes (2017) for a proof. Note that the latter condition cannot be directly derived from proposition 1 by simply considering $\nu \to 1$. This is because with one single state of nature, constraint (3) is missing so that the maximization programs with and without intermittency are not comparable.

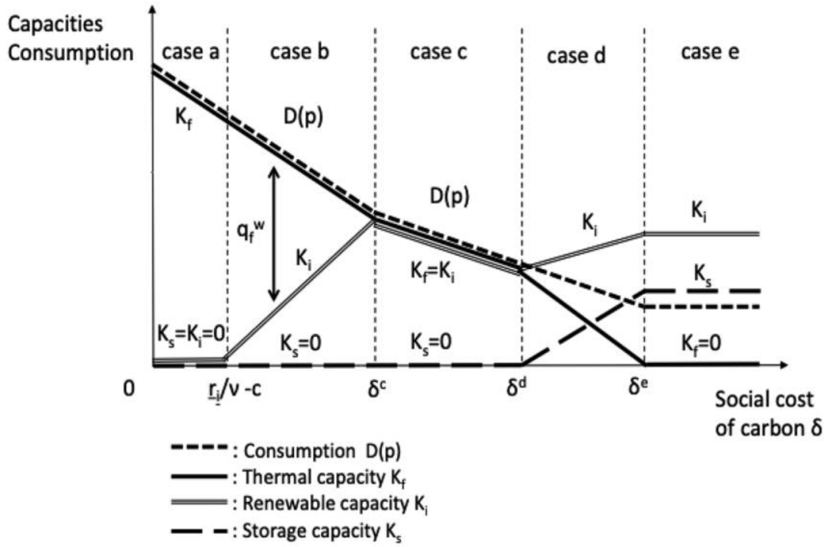

Figure 1. Capacity, production, and consumption when the social cost of carbon varies

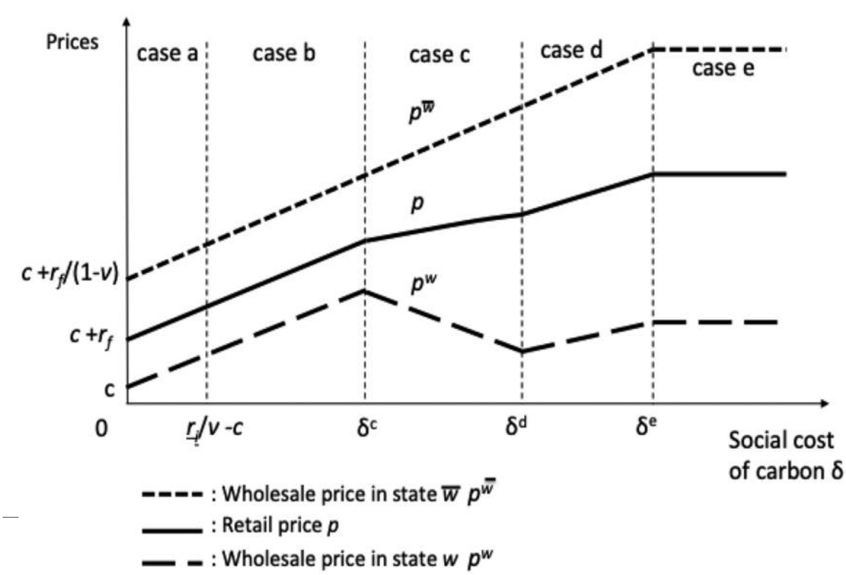

Figure 2. Prices when the social cost of carbon varies

prices $p^w, p^{\bar{w}}, p$ are increasing functions of δ. The only difference between cases *a* and *b* is that, in case *b*, $p^w = c + \delta > (\underline{r}_i/\nu)$ allows the most efficient green producers to enter and produce in state w up to the point where $\tilde{r}_i/\nu = p^w$, obliging thermal power plants to reduce production below capacity. The active wind power producers, that is, those with $\underline{r}_i \leq r_i < \tilde{r}_i$, obtain inframarginal profits.

In case *c*, the wholesale electricity prices are given by the conditions of zero marginal profit for each type of producer in each state of nature. In state w, wind power producers install capacity up to the threshold cost $\tilde{r}_i^c = \nu p^w$ of the least profitable turbines. Remarkably, $\tilde{r}_i^c$, implicitly defined by a fixed point condition, is decreasing with δ and so is p^w: a higher carbon tax lowers the price of wind power in case *c*. In state $\bar{w}$ where thermal power plants are used at full capacity, the price of electricity $p^{\bar{w}} = c + \delta + (r_f/[1 - \nu])$ covers thermal power's capacity cost r_f even though the plants are running only a part $1 - \nu$ of the year. Those wholesale electricity prices yield a retail price $p = \nu p^w + (1 - \nu)p^{\bar{w}} = \tilde{r}_i^c + (1 - \nu)(c + \delta) + r_f$, which is the social cost of the marginal kilowatt-hour on average over the period. It yields a demand for electricity in both states of nature equal to $D(\tilde{r}_i^c + (1 - \nu)(c + \delta) + r_f)$, equal to the quantity produced at first-best.

4.3. Energy Mix with Storage

4.3.1. Optimal Quantities

Storing wind power in state w to supply electricity in state $\bar{w}$ becomes socially optimal when it is cheaper than the social cost of thermal power. Comparing the two costs defines the threshold δ^d in appendix A. In case *d* energy storage does not fully replace thermal power: due to the increasing marginal cost of renewables, stored wind power complements thermal power production in state $\bar{w}$. For stored intermittent power, one kilowatt-hour supplied requires storing λ^{-1} kWh of wind power (with $\lambda^{-1} > 1$) at a cost equal to the sum of the cost of storage equipment r_s and the marginal cost of wind power production $\tilde{r}_i/\nu$. Overall, the marginal cost of one kilowatt supplied in state $\bar{w}$ with stored wind power is $\lambda^{-1}[r_s + (\tilde{r}_i/\nu)]$. Equalizing the two marginal social costs determines the marginal cost $\tilde{r}_i^d$ that, in turn, determines the wind power production capacity $K_i = \bar{K}F(\tilde{r}_i^d)$. It is increasing with the social cost of carbon δ. The same holds for storage capacity K_s because more wind power is produced and stored as thermal power becomes more harmful to the environment. On the other hand, thermal power capacity and production decrease with δ. In other words, the intermittent energy that already monopolized state w is progressively invading state $\bar{w}$ by means of storage, like a more competitive technology located in one country would gain market shares in another thanks to exports.

In case *e*, the social cost of carbon is so high that thermal power is no longer in the socially optimal mix. All electricity production comes from renewables available in state w, with more than half (because of conversion losses) stored to supply in state $\bar{w}$ the same quantity as in state w, that is $K_i - (K_s/\nu) = \lambda K_s/(1 - \nu)$. The marginal cost of providing one kilowatt-hour is $\tilde{r}_i^e/\nu$ in state w and $\lambda^{-1}[r_s + (\tilde{r}_i^e/\nu)]$ in state $\bar{w}$ as seen above.

4.3.2. Market Outcome

With active storage operators, the two wholesale prices are linked by a no arbitrage condition. Indeed, it costs r_s to install one unit of capacity that allows buying one unit of energy in state w and selling $\lambda < 1$ units in state $\bar{w}$. Then there is entry in the storage activity until profits vanish, that is, $\lambda p^{\bar{w}} - p^w - r_s = 0$. In state w, storage operators are buyers who compete with retailers; in state $\bar{w}$ they are sellers competing with thermal power producers.

In case d, thermal producers are still active. Then the wholesale electricity price $p^{\bar{w}}$ must cover their cost $c + \delta + (r_f/[1 - \nu])$. The retail price p reflects the marginal cost of producing one kilowatt-hour anytime with the bundle of technologies: (i) wind power in state w (for both final consumption and storage) and (ii) thermal output plus destored energy in state $\bar{w}$. It is increasing with δ, which implies that electricity consumption $D(p)$ decreases with δ despite an increased investment in renewables K_i.

In case e, we still have $p^w = \tilde{r}_i^e/\nu$ in state w and, using the no-arbitrage condition in storage, $p^{\bar{w}} = \lambda^{-1}[(\tilde{r}_i^e/\nu) + r_s]$. But now, the environmental cost is so high that $\lambda^{-1}[(\tilde{r}_i^e/\nu) + r_s] < c + \delta + (r_f/[1 - \nu])$: then, there is no place for thermal production.

The retail price p reflects the marginal cost of providing one kilowatt-hour regardless of the state of nature using wind power and energy storage. It is $\tilde{r}_i^e/\nu$ in state w and $\lambda^{-1}[r_s + (\tilde{r}_i^e/\nu)]$ in state $\bar{w}$ as seen above. Then $p = \tilde{r}_i^e + (1 - \nu)\lambda^{-1}[(\tilde{r}_i^e/\nu) + r_s]$. Demand at this price defines the marginal green equipment with cost $\tilde{r}_i^e$; then wind power capacity is $K_i = \bar{K}F(\tilde{r}_i^e)$. It is strictly higher than the final consumption $D(p)$ since a fraction K_s/ν must be stored. Storage capacity K_s is tailored to power production from renewables and demand according to the nonreactivity constraint. In case e, electricity is 100% renewable. The energy mix is disconnected from the social cost of carbon.[20]

It is noteworthy that, in case e, the relationship between electricity consumption $D(p)$, renewable capacity K_i, and storage capacity K_s depends solely on two parameters: the energy efficiency of storage λ and the load factor ν. Indeed, without thermal power, the nonreactivity constraint (3) that determines consumption $D(p)$ in the two states of nature becomes:

$$K_i - \frac{K_s}{\nu} = \frac{\lambda K_s}{1 - \nu}, \tag{10}$$

which implies $K_i = [1 + ([1 - \nu]/\lambda\nu)]D(p)$, that is, production capacity exceeds consumption. The difference between K_i and $D(p)$ is decreasing with energy efficiency λ

20. Recall that in our model only thermal power plants are emitting pollutants. We abstract from the carbon footprint of windmills, storage facilities, grid expansion, and anything else related to electricity provision.

and the load factor ν. Electricity production is $\nu K_i = [\nu + (1 - \nu)\lambda^{-1}]D(p)$. It is always higher than consumption as long as storage needs energy that is $\lambda < 1$. Similarly, we have $K_s = (1 - \nu)\lambda^{-1}D(p)$. Therefore the amount of energy stored is higher than consumption if the energy lost with the storage technology $1 - \lambda$ is higher than the load factor ν. It is lower otherwise.[21]

5. PUBLIC POLICY

We now assume that greenhouse gas emissions cannot be taxed at the social cost of carbon or capped while intermittent energy is socially desirable. It means that the market-based provision of electricity inefficiently relies on the technology thermal. We investigate which public policies are likely to implement the optimal energy mix under competition. Technically speaking, we aim at implementing the capacities and productions determined in cases *b*–*e* of proposition 1 in an economy where equilibrium prices do not reflect the social cost of carbon δ. We consider policies that are implemented worldwide: supports to renewables such as feed-in tariffs (FIT) and renewable portfolio standard (RPS), capacity markets, and support to energy storage equipments. Since our results are of the same flavor as FIT and RPS, we focus on FIT in the main text and relegate our analysis of RPS to appendix B.

5.1. Feed-In Tariffs and Consumption Tax

Under FIT, public authorities commit to purchasing wind power at a given price p^i per kilowatt-hour higher than the wholesale market price.[22] FIT are usually financed by a tax on electricity consumption that we will denote as t per kilowatt-hour. The unit price paid by consumers is thus $p + t$. In most countries using this tool, the FIT p^i and the tax t are linked through a budget-balancing constraint: the difference between the price paid to wind-power producers p^i and the wholesale price of electricity p^w must be covered by the tax revenue collected from consumers. To keep things simple, we focus on cases *b* and *c* where large-scale storage is not profitable yet, as it corresponds to the current state of technologies. In these cases, electricity consumption is equal to the thermal power capacity $q = K_f$, the tax revenue is tK_f, while the price gap $p^i - p^w$ is compensated on the νK_i kilowatt-hours of wind power consumed within the same time period. Therefore the budget-balance constraint is:

$$tK_f \geq \nu\left(p^i - p^w\right)K_i. \qquad (11)$$

21. Without energy loss $\lambda = 1$, the relationship between capacities and consumption boils down to $D(p) = \nu K_i$ (consumption equals production) and $K_s = (1 - \nu)D(p)$ (energy stored equals total consumption in state $\bar{w}$).

22. A milder form of green subsidy is the feed-in premium (FIP), which is a subsidy to wind power production on top of the market price. In our model, FIT and FIP are equivalent.

We show that (11) must hold with a strict inequality to implement the first-best energy mix without storage. Let us consider case *b* in proposition 1. The FIT must be set to $p^i = c + \delta$ in order to induce first-best investment in renewables, namely, $K_i = \bar{K}F(\nu(c + \delta))$. However, given the competitive wholesale prices without carbon tax or cap $p^w = c$ and $p^{\bar{w}} = c + (r_f/[1 - \nu])$, binding the budget constraint (11) with $p^i = c + \delta$, leads to a tax rate of $t = (\nu K_i/K_f)\delta$. Under this tax rate, given that the zero-profit condition of the retailers yields a retail price $p = c + r_f$, the posttax retail price is $p + t = c + r_f + (\nu K_i/K_f)\delta$, which is strictly lower than the one that implements first-best, namely, $c + r_f + \delta$ (see case *b* in proposition 1). Electricity is too cheap, which results in overconsumption of thermal powered electricity and overinvestment in thermal power capacity. For the right price signal to be sent to final consumers, the tax rate must be such that $p + t = c + r_f + \delta$, which leads to a tax rate of $t = \delta > (\nu K_i/K_f)\delta$, thereby inducing a budget surplus, that is, the budget-balance constraint (11) is met with a strict inequality.

The same reasoning carries out in cases *c* and *d*: as compared to first-best, a FIT induces too much electricity production as long as thermal power plants are active. The tax that finances the FIT is not high enough to reduce thermal power production at the efficient level. The tax rate should reflect its social cost. It is only when the socially efficient energy mix is carbon free (case *e*) that it can be implemented with FIT combined with a support to energy storage (see sec. 5.3).

Incentive-based fiscal policies aiming at mitigating pollution externalities generate a budget surplus that has to be assigned to stakeholders without altering their behavior (e.g., redistributed to consumers in a way unrelated to their energy consumption). Similarly, a surplus is generated with the next policy we consider, which combines a price cap with capacity payments. We will show that the surplus can be assigned to thermal power producers or electricity retailers depending on whether the payments are auctioned or set by the regulator.

5.2. Feed-In Tariffs and Capacity Payment to Thermal Plants

Instead of launching a Pigouvian carbon tax, governments can use two instruments (in addition to a FIT financed by a tax on consumption) to implement the efficient energy mix without storage: a price cap on electricity and capacity payments. Indeed capping electricity price on the wholesale market to $\bar{p}$ with $c < \bar{p} < c + (r_f/[1 - \nu])$ would put the thermal power producers out of business as they would not be able to recoup their equipment cost. However, a subsidy for each kilowatt of capacity up to a level defined by the regulator can bring them back into business. Setting the maximal capacity eligible to subsidies to the first-best level $K_f = D(c + r_f + \delta)$ would ensure that producers invest at first-best. Hence, the oversupply of thermal powered electricity induced by FIT can be compensated by lowering the thermal power producers' profit in state $\bar{w}$ with a price cap while, at the same time, increasing it by remunerating investment in capacity up to a level that would implement first-best. Capping the energy price and subsidizing the installed capacity is now a public policy often observed in the electricity industry. The proof is straightforward given the equilibrium conditions that determine prices and quantities. Let us see how to determine the capacity payment that implements first-best for a given price cap in case b. Case c proceeds similarly and is therefore omitted.

Under this policy regime, wholesale prices fluctuate between $p^w = c$ in state w and the price cap $p^{\bar{w}} = \bar{p}$ in state $\bar{w}$. Production is at first-best as (i) wind energy converters have priority in the merit order in state w and (ii) thermal plants supply electricity in state $\bar{w}$ with the capacity limited to the first-best level. Let us denote the capacity payment per kilowatt by σ_f. With those wholesale prices, the profit of the thermal power producers includes the revenue net of operating cost $\bar{p} - c$ from the $(1 - \nu)K_f$ megawatt-hours of electricity produced minus the capacity cost net of the subsidy $r_f - \sigma_f$ from the K_f megawatts of capacity required, that is, $(1 - \nu)(\bar{p} - c)K_f - (r_f - \sigma_f)K_f$. Auctioned capacity payments would drive down this profit to zero, which yields a capacity payment of:

$$\sigma_f = r_f - (1 - \nu)(\bar{p} - c). \tag{12}$$

Thermal power production capacity determines the retail electricity price which matches demand at first-best $K_f = D(c + r_f + \delta)$. The final price paid by consumers, which includes the tax t that finances the FIT and the subsidy σ_f to be paid to thermal power producers, boils down to $p + t + \sigma_f = c + r_f + \delta$ (see case b). Using $t = (\nu K_i/K_f)\delta$ to cover the FIT and (12) to balance the budget of thermal producers, we obtain the retail electricity price:

$$p = \nu c + (1 - \nu)\bar{p} + \left(1 - \frac{\nu K_i}{K_f}\right)\delta.$$

With auctioned capacity payments defined in (12), electricity retailers take advantage of the limited support to capacity by enjoying a profit of $p - (\nu p^w + (1 - \nu)\bar{p}) = (1 - [\nu K_i/K_f])\delta$ on each kilowatt-hour. Alternatively, a capacity payment set by the regulator as in Spain (see Fabra 2018) is likely to allow thermal power producers to gain a positive profit at the expense of electricity retailers. The level of σ_f determines how producers and retailers are sharing the surplus from capacity scarcity induced by the price cap.[23]

5.3. Feed-In Tariffs and Capacity Payments to Storage Plants

When storage is socially efficient, another policy must be added: a subsidy on storage equipment. We show that the optimal energy mix with renewables, thermal power,

23. It is worth noting that the choice of the price cap $\bar{p}$ does not impact profits, only σ_f does.

and storage, that is, case *d*, can be implemented by combining FIT (and the associated tax on consumption) with a price cap and capacity mechanism to both thermal power and storage equipment. The same reasoning carries out for RPS (see app. B).

First, a FIT of $p^i = \tilde{r}_i^d/\nu$ induces first-best investment in wind power. Second, paying σ_f as defined in (12) for every kilowatt of thermal capacity up to the socially optimal capacity K_f defined in proposition 1*d* makes sure that the thermal power plants are financially sustainable for every price cap $\bar{p}$ such that $c < \bar{p} < c + (r_f/[1 - \nu])$. Third, the profit per kilowatt-hour to storage operators who buy electricity in state w at price p^w and sell it in state $\bar{w}$ at price $p^{\bar{w}}$ is:

$$p^{\bar{w}} - \lambda^{-1}[p^w + r_s - \sigma_s], \tag{13}$$

where σ_s denotes the payment per kilowatt-hour of storage capacity. Since wholesale market prices are $p^w = c$ and $p^{\bar{w}} = \bar{p}$, subsidizing the K_s kilowatt-hours of storage capacity defined in proposition 1*d* with a payment $\sigma_s = c + r_s - \lambda\bar{p}$ per kilowatt-hour equalizes the storage operator's profit in (13) to zero. Hence the mechanism raises funds to finance the needed storage capacity, and any extra investment in storage is not profitable. As for thermal power capacity, it can be reached by auctioning the subsidized storage capacity: the competitive bid is then σ_s defined above.

Next, we move to the efficient energy mix without thermal power described in proposition 1*e*. As before, a FIT of $p^i = \tilde{r}_i^e/\nu$ induces optimal investment in renewables. To obtain first-best, thermal power plants must be excluded from electricity provision. It can be done by taxing thermal power equipment (instead of subsidizing it) to make it unprofitable or by banning fossil-fueled electricity. Getting rid of fossil fuel is enough to obtain first-best. With only wind power and storage, the electricity prices on the wholesale and retail market defined in proposition 1*e* satisfy the zero-profit conditions of the least profitable wind power producers, storage operators, and electricity retailers. Hence, investment, production, and consumption are optimal.

We summarize our results in the following proposition.

Proposition 2: The optimal energy mix can be implemented by combining support to renewables such as feed-in tariffs (financed by a tax on consumption) and renewable portfolio standards with a price cap and volume-limited capacity payments for thermal power and storage equipment.

Recall that in our model there is only one type of energy storage technology and one type of fossil-fueled power generation. With heterogeneous technologies, a uniform subsidization policy can distort investment decisions by increasing the profits of inframarginal plants, then modify the energy mix. Consequently, any attempt to generalize proposition 2 should take account of differentiated levels of emissions from thermal plants and different conversion losses in storage devices.

Another limitation is due to how we model uncertainty. With one single parameter ν to represent the lack of reliability of intermittent renewables, we cannot analyze subtle changes in the provision of renewables such as mean-preserving spread. With highly variable renewables availability, the type of generation backup and/or storage needed to meet the needs of nonresponsive consumers are quite different than what is required to compensate low variance. Then the capacity mechanism to implement should depend on the uncertainty characteristics.

6. CONCLUSION

Climate change mitigation requires the replacement of fossil-fuel energy with renewables such as wind and solar power. It has been fostered through diverse policies implemented worldwide, from carbon tax to feed-in tariffs and renewable portfolio standards. The intermittent nature of renewables, coupled with the lack of consumers' responsiveness 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 power plants and/or storage). As a result, fossil fuel and renewables are not substitutes in all states of nature. They are indeed substitutes every time the wind is blowing. But when there is no wind and consumers still want power, thermal technology is the indispensable complement to wind turbines, at least until storage becomes cheap enough and carbon expensive enough to make renewables the exclusive source of electricity production.

Because of the intermittency of renewables, the impact of environmental policies is by no means trivial. In particular, the support to renewables through feed-in tariffs (FIT) or renewable portfolio standards (RPS) results in too much thermal power production. Thermal power can be contained with a price cap and capacity payment. When carefully designed, both instruments in addition to FIT or RPS allow implementing the socially efficient energy mix for electricity generation.

Technological innovations provide solutions for the intermittency of renewable sources of energy. Our model allows to identify the components of their social value. Energy storage, in batteries or by pumping water into upstream reservoirs, reduces the burden of intermittency by transferring energy from low-value to high-value dates or states of nature. The marginal value of energy storage depends on the cost difference between intermittent and reliable sources of energy and on energy conversion losses. It is reflected by the difference in electricity prices on the wholesale market. Private investment in storage is efficient when the social cost of carbon is embedded in wholesale prices. Otherwise, storage should be subsidized to reward greenhouse gas emission saving. It is only when thermal power can be left out of the market that FIT or RPS are enough to induce optimal investment in storage facilities.

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. Wind energy converters 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. But this spatial dispersion requires investment in transmission. Other intermittent sources such as tide or wave power can be used to increase the supply of energy by reducing overall intermittency. Our model can be extended to accommodate several intermittent sources of energy with heterogeneous costs and occurrences. 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 is qualitatively valid since intermittent energy capacity must be backed up with thermal power facilities or complemented with storage and demand response.

Finally, our analysis ignores several important issues related to the transition to decarbonating electricity generation: the variability of demand for electricity and its adequacy with the supply from intermittent energy sources, the phasing out of fossil-fueled equipment and the resulting stranded costs, the flexibility of reliable sources of energy, including their starting, stopping, and ramping costs, as well as the redesigning of the transmission infrastructure. These issues could be addressed using an extension of our framework.

APPENDIX A

Proof of Proposition 1

A1. Optimal Quantities

Denoting γ, $\underline{\mu}_f$, $\bar{\mu}_f$, $\underline{\mu}_i$, μ_f, and μ_s the multipliers respectively associated with the constraints (4), (5), (6), (7), (8), and (9), the Lagrange function corresponding to the program can be written as

$$\begin{aligned}\mathcal{L} = {} & \nu\left[S\left(\bar{K}F(\tilde{r}_i) + q_f^w - \frac{K_s}{\nu}\right) - (c+\delta)q_f^w + \underline{\mu}_f q_f^w + \bar{\mu}_f\left(K_f - q_f^w\right) + \underline{\mu}_i(\tilde{r}_i - \underline{r}_i)\right] \\ & + \nu\gamma\left(\bar{K}F(\tilde{r}_i) + q_f^w - \frac{K_s}{\nu} - K_f - \frac{\lambda K_s}{1-\nu}\right) \\ & + (1-\nu)\left[S\left(K_f + \frac{\lambda K_s}{1-\nu}\right) - (c+\delta)K_f\right] \\ & - r_f K_f - \bar{K}\int_{\underline{r}_i}^{\tilde{r}_i} r_i dF(r_i) + \mu_f K_f - r_s K_s + \mu_s K_s.\end{aligned}$$

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

$$q_f^w : \nu\left[S'(.) - (c+\delta) + \underline{\mu}_f - \bar{\mu}_f + \gamma\right] = 0, \tag{A1}$$

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

$$\widetilde{r}_i : \nu\left[S'(.) + \underline{\mu}_i' + \gamma\right] - \widetilde{r}_i = 0, \tag{A3}$$

$$K_s : -S'(.)(1-\lambda) - \gamma\left[1 + \frac{\nu\lambda}{1-\nu}\right] + \mu_s - r_s = 0, \tag{A4}$$

where $\underline{\mu}_i' \equiv \underline{\mu}_i/\bar{K}f(\tilde{r}_i)$, $S'(.)$ denotes $S'(\bar{K}F(\tilde{r}_i) + q_f^w - [K_s/\nu]) = S'(K_f + [\lambda K_s/(1-\nu)])$, plus the complementary slackness conditions derived from the five inequality constraints (5)–(9).

Combining (A1) and (A3) yields:

$$\frac{\widetilde{r}_i}{\nu} = \bar{\mu}_f + \underline{\mu}_i' - \underline{\mu}_f + c + \delta. \tag{A5}$$

Furthermore, combining (A1) and (A2) leads to:

$$\gamma = \bar{\mu}_f - r_f - (1-\nu)\underline{\mu}_f + \mu_f. \tag{A6}$$

a. First, without intermittent energy (case *a* in proposition 1), we have that $\widetilde{r}_i = \underline{r}_i$ and $\underline{\mu}_i' \geq 0$. Also $K_f > 0$ by (2) so that $\mu_f = 0$. Moreover, since $\bar{K}F(\widetilde{r}_i) = 0$, the nonreactivity condition (4) implies $q_f^w = K_f + K_s[(1/\nu) + (\lambda/[1-\nu])]$, which, combined with $q_f^w \leq K_f$, implies $K_s = 0$ and $q_f^w = K_f$, and therefore $\underline{\mu}_f = 0$ and $\bar{\mu}_f \geq 0$. Hence, condition (A5) implies $\underline{r}_i/\nu \geq c + \delta$. Since this is a necessary condition for $K_i = 0$, by contraposition

$$\delta \geq \delta^b \stackrel{\text{def}}{=} \frac{\underline{r}_i}{\nu} - c \tag{A7}$$

is sufficient for $K_i > 0$.

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

b. With investment in intermittent energy $K_i > 0$, we have $\widetilde{r}_i > \underline{r}_i$ and $\underline{\mu}_i' = 0$ in (A5), which becomes $\widetilde{r}_i/\nu = \bar{\mu}_f - \underline{\mu}_f + c + \delta$. Let us assume first that $q_f^w > 0$ (case *b*). Moreover, the nonreactivity constraint with $K_i > 0$ and $K_s = 0$ implies $q_f^w < K_f$, hence $\bar{\mu}_f = 0$. Thus the investment in renewables is given by $\tilde{r}_i/\nu = c + \delta$. Next, (A6) with $\underline{\mu}_f = \mu_f = 0$ leads to $\gamma = \bar{\mu}_f - r_f$. Substituting γ into (A2) and (A4) yields:

$$c + \delta + r_f = \frac{1}{1-\lambda}\left[\left(r_f - \bar{\mu}_f\right)\left(1 + \frac{\lambda\nu}{1-\nu}\right) + \mu_s - r_s\right]. \tag{A8}$$

Since μ_s and $\bar{\mu}_f$ are the only endogenous variables in (A8), except for very specific parameter values, we cannot have both multipliers nil at the same time. Therefore if

$\bar{\mu}_f = 0$ then $\mu_s > 0$: no storage is installed when $K_f > q_f^w > 0$. Equation (A6) with $\mu_f = \underline{\mu}_f = \bar{\mu}_f = 0$ leads to $\gamma = -r_f$. The nonreactivity constraint (3) with $K_s = 0$ yields the installed capacity of thermal power $K_f = K_i + q_f^w = S'^{-1}(c + \delta + r_f)$ as well as the production of fossil energy in state w, $q_f^w = K_f - K_i = S'^{-1}(c + \delta + r_f) - \bar{K}F(\nu(c + \delta))$ given the cost $\tilde{r}_i/\nu = c + \delta$ of the marginal investment in renewables.

Let $\Delta_c(\delta) \equiv S'^{-1}(c + \delta + r_f) - \bar{K}F(\nu(c + \delta)) > 0$. Since $\Delta_c'(\delta) < 0$ and $\Delta_c(0) = S'^{-1}(c + r_f) > 0$, we have that $\Delta_c(\delta) > 0$ for every $\delta < \delta^c$, where δ^c is uniquely defined by $\Delta_c(\delta^c) = 0$, that is:

$$\bar{K}F(\nu(c + \delta^c)) = S'^{-1}\left(c + r_f + \delta^c\right). \tag{A9}$$

Hence $K_f > q_f^w > 0$ for $\delta < \delta^c$, and $q_f^w = 0$ for $\delta \geq \delta^c$ whenever $K_s = 0$.

c. Suppose now that $\delta \geq \delta^c$ and $K_s = 0$ so that $q_f^w = 0$ and $K_f > 0$ (case c). Then $\bar{\mu}_f = \mu_f = 0$, which in (A6) yields $\gamma = -(1 - \nu)\underline{\mu}_f - r_f$. Substitute it into (A2) and (A3) to obtain $\underline{\mu}_f = -(\tilde{r}_i/\nu) + (c + \delta)$ which, in (A1) leads to $S'(.) = (1 - \nu)(c + \delta) + \tilde{r}_i + r_f$. Using the nonreactivity constraint (3) with $K_s = 0$, we thus obtain:

$$S'(K_i) = S'\left(K_f\right) = (1 - \nu)(c + \delta) + \tilde{r}_i + r_f, \tag{A10}$$

Substituting $K_i = \bar{K}F(\tilde{r}_i) = K_f$ in (A10) yields:

$$\bar{K}F(\tilde{r}_i^c) = K_f = S'^{-1}\left((1 - \nu)(c + \delta) + \tilde{r}_i^c + r_f\right), \tag{A11}$$

which determines both K_f and $\tilde{r}_i^c$, the latter being a fixed point in the relationship. It clearly depends on the value of δ.

Substituting $S'(.) = (1 - \nu)(c + \delta) + \tilde{r}_i^c + r_f$ and (from [A3]) $S'(.) + \gamma = \tilde{r}_i^c/\nu$ into (A4) shows that $\mu_s > 0$ (no investment in storage) as long as:

$$\left(\frac{\tilde{r}_i^c}{\nu} + r_s\right)\lambda^{-1} > c + \delta + \frac{r_f}{1 - \nu}. \tag{A12}$$

Let δ^d be the value of δ for which (A12) holds as an equality. Differentiating (A11) shows that $\tilde{r}_i^c$ is decreasing with δ and, therefore, the left-hand side of (A12) is also decreasing with δ while the right-hand side is increasing with δ which shows that δ^d is unique.

d. Assume now $\delta > \delta^d$ so that (A12) is reversed and therefore $K_s > 0$. Knowing that $\mu_s = \mu_f = \underline{\mu}_i' = \bar{\mu}_f = 0$, conditions (A2), (A3), and (A4) joint with (3) are a set of four equations to determine the four unknowns: K_f, K_i, K_s, and γ. As in paragraph **c** above, we have that $S'(.) + \gamma = \tilde{r}_i/\nu$ and $S'(.) = (1 - \nu)(c + \delta) + r_f + \tilde{r}_i$. Inserting these two values into (A4) we obtain the cost of the less efficient intermittent plant:

$$\tilde{r}_i^d = \lambda\nu\left[c + \delta + \frac{r_f}{1 - \nu}\right] - \nu r_s \tag{A13}$$

and the associated volume $K_i = \bar{K}F(\tilde{r}_i^d)$. Using (A13) and $S'(K_i - [K_s/\nu]) = (c + \delta)(1 - \nu) + r_f + \tilde{r}_i^d$ we can determine the storage capacity:

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

Finally, using these values and the nonreactivity constraint (3), we derive the thermal investment $K_f = K_i - ([1/\nu] + [\lambda/(1 - \nu)])K_s$. Note that since $S'' < 0$, $K_i - (K_s/\nu)$ is decreasing with δ, whereas K_s is increasing. We deduce that the optimal thermal capacity must decrease when δ increases. This zone ends out when $K_f = 0$, that is, when δ is equal to the threshold δ^e such that:

$$\delta^e \stackrel{\text{def}}{=} \arg\left[S'^{-1}\left((c + \delta)(1 - \nu) + r_f + \tilde{r}_i^d\right) = \frac{\lambda\nu}{1 - \nu + \lambda\nu}\bar{K}F\left(\tilde{r}_i^d\right)\right],$$

where $\tilde{r}_i^d$ is defined in (A13).

e. Finally, let us consider the case $\delta > \delta^e$ and thus $K_f = 0 = q_f^w$ while $K_s > 0$ (storage without thermal power). The nonreactivity constraint (3) yields:

$$K_s = \frac{\nu(1 - \nu)}{1 - \nu + \lambda\nu}K_i. \tag{A14}$$

Next, by combining (A3) and (A4), we obtain:

$$S'(.) = \tilde{r}_i + (1 - \nu)\lambda^{-1}\left[r_s + \frac{\widetilde{r_i}}{\nu}\right].$$

Using the nonreactivity constraint (3), we get:

$$K_i - \frac{K_s}{\nu} = S'^{-1}\left(\tilde{r}_i + (1 - \nu)\lambda^{-1}\left[r_s + \frac{\widetilde{r_i}}{\nu}\right]\right).$$

Combining the above relationship with (A14) and $K_i = \bar{K}F(\tilde{r}_i)$ we obtain the equation that defines the cost of the optimal marginal equipment in renewable energy $\tilde{r}_i^e$ as a fixed point:

$$\bar{K}F(\tilde{r}_i^e) = S'^{-1}\left(\tilde{r}_i^e\left(1 + \frac{1 - \nu}{\lambda\nu}\right) + \frac{1 - \nu}{\lambda}r_s\right)\left[1 + \frac{1 - \nu}{\lambda\nu}\right].$$

A2. Competitive Prices

In a competitive framework, unit prices p, p^w, and $p^{\bar{w}}$ are independent of individual decisions. We assume that carbon emissions are taxed at their social cost δ per unit.

A2.1. Agents' Plans

- Thermal producers earn $\pi_f = \nu(p^w - c - \delta)q_f^w + (1 - \nu)(p^{\bar{w}} - c - \delta)K_f - r_f K_f$, $q_f^w \leq K_f$.

(i) Whenever $p^w > c + \delta$ they fix $q_f^w = K_f$ and they earn $\pi_f = [\nu p^w + (1-\nu)p^{\bar{w}} - (c + \delta + r_f)]K_f$. Then, if $\nu p^w + (1-\nu)p^{\bar{w}} > c + \delta + r_f$, they fix $K_f > 0$; otherwise $K_f = 0$.

(ii) Whenever $p^w < c + \delta$ they fix $q_f^w = 0$ and they earn $\pi_f = [(1-\nu)(p^{\bar{w}} - c - \delta) - r_f]K_f$. Then if $p^{\bar{w}} > c + \delta + (r_f/[1-\nu])$ they fix $K_f > 0$; otherwise $K_f = 0$.

(iii) Whenever $p^w = c + \delta$ they fix any value $q_f^w \in [0, K_f]$, $K_f > 0$ if $p^{\bar{w}} \geq c + \delta + (r_f/[1-\nu])$ and $K_f = 0$ otherwise.

- Renewable producers earn $\pi_i = \nu p^w \bar{K} F(r_i) - \bar{K}\int_{\underline{r}_i}^{r_i} x dF(x)$, $r_i \geq \underline{r}_i$. Their best choice is given by $\nu p^w = r_i$ if $\nu p^w > \underline{r}_i$; Otherwise, $K_i = 0$
- Storage operators install K_s, fill it with a flow s^w during each of the h^w hours of the w (low price) period and empty it with a flow $s^{\bar{w}}$ during each of the $h^{\bar{w}}$ hours of the $\bar{w}$ (high price) period. Then they earn $\pi_s = -r_s K_s - p^w h^w s^w + p^{\bar{w}} h^{\bar{w}} s^{\bar{w}}$ constrained by $h^w s^w \leq K_s$ and $h^{\bar{w}} s^{\bar{w}} \leq \lambda h^w s^w$. Saturating the constraints, the profit function is $\pi_s = (\lambda p^{\bar{w}} - p^w - r_s)K_s$. The best choice is $K_s > 0$ if $\lambda p^{\bar{w}} - p^w > r_s$; otherwise $K_s = 0$.
- Consumers earn $S(q) - pq$. They buy $q = D(p) \stackrel{\text{def}}{=} S'^{-1}(p) \geq 0$.
- Retailers earn $\pi_r = (p - \nu p^w - (1-\nu)p^{\bar{w}})q$. They operate as long as $p \geq \nu p^w + (1-\nu)p^{\bar{w}}$.
- Equilibrium conditions $q = \bar{K}F(\widetilde{r}_i) + q_f^w - (K_s/\nu) = K_f - (\lambda K_s/[1-\nu])$
- Free entry condition: in each market segment profit is 0 for the last firm in.

A2.2. Parameterized Equilibrium

- Case *a*: When $\delta < (\underline{r}_i/\nu) - c$, to obtain $K_i = 0$, $q = q_f^w = K_f = S'^{-1}(c + r_f + \delta)$, $K_s = 0$ we need $p^w = c + \delta$, $p^{\bar{w}} = c + \delta + (r_f/[1-\nu])$, $p = c + r_f + \delta$. Indeed, $p^w < \underline{r}_i/\nu$ allows us to keep unprofitable renewables out of the market. Thermal plants produce at full capacity in state w but they earn a zero operating profit. This is why $p^{\bar{w}}$ must be high enough to reimburse the fixed cost during period $\bar{w}$. The price p paid by consumers matches the long-run marginal cost (including the environmental cost δ per kilowatt-hour) and allows retailers to balance their budget.

$$p = \nu p^w + (1-\nu)p^{\bar{w}} = c + r_f + \delta. \tag{A15}$$

  Capacity is determined by demand at this price $K_f = D(c + \delta + r_f)$. Finally, with a high cost of storage equipment r_s and a low conversion efficiency λ, the gains in state $\bar{w}$ are not large enough to have $\lambda(r_f/[1-\nu]) - (1-\lambda)(c+\delta) - r_s \geq 0$. Then $K_s = 0$.
- Case *b*: Prices are the same as in the former case. But now, since $\delta > (\underline{r}_i/\nu) - c$, we have $p^w > \underline{r}_i/\nu$ so that entrepreneurs invest in renewables up to the

point where $\tilde{r}_i = \nu p^w = \nu(c + \delta)$. In state w thermal plants provide the difference $q_f^w = K_f - K_i$ and get a zero operating profit, which necessitates $p^{\bar{w}} = c + \delta + (r_f/[1 - \nu])$ to recoup the fixed cost in state $\bar{w}$. Investment in wind power is $K_i = \bar{K}F(\nu(c + \delta))$. Investment in thermal power adjusts to demand $D(p)$ with the retail price defined in (A15), which yields $K_f = D(c + \delta + r_f)$. It shows that, as δ increases, investment in wind power K_i also increases, whereas thermal power capacity K_f decreases.[24] As for storage operators, entry is even less profitable than in case a since their unit margin $\lambda(r_f/[1 - \nu]) - (1 - \lambda)(c + \delta) - r_s$ decreases with δ.

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

$$p^w = \frac{\tilde{r}_i^c}{\nu}. \tag{A16}$$

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

$$p^{\bar{w}} = c + \delta + \frac{r_f}{1 - \nu}. \tag{A17}$$

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 (A16) and (A17), respectively, yields a retail price equal to

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

Investment in both sources of energy is driven by the above retail price: $K_i = K_f = D(p) = D(\tilde{r}_i + (1 - \nu)(c + \delta) + r_f)$ which defines $\tilde{r}_i^c$. Both investments K_i and K_f decrease when δ increases. Again storage is not profitable because $p^w + r_s > \lambda p^{\bar{w}}$.

- Case d: By buying energy in state w to sell it in state $\bar{w}$, storage operators push p^w up and $p^{\bar{w}}$ down to $p^{\bar{w}} = c + \delta + (r_f/[1 - \nu])$ which is necessary to balance the budget of the thermal power producers. Entry stops when the zero-profit condition per kilowatt-hour is reached:

$$\lambda p^{\bar{w}} - p^w = r_s. \tag{A18}$$

Combining with $p^{\bar{w}}$ we obtain $p^w = \lambda(c + \delta + [r_f/(1 - \nu)]) - r_s$. Given this price, we deduce the marginal operator of green production: $\tilde{r}_i^d = \nu p^w$. The

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

zero-profit condition for retailers determines the retail price of electricity $p = (1 - \nu + \nu\lambda)(c + \delta + [r_f/(1 - \nu)]) - \nu r_s$, then demand $D(p)$ and capacities K_s and K_f.

- Case e: To keep thermal producers out of activity, we now need $p^{\bar{w}} < c + \delta + (r_f/[1 - \nu])$. As in case d the zero-profit condition for the less efficient turbine yields $p^w = \tilde{r}_i^e/\nu$ while the zero-profit condition for the storage facility leads to $p^{\bar{w}} = \lambda^{-1}[(\tilde{r}_i^e/\nu) + r_s]$. The zero-profit condition for retailers yields the retail price of electricity p. Since $K_f = 0$, all these values are related by:

$$S'\left(\frac{\lambda K_s}{1 - \nu}\right) = S'\left(\bar{K}F(\tilde{r}_i) - \frac{K_s}{\nu}\right) = p = \nu p^w + (1 - \nu)p^{\bar{w}}$$
$$= \tilde{r}_i^e + (1 - \nu)\lambda^{-1}\left[\frac{\tilde{r}_i^e}{\nu} + r_s\right].$$

APPENDIX B

Renewable Portfolio Standards

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 given share of "green" electricity. They are required to purchase renewable energy credits (REC) or green certificates produced by state-certified renewable generators, which guarantees that the targeted share is achieved. For each kilowatt-hour sold, renewable energy producers issue an REC. Retailers and big consumers are required to buy enough credits to meet their target. In our model, an 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 $\alpha = \nu K_i/K_f$. Wind producers issue REC that they sell to electricity suppliers at price g. They thus obtain $p^w + g$ per kWh where p^w is the wholesale price in state w. Retailers buy αq REC in addition to electricity in the wholesale market when supplying q kilowatt-hour 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:

$$p^w + g = \frac{\tilde{r}_i}{\nu}, \tag{B1}$$

$$p = \nu\left[p^w + g\frac{K_i}{K_f}\right] + (1 - \nu)p^{\bar{w}}. \tag{B2}$$

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 converter

$\tilde{r}_i/\nu$ as shown in (B1). Retailers transfer the additional cost of producing electricity from renewables to consumers by increasing electricity prices by $\nu(K_i/K_f)g = \alpha g$.

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 $p^w = c$ (recall that there is no Pigou tax). The equipment cost is covered in state $\bar{w}$ with a wholesale market price $p^{\bar{w}} = c + (r_f/[1 - \nu])$. Replacing the wholesale prices by their values into (B1) and (B2) yields:

$$g = \frac{\tilde{r}_i}{\nu} - c, \tag{B3}$$

$$p = c + r_f + \alpha\left[\frac{\tilde{r}_i}{\nu} - c\right]. \tag{B4}$$

According to condition (B3), 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 in state w. Condition (B4) 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 an 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.

The optimal energy mix without storage (case *b* in proposition 1) can be implemented by means of RPS combined with a tax on electricity consumption. Setting the RPS α to foster first-best investment in renewables $K_i = \bar{K}F(\nu(c + \delta))$ in case *b* of proposition 1 determines the cost of the marginal wind turbine $\tilde{r}_i = \nu(c + \delta)$. It leads to a retail price $p = c + r_f + \alpha\delta$ in (B4). It is strictly lower than the one inducing first-best electricity consumption $p = c + r_f + \delta$ as $\alpha < 1$. As a result, too much electricity using fossil fuel will be produced. A tax on electricity consumption set at the level $t = \delta(1 - \alpha)$ leads to retailing price $p + t = c + r_f + \alpha\delta + (1 - \alpha)\delta = c + r_f + \delta$, which is the price that induces first-best consumption (see proposition 1*b*).

The optimal energy mix without storage can also be implemented by means of RPS combined with a price cap and volume-limited capacity payments. Capping wholesale electricity price by $\bar{p}$ with $c < \bar{p} < c + (r_f/[1 - \nu])$ and subsidizing $K_f = D(c + r_f + \delta)$ kilowatts of capacity at a rate σ_f defined in (12) would implement first-best under RPS with $\alpha = \nu K_i/K_f$ where $K_i = \bar{K}F(\nu(c + \delta))$ and $K_f = D(c + r_f + \delta)$ as defined in proposition 1*b*.

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