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Stefan Ambec and Claude Crampes

Toulouse School of Economics

Real-time electricity pricing to balance green energy intermittency

Stefan Ambec* and Claude Crampes†‡

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Abstract

The presence of consumers able to respond to changes in wholesale electricity prices facilitates the penetration of renewable intermittent sources of energy such as wind or sun power. We investigate how adapting demand to intermittent electricity supply by making consumers price-responsive - thanks to smart meters and home automation appliances - impacts the energy mix. We show that it almost always reduces carbon emissions. Furthermore, when consumers are not too risk-averse, demand response is socially beneficial because the loss from exposing consumers to volatile prices is more than offset by lower production and environmental costs. However, the gain is decreasing when the proportion of reactive consumers increases. Therefore, depending on the costs of the necessary smart hardware, it may be non-optimal to equip the whole population.

Keywords: electricity, intermittency, renewables, dynamic pricing, demand response, smart meters.

JEL codes: D24, D62, Q41, Q42, Q48.

*Corresponding author: Toulouse School of Economics, INRAE, University of Toulouse, 1 Esplanade de l'Université, 31 080 Toulouse Cedex 06, France, Phone: +33 5 61 12 85 16, Fax:: +33 5 61 12 85 20, e-mail: `stefan.ambec@tse-fr.eu`.

†Toulouse School of Economics, University of Toulouse, France.

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1 Introduction

Having consumers reactive to scarcity signals is an essential ingredient to reach efficiency in the allocation of resources. In standard markets, scarcity is signaled by time-varying prices. However, processing information and adapting consumption accordingly is not a simple problem for consumers, in particular when consumption decisions must be taken very frequently and prices vary several times a day. This is the case for electricity. Consumers do not buy a bulk of electricity at a given price, store it at home for several days or weeks, and take it out of storage according to their versatile needs. For long, the solution has been to sign a contract with a fixed price of electricity regardless of the timing of consumption. For a given total quantity purchased, consumers who withdraw energy off-peak and those who do it at peak periods are billed the same. Households are charged a fixed price by default in most countries.[1] They might sometimes be able to opt to some sort of time-varying price, the most popular being Time-of-Use (TOU),[2] more rarely Critical Peak Pricing (CPP).[3] Big industrial and commercial consumers have also access to some form of real-time price adjustment through voluntary load shedding, i.e. being rewarded for reducing consumption below business-as-usual levels during peak periods.[4] However, most consumers stick to a fixed price contract.[5]

The time-invariant pricing paradigm has recently been challenged by two novelties in electricity provision. The first one has to do with digitization. The development of smart-meters make real-time pricing technologically feasible in large scale. Furthermore, consumers can now download free apps in their smartphones that help them reacting to price changes. They receive day-ahead price signals and they can adjust their consumption in real-time with a couple of clicks. They can also program their consumption in advance with automatic switching devices or directly in their electric appliances (laundry, air-conditioners, heating

[1] With the notable exception of Spain which charges wholesale electricity prices by default, see (Roldán-Fernández et al. 2017).

[2] TOU prices vary according to a daily schedule, mostly peak versus off-peak hours.

[3] Under CPP, the electricity price is increased during declared peak-hours, with a requirement notice period (e.g. previous day), potentially with limitation in duration per year.

[4] On load-shedding, see Crampes and Léautier (2015) and Crampes and Waddams (2017). Some large consumers have contracts that contains a clause of interruptible load allowing the system operator to automatically amend their level of consumption. Interruptible consumers are paid for this service. In January 2019, the French system operator RTE used this possibility to contribute to the restoration of the frequency of the European transmission system that was experiencing a potentially damageable drop (ENSTO-E, 2019).

[5] For instance, Schneider and Sunstein (2017) reports that 3.56 %, 6.76 % and 10.13 % of US residential, commercial and industrial electricity consumers respectively were exposed to some form of time-varying pricing in 2014.

systems), depending on weather conditions and other demand shocks, and possibly on prices.

The second novelty that makes Real-Time Pricing (RTP) more adapted to nowadays electricity provision is the penetration of intermittent renewable energies such as solar and wind into the energy mix. Clearly, with these technologies the degree of energy scarcity is permanently changing, partially in a predictable way, partially in an erratic way. Weather conditions impact not only demand for electricity but also supply. Balancing the system becomes more complex with a high share of wind and solar power. Having consumers reacting to wholesale electricity prices would certainly help. In addition, the presence of reactive consumers would improve both the economical and environmental value of intermittent renewables by reducing the dependance to polluting conventional sources of energy such as natural gas and coal.

What are the private and social gains of making consumers reactive to electricity RTP? The question has been analyzed by Borenstein and Holland (2005) and Joskow and Tirole (2007) in a framework where demand is the source of uncertainty. Electricity is produced from conventional energy sources (fossil and/or nuclear) and power plants can be called anytime. Consumers benefit from RTP by avoiding curtailment and/or simply adapting their current demand to price.

We investigate the same question with uncertainty on the supply side. Our analysis is motivated by the transition to a decarbonated energy mix which replaces thermal power with wind and solar power. Making consumers responsive to wholesale prices that intermittent energy sources make random and/or cyclical is a crucial ingredient of this transition. A better match between electricity consumption and production reduces the need to back-up windmills and PV panels with thermal power facilities or storage capacity (as analyzed in Ambec and Crampes 2012, 2019). It thus impacts the optimal investment in production capacities from both sources of energy. Reversely, investment into wind and solar power production capacities changes the benefit of making consumers reactive.

In Borenstein and Holland (2005) or Joskow and Tirole (2007), random demand is exogenous to the model whereas in our framework, the choice of wind and solar power production capacities allows to control the level of residual demand for thermal power. Both types of models result in uncertain residual demand. However, by assuming that all the source of uncertainty is on the supply side, the uncertainty magnitude is increasing with the penetration of renewables in our model: the more windmills and PV panel are installed, the higher is the variation of supply with weather conditions. Hence, the optimal investment in renewable is closely related to how consumers can cope with uncertainty by reacting to real-time prices. Our framework relates two sides of the energy transition: demand response (measured by the share of consumers reacting to RTP) and decarbonation (measured by the social cost of carbon). It allows to investigate a further research question: what is the role of demand response in the decarbonation of the electricity mix?

Conceptually, we extend Ambec and Crampes (2019) by assuming that a share of consumers are 'reactive' in the sense that they adapt their electricity consumption to wholesale market prices.[6] We characterize the optimal energy mix with a given share of reactive consumers and its decentralization in competitive market with a pigouvian carbon tax. We find that, compared to Ambec and Crampes (2019), the presence of reactive consumers modifies the energy mix not only quantitively by also qualitatively. More precisely, in Ambec and Crampes (2019), thermal power plants are running below their production capacity when the wind is blowing and/or the sun is shining because they are used as back-up. In contrast, having reactive consumers allows exploiting the full capacity of thermal power equipments regardless of weather conditions. We also show that, for a given carbon tax, making more consumers reactive to wholesale prices reduces carbon emissions in almost all parameter configurations.[7] Hence, a policy that supports RTP mitigates climate change, even if there is a "rebound effect".

We vary the share of reactive consumers to find out the social benefit of RTP. We identify three impacts of RTP. First, it exposes consumers to volatile consumption which lowers their welfare. Second, it lowers economic and environmental costs by reducing both thermal powered capacity and production. Third, it increases economic costs by requiring more renewables. We show that, if consumers are not too risk-averse and/or price-inelastic, the RTP is both socially and individually beneficial. Yet the marginal benefit from RTP decreases with the share of reactive consumers. The latter result suggests that, since reacting to RTP incurs technological and behavioral costs, not all consumers should be equipped with smart-meters and automatic load-switching devices.[8]

Our theoretical analysis complements many recent empirical studies on time-varying pricing. Experimental evidence suggests that household do react to CPP provided that they get real-time feedback on the quantity of electricity consumed via an in-home display (Allcott, 2011, Houde et al. 2013, Jessoe and Rapson, 2014). They reduce their consumption during the window of critical peak price (a couple of hours), and increase their consumption just after this period, compared to the household with a fixed-price contract (Jessoe and Rapson, 2014). They might also reduce their consumption around the window of price increase (Andersen et

[6]Helm and Mier (2019) investigate a similar model of electricity provision from intermittent sources with consumers reacting to electricity prices in the wholesale market. They show that the first-best can be implemented with a small share of non-reactive consumers. However, unlike us, they do not identify the private and social value of making consumers reactive to wholesale prices.

[7]On the same vein, Dato et al. 2020 find that smart meter deployment can increase or decrease greenhouse gas emissions.

[8]This result is in line with Léautier (2014) who estimates that the average benefit from making consumers price-responsive is well below the cost of installing the necessary smart-meters in France.

al. 2017). Households react even more to CPP by reducing further their consumption if they are equipped with automation technologies (Bollinger and Hartmann, 2016, Gillan, 2017).[9] They are more likely to respond if they are given the option to opt-in to time-varying pricing rather than getting it by default (Fowlie et al. 2017).

The article is organized as follows. In section 2, we determine the optimal energy mix when a given proportion of consumers are price reactive. We also compute the wholesale and retail prices allowing to decentralize the first-best allocation. In section 3, we analyze the effects of a policy aimed at increasing the number of price-sensitive consumers. The global outcome is positive in terms of net consumer surplus. We discompose it into a negative component due to the exposure of consumers to risk and the increased cost in generators using renewables, off-set by a gain due to the decrease in the production of plants burning fossil fuel. The gain is also positive if the consumer's welfare exhibits some risk-aversion. We conclude by briefly discussing the impact of time-varying pricing on inequality among households and on competition in the power sector, and the omission of behavioral dimensions in the welfare.

2 Optimal energy mix with reactive consumers

We first introduce the analysis framework where electricity production can come from both intermittent green sources and reliable but polluting plants, and some consumers buy energy at spot prices while others sign a fixed-price contract with a retailer. In subsection 2.2 we determine the optimal energy mix as a function of the environmental cost induced by burning fossil fuel. We also compute the wholesale and retail prices that implement the first best. In subsection 2.3 we compare the polluting emissions respectively due to the price-responsive and non price-responsive consumers. Finally, subsection 2.4 examines how changes in the proportion of price responsive consumers affects the energy mix and the resulting emissions.

2.1 The model

We consider a model of energy production and supply where electricity can be produced by means of two technologies. One, the "fossil" source, is a fully controlled but polluting technology (e.g. plants burning coal, oil or natural 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. 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 SO2, NOx, or particulate matters. Let us denote by $\delta > 0$ the

[9] For commercial and industrial consumers, Blonz (2020) finds a reduction of consumption by 13.5% during critical peaks in California with CPP.

environmental marginal damage due to thermal power, that is, the social damage from CO_2 emissions per kilowatt-hour of electricity generated.[10]

The second technology relies on a clean but 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, e.g. wind is blowing. There are 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 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. The total potential capacity that can be installed at cost r_i is $\bar{K}$ for every r_i. We assume that investing in new intermittent capacity has no effect on the probability of occurrence of state w. The probability only depends on the frequency of windy days (or sunny hours for solar energy). Investing only increases the amount of energy produced in state w.[11] All along the paper, we assume that electricity cannot be stored, transported or curtailed.[12] The only way to balance supply and demand is then to rely on production adjustment and/or demand adjustment through price variation.

We assume a continuum of identical consumers of mass one. All consumers derive a gross utility $S(q)$ from the consumption of q kilowatt-hours of electricity. Utility is a continuous derivable function with $S' > 0$ and $S'' < 0$. If there is a market for electricity at unit price p, the inverse demand per consumer is $P(q) = S'(q)$ and the direct demand function is $D(p) = S'^{-1}(p)$, derived from the solution to $\max_q S(q) - pq$. The demand function is the same for all but the price to consider is different: p stands for the wholesale or the retail price depending on whether the consumer is price responsive or not. The retail price does not vary

[10] The assumption of constant marginal damage makes sense for global pollution problems such as greenhouse gas emissions because local thermal power production has a small impact on climate change. For local pollution such as SO_2, NOx or particulates, a marginal damage increasing with emissions would be more appropriate. In this case, the Pigouvian tax rate would vary with the level of emissions. Furthermore, we do not consider the co-benefit of improving air quality by reducing CO2 emissions (see Ambec and Coria, 2018).

[11] This assumption can be relaxed by allowing for more states of nature, that is by changing the occurrence of intermittent energy from several sources. See Ambec and Crampes (2012), Section 4, and Yang (2020), Section 4.2.

[12] By contrast, rationing is at the core of the papers of Joskow and Tirole (2007) and Léautier (2014). However, they both show that only non-reactive consumers should be rationed, which is still non feasible on technical grounds for most consumers as they all are supplied through the same distribution lines. In the future it might be possible to separate the two types thanks to smart appliances and meters. Our hypothesis of no-rationing is consistent to electricity provision in developed countries.

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.[13]

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. Since non-reactive consumers want to buy the same quantity whatever the state of nature, as long as they cannot be rationed and neglecting the operation costs of retailers, the retailer's zero profit condition boils down to $p = \nu p^w + (1-\nu)p^{\bar{w}}$, i.e. the retail price of one kilowatt-hour of electricity sold to non-reactive consumers is equal to its expected price in the wholesale market. Carbon emissions are taxed at the Pigou rate equal to its social cost δ per kilowatt-hour, and the revenue from this tax is used in a neutral way by the government. Lastly, we assume that

$$S'(0) > c + r_f + \delta. \tag{1}$$

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

The proportion of electricity consumers who react to price variations in the wholesale market is denoted by β ($1 \geq \beta \geq 0$). Reactive consumers (subscript "r") buy q_r^w kilowatt-hours in state w and $q_r^{\bar{w}}$ in state $\bar{w}$. We denote by $q_{\bar{r}}$ the electricity consumption of non-reactive consumers (subscript $\bar{r}$).

2.2 Optimal energy mix

First note that we can directly state that $q_i^{\bar{w}} = 0$, $q_f^{\bar{w}} = K_f$ and $q_i^w = K_i = \bar{K}F(\tilde{r}_i)$ where $\tilde{r}_i \geq \underline{r}_i$. Indeed, without wind (in state $\bar{w}$) there is no generation from wind turbines. As for $q_f^{\bar{w}} = K_f$ and $q_i^w = K_i$, they are justified by the costs of capacity, r_f and $\tilde{r}_i$: it would be inefficient not to produce at full capacity with technology f in state $\bar{w}$ and with technology i in state w respectively. Finally $K_i = \bar{K}F(\tilde{r}_i)$ because turbines will be installed in the order of increasing cost. Note that assuming the possibility of having $q_f^{\bar{w}} = K_f$ and $q_f^w < K_f$ is a strong implicit hypothesis on the flexibility of technology f.

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:

$$\begin{aligned} EW &= \beta[\nu S(q_r^w) + (1-\nu)S(q_r^{\bar{w}})] + (1-\beta)S(q_{\bar{r}}) \\ &\quad -\nu(c+\delta)q_f^w - (1-\nu)(c+\delta)K_f \\ &\quad -\bar{K}\int_{\underline{r}_i}^{\tilde{r}_i} r_i dF(r_i) - r_f K_f. \end{aligned} \tag{2}$$

[13] We assume that consumers have signed a contract that prevents any possibility of arbitrage afterwards.

The two terms in the first line are the gross expected surplus of reactive and non-reactive consumers respectively. The two terms in the second line are the operating costs of the fossil fuel technology (including the environmental damage) in states of nature w and $\bar{w}$ respectively. There is no operating cost for the renewable source. Finally the third line represents the capacity costs of the renewable and the fossil-fuel technologies respectively.

The constraints of the problem are:[14]

$$
\begin{aligned}
K_f &= \beta q_r^{\bar{w}} + (1-\beta) q_{\bar{r}} && (3)\\
\bar{K}F(\tilde{r}_i) + q_f^w &= \beta q_r^w + (1-\beta) q_{\bar{r}} && (4)\\
q_f^w &\geq 0 && (5)\\
q_f^w &\leq K_f && (6)\\
\tilde{r}_i &\geq \underline{r}_i && (7)
\end{aligned}
$$

The first two constraints (3) and (4) are the market clearing conditions in states of nature $\bar{w}$ and w respectively. Each condition equalizes electricity supply from the two technologies with demand from both types of consumers. The third constraint requires that electricity production from fossil fuel in state w be non-negative, and the fourth constraint precludes it from exceeding production capacity. The fifth constraint (7) states that the threshold capacity cost $\tilde{r}_i$ of renewables is bounded downward by the lowest cost $\underline{r}_i$.

The solution to welfare maximization varies with the parameter values in a complex way because the thresholds between the different types of dispatching depend on the number of reactive consumers. Let $\delta_1(\beta)$ denote the solution to

$$\beta\left[D(c+\delta_1) - D\left(c+\delta_1+\frac{r_f}{1-\nu}\right)\right] = \bar{K}F(\nu(c+\delta_1)), \tag{8}$$

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

$$\beta D(c+\delta_2) + (1-\beta)D(c+\delta_2+r_f) = \bar{K}F(\nu(c+\delta_2)). \tag{9}$$

As shown by (28) in Appendix A, 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 and the solution with production below capacity. The second equation is derived from $q_f^w = 0$. It separates the solution where the fossil technology is used in state w and the solution where all production in state w comes from the intermittent technology.

Solving the above program and characterizing the equilibrium prices in the wholesale and retailing markets allowing to decentralize the first best allocation, we obtain the following

[14] We omit sign constraints on the three consumption variables because we already know they are strictly positive by (1).

proposition.[15] The proof is in Appendix A.

Proposition 1 *The optimal levels of capacity and output, and the prices that decentralize them, are such that:*

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

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

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

(b) for $\delta^a \le \delta \le \delta_2(\beta)$*: both sources of energy are used in state* w

(b1) for $\delta^a \le \delta \le \delta_1(\beta)$*: thermal power is used at full capacity in state* w

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

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

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

(b2) for $\delta_1(\beta) \le \delta \le \delta_2(\beta)$*: thermal power is used below capacity in state* w[16]

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

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

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

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

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

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 1 is illustrated in Figure 1. The frontiers between the different zones are discussed in subsection 2.4.

Proposition 1 generalizes the optimal energy mix described in Ambec and Crampes (2019) to the case where a fraction of consumers are reactive to spot prices. Importantly, the presence of reactive consumers introduces a discontinuity in the optimal energy mix. Indeed, the above

[15] Note that the optimal energy mix described in Proposition 1 differs slightly from the one derived in Helm and Mier (2019) because intermittency is modeled differently. Helm and Mier (2019) assume a continuum of states of nature with a minimal supply of intermittent source of energy in the worst scenario. Thermal power plants can be used at full capacity and below capacity during windy days in their model while we do have two distinct cases ($b1$) and ($b2$) in ours. Furthermore, no thermal power production is installed when wind power is cheap in Helm and Mier (2019), whereas we always need thermal power equipments in our model to provide electricity when the wind is not blowing.

[16] As shown in the Appendix, this case is valid if ν is below a critical value $\widehat{\nu}$. Otherwise, case (b.2) vanishes for large values of β.

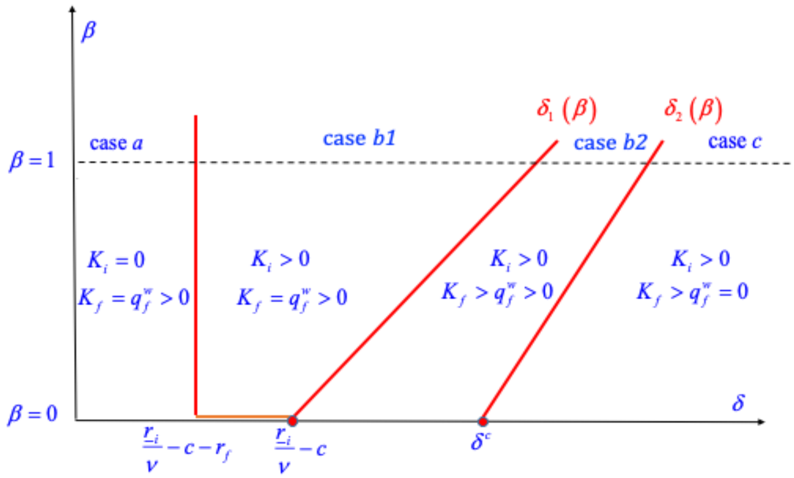

Figure 1: Optimal energy mix with a share of reactive consumers

energy mix and prices determined for $\beta > 0$ have strong differences with the case where $\beta = 0$ analyzed in Proposition 1 of Ambec and Crampes (2019). When $\beta = 0$, the optimal energy mix as a function of the environmental cost δ is represented along the x-axis in Figure 1. It has only three zones[17]: (a), $(b2)$ and (c). In zone (a), no wind turbine should be installed. All production comes from the plants burning fossil fuel at full capacity, whatever the state of nature. In zone $(b2)$, wind turbines are installed. Thermal power plants are producing in both states of nature, at full capacity in state $\bar{w}$ and below capacity in state w to complement wind power. In zone (c), wind turbines are the only electricity producers in state w, and thermal power plants only produce in state $\bar{w}$, both at full capacity.

The presence of reactive consumers modifies the optimal energy mix described in Ambec and Crampes (2019) on three features. First, as long as $\beta > 0$, an additional zone labeled $(b1)$ shows up. In this zone, thermal power plants are producing at full capacity in both states of nature w and $\bar{w}$. Having the f capacity fully used while the i technology is operating is not a solution for only non-reactive consumers because the constraint that maintains the output equality in the two states of nature $K_i+q_f^w = K_f$ makes it necessary to have $q_f^w < K_f$ whenever $K_i > 0$. In contrast, thanks to reactive consumers, thermal power plants can now be run at full capacity on windy days because reactive consumers actively participate in the balancing of the system. We can see it by combining (3) and (4). It gives $K_i + q_f^w = K_f + \beta(q_r^w - q_r^{\bar{w}})$ which allows to have $q_f^w = K_f$ even if $K_i > 0$.

Second, introducing some reactive consumers lowers the threshold social value of carbon above which wind power becomes socially beneficial. The threshold is now $\frac{r_i}{\nu} - (c+r_f)$ whereas

[17]The proof is in Ambec and Crampes (2019).

with only non-reactive consumers ($\beta = 0$), it is $\frac{r_i}{\nu} - c$. The reason is, without consumer's adaptation, thermal power plants are used below full capacity in state w when wind turbines are active (case (b) of Proposition 1 in Ambec and Crampes 2019). Therefore the opportunity benefit to take into consideration is only the *operating cost* of fossil plants $c+\delta$. Now, with the presence of reactive consumers that results in the emergence of case ($b1$), the thermal power plants are fully used in state w. The threshold becomes $\frac{r_i}{\nu} - (c + r_f)$ because 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 $c + \delta + r_f$. As a consequence, there is a discontinuity in the threshold when jumping from $\beta = 0$ to $\beta > 0$.[18]

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

2.3 Consumption and carbon emissions

We now compare the consumption and the carbon emission of reactive and non-reactive consumers. 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 consume less than non-reactive consumers when the price is higher (in state $\bar{w}$) and more when the price in lower (in state w). They switch between consumption sources across states of nature or dates: consumption from a representative reactive consumer is $D(p^w)$ and $D(p^{\bar{w}})$ in states w and $\bar{w}$ respectively, while a representative non-reactive consumer consumes $D(p)$ is both states of nature. From this perspective, reactive consumers are substitutes to storage as they are able to 'transfer' electricity from one state of nature to another by shifting their consumption. Such up and down adaptation to price variations by reactive consumers has been documented empirically by Jessoe and Rapson (2014).

How a reactive consumer's total consumption $\nu D(p^w) + (1-\nu)D(p^{\bar{w}})$ compares to that of a non-reactive consumer $D(p_{\bar{r}})$ depends on the curvature of the demand-function $D(p)$. Since $p = \nu p^w + (1-\nu)p^{\bar{w}}$, $D(p)$ linear implies $D(p) = \nu D(p^w) + (1-\nu)D(p^{\bar{w}})$: both types consume the same amount of electricity across states of nature. If $D(p)$ is strictly convex (i.e. $D''(p) > 0$), by the Jensen inequality, $D(p) = D(\nu p^w + (1-\nu)p^{\bar{w}}) < \nu D(p^w) + (1-\nu)D(p^{\bar{w}})$: reactive consumers consume more than non-reactive consumers. Reversely, if $D(p)$ is strictly concave (i.e. $D''(p) < 0$), $D(p) = D(\nu p^w + (1-\nu)(p^{\bar{w}}) > \nu D(p^w) + (1-\nu)D(p^{\bar{w}})$ so that reactive consumers consume less that non-reactive consumers. Hence, the difference in terms of overall electricity consumption depends on the variation of price-elasticity along the demand curve.

[18]This discontinuity confirms that the introduction of reactive consumers is not equivalent to just increasing ν in the case of non-reactive consumers only, as if it was possible to use wind power more often.

Being reactive induces more consumption through a 'rebound effect' when $D(p)$ is convex, that is when demand becomes less elastic with higher price. In the opposite case, adjusting consumption to wholesale prices reduces total electricity consumption.

When it comes to environmental externalities, the pollution induced by the electricity consumed by reactive consumers is generally lower. It is so even when they consume more than non-reactive consumers. It is only in cases $(b1)$ and $(b2)$ in Proposition 1 that more electricity bought by reactive consumers might translate into more emissions. However it is unlikely as they consume more when the energy mix is cleaner in state w and less when it is dirtier in state $\bar{w}$. To get more emissions, it should be such that the extra kilowatt-hours consumed in state w pollute more than the one saved in state $\bar{w}$, formally if $\alpha\nu(q_r^w - q_{\bar{r}}) > (1-\nu)(q_{\bar{r}} - q_r^{\bar{w}})$ where $\alpha \equiv \dfrac{q_f^w}{K_i + q_f^w}$ is the carbon content per kilowatt-hour relative to fossil fuel. Yet, even if it is case, we will show in the next subsection that making consumers reactive *almost always* reduces polluting emissions.

2.4 Energy mix adjustment to more demand-response

We examine how the optimal energy mix varies with the proportion of reactive consumers. We derive three corollaries to Proposition 1 that highlight the role of reactive consumers in the energy market penetration by intermittent renewables.

Corollary 1 *When energy supply is intermittent, increasing the share of reactive consumers reduces polluting emissions in cases* $(b2)$ *and* (c). *It also reduces emissions in case* $(b1)$ *as long as* β *is not too large.*

To investigate how increasing demand response impacts greenhouse gas emissions when $K_i > 0$, since total emissions are increasing with the production from thermal plants, we just have to compute the derivative of $\nu q_f^w + (1-\nu)K_f$ with respect to β.

Consider first the simplest case $(b2)$. Since $K_f = \beta D(p^{\bar{w}}) + (1-\beta)D(p)$ and $q_f^w = K_f - K_i$, the emissions are equal to $\beta D(p^{\bar{w}}) + (1-\beta)D(p) - \nu K_i$ where $p^w = c + \delta = \frac{\tilde{r}_i}{\nu}$, $p = c + r_f + \delta$. Neither the prices p^w, p nor the renewables cost $\tilde{r}_i$ vary with β; therefore we obtain

$$\frac{d[\nu q_f^w + (1-\nu)K_f]}{d\beta} = D(p^{\bar{w}}) - D(p) < 0,$$

since $p^{\bar{w}} > p$.

In case (c), we have $q_f^w = 0$ so that polluting emissions are proportionate to $K_f = \beta D(p^{\bar{w}}) + (1-\beta)D(p)$, where $p^{\bar{w}} = c + \delta + \frac{r_f}{1-\nu}$, $p = \tilde{r}_i + (1-\nu)(c+\delta) + r_f$. Then,

$$\frac{dK_f}{d\beta} = \left[D(p^{\bar{w}}) - D(p)\right] + (1-\beta)D'(p)\frac{d\tilde{r}_i}{d\beta}$$

with $\frac{d\tilde{r}_i}{d\beta} > 0$ by (37). Here again polluting emissions decrease when β is increased.

Consider now case $(b1)$. Since $q_f^w = K_f$, emissions are equal to $K_f = \beta D(p^{\bar{w}}) + (1-\beta)D(p)$ with $p^{\bar{w}} = c + \delta + \frac{r_f - \tilde{r}_i}{1-\nu}$, $p = c + r_f + \delta$. Consequently,

$$\frac{dK_f}{d\beta} = \left[D(p^{\bar{w}}) - D(p)\right] - \beta D'(p^{\bar{w}}) \frac{d\tilde{r}_i}{d\beta} \frac{1}{1-\nu}$$

where $\frac{d\tilde{r}_i}{d\beta} > 0$ by (36). Then, the two terms have opposite signs. If β is large and/or ν is large and/or demand is very reactive to high prices and/or renewables costs are sharply increasing, the second term can offset the first one and polluting emissions increase with the proportion of reactive consumers.

We see that the first consequence of an increase in the number of reactive consumers, which is to consume less in state $\bar{w}$ than if they pay the retail price $(D(p^{\bar{w}}) - D(p) < 0)$ must be complemented with the effect of the switch on prices. The latter reinforces the decrease in emissions in case c, but it alleviates it in case $(b1)$. This additional effect is generally underestimated in environmental policy.

Corollary 2 *Increasing the share of price reactive customers has no impact on the retail price, except in zone (c) where it increases.*

Indeed in zones (a), $(b1)$ and $(b2)$ we have $p = c + r_f + \delta$, because the fossil-fuel technology produces in both states of nature, then the price equals its long run marginal social cost, which does not vary with thermal power capacity and production. Consequently, even if changing β does modify the installed thermal power capacity K_f, it has no effect on its long run marginal social cost, hence on the retail price. However it is not the case in zone (c) because the retail price $p = \tilde{r}_i + (1-\nu)(c+\delta) + r_f$ depends on the renewable energy long term marginal cost which varies with production capacity K_i. A larger β requires more capacity K_i which, because the cost of renewable increases with capacity, pushes the wholesale price $p^w = \frac{\tilde{r}_i}{\nu}$ in state w up. Hence a larger retail price.[19]

Corollary 3 *Non coordinated public policy decisions can result in energy mix switches with disturbing effects on prices and emissions.*

This is the consequence of having frontiers $\delta_1(\beta)$ and $\delta_2(\beta)$ increasing in β in Figure 1. Suppose for example that we are in zone $(b1)$ with the use of thermal power plants at full capacity even when the wind energy converters are spinning. A drastic increase of the carbon

[19]The latter result differs from Léautier (2014) who finds that retail price does not vary with the share of reactive consumers.

tax δ might drive the energy mix into zone ($b2$) where thermal power plants are now used below capacity on windy days. If, later, price responsiveness is strongly encouraged with a big push on β, we can be driven back into the energy mix of type ($b1$), where thermal power plants are running again at full capacity on windy days, but with a lower capacity given Corollary 1. This requires capacity adaptations that can be avoided by inverting the order of decisions (first increase β, then δ), or by increasing both simultaneously.

3 Social benefit of reactive consumers

To evaluate the social benefit of making more consumers reactive, we differentiate the expected social welfare defined in (2) with respect to the percentage of reactive consumers β and we discuss the resulting components in two lemma followed by two propositions.[20]

Lemma 1 *The marginal expected social surplus due to an increase in β is given by:*

$$[\nu S(q_r^w) + (1-\nu)S(q_r^{\bar{w}}) - S(q_{\bar{r}})] + [(1-\nu)(c+\delta) + r_f](q_{\bar{r}} - q_r^{\bar{w}}) - \tilde{r}_i(q_r^w - q_{\bar{r}}). \tag{10}$$

The proof of Lemma 1, in Appendix B.1, uses the market-clearing conditions (3) and (4) and the envelope theorem.

Formula (10) decomposes the impact of the marginal increase of the share of reactive consumer into three terms. The first term between square brackets is the variation in expected surplus or utility from making consumers reactive. It is negative by the following Lemma proved in Appendix B.2.

Lemma 2 *The expected gross surplus of being a reactive consumer is smaller than the gross surplus of being non-reactive: $S(q_{\bar{r}}) > \nu S(q_r^w) + (1-\nu)S(q_r^{\bar{w}})$ where $q_{\bar{r}} = D(p)$, $q_r^w = D(p^w)$, and $q_r^{\bar{w}} = D(p^{\bar{w}})$ with $p = \nu p^w + (1-\nu)p^{\bar{w}}$.*

Switching from a constant price to state-contingent prices reduces gross surplus as it obliges consumers to modify their consumption of electricity across time, depending on the states of nature. They prefer a constant consumption because, with a concave S, they are averse to state-dependent consumption.[21] The more risk averse in terms of quantities, the greater this utility loss.[22]

[20]Recall that we discard private benefits from consuming green electricity such as the warm-glow effect (Andreoni, 1990, Ma and Burton, 2016, Ambec and De Donder, 2020).

[21]Notice that $S(q_r^w)+(1-\nu)S(q_r^{\bar{w}})-S(q_{\bar{r}}) < 0$ cannot be directly inferred 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.

[22]In line with this result, Qiu et al. (2017) find that risk-averse consumers are less likely to enroll for time-of-use electricity pricing programs in the U.S.

The second term in (10) 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 polluting emissions.

The third term in (10) is the extra cost of wind power due to reactive consumers' higher demand in state w. Consumption in state w is increased by $q_r^w - q_{\bar{r}}$, at marginal cost $\tilde{r}_i$.

With negative and positive terms, the sign of (10) seems ambiguous. To be able to sign (10), note that by replacing marginal costs by prices from Proposition 1, we can express (10) as a variation of consumers' net expected welfare:

$$\nu \left(S(q_r^w) - p^w q_r^w \right) + (1-\nu) \left(S(q_r^{\bar{w}}) - p^{\bar{w}} q_r^{\bar{w}} \right) - \left(S(q_{\bar{r}}) - p q_{\bar{r}} \right). \tag{11}$$

The marginal benefit of demand response in (11) is simply the expected net surplus of being reactive for the consumers. It implies that social and individual interests are aligned when it comes to demand response: it is optimal to increase the share of reactive consumers as long as those consumers benefit from being reactive.

To sign (11) we show in Appendix B.3 that the net social surplus $S(D(p)) - pD(p)$ is a convex function of the power price p. This means that the expected net social surplus is higher with state-contingent prices p^w and $p^{\bar{w}}$ than with the average of those prices p. Hence, (11) is strictly positive. We summarize our findings in the following proposition:

Proposition 2 *When the energy mix contains intermittent sources, the impact of an increase in demand response on welfare is threefold: (i) a loss from exposing risk-averse consumers to volatile consumptions, (ii) lower costs and emissions from reducing thermal powered electricity, and (iii) increased costs from the installation of more renewables. The net impact is positive.*

The result that consumers benefit from being reactive relies on the assumption of perfect competition and our measure of consumer's welfare. It is known since Waugh (1944) that consumers' net surplus is higher with variable prices than with their constant average price. Turnovsky et al (1980) have shown that it is due to the convexity of the indirect utility function with respect to price. It implies that real-time pricing is beneficial on the ground of expected consumer's net surplus. We clearly identify the basic components of this net gain: reactive consumers are better-off because, even though they are worse off in terms of gross surplus, they disburse much less than consumers paying a fixed price. In the next proposition, we show that this gain decreases with the share of reactive consumers.

Proposition 3 *The expected marginal social welfare is decreasing with the proportion of reactive consumers β.*

The proof is in Appendix C. This result is important because we have ignored so far the cost of installing smart meters and load-shedding appliances at consumers' locations. Such costs should be compared with the aforementioned benefit of increasing demand response. With a decreasing expected marginal social welfare, if the marginal cost of increasing β is increasing or constant (for example the unit cost of a smart meter), we most likely will find an interior solution: not all consumers should be equipped with smart meters.[23] It is so even with homogenous consumers because the higher proportion of reactive consumers reduces the need for price reactivity. It thus weakens the advantages of investing in smart appliances to make more consumers dependent on states of nature.

We close the section by investigating the robustness of Proposition 2 to more general measures of the consumer's welfare. By using the net consumer surplus $S(D(p)) - pD(p)$, we implicitly assumed that consumers are neutral regarding variations of monetary gains. Risk aversion can be embedded easily into the consumer's welfare by considering a concave utility function applied to the net monetary consumer's surplus. Formally, we define the consumer's indirect utility with respect to price p as $V(p) \stackrel{def}{=} U(S(D(p)) - pD(p))$ with $U'(C) > 0$ and $U''(C) \leq 0$ for any $C > 0$. Let us denote the Arrow-Pratt coefficient of relative risk aversion as a function of price by $\rho(p) \stackrel{def}{=} -[S(D(p)) - pD(p))] \dfrac{U''(S(D(p)) - pD(p))}{U'(S(D(p)) - pD(p)}$ and the price-elasticity of demand by $\epsilon(p) \stackrel{def}{=} -\dfrac{p}{D(p)} D'(p)$. In Appendix D we establish the following last proposition:

Proposition 4 *Consumers benefit (resp. loose) from real-time pricing if* $\dfrac{S(D(p)) - pD(p)}{pD(p)} > \dfrac{\rho(p)}{\epsilon(p)}$ *(resp. $<$) for any $p \in [p^w, p^{\bar{w}}]$.*

Proposition 4 generalizes the last sentence of Proposition 2 to risk-adverse consumers. It relates the convexity or concavity of the indirect utility function $V(p)$ with respect to price with the net benefit from electricity consumption, relative risk aversion and price-elasticity of demand. It is convex for every $p \in [p^w, p^{\bar{w}}]$ if consumers' net valuation of electricity consumption per dollar spent is higher that the ratio of their absolute risk aversion over the price-elasticity of demand for any price level of the real-time pricing. In this case, consumers benefit from adapting their demand to variable prices rather than paying a constant price equals to the mean. It is concave if the reverse inequality holds for every $p \in [p^w, p^{\bar{w}}]$, in which case consumers prefer a constant electricity price equal to the mean of variable prices.

Remarkably, both the level and variability of prices matter in Proposition 4. High electricity prices make consumers more likely to be worse off with real-time pricing as the consumer's

[23] Léautier (2014) finds a similar result of partial equipment with smart-meters using simulations calibrated on France.

surplus from electricity consumption net of spending per dollar is low.[24] Higher price volatility might lead to an ambiguous result as the inequality may be reverse for different levels of prices.

Bringing Proposition 4 to data is not straightforward. It is difficult to get estimates of parameters on both side of the inequality. The most challenging part is certainly the left-hand side - the net value of electricity per monetary unit- for two reasons. First, it is defined for a consumption level during a certain period of time. Should we take hourly, daily or monthly consumption? The model is agnostic on this time-span dimension. Second, it requires to infer consumer's valuation of electricity consumption, which is difficult to obtain and varies a lot.[25]

On the right-hand side, we can obtain more precise estimates of both the the relative risk aversion and the price-elasticity of electricity demand. Using data from surveys, Gandelman and Hernàndez-Murillo (2015, 2017) obtain relative risk aversions in 75 countries close to 1, ranging from 0.27 to 1.55 in developed countries. In the meta-analysis performed by Labandeira et al. (2017), the average price-elasticity of electricity demand is 0.126 in absolute value (in the short-run), while EPRI reports 0.3 for households (with a range 0.2-0.6). With $\rho = 1$ and $\epsilon = 0.126$, we obtain a ratio $\rho/\epsilon \approx 8$, which means that the net value of electricity per doller must be more than eight dollars for each dollar spent to make consumers better off with real-time pricing. With the higher value of elasticity $\epsilon = 0.3$, the ratio reduces to 3.33 so more than 3 times the dollar spent. Using the range 0.27 to 1.55, the ratio varies between 1 and 5.

4 Conclusion

Smart meters with load-switch devices and batteries help consumers to adapt electricity consumption to price changes. Although making consumers reactive reduces production and environmental costs − including the back-up equipment cost and pollution induced by thermal power − it exposes consumers to price fluctuations that force them to adjust their consumption over states of nature. Such risk exposure effects should be incorporated into the cost-benefit analysis of installing smart meters and charging real-time electricity prices. Our paper identifies the main ingredients of this cost-benefit analysis. It also relates the economic and environmental value of intermittent renewables to demand response. A higher share of reactive consumers does not only reduce pollution and thermal power production capacity in

[24]Note that the condition in Proposition 4 implicitly includes parameters related to the economic and environmental costs of electricity provision through price p. In particular, the higher the social cost of carbon (and carbon tax) δ, the higher the price range $[p^w, p^{\bar{w}}]$ and spending $pD(p)$.

[25]For instance, the so-called value of lost load (VOLL), based on consumers' willingness to pay to avoid a blackout for a period of time, lays in a range 0-45 euros per kWh in Europe (Schröder and Kuckshinrichs, 2015, ACER, 2018).

most cases, it also allows to better exploit this capacity across time. Consumers benefit from real-time electricity pricing provided that they are not too risk-adverse and their demand is sufficiently elastic. However, the gain decreases with the proportion of price-reactive consumers. Hence, real-time pricing is socially efficient up to a point where the smart meters and appliances costs offset the gains.

We conclude with three remarks. The first one is about the distributional consequences of having a share of the population reactive to real-time prices. Empirical evidences show that individuals that are more likely to optimize their energy use are more educated (Mills and Schleich 2010, Brounen et al. 2013) and consume more energy (Blasch et al. 2019). Hence, the people who are the more likely to remain with a fixed price contract are the less educated and poorest. Not only they do not benefit from smart meters but they can also be hurt by an increase of the share reactive consumers. Indeed, as explained in the discussion of Corollary 2, an increase of β have the adverse effect of increasing the retail price due to the investment into additional weakly profitable windmills in the case where the Pigouvian tax δ is high (case c). Some form of redistribution is thus required to compensate the adverse effect of real-time pricing on non-reactive consumers, especially if they are more vulnerable to high energy costs. Otherwise, this effect will add up to the hostility to energy transition.

The second remark has to do with market power. Along the paper we have assumed perfect competition in both electricity wholesale and retailing market. Like in Joskow and Tirole (2007), we might investigate how our results extend to imperfect competition. Clearly, the exercise of market power by either producers or retailers should increase the benefit of switching to real-time pricing. It is obviously so if imperfect competition is at the retail stage as reactive consumers can bypass retailing prices by being charged wholesale prices. The same is true in case of barriers to entry at the production stage for thermal or nuclear electricity. Moving to real-time pricing can be a strategy to partly escape the exercise of market power by dominant thermal and nuclear producers. Electricity consumption is adjusted over time to take advantage of a more competitive sector thanks to small wind and solar producers. Yet household with fixed price contracts are captive as the retail price is often fully determined by thermal power production costs (see cases ($b1$) and ($b2$) in Proposition 1). Hence, with market power in the electricity sector, favoring real-time pricing by installing smart-meters and home automation devices is not only a policy to support the energy transition. It also fosters competition to the benefit of consumers.

The third remark is related to our measure of consumers' welfare. By relying on the consumer's surplus or utility, we ignore some behavioral dimensions of welfare. On the benefit side, we abstract from behavioral motives for moving to real-time pricing such as the desire to consume green electricity. Experimental evidence (Krishnamurthy and Kriström, 2015, Ma and Burton, 2016) and electricity suppliers' business strategies[26] suggest that some consumers are willing to pay more for electricity coming from renewable sources. Such source-dependent valuation of electricity consumption could be imbedded in the social objective function using tools from behavioral economics such as warm-glow utility (see Andreoni, 1990, Ma and Burton, 2016, Ambec and De Donder, 2020). On the cost side, reacting to real-time prices requires receiving price alerts and responding to them (Jessoe and Rapson, 2014) or installing automation devices (Bollinger and Hartmann, 2020). Both might be costly at least for some consumers. Including such behavioral considerations in a full cost-benefit analysis of real time pricing remains to be done.

[26]Many suppliers advertise green electricity as their main or only source of energy, see for instance: www.greenenergyuk.com

A Proof of Proposition 1

A.1 Welfare maximisation

Denoting $\gamma_{\bar{w}}$,γ_w, $\underline{\mu}_f$,$\overline{\mu}_f$ and $\underline{\mu}_i$ the multipliers associated with the constraints (3), (4), (5), (6) and (7) respectively, the Lagrange function corresponding to the program can be written as

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

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

$$q_r^w : S'(q_r^w) = \gamma_w \tag{12}$$

$$q_r^{\overline{w}} : S'(q_r^{\bar{w}}) = \gamma_{\bar{w}} \tag{13}$$

$$q_{\bar{r}} : S'(q_{\bar{r}}) = \nu\gamma_w + (1-\nu)\gamma_{\bar{w}} \tag{14}$$

$$q_f^w : -(c+\delta) + \gamma_w - \bar{\mu}_f + \underline{\mu}_f = 0 \tag{15}$$

$$K_f : -(1-\nu)(c+\delta) - r_f + (1-\nu)\gamma_{\bar{w}} + \nu\bar{\mu}_f = 0 \tag{16}$$

$$\tilde{r}_i : -\tilde{r}_i + \nu\gamma_w + \nu\underline{\mu}_i' = 0 \tag{17}$$

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

$$S'(q_r^w) = c + \delta + \bar{\mu}_f - \underline{\mu}_f \tag{18}$$

$$S'(q_r^{\bar{w}}) = c + \delta + \frac{r_f - \nu\bar{\mu}_f}{1-\nu} \tag{19}$$

$$S'(q_{\bar{r}}) = \nu S'(q_r^w) + (1-\nu)S'(q_r^{\bar{w}}) \tag{20}$$

$$S'(q_r^w) = \frac{\tilde{r}_i}{\nu} - \underline{\mu}_i' \tag{21}$$

From (18) and (21), we obtain

$$\frac{\widetilde{r}_i}{\nu} = c + \delta + \bar{\mu}_f - \underline{\mu}_f + \underline{\mu}_i'. \tag{22}$$

• Case (a). Without intermittent energy, we have $\tilde{r}_i = \underline{r}_i$ and $\underline{\mu}_i' \geq 0$. Moreover, since $\bar{K}F(\widetilde{r}_i) = 0$, the quantity- balancing constraints (3) and (4) imply

$$K_f - q_f^w = \beta(q_r^{\bar{w}} - q_r^w). \tag{23}$$

We show by contradiction that $q_f^w = K_f$. Suppose $q_f^w < K_f$. It entails that $\bar{\mu}_f = 0$ by the corresponding complementary slackness condition, and $q_r^w < q_r^{\bar{w}}$ by (23). Consequently $S'(q_r^w) > S'(q_r^{\bar{w}})$ since $S^{"}(.) < 0$ which, combined with (18) and (19), leads to $\frac{r_f}{1-v} < -\underline{\mu}_f$, a contradiction since $\underline{\mu}_f \geq 0$. Hence, $q_f^w = K_f$ and $q_r^w = q_r^{\bar{w}}$,where $q_f^w = K_f$ is true for any $\beta \geq 0$. This implies $\underline{\mu}_f = 0$ and $\bar{\mu}_f = r_f$ by (18) and (19). Then $q_{\bar{r}} = q_r^w = q_r^{\bar{w}} = S'^{-1}(c+\delta+r_f)$. By (21) $\underline{\mu}_i' = \frac{r_i}{\nu} - S'(q_r^w) \geq 0 \Longrightarrow \frac{\underline{r}_i}{\nu} \geq c+\delta+r_f$, or

$$\delta \leq \delta^a \overset{def}{=} \frac{\underline{r}_i}{\nu} - (c+r_f) \tag{24}$$

Decentralization of case (a). This allocation can be decentralized by the price system $p^w = p^{\bar{w}} = p = c+\delta+r_f$. Indeed, wholesale prices are low enough to discourage renewables ($p^w = c+r_f+\delta \leq \frac{\underline{r}_i}{\nu}$), high enough to balance the budget of thermal producers ($\nu p^w + (1-\nu)p^{\bar{w}} \geq c+\delta+r_f$) and such that consumers demand the first best quantity. Actually, with non contingent prices they all demand the same quantity given by $\max\limits_q S(q) - pq \Longrightarrow q = S^{'-1}(c+\delta+r_f)$. At equilibrium, demand equals supply: $S^{'-1}(c+\delta+r_f) = K_f = q_f^w, K_i = 0$.

For $\delta > \delta^a$, there is investment in intermittent energy (cases (b) and (c)): $\tilde{r}_i > \underline{r}_i$ and $\underline{\mu}_i' = 0$. In case (b), discomposed into $(b1)$ and $(b2)$, we have $q_f^w > 0$, then $\underline{\mu}_f = 0$.

• Case $(b1)$. Assume first that $\bar{\mu}_f > 0$, and then $q_f^w = K_f$. By equation (22), $\bar{\mu}_f = \frac{\tilde{r}_i}{\nu} - (c+\delta)$ which, combined with (18) and (19) leads to $q_r^w = S'^{-1}\left(\frac{\tilde{r}_i}{\nu}\right)$ and $q_r^{\bar{w}} = S'^{-1}\left(\frac{c+\delta+r_f-\tilde{r}_i}{1-\nu}\right)$. The cost of the marginal wind turbine $\tilde{r}_i$ is defined by combining the production-consumption constraints (3) and (4) with $q_f^w = K_f$. It is the solution $\tilde{r}_i$ of the following equation:

$$\bar{K}F(\tilde{r}_i) = \beta\left[S'^{-1}\left(\frac{\tilde{r}_i}{\nu}\right) - S'^{-1}\left(\frac{c+\delta+r_f-\tilde{r}_i}{1-\nu}\right)\right] \tag{25}$$

In this zone, having $K_i > 0$ clearly necessitates $\beta > 0$.

Decentralization of case (b1). Competitive state-dependent prices are $p^w = \frac{\tilde{r}_i}{\nu}$ and $p^{\bar{w}} = \dfrac{c+\delta+r_f-\tilde{r}_i}{1-\nu}$. Combined with (20), they lead to $q_{\bar{r}} = D(c+\delta+r_f)$ and $p = \nu p^w + (1-\nu)p^{\bar{w}} = c+\delta+r_f$. In a decentralized framework, equation (25) stands for the equilibrium between supply (left-hand side) and demand (right-hand side) for renewables. Supply is increasing in r_i and nil if $r_i \leq \underline{r}_i$. Demand is decreasing in r_i and nil if $\nu(c+\delta+r_f) \leq r_i$. Then equilibrium exists only if $\underline{r}_i \leq \nu(c+\delta+r_f)$. It results that the switch from case (a) to case $(b1)$ is when $\bar{K}F(\underline{r}_i) \geq 0 \Longrightarrow \frac{\underline{r}_i}{\nu} \leq \dfrac{c+\delta+r_f-\underline{r}_i}{1-\nu}$ (if $\beta > 0$), that is $\delta \geq \frac{\underline{r}_i}{\nu} - (c+r_f)$.

• Case $(b2)$. Suppose now that $\overline{\mu}_f = 0$ which holds when $q_f^w < K_f$. Conditions (18) and (19) become $S'(q_r^w) = c+\delta$ and $S'(q_r^{\bar{w}}) = c+\delta+\frac{r_f}{1-\nu}$ respectively, which 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, combined with (20), non-state dependent consumption for the others: $q_{\bar{r}} = D(c+\delta+r_f)$.

Thermal power capacity is determined by the market-clearing condition in state $\bar{w}$ (3), that is:

$$K_f = \beta q_r^{\bar{w}} + (1-\beta)q_{\bar{r}} = \beta D\left(c+\delta+\frac{r_f}{1-\nu}\right) + (1-\beta)D\left(c+\delta+r_f\right). \tag{26}$$

The market clearing condition in state w (4) yields:

$$q_f^w = \beta D(c+\delta) + (1-\beta)D(c+\delta+r_f) - \bar{K}F(\nu(c+\delta)) \tag{27}$$

We see that $K_i > 0$, $K_f > q_f^w > 0$ for both $\beta = 0$ and $\beta > 0$.

Decentralization of case (b2). These quantities can be decentralized by state-dependent market prices $p^w = c+\delta$ and $p^{\bar{w}} = c+\delta+\frac{r_f}{1-\nu}$ and retail price $p = c+\delta+r_f$. Indeed, these prices satisfy the zero-profit condition for thermal power producers and electricity retailers. Condition (22) yields the cost of the marginal wind turbines $\tilde{r}_i = \nu(c+\delta)$ and, therefore, the installed wind power capacity is $K_i = \bar{K}F(\nu(c+\delta))$. The switch from case ($b1$) to case ($b2$) arises when q_f^w is no longer equal to K_f, then by (26) and (27), when $\beta D(c+\delta) - \bar{K}F(\nu(c+\delta)) < \beta D\left(c+\delta+\frac{r_f}{1-\nu}\right)$. Let $\delta_1(\beta)$ denote the solution to:

$$\beta\left[D(c+\delta_1) - D\left(c+\delta_1+\frac{r_f}{1-\nu}\right)\right] = \bar{K}F(\nu(c+\delta_1)) \tag{28}$$

Then case ($b2$) begins when $\delta \geq \delta_1(\beta)$. Since $q_f^w > 0$, the right-hand side of (27) 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 (27). Then case ($b2$) ends when $\delta \geq \delta_2(\beta)$.

• Case (c). Consider now 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 (19) and (21), 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 (20) yields $q_{\bar{r}} = D(\tilde{r}_i + (1-\nu)(c+\delta)+r_f)$. In (19) and (21), those equalities give $q_r^{\bar{w}} = D\left(c+\delta+\frac{r_f}{1-\nu}\right)$ and $q_r^w = D\left(\frac{\tilde{r}_i}{\nu}\right)$. The market-clearing condition in state $\bar{w}$ (3) gives $K_f = \beta D\left(c+\delta+\frac{r_f}{1-\nu}\right) + (1-\beta)D\left(\tilde{r}_i+(1-\nu)(c+\delta)+r_f\right)$, whereas the one in state w (4) defines $\tilde{r}_i$ uniquely as

$$\bar{K}F\left(\tilde{r}_i\right) = \beta D\left(\frac{\tilde{r}_i}{\nu}\right) + (1-\beta)D\left(\tilde{r}_i+(1-\nu)(c+\delta)+r_f\right). \tag{29}$$

Decentralization of case (c). 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. Indeed, reactive consumers buy $q_r^w = S'^{-1}(\frac{\tilde{r}_i}{\nu})$

in state w and $q_r^{\bar{w}} = S'^{-1}\left(c+\delta+\frac{r_f}{1-\nu}\right)$ in state $\bar{w}$, whereas non reactive consumers buy $q_{\bar{r}} = S'^{-1}(\tilde{r}_i+(1-\nu)(c+\delta)+r_f)$ in both states of nature. In state w total demand $\beta q_r^w+(1-\beta)q_{\bar{r}}$ is equal to supply K_i by (29) and $q_f^w = 0$ because $p^w = \frac{\tilde{r}_i}{\nu} < c+\delta$. In state $\bar{w}$, total demand $\beta q_r^{\bar{w}}+(1-\beta)q_{\bar{r}}$ equals supply K_f by (26). These prices cover the costs of the thermal producers, of the marginal wind turbine, and of the retailers.

A.2 Zoning

First, using equation (8), let us define

$$\beta_1(\delta) = \frac{\bar{K}F(\nu(c+\delta))}{D(c+\delta) - D\left(c+\delta+\frac{r_f}{1-\nu}\right)} \tag{30}$$

The derivative with respect to δ is

$$\frac{\partial\beta_1(\delta)}{\partial\delta} = \frac{\bar{K}\nu f(\nu(c+\delta)) - \beta_1(\delta)\left[D'(c+\delta) - D'\left(c+\delta+\frac{r_f}{1-\nu}\right)\right]}{D(c+\delta) - D\left(c+\delta+\frac{r_f}{1-\nu}\right)} \tag{31}$$

The denominator is positive. A weakly convex demand function is sufficient for the numerator also to be positive. Then under this convexity condition, $\beta_1(\delta)$ is increasing in δ. Note that when $\beta_1(\delta) = 0$, $\bar{K}F(\nu(c+\delta)) = 0$ so that $\nu(c+\delta) = \underline{r}_i$. The later equality implies that the threshold δ which divides cases $(b1)$ and $(b2)$ on the X-axis in Figure 1 is equal to $\frac{\underline{r}_i}{\nu} - c$.

Second, using (9), let us define

$$\beta_2(\delta) = \frac{\bar{K}F(\nu(c+\delta)) - D(c+\delta+r_f)}{D(c+\delta) - D(c+\delta+r_f)} \tag{32}$$

representing the frontier between the sets of parameters where $q_f^w \geq 0$, the function q_f^w being defined in (27). The derivative with respect to δ is

$$\frac{\partial\beta_2(\delta)}{\partial\delta} = \frac{\bar{K}\nu f(\nu(c+\delta)) - \beta_2(\delta)D'(c+\delta) - (1-\beta_2(\delta))D'(c+\delta+r_f)}{D(c+\delta) - D(c+\delta+r_f)} > 0 \tag{33}$$

Then $\beta_2(\delta)$ is increasing in δ. Note that when $\beta_2(\delta) = 0$, $\bar{K}F(\nu(c+\delta)) - D(c+\delta+r_f) = 0$ which corresponds to the threshold δ_0 in Figure 1.

Let us denote $\delta_1(\beta)$ and $\delta_2(\beta)$ the inverse functions of $\beta_1(\delta)$ and $\beta_2(\delta)$ respectively. How do $\delta_1(\beta)$ and $\delta_2(\beta)$ compare? On the X-axis in Figure 1 when $\beta = 0$, we know that $\delta_1(0) = \frac{\underline{r}_i}{\nu} - c < \delta_0 = \delta_2(0)$ where the inequality comes from $\bar{K}F(\nu(c+\delta_1(0))) = 0 < \bar{K}F(\nu(c+\delta_0)) = D(c+\delta_0+r_f)$ by definition of $\delta_1(0)$ and δ_0. We know from our above analysis of $\beta_1(\delta)$ and $\beta_2(\delta)$ that, as β increases, both $\delta_1(\beta)$ and $\delta_2(\beta)$ increase but $\delta_2(\beta)$ increases more than $\delta_1(\beta)$. They might therefore cross at some point $\hat{\beta}$ such that $\delta_1(\hat{\beta}) = \delta_2(\hat{\beta})$, in which case zone $(b2)$ vanishes for $\beta \geq \hat{\beta}$. In Figure 1 we assume that it is not the case: $\delta_1(\hat{\beta})$ and $\delta_2(\hat{\beta})$ never cross for any $\beta \in (0,1)$.

B Proof of Proposition 2

B.1 Marginal social benefit from increasing β

Let EW denote the expected social surplus defined in (2). 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

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

after integrating 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 (3) and (4), we write the expected cost as a function of β and the control variables:

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

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

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

B.2 Consumer's expected gross 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 $g''(p) = S''(D(p))[D'(p)]^2 + S'(D(p))D''(p)$. For $g(p)$ to be concave ($g''(p) \leq 0$), we need

$$D''(p) \leq -\frac{S''(D(p))[D'(p)]^2}{S'(D(p))}. \tag{34}$$

Since $S'(.) > 0$ $S''(.) < 0$, the right-hand side is positive. Condition (34) 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.[27]

[27] Intuitively, a very convex demand means a strong variation of price-elasticity along the curve. At the limit, demand is inelastic for high prices $p^{\bar{w}}$ and very elastic for low prices p^w. Reactive consumers would benefit a great deal from a reduced price of electricity from thermal powered plants $p^{\bar{w}}$ (since their consumption would remain almost unchanged) without being hurt too much by a higher price of wind power with the installation of more wind turbines.

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 1, the last inequality becomes $g(p) > \nu g(p^w) + (1-\nu)g(p^{\bar{w}})$ which, given the definition of $g(p)$, $q_{\bar{r}} = D(p)$, $q_r^w = D(p^w)$, and $q_r^{\bar{w}} = D(p^{\bar{w}})$, leads to $S(q_{\bar{r}}) > \nu S(q_r^w) + (1-\nu)S(q_r^{\bar{w}})$.

B.3 Consumer's expected net surplus

Let $h(p) \equiv S(D(p)) - pD(p)$ be the consumer's surplus net of expenditures as a function of prices. 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 the Jensen's 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 $h(p)$, $q_{\bar{r}} = D(p)$, $q_r^w = D(p^w)$, and $q_r^{\bar{w}} = D(p^{\bar{w}})$, the last inequality leads to:

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

C Proof of Proposition 3

Applying the envelope theorem, the second derivative of the expected welfare $EW(x,\beta)$ with respect to β is

$$\begin{aligned} \frac{d^2 EW(x,\beta)}{d\beta^2} &= -\nu q_r^w \frac{dp^w}{d\beta} - (1-\nu) q_r^{\bar{w}} \frac{dp^{\overline{w}}}{d\beta} + q_{\bar{r}} \frac{dp}{d\beta} \\ &= -\nu \left(q_r^w - q_{\bar{r}}\right) \frac{dp^w}{d\beta} + (1-\nu)\left(q_{\bar{r}} - q_r^{\bar{w}}\right) \frac{dp^{\overline{w}}}{d\beta} \end{aligned} \tag{35}$$

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

- In case (*b1*), by differentiation of (25) ,we obtain,

$$\frac{d\tilde{r}_i}{d\beta} = \frac{q_r^w - q_r^{\bar{w}}}{\overline{K} f\left(\tilde{r}_i\right) - \beta \left[\frac{1}{\nu} D'\left(\frac{\tilde{r}_i}{\nu}\right) + \frac{1}{1-\nu} D'\left(\frac{c+\delta+r_f-\tilde{r}_i}{1-\nu}\right)\right]} > 0 \tag{36}$$

  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 (35) to obtain

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

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

- In case (c), by differentiation of (29) ,we obtain,

$$\frac{d\tilde{r}_i}{d\beta} = \frac{q_r^w - q_r^{\bar{w}}}{\bar{K} f(\tilde{r}_i) - \frac{\beta}{\nu} D'(\frac{\tilde{r}_i}{\nu}) - (1-\beta) D'(\tilde{r}_i + (1-\nu)(c+\delta) + r_f)} > 0. \tag{37}$$

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

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

Note 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).

D Proof of Proposition 4

First, notice that since $U(.)$ is an increasing concave transformation of the social surplus, $V(p)$ is a measure of welfare and the first-theorem of welfare applies so that the efficient energy mix can be decentralized under prefect competition and Pigouvian taxation. Consumers equalize their marginal utility of electricity consumption to price, i.e. $S'(q) = p$ and perfect competition implies that prices reflect marginal social costs as in Proposition 1. In particular, the retailing constant price p still equals the average of the wholesale prices, i.e. $p = \nu p^w + (1-\nu) p^{\bar{w}}$.

The first derivative of the indirect utility function $V(p) \stackrel{def}{=} U(S(D(p)) - pD(p))$ is:

$$V'(p) = U'(.) \left\{ [S'(D(p)) - p] D'(p) - D(p) \right\} = -U'(.) D(p) < 0$$

since demand $D(p)$ at any arbitrary price p is such that $S'(D(p)) = p$. Therefore $V(p)$ is decreasing with p.

The second derivative of $V(p)$ is:

$$V''(p) = U''(.)(D(p))^2 - U'(.) D'(p). \tag{38}$$

The function $V(p)$ is convex if $V''(p) > 0$, which, using (38), leads to:

$$-\frac{D'(p)}{D(p)} > \frac{-U''(.)}{U'(.)} D(p).$$

Multiplying both sides of the above inequality by $p\,[S(D(p)) - pD(p)]$ and using the definition of $\rho(p)$ and $\epsilon(p)$ we obtain the inequality in Proposition 4.

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