Electricity Demand Response and Responsiveness Incentives

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Agenda

Motivations

Demand Response (DR)

- Contract between a consumer and a producer (or a retailer)
- The consumer is paid to reduce consumption a certain number of days choosen by the producer.
- The number of days of price events is determined at inception.
- The days are choosen dynamically (price event day) and the customer is informed the day before.

Forms of DR

- Domestic: lower price on non–event price day (10 c/kWh vs normal tariff of 15 c/kWh) higher price during price event days (67 c/kWh). Around 30 price–event days per year.
- Rebate: consumer's receives money for the consumption they saved compared to a baseline. Used in industry. Potential baseline manipulation.

Remark

- DR programs reduce consumption level on average but with a significant variance in consumers response.
- Faruqui and Sergici (2010) reports a range of response between 10% and 50% across experiments.
- Low Carbon London (LCL) pricing trial in 2013 reports a range of variation between -200 W and +200 W for consumptions of order of 1,000 W (Schofield et. al. 2014)
- Other experiment reports an average reduction of 78 kW with a standard deviation of 30 kW for a furniture store (Mathieu 2011).

DR contract fails to enhance responsiveness, i.e. achieving a regular consumption reduction.

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Question

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- We provide closed-fom solution of the optimal contract in the case of linear energy value.
- We show that the optimal contract has a rebate form... which is baseline–proofness.
- Using LCL data, we illustrate the potential benefits from responsiveness incentives.

Non-exhaustive literature on PA and continuous–time

- Laffont and Martimort, *The Theory of Incentives*, Princeton, 2002.
- Holmström and Milgrom, *Econometrica*, 1987.
- Sannikov, *Rev. Econ. Stud.*, 2008.
- Cvitanič, Possamaï & Touzi, Dynamic programming approach to Principal-Agent problems, *Finance & Stochastics*, 2018.
- Crampes & Léautier, *J. Reg. Eco.*, 2015.

Non-exhaustive literature on DR

- Brown and Sappington, *J. Reg. Eco.*, 2016.
- Chao, *J. Reg. Eco.*, 2011.
- Chao and De Pillis, *J. Reg. Eco.*, 2013.
- Crampes & Léautier, *J. Reg. Eco.*, 2015.
- Hogan, FERC, 2009, 2010.

Model

The consumer (The Agent)

We focus on one single price event of duration T. Dynamics of the consumption during the price event follows:

$$X_T^{a,b} = X_0 + \int_0^T (-\sum_{i=1}^N a_i(s))ds + \int_0^T \sum_{i=1}^N \sigma_i \sqrt{b_i(s)} dW_s^i$$

a_i and b_i efforts to reduce average consumption and volatility of usage i
Consumer's criterion:

$$V^A(\xi) := \sup_{\nu:=(a,b)} J_{\mathrm{A}}(\xi,\nu) := \mathbb{E}^\nu \left[U_A\Big(\xi + \int_0^T \left(f(X_s^\nu) - c(\nu_s)\right) ds\Big)\right]$$

with $U_A(x) = -e^{-r\,x}$, $f(x) = \kappa x$, constant marginal value κ

$$c(a,b) := \underbrace{\frac{1}{2}\sum_{i=1}^N \frac{{a_i}^2}{\mu_i}}_{c_1(a)} + \underbrace{\frac{1}{2}\sum_{i=1}^N \frac{\sigma_i({b_i}^{-1}-1)}{\lambda_i}}_{c_2(b)},\ 0 \le a_i,\ \ 0 < b_i \le 1.$$

The producer (The Principal)

$$J_{\mathrm{P}}(\xi,\nu) := \mathbb{E}^{\nu}\Big[U\Big(-\xi - \int_0^T g(X_s)ds - \frac{h}{2}\langle X\rangle_T\Big)\Big] \text{with } U(x) = -e^{-p\,x}$$

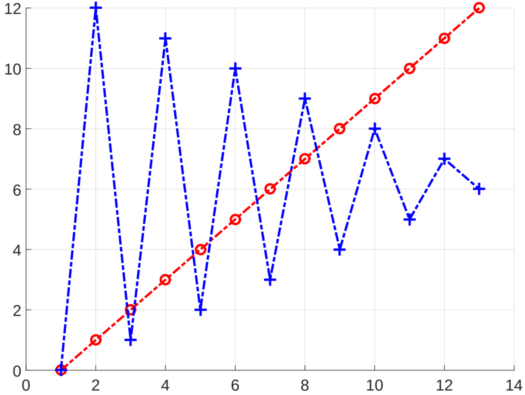
- $g(x) = \theta x$ generation cost function with constant marginal cost θ
- h direct cost of volatility

Producer's objective:

$$V^{\mathrm{sb}} := \sup_{\xi} J_{\mathrm{P}}(\xi, \nu^{\star}(\xi)).$$

together with the participation constraint of the consumer

$$V_A(\xi) \geq R_0 =: -e^{-rL_0}.$$



Total consumption X = Total consumption X

$\langle X\rangle = 1^2 + 1^2 + ... + 1^2 = 12$ $\qquad$ $\langle X\rangle = 12^2 + 11^2 + 10^2.. + 1^2 = 650$

Remarks

- Timing: first, the producer proposes a paying rule, knowing L_0; then, the consumer accepts or reject the contract: if he accepts, the price event happens later; the producer measures $X_.$ and pays or charges the consumer.
- The producer does not observe the efforts a and b on usages. She only observes the consumption X.
- The problem is non–Markovian. The contract is written on the observation of the whole path of the consumption on $[0, T]$.
- This problem is designated as the second–best.

First–best

$$V^{\mathrm{FB}} := \sup_{\xi,\nu} \left\{ J_{\mathrm{P}}(\xi,\nu) \quad : J_{\mathrm{A}}(\xi,\nu) \geq R_0 \right\}$$

Consumer's Hamiltonian

$$H(z,\gamma) := H_{\mathrm{m}}(z) + H_{\mathrm{v}}(\gamma),\ \ z,\gamma \in \mathbb{R},$$

where

$$H_{\mathrm{m}}(z) := -\inf_{a\geq 0}\left\{a\cdot \mathbf{1}z + c_1(a)\right\}, \quad H_{\mathrm{v}}(\gamma) := -\frac{1}{2}\inf_{b\in(0,1]}\left\{c_2(b) - \gamma|\sigma(b)|^2\right\},$$

which admists the minimizer

$$\widehat{a}_j(z) := \mu_j z^-, \quad \widehat{b}_j(\gamma) := 1 \wedge \left(\lambda_j \gamma^-\right)^{-\frac{1}{2}}.$$

Optimal contract [Cvitanic, Possamaï & Touzi (2018)]

- The optimal contract is of the form:

$$Y^{Y_0,Z,\Gamma} := Y_0 + \int_0^t Z_s dX_s + \frac{1}{2}\int_0^t (\Gamma_s + rZ_s{}^2) d\langle X\rangle_s - \int_0^t \big(H(Z_s,\Gamma_s) + f(X_s)\big) ds,$$

  where Z_s and Γ_s are payment rates for efforts on the average consumption and on volatility, and $H(Z_s, \Gamma_s) + f(X_s)$ is the natural benefit the consumer gets when receiving incentives Z_s, Γ_s.
- Whatever the processes Z and Γ, one has $V^A(Y^{Y_0,Z,\Gamma}) = U_A(Y_0)$.

- Whatever the payment rates Z and Γ, the Agent will receive his required reservation utility.
- Thus, the Principal can use the payment rates to solve his own optimisation problem, using standard stochastic control methods.

Optimal contract

First-best

The optimal first-best contract is given by:

$$\xi_{\text{fb}} = L_0 - \kappa X_0 T + \int_0^T c(\nu_t)dt + \int_0^T \pi^{\text{e}}_{\text{fb}}(X_0 - X_t)\,dt - \frac{1}{2}\int_0^T \pi^{\text{v}}_{\text{fb}} d\langle X\rangle_t,$$

where

$$\pi^{\text{e}}_{\text{fb}} := \frac{r}{r+p}\kappa + \frac{p}{r+p}\theta, \qquad \pi^{\text{v}}_{\text{fb}} := \frac{p}{r+p}h,$$

and the optimal efforts are:

$$a_{\text{fb}}(t) := \mu\delta^-(T-t), \quad b_{\text{fb}}(t) := 1 \wedge \Big(\lambda(h + \rho\,\delta^2(T-t)^2)\Big)^{-\frac{1}{2}},$$

with $\delta := \kappa - \theta$.

- $\delta > 0 \Rightarrow$ off–peak hours; $\delta < 0 \Rightarrow$ peak hours.
- Price of energy: constant convex combination of marginal cost and value
- Price of volatility: constant risk–sharing of the direct cost of volatility
- The contract has a rebate form.

Second–best without responsiveness incentives

The second–best optimal contract without responsiveness incentives is given by $\xi_{\mathsf{sb}_m} = \xi^{\mathsf{f}}_{\mathsf{sb}_m} + \xi^{\mathsf{v}}_{\mathsf{sb}_m}$ where

$$\xi^{\mathsf{f}}_{\mathsf{sb}_m} = L_0 - \kappa T X_0 + \frac{1}{2}\int_0^T r z^2_{\mathsf{sb}_m}(t)|\sigma|^2 dt - \int_0^T H_{\mathrm{m}}(z_{\mathsf{sb}_m}(t))dt,$$

$$\xi^{\mathsf{v}}_{\mathsf{sb}_m} = \int_0^T \pi^{\mathsf{e}}_{\mathsf{sb}_m}\big(X_0 - X_t\big)dt,$$

where

$$\pi^{\mathsf{e}}_{\mathsf{sb}_m} := (1-\Lambda)\kappa + \Lambda\theta,$$

and the optimal payment rate is $z_{\mathsf{sb}_m}(t) = \Lambda\delta(T-t)$ with

$$\Lambda := \frac{p|\sigma|^2 + \bar{\mu}\mathbf{1}_{\{\delta<0\}}}{(p+r)|\sigma|^2 + \bar{\mu}\mathbf{1}_{\{\delta<0\}}}.$$

- No price of volatility.
- Prices of energy is a constant convex combination of marginal cost and value of energy.
- In peak–period, the price depend on the volatilities and the costs of efforts.
- The contract has a rebate form where the initial consumption level is the baseline.
- Baseline–proofness: Whatever the initial condition (baseline), the consumer gets no more than L_0.

Second–best with responsiveness incentives

The second–best optimal contract is given by $\xi_{\text{sb}} = \xi^{\text{f}}_{\text{sb}} + \xi^{\text{v}}_{\text{sb}}$ where

$$\xi^{\text{f}}_{\text{sb}} := L_0 - \kappa T X_0 - \int_0^T H(z_{\text{sb}}, \gamma_{\text{sb}})(t)dt$$

$$\xi^{\text{v}}_{\text{sb}} := \int_0^T \pi^{\text{e}}_{\text{sb}}(t)\big(X_0 - X_t\big)dt - \frac{1}{2}\int_0^T \pi^{\text{v}}_{\text{sb}}(t)d\langle X\rangle_t,$$

and

$$\pi^{\text{e}}_{\text{sb}}(t) := \kappa + z'_{\text{sb}}(t), \qquad \pi^{\text{v}}_{\text{sb}}(t) := h + p\big(z_{\text{sb}}(t) - \delta(T-t)\big)^2,$$

where z_{sb} is a deterministic function of time, solution of a scalar optimisation problem for each time. The optimal efforts are

$$a_{\text{sb}}(t) := \mu z_{\text{sb}}(t)^-, \quad b_{\text{sb}}(t) := 1 \wedge \Big(\lambda\gamma_{\text{sb}}(t)^-\Big)^{-\frac{1}{2}},$$

$$\gamma_{\text{sb}}(t) := -h - r z_{\text{sb}}(t)^2 - p(z_{\text{sb}}(t) - \delta(T-t))^2.$$

- Prices of energy and volatilty are now non–constant deterministic function of time.
- Price of volatility is always greater than the first–best price.
- In peak–hours, the price of energy is also greater than the first–best.
- The contract has a rebate form where the initial consumption level is the baseline.
- Baseline–proofness: Whatever the initial condition (baseline), the consumer gets no more than L_0.

Numerical illustration

Calibration

- Make extensive use of the Low Carbon London 2013 pricing trial.
- We interpret the LCL pricing trial as the implementation of the optimal contract with uncontrolled responsiveness and linear energy value.

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Parameters shopping list

$$T \quad \sigma \quad \kappa \quad \theta \quad h \quad p \quad r \quad \mu_i \quad \lambda_i$$

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T	h	κ	θ	p	r	σ	μ	λ
5.5	$4.0\ 10^{-3}$	11.76	67.2	$0.6\ 10^{-2}$	$0.57\ 10^{-2}$	85	$9.3\ 10^{-5}$	$2.8\ 10^{-2}$

Table: Nominal values for model parameters.

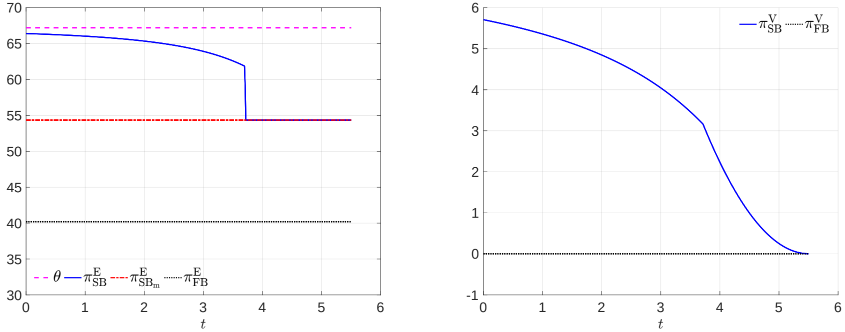

Figure: Prices for energy (p/kWh) and volatilty (p/kW^2).

Conservative estimate of the benefit from responsiveness incentives

	First–best	Second–best with responsiveness	Second–best without responsiveness
Cost of effort c_1	5.97	5.97	4.68
Cost of effort c_2	0.40	0.59	0
Total cost of effort	6.37	6.56	4.68
Producer's benefit	6.76	6.21	5.40
Average consumption reduction	52.15	45.17	40.00
Standard deviation consumption	46.49	39.61	85.06

Table: Costs in pence, consumption and standard deviation in Watt.

Perspectives

- Limited liability (no negative payments).
- Group of consumers with different energy valuation (adverse selection)
- Making a pricing trial with responsiveness incentives.

Practice

Index the contract on the quadratic variation

Use the approximation of the quadratic variation $\langle X \rangle_T$

$$\langle X \rangle_T \approx \sum_{i=0}^{n-1} \left(X_{t_{i+1}} - X_{t_i}\right)^2.$$

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Index on the event–per–event variations of the consumption

On event k, the producer measure the quantity

$$\bar{X}_k := \int_0^T X_t dt$$

and charges the consumer a cost proportional to the quantity

$$\mathbb{V}_k := |\bar{X}_k - X_{\mathrm{c}}|$$

where X_{c} is a contractualised targeted consumption in the spirit of Chao (2011).

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