Decarbonizing electricity generation with intermittent sources of energy

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Motivation

- Increased penetration of intermittent renewables (wind, solar)
- Retail price of electricity does not vary with wind or sun
- Tractable model of energy investment and production with pollution, intermittent energy and non-reactive consumers
- Impact on competitive markets
- Impact of public policy to support renewables:
  - Carbon tax
  - Feed-in tariff (FIT)
  - Renewable portfolio standard (RPS)
- Examine technological solutions to intermittency:
  - Energy storage
  - Demand response with smart meters

Main messages

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- Renewable and storage capacities are complement
- Demand response always increases welfare despite price volatility

Fossil source f

- Production q_f with marginal cost c
- Capacities K_f with marginal cost r_f
- Capacity constraint $q_f \leq K_f$
- Long term private marginal cost of 1 kWh is $c + r_f$
- Marginal damage / carbon tax par kWh of fossil fuel δ
- Long term social marginal cost of 1 kWh is $c + r_f + \delta$

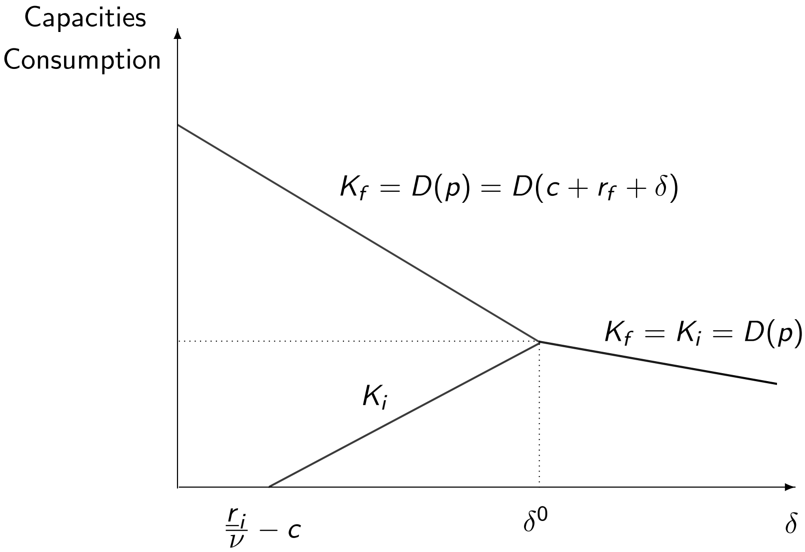
Intermittent source i

- Production q_i with 0 marginal cost
- Capacities K_i with marginal cost $r_i \in [\underline{r}_i, +\infty)$ with distribution f and cumulative F and total capacity $\bar{K}$
- Capacity constraint $q_i \leq K_i$
- Available only in state w (not in state $\overline{w}$) which occurs with probability ν (probability $1 - \nu$)
- Long term marginal cost of ν kWh (1 kWh in state w) is r_i
- Long term marginal cost of 1 kWh on average $\frac{r_i}{\nu}$

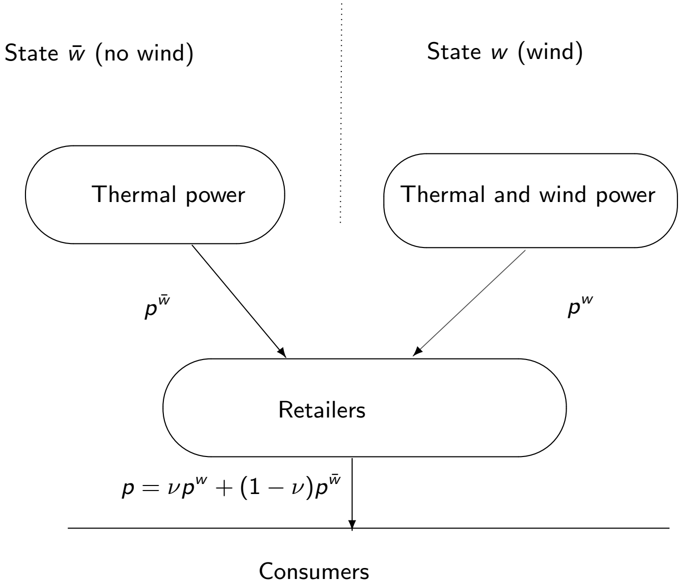
Consumers

- Utility or Surplus $S(q)$ concave $(S' > 0,\ S'' < 0)$
- Demand function $D(p) = S'^{-1}(p)$
- Retail electricity price p
- Constant retail price: $q = D(p) = q^w = q^{\bar{w}} = K_f$
- Back-up constraint: $K_i + q_f^w = K_f$

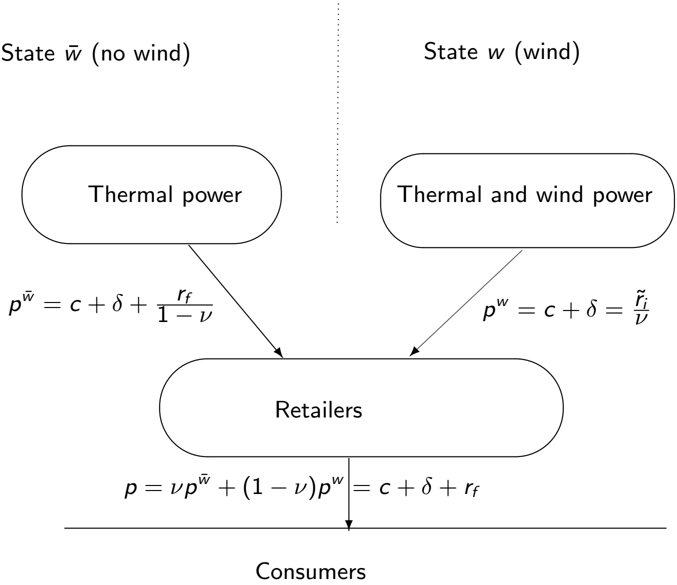
Optimal energy mix



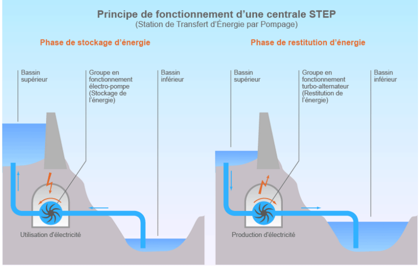
Markets


State $\bar{w}$ (no wind)
State w (wind)
Thermal power
Thermal and wind power
$p^{\bar{w}}$
p^{w}
Retailers
$p = \nu p^{w} + (1-\nu)p^{\bar{w}}$
Consumers

Market prices with a carbon tax δ



Energy storage



Energy storage

- Storage capacity K_s at cost r_s
- Energy efficiency of storing technology $\lambda \leq 1$
- New back-up constraint:

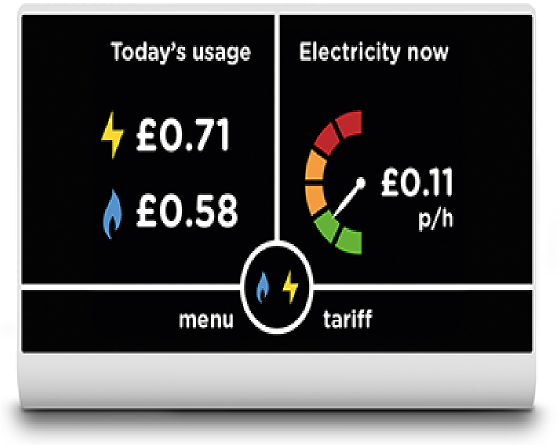
$$K_i + q_f^w - \frac{K_s}{\nu} = K_f + \frac{\lambda K_s}{1-\nu}$$

- Efficient investment in storage capacity:

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

- Renewables and storage are complement: $\tilde{r}_i$ increases when λ increases and r_s decreases
- $q_f^w = 0$ if storage

Reactive consumers with smart meters



Smart meters with state-dependent prices

- Share β of reactive consumers paying wholesale prices $p^{\bar{w}}$ and p^{w}
- Share $1-\beta$ of non-reactive consumers paying retail price p
- Back-up constraint relaxed with market clearing conditions:

$$\begin{aligned} K_f &= \beta q_r^{\bar{w}} + (1-\beta) q_{\bar{r}} \\ K_i + q_f^{w} &= \beta q_r^{w} + (1-\beta) q_{\bar{r}} \end{aligned}$$

Marginal benefit of making consumers reactive

- Differentiating expected social welfare with respect to β:

$$\underbrace{[\nu S(q_r^w) + (1-\nu)S(q_r^{\bar{w}}) - S(q_{\bar{r}})]}_{-} - \tilde{r}_i \underbrace{(q_r^w - q_{\bar{r}})}_{+}$$

$$+[(1-\nu)(c+\delta) + r_f]\underbrace{(q_{\bar{r}} - q_r^{\bar{w}})}_{+}$$

- Always positive: positive share of reactive consumers optimal $\beta > 0$