Decarbonizing electricity generation with intermittent sources of energy

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Motivation

- Intermittent sources of energy (wind, solar,...)
- Retail price of electricity does not vary with wind or sun
- Pollution (greenhouse gases, SO2, NOX,...)
- Several policy instruments:
  - Carbon tax
  - Feed-in tariff (FIT) or feed-in premium (FIP)
  - Renewable portfolio standard (RPS)
- Impact of policies with intermittent energy and non-reactive consumers

Overview

- First-best energy mix with wind power capacity back-up with thermal power
- Carbon tax implements first-best but not FIT or RPS: too much electricity consumption
- Tax on electricity consumption should complement FIT or RPS to implement first-best
- Social benefit of energy storage and smart meters
- With a monopoly thermal power producer:
  - Introduction of wind power competitive fringe increases electricity price
  - First-best achieved with state-contingent carbon tax or price cap and carbon tax

Related literature

- Optimal and decentralized mix of energy with intermittent sources:
  Ambec and Crampes (2012), Rubin and Babcock (2013), Garcia, Alzate and Barrera (2012), Rouillon (2013), Baranes, Jacquemin and Poudou (2014)

- Pollution externalities and R&D spillovers with clean and dirty technologies:
  Fischer and Newell (2008), Acemoglu et al. (2012)

Fossil source f

- Production q_f with marginal cost c
- Capacities K_f with marginal r_f
- Capacity constraint $q_f \leq K_f$
- Long term private marginal cost of 1 kWh is $c + r_f$
- Environmental damage par kWh of fossil fuel $\delta > 0$
- 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 $D(p) = S'^{-1}(p)$
- Constant retail price / non-reactive consumers:
  $q = q^w = q^{\bar{w}} = K_f$

Social optimum

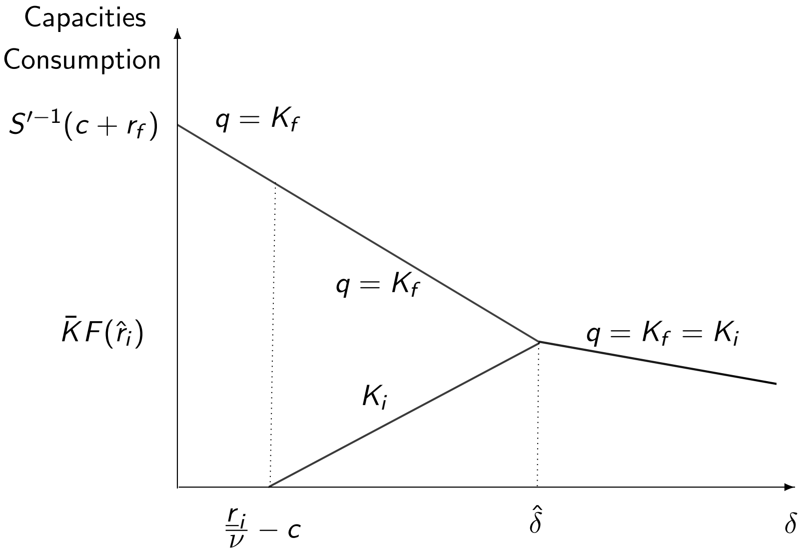
K_f, K_i and q_f^w maximize:

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

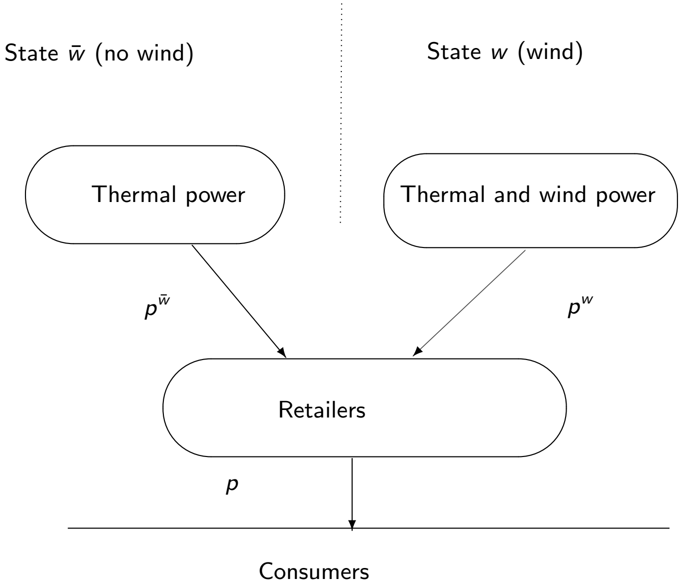
s.t.

$$\begin{aligned} K_i + q_f^w &= K_f \\ K_f \geq q_f^w &\geq 0 \\ K_i &= \bar{K}F(\tilde{r}_i) \end{aligned}$$

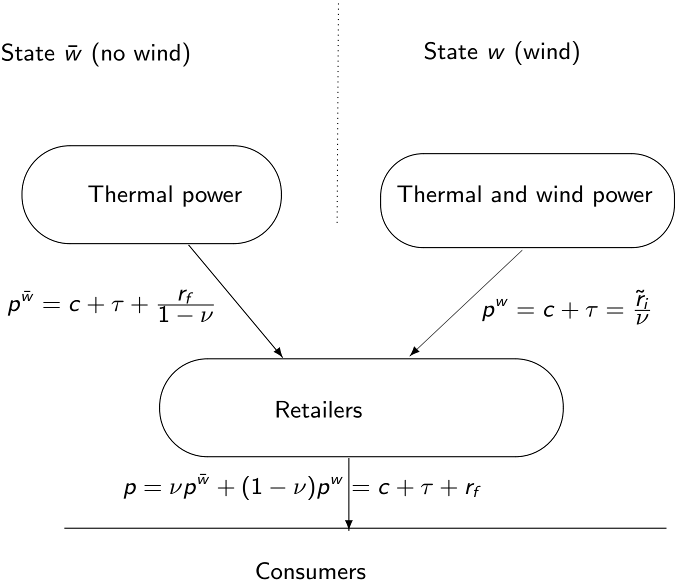
Social optimum



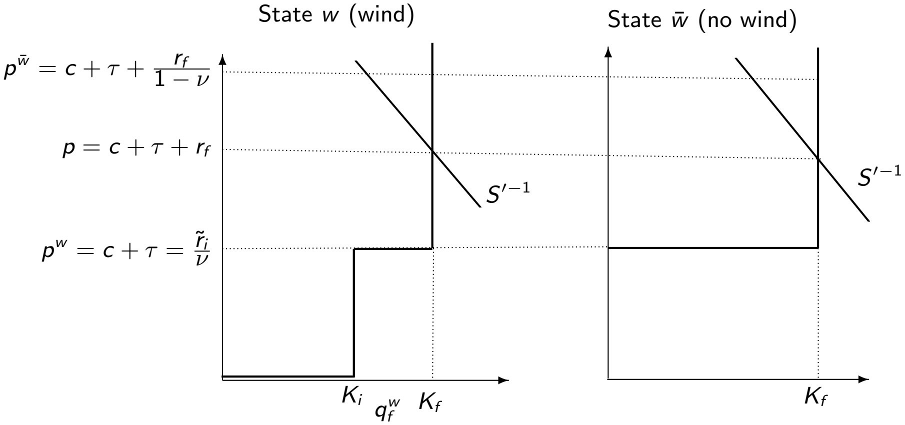
Competitive equilibrium



Competitive equilibrium with carbon tax τ



Merit order



State w (wind)
State $\bar{w}$ (no wind)
$p^{\bar{w}} = c + \tau + \frac{r_f}{1-\nu}$
$p = c + \tau + r_f$
$p^w = c + \tau = \frac{\tilde{r}_i}{\nu}$
S'^{-1}
S'^{-1}
K_i
q_f^w
K_f
K_f

First result

- Pigou tax $\tau = \delta$ implements first-best

Feed-in tariff (FIT)

- Regulated price for intermittent energy p^i
- Tax t per kWh consumed
- Budget-balance constraint:

$$K_f t \geq \nu(p^i - p^w)K_i$$

- First-best if $p^i = c + \delta$ and $p + t = c + r_f + \delta$ therefore $t = \delta$: budget surplus!
- If $p^i = c + \delta$ to obtain K_i and tax t that binds the budget-balance constraint then **over-consumption**!
- Same story with feed-in premium

Renewable Portfolio Standard (RPS)

- Share α of energy consumption supplied with renewable energy
- Renewable energy credits (REC) issue for each kWh of renewable energy
- Retailers buy REC at price g to comply with RPS
- Zero profit condition for wind power producers and retailers:

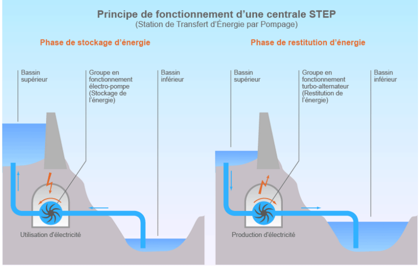
$$p^w + g = \frac{\tilde{r}_i}{\nu}$$

$$p = \nu p^w + (1 - \nu) p^{\bar{w}} + \alpha g$$

- Optimal share α^* leads to a price of REC $g = \delta$
- Retail price $p = c + r_f + \delta\alpha < c + r_f + \delta$ too low, too much electricity consumption
- Must be complemented with a tax on electricity or fossil fuel

$$\tau = \delta\,(1 - \alpha) < \delta$$

Energy storage facility



Energy storage

- s kWh can stored in state w to be used in stated $\bar{w}$
- Energy cost of storing (pumping) $\lambda \leq 1$: λs kWh produced in state $\bar{w}$ with s stored in state w
- Private and social benefit of storing energy?
- Efficient storage maximizes:

$$
\begin{aligned}
&\nu \left[S(\bar{K}F(K_i) + q_f^w - s) - (c+\delta) q_f^w \right] \\
&\quad + (1-\nu) \left[S(K_f + \lambda s) - (c+\delta) K_f \right] \\
&\qquad - \bar{K} \int_{\underline{r}_i}^{\tilde{r}_i} r_i dF(r_i) - r_f K_f
\end{aligned}
$$

s.t.

$$
K_i + q_f^w - s = K_f + \lambda s
$$

Social and private marginal benefit of storage

- The FOCs lead to a social marginal benefit of:

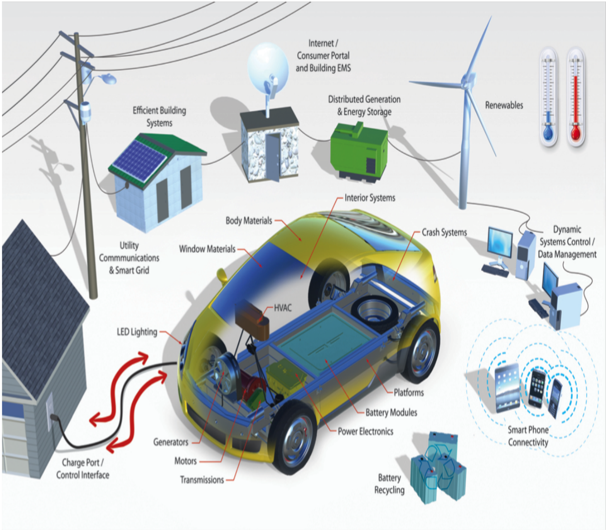
$$\lambda[(1-\nu)(c+\delta)+r_f]-\tilde{r}_i$$

- Private marginal benefit of storage with carbon tax:

$$(1-\nu)p^{\bar{w}}-\nu p^{w}$$

- Equal to the social benefit with equilibrium prices $p^{\bar{w}}=c+\tau+\frac{r_f}{1-\nu}$, $p^{w}=\frac{\tilde{r}_i}{\nu}$ and Pigou tax $\delta=\tau$
- Private incentives in competitive market aligned with social welfare

Smart meters with contingent pricing



A reactive consumer

Smart meters with state-contingent prices

- Share β of reactive consumers paying wholesale price $p^{\bar{w}}$ and p^{w}
- Share $1-\beta$ of non reactive consumers paying fixed price $p = \nu p^{w} + (1-\nu) p^{\bar{w}}$
- Market clearing conditions:

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

Marginal benefit of making consumers reactive

- Expected welfare with a proportion β of reactive consumers:

$$\beta[\nu S(q_r^w)+(1-\nu)S(q_r^{\bar{w}})]+(1-\beta)S(q_{\bar{r}})-\nu(c+\delta)q_f^w-(1-\nu)(c+\delta)K_f$$

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

- Differentiating with respect to β:

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

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

- Risk-averse consumers prefer fixed price contract

Environmental policy with market power

- Monopoly thermal power producer
- Competitive fringe of of wind power producers
- Impact of competition from wind power on price?
- Optimal tax? Regulation instruments to reach first-best?

Program of the monopoly thermal power

q_f^w and K_f maximize:

$$\nu \left[P(q_f^w + K_i) - (c + \tau^w)\right] q_f^w + (1-\nu)\left[P(K_f) - (c + \tau^{\bar{w}})\right] K_f - r_f K_f$$

s.t.

$$\begin{aligned} P(K_i + q_f^w) &= \frac{\tilde{r}_i}{\nu} \\ K_i &= \bar{K} F(\tilde{r}_i) \end{aligned}$$

First-order conditions

$$
\begin{aligned}
q_f^w \quad &: \quad P(q_f^w + K_i) + P'(q_f^w + K_i)\left(1 + \frac{dK_i}{dq_f^w}\right) q_f^w = c + \tau^w \\
K_f \quad &: \quad P(K_f) + P'(K_f)K_f = c + \tau^{\bar{w}} + \frac{r_f}{1-\nu}
\end{aligned}
$$

Implementation of first-best

- State-contigent taxes;

$$\tau^{w} = \delta + \frac{p^{w}}{\epsilon}\left(1 + \frac{dK_i}{dq_f^{w}}\right)\frac{q_f^{w}}{K_f}$$
$$\tau^{\bar{w}} = \delta + \frac{p^{\bar{w}}}{\epsilon}$$

with $\tau^{\bar{w}} < \tau^{w}$

- Price cap $p^{\bar{w}}$ and carbon tax τ^{w}

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- Marginal value of storage = cost difference
- Social value of smart meters not always positive because risk
- Competitive fringe of wind power produce is not enough to get efficiency
- Regulation with state-contingent carbon taxes or price cap and carbon tax