Subsidising Renewables but Taxing Storage? Second-Best policies with Imperfect Carbon Pricing

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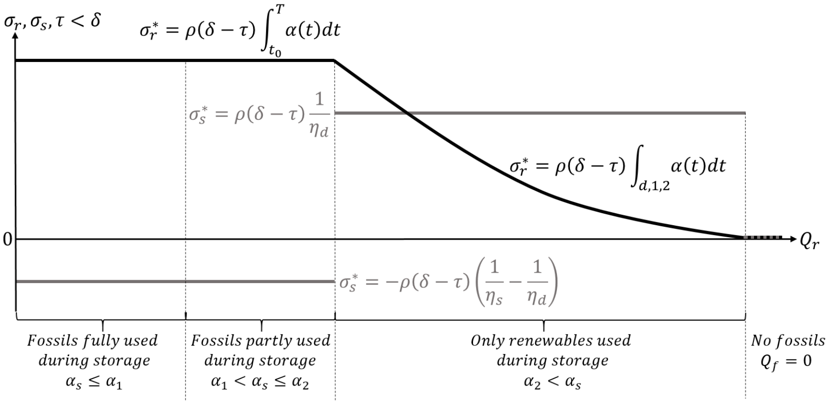
Focus

- policy aim: transition to an energy system that is largely based on renewabes
  - mainly in order to reduce CO_2 emissions
- wind and solar are characterized by high intermittency of supply
- electricity storage important instrument to address intermittency
  - punped-storage plants, small (electric cars) and large scale batteries (Tesla in Australia, Florida), power to gas
- Externality that we consider are CO_2 emissions
  - in particular, we abstract from research spillovers and other issues, that may also motivate policy interventions

Focus

- model with 3 technologies
  - pollutive fossils, intermittent renewables and storage
- important assumptions:
  - greenfield setting
  - dynamic electricity pricing
    - Helm & Mier (2018) show that (for model without storage) similar results obtain if only a subset of consumers can react to short term price fluctuations
- we compare
  1. first-best Pigouvian tax that (fully) internalizes the externality
     - often not feasible, e.g. for political economy reasons
  2. second-best subsidies for renewable and storage capacities
- real world subsidies are often FIT
  - for low market shares of renewables, similar to capacity subsidies
  - for high market shares of renewables, obviously sub-optimal because wasteful excess production is remunerated

Optimal subsidies for linear demand and capacity costs



Literature

- most of the literature on electricity marketes with renewables uses numerical simulations
  - Green and Vasilakos (2010), Liski and Vehviäinen (2015), Hirth (2013)
- subsection in Ambec and Crampes (2017) also consider model with fossils, intermittent renewables and storage
  - Competitive energy storage increases investment into intermittent renewables
  - private and social incentives to invest in energy storage are alined with a socially efficient carbon tax
  - stylized intermittency: availability of renewables either 0 or 1
    - assumption of 0 availability more problematic than binary states
- binary states (usually peak & off-peak demand) common in general literature on storage
  - e.g., Gravelle (1976), Crampes and Moreaux (2001)

Literature

- Durmaz (2014) also consider model with fossils, intermittent renewables and storage
  - no policy instruments
  - problem not fully analytically tractable
  - uses dynamic programming rather than optimal control
- Abrell, Rausch & Streitberger (2018)
  - 2 intermittent renewables with different binary availability
  - compares various subsidy schemes, no storage
  - combination of analytical results and numerical simulations
- Helm and Mier (2016): efficient market diffusion of intermittent renewables
  - similar model set-up, but
  - no storage, no policy instruments
- Wirl (1988), Steffen & Weber (2016): similar way to model storage as optimal control problem

Model and assumptions

- three technologies: $j = r$ (renewables), f (fossils), s (storage)
- only fossils and storage dispatchable (electricity production can be freely varied at every point in time up to the limit of their installed/stored capacity)
- convention: lower case letters denote choices of firms, capital letters for aggregate values
- q_j : capacity of a firm operating with technology j
  - $Q_j = n_j q_j$: overall capacity of technology j
- $c_j(Q_j)q_j$: capacity costs of a firm operating with technology j
  - $c_j(Q_j)$: costs of providing one unit of capacity that individual firm takes as given
  - $c_f'(Q_f) \geq 0$, but for renewables and storage we allow
    - $c_j'(Q_j) < 0$ due to learning (Green & Léautier, 2017),
    - $c_j'(Q_j) > 0$ as best sites are used first (Abrell, Rausch & Streitberger, 2018)
    - $c_j'(Q_j) = 0$ (Helm and Mier, 2016)

Model and assumptions

- k_f: variable production costs of fossils ($k_r = k_s = 0$)
- δ : environmental unit cost of fossils
- $\tau \geq 0$: CO_2 tax
- $b_f = \tau + k_f$: total unit costs of fossil firm
- y_j, output of technology j
  - i.e., $y_s(t) < 0$ means that electricity is stored
- s: level of stored electricity
- $\dot{s} = -\eta(t) y_s(t)$, where $\eta(t)$ are conversion losses of electricity from storage
  - $\eta(t) = \eta_s \in (0,1]$ at times of storage ($y_s(t) < 0$)
  - $\eta(t) = \eta_d \geq 1$ at times of destorage ($y_s(t) > 0$)

Model and assumptions

- $\alpha(t)Q_r$, available capacity of renewables, where $\alpha(t) \in [0,1]$
- we assume that $\alpha(t)$ follows a regular pattern
    - e.g., daily fluctuations of solar power (see below for details)
- storage serves to balance these fluctuations
    - "representative" period: one cycle during which the storage is filled and emptied
- lifetime of installed capacities: m such cycles

Model and assumptions

- subsidies financed by lump-sum taxation
- we exclude several real-world complications such as rampage costs, periodic demand and supply uncertainty (may lead to outage costs)
- Timing (solution by backwards induction)
    - Stage 1: regulator chooses subsidies for renewables and storage capacities
    - Stage 2: competitive firms choose their respective capacities
    - Stage 3: production & consumption decisions

Stage 3: Production of a fossil firms

- consider one representative storage period (e.g. day-night cycle) ranging from $t = t_0$ to $t = T$
- perfect competition
- problem of a fossil firm ($\pi_f(y_f^*(q_f))$ denotes the value function):

$$\pi_f(y_f^*(q_f)) \quad := \quad \max_{y_f(t)} \int_{t_0}^{T} (p(t) - b_f)\, y_f(t)\, dt \ \text{ such that}$$
$$y_f(t) \leq q_f,$$

- first-order conditions (sufficient due to linearity of objective)

$$\begin{aligned} p(t) - b_f - \mu_f(t) &\leq 0 \; [= 0, \text{ if } y_f^*(t) > 0], \\ q_f - y_f(t) &\geq 0, \ \mu_f(t) \geq 0, \ \mu_f(t)[q_f - y_f(t)] = 0. \end{aligned}$$

Stage 3: Production of a renewable firm

- problem of a renewable firm ($\pi_r(y_r^*(q_r))$ denotes the value function):

$$\pi_r(y_r^*(q_r)) := \max_{y_r(t)} \int_{t_0}^{T} p(t)\, y_r(t)\, dt \text{ such that}$$
$$y_r(t) \leq \alpha(t)\, q_r,$$

- first-order conditions

$$p(t) - \mu_r(t) \leq 0 \left[= 0, \text{ if } y_r(t)^* > 0\right],$$
$$\alpha(t)\, q_r - y_r \geq 0, \ \mu_r(t) \geq 0, \ \mu_r(t)\left[\alpha(t)\, q_r - y_r(t)\right] = 0.$$

- note: production choices in t have no effects on other periods

Stage 3: Production of a storage firm

- storage firms: optimal control problem with state space constraints
  - control variable: storage decision $y_s(t)$
  - state variable: s, level of stored electricity

$$
\begin{aligned}
\pi_s\left(y_s^*(q_s)\right) &:= \max_{y_s(t)} \int_{t_0}^{T} p(t)\, y_s(t)\, dt \text{ such that} \\
\dot{s}(t) &= -\eta(t)\, y_s(t), \\
s(t_0) &= s(T), \\
s(t) &\leq q_s, \\
s(t) &\geq 0.
\end{aligned}
$$

- Hamiltonian and Lagrangian

$$
\mathscr{H}\left(y_s(t)\right) = p(t)\, y_s(t) - \lambda(t)\, \eta(t)\, y_s(t)
$$

$$
\mathscr{L}_s(t) = \mathscr{H}\left(y_s(t)\right) + \varphi_s(t)\left(q_s - s(t)\right) + \varphi_d(t)\, s(t)
$$

Stage 3: Production of a storage firm

- first-order optimality conditions

$$\begin{aligned}
\frac{\partial \mathscr{L}_s(t)}{\partial y_s(t)} &= p(t) - \lambda(t)\eta(t) = 0, \\
\dot{s}(t) &= \frac{\partial \mathscr{L}_s(t)}{\partial \lambda(t)} = -\eta(t) y_s(t), \\
\dot{\lambda}(t) &= -\frac{\partial \mathscr{L}_s(t)}{\partial s(t)} = \varphi_s(t) - \varphi_d(t), \\
\frac{\partial \mathscr{L}_s(t)}{\partial \varphi_s(t)} &= q_s - s(t) \geq 0, \;\; \varphi_s(t) \geq 0, \; \varphi_s(t)(q_s - s(t)), \\
\frac{\partial \mathscr{L}_s(t)}{\partial \varphi_d(t)} &= s(t) \geq 0, \;\; \varphi_d(t) \geq 0, \; \varphi_l(t) s(t), \\
s(t_0) &= s(T).
\end{aligned}$$

Consumers

- utility maximization leads to an inverse demand function, $p(x)$, and
- consumption choices on competitive electricity market maximize consumer surplus:

$$w(x^*) := \max_{x(t)} \int_{t_0}^{T} \left[\int_{p(t)}^{p_{\max}} x(\tilde{p})\, d\tilde{p} \right] dt \quad \text{such that}$$

$$x(t) \leq \sum_j Y_j(t),$$

- first-order conditions

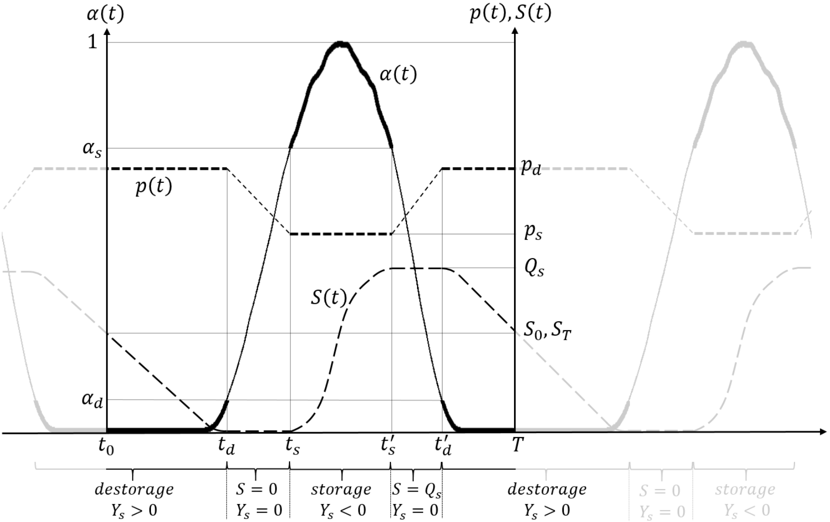
$$-\frac{dp(t)}{dx(t)} x(t) - \nu(t) \leq 0 \left[= 0, \text{ if } x(t)^* > 0\right],$$

$$\sum_j Y_j(t) - x(t) \geq 0 \quad \nu(t) \geq 0,\ \nu(t) \left(\sum_j Y_j(t) - x(t) \right) = 0.$$

Solution of optimal control problem

- we need to impose more structure on availability of renewables $\alpha(t)$
- in our general model we assume:
  - at the starting and end point of a representative period $\alpha(t_0) = \alpha(T) = 0$
  - $\alpha(t)$ is (weakly) increasing until reaching the maximum availability of 1
  - thereafter $\alpha(t)$ is (weakly) decreasing
- e.g. in many countries, a day-night cycle of solar power roughly has shape of a sinus curve

PV production in Germany, 30 June 2018

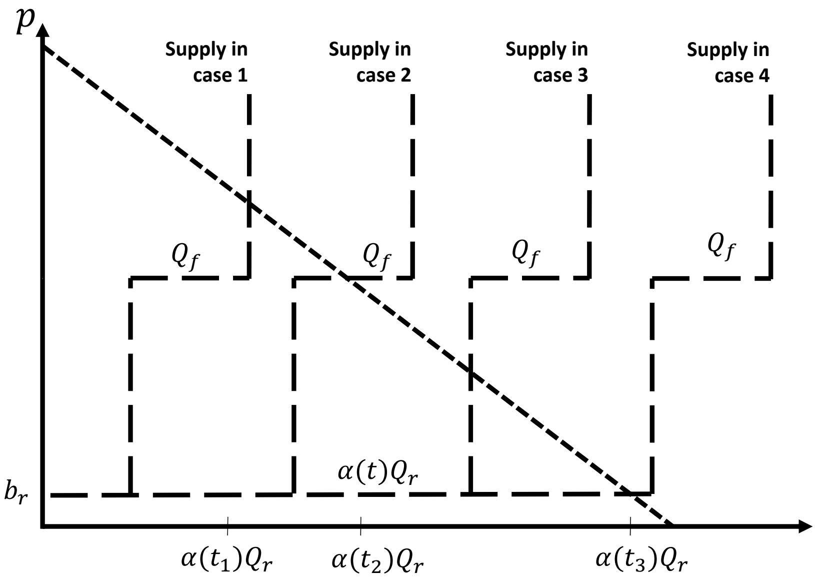


Solution at production stage

i	availability of renewables	$Y_{ri}(t)$	$Y_{fi}(t)$	$Y_{si}(t)$
d	$0 \leq \alpha(t) \leq \alpha_d$	$\alpha(t)\,Q_r$	Q_f	$(\alpha_d - \alpha(t))\,Q_r$
1	$\alpha_d < \alpha(t) \leq \min\{\alpha_1, \alpha_s\}$	$\alpha(t)\,Q_r$	Q_f	0
2	$\min\{\alpha_1, \alpha_s\} < \alpha(t) \leq \min\{\alpha_2, \alpha_s\}$	$\alpha(t)\,Q_r$	$x(b_f) - \alpha(t)\,Q_r$	0
3	$\min\{\alpha_2, \alpha_s\} < \alpha(t) \leq \min\{\alpha_3, \alpha_s\}$	$\alpha(t)\,Q_r$	0	0
4	$\min\{\alpha_3, \alpha_s\} < \alpha(t) \leq \alpha_s$	$x(0)$	0	0
s	$\alpha_s < \alpha(t) \leq 1$	*	$Y_f(\alpha_s)$	$(\alpha_s - \alpha(t))\,Q_r$

* $\min\{\alpha(t)\,Q_r, x(0) - Y_s(t)\}$

The 4 cases in intermediate stage



Intermediate period - cases and diffusion stages

- as renewables capacities rise, more of the intermediate cases 1 to 4 obtain
  - diffusion stage V (very low renewables): only case 1
    - fossil capacities fully used during storage
  - diffusion stage L (low renewables): only case 1 & 2
    - fossil capacities partly used during storage
  - diffusion stage M (medium renewables): only case 1, 2 & 3
    - only renewables capacities used during storage
  - diffusion stage H (high renewables): all 4 cases
    - only renewables capacities used during storage

Stage 2: Capacity choices of competitive firms

- remember that
  - $\pi_j\left(y_j^*\left(q_j\right)\right)$, $j = f, r, s$ are maximum profits during 1 representative cycle for given capacities
  - by construction, production choices in one cycle have no effect on other cycles
- hence: net present value of profits over lifetime of capacities

$$\sum_{z=1}^{m} \frac{1}{(1+r)^z} \pi_j\left(y_j^*\left(q_j\right)\right) = \rho \pi_j\left(y_j^*\left(q_j\right)\right)$$

- Firms maximization problem

$$\pi_f\left(q_f^*(\theta), \theta\right) := \max_{q_f} \rho \int_{t_0}^{T} \left(p(t) - k_f - \tau\right) y_f^*(t, q_f) dt - c_f\left(Q_f\right) q_f$$

$$\pi_r\left(q_r^*(\theta), \theta\right) := \max_{q_r} \rho \int_{t_0}^{T} p(t) y_r^*(t, q_r) dt - \left(c_r(Q_r) - \sigma_r\right) q_r$$

$$\pi_s\left(q_s^*(\theta), \theta\right) := \max_{q_s} \rho \int_{t_0}^{T} p(t) y_s^*(t, q_s) dt - \left(c_s(Q_s) - \sigma_s\right) q_s$$

Firms' capacity choices

- Competitive firms take prices as well as the occurrence of cases, and hence times t where they start as given
- first-order conditions of representative fossil, renewable and storage firms:

$$\begin{aligned}
\rho \int_{t_0}^{T} (p(t) - k_f - \tau) \frac{dy_f^*(t, q_f)}{dq_f} dt - c_f(Q_f) &= 0 \\
\rho \int_{t_0}^{T} p(t) \frac{dy_r^*(t, q_r)}{dq_r} dt - c_r(Q_r) + \sigma_r &= 0 \\
\rho \int_{t_0}^{T} p(t) \frac{dy_s^*(t, q_s)}{dq_s} dt - c_s(Q_s) + \sigma_s &= 0
\end{aligned}$$

- different diffusion stages are associated with different ranges of integration
  - hence different solutions obtain
  - makes the analysis tedious, but essential for appropriate representation of intermittency

Stage 1: subsidies for renewables and storage

- regulator chooses subsidies so as to maximize welfare:

$$\max_{\sigma_r,\sigma_s,\tau} \rho w\left(x^*\right)+\sum_j n_j \pi_j\left(q_j^*\left(\theta\right),\theta\right)-\sigma_r Q_r-\sigma_s Q_s-\rho(\delta-\tau)\int_{t_0}^{T} Y_f\left(t,\mathbf{Q}\right)dt$$

- 1st term: NPV of consumers surplus (value function of stage 3
- 2nd term: NPV of producer surplus (value function of stage 2)
- terms 3-4: subsidy costs
- last term: damage costs and income from pollution tax
  - non-internalized externality

- solution procedure: consumer and producer surplus are value functions
- envelope theorem: only partial derivatives $\frac{\partial}{\partial \sigma_j}, \frac{\partial}{\partial \tau}$ for these 2 terms, yielding FOCs

$$-\sigma_r \frac{dQ_r}{d\sigma_j} - \sigma_s \frac{dQ_s}{d\sigma_j} - \rho(\delta - \tau) \int_{t_0}^{T} \frac{dY_f(t, \mathbf{Q})}{d\sigma_j} dt = 0, \;\; j = r, s$$

$$-\sigma_r \frac{dQ_r}{d\tau} - \sigma_s \frac{dQ_s}{d\tau} - \rho(\delta - \tau) \int_{t_0}^{T} \frac{dY_f(t, \mathbf{Q})}{d\tau} dt = 0$$

Theorem

The first-best solution obtains with a Pigouvian tax on fossils, $\tau^* = \delta$, and no subsidies for renewable and storage capacities.

- *derivatives depend on diffusion stage. Hence they require separate analysis.*

Fossil capacities fully used during storage ($\alpha_s < \alpha_1$)

Theorem

Suppose that $\alpha_s < \alpha_1$. Then the optimal subsidies of renewable and storage capacities are

$$\sigma_r^* = \rho \int_{t_0}^{T} dt \frac{\int_{t_0}^{T} \frac{\partial p(t)}{\partial x(t)} \alpha(t)\, dt}{\int_{t_0}^{T} \frac{\partial p(t)}{\partial x(t)} dt - \frac{c_f'(Q_f)}{\rho}} (\delta - \tau),$$

$$\sigma_s^* = \rho \int_{t_0}^{T} dt \frac{-\frac{1}{\eta_s}\frac{\partial p_s}{\partial x_s} + \frac{1}{\eta_d}\frac{\partial p_d}{\partial x_d}}{\int_{t_0}^{T} \frac{\partial p(t)}{\partial x(t)} dt - \frac{c_f'(Q_f)}{\rho}} (\delta - \tau).$$

These subsidies implement the first-best solution. *Moreover, for any $\tau < \delta$, the renewable subsidy is strictly positive, whereas the storage subsidy is negative if and only if $\frac{1}{\eta_d}\left|\frac{\partial p_d}{\partial x_d}\right| < \frac{1}{\eta_s}\left|\frac{\partial p_s}{\partial x_s}\right|$.*

Fossil capacities fully used during storage ($\alpha_s < \alpha_1$)

- fraction represent $-\int_{t_0}^{T} \frac{\partial Y_f(t)}{\partial Q_r} dt$ and $-\int_{t_0}^{T} \frac{\partial Y_f(t)}{\partial Q_s} dt$
- high efficiency losses during destorage (high η_d) and storage (low η_s) strengthen case for taxing storage
- one would expect that demand is more price responsive during high prices of destorage
  - $|\frac{\partial x_d}{\partial p_d}| > |\frac{\partial x_s}{\partial p_s}| \Longleftrightarrow |\frac{\partial p_d}{\partial x_d}| < |\frac{\partial p_s}{\partial x_s}|$

Corollary

Let $\alpha_s < \alpha_1$ and assume that $\frac{\partial^2 p}{\partial x^2} = 0$. For any $\tau < \delta$, it is optimal ***to tax storage capacities if there are conversion losses of storage****. If the fossil technology has constant unit costs—i.e., $c_f'(Q_f) = 0$—then optimal subsidies are $\sigma_r^* = \rho(\delta - \tau) \int_{t_0}^{T} \alpha(t)\, dt$ and $\sigma_s^* = -\rho(\delta - \tau)\left(\frac{1}{\eta_s} - \frac{1}{\eta_d}\right)$.*

Optimal subsidies: Intution

- when starting to write the paper I expected the following:
  - without Pigouvian tax, there are too much fossil capacities
  - second best instrument: support renewables
    - by a subsidy for renewables
    - and a subsidy for storage, since storage makes renewables more competitive
  - however, the market already cares for the second effect
    - more renewables trigger more storage
    - hence no need to further subsidize storage
  - moreover, renewables are best targeted directly by subsidizing renewables
    - not by subsidizing storage

Optimal storage subsidies: Intution

- **what matters is the effect of storage on incentives to invest in fossils**
- for $\alpha(t)$ low, destorage reduces the electricity price
  - this reduces incentives to invest in fossils
- for high $\alpha(t)$, storage raises the electricity price
  - this raises incentives to invest in fossils
- the price increasing effect during storage is stronger due to efficiency losses of storage
  - storage: more than one electricity unit from the market needed to fill the store by one unit
  - destorage: less than one electricity unit from the store arrives at the market
- this motivates the tax on storage

Fossil capacities partly used during storage ($\alpha_1 < \alpha_s \leq \alpha_2$)

Theorem

Suppose that $\alpha_1 < \alpha_s \leq \alpha_2$. Then, optimal subsidies of renewable and storage capacities follow from

$$\sigma_r^* = \rho \left(\int_{d,1} dt \frac{\int_{d,1} \frac{\partial p(t)}{\partial x(t)} \alpha(t)\, dt}{\int_{d,1} \frac{\partial p(t)}{\partial x(t)} dt - \frac{c_f'(Q_f)}{\rho}} + \int_{2,s} \alpha(t)\, dt \right) (\delta - \tau),$$

$$\sigma_s^* = \rho \left(\int_{d,1} dt \frac{\frac{1}{\eta_d} \frac{\partial p_d}{\partial x_d}}{\int_{d,1} \frac{\partial p(t)}{\partial x(t)} dt - \frac{c_f'(Q_f)}{\rho}} - \frac{1}{\eta_s} \right) (\delta - \tau).$$

For any $\tau \neq \delta$, these ***subsidies do not implement the first-best solution****, and for $\tau < \delta$ raising the tax on fossil pollution would increase welfare. Moreover, for any $\tau < \delta$, the renewable subsidy is strictly positive, whereas the storage subsidy is negative if and only if $\frac{1}{\eta_d} \frac{\partial p_d}{\partial x_d} \frac{\int_{d,1} dt}{\int_{d,1} \frac{\partial p(t)}{\partial x(t)} dt - \frac{c_f'(Q_f)}{\rho}} < \frac{1}{\eta_s}$.*

Fossil capacities partly used during storage ($\alpha_1 < \alpha_s \leq \alpha_2$)

- inefficiency of subsidies: a tax would raise the market price $b_f = k_f + \tau$ during case 2 and storage
  - but subsidies not because with them the price is $b_f = k_f$, i.e. independent of subsidy
  - hence subsidies lead to higher electricity consumption that is met with pollutive fossils during these periods
- no price effects during stage 2 and storage also explains "simpler" optimal subsidies

Corollary

Let $\alpha_1 < \alpha_s \leq \alpha_2$ and assume that $\frac{\partial^2 p}{\partial x^2} = 0$. For any $\tau < \delta$, it is optimal to tax storage capacities when $c_f'(Q_f) > 0$ and/or when there are round-trip efficiency losses of storage. If the fossil technology has constant unit costs—i.e., $c_f'(Q_f) = 0$—then optimal subsidies are $\sigma_r^* = \rho(\delta - \tau) \int_{t_0}^{T} \alpha(t)\, dt$ and $\sigma_s^* = -\rho(\delta - \tau)\left(\frac{1}{\eta_s} - \frac{1}{\eta_d}\right)$.

Only renewables capacities used during storage ($\alpha_2 < \alpha_s$)

Theorem

Suppose that $\alpha_2 < \alpha_s$ so that no fossil capacities are used during the storage period. Then, optimal subsidies of renewable and storage capacities are

$$\sigma_r^* = \rho \left(\int_{d,1} dt \frac{\int_{d,1} \frac{\partial p(t)}{\partial x(t)} \alpha(t)\, dt}{\int_{d,1} \frac{\partial p(t)}{\partial x(t)} dt - \frac{c_f'(Q_f)}{\rho}} + \int_2 \alpha(t)\, dt \right) (\delta - \tau), \quad (1)$$

$$\sigma_s^* = \rho \left(\int_{d,1} dt \frac{\frac{1}{\eta_d} \frac{\partial p_d}{\partial x_d}}{\int_{d,1} \frac{\partial p(t)}{\partial x(t)} dt - \frac{c_f'(Q_f)}{\rho}} \right) (\delta - \tau). \quad (2)$$

For any $\tau \neq \delta$, these subsidies do not implement the first-best solution. Moreover, for any $\tau < \delta$, ***both subsidies are strictly positive****, and raising the tax on fossil pollution would increase welfare.*

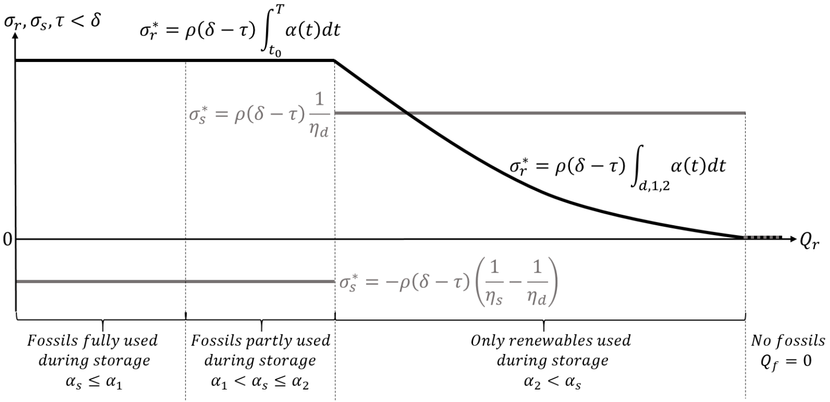
Only renewables capacities used during storage ($\alpha_2 < \alpha_s$)

- fossils no longer benefit from price increasing effect of storage capacities during the storage period
  - simply because fossils do not produce during storage
- but fossils still suffer from price decreasing effect during destorage

Corollary

Let $\alpha_2 < \alpha_s$ and assume that $\frac{\partial^2 p}{\partial x^2} = 0$ and $c_f'(Q_f) = 0$. Then, the optimal subsidy for renewable capacities is $\sigma_r^* = \rho(\delta - \tau)\int_{d,1,2} \alpha(t)\,dt$ and, thus, decreasing in the level of renewable capacities. The optimal subsidy for storage capacities is constant at $\sigma_s^* = \rho(\delta - \tau)\frac{1}{\eta_d}$.

Optimal subsidies for linear demand and capacity costs



Concluding remarks

- 1st best policy is a Pigouvian tax on fossils
- subsidies on renewable and storage capacities are
  - first-best for low levels of renewables (and storage)
  - only second-best for higher levels of renewables
  - and much more complicated
- optimal subsidies for renewables
  - start high and are reduced as economy less based on fossils
- optimal subsidies for storage
  - start with negative values, but turn positive as economy less based on fossils
- These effects depend on the different effects of intermittency as the share of renewables rises
- Implications for subsidies to electric vehicles?
- Learning may provide overriding argument to subsidize storage