Optimal subsidies for renewables and storage capacities

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Electricity is difficult ... but we solved the problem ... by creating a new problem!

- Technological constraints solved by **"perfect" old world**

Climate change is the biggest market failure the world has ever seen. – Nicholas Stern

- **Climate change** (carbon externality)

- Policy aim: **100% renewables**
- Not feasible (Heard et al. 2017) due to **reliability of intermittent renewables like wind and solar**
- Feasible (Brown et al. 2018) with **storage**

In a nutshell

Real world observations

- Fossils cause pollution but **carbon prices are (too) low**
- Renewable energies are (highly) subsidized but storage not
- Carbon externality is (mainly) used to motivate this (other: induced technological change)

Setup

- **Carbon tax is political not feasible** but subsidizing investments in renewables and storage capacity
- No dynamic investment issues (**no induced technological change**) to focus on the **carbon externality**
- No uncertainty, no periodic load, no ramping issues
- **Intermittency**, **dynamic control storage problem**

At which point a regulator should stop promoting renewables and start subsidizing storage?

1. Renewables must be subsidized
2. Storage must be taxed if renewables capacity is small

Literature

Pollution control
(e.g. Baumol and Oates 1975, Polinsky 1979 Can, Requate and Unold 2003 EER, Bläsi and Requate 2010 PFM)
... Without dynamic investment issues a (Pigouvian) carbon tax is efficient (1st best)

Renewable support policies
(e.g. Fabra and Reguant 2014 AER, Liski and Vehviläinen 2016 WP)
... So far we know **no literature about storage support policies** (partly Ambec and Crampes 2017 WP)

Electricity markets with renewables
(e.g. Joskow 2011 AER PP, Borenstein 2012 JEPer, Ambec and Crampes 2012 REE, Helm and Mier 2018 WP)

Storage (e.g. Gravelle 1976 EJ, Crampes and Moreaux 2010 EE, Steffen and Weber 2013 EE)

Model

Three technologies, $j = r, f, s$

1. Renewables r
2. Fossils f
3. Storage s

Two policy instruments

- Carbon tax $\tau \geq 0$ (1st best)
- Capacity subsidy σ_j (2nd best)

Three stage game (solved by backward induction)

1. Subsidy choices of a regulator σ_r, σ_s
2. Capacity choices of perfectly competitive firms q_j
3. Production y_j and demand x choices of firms and consumers for each $t \in [0, T]$

- Inverse demand is (weakly) decreasing, $\frac{\partial p}{\partial x} \leq 0$
- Firms take total production, total capacity and prices as given

Stage 3 - Production choices

1. Renewables r
   - $y_r(t) \leq \alpha(t) q_r$, where $\alpha(t) \in [0,1]$ (**intermittency**)
   - Marginal production costs of 0

$$\pi_{ry} := \max_{y_r(t)} \int_0^T p(t) y_r(t) \, dt$$

2. Fossils f
   - $y_f(t) \leq q_f$ (fully dispatchable)
   - **Damage of** $\delta \int_0^T y_f(t) \, dt$ (carbon externality)
   - Marginal production costs of b_f

$$\pi_{fy} := \max_{y_f(t)} \int_0^T (p(t) - b_f) y_f(t) \, dt$$

Stage 3 - Production and demand choices

3. Storage s with **conversion losses** $\eta(t)$ (optimal control problem)
   - $\eta(t) = \eta_s \in (0,1]$ at times of storage ($y_s < 0$)
   - $\eta(t) = \eta_d \geq 1$ at times of destorage ($y_s > 0$)
   - $S(0) = S(T)$, initial and terminal condition
   - $0 \leq S \leq q_s$, level constraint

$$\pi_{sy} := \max_{y_s(t)} \int_0^T p(t)\, y_s(t)\, dt \text{ such that}$$

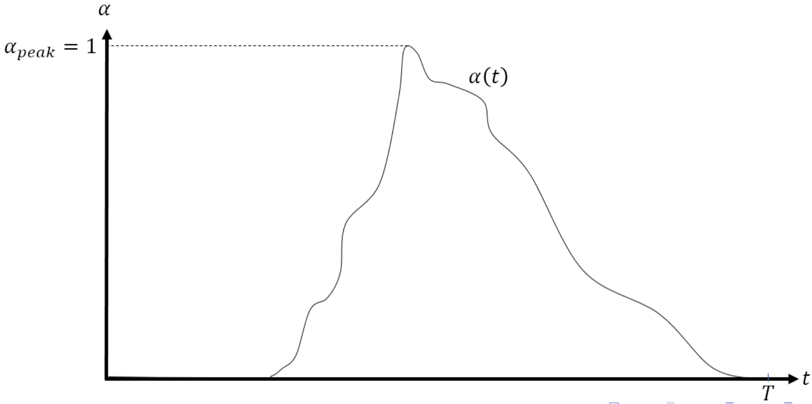
$$\frac{dS}{dt} = -\eta(t)\, y_s(t)$$

- Consumer surplus maximization

$$w := \max_{x(t)} \int_0^T \int_{p(t)}^{WTP_{max}} x(\tilde{p})\, d\tilde{p}\, dt$$

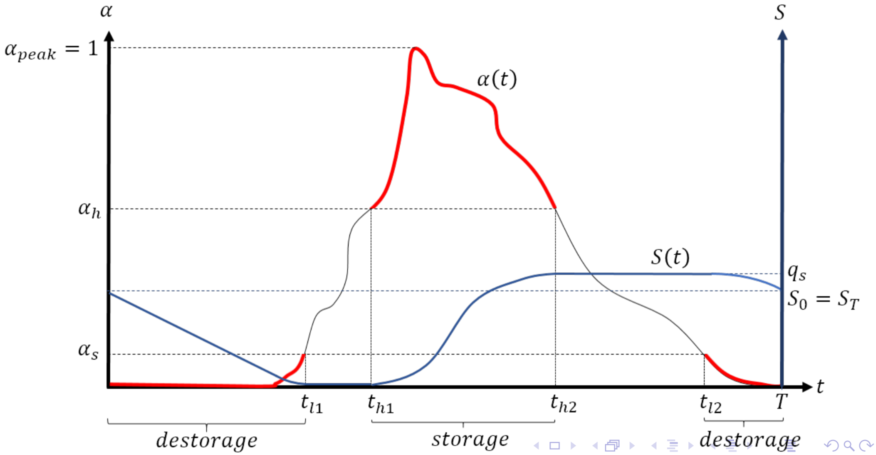
Stage 3 - Availability of renewables

- **Representative cycle** from 0 to T (solar night-day or wind seasonality)
- $\alpha(t)$ is (weakly) monotonically increasing up to α_{peak} and then (weakly) monotonically decreasing



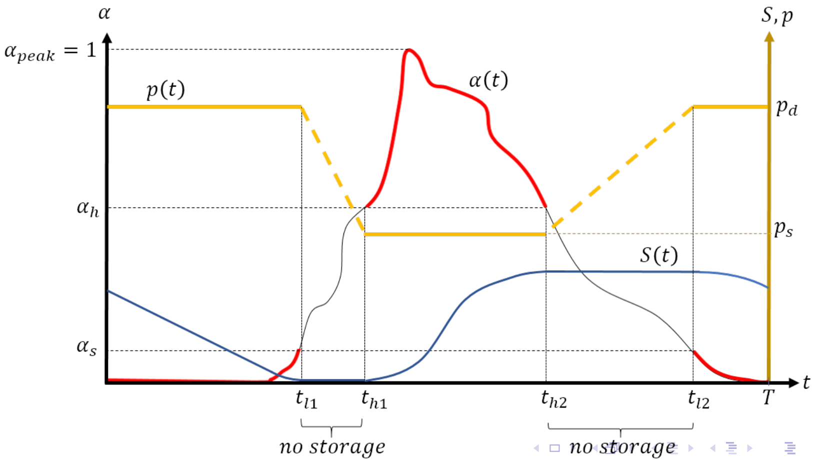
Stage 3 - Explaining storage level

1. **Destorage** period for low α until the storage is empty
2. Intermediate period (**no storage**)
3. **Storage** period for high α until the storage is refilled



Stage 3 - Explaining prices

1. Destorage period with **constant** p_d
2. Intermediate period (no storage) with $p_s \leq p \leq p_d$
3. Storage period with **constant** $p_s < p_d$



Stage 2 - Capacity choices

Profit maximization with capacity costs and subsidies

$$\begin{aligned}\pi_r(\sigma) &:= \max_{q_r} \pi_{ry} - (c_r(Q_r) - \sigma_r) q_r, \\ \pi_f(\sigma) &:= \max_{q_f} \pi_{fy} - c_f(Q_f) q_f, \\ \pi_s(\sigma) &:= \max_{q_s} \pi_{sy} - (c_s(Q_s) - \sigma_s) q_s.\end{aligned}$$

- Total capacity $Q_j = n_j q_j$
- Capacity costs $c_j(Q_j) q_j$ with $\frac{\partial c_j(Q_j) q_j}{\partial q_j} = c_j(Q_j)$ and $\frac{\partial c_f}{\partial Q_f} \geq 0$
- Subsidies $\sigma_j q_j$ for $j = r, s$

Stage 1 - Subsidy choices

Welfare = consumer surplus + profits − damage costs− subsidy costs

$$\max_{\sigma_r,\sigma_s} W(\sigma) = w + \pi(\sigma) - \delta \int_0^T y_f(t)\,dt - \sum_j \sigma_j Q_j$$

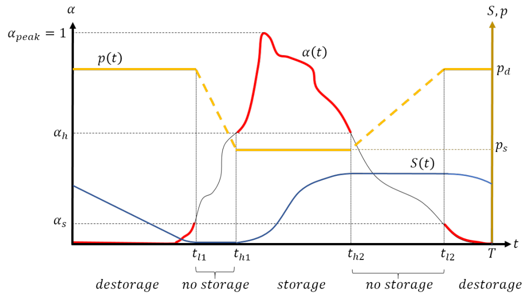
- w, value function of consumer surplus maximization in stage 3
- $\pi(\sigma) := \sum_j n_j \pi_j(\sigma)$, value function of producer surplus maximization in stage 2

Applying envelope theorem yielding FOCs for $j = r, s$

$$\sigma_r \frac{\partial Q_r}{\partial \sigma_j} + \sigma_s \frac{\partial Q_s}{\partial \sigma_j} = -\delta \int_0^T \frac{\partial y_f(t)}{\partial \sigma_j} dt$$

Remember - Explaining prices

1. Destorage period with **constant** p_d
2. Intermediate period (no storage) with $p_s \leq p \leq p_d$
3. Storage period with **constant** $p_s < p_d$

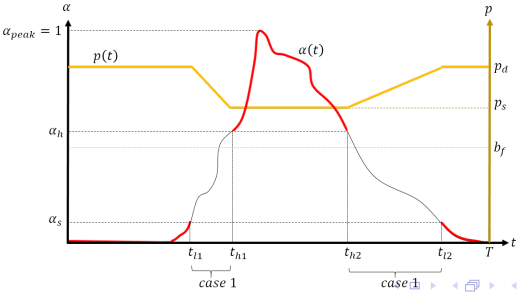


- Notation: d (destorage), s (storage), 1 (case 1), 2 (case 2)
- Obvious solution is the only solution if $\frac{\partial Q_r}{\partial \sigma_r}\frac{\partial Q_s}{\partial \sigma_s} + \frac{\partial Q_r}{\partial \sigma_s}\frac{\partial Q_s}{\partial \sigma_r} \neq 0$

Really, subsidizing renewables but taxing storage?

Very low renewables, i.e. $Q_r + Q_f < x(b_f)$
Renewables and fossil fully used during destorage, storage and in case 1

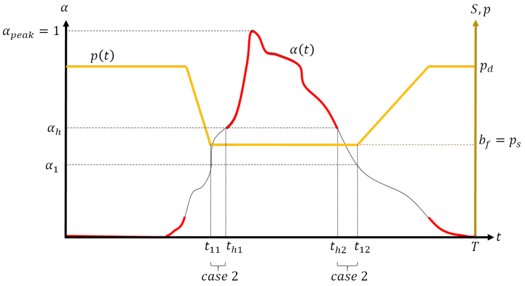
$$0 = \left(\delta \frac{\int_{d,1,s} \frac{\partial p(t)}{\partial Q_r} dt}{\int_{d,1,s} \frac{\partial p(t)}{\partial Q_f} dt - \frac{\partial c_f}{\partial Q_f}} - \sigma_r\right) \frac{\partial Q_r}{\partial \sigma_j}$$
$$+ \left(\delta \frac{\int_{d} \frac{\partial p(t)}{\partial Q_s} dt + \int_{s} \frac{\partial p(t)}{\partial Q_s} dt}{\int_{d,1,s} \frac{\partial p(t)}{\partial Q_f} dt - \frac{\partial c_f}{\partial Q_f}} - \sigma_s\right) \frac{\partial Q_s}{\partial \sigma_j}$$



Still, storage subsidies might be efficient!

Low renewables, i.e. $Q_r < x(b_f)$ and $Q_r + Q_f > x(b_f)$
Fossil not fully used in case 2 and during storage

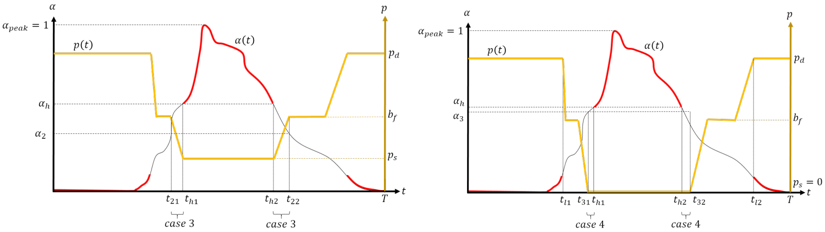
$$0 = \left(\sigma_r - \delta\left[\int_{d,1} dt \frac{\int_{d,1} \frac{\partial p(t)}{\partial Q_r} dt}{\int_{d,1} \frac{\partial p(t)}{\partial Q_f} dt - \frac{\partial c_f}{\partial Q_f}} + \int_2 \alpha(t)\, dt + \int_s dt \frac{\partial(a_h Q_r)}{\partial Q_r}\right]\right)\frac{\partial Q_r}{\partial \sigma_j}$$
$$+ \left(\sigma_s - \delta\left[\int_{d,1} dt \frac{\int_{d} \frac{\partial p(t)}{\partial Q_s} dt}{\int_{d,1} \frac{\partial p(t)}{\partial Q_f} dt - \frac{\partial c_f}{\partial Q_f}} + \int_s dt \frac{\partial(a_h Q_r)}{\partial Q_s}\right]\right)\frac{\partial Q_s}{\partial \sigma_j}$$



Subsidizing storage if renewable capacity is high!

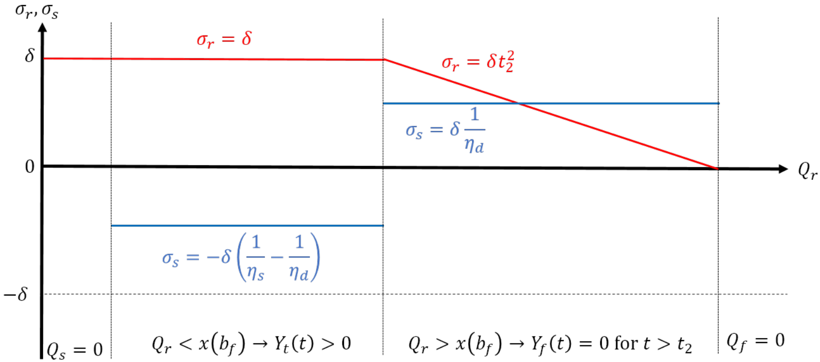
Medium and high renewables, i.e. $Q_r > x(b_f)$
Renewables fully used but fossils not at all in case 3 and during storage

$$0 = \left(\sigma_r - \delta\left[\int_{d,1} dt \frac{\int_{d,1} \frac{\partial p(t)}{\partial Q_r} dt}{\int_{d,1} \frac{\partial p(t)}{\partial Q_f} dt - \frac{\partial c_f}{\partial Q_f}} + \int_2 \alpha(t)\, dt\right]\right) \frac{\partial Q_r}{\partial \sigma_j} + \left(\sigma_s - \delta \int_{d,1} dt \frac{\int_d \frac{\partial p(t)}{\partial Q_s} dt}{\int_{d,1} \frac{\partial p(t)}{\partial Q_f} dt - \frac{\partial c_f}{\partial Q_f}}\right) \frac{\partial Q_s}{\partial \sigma_j}$$



Simplified "double linear" model

- Inverse demand is linear, i.e. $p(t) = \frac{A - x(t)}{\gamma}$
- Renewable availability follows a symmetric triangle from 0 to $T = 2$ with $\alpha(t) = t$ for all $t \leq 1$ and $\alpha(t) = 2 - t$ for all $t > 1$



Main results

Starting intuition: 2nd best should be a subsidy for renewables and a subsidy for storage since storage makes renewables more competitive

But we found that total renewables capacity matters

- if $Q_r + Q_f < x(b_f)$ (very low), then $\sigma_r > 0$ but $\sigma_s < 0$
- if $Q_r < x(b_f)$ and $Q_r + Q_f > x(b_f)$ (low), then $\sigma_r > 0$ but $\sigma_s \lesseqgtr 0$
- if $Q_r > x(b_f)$ (medium/high), then $\sigma_r, \sigma_s > 0$ (starting intuition)

Simplified "double linear" model

- if $Q_r < x(b_f)$ (very low/low),
  then $\sigma_r = \delta = \delta \int_0^T \alpha(t)\,dt$ and $\sigma_r = -\delta\left(\frac{1}{\eta_s} - \frac{1}{\eta_d}\right)$
- if $Q_r > x(b_f)$(medium/high),
  then $\sigma_r = \delta t_2^2 = \delta \int_{d,1,2} \alpha(t)\,dt$ and $\sigma_s = \delta \frac{1}{\eta_d}$

Concluding remarks

General model: **Marginal subsidies must be equal to marginal damages**

- Renewables must be subsidized
- Storage must be taxed for very low renewables, inconclusive results for low but subsidized for medium/high

Simplified model: **Technologies must be subsidized in high of the mitigated pollution damage**

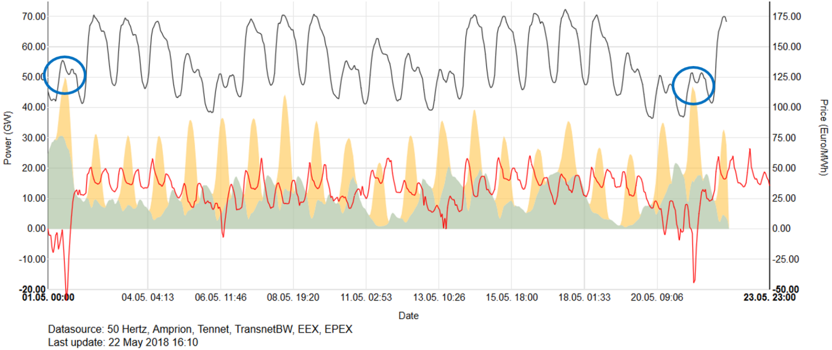
- Conversion losses of storage are “dirty” if (very) low renewables
- Storage is “clean” if only renewables are used during the storage period (medium/high renewables)
- (Other: No subsidy-tax-symmetry)

Restrictions

- Monotonically increasing/decreasing $\alpha(t)$ to abstract from multiple destorage/storage cycles
- No technological change (but similar effects regarding the carbon externality: renewables subsidies should fall in Q_r)

Outlook - German power sector in May 2018

Left axis: demand (black), solar production (yellow), wind production (green); right axis: day-ahead price (red)



Maybe we should start subsidizing storage capacities soon ... at least if the carbon externality is our motivation only!

Thank you very much for your attention!

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