Subsidies for Renewable Energies in the Presence of Learning Effects and Market Power

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- In Europe, feed-in tariffs particularly effective in promoting the rapid expansion of RES-E capacity and production
- Claim: policy intervention is justified in the early stage of RES-E use to spur learning by doing and enable RES-E producers to move downwards on their learning curves, until they become competitive wrt conventional electricity producers

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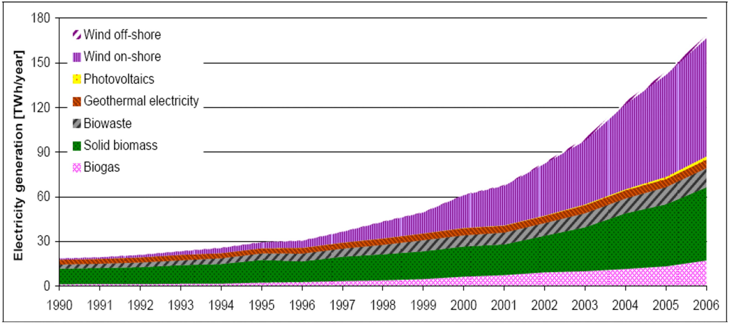

Figure: Development of electricity generation from renewable electricity in the EU-27 (excluding hydropower)

Contributions

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1. Oligopolistic competition in the fossil fuel electricity sector
2. Learning by doing in the RES-E equipment industry
3. Oligopolistic competition in the RES-E equipment industry

Division of the electricity network in Germany

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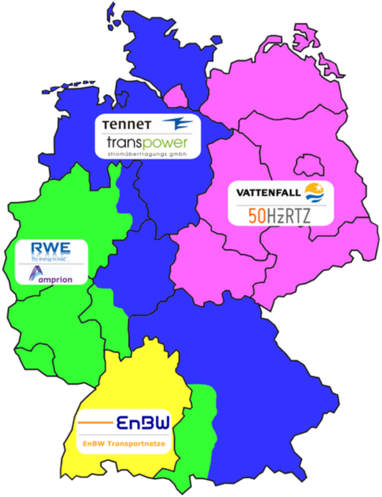

Learning curves for wind turbines and PV modules

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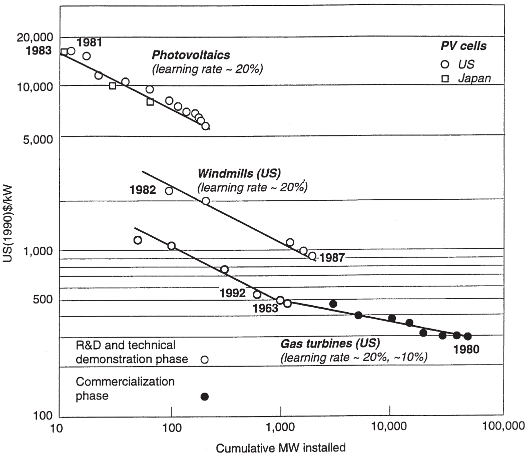

Source: Grübler et al., 1999

Market shares in the wind turbine industry

Market shares in the wind turbine industry

- Six market leaders in the wind turbine industry: Vestas (Denmark), GE Wind (US), Gamesa (Spain), Enercon (Germany), Suzlon (India), Siemens (Germany) $\rightarrow$ 85% of world market in 2008
- Smaller expanding players: Sinovel (China), Acciona (Spain), Goldwind (China), Nordex (Germany)

- However, many turbine manufacturers are still mainly active in their domestic and neighboring markets $\rightarrow$ e.g. Enercon, Vestas, and Siemens supply over 50% of the German, Dutch, and UK markets, respectively

Source: BTM-C, 2009

The firms: fossil fuel utilities

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Cost

- $K_t(k_t)$
- $K_t'(k_t) > 0$, $K_t''(k_t) > 0$

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Profit

- $\pi_t^F(k_t) = P_t(Q_t)k_t - K_t(k_t) - \tau_t k_t$
- $P_t(Q_t)$: downwards sloping inverse demand function for electricity
- Q_t : total electricity production
- τ_t : emission tax
- $t = 1, 2$

The firms: RES-E generators

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Cost

- $C^t(q_t, \tilde{x})$ with $\tilde{x}$: location parameter
- $C^t_q > 0, C^t_{\tilde{x}} > 0, C^t_{qq} > 0, C^t_{q\tilde{x}} > 0, C^t_{\tilde{x}\tilde{x}} > 0$

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- $C_q^t > 0$, $C_{\tilde{x}}^t > 0$, $C_{qq}^t > 0$, $C_{q\tilde{x}}^t > 0$, $C_{\tilde{x}\tilde{x}}^t > 0$

Profit

- $\pi_t^G(q_t, \tilde{x}) = P_t(Q_t)q_t - C^t(q_t, \tilde{x}) - b_t$
- b_t : RES-E equipment price
- $Q_t = \int_0^{X_t} q_t(\tilde{x})d\tilde{x} + mk_t$
- $P_t(Q_t)q_t(X_t) - C^t(q_t, X_t) - b_t = 0$: zero-profit condition
- X_t : marginal RES-E producer

The firms: RES-E equipment producers

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Cost

- $\Gamma^1(y_1)$, $\Gamma^2(y_2, L)$ with $L = y_1 + (n-1)\varepsilon\tilde{y}_1$
- $\Gamma^t_{y_t} > 0$, $\Gamma^t_{y_t y_t} > 0$,$\Gamma^2_L < 0$, $\Gamma^2_{y_2 L} < 0$, $\Gamma^2_{LL} > 0$

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Profit

- $\pi^E_t(y_1, y_2) = [B_1(X_1)+\sigma_1]y_1 - \Gamma^1(y_1) + \delta\big[[B_2(X_2)+\sigma_2]y_2 - \Gamma^2(y_2, L)\big]$
- $B_t(X_t)$: inverse demand function for RES-E equipment defined by zero-profit condition of marginal RES-E generator
- $X_t = ny_t$: total number of RES-E equipment with n firms in the RES-E equipment industry
- σ_t : output subsidy
- δ : discount factor

Welfare

Welfare

$$W = \int_0^{Q_1} P_1(Q)dQ - mK_1(k_1) - \int_0^{X_1} C_1(q_1, \tilde{x})d\tilde{x} - n\Gamma_1(y_1) - D_1(mk_1) + \delta\left[\int_0^{Q_2} P_2(Q)dQ - mK_2(k_2) - \int_0^{X_2} C_2(q_2, \tilde{x})d\tilde{x} - n\Gamma_2(y_2, L) - D_2(mk_2)\right]$$

- Emission damage: $D_t(mk_t)$ with $D_t'(mk_t) > 0$, $D_t''(mk_t) \geq 0$
- Number of fossil fuel utilities: m

FOC for profit maximization

FOC for profit maximization

Fossil fuel firms:

$$P_t(Q_t) + P_t'(Q_t)k_t - K_t'(k_t) - \tau_t = 0 \quad (1)$$

RES-E generators:

$$P_t(Q_t) - C_q^t(q_t, \tilde{x}) = 0 \qquad \forall \tilde{x} \in [0, X_t] \quad (2)$$

RES-E equipment producers:

$$\begin{aligned} B_1(X_1) + B_1'(X_1)y_1 + \sigma_1 - \Gamma_{y_1}^1(y_1) & \quad (3) \\ +\delta\left[B_2'(X_2)(n-1)\frac{\partial \tilde{y_2}}{\partial y_1} - \Gamma_L^2(y_2, L)\right] &= 0 \end{aligned}$$

$$B_2(X_2) + B_2'(X_2)y_2 + \sigma_2 - \Gamma_{y_2}^2(y_2; L) = 0 \quad (4)$$

FOC for welfare maximization

FOC for welfare maximization

Welfare:

$$W_{k_t} = P_t(Q_t) - K_t'(k_t) - D_t'(mk_t) = 0 \tag{5}$$

$$W_{q_t} = P_t(Q_t) - C_q^t(q_t, \tilde{x}) = 0 \qquad \tilde{x} \in [0, X_t] \tag{6}$$

$$\begin{aligned} W_{y_1} = {} & P_1(Q_1)q_1(X_1) - C^1(q_1, X_1) - \Gamma_{y_1}^1(y_1) \\ & -\delta\left[\Gamma_L^2(y_2, L)(1 + (n-1)\varepsilon)\right] = 0 \end{aligned} \tag{7}$$

$$W_{y_2} = P_2(Q_2)q_2(X_2) - C^2(q_2, X_2) - \Gamma_{y_2}^2(y_2, L) = 0 \tag{8}$$

Optimal Policy

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Optimal emission tax in both periods

$$\tau_t^* = \overbrace{P_t'(Q_t^*)}^{-}\, k_t^* + \overbrace{D_t'(mk_t^*)}^{+}$$

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Optimal subsidy in period 1

$$\sigma_1^* = -\overbrace{B_1'(X_1^*)y_1^*}^{-} - \overbrace{\delta(n-1)\varepsilon\Gamma_L^2(y_2^*, L^*)}^{-} - \overbrace{\delta B_2'(X_2^*)(n-1)\frac{\partial \tilde{y}_2{}^*}{\partial y_1}}^{+}$$

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Optimal subsidy in period 2

$$\sigma_2^* = -\overbrace{B_2'(X_2^*)y_2^*}^{-}$$

Optimal Policy

Optimal Policy

- **Optimal tax in both periods** corrects for marginal damage caused by pollution and the too low level of output due to oligopolistic competition in the fossil-fuel industry
- **Optimal subsidy in the first period** corrects for the output contraction due to oligopolistic competition, the strategic output expansion of the firms in the first period in order to shift their reaction curves outwards in the second period, and the learning spill-overs neglected by individual firms
- **Optimal subsidy in the second period** only corrects for the output contraction due to oligopolistic competition the the RES-E equipment industry

The impact of market structure on the policy instruments

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The impact of market structure in the fossil fuel industry

$$\frac{\partial \tau_1}{\partial m} > 0 \qquad \frac{\partial \tau_2}{\partial m} > 0 \qquad \frac{\partial \sigma_1}{\partial m} \lesseqgtr 0 \qquad \frac{\partial \sigma_2}{\partial m} \lesseqgtr 0$$

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The impact of market structure in the RES-E equipment industry

$$\frac{\partial \tau_1}{\partial n} < 0 \qquad \frac{\partial \tau_2}{\partial n} < 0 \qquad \frac{\partial \sigma_1}{\partial n} < 0 \qquad \frac{\partial \sigma_2}{\partial n} < 0$$

Feed-In Tariffs

Feed-In Tariffs

- **RES-E generators** receive a feed-in tariff ζ_t per unit of electricity produced in each period
- Feed-in tariffs paid by the government
- Exogenous emission tax
- No subsidy in the RES-E equipment sector

Profit of RES-E generators

$$\pi_t^G(q_t, \tilde{x}, \zeta_t) = \zeta_t q_t - C^t(q_t, \tilde{x}) - b_t$$

Second-Best Optimal Policy

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3. $\overbrace{\delta\Gamma_L^2(n-1)\varepsilon}^{+}$: learning by doing and the degree of learning spill-overs in the RES-E equipment industry
4. $\overbrace{B^1_{X_1}(X_1, \zeta_1)y_1}^{-} + \overbrace{\delta B^2_{X_2}(X_2, \zeta_2)(n-1)\frac{\partial \tilde{y}_2}{\partial y_1}}^{+}$: strategic effects in the RES-E equipment industry in t=1

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5. $\overbrace{B^2_{X_2}(X_2, \zeta_2) y_2}^{-}$: strategic effects in the RES-E equipment industry in t=2

Welfare implications

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Table: Welfare loss of a second-best feed-in tariff policy versus the first-best policy

	Welfare (fb)	Exog. tax rate	Welfare (sb)	Welfare loss (%)
Oligopoly in the fossil-fuel industry only	143.224	0	139.052	3.0
		$\frac{1}{2}\tau^*$	142.526	0.05
		τ^*	143.224	0
Oligopoly in the fossil-fuel and RES-E equipment industries	143.224	0	126.913	12.8
		$\frac{1}{2}\tau^*$	131.988	8.5
		τ^*	133.418	7.3

Functional forms: $P(Q_t^G, k_t) = A - B(mk_t + Q_t^G)$, $C^t(q_t) = \frac{1}{2}c(q_t + f\tilde{x})^2$, $K_t(k_t) = \frac{h}{2}k_t^2$, $\Gamma^1(y_1) = \frac{\gamma}{2}y_1^2$, $\Gamma^2(y_2, L) = \frac{\gamma}{4}(y_2 - bL)^2 + \frac{\gamma}{4}y_2^2$, $D_t(mk_t) = \frac{d}{2}mk_t^2$

Parameter values (baseline): $A = 10$, $B = 0.5$, $h = 0.1$, $b = 0.1$, $\gamma = 0.2$, $c = 0.5$, $f = 0.5$, $\varepsilon = 0.5$, $d = 1$

The impact of market structure on the feed-in tariffs

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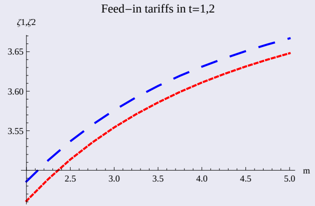
Increasing the number of firms in the fossil fuel industry



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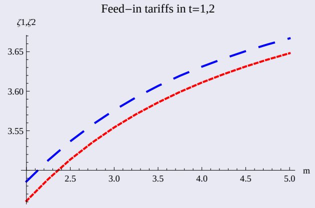
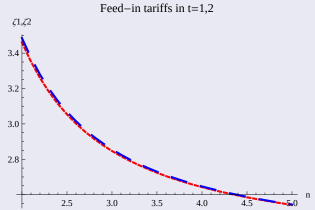


Increasing the number of firms in the RES-E equipment industry



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- FITs should be increased in response to increasing competition in the fossil fuel industry and decreased in response to increasing competition in the RES-E equipment sector.
- With imperfect competition in the RES-E equipment industry, FITs should be higher in the second than in the first period.

References

Emission taxation in imperfectly competitive markets

cf. *Buchanan, 1969, Lee, 1975, Barnett, 1980*

Learning-by-doing and learning spill-overs in imperfectly competitive markets

cf. *Spence, 1981, Fudenberg and Tirole, 1983, Goulder and Mathai, 2000, Bramoullé and Olson, 2005, Fischer and Newell, 2008*

Learning effects in the renewable energy sector

cf. *Grübler et al., 1999, Hansen et al., 2003, Junginger et al., 2005, Isoard and Soria, 2001, McDonald and Schrattenholzer, 2001, van der Zwan and Rabl, 2004, Neij, 1997 and 1999*

Composition of $\frac{\partial \tilde{y_2}}{\partial y_1}$

$$\frac{\partial \tilde{y_2}}{\partial y_1} = \frac{\Gamma^2_{y_2 L}(B_2' + B_2'' \tilde{y_2}) + \varepsilon[\Gamma^2_{\tilde{y_2}\tilde{L}}\Gamma^2_{y_2 y_2} - \Gamma^2_{\tilde{y_2}\tilde{L}}(2B_2' + B_2'' y_2)]}{-\Gamma^2_{\tilde{y_2}\tilde{y_2}}\Gamma^2_{y_2 y_2} - (n+1)(B_2')^2 + \Gamma^2_{\tilde{y_2}\tilde{y_2}}(2B_2' + B_2'' y_2) + \Gamma^2_{y_2 y_2}(nB_2' + (n-1)B_2''\tilde{y_2}) - (y_2 + (n-1)\tilde{y_2})B_2' B_2''}$$

- $\frac{\partial \tilde{y_2}}{\partial y_1}$: Comparative statics effect of increasing output of firm 1 in the first period on output of the other firms in the second period
- $\tilde{y_2}$: Output of all other turbine firms in the second period
- Assuming that the spill-over coefficient ε is not too large, by convexity of the inverse demand function this expression becomes negative. This implies that an increase in output by firm 1 in the first period has a negative effect on the output decisions of the other firms in the second period

Second-best optimal feed-in tariffs

$$\begin{aligned}\zeta_1^{oc} =& P_1(Q_1) + [D_1'(mk_1) - \tau_1 + P_1'(Q_1)k_1] \frac{H_2 m \frac{\partial k_1}{\partial \zeta_1} - H_1 m \frac{\partial k_1}{\partial \zeta_2}}{C_2 H_1 - C_1 H_2} \\ & - [B^1_{X_1}(X_1, \zeta_1) y_1 + \delta B^2_{X_2}(X_2, \zeta_2)(n-1) \frac{\partial \tilde{y_2}}{\partial y_1} + \delta \Gamma^2_L (n-1)\epsilon] \frac{H_1 n \frac{\partial y_1}{\partial \zeta_2} - H_2 n \frac{\partial y_1}{\partial \zeta_1}}{C_2 H_1 - C_1 H_2} \\ & + \delta [D_2'(mk_2) - \tau_2 + P_2'(Q_2)k_2] \frac{H_2 m \frac{\partial k_2}{\partial \zeta_1} - H_1 m \frac{\partial k_2}{\partial \zeta_2}}{C_2 H_1 - C_1 H_2} \\ & - \delta B^2_{X_2}(X_2, \zeta_2) y_2 \frac{H_1 n \frac{\partial y_2}{\partial \zeta_2} - H_2 n \frac{\partial y_2}{\partial \zeta_1}}{C_2 H_1 - C_1 H_2}\end{aligned} \tag{9}$$

where C_1, C_2, H_1, and H_2 denote the reaction of green electricity production when the subsidy rate changes in a particular period, i.e.

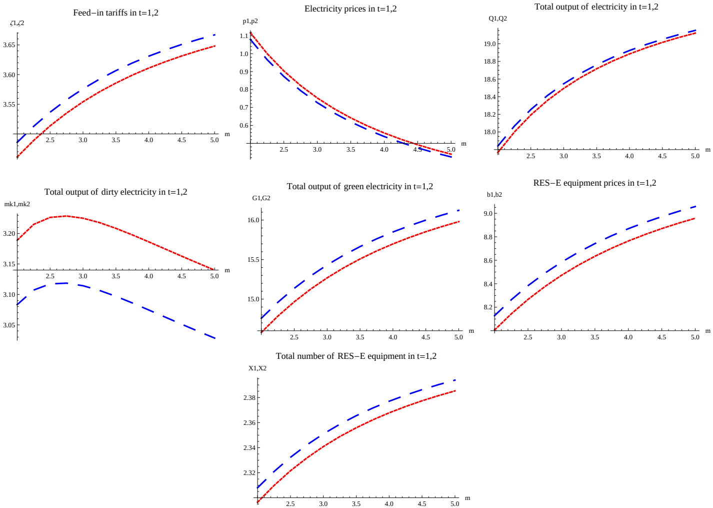
$C_1 = q_1(X_1) \frac{\partial X_1}{\partial \zeta_1} + \int_0^{X_1} \frac{\partial q_1(\tilde{x})}{\partial \zeta_1} d\tilde{x}$, $C_2 = q_1(X_1) \frac{\partial X_1}{\partial \zeta_2}$,
$H_1 = q_2(X_2) \frac{\partial X_2}{\partial \zeta_1}$ and $H_2 = q_2(X_2) \frac{\partial X_2}{\partial \zeta_2} + \int_0^{X_2} \frac{\partial q_2(\tilde{x})}{\partial \zeta_2} d\tilde{x}$.

Numerical example: functional forms

Table: Functional forms

Functional form	Description
$C_t(q_t) = \frac{1}{2}c(q_t + f\tilde{x})^2$	Cost function of the RES-E generators
$K_t(k_t) = \frac{h}{2}k_t^2$	Cost function of the fossil fuel firms
$\Gamma^1(y_1) = \frac{\gamma}{2}y_1^2$	Cost function of the RES-E equipment producers in t=1
$\Gamma^2(y_2, L) = \frac{\gamma}{4}(y_2 - bL)^2 + \frac{\gamma}{4}y_2^2$	Cost function of the RES-E equipment producers in t=2
$D_t(mk_t) = \frac{d}{2}mk_t^2$	Pollution damage
$P_t(Q_t^G, k_t) = A - B(mk_t + Q_t^G)$	Demand function for electricity

The impact of market structure in the fossil fuel industry



The impact of market structure in the RES-E equipment industry