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Pure or Hybrid?: Policy Options for Renewable Energy [1]

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Introduction

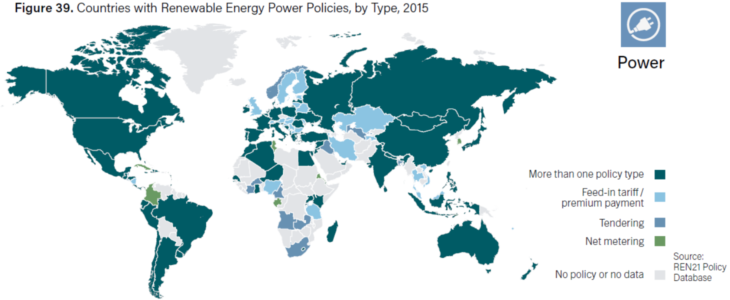
Motivation

- Recently policymakers have implemented various policies for reducing greenhouse gas emissions.
    - Concerns about global warming and climate change
- Policies for supporting and promoting renewable energy
    - Feed-in tariff: FiT
    - Feed-in premium
    - FiT-contract for difference
    - Renewable portfolio standards: RPS

    → Directly impact the power prices and outputs by favoring power produced by renewables.

→ What is the difference among those policies?

Renewable Energy Policy



- REN21 "Renewables 2016 Global Status Report"
  - Many countries have implemented more than one policy.
  - → There is a need to understand their market impacts and compare to either RPS or FiT alone.

Related papers

- **Relationship between renewable energy policy scheme and market equilibrium**
  - **Fischer (2010): Effect of RPS on market equilibrium in perfect competitive markets**
  - **Tanaka and Chen (2013): Allow for the market power in Stackelberg equilibrium**
  - **Hibiki and Kurakawa (2013): Compare social welfare under FiT and RPS**
  - **Siddiqui, Tanaka, and Chen (2016): Provide the endogenous setting of the RPS target from a policymaker's perspective.**
- **Policy mix**
  - **Böhringer and Behrens (2015): Interactions between emission caps and renewable energy polies**

Research Objective

- **Examine the efficiency of the "hybrid" policy consisting of RPS and FiT.**
  - **Compare it to the "pure" policy scheme $\rightarrow$ either RPS or FiT**
  - **Derive optimal RPS target, and FiT price.**

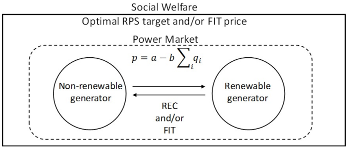
$\rightarrow$ **RQ: Which policy is efficient for social welfare?**

Problem Formulation

Assumption and Setting

- Consider two types of power producers in the electricity industry:
  - Non-renewable: NRE
  - Renewable: RE
- Setting of the market competition: Cournot except FiT scheme
- These two types of producers are jointly subject to a RPS requirement while only the RE producer is supported by the FiT scheme.

→ The RE generator's profit is indirectly impacted by the power price through the FiT scheme.



Assumption and Setting (cont'd)

- **Quadratic production cost function:**
  - **NRE:** $c_n(q_n) = \frac{1}{2}c_n q_n^2$
  - **RE:** $c_r(q_r) = \frac{1}{2}c_r q_r^2$
    - q_n: **NRE production (MWh)**
    - q_r: **RE production (MWh)**
    - $c_n < c_r$
- **Electricity price:**
  - $p(q_n, q_r) = a - b(q_n + q_r)$
    - a: **Intercept of the inverse demand function ($/MWh)**
    - b: **Slope of inverse demand function (dollar/MWh^2)**
- **Damage cost of greenhouse gas emissions:**
  - **Quadratic function of output:** $d(q_n) = \frac{1}{2}kq_n^2$
    - k: **Rate of increase in marginal damage cost ($/MWh^2)**

4 schemes

- Central planning (CP): Benchmark case
  - A central planner simultaneously decides outputs for all power generations by maximizing the social welfare.
- FIT
  - Only the RE generator is supported by the FiT that is optimally determined by the government at the upper level.
- RPS
  - At lower level, NRE and RE generators choose the outputs subject to the RPS target determined by the government at the upper level by maximizing social welfare.
- Hybrid Policy (HP)
  - NRE and RE generators decide their outputs subject to a combination of RPS and FiT with both the RPS target and the FiT price determined by the government.

The Model

CP

- The CP selects generation of either type in order to maximise SW by solving the following QP:

$$\max_{q_n \geq 0, q_r \geq 0} \int_0^{q_n+q_r} p(q')dq' - c_n(q_n) - c_r(q_r) - d_n(q_n)$$

- KKTconditions:

$$0 \leq q_n \perp -a + b(q_n + q_r) + c_n q_n + k q_n \geq 0$$
$$0 \leq q_r \perp -a + b(q_n + q_r) + c_r q_r \geq 0$$

- Optimal interior solutions:

$$q_n^* = \frac{a c_r}{b(c_n + c_r + k) + c_r(c_n + k)}$$
$$q_r^* = \frac{a(c_n + k)}{b(c_n + c_r + k) + c_r(c_n + k)}$$
$$p^* = \frac{a c_r(c_n + k)}{b(c_n + c_r + k) + c_r(c_n + k)}$$

- Output ratio of electricity from renewable sources:

$$\alpha^* = \frac{c_n + k}{c_n + c_r + k}$$

FIT: Lower-level

- **Profit maximisation:**

$$\max_{q_n \geq 0} \quad p\left(q_n + q_r\right) - c_n\left(q_n\right) - p^{FIT} q_r$$

$$\max_{q_r \geq 0} \quad p^{FIT} q_r - c_r\left(q_r\right)$$

- **KKTconditions:**

$$0 \leq q_n \perp -a + 2b\left(q_n + q_r\right) + c_n q_n \geq 0$$

$$0 \leq q_r \perp -p^{FIT} + c_r q_r \geq 0$$

- **Optimal interior solutions:**

$$\hat{q}_n = \frac{a c_r - 2b p^{FIT}}{c_r\left(2b + c_n\right)}$$

$$\hat{q}_r = \frac{p^{FIT}}{c_r}$$

$$\hat{p} = \frac{a c_r\left(b + c_n\right) - b c_n p^{FIT}}{c_r\left(2b + c_n\right)}$$

FIT: Upper-level

- **Social welfare maximisation:**

$$\max_{\{p^{FIT}>p\}\cup\{q_n,q_r\}} \quad \int_0^{q_n+q_r} p(q')dq' - c_n(q_n) - c_r(q_r) - d_n(q_n)$$

$$\text{s.t} \quad 0 \leq q_n \perp -a + 2b(q_n+q_r) + c_n q_n \geq 0$$

$$0 \leq q_r \perp -p^{FIT} + c_r q_r \geq 0$$

- **KKTcondition:**

$$\frac{ac_n}{c_r(2b+c_n)} - \frac{bc_n\left(ac_r + c_n p^{FIT}\right)}{c_r^2(2b+c_n)^2} + (c_n+k)\frac{2b\left(ac_r - 2bp^{FIT}\right)}{c_r^2(2b+c_n)^2} - \frac{p^{FIT}}{c_r} = 0$$

- **Optimal interior solutions:**

$$\hat{p}^{FIT} = \begin{cases} \hat{p} & (p^{FIT} < \hat{p}) \\ \frac{ac_r\left(3bc_n+2bk+c_n^2\right)}{c_r(2b+c_n)^2+4b^2(c_n+k)+bc_n^2} & (p^{FIT} \geq \hat{p}) \end{cases}$$

RPS: Lower-level

- **Profit maximisation:**

$$\max_{q_n \geq 0} \quad pq_n - c_n(q_n) - \alpha p^{REC} q_n$$

$$\max_{q_r \geq 0} \quad pq_r - c_r(q_r) + (1-\alpha) p^{REC} q_r$$

- **KKTconditions:**

$$0 \leq q_n \perp -a + b(q_n + q_r) + bq_n + c_n q_n + \alpha p^{REC} \geq 0$$

$$0 \leq q_r \perp -a + b(q_n + q_r) + bq_r + c_r q_r - (1-\alpha) p^{REC} \geq 0$$

- **Market clearing condition for REC:**

$$0 \leq p^{REC} \perp q_r - \alpha(q_n + q_r) \geq 0$$

- **Optimal interior solutions:**

$$\bar{q}_n = \frac{a(1-\alpha)}{(2b + c_n + c_r)\alpha^2 - 2(b + c_n)\alpha + (2b + c_n)}$$

$$\bar{q}_r = \frac{a\alpha}{(2b + c_n + c_r)\alpha^2 - 2(b + c_n)\alpha + (2b + c_n)}$$

$$\bar{p}^{REC} = \frac{a[(2b + c_n + c_r)\alpha - (b + c_n)]}{(2b + c_n + c_r)\alpha^2 - 2(b + c_n)\alpha + (2b + c_n)}$$

$$\bar{p} = \frac{a\left[(2b + c_n + c_r)\alpha^2 - 2(b + c_n)\alpha + (b + c_n)\right]}{(2b + c_n + c_r)\alpha^2 - 2(b + c_n)\alpha + (2b + c_n)}$$

RPS: Upper-level

- **Social welfare maximisation:**

$$\max_{\{0\le\alpha\le1\}\cup\{q_n,q_r\}\cup\{p^{REC}\}} \int_0^{q_n+q_r} p(q')dq' - c_n(q_n) - c_r(q_r) - d_n(q_n)$$

$$\begin{aligned}\text{s.t}\quad & 0 \le q_n \perp -a + b(q_n+q_r) + bq_n + c_n q_n + \alpha p^{REC} \ge 0\\ & 0 \le q_r \perp -a + b(q_n+q_r) + bq_r + c_r q_r - (1-\alpha)p^{REC} \ge 0\\ & 0 \le p^{REC} \perp q_r - \alpha(q_n+q_r) \ge 0\end{aligned}$$

- **KKTcondition:**

$$\frac{1}{F(\alpha)^3}\Big[(4b+c_n+c_r-k)(2b+c_n+c_r)\alpha^3 - 3(2b+c_n-k)(2b+c_n+c_r)\alpha^2 + \left(8b^2+3c_n^2-4bk-3kc_n+10bc_n+4bc_r+c_nc_r-2kc_r\right)\alpha - \left(2b^2+4bc_n+c_n^2-kc_n\right)\Big] = 0$$

  - $F(\alpha) = (2b+c_n+c_r)\alpha^2 - 2(b+c_n)\alpha + (2b+c_n)$

HP: Lower-level

- **Profit maximisation:**

$$\max_{q_n \geq 0} \quad p\left(q_n + q_r\right) - c_n\left(q_n\right) - p^{FIT} q_r - \left(\alpha q_n - q_r\right) p^{REC}$$

$$\max_{q_r \geq 0} \quad p^{FIT} q_r - c_r\left(q_r\right) + \left(1 - \alpha\right) p^{REC} q_r$$

- **KKTconditions:**

$$0 \leq q_n \perp -a + 2b\left(q_n + q_r\right) + c_n q_n + \alpha p^{REC} \geq 0$$

$$0 \leq q_r \perp -p^{FIT} + c_r q_r - \left(1 - \alpha\right) p^{REC} \geq 0$$

- **Market clearing condition for REC:**

$$0 \leq p^{REC} \perp 2q_r - \alpha(q_n + q_r) \geq 0$$

- **Optimal interior solutions:**

$$\dot{q}_n = \frac{\left(2 - \alpha\right)\left[\left(p^{FIT} - a\right)\alpha + a\right]}{\left(c_n + c_r\right)\alpha^2 + \left(4b + 3c_n\right)\alpha + 2\left(2b + c_n\right)}$$

$$\dot{q}_r = \frac{\alpha\left[\left(p^{FIT} - a\right)\alpha + a\right]}{\left(c_n + c_r\right)\alpha^2 + \left(4b + 3c_n\right)\alpha + 2\left(2b + c_n\right)}$$

$$\dot{p}^{REC} = \frac{\left(c_n p^{FIT} + a c_r\right)\alpha - 2\left(2b + c_n\right)p^{FIT}}{\left(c_n + c_r\right)\alpha^2 + \left(4b + 3c_n\right)\alpha + 2\left(2b + c_n\right)}$$

$$\dot{p} = \frac{\left[a\left(c_n + c_r\right)\right]\alpha^2 - \left[a\left(2b + 3c_n\right) + 2bp^{FIT}\right]\alpha + 2a\left(b + c_n\right)}{\left(c_n + c_r\right)\alpha^2 + \left(4b + 3c_n\right)\alpha + 2\left(2b + c_n\right)}$$

HP: Upper-level

- **Social welfare maximisation:**

$$\max_{\{p^{FIT}>p,\,0\leq\alpha\leq 1\}\cup\{q_n,q_r\}\cup\{p^{REC}\}} \int_0^{q_n+q_r} p(q')dq' - c_n(q_n) - c_r(q_r) - d_n(q_n)$$

$$\text{s.t} \quad 0 \leq q_n \perp -a + 2b(q_n+q_r) + c_n q_n + \alpha p^{REC} \geq 0$$

$$0 \leq q_r \perp -p^{FIT} + c_r q_r - (1-\alpha)p^{REC} \geq 0$$

$$0 \leq p^{REC} \perp 2q_r - \alpha(q_n+q_r) \geq 0$$

- **KKTconditions:**

$$\frac{\alpha\left[2aF(\alpha) - G(\alpha)H(\alpha)\right]}{F(\alpha)^2} = 0$$

$$\frac{2a\left[F'(\alpha)G(\alpha) + F(\alpha)G'(\alpha)\right] - \frac{1}{2}G(\alpha)\left[G(\alpha)H'(\alpha) + 2G'(\alpha)H(\alpha)\right]}{F(\alpha)^2}$$

$$-\frac{2\left[2aF(\alpha) - \frac{1}{2}G(\alpha)H(\alpha)\right]F'(\alpha)G(\alpha)}{F(\alpha)^3} = 0$$

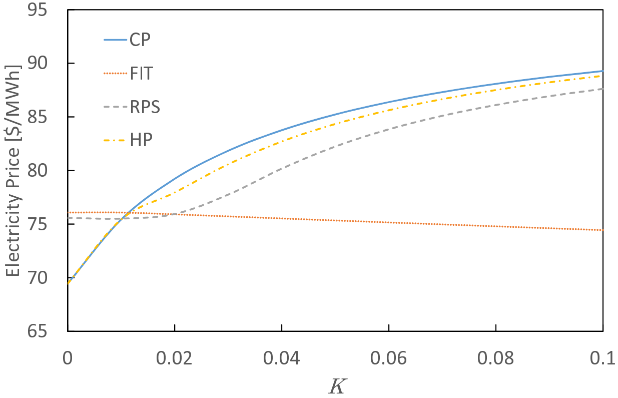
  - $F(\alpha) = (c_n + c_r)\alpha^2 - (4b + 3c_n)\alpha + 2(2b + c_n)$
  - $G(\alpha) = \left(p^{FIT} - a\right)\alpha + a$
  - $H(\alpha) = 4b + (c_n + k)(2-\alpha)^2 + c_r\alpha^2$

Numerical Analysis

Parameters

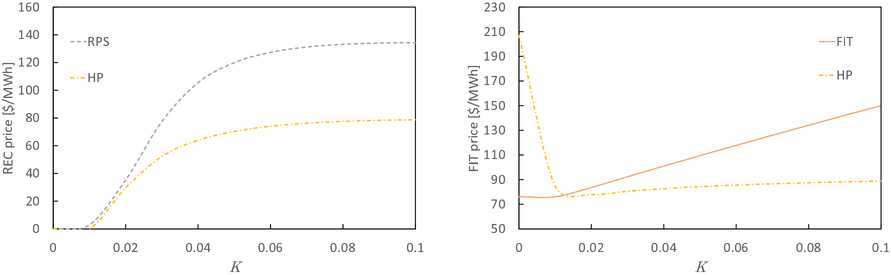
Intercept of the inverse demand function	a	100
Slope of inverse demand function	b	0.01
NRE production	c_n	0.025
RE production	c_r	0.25
Rate of increase in marginal damage cost	k	[0, 0.1]

Equilibrium Electricity Price



- **The electricity price for FIT is smaller than those for other policies.**
  - **Incentive of increases in the productions due to the fixed price**
  - **NRE sells those in the market**

Equilibrium REC and FIT Prices



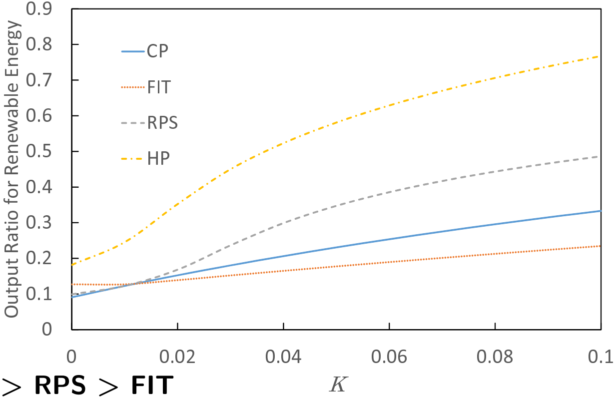
- **REC price: HP $<$ PRS**

  $\rightarrow$ The demand for REC decreases due to FIT.

- **FiT price: HP $<$ PRS**
  - **FiT price decreases and becomes the same as the electricity price.**

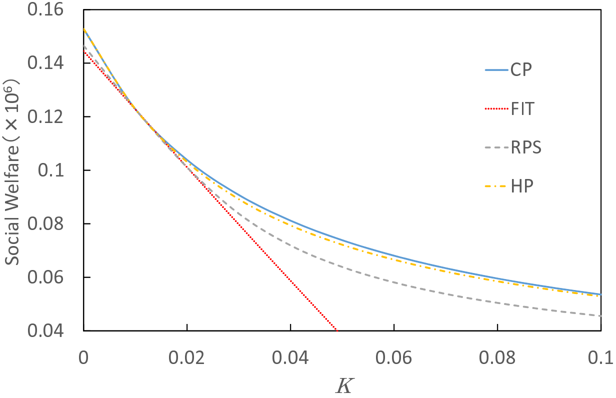
  $\rightarrow$ Mitigate the increases in FiT price due to RPS scheme

Optimal RPS Target and Output Ratio for Renewable Source



- **HP > RPS > FIT**
  - **Effect of the REC market and FiT**
- **FiT scheme**
  - **NRE needs to produce and sell relatively large electricity in order to buy RE's electricity through FiT.**

Social Welfare



- **Order of the maximised social welfare: HP > RPS > FIT**
  → Large producer surplus and small damage cost

Conclusions

Summary and Future Work

- Efficiency of the hybrid policies, i.e., RPS and FiT
- Compare it to the single policy scheme (either RPS or FiT)
  - Maximized social welfare for the hybrid policy is greater than those for single policies, e.g., RPS or FiT
  - The ratio of renewable energy output to the non-renewables is greater than that under the single policy.
- Directions for future research
  - Verify findings analytically
  - Extend the model to introduce uncertainty of the demand
  - Allow for investment decisions and capacity choice for renewable energy