Renewable-based generation expansion under a green certificate market

NESS 2015

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Motivation

- "The Renewable Energy Directive establishes an overall policy for the production and **promotion of energy from renewable sources** in the EU. It requires the EU to fulfil at least 20% of its total energy needs with renewables by 2020 to be achieved through the attainment of individual national targets."
- "Energy markets alone cannot deliver the desired level of renewables in the EU, meaning that national **support schemes may be needed** to overcome this market failure and spur increased investment in renewable energy. If these public interventions are not **carefully designed**, they can distort the functioning of the energy market and lead to higher costs for European households and businesses."
- "Different instruments can be used to support renewables production in the EU. The most commonly used ones are feed-in tariffs, feed-in premiums, **quota obligations**, tax exemptions and investment aid."

Source: www.ec.europa.eu/energy/

Quota obligation scheme

- A **quota** of the power sold by suppliers has to be produced from RES
- **Certificates** are used to track and verify the compliance of the quota
- Qualified RES receive certificates for each generated unit
- Conventional producers can buy certificates in the market
- "In most countries which have introduced quota obligations, a **penalty** is applied for non-compliance that effectively sets a ceiling on the price of the certificate/greenness."[1]
- Current EU countries with quota obligation schemes: Belgium, Italy, Norway, Poland, Romania, Sweden and UK.[2]

[1] European Commission guidance for the design of renewables support schemes, 2013
[2] Council of European Energy Regulators (CEER, 2015)

Research question

Investigate the impact of quota obligations and certificate trading on renewable-based generation expansion

Literature review

- Impact of certificates on operation (no capacity constraints):
  - Monopoly: Sun and Nie (2015)
  - Perfect competition: Jensen and Skytte (2002); Aune et al. (2012)
  - Imperfect competition: Tamás et al. (2010); Tanaka and Chen (2013)
- Impact of certificates on investments:
  - Exogenous prices: Genesi et al. (2009); Careri et al. (2011); Boomsma et al. (2012)
  - Endogenous prices:
    - Perfect competition: Amundsen and Mortensen (2001); Marchenko (2008)
    - Imperfect competition: Linares et al. (2008) no certificate prices (quota imposed as a constraint) & open-loop equilibria (investment and operation decisions made simultaneously)
- Non-compliance penalty systematically disregarded

Contribution

- A family of capacity expansion models for renewable-based generation that include the trading of both electricity and certificates in a liberalized market with a given quota obligation:
  - Central planner (benchmark)
  - Perfect competition (open-loop, complementarity model)
  - Imperfect competition (Cournot players, closed-loop, MPEC)

- Investigate the influence of the non-compliance penalty on renewable-based generation expansion under perfect and imperfect competition.

Assumptions

- Static generation expansion models (one target year)
- Time segments t to characterize system conditions
- Two different generation technologies:
  - Renewable(r):
    - Short-run marginal cost equal to 0
    - Variable capacity factor ρ_t
    - Linear investment cost $c^i\overline{q}^r$
  - Non-renewable(n):
    - Quadratic short-run marginal cost $\frac{a}{2}(q_t^n)^2 + bq_t^n$
    - Fixed capacity $\overline{q}^n$
- Linear inverse demand function $p_t = \alpha_t - \beta_t\left(q_t^n + q_t^r\right)$
- No network constraints
- A quota obligation κ with a non-compliance penalty π
- Certificates traded once at the end of the planning horizon

Central planner

$$\underset{\overline{q}^r, q_t^r, q_t^n}{\text{Maximize}} \quad \sum_t \tau_t \left(\underbrace{\boxed{\alpha_t d_t - \frac{1}{2}\beta_t (d_t)^2}}_{\text{Demand utility}} - \underbrace{\boxed{\frac{1}{2}a(q_t^n)^2 + bq_t^n}}_{\text{Fuel cost}} \right) - \underbrace{\boxed{c^i \overline{q}^r}}_{\text{Inv. cost}}$$

subject to

$\boxed{\overline{q}^r \geqslant 0}$ Positive capacity

$\boxed{0 \leqslant q_t^r \leqslant \rho_t \overline{q}^r, \quad \forall t}$ Renewable capacity

$\boxed{0 \leqslant q_t^n \leqslant \overline{q}^n, \quad \forall t}$ Non-renewable capacity

$\boxed{d_t = q_t^r + q_t^n, \quad \forall t}$ Balance equation

$\boxed{\sum_t \tau_t q_t^r \geqslant \kappa \sum_t \tau_t d_t}$ Quota obligation

Perfect competition (renewable player)

$$\underset{\overline{q}^r, q_t^r, c^r}{\text{Minimize}} \quad -\underbrace{\boxed{\sum_t \tau_t p_t q_t^r}}_{\text{Revenue power}} - \underbrace{\boxed{\lambda c^r}}_{\text{Revenue certificates}} + \underbrace{\boxed{c^i \overline{q}^r}}_{\text{Inv. cost}}$$

subject to

$$\boxed{\overline{q}^r \geqslant 0 : \gamma} \quad \text{Positive capacity}$$

$$\boxed{0 \leqslant q_t^r \leqslant \rho_t \overline{q}^r : \underline{\eta}_t^r, \overline{\eta}_t^r, \quad \forall t} \quad \text{Production limits}$$

$$\boxed{0 \leqslant c^r \leqslant (1-\kappa) \sum_t \tau_t q_t^r : \underline{\mu}^r, \overline{\mu}^r} \quad \text{Certificate limits}$$

p_t assumed as external parameter, i.e., $\frac{\partial p_t}{\partial q_t^r} = 0$

Perfect competition (non-renewable player)

$$\underset{q_t^n, c^n}{\text{Minimize}}$$

$$\sum_t \tau_t \left(\underbrace{\boxed{\frac{1}{2} a (q_t^n)^2 + b q_t^n}}_{\text{Fuel cost}} - \underbrace{\boxed{p_t q_t^n}}_{\text{Revenue power}} \right) + \underbrace{\boxed{\lambda c^n}}_{\text{Certificates cost}} + \underbrace{\boxed{\pi \left(\kappa \sum_t \tau_t q_t^n - c^n \right)}}_{\text{Penalty}}$$

subject to

$$\boxed{0 \leqslant q_t^n \leqslant \overline{q}^n : \underline{\eta}_t^n, \overline{\eta}_t^n, \quad \forall t} \quad \text{Production limits}$$

$$\boxed{0 \leqslant c^n \leqslant \kappa \sum_t \tau_t q_t^n : \underline{\mu}^n, \overline{\mu}^n} \quad \text{Certificate limits}$$

p_t assumed as external parameter, i.e., $\frac{\partial p_t}{\partial q_t^n} = 0$

Perfect competition (complementarity model)

$$\boxed{\begin{aligned}
&0 \leqslant \overline{q}^r \perp c^i - \sum_t \rho_t \overline{\eta}_t^r \geqslant 0 \\
&0 \leqslant q_t^r \perp -\tau_t p_t + \overline{\eta}_t^r - (1-\kappa)\tau_t \overline{\mu}^r \geqslant 0, \quad \forall t \\
&0 \leqslant \rho_t \overline{q}^r - q_t^r \perp \overline{\eta}_t^r \geqslant 0, \quad \forall t \\
&0 \leqslant c^r \perp -\lambda + \overline{\mu}^r \geqslant 0 \\
&0 \leqslant (1-\kappa) \sum_t \tau_t q_t^r - c^r \perp \overline{\mu}^r \geqslant 0
\end{aligned}}$$

KKT renewable

$$\boxed{\begin{aligned}
&0 \leqslant q_t^n \perp \tau_t \left(a q_t^n + b \right) - \tau_t p_t + \pi \kappa \tau_t + \overline{\eta}_t^n - \kappa \tau_t \overline{\mu}^n \geqslant 0, \quad \forall t \\
&0 \leqslant \overline{q}^n - q_t^n \perp \overline{\eta}_t^n \geqslant 0, \quad \forall t \\
&0 \leqslant c^n \perp \lambda - \pi + \overline{\mu}^n \geqslant 0 \\
&0 \leqslant \kappa \sum_t \tau_t q_t^n - c^n \perp \overline{\mu}^n \geqslant 0
\end{aligned}}$$

KKT non-renewable

$$\boxed{p_t = \alpha_t - \beta_t \left(q_t^n + q_t^r \right), \quad \forall t}$$

Power market clearing

$$\boxed{0 \leqslant \lambda \perp \left(c^r - c^n \right) \geqslant 0}$$

Certificate market clearing

Strategic behavior (renewable player)

$$\underset{\overline{q}^r, q_t^r, c^r}{\text{Minimize}} \quad - \underbrace{\boxed{\sum_t \tau_t p_t q_t^r}}_{\text{Revenue power}} - \underbrace{\boxed{\lambda c^r}}_{\text{Revenue certificates}}$$

subject to

$$\boxed{0 \leqslant q_t^r \leqslant \rho_t \overline{q}^r : \underline{\eta}_t^r, \overline{\eta}_t^r, \quad \forall t} \quad \text{Production limits}$$

$$\boxed{0 \leqslant c^r \leqslant (1-\kappa) \sum_t \tau_t q_t^r : \underline{\mu}^r, \overline{\mu}^r} \quad \text{Certificate limits}$$

Influence of quantity on p_t is accounted for, i.e., $\frac{\partial p_t}{\partial q_t^r} = -\beta_t$

Strategic behavior (non-renewable player)

$$\underset{q_t^n, c^n}{\text{Minimize}}$$

$$\sum_t \tau_t \left(\underbrace{\boxed{\frac{1}{2}a(q_t^n)^2 + bq_t^n}}_{\text{Fuel cost}} - \underbrace{\boxed{p_t q_t^n}}_{\text{Revenue power}} \right) + \underbrace{\boxed{\lambda c^n}}_{\text{Certificates cost}} + \underbrace{\boxed{\pi \left(\kappa \sum_t \tau_t q_t^n - c^n \right)}}_{\text{Penalty}}$$

subject to

$$\boxed{0 \leqslant q_t^n \leqslant \overline{q}^n : \underline{\eta}_t^n, \overline{\eta}_t^n, \quad \forall t} \quad \text{Production limits}$$

$$\boxed{0 \leqslant c^n \leqslant \kappa \sum_t \tau_t q_t^n : \underline{\mu}^n, \overline{\mu}^n} \quad \text{Certificate limits}$$

Influence of quantity on p_t is accounted for, i.e., $\frac{\partial p_t}{\partial q_t^n} = -\beta_t$

Strategic players (MPEC)

$$\boxed{\begin{aligned}
&0 \leqslant q_t^r \perp -\tau_t p_t + \tau_t \beta_t q_t^r + \overline{\eta}_t^r - (1-\kappa)\tau_t \overline{\mu}^r \geqslant 0, \quad \forall t \\
&0 \leqslant \rho_t \overline{q}^r - q_t^r \perp \overline{\eta}_t^r \geqslant 0, \quad \forall t \\
&0 \leqslant c^r \perp -\lambda + \overline{\mu}^r \geqslant 0 \\
&0 \leqslant (1-\kappa) \sum_t \tau_t q_t^r - c^r \perp \overline{\mu}^r \geqslant 0
\end{aligned}}$$

KKT renewable

$$\boxed{\begin{aligned}
&0 \leqslant q_t^n \perp \tau_t \left(a q_t^n + b \right) - \tau_t p_t + \tau_t \beta_t q_t^n + \pi \kappa \tau_t + \overline{\eta}_t^n - \kappa \tau_t \overline{\mu}^n \geqslant 0, \quad \forall t \\
&0 \leqslant \overline{q}^n - q_t^n \perp \overline{\eta}_t^n \geqslant 0, \quad \forall t \\
&0 \leqslant c^n \perp \lambda - \pi + \overline{\mu}^n \geqslant 0 \\
&0 \leqslant \kappa \sum_t \tau_t q_t^n - c^n \perp \overline{\mu}^n \geqslant 0
\end{aligned}}$$

KKT non-renewable

$$\boxed{p_t = \alpha_t - \beta_t \left(q_t^n + q_t^r \right), \quad \forall t}$$

Power market clearing

$$\boxed{0 \leqslant \lambda \perp \left(c^r - c^n \right) \geqslant 0}$$

Certificate market clearing

Strategic players (MPEC)

$$\underset{\overline{q}^r}{\text{Minimize}} \quad -\sum_t \tau_t p_t q_t^r - \lambda c^r + c^i \overline{q}^r$$

subject to

$$\overline{q}^r \geqslant 0$$

$$\boxed{\begin{aligned}
&0 \leqslant q_t^r \perp -\tau_t p_t + \tau_t \beta_t q_t^r + \overline{\eta}_t^r - (1-\kappa)\tau_t \overline{\mu}^r \geqslant 0, \quad \forall t \\
&0 \leqslant \rho_t \overline{q}^r - q_t^r \perp \overline{\eta}_t^r \geqslant 0, \quad \forall t \\
&0 \leqslant c^r \perp -\lambda + \overline{\mu}^r \geqslant 0 \\
&0 \leqslant (1-\kappa)\sum_t \tau_t q_t^r - c^r \perp \overline{\mu}^r \geqslant 0
\end{aligned}}$$

KKT renewable

$$\boxed{\begin{aligned}
&0 \leqslant q_t^n \perp \tau_t \left(a q_t^n + b\right) - \tau_t p_t + \tau_t \beta_t q_t^n + \pi\kappa\tau_t + \overline{\eta}_t^n - \kappa\tau_t \overline{\mu}^n \geqslant 0, \quad \forall t \\
&0 \leqslant \overline{q}^n - q_t^n \perp \overline{\eta}_t^n \geqslant 0, \quad \forall t \\
&0 \leqslant c^n \perp \lambda - \pi + \overline{\mu}^n \geqslant 0 \\
&0 \leqslant \kappa \sum_t \tau_t q_t^n - c^n \perp \overline{\mu}^n \geqslant 0
\end{aligned}}$$

KKT non-renewable

$$\boxed{p_t = \alpha_t - \beta_t \left(q_t^n + q_t^r\right), \quad \forall t}$$

Power market clearing

$$\boxed{0 \leqslant \lambda \perp \left(c^r - c^n\right) \geqslant 0}$$

Certificate market clearing

Data

- Planning horizon: one single target year
- Investment cost: 250k€/MW
- Fossil-based generation capacity: 1000MW
- Fuel cost: $a = 0.04$€/MWh^2, $b = 20$€/MWh
- Inverse demand function: $\alpha_t = 100$€/MWh, $\beta_t = 0.1$€/MWh^2
- Renewable capacity factor variability

ρ_t (p.u.)	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
τ_t (h)	1486	1328	975	780	685	586	489	538	608	1064	220

Central planner

κ(%)	$\overline{q}^r$(MW)	$\mathcal{SW}$(€M)	Π^r(€M)
0	0	200	0
10	143	185	-15
20	278	168	-28
30	402	150	-39
40	509	130	-46
50	594	111	-49
60	648	91	-49
70	656	71	-43
80	615	51	-30

- Integrating non-fully competitive renewable-based generation reduces the social welfare

Perfect competition ($\kappa = 40\%$)

π (€/cer)	$\overline{q}^r$ (MW)	η (%)	λ (€/cer)	$\mathcal{SW}$ (€M)	Π^r (€M)
0	0	0	0	200	0
10	0	0	0	200	0
20	0	0	0	198	0
30	0	0	0	196	0
40	323	26	40	156	0
50	509	40	44	130	0
60	509	40	44	130	0
70	509	40	44	130	0
80	509	40	44	130	0

- If $\pi < 40$, prices are not high enough to trigger investments
- If $\pi = 40$, investment is triggered but not enough to satisfy quota (penalties apply)
- If $\pi > 40$, triggered investments comply with desired quota

Perfect competition (penetration levels)

	κ								
π	0%	10%	20%	30%	40%	50%	60%	70%	80%
0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0
40	0	10	20	29	26	23	19	14	9
50	0	10	20	30	40	50	54	54	54
60	0	10	20	30	40	50	60	67	68
70	0	10	20	30	40	50	60	70	80
80	0	10	20	30	40	50	60	70	80

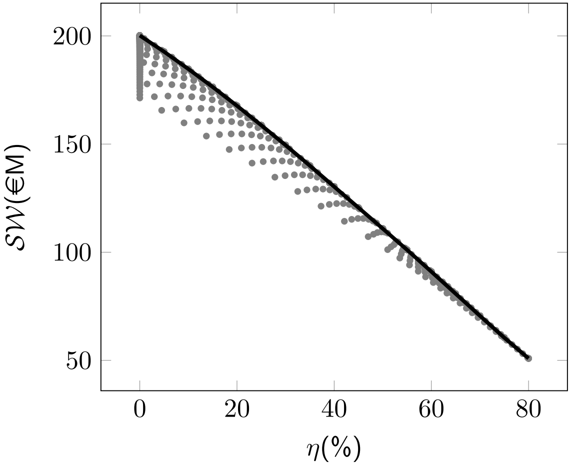
- Non-compliance penalty must be high enough to trigger the desired investment levels

Perfect competition (social welfare)

	κ								
π	0%	10%	20%	30%	40%	50%	60%	70%	80%
0	200	200	200	200	200	200	200	200	200
10	200	200	200	200	200	199	199	199	198
20	200	200	200	199	198	197	196	194	192
30	200	200	199	198	196	193	190	186	182
40	200	185	168	152	156	159	160	161	160
50	200	185	168	150	130	111	102	101	97
60	200	185	168	150	130	111	91	76	72
70	200	185	168	150	130	111	91	71	51
80	200	185	168	150	130	111	91	71	51

- Very high penalties do not reduce the social welfare

Central planner vs. perfect competition



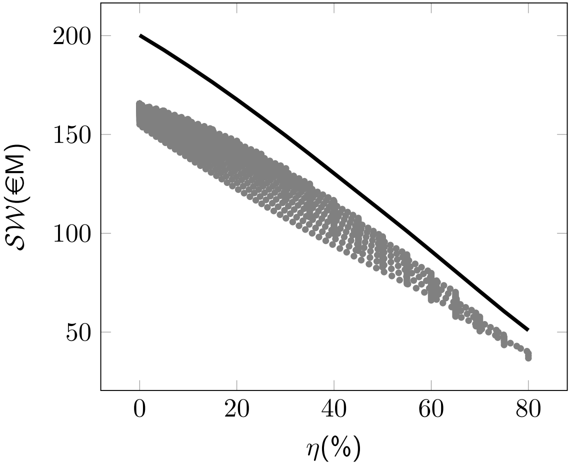
- Under perfect competition and proper penalty values, the quota obligation is satisfied at the maximum social welfare

Strategic players ($\kappa = 40\%$)

π (€/cer)	$\overline{q}^r$ (MW)	η (%)	λ (€/cer)	$\mathcal{SW}$ (€M)	Π^r (€M)
0	0	0	0	166	0
10	28	3	10	159	0
20	127	15	20	146	2
30	227	27	30	133	7
40	326	38	40	120	14
50	330	40	50	114	23
60	308	40	60	109	30
70	286	40	70	105	37
80	264	40	80	100	42

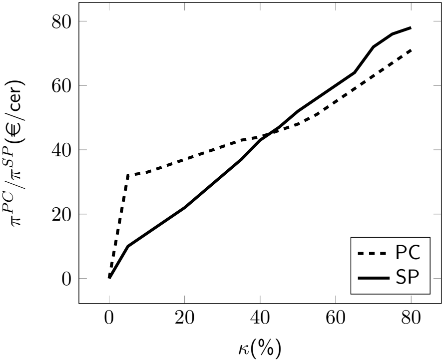
- If $\pi < 50$, power prices are increased because of the exercise of market power and therefore investment is triggered even for low penalties
- If $\pi = 50$, quota achieved at the maximum social welfare
- If $\pi > 50$, quota achieved with a decrease of the social welfare

Strategic players (central planner vs. strategic players)



- Under strategic behavior, there is an optimal penalty value that triggers the required investment

Optimal penalty values



- For low quotas, r increases power prices by withholding capacity and investment is triggered even for low certificate prices
- For high quotas, r must keep most of its certificates and then higher certificate prices are required to trigger investment

Conclusions

- A family of generation expansion models to investigate the impact of green certificates to promote renewable-based electricity production
  - Central-planner model (quadratic optimization)
  - Perfect competition (complementarity problem)
  - Strategic behavior (MPEC)
- Green certificates represent an adequate policy instrument to support investments in renewable-based capacity
- The non-compliance penalty significantly impacts the incentives to invest in renewable-based generation capacity
- The level of competition among generating companies affects the optimal design of a certificate market and the achievement of renewable-based generation penetration goals

Future work

- Increase number of players (ongoing work)
- Include network constraints (ongoing work)
- Intermediate competition levels
- Multi-year horizon with banking of certificates
- Include uncertainty and risk aversion
- Compare with other support schemes (ongoing work)

Thanks for the attention!

Questions?

Website: https://sites.google.com/site/slv2pm/

References I

Amundsen, E. S. and Mortensen, J. r. B. (2001). The Danish Green Certificate System: some simple analytical results. *Energy Econ.*, 23(5):489–509.

Aune, F. R., Dalen, H. M., and Hagem, C. (2012). Implementing the EU renewable target through green certificate markets. *Energy Econ.*, 34(4):992–1000.

Boomsma, T. K., Meade, N., and Fleten, S.-E. (2012). Renewable energy investments under different support schemes: A real options approach. *Eur. J. Oper. Res.*, 220(1):225–237.

Careri, F., Member, S., Genesi, C., Marannino, P., Montagna, M., Rossi, S., and Siviero, I. (2011). Generation Expansion Planning in the Age of Green Economy. *IEEE Trans. Power Syst.*, 26(4):2214–2223.

References II

Genesi, C., Granelli, G. P., Marannino, P., Montagna, M., Rossi, S., Siviero, I., Desiata, L., and Gentile, G. (2009). Impact of renewable energy quotas and emission trade on generation planning. In *2009 IEEE Bucharest PowerTech Innov. Ideas Towar. Electr. Grid Futur.*

Jensen, S. G. and Skytte, K. (2002). Interactions between the power and green certificate markets. *Energy Policy*, 30:425–435.

Linares, P., Santos, F. J., Ventosa, M., Lapiedra, L., and Javier Santos, F. (2008). Incorporating oligopoly, CO2 emissions trading and green certificates into a power generation expansion model. *Automatica*, 44(6):1608–1620.

Marchenko, O. V. (2008). Modeling of a green certificate market. *Renew. Energy*, 33:1953–1958.

Sun, P. and Nie, P.-y. (2015). A comparative study of feed-in tariff and renewable portfolio standard policy in renewable energy industry. *Renew. Energy*, 74:255–262.

References III

Tamás, M. M., Bade Shrestha, S., and Zhou, H. (2010). Feed-in tariff and tradable green certificate in oligopoly. *Energy Policy*, 38(8):4040–4047.

Tanaka, M. and Chen, Y. (2013). Market power in renewable portfolio standards. *Energy Econ.*, 39(0):187–196.