Renewable-based generation expansion under a green certificate market

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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
- Qualified RES receive certificates for each generated unit
- Suppliers buy certificates in the market
- **Certificates** are used to track and verify the compliance of the quota
- "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)

Contribution

- Development of complementarity models to determine the capacity expansion of renewable-based generation including the trading of both electricity and certificates:
  - Central planner (benchmark)
  - Perfect competition / Strategic behavior
- Compare with feed-in-tariff support scheme.
- Coordination of support schemes between interconnected areas.

Assumptions

- Static generation expansion models (one target year)
- Time segments t of duration τ_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 $c^i \overline{q}^r$
    - Price-taker
  - 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 $p_t = \alpha - \beta\left(q_t^n + q_t^r\right)$
- No network constraints
- No uncertainty

Central planner

$$\underset{\overline{q}^r \geqslant 0, q_t^r \geqslant 0, q_t^n \geqslant 0}{\text{Maximize}} \quad \sum_t \tau_t \left(\underbrace{\boxed{\alpha d_t - \frac{1}{2}\beta \left(d_t\right)^2}}_{\text{Demand utility}} - \underbrace{\boxed{\frac{1}{2}a(q_t^n)^2 + bq_t^n}}_{\text{Fuel cost}} \right) - \underbrace{\boxed{c^i \overline{q}^r}}_{\text{Inv. cost}}$$

subject to

$$\boxed{q_t^r \leqslant \rho_t \overline{q}^r : \tau_t \eta_t^r, \quad \forall t} \quad \text{Renewable capacity}$$

$$\boxed{q_t^n \leqslant \overline{q}^n : \tau_t \eta_t^n, \quad \forall t} \quad \text{Non-renewable capacity}$$

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

$$\boxed{\sum_t \tau_t q_t^r \geqslant \kappa \sum_t \tau_t d_t : \phi} \quad \text{Quota obligation}$$

Renewable producer (with certificates)

$$\underset{\overline{q}^r \geqslant 0, q_t^r \geqslant 0, c^r \geqslant 0}{\text{Maximize}} \quad \underbrace{\boxed{\sum_t \tau_t p_t q_t^r}}_{\text{Revenue power}} \quad \underbrace{\boxed{\lambda c^r}}_{\text{Revenue certificates}} \quad - \quad \underbrace{\boxed{c^i \overline{q}^r}}_{\text{Inv. cost}}$$

subject to

$$\boxed{q_t^r \leqslant \rho_t \overline{q}^r \, : \tau_t \eta_t^r, \quad \forall t} \quad \text{Production limits}$$

$$\boxed{c^r \leqslant \sum_t \tau_t q_t^r \, : \mu^r} \quad \text{Certificate limits}$$

Conventional producer

$$\underset{q_t^n \geqslant 0}{\text{Maximize}} \quad \sum_t \tau_t \left(\underbrace{\boxed{p_t q_t^n}}_{\text{Revenue power}} - \underbrace{\boxed{\frac{1}{2} a (q_t^n)^2 + b q_t^n}}_{\text{Fuel cost}} \right)$$

subject to

$$\boxed{q_t^n \leqslant \overline{q}^n : \tau_t \eta_t^n, \quad \forall t} \text{ Production limits} \tag{3a}$$

Complementarity model (certificates)

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

KKT renewable

$$\boxed{\begin{aligned}
&0 \leqslant q_t^n \perp \left(a q_t^n + b - \frac{\partial p_t}{\partial q_t^n} q_t^n - p_t + \eta_t^n\right) \geqslant 0, \quad \forall t \\
&0 \leqslant (\overline{q}^n - q_t^n) \perp \eta_t^n \geqslant 0, \quad \forall t
\end{aligned}}$$

KKT conventional

$$\boxed{\begin{aligned}
&p_t + \kappa\lambda = \alpha - \beta\left(q_t^n + q_t^r\right), \quad \forall t \\
&d_t = q_t^n + q_t^r, \quad \forall t
\end{aligned}}$$

Power market clearing

$$\boxed{\begin{aligned}
&0 \leqslant \lambda \perp \left(c^r + c^s - \kappa \sum_t \tau_t d_t\right) \geqslant 0 \\
&0 \leqslant c^s \perp \left(\overline{\lambda} - \lambda\right) \geqslant 0
\end{aligned}}$$

Certificate market clearing

Certificates vs. Central

Certificates ($\frac{\partial p_t}{\partial q_t^n} = 0$ & $0 < \lambda < \overline{\lambda}$)

$$0 \leqslant \overline{q}^r \perp \left(c^i - \sum_t \tau_t \rho_t \eta_t^r \right) \geqslant 0$$

$$0 \leqslant q_t^r \perp (-p_t + \eta_t^r - \lambda) \geqslant 0, \quad \forall t$$

$$0 \leqslant (\rho_t \overline{q}^r - q_t^r) \perp \overline{\eta}_t^r \geqslant 0, \quad \forall t$$

$$0 \leqslant q_t^n \perp (a q_t^n + b - p_t + \eta_t^n) \geqslant 0, \quad \forall t$$

$$0 \leqslant (\overline{q}^n - q_t^n) \perp \eta_t^n \geqslant 0, \quad \forall t$$

$$p_t + \kappa\lambda = \alpha - \beta \left(q_t^n + q_t^r \right), \quad \forall t$$

$$d_t = q_t^n + q_t^r, \quad \forall t$$

$$0 \leqslant \lambda \perp \left(\sum_t \tau_t q_t^r - \kappa \sum_t \tau_t d_t \right) \geqslant 0$$

Central

$$0 \leqslant \overline{q}^r \perp \left(c^i - \sum_t \tau_t \rho_t \eta_t^r \right) \geqslant 0$$

$$0 \leqslant q_t^r \perp (-p_t + \eta_t^r - \phi) \geqslant 0, \quad \forall t$$

$$0 \leqslant (\rho_t \overline{q}^r - q_t^r) \perp \overline{\eta}_t^r \geqslant 0, \quad \forall t$$

$$0 \leqslant q_t^n \perp (a q_t^n + b - p_t + \eta_t^n) \geqslant 0, \quad \forall t$$

$$0 \leqslant (\overline{q}^n - q_t^n) \perp \eta_t^n \geqslant 0, \quad \forall t$$

$$p_t + \kappa\phi = \alpha - \beta \left(q_t^n + q_t^r \right), \quad \forall t$$

$$d_t = q_t^n + q_t^r, \quad \forall t$$

$$0 \leqslant \phi \perp \left(\sum_t \tau_t q_t^r - \kappa \sum_t \tau_t d_t \right) \geqslant 0$$

Renewable producer (feed-in-tariff)

$$\underset{\overline{q}^r \geqslant 0, q_t^r \geqslant 0, c^r \geqslant 0}{\text{Maximize}} \quad \underbrace{\boxed{\sum_t \tau_t p_t q_t^r}}_{\text{Revenue power}} + \underbrace{\boxed{t \sum_t \tau_t q_t^r}}_{\text{Revenue feed-in-tariff}} \quad - \underbrace{\boxed{c^i \overline{q}^r}}_{\text{Inv. cost}}$$

subject to

$$\boxed{q_t^r \leqslant \rho_t \overline{q}^r \; : \tau_t \eta_t^r, \quad \forall t} \quad \text{Production limits}$$

Complementarity model (feed-in-tariff)

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

KKT renewable

$$\boxed{\begin{aligned} &0 \leqslant q_t^n \perp \left(a q_t^n + b - \frac{\partial p_t}{\partial q_t^n} q_t^n - p_t + \eta_t^n \right) \geqslant 0, \quad \forall t \\ &0 \leqslant (\overline{q}^n - q_t^n) \perp \eta_t^n \geqslant 0, \quad \forall t \end{aligned}}$$

KKT conventional

$$\boxed{\begin{aligned} p_t &= \alpha - \beta \left(q_t^n + q_t^r \right), \quad \forall t \\ d_t &= q_t^n + q_t^r, \quad \forall t \end{aligned}}$$

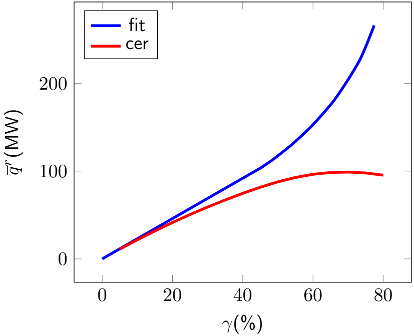
Power market clearing

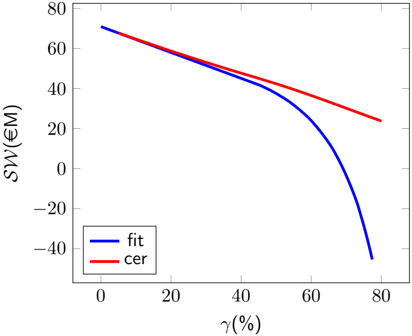
Data

- Planning horizon: one single target year
- Investment cost: 350k€/MW
- Fossil-based generation capacity: 1000MW
- Fuel cost: $a = 0€/\text{MWh}^2$, $b = 20€/\text{MWh}$
- Inverse demand function: $\alpha = 200€/\text{MWh}$, $\beta = 2€/\text{MWh}^2$
- 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

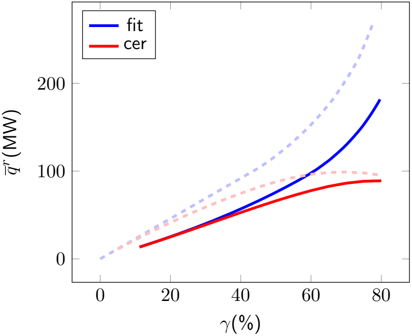
Perfect competition

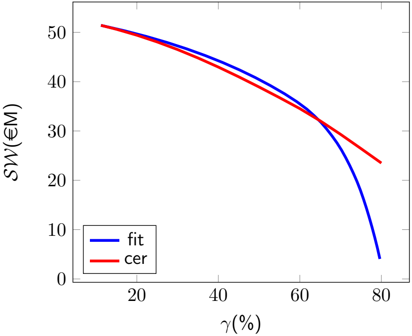




- With certificates the demand is reduced due to the certificate payment and lower renewable capacity is required to achieve a given quota.
- Certificates lead to the maximum social welfare. Feed-in-tariff reduces the social welfare, specially for high quotas.

Imperfect competition





- Strategic behavior of conventional producers increases prices, reduces demand and the required renewable capacity investment.
- Feed-in-tariff may lead to higher social welfare than a certificate market.

Support schemes in Europe [3]

What about coordination?

Country	Solar	Wind
Austria	FIT	FIT
Belgium	REC	REC
Denmark	FIT	FIT
Germany	FIT/FIP	FIT/FIP
Italy	FIT	REC
Spain	FIT	FIT
Sweden	REC	REC
Norway	REC	REC

[3] Council of European Energy Regulators (CEER, 2015)

Complementarity model (2 zones, perfect competition)

$$0 \leqslant \overline{q}^{ra} \perp \left(c^i - \sum_t \tau_t \rho_t \eta_t^{ra}\right) \geqslant 0$$

$$0 \leqslant q_t^{ra} \perp (-p_t^a + \eta_t^{ra} - \mu^r) \geqslant 0, \forall t$$

$$0 \leqslant (\rho_t \overline{q}^{ra} - q_t^{ra}) \perp \overline{\eta}_t^{ra} \geqslant 0, \forall t$$

$$0 \leqslant c^r \perp (-\lambda + \mu^r) \geqslant 0$$

$$0 \leqslant \left(\sum_t \tau_t q_t^{ra} - c^r\right) \perp \mu^r \geqslant 0$$

$$0 \leqslant q_t^{na} \perp (a q_t^{na} + b - p_t^a + \eta_t^{na}) \geqslant 0, \forall t$$

$$0 \leqslant (\overline{q}^{na} - q_t^{na}) \perp \eta_t^{na} \geqslant 0, \forall t$$

$$p_t^a + \kappa\lambda = \alpha - \beta\left(q_t^{na} + q_t^{ra} - f_t^{ab}\right), \forall t$$

$$d_t^a = q_t^{na} + q_t^{ra} - f_t^{ab}, \forall t$$

$$0 \leqslant \lambda \perp \left(c^r + c^s - \kappa \sum_t \tau_t d_t^a\right) \geqslant 0$$

$$0 \leqslant c^s \perp \left(\overline{\lambda} - \lambda\right) \geqslant 0$$

$$0 \leqslant \overline{q}^{rb} \perp \left(c^i - \sum_t \tau_t \rho_t \eta_t^{rb}\right) \geqslant 0$$

$$0 \leqslant q_t^{rb} \perp \left(-p_t^b - t + \eta_t^{rb}\right) \geqslant 0, \forall t$$

$$0 \leqslant \left(\rho_t \overline{q}^{rb} - q_t^{rb}\right) \perp \overline{\eta}_t^{rb} \geqslant 0, \forall t$$

$$0 \leqslant q_t^{nb} \perp \left(a q_t^{nb} + b - p_t^b + \eta_t^{nb}\right) \geqslant 0, \forall t$$

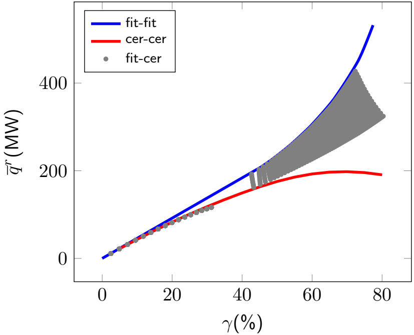
$$0 \leqslant \left(\overline{q}^{nb} - q_t^{nb}\right) \perp \eta_t^{nb} \geqslant 0, \forall t$$

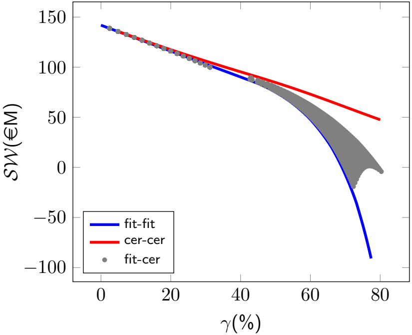
$$p_t^b = \alpha - \beta\left(q_t^{nb} + q_t^{rb} + f_t^{ab}\right), \forall t$$

$$d_t^b = q_t^{nb} + q_t^{rb} + f_t^{ab}, \forall t$$

$$p_t^a = p_t^b, \quad \forall t$$

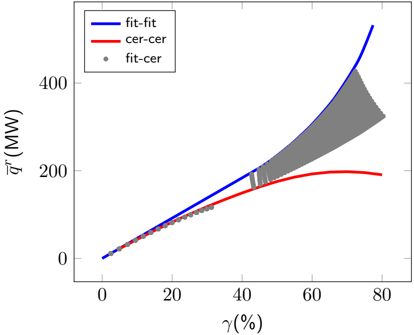
2 areas (perfect competition)

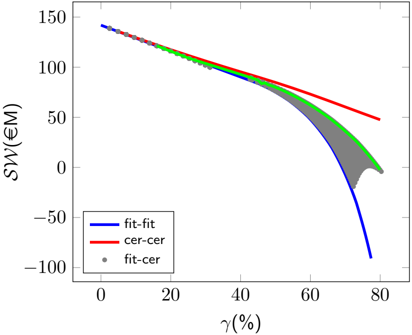




- Different combinations of feed-in-tariff and certificates market parameters lead to different social welfare for a given renewable penetration.

2 areas (perfect competition)





- Different combinations of feed-in-tariff and certificates market parameters lead to different social welfare for a given renewable penetration.

2 areas (perfect competition)

κ(%)	t(€/MWh)	$\overline{q}^{ra}$(MW)	$\overline{q}^{rb}$(MW)	$\mathcal{SW}$(€M)	γ(%)	$\overline{f}^{ab}$(MW)
21	0	43.4	0	129.1	10	25.9
75	0	113.1	0	102.1	30	71.7
45	92	81.6	124	80.6	50	10.3
76	150	94.9	178	38.1	70	28.5

- For low values of the global renewable target, only certificate trading is in place.
- For larger values of the global renewable target, a combination of certificates and feed-in-tariff lead to the maximum social welfare.
- The optimal integration of renewables under support schemes also depends on transmission capacities.

2 areas (perfect competition)

κ(%)	t(€/MWh)	$\overline{q}^{ra}$ (MW)	$\overline{q}^{rb}$ (MW)	$\mathcal{SW}^a$ (€M)	$\mathcal{SW}^b$ (€M)	$\mathcal{SW}$ (€M)	γ (%)	$\overline{f}^{ab}$ (MW)
65	92	102.7	92.8	34.4	45.4	79.8	50	19.9
10	94	22.3	206.5	68.3	8.6	76.9	50	2.4

- Maximizing total social welfare may lead to unfair welfare distribution among interconnected systems.

Summary

- A family of complementarity models to investigate the impact of green certificates to promote renewable-based electricity production
  - Perfect competition / Strategic behavior
  - Compared with feed-in-tariff
  - One area / Two areas
- Green certificates achieve required renewable penetration levels at the maximum social welfare (without uncertainty)
- Under perfect competition, Feed-in-tariff schemes lead to larger amounts of renewable capacity and lower social welfare.
- Exercise of market power by conventional producer impacts the optimal support scheme to promote renewable generation.
- Coordination of support schemes is required to achieve global targets at the maximum social welfare.

Future work

- Include investment decisions of conventional generation (ongoing)
- Include long-term uncertainties and risk-averse players (ongoing)
- Obtain close-form solutions for the proposed equilibrium models
- Intermediate competition levels (conjectural variations)
- Multi-year horizon with banking of certificates
- Further investigate the synergies of transmission expansion and support scheme coordination among interconnected countries
- Consider areas with asymmetric fuel costs, inverse demand functions, competitiveness levels, renewable capacity factors, correlation, etc.

Final goal

$$\min_{\overline{f}_{ij},\kappa_i,\overline{\lambda}_i} \quad \underbrace{\boxed{\sum_{it} \tau_t \left(-\alpha_i d_{it} + \frac{1}{2}\beta_i d_{it}^2 + \frac{1}{2} a_i \left(q_{it}^n\right)^2 + b_i q_{it}^n \right)}}_{\text{Social welfare}} + \underbrace{\boxed{\sum_{ij} c_{ij}^I \overline{f}_{ij}}}_{\text{Transmission expansion cost}}$$

subject to

- Global renewable penetration target
- Local target constraints / redistribution of support schemes costs
- Optimality conditions of players
- Electricity market clearing
- Certificates market clearing
- Trading of certificates among countries
- Network constraints

Thanks for the attention!

Questions?

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