Renewable-based generation expansion under a green certificate market

INFORMS 2015

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¹University of Copenhagen, funded by FEMs project (www.futureelmarket.dk)

November, 4, 2015
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.\(^2\)

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\(^1\) 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 $\tau_t$ to characterize system conditions
- Two different generation technologies:
  - Renewable($r$):
    - Short-run marginal cost equal to 0
    - Variable capacity factor $\rho_t$
    - Linear investment cost $c^i_q^r$
    - Price-taker
  - Non-renewable($n$):
    - Quadratic short-run marginal cost $\frac{a}{2}(q_t^n)^2 + bq_t^n$
    - Fixed capacity $\bar{q}^n$
- Linear inverse demand function $p_t = \alpha - \beta (q_t^n + q_t^r)$
- No network constraints
- No uncertainty
Central planner

Maximize \( \sum_t \tau_t \left( \alpha d_t - \frac{1}{2} \beta (d_t)^2 - \frac{1}{2} a(q_t^n)^2 + b q_t^n \right) \) - \( c^i q^r \)

subject to

- \( q^r_t \leq \rho_t q^r : \tau_t \eta^r_t, \forall t \) \hspace{1cm} \text{Renewable capacity}
- \( q^n_t \leq q^n : \tau_t \eta^n_t, \forall t \) \hspace{1cm} \text{Non-renewable capacity}
- \( d_t = q^r_t + q^n_t : p_t, \forall t \) \hspace{1cm} \text{Balance equation}
- \( \sum_t \tau_t q^r_t \geq \kappa \sum_t \tau_t d_t : \phi \) \hspace{1cm} \text{Quota obligation}
Renewable producer (with certificates)

Maximize
\[
\frac{q^r}{\tau} \geq 0, q_t^r \geq 0, c^r_t \geq 0
\]
\[
\sum_t \tau_t p_t q_t^r - \lambda c^r - c^i_q^r
\]
Revenue power
Revenue certificates
Inv. cost

subject to
\[
q_t^r \leq \rho_t q^r : \tau_t \eta_t^r, \quad \forall t
\]
Production limits
\[
c^r \leq \sum_t \tau_t q_t^r : \mu^r
\]
Certificate limits
Conventional producer

Maximize \( \sum_t \tau_t \left( \frac{p_t q_t^n}{\text{Revenue power}} - \frac{1}{2} a(q_t^n)^2 + b q_t^n \right) \)

subject to

\( q_t^n \leq \bar{q}^n : \tau_t \eta_t^n, \quad \forall t \)

Production limits

(3a)
Complementarity model (certificates)

\[ 0 \leq \overline{q}^r \perp \left( c^i - \sum_t \tau_t \rho_t \eta_t^r \right) \geq 0 \]
\[ 0 \leq q_t^r \perp (-p_t + \eta_t^r - \mu^r) \geq 0, \quad \forall t \]
\[ 0 \leq (\rho_t \overline{q}^r - q_t^r) \perp \eta_t^r \geq 0, \quad \forall t \]
\[ 0 \leq c^r \perp (-\lambda + \mu^r) \geq 0 \]
\[ 0 \leq \left( \sum_t \tau_t q_t^r - c^r \right) \perp \mu^r \geq 0 \]

\[ 0 \leq q_t^n \perp \left( a q_t^n + b - \frac{\partial p_t}{\partial q_t^n} q_t^n - p_t + \eta_t^n \right) \geq 0, \quad \forall t \]
\[ 0 \leq (\overline{q}^n - q_t^n) \perp \eta_t^n \geq 0, \quad \forall t \]

\[ p_t + \kappa \lambda = \alpha - \beta (q_t^n + q_t^r), \quad \forall t \]
\[ d_t = q_t^n + q_t^r, \quad \forall t \]

\[ 0 \leq \lambda \perp \left( c^r + c^s - \kappa \sum_t \tau_t d_t \right) \geq 0 \]
\[ 0 \leq c^s \perp (\overline{\lambda} - \lambda) \geq 0 \]
Certificates \( \frac{\partial p_t}{\partial q_t} = 0 \) \& \( 0 < \lambda < \bar{x} \)

\begin{align*}
0 &\leq \bar{q}_r \perp \left( c^i - \sum_t \tau_t \rho_t \eta_t^r \right) \geq 0 \\
0 &\leq q_t^r \perp (-p_t + \eta_t^r - \lambda) \geq 0, \quad \forall t \\
0 &\leq (\rho_t \bar{q}_r - q_t^r) \perp \eta_t^r \geq 0, \quad \forall t \\
0 &\leq q_t^n \perp (a q_t^n + b - p_t + \eta_t^n) \geq 0, \quad \forall t \\
0 &\leq (\bar{q}_r^n - q_t^n) \perp \eta_t^n \geq 0, \quad \forall t \\
p_t + \kappa \lambda = \alpha - \beta (q_t^n + q_t^r), \quad \forall t \\
d_t = q_t^n + q_t^r, \quad \forall t \\
0 &\leq \lambda \perp \left( \sum_t \tau_t q_t^r - \kappa \sum_t \tau_t d_t \right) \geq 0
\end{align*}

Central

\begin{align*}
0 &\leq \bar{q}_r \perp \left( c^i - \sum_t \tau_t \rho_t \eta_t^r \right) \geq 0 \\
0 &\leq q_t^r \perp (-p_t + \eta_t^r - \phi) \geq 0, \quad \forall t \\
0 &\leq (\rho_t \bar{q}_r - q_t^r) \perp \eta_t^r \geq 0, \quad \forall t \\
0 &\leq q_t^n \perp (a q_t^n + b - p_t + \eta_t^n) \geq 0, \quad \forall t \\
0 &\leq (\bar{q}_r^n - q_t^n) \perp \eta_t^n \geq 0, \quad \forall t \\
p_t + \kappa \phi = \alpha - \beta (q_t^n + q_t^r), \quad \forall t \\
d_t = q_t^n + q_t^r, \quad \forall t \\
0 &\leq \phi \perp \left( \sum_t \tau_t q_t^r - \kappa \sum_t \tau_t d_t \right) \geq 0
\end{align*}
Renewable producer (feed-in-tariff)

Maximize \( \frac{\text{Revenue power}}{\frac{\text{Revenue feed-in-tariff}}{\frac{\text{Inv. cost}}{\sum_t \tau_t p_t q^r_t}} + \sum_t \tau_t q^r_t} - c^i \bar{q}^r \)

subject to

\( q_t^r \leq \rho_t \bar{q}^r : \tau_t \eta_t^r, \quad \forall t \)
Complementarity model (feed-in-tariff)

KKT renewable

\[ 0 \leq \bar{q}^r \perp \left( c^i - \sum_t \tau_t \rho_t \eta_t^r \right) \geq 0 \]
\[ 0 \leq q_t^r \perp (-p_t - t + \eta_t^r) \geq 0, \quad \forall t \]
\[ 0 \leq (\rho_t \bar{q}^r - q_t^r) \perp \bar{\eta}_t^r \geq 0, \quad \forall t \]

KKT conventional

\[ 0 \leq q_t^n \perp \left( a q_t^n + b - \frac{\partial p_t}{\partial q_t^n} q_t^n - p_t + \eta_t^n \right) \geq 0, \quad \forall t \]
\[ 0 \leq (\bar{q}^n - q_t^n) \perp \eta_t^n \geq 0, \quad \forall t \]

Power market clearing

\[ p_t = \alpha - \beta \left( q_t^n + q_t^r \right), \quad \forall t \]
\[ d_t = q_t^n + q_t^r, \quad \forall t \]
Data

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

<table>
<thead>
<tr>
<th>$\rho_t$ (p.u.)</th>
<th>0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_t$ (h)</td>
<td>1486</td>
<td>1328</td>
<td>975</td>
<td>780</td>
<td>685</td>
<td>586</td>
<td>489</td>
<td>538</td>
<td>608</td>
<td>1064</td>
<td>220</td>
</tr>
</tbody>
</table>
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.
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

What about coordination?

<table>
<thead>
<tr>
<th>Country</th>
<th>Solar</th>
<th>Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>FIT</td>
<td>FIT</td>
</tr>
<tr>
<td>Belgium</td>
<td>REC</td>
<td>REC</td>
</tr>
<tr>
<td>Denmark</td>
<td>FIT</td>
<td>FIT</td>
</tr>
<tr>
<td>Germany</td>
<td>FIT/FIP</td>
<td>FIT/FIP</td>
</tr>
<tr>
<td>Italy</td>
<td>FIT</td>
<td>REC</td>
</tr>
<tr>
<td>Spain</td>
<td>FIT</td>
<td>FIT</td>
</tr>
<tr>
<td>Sweden</td>
<td>REC</td>
<td>REC</td>
</tr>
<tr>
<td>Norway</td>
<td>REC</td>
<td>REC</td>
</tr>
</tbody>
</table>

3Council of European Energy Regulators (CEER, 2015)
**Complementarity model (2 zones, perfect competition)**

\[ 0 \leq q^r_a \perp \left( c^i - \sum_t \tau_t \rho_t \eta^r_a \right) \geq 0 \]

\[ 0 \leq q^r_a \perp (-p^a_t + \eta^r_a - \mu^r) \geq 0, \forall t \]

\[ 0 \leq (\rho_t q^r_a - q^r_a) \perp \eta^r_a \geq 0, \forall t \]

\[ 0 \leq c^r \perp (-\lambda + \mu^r) \geq 0 \]

\[ 0 \leq \left( \sum_t \tau_t q^r_a - c^r \right) \perp \mu^r \geq 0 \]

\[ 0 \leq q^a_t \perp (aq^a_t + b - p^a_t + \eta^a_t) \geq 0, \forall t \]

\[ 0 \leq (\bar{q}^a_t - q^a_t) \perp \eta^a_t \geq 0, \forall t \]

\[ p^a_t + \kappa \lambda = \alpha - \beta \left( q^a_t + q^r_a - f^a_{tb} \right), \forall t \]

\[ d^a_t = q^a_t + q^r_a - f^a_{tb}, \forall t \]

\[ 0 \leq \lambda \perp \left( c^r + c^s - \kappa \sum_t \tau_t d^a_t \right) \geq 0 \]

\[ 0 \leq c^s \perp (\bar{\lambda} - \lambda) \geq 0 \]

\[ 0 \leq q^b_t \perp \left( c^i - \sum_t \tau_t \rho_t \eta^b_t \right) \geq 0 \]

\[ 0 \leq q^b_t \perp (-p^b_t - t + \eta^b_t) \geq 0, \forall t \]

\[ 0 \leq (\rho_t q^b_t - q^b_t) \perp \eta^b_t \geq 0, \forall t \]

\[ 0 \leq q^b_t \perp (aq^b_t + b - p^b_t + \eta^b_t) \geq 0, \forall t \]

\[ 0 \leq (\bar{q}^b_t - q^b_t) \perp \eta^b_t \geq 0, \forall t \]

\[ p^b_t = \alpha - \beta \left( q^b_t + q^r_t + f^a_{tb} \right), \forall t \]

\[ d^b_t = q^b_t + q^r_t + f^a_{tb}, \forall t \]

\[ p^a_t = p^b_t, \forall t \]
Different combinations of feed-in-tariff and certificates market parameters lead to different social welfare for a given renewable penetration.
Different combinations of feed-in-tariff and certificates market parameters lead to different social welfare for a given renewable penetration.
2 areas (perfect competition)

<table>
<thead>
<tr>
<th>$\kappa$ (%)</th>
<th>$t (\epsilon/\text{MWh})$</th>
<th>$q^r_a \text{ (MW)}$</th>
<th>$q^r_b \text{ (MW)}$</th>
<th>$SW (\epsilon \text{M})$</th>
<th>$\gamma$ (%)</th>
<th>$f^{ab} \text{ (MW)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>0</td>
<td>43.4</td>
<td>0</td>
<td>129.1</td>
<td>10</td>
<td>25.9</td>
</tr>
<tr>
<td>75</td>
<td>0</td>
<td>113.1</td>
<td>0</td>
<td>102.1</td>
<td>30</td>
<td>71.7</td>
</tr>
<tr>
<td>45</td>
<td>92</td>
<td>81.6</td>
<td>124</td>
<td>80.6</td>
<td>50</td>
<td>10.3</td>
</tr>
<tr>
<td>76</td>
<td>150</td>
<td>94.9</td>
<td>178</td>
<td>38.1</td>
<td>70</td>
<td>28.5</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>$\kappa (%)$</th>
<th>$t ($/\text{MWh})$</th>
<th>$\bar{q}^{ra} (\text{MW})$</th>
<th>$\bar{q}^{rb} (\text{MW})$</th>
<th>$SW^a (\text{€M})$</th>
<th>$SW^b (\text{€M})$</th>
<th>$SW (\text{€M})$</th>
<th>$\gamma (%)$</th>
<th>$f^{ab} (\text{MW})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>92</td>
<td>102.7</td>
<td>92.8</td>
<td>34.4</td>
<td>45.4</td>
<td>79.8</td>
<td>50</td>
<td>19.9</td>
</tr>
<tr>
<td>10</td>
<td>94</td>
<td>22.3</td>
<td>206.5</td>
<td>68.3</td>
<td>8.6</td>
<td>76.9</td>
<td>50</td>
<td>2.4</td>
</tr>
</tbody>
</table>
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. \( \frac{1}{\bar{f}_{ij}, \kappa_i, \bar{\lambda}_i} \sum_{it} \tau_t \left( -\alpha_i d_{it} + \frac{1}{2} \beta_i d_{it}^2 + \frac{1}{2} a_i (q_{it}^n)^2 + b_i q_{it}^n \right) + \sum_{ij} c_{ij} \bar{f}_{ij} \)

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/