Economic and Environmental Consequences of Market Power in the South-East Europe Regional Electricity Market

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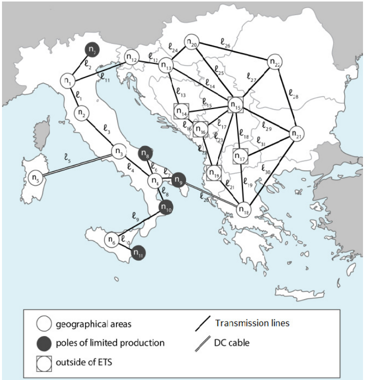
Introduction

South-East Europe Regional Electricity Market (SEE-REM)

- **SEE-REM comprises both EU members subject to the EU Emissions Trading System (ETS) and non-EU members exempt from it**



Electricity and Permit Markets

- Exercise of market power in an electricity market has attracted attention in the literature, whereas the interaction of a product and permit market both subject to market power has been less investigated (Kolstad and Wolak, 2003)
- Manipulation of electricity and permit prices can affect carbon leakage as electricity imports increase from regions without environmental regulation (Fischer and Fox, 2012)
- Regional electricity markets with partial coverage of cap-and-trade (C&T) systems are vulnerable to emission leakage (Burtraw et al., 2006; Višković et al., 2017)
- Stackelberg leader firm could manipulate prices in both electricity and permit markets (Chen et al., 2018)

Research Objective

- Assess market power in both electricity and CO_2 permit markets under a C&T scheme in a transmission-constrained test network of SEE-REM
- Incentives of a strategic producer, Enel, which owns 23% of the capacity in Italy
- Stackelberg leader-follower model of power market
- Compare perfect competition, market power in electricity markets only, and market power in both electricity and permit markets

Findings

- **Under environmental regulation, Stackelberg leader, Enel, may produce more output in total than that in perfect competition, while fringe firms in Italy decrease their outputs**
- **Enel has the incentive to withhold coal to lower the C&T permit price when it has market power in both electricity and permit markets**
- **Carbon leakage in non-ETS countries of SEE-REM under environmental regulation**
- **In total, emissions decrease in SEE-REM as environmental regulation becomes more stringent in spite of carbon leakage**

Mathematical Formulation

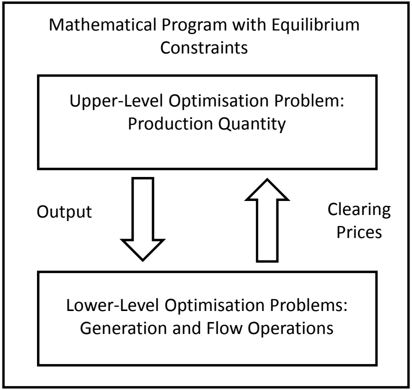
Setup

- **Linear inverse demand function at each node, $D^{int}_{t,n} - D^{slp}_{t,n} d_{t,n}$, thus quadratic gross benefit function**
- **Generation, $x_{t,n,i,u}$, with constant marginal costs, $C_{n,i,u}$, generation capacities, $X_{n,i,u}$, and emission rates, $E_{n,i,u}$**
- **Cap, Z, in a C&T with shadow permit price, ρ**
- **DC load flow, $f_{t,\ell}$, based on network transfer admittance, $H_{n,\ell}$, and incidence, $A_{n,\ell}$, with voltage angles, $v_{t,n}$**
- **Transmission capacities, $K_{t,\ell}$**
- **Perfect competition [PC], Stackelberg with tax [S-T], Stackelberg with C&T [S]**

Stackelberg Model of Power Market

- **Upper-level problem: leader firm maximises profit w.r.t generation levels of units, $x_{t,n,s,u}$, anticipating the outcomes of the lower-level problems**
- **Lower-level problems:**
  - **Follower firms maximise profit from power generation, $x_{t,n,j,u}$**
  - **Welfare-maximising ISO manages flows, $f_{t,\ell}$, and consumption, $d_{t,n}$**
  - **Market clearing of emissions permits under a C&T**
- **Lower-level problems can be formulated as a single optimisation problem, i.e., quadratic program (QP)**
- **Bi-level problem is recast as a mathematical program with equilibrium constraints (MPEC), which is converted into a mixed-integer quadratic program (MIQP)**

Bi-Level Modelling



Lower-Level QP

$$\max_{\Xi} \sum_t N_t \Big[\sum_n \Big(D^{int}_{t,n} d_{t,n} - \frac{1}{2} D^{slp}_{t,n} d^2_{t,n} - \sum_j \sum_{u \in \mathcal{U}_{n,j}} C_{n,j,u} x_{t,n,j,u} \Big) \Big] \quad (1)$$

s.t.

$$N_t(x_{t,n,j,u} - X_{n,j,u}) \leq 0 \ \ (\beta_{t,n,j,u}), \ \forall t, n, j, u \in \mathcal{U}_{n,j} \quad (2)$$

$$N_t(-f_{t,\ell} - K_{t,\ell}) \leq 0 \ \ (\mu^-_{t,\ell}), \ \forall t, \ell \quad (3)$$

$$N_t(f_{t,\ell} - K_{t,\ell}) \leq 0 \ \ (\mu^+_{t,\ell}), \ \forall t, \ell \quad (4)$$

$$N_t(f_{t,\ell^{AC}} - \sum_{n^{AC} \in \mathcal{N}^{AC}} H_{n^{AC},\ell^{AC}} v_{t,n^{AC}}) = 0 \ \ (\gamma_{t,\ell^{AC}}), \ \forall t, \ell^{AC} \in \mathcal{L}^{AC} \quad (5)$$

$$N_t \Big(d_{t,n} - \sum_i \sum_{u \in \mathcal{U}_{n,i}} x_{t,n,i,u} + \sum_\ell A_{n,\ell} f_{t,\ell} \Big) = 0 \ \ (\lambda_{t,n}), \ \forall t, n \quad (6)$$

$$-Z + \sum_t \sum_{n \in \mathcal{N}^{ETS}} \sum_i \sum_{u \in \mathcal{U}_{n,i}} N_t E_{n,i,u} x_{t,n,i,u} \leq 0 \ \ (\rho) \quad (7)$$

where $\Xi \equiv \{d_{t,n} \geq 0, x_{t,n,j,u} \geq 0, f_{t,\ell}, v_{t,n}\}$

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$$-Z + \sum_t \sum_{n \in \mathcal{N}^{ETS}} \sum_i \sum_{u \in \mathcal{U}_{n,i}} N_t E_{n,i,u} x_{t,n,i,u} \leq 0 \;\; (\rho) \quad (7)$$

where $\Xi \equiv \{d_{t,n} \geq 0, x_{t,n,j,u} \geq 0, f_{t,\ell}, v_{t,n}\}$

KKT Conditions for Lower Level

$$0 \leq x_{t,n,j,u} \perp N_t\Big(-\lambda_{t,n} + C_{n,j,u} + \rho E_{n,j,u} + \beta_{t,n,j,u}\Big) \geq 0, \ \forall t, j, u \in \mathcal{U}_{n,j}, n \in \mathcal{N}^{ETS} \tag{8}$$

$$0 \leq x_{t,n,j,u} \perp N_t\Big(-\lambda_{t,n} + C_{n,j,u} + \beta_{t,n,j,u}\Big) \geq 0, \ \forall t, j, u \in \mathcal{U}_{n,j}, n \in \mathcal{N} \setminus \mathcal{N}^{ETS} \tag{9}$$

$$0 \leq d_{t,n} \perp N_t\Big(-D^{int}_{t,n} + D^{slp}_{t,n} d_{t,n} + \lambda_{t,n}\Big) \geq 0, \ \forall t, n \tag{10}$$

$$f_{t,\ell^{AC}} \text{ u.r.s. } N_t\Big(-\sum_{n^{AC} \in \mathcal{N}^{AC}} \lambda_{t,n^{AC}} A_{n^{AC},\ell^{AC}} - \gamma_{t,\ell^{AC}} + \mu^-_{t,\ell^{AC}} - \mu^+_{t,\ell^{AC}}\Big) = 0, \ \forall t, \ell^{AC} \in \mathcal{L}^{AC} \tag{11}$$

$$f_{t,\ell} \text{ u.r.s. } N_t\Big(-\sum_{n} \lambda_{t,n} A_{n,\ell} + \mu^-_{t,\ell} - \mu^+_{t,\ell}\Big) = 0, \ \forall t, \ell \in \mathcal{L} \setminus \mathcal{L}^{AC} \tag{12}$$

$$v_{t,n^{AC}} \text{ u.r.s. } N_t\Big(\sum_{\ell^{AC} \in \mathcal{L}^{AC}} H_{n^{AC},\ell^{AC}} \gamma_{t,\ell^{AC}}\Big) = 0, \ \forall t, n^{AC} \in \mathcal{N}^{AC} \tag{13}$$

$$0 \leq \beta_{t,n,j,u} \perp N_t(X_{n,j,u} - x_{t,n,j,u}) \geq 0, \ \forall t, n, j, u \tag{14}$$

$$\gamma_{t,\ell^{AC}} \text{ u.r.s. } N_t\Big(f_{t,\ell^{AC}} - \sum_{n^{AC} \in \mathcal{N}^{AC}} H_{n^{AC},\ell^{AC}} v_{t,n^{AC}}\Big) = 0, \ \forall t, \ell^{AC} \in \mathcal{L}^{AC} \tag{15}$$

$$0 \leq \mu^-_{t,\ell} \perp N_t(f_{t,\ell} + K_{t,\ell}) \geq 0, \ \forall t, \ell \tag{16}$$

$$0 \leq \mu^+_{t,\ell} \perp N_t(-f_{t,\ell} + K_{t,\ell}) \geq 0, \ \forall t, \ell \tag{17}$$

$$\lambda_{t,n} \text{ u.r.s. } N_t\Big(d_{t,n} - \sum_{i}\sum_{u} x_{t,n,i,u} + \sum_{\ell} A_{n,\ell} f_{t,\ell}\Big) = 0, \ \forall t, n \tag{18}$$

$$0 \leq \rho \perp Z - \sum_{t} \sum_{n \in \mathcal{N}^{ETS}} \sum_{i}\sum_{u} N_t E_{n,i,u} x_{t,n,i,u} \geq 0 \tag{19}$$

Upper-Level MPEC

$$\max_{\Gamma \cup \Xi \cup \Psi} \sum_t N_t \left(\sum_n \sum_{u \in \mathcal{U}_{n,s}} \Big(\lambda_{t,n} - (C_{n,s,u} + \rho E_{n,s,u}) \Big) x_{t,n,s,u} \right) \quad (20)$$

s.t.

$$N_t(x_{t,n,s,u} - X_{n,s,u}) \leq 0 \;\; (\beta_{t,n,s,u}), \;\; \forall t, n, u \in \mathcal{U}_{n,s} \quad (21)$$

Lower-level KKT conditions (8) – (19)

where $\Gamma \equiv \{x_{t,n,s,u} \geq 0\}$ **and**
$\Psi \equiv \{\beta_{t,n,j,u} \geq 0, \gamma_{t,\ell^{AC}}, \lambda_{t,n}, \mu^-_{t,\ell} \geq 0, \mu^+_{t,\ell} \geq 0, \rho \geq 0\}$

Upper-Level MPEC

$$\max_{\Gamma \cup \Xi \cup \Psi} \sum_t N_t \left(\sum_n \sum_{u \in \mathcal{U}_{n,s}} \Big(\lambda_{t,n} - (C_{n,s,u} + \rho E_{n,s,u}) \Big) x_{t,n,s,u} \right) \tag{20}$$

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Resolution of Non-Linearities

- **Apply QP strong duality to convexify bilinear terms in objective function (Dorn, 1960; Huppmann and Egerer, 2015)**

$$\sum_t N_t \Big(\sum_n D^{int}_{t,n} d_{t,n} - \sum_n D^{slp}_{t,n} d^2_{t,n} - \sum_\ell (\mu^-_{t,\ell} + \mu^+_{t,\ell}) K_{t,\ell} - \sum_n \sum_i \sum_u C_{n,i,u} x_{t,n,i,u} - \sum_n \sum_j \sum_u \beta_{t,n,j,u} X_{n,j,u} \Big) - \rho Z \quad (22)$$

- **Complementarity conditions, i.e., $0 \leq a \perp b \geq 0$, are resolved disjunctively as $a \leq Mw; b \leq M(1-w); a, b \geq 0; w \in \{0,1\}$ (Fortuny-Amat and McCarl, 1981)**
- **MPEC may be rendered as an MIQP**

Numerical Examples

Demand

- Net out non-hydro renewable production from demand
- Time is represented by taking 4 representative hours for each of the 12 months of the year 2013
- Derive the load curve based on the number of hours in time block

	Number of days in month		
Blocks	31	28	30
Base load	520	470	504
Shoulder load	186	168	180
Peak load	30	27	28
Super-peak load	8	7	8

Technology Availability and Scenarios

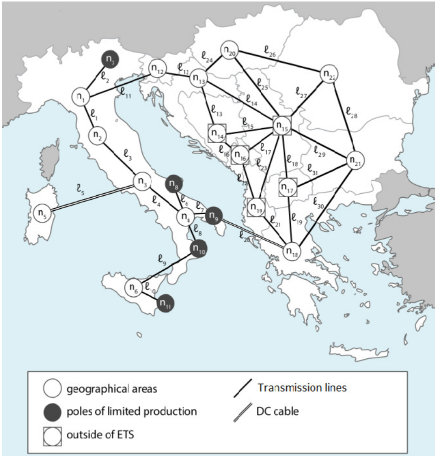
Technology	Natural Gas	Coal	Oil	Nuclear	Lignite
Availability factor (%)	75	84	86	90	85

Scenario	Description
PC-B0 to PC-B40	Perfect competition with ETS cap equal to 0%-40% reduction in emissions
S-T-B0 to S-T-B40	Stackelberg with carbon tax equal to the respective PC scenario permit price
S-B0 to S-B40	Stackelberg with ETS cap equal to 0%-40% reduction in emissions

- Assume that the Stackelberg leader is Enel, which owns 23% of the capacity in Italy

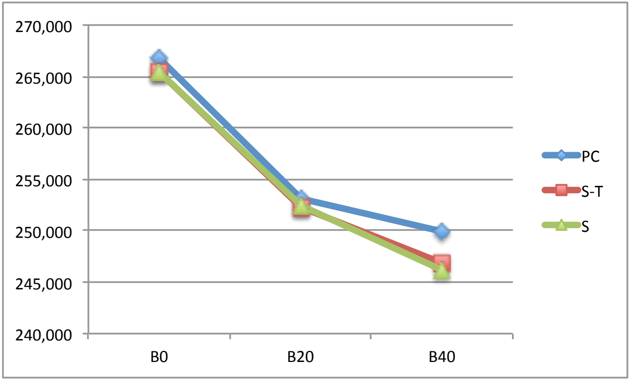
SEE-REM Network Topology

- **Stylised 22-node network of SEE-REM that spans EU and non-EU countries**



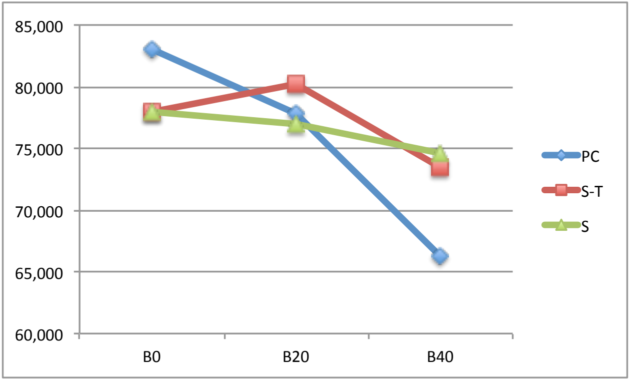
Total Production (GWh) by Enel and Fringes in Italy

- **Total outputs by Enel and Fringes in Italy decrease as environmental regulation becomes more stringent**



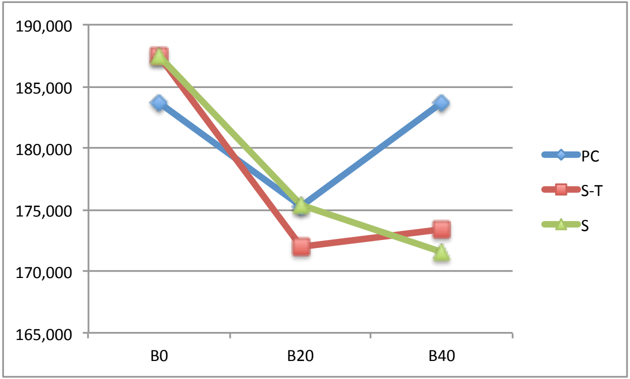
Total Production (GWh) by Enel

- **Stackelberg leader, Enel, attempts to maintain its output level to make profits**
- **Under environmental regulation, Enel strategically produces more output in total than that in perfect competition**



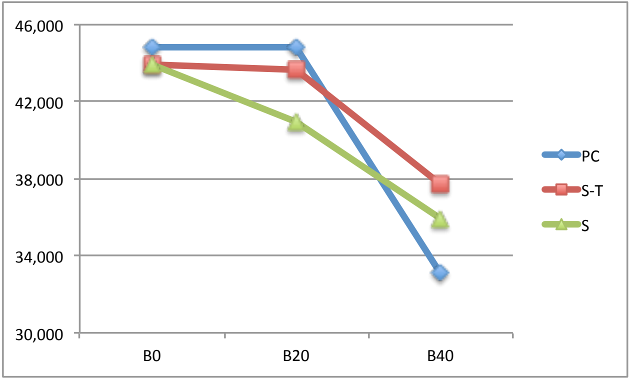
Total Production (GWh) by Fringes in Italy

- **This is at the expense of fringes, which produce less output in total than that in perfect competition under environmental regulation**



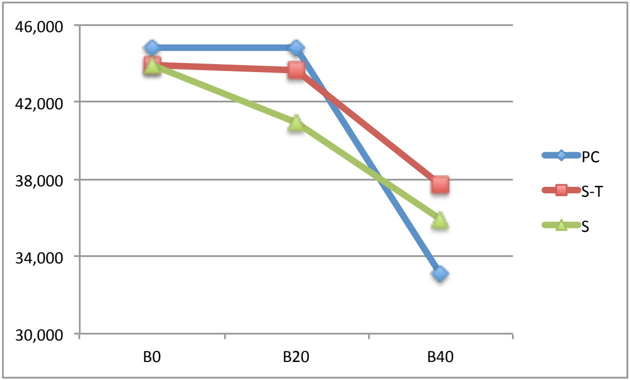
Coal Production (GWh) by Enel

- Enel decreases its “dirtier” coal production as environmental regulation becomes more stringent
- Coal production can be greater than that in perfect competition (B40)



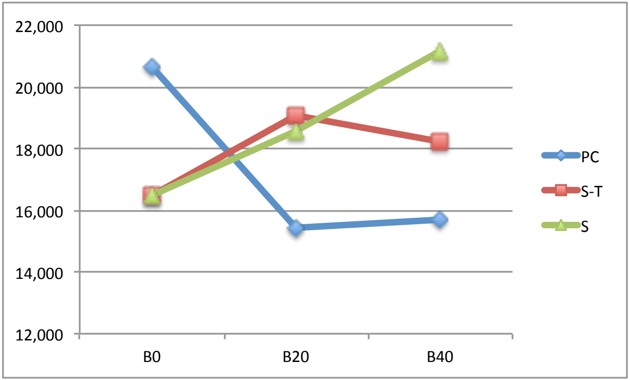
Coal Production (GWh) by Enel

- **Compared to the case of exogenous tax, Enel has the incentive to withhold coal to lower the C&T permit price when it has market power in both electricity and permit markets**



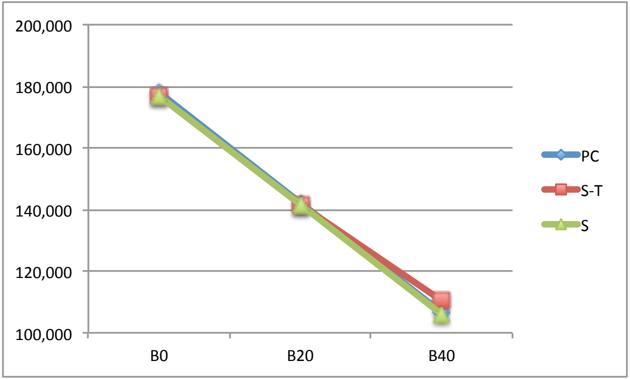
Natural-Gas Production (GWh) by Enel

- Enel even expands its “cleaner” natural-gas production as environmental regulation becomes more stringent to make up for decreases in “dirtier” coal production
- Natural-gas production can be greater than that in perfect competition (B20 and B40)



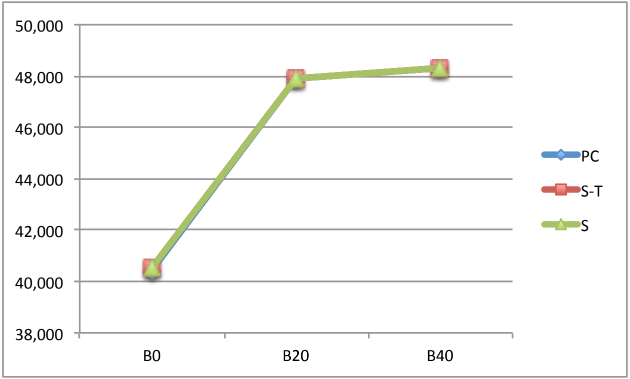
CO_2 Emissions (kt) in ETS Countries of SEE-REM

- **CO_2 Emissions in ETS Countries of SEE-REM decrease as environmental regulation becomes more stringent**



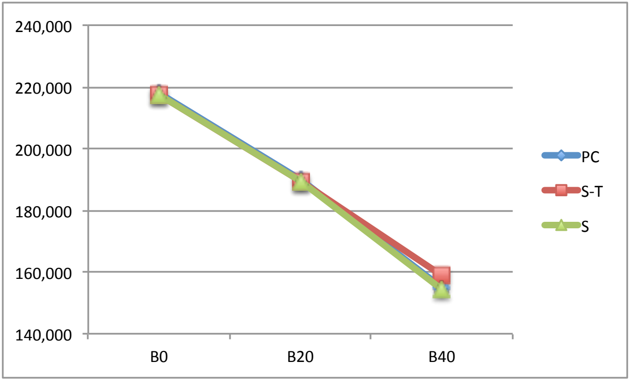
CO_2 Emissions (kt) in Non-ETS Countries of SEE-REM

- **Carbon leakage in non-ETS countries of SEE-REM under environmental regulation**



CO_2 Emissions (kt) in ETS and Non-ETS Countries of SEE-REM

- **In total, emissions decrease in SEE-REM as environmental regulation becomes more stringent**

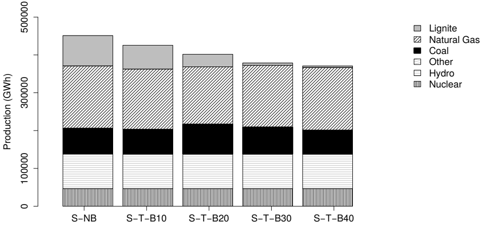


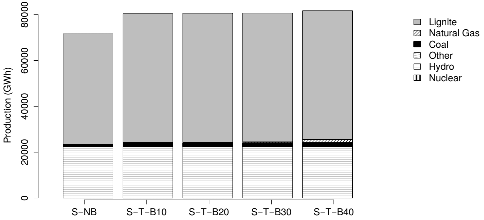
Conclusions

Summary

- **Allow for market power in both product and permit markets to assess its impact on generation output and leakage**
  - **Under environmental regulation, Stackelberg leader, Enel, may produce more output in total than that in perfect competition at the expense of fringes**
  - **Enel has the incentive to withhold coal to lower the C&T permit price by exercising market power**
  - **Carbon leakage within SEE-REM might not be significant**
- **Future work: expand analysis outside SEE-REM, examine investment decisions**

Appendix: Generation Mix under S-T





Appendix: Generation Mix under S