Evaluating the Impact of Average Cost Based Contracts on the Industrial Sector in the European Emission Trading Scheme

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Background on the European Emission Trading Scheme (EU-ETS)

- Cap and Trade System;
- EU Member States target: reduction by 8% from 1990 emission level by the end of the first Kyoto commitment period 2008 – 2012;
- Two Phases: (2005-2007) and (2008-2012);
- The extension of the EU-ETS is currently in discussion;
- Free Allowances (this will apparently be reviewed in the updated version of the EU-ETS)

Backside Effects of the Application of the EU-ETS

- Allowance price volatility (between 30 €/ton and less than 1 €/ton);
- "Windfall" profits of power companies;
- Concern of competitiveness;
- Over-allocation of emission permits of the first Phase;
- Intense discussions about allowance allocation methods (auctioning or grandfathering?)

Outline (1)

1. **Introduction**
   - *Impacts of the European Emission Trading Scheme (EU-ETS) on Industrial Sectors*
2. **General Assumptions**
   - *Exogenous and Endogenous Capacity*;
   - *Common Model Assumptions*

Outline (2)

Exogenous Capacity

3. **Reference Model**
    - *Reference Model*;
    - *Complementarity Conditions Form of the Reference Model*;
    - *Main Results of the Reference Model*

4. **Accommodating Large Electricity Consumers by Special Contracts**
    - *Single Average Cost Pricing Model*;
    - *Nodal Average Cost Pricing Model*;
    - *Results Comparison*

Outline (3)

Endogenous Capacity

5. **Investment Problem**
   - *New Assumptions*;
   - *Reference Model*;
   - *Complementarity Conditions Form of the Reference Model*;
   - *Results of the Reference Model*
6. **Special Contracts**
   - *Case I: Single Average Cost Pricing Model*;
   - *Case I: Nodal Average Cost Pricing Model*;
   - *Results Comparison*
   - *Case II: Single Average Cost Pricing Model*;
   - *Case II: Nodal Average Cost Pricing Model*;
   - *Results Comparison*
7. **Conclusion**
8. **Appendix**

Impacts of the EU-ETS on Industrial Sectors

The application of the EU-ETS affects the industries' cost structure in two ways:

1. **Direct** (Abatement costs and Allowance Price)
2. **Indirect** (Higher Electricity Price)

The combination of these two factors may endanger industrial competitiveness on international markets. This would imply:

1. Reduced industrial activity;
2. Leakage

Some Evidences

- *...in the steel sector, the integrated production route is expected to be impacted in its competitiveness. In some cases, production might be relocated to other areas....*
- *..the cost for a typical European cement production process will increase by 36.5%...By far the largest share of the cost increase is from direct emissions (93%).*
- In the Electric Arc Furnaces (EAF) steel process, *electricity can account for between 50-85 per cent of total energy inputs...The global CO_2 emissions from EAF process therefore depend on the fuel used to produce electricity.*

See McKinsey and Ecofys (2006) and Reinaud J. (2005).

Possible solutions

For these reasons, industrial consumers demand:

1. Special regulations to avoid the pass through of allowance prices in the marginal costs of energy;
2. Special contracts whereby they can buy electricity at the average production costs.

NOTE:

- We focus our attention on the second point;
- However, "other solutions" are also discussed like border tax adjustments

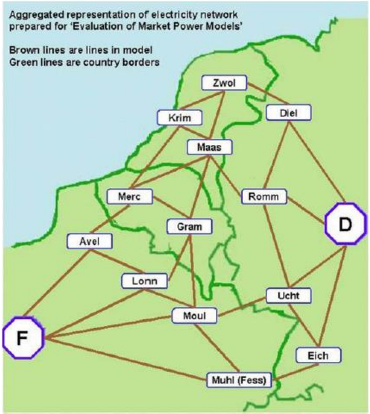
Model Analyzed

We consider two main problems:

1. **Exogenous Capacity** (Fixed capacity)
2. **Endogenous Capacity** (With Investments)

Market Studied

All the models studied are applied to a prototype market of Northwestern Europe[1].



[1] Data source: Energy Research Centre of the Netherlands

Model Assumptions (1)

Models common assumptions:

- $i = 7$ active nodes;
- $f = 9$ electricity generating companies;
- $m = 8$ technologies adopted to produce electricity (hydro, wind, nuclear, lignite, coal, CCGT, natural gas and oil based plants);
- $c = 2$ market segments (large industries (1) and small consumers (2));
- $t = 2$ periods with different durations (off-peak (s) and peak (w));
- $l = 28$ transmission lines;
- Stepwise marginal cost curves are used to represent generators' supply functions.

Model Assumptions (2)

Consumers' electricity demand

We know that:

1. Large industries are more price elastic than small consumers. They may relocate their production activities outside European countries;
2. Large industries' demand is constant over the year;

To account for the first assumption, we set the following reference demand elasticities:

- Small consumers: **0.1**
- Large industries: $\mathbf{1}^{*}$

$*$ Taken from a slide of Newbery: there is an almost complete lack of information of demand response of large industrial consumers

Model Assumptions (3)

Fuel costs

	Cost	
	€/MWh	€/GJ
Coal	8	2.22
Natural gas	15	4.15

Plant operational costs

MWh	Plant operational cost	Efficiency
Coal	19.51	0.41
CCGT	35.74	0.50

References:
www.bafa.de/1/de/service/statistiken/kraftwerkssteinkohle.php
www.bmwi.de/BMWi/Navigation/Energie/Energiestatistiken/energiestatistiken, did = 53736.*html*

Exogenous Capacity

Principle

Setup

Setup

1. Generation capacities are fixed;
2. Large industrial consumers are allowed to conclude long-term contracts at "average cost";
3. The "average cost" is determined as the average of variable and capacity charges of the capacity allocated to these contracts as well as transmission costs computed in a zonal price system;
4. The power sector operates as a bubble as far as the EU-ETS is concerned

Principle

Behavioral Assumptions and Issues

Behavioral Assumptions

- Generation companies choose how to allocate their capacity to the large industries/rest segments of the market;

Issues

- Average cost pricing introduces non convexities in the models and hence possibly an absence or a multiplicity of solution

Summary of the Models Analyzed

		Pricing System	Emission Constraint	Transmission Constraint
Reference Case	***Households***	Short-run marginal cost	Included	Included
	Industry	Short-run marginal cost	Included	Included
Single Average Cost Model	***Households***	Short-run marginal cost	Included	Included
	Industry	***Average Cost***	Included	Included
Nodal Average Cost Model	***Households***	Short-run marginal cost	Included	Included
	Industry	***Average Cost***	Included	***Not Included***

Emission cap E of the power sector: 397 Mio/ton[2].

[2]Source: Own computations based on data provided by CITL

Reference Scenario Model

Electricity companies' maximization problem

Each electricity generating company f maximizes its profit:

$$max. \sum_{t,i} p_i^t \cdot g_{f,i}^t \cdot hour^t + \tag{1}$$

$$-\sum_{t,i,m} cost_{f,i,m} \cdot gp_{f,i,m}^t \cdot hour^t +$$

$$+\lambda \cdot (NAP_f - \sum_{t,i,m} gp_{f,i,m}^t \cdot em_m \cdot hour^t)$$

accounting for the following constraints:

- **Generation balance**

$$\sum_m gp_{f,i,m}^t - g_{f,i}^t \geq 0 \qquad (\eta_{f,i}^t) \tag{2}$$

- **Generation capacity constraint**

$$Cap_{f,i,m} - gp_{f,i,m}^t \geq 0 \qquad (\nu_{f,i,m}^t) \tag{3}$$

Reference Scenario Model

Consumers' surplus maximization problem

- **Industry**

$$max. \qquad \sum_{t=s,w} [hour^t \cdot \int_0^{d_i^{t,1}} P_i^{t,1}(\epsilon) \cdot d\epsilon - hour^t \cdot p_i^t \cdot d_i^{t,1}] \tag{4}$$

$$d_i^{s,1} - d_i^{w,1} = 0 \tag{5}$$

- **Households**

$$max. \qquad hour^t \cdot \int_0^{d_i^{t,2}} P_i^{t,2}(\epsilon) \cdot d\epsilon - hour^t \cdot p_i^t \cdot d_i^{t,2} \tag{6}$$

Reference Scenario Model

Global Constraints

- **Market Balance**

$$\sum_{f,i} g_{f,i}^t - \sum_i d_i^{t,1} - \sum_i d_i^{t,2} = 0 \quad (p^t) \tag{7}$$

- **Electricity Price**

$$p_i^t = p^t + \sum_l (-\mu_l^{t,+} + \mu_l^{t,-}) \cdot PTDF_{l,i} \quad (p_i^t) \tag{8}$$

- **Transmission Constraint**

$$Linecap_l \mp (\sum_i PTDF_{l,i} \cdot (\sum_f g_{f,i}^t - d_i^{t,1} - d_i^{t,2})) \geq 0 \quad (\mu_l^{t,\pm}) \tag{9}$$

- **Emission Constraint**

$$E - \sum_{t,f,i,m} gp_{f,i,m}^t \cdot em_m \cdot hour^t \geq 0 \quad (\lambda) \tag{10}$$

Complementarity Conditions Form of the Reference Model

- **Generators' conditions**

$$0 \leq -p_i^t + \eta_{f,i}^t \perp g_{f,i}^t \geq 0 \tag{11}$$

$$0 \leq cost_{f,i,m} + em_m \cdot \lambda + \nu_{f,i,m}^t - \eta_{f,i}^t \perp gp_{f,i,m}^t \geq 0 \tag{12}$$

$$0 \leq Cap_{f,i,m} - gp_{f,i,m}^t \perp \nu_{f,i,m}^t \geq 0 \tag{13}$$

$$0 \leq \sum_m gp_{f,i,m}^t - g_{f,i}^t \perp \eta_{f,i}^t \geq 0 \tag{14}$$

- **Industry and Households' conditions**

$$0 \leq p_i^s - \alpha_i - a_i^{s,1} + b_i^{s,1} \cdot d_i^{s,1} \cdot \perp d_i^{s,1} \geq 0 \tag{15}$$

$$0 \leq p_i^w + \alpha_i - a_i^{w,1} + b_i^{w,1} \cdot d_i^{w,1} \cdot \perp d_i^{w,1} \geq 0 \tag{16}$$

$$0 \leq d_i^{s,1} - d_i^{w,1} \perp \alpha_i \geq 0 \tag{17}$$

$$0 \leq p_i^t - a_i^{t,2} + b_i^{t,2} \cdot d_i^{t,2} \cdot \perp d_i^{t,2} \geq 0 \tag{18}$$

Complementarity Conditions Form of the Reference Model

- **Market balance equilibrium**

$$0 \leq \sum_{f,i} g_{f,i}^{t} - \sum_{i} d_{i}^{t,1} - \sum_{i} d_{i}^{t,2} \perp \ phub^{t} \geq 0 \tag{19}$$

- **Electricity prices**

$$0 \leq p_{i}^{t} - phub^{t} - \sum_{m} (-\mu_{l}^{t,+} + \mu_{l}^{t,-}) \cdot PTDF_{l,i} \perp p_{i}^{t} \geq 0 \tag{20}$$

- **Transmission constraints**

$$0 \leq Linecap_{l} \mp (\sum_{i} PTDF_{l,i} \cdot (\sum_{f} g_{f,i}^{t} - d_{i}^{t,1} - d_{i}^{t,2})) \perp \mu_{l}^{t,\pm} \geq 0 \tag{21}$$

- **Emission constraint**

$$0 \leq E - \sum_{t,f,i,m} g_{f,i,m}^{t} \cdot em_{m} \cdot hour_{i}^{t} \perp \lambda \geq 0 \tag{22}$$

Main Results

With our input data, the introduction of the ETS in Europe causes:

- A global increase of electricity prices;
- A global decrease of the industrial electricity consumption;
- Emission Allowance price: 26.65 €/ton

Reference Case with and without ETS

Demand Comparison (Industrial Sector)

- **Relative Changes in Industrial Consumers' Hourly Demand**

MW	Without ETS	With ETS	Relative Changes
Germany	32,723	25,107	-23.3%
France	24,893	24,912	0.07%
Merchtem	3,615	3,528	-2.4%
Gramme	2,013	1,963	-2.5%
Krimpen	2,742	2,595	-5.3%
Maastricht	947	886	-6.4%
Zwolle	1,825	1,612	-11.7%
Total	**68,758**	**60,603**	**-12%**

Reference Case with and without ETS

Electricity Price Comparison

- **Electricity Price Changes in Summer**

€/MWh	Without ETS	With ETS	Relative change
Germany	19.51*	44.94	130%
France	4.50**	5.10	13%
Merchtem	35.62	47.13	32%
Gramme	19.51	27.81	43%
Krimpen	35.62	47.13	32%
Maastricht	35.62	47.13	32%
Zwolle	30.71	46.23	51%

∗ Short-run marginal cost of coal plants

∗∗ Short-run marginal cost of nuclear plants

Reference Case with and without ETS

Electricity Price Comparison

Under the EU-ETS, electricity prices increase in summer because:

- Power producers partially shift from coal technologies to CCGT power stations at the observed values of CO_2 price;
- Under the EU-ETS, the utilization of CCGT increases (from 2,916 MW (without EU-ETS) to 3,966 MW (with EU-ETS)), while coal technologies produce less (from 20,771 MW (without EU-ETS) to 8,770 MW (with EU-ETS));
- CCGT installations emit less than coal fuel based technologies, but they are more expensive;
- CCGT technologies, together with the pass through of the allowance price, set the electricity price at a higher level than the coal based plants, operating without the ETS

Reference Case with and without ETS

Electricity Price Comparison

- **Electricity Price Changes in Winter**

€/MWh	Without ETS	With ETS	Relative change
Germany	52.21	47.33	-9%
France	48.01	47.33	-1%
Merchtem	57.23	47.33	-17%
Gramme	53.50	47.33	-12%
Krimpen	55.15	47.33	-14%
Maastricht	54.34	47.33	-13%
Zwolle	54.06	47.33	-12%

Reference Case with and without ETS

Electricity Price Comparison

Under the EU-ETS, electricity prices decrease in winter because:

- Electricity demand decreases;
- Low-efficiency natural gas plants and oil based stations are shut down and are substituted by CCGT;

Reference Case with and without ETS

Electricity Price Comparison

In accordance with our input data:

1. Old natural gas based plants are the last technology in merit order;
2. A natural gas based station, in average, has a variable cost of 55.08 €/MWh;
3. The average variable cost of a CCGT plant is 35.74 €/MWh;
4. The emission opportunity cost associated with a CCGT station is 11.51 €/MWh[3];
5. Under the EU-ETS, a CCGT power plant totally cost 47.25 €/MWh, that is almost the price given by the model

The EU-ETS makes CCGT less expensive than low-efficiency natural gas plants and this explains why power producers abandon natural gas and oil based plants in favor of CCGT technologies

[3] This value is given multiplying the allowance price (26.65 €/MWh) by the CCGT emission factor (0.432 ton/MWh)

Characteristics of the Industrial Sectors

Electricity–intensive consumers demand special electricity services:

1. The bulk of their demand is long-run and with very high load;
2. They are also able to finance the construction and operation of large generation units.

As a consequence one can consider:

1. Market splitting and price discrimination between households and industrial consumers;
2. Application of the average cost pricing to industrial sector.

Single Average Cost Pricing Model

Industrial consumers constitute a power purchase consortium that buys power from plants located in different nodes of the network. The total average cost accounts for two components:

1. **Average Production Cost (*$pprod^1$*)**
   It is the price paid by industries to generators. It is constant throughout the year:

$$pprod^1 = \frac{\sum_t hour^t (\sum_{f,i,m}(gp^{t,1}_{f,i,m} \cdot (cost_{f,i,m} + em_m \cdot \lambda)))}{\sum_{t,i} d_i^{t,1} \cdot hour^t} + \\ + \frac{\sum_{f,i,m} FC_{f,i,m} \cdot G^1_{f,i,m}}{\sum_{t,i} d_i^{t,1} \cdot hour^t}$$

where $G^1_{f,i,m}$ is the installed capacity dedicated to industrial consumer and $FC_{f,i,m}$ the associated annual fixed costs

Single Average Cost Pricing Model

2. **Average Transmission Cost ($ptrans^1$)**
   It corresponds to the transmission charges that industrial consumers have to pay to the Transmission System Operator (TSO)

$$ptrans^1 = \frac{\sum_t hour_t(\sum_{l,i} PTDF_{l,i} \cdot (\sum_f g_{f,i}^{t,1} - d_i^{t,1}) \cdot (-\mu_l^{t,+} + \mu_l^{t,-}))}{\sum_{t,i} d_i^{t,1} \cdot hour^t}$$

3. **Total Average Price (p^1)**
   It is given by the sum of the production and the transmission average costs. It corresponds to the global electricity price faced by industrial consumers:

$$p^1 = pprod^1 + ptrans^1$$

Single Average Cost Price Model

Electricity companies' maximization problem

Each electricity generating company f maximizes its profit:

$$max. \quad pprod^1 \cdot \sum_{t,i} g_{f,i}^{t,1} \cdot hour^t + \sum_{t,i} p_i^{t,2} \cdot g_{f,i}^{t,2} \cdot hour^t + \tag{23}$$

$$- \sum_{t,i,m} cost_{f,i,m} \cdot gp_{f,i,m}^{t,1} \cdot hour^t - \sum_{t,i,m} cost_{f,i,m} \cdot gp_{f,i,m}^{t,2} \cdot hour^t +$$

$$+\lambda \cdot (NAP_f - (\sum_{t,i,m} gp_{f,i,m}^{t,1} \cdot em_m \cdot hour^t + \sum_{t,i,m} gp_{f,i,m}^{t,2} \cdot em_m \cdot hour^t))$$

subject to:

$$\sum_m gp_{f,i,m}^{t,1} - g_{f,i}^{t,1} \geq 0 \quad (\eta_{f,i}^{t,1}) \tag{24}$$

$$\sum_m gp_{f,i,m}^{t,2} - g_{f,i}^{t,2} \geq 0 \quad (\eta_{f,i}^{t,2}) \tag{25}$$

$$G_{f,i,m}^1 - gp_{f,i,m}^{t,1} \geq 0 \quad (\nu_{f,i,m}^{t,1}) \tag{26}$$

$$G_{f,i,m}^2 - gp_{f,i,m}^{t,2} \geq 0 \quad (\nu_{f,i,m}^{t,2}) \tag{27}$$

$$Cap_{f,i,m} - G_{f,i,m}^1 - G_{f,i,m}^2 \geq 0 \qquad (\gamma_{f,i,m}) \tag{28}$$

Single Average Cost Price Model

Consumers' surplus maximization problem

- **Industrial consumers**

$$max. \qquad hour^t \cdot \int_0^{d_i^{t,1}} P_i^{t,1}(\epsilon) \cdot d\epsilon - hour^t \cdot p^1 \cdot d_i^{t,1} \quad (d_i^{t,1}) \tag{29}$$

- **Small consumers**

$$max. \qquad hour^t \cdot \int_0^{d_i^{t,2}} P_i^{t,2}(\epsilon) \cdot d\epsilon - hour^t \cdot p_i^{t,2} \cdot d_i^{t,2} \quad (d_i^{t,2}) \tag{30}$$

Single Average Cost Price Model

Global Constraints (1)

- **Market Balance for Small Consumers**

$$\sum_{f,i} g_{f,i}^{t,2} - \sum_{i} d_i^{t,2} = 0 \quad (phub^{t,2}) \tag{31}$$

- **Marginal Electricity Prices (Small Consumers)**

$$p_i^{t,2} = phub^{t,2} + (\sum_{l}(-\mu_l^{t,+} + \mu_l^{t,-}) \cdot PTDF_{l,i}) \quad (p_i^{t,2}) \tag{32}$$

- **Market Balance for Industrial Consumers**

$$\sum_{f,i} g_{f,i}^{t,1} - \sum_{i} d_i^{t,1} = 0 \quad (\beta^{t,1}) \tag{33}$$

Single Average Cost Price Model

Global Constraints (2)

- **Transmission Constraints**

$$Linecap_l \mp (\sum_i PTDF_{l,i} \cdot (\sum_{f,i} g_{f,i}^{t,1} + \sum_{f,i} g_{f,i}^{t,2} - d_i^{t,1} - d_i^{t,2})) \geq 0 \quad (\mu_l^{t,+}) \quad (34)$$

- **Emission Constraint**

$$E - (\sum_{t,f,i,m} em_m \cdot gp_{f,i,m}^{t,1} \cdot hour^t + \sum_{t,f,i,m} em_m \cdot gp_{f,i,m}^{t,2} \cdot hour^t) \geq 0 \quad (\lambda) \quad (35)$$

Complementarity Conditions Form of the Single Average Cost Price Model

Small Consumers

- **Small consumers (as before except for (43))**

$$0 \leq \eta_{f,i}^{t,2} - p_i^{t,2} \perp g_{f,i}^{t,2} \geq 0 \tag{36}$$

$$0 \leq cost_{f,i,m} + \lambda \cdot em_m + \nu_{f,i,m}^{t,2} - \eta_{f,i}^{t,2} \perp gp_{f,i,m}^{t,2} \geq 0 \tag{37}$$

$$0 \leq \sum_m gp_{f,i,m}^{t,2} - g_{f,i}^{t,2} \perp \eta_{f,i}^{t,2} \geq 0 \tag{38}$$

$$0 \leq G_{f,i,m}^2 - gp_{f,i,m}^{t,2} \perp \nu_{f,i,m}^{t,2} \geq 0 \tag{39}$$

$$0 \leq \sum_{f,i} g_{f,i}^{t,2} - \sum_i d_i^{t,2} \perp phub^{t,2} \geq 0 \tag{40}$$

$$0 \leq p_i^{t,2} - a_i^{t,2} + b_i^{t,2} \cdot d_i^{t,2} \perp d_i^{t,2} \geq 0 \tag{41}$$

$$0 \leq p_i^{t,2} - phub^{t,2} - (\sum_l (-\mu_l^{t,+} + \mu_l^{t,-}) \cdot PTDF_{l,i}) \perp p_i^{t,2} \geq 0 \tag{42}$$

$$0 \leq \gamma_{f,i,m} - \sum_t \nu_{f,i,m}^{t,2} \cdot proportion^t \perp G_{f,i,m}^2 \geq 0 \tag{43}$$

Complementarity Conditions Form of the Single Average Cost Price Model

Industrial Consumers (1)

- **Industrial consumers**

The following is similar to the small consumers' problem and intended to guarantee production efficiency (merit order) when demand results from a price p^1:

$$0 \leq \eta_{f,i}^{t,1} - \beta^{t,1} - (\sum_l (-\mu_l^{t,+} + \mu_l^{t,-}) \cdot PTDF_{l,i}) \perp g_{f,i}^{t,1} \geq 0 \tag{44}$$

$$0 \leq cost_{f,i,m} + \lambda \cdot em_m + \nu_{f,i,m}^{t,1} - \eta_{f,i}^{t,1} \perp gp_{f,i,m}^{t,1} \geq 0 \tag{45}$$

$$0 \leq \sum_m gp_{f,i,m}^{t,1} - g_{f,i}^{t,1} \perp \eta_{f,i}^{t,1} \geq 0 \tag{46}$$

$$0 \leq G_{f,i,m}^1 - gp_{f,i,m}^{t,1} \perp \nu_{f,i,m}^{t,1} \geq 0 \tag{47}$$

$$0 \leq \sum_{f,i} g_{f,i}^{t,1} - \sum_i d_i^{t,1} \perp \beta^{t,1} \geq 0 \tag{48}$$

$$0 \leq p^1 - a_i^{t,1} + b_i^{t,1} \cdot d_i^{t,1} \perp d_i^{t,1} \geq 0 \tag{49}$$

Complementarity Conditions Form of the Single Average Cost Price Model

Industrial Consumers (2)

The following (except (54)) computes the price p^1 as an average cost:

$$0 \leq pprod^1 - \frac{\sum_t hour^t(\sum_{f,i,m}(gp^{t,1}_{f,i,m} \cdot (cost_{f,i,m} + em_m \cdot \lambda)))}{\sum_{t,i} d_i^{t,1} \cdot hour^t} - \frac{\sum_{f,i,m} FC_{f,i,m} \cdot G^1_{f,i,m}}{\sum_{t,i} d_i^{t,1} \cdot hour^t} \perp pprod^1 \geq 0 \tag{50}$$

$$0 \leq ptrans^1 - \frac{\sum_t hour^t(\sum_{l,i} PTDF_{l,i} \cdot inj_i^t \cdot (-\mu_l^{t,+} + \mu_l^{t,-}))}{\sum_{t,i} d_i^{t,1} \cdot hour^t} \perp ptrans^1 \geq 0 \tag{51}$$

$$0 \leq inj_i^t - \sum_f g^{t,1}_{f,i} + d_i^{t,1} \perp inj_i^1 \geq 0 \tag{52}$$

$$0 \leq p^1 - pprod^1 - ptrans^1 \perp p^1 \geq 0 \tag{53}$$

$$0 \leq \gamma_{f,i,m} - \sum_t \nu^{t,1}_{f,i,m} \cdot proportion^t \perp G^1_{f,i,m} \geq 0 \tag{54}$$

Complementarity Conditions of the Single Average Cost Price Model

Global Constraints

- **Transmission constraints (similar, but not identical to the reference model)**

$$0 \leq Linecap_l \mp (\sum_i PTDF_{l,i} \cdot (\sum_f g_{f,i}^{t,1} + \sum_f g_{f,i}^{t,2} - d_i^{t,1} - d_i^{t,2})) \perp \mu_l^{t,+} \geq 0 \quad (55)$$

- **Global capacity constraint**

$$0 \leq Cap_{f,i,m} - G_{f,i,m}^1 - G_{f,i,m}^2 \perp \gamma_{f,i,m} \geq 0 \quad (56)$$

- **Emission constraint (similar, but not identical to the reference model)**

$$0 \leq E - (\sum_{t,f,i,m} em_m \cdot gp_{f,i,m}^{t,1} \cdot hour^t + \sum_{t,f,i,m} em_m \cdot gp_{f,i,m}^{t,2} \cdot hour^t) \perp \lambda \geq 0 \quad (57)$$

Complementarity Conditions Form of the Single Average Cost Price Model

Capacity allocation mechanism

- **Capacity allocation mechanism**

$$0 \leq \gamma_{f,i,m} - \sum_t \nu^{t,2}_{f,i,m} \cdot proportion^t \perp G^2_{f,i,m} \geq 0 \quad (43)$$

$$0 \leq \gamma_{f,i,m} - \sum_t \nu^{t,1}_{f,i,m} \cdot proportion^t \perp G^1_{f,i,m} \geq 0 \quad (54)$$

$$0 \leq Cap_{f,i,m} - G^1_{f,i,m} - G^2_{f,i,m} \perp \gamma_{f,i,m} \geq 0 \quad (56)$$

These three relations equalize the marginal value of the capacity allocated by a firm to the two segments of the market

Results of the Single Average Cost Pricing Model

Single Average Cost Price

- **Single Average Cost Price**

Cost components	**€/MWh**
Fuel	10.62
Transmission	-2.81^*
Emission	9.98
Fixed costs	17.59
Average cost price	**35.37**

Emission allowance price: $40.22e/ton^{**}$.

$*$ Transmission costs are negative because they are given by the sum of negative values. These negative values are influenced both by the PTDF signs and by flow directions (France export to Germany and Belgium which in its turn deliver power to the Netherlands).

$**$ (To be compared with 26.65 €/ton in the reference model)

Results of the Single Average Cost Pricing Model

Electricity Price Comparison (Small Consumers)

- **Relative changes in small consumers' electricity prices (Summer)**

SUMMER			
€/MWh	**Reference Case**	**Single average cost**	**Relative changes**
Germany	44.94	53.12	18%
France	5.10	4.50	-12%
Merchtem	47.13	57.89	23%
Gramme	27.81	38.17	37%
Krimpen	47.13	54.29	15%
Maastricht	47.13	52.36	11%
Zwolle	46.23	53.00	15%

- **Relative changes in small consumers' electricity prices (Winter)**

WINTER			
€/MWh	**Reference Case**	**Single average cost**	**Relative changes**
Germany	47.33	73.88	56%
France	47.33	57.89	22%
Merchtem	47.33	97.03	105%
Gramme	47.33	80.85	71%
Krimpen	47.33	87.66	85%
Maastricht	47.33	84.10	78%
Zwolle	47.33	82.63	75%

Results of the Single Average Cost Pricing Model

Demand Comparison (Industrial Consumers)

- **Comparison of the Industrial Consumers' Hourly Demand**

MW	Reference case	Single average cost	Relative changes
Germany	25,107	33,089	32%
France	24,912	20,672	-17%
Merchtem	3,528	4,805	36%
Gramme	1,963	2,065	5%
Krimpen	2,595	3,535	36%
Maastricht	886	1,207	36%
Zwolle	1,612	2,166	34%
Total	**60,603**	**67,539**	**11%**

Results of the Single Average Cost Pricing Model

Demand Comparison (Small Consumers)

- **Comparison of the Small Consumers' Hourly Demand (Summer)**

SUMMER			
MW	**Reference Case**	**Single average cost**	**Relative changes**
Germany	18,746	18,358	-2.1%
France	22,096	22,127	0.1%
Merchtem	1,287	1,251	-2.7%
Gramme	577	563	-2.5%
Krimpen	2,897	2,845	-1.8%
Maastricht	690	681	-1.3%
Zwolle	1,151	1,131	-1.7%
Total	**47,444**	**46,955**	**-1%**

- **Comparison of the Small Consumers' Hourly Demand (Winter)**

WINTER			
MW	**Reference case**	**Single Average cost**	**Relative changes**
Germany	47,940	44,699	-7%
France	44,542	43,344	-3%
Merchtem	4,496	3,927	-13%
Gramme	1,924	1,760	-9%
Krimpen	7,332	6,579	-10%
Maastricht	1,777	1,610	-9%
Zwolle	2,977	2,710	-9%
Total	**110,988**	**104,629**	**-6%**

Results of the Single Average Cost Pricing Model

Demand Comparison (Global Annual Demand)

- **Comparison of the Consumers' Global Annual Demand**

GLOBAL ANNUAL DEMAND			
MWh	**Reference case**	**Single average cost**	**Relative changes**
Germany	489,951,121	546,134,302	11.5%
France	493,129,840	451,810,460	-8.4%
Merchtem	53,803,596	62,747,254	16.6%
Gramme	27,136,277	27,359,393	0.8%
Krimpen	64,187,582	69,418,178	8.1%
Maastricht	17,750,349	19,911,214	12.2%
Zwolle	30,820,955	34,601,307	12.3%
Total	**1,176,779,721**	**1,211,982,108**	**3.0%**

Results of the Single Average Cost Pricing Model

Capacity Dedicated to Industrial Consumers

- **Capacity Dedicated to Industrial Consumers (with respect to the total installed capacity)**

	Hydro	Wind	Nuclear	Lignite	Coal	CCGT
Germany	100%	73%	63%	65%	0%	28%
France	64%	100%	49%	0%	0%	0%
Merchtem		100%	65%		66%	53%
Gramme	100%	100%	80%		0%	0%
Krimpen		100%	100%		0%	78%
Maastricht		100%				0%
Zwolle		100%			0%	43%
Total	**72%**	**75%**	**54%**	**64%**	**3%**	**28%**

Results of the Single Average Cost Pricing Model

Summary

The comparison with respect to the reference case shows that:

1. Single average cost price is lower than marginal cost prices found in the reference case. This holds for all nodes except for France[4];
2. Industries globally increase their electricity consumption by 11% (p.a.);
3. Small consumers face higher electricity prices especially in winter, when oil and natural gas based plants in addition with emission allowance set their power prices;
4. Emission allowance price is very high 40.22 €/ton;
5. Industries require more electricity than in the reference case. This makes the consumers' global demand increasing and then power producers exploit all the available capacity. This explains why emission allowances are so expensive

[4] Their summer marginal electricity price was very low: only 5.10 €/MWh

Nodal Average Cost Pricing Model

This model differs from the previous one by the fact that:

1. Industrial consumers buy electricity through special contracts with local generators;
2. Industries are then supplied only with electricity produced at the node where they are located;
3. Electricity intensive industrial users do not have to pay transmission costs;
4. Electricity average cost prices differ per node in accordance with the technology employed to generate power.

Nodal Average Cost Pricing Model

The average cost price varies with the node. The obtained prices p_i^1 are functions of the variable cost components (fuel and emission) and of the fixed charges.

$$p_i^1 = \frac{\sum_t hour^t(\sum_{f,m}(gp_{f,i,m}^{t,1} \cdot (cost_{f,i,m} + em_m \cdot \lambda)))}{\sum_t d_i^{t,1} \cdot hour^t} + \frac{\sum_{f,m} FC_{f,m,i} \cdot G_{f,i,m}^1}{\sum_t d_i^{t,1} \cdot hour^t}$$

where $G_{f,i,m}^1$ is the installed capacity dedicated to industrial consumers and $FC_{f,m,i}$ are the corresponding annual fixed costs

Results of the Nodal Average Cost Pricing Model

Nodal Average Cost Price

- **Nodal Average Cost Prices**

€/MWh	Fuel	Emission	Fixed	Average cost price
Germany	9.54	15.15	17.63	**42.32**
France	4.44	0.00	13.48	**17.92**
Merchtem	21.36	7.22	10.20	**38.78**
Gramme	14.77	4.41	11.53	**30.70**
Krimpen	30.39	11.11	10.90	**52.40**
Maastricht	34.57	12.93	10.84	**58.34**
Zwolle	35.62	13.33	8.53	**57.47**

Emission Allowance Price: $30.85e/ton^*$

∗ (To be compared with 26.65 €/ton (reference model) and 40.22 €/ton (single average cost model))

Results of the Nodal Average Cost Pricing Model

Electricity Price Comparison (Industrial Consumers)

- **Relative Changes in Industrial Electricity Prices**

	% *Reference**	**%** *Single***
Germany	-8%	20%
France	-21%	-49%
Merchtem	-18%	10%
Gramme	-14%	-13%
Krimpen	11%	48%
Maastricht	24%	65%
Zwolle	23%	63%

∗ Relative changes of nodal average cost prices with respect to the average of those of the reference case

∗∗ Relative changes of nodal average cost prices with respect to those of the single average cost price model

Results of the Nodal Average Cost Pricing Model

Electricity Price Comparison (Small Consumers)

- **Relative Changes in Small Consumers' Electricity Prices (Summer)**

SUMMER			
€/MWh	**Single average cost**	**Nodal average cost**	**Relative changes**
Germany	53.12	48.95	-8%
France	4.50	48.95	988%
Merchtem	57.89	48.95	-15%
Gramme	38.17	48.95	28%
Krimpen	54.29	48.95	-10%
Maastricht	52.36	48.95	-7%
Zwolle	53.00	48.95	-8%

- **Relative Changes in Small Consumers' Electricity Prices (Winter)**

WINTER			
€/MWh	**Single average cost**	**Nodal average cost**	**Relative changes**
Germany	73.88	61.20	-17%
France	57.89	70.43	22%
Merchtem	97.03	90.08	-7%
Gramme	80.85	72.00	-11%
Krimpen	87.66	64.97	-26%
Maastricht	84.10	48.95	-42%
Zwolle	82.63	58.89	-29%

The huge increase of French small consumers' price in summer explains the drop in their electricity demand.

Results of the Nodal Average Cost Pricing Model

Demand Comparison (Industrial Consumers (1))

- **Comparison of the Industrial Consumers' Demand**

MW	Reference case	Single Average cost	Nodal Average cost
Germany	25,107	33,089	27,935
France	24,912	20,672	28,755
Merchtem	3,528	4,805	4,438
Gramme	1,963	2,065	2,281
Krimpen	2,595	3,535	2,186
Maastricht	886	1,207	586
Zwolle	1,612	2,166	1,093
Total	**60,603**	**67,539**	**67,273**

Results of the Nodal Average Cost Pricing Model

Demand Comparison (Industrial Consumers (2))

- **Relative Changes in Industrial Consumers' Hourly Demand**

	% *Reference**	% *Single***
Germany	11%	-16%
France	15%	39%
Merchtem	26%	-8%
Gramme	16%	10%
Krimpen	-16%	-38%
Maastricht	-34%	-51%
Zwolle	-32%	-50%
Total	**11%**	**-0.4%**

∗ Relative changes in industrial demand given by the comparison between the reference and the nodal average cost cases

∗∗ Relative changes in industrial demand given by the comparison between the single and the nodal average cost pricing cases

Results of the Nodal Average Cost Pricing Model

Demand Comparison (Small Consumers)

- **Comparison of the Small Consumers' Hourly Demand (Summer)**

SUMMER			
MW	**Single average cost**	**Nodal average cost**	**Relative changes**
Germany	18,358	18,555	1%
France	22,127	19,868	-10%
Merchtem	1,251	1,281	2%
Gramme	563	547	-3%
Krimpen	2,845	2,884	1%
Maastricht	681	687	1%
Zwolle	1,131	1,143	1%
Total	**46,955**	**44,966**	**-4%**

- **Comparison of the Small Consumers' Hourly Demand (Winter)**

WINTER			
MW	**Single average cost**	**Nodal average cost**	**Relative changes**
Germany	44,699	46,247	3%
France	43,344	41,921	-3%
Merchtem	3,927	4,007	2%
Gramme	1,760	1,803	2%
Krimpen	6,579	7,003	6%
Maastricht	1,610	1,770	10%
Zwolle	2,710	2,890	7%
Total	**104,629**	**105,639**	**1%**

Globally, small consumers' demand decreases in summer. This is mainly due to the cut of 10% of the French small consumers demand

Results of the Nodal Average Cost Pricing Model

Demand Comparison (Global Annual Demand (1))

- **Comparison of the Global Annual Demand**

GLOBAL ANNUAL DEMAND			
MWh	**Reference case**	**Single average cost**	**Nodal average cost**
Germany	489,951,121	546,134,302	507,606,506
France	493,129,840	451,810,460	505,855,053
Merchtem	53,803,596	62,747,254	59,972,043
Gramme	27,136,277	27,359,393	29,330,033
Krimpen	64,187,582	69,418,178	59,338,313
Maastricht	17,750,349	19,911,214	15,074,774
Zwolle	30,820,955	34,601,307	25,917,735
Total	**1,176,779,721**	**1,211,982,108**	**1,203,094,458**

Results of the Nodal Average Cost Pricing Model

Demand Comparison (Global Annual Demand (2))

- **Relative Changes in Global Annual Demand**

	% *Reference**	% *Single***
Germany	4%	-7%
France	3%	12%
Merchtem	11%	-4%
Gramme	8%	7%
Krimpen	-8%	-15%
Maastricht	-15%	-24%
Zwolle	-16%	-25%
Total	**2%**	**-1%**

∗ Relative changes in industrial demand given by the comparison between the reference and the nodal average cost cases

∗∗ Relative changes in industrial demand given by the comparison between the single and the nodal average cost pricing cases

Results of the Nodal Average Cost Pricing Model

Capacity Dedicated to Industrial Consumers

- **Capacity Dedicated to Industrial Consumers (with respect to the total installed capacity)**

	Hydro	Wind	Nuclear	Lignite	Coal	CCGT
Germany	51%	56%	69%	55%	18%	0%
France	7%	0%	62%	0%	0%	0%
Merchtem		0%	98%		0%	93%
Gramme	77%	35%	68%		0%	63%
Krimpen		26%	100%		0%	41%
Maastricht		17%				19%
Zwolle		0%			0%	23%
Total	**16%**	**53%**	**66%**	**55%**	**11%**	**18%**

Results of the Nodal Average Cost Pricing Model

Summary

1. Industrial consumers require almost an identical amount of electricity in the two average cost pricing scenarios;
2. The global annual demand is higher than in the reference case (+2% increase) and lower than in single average cost case (-1% decrease). This explains why in the nodal average cost case emission allowance price is higher than in the reference model, but lower than in single average cost scenario

The combination of these effects explains why emission allowance price falls to 30.85 €/ton

Main Results

The application of these special pricing policies seems to have a general positive effect on industries. In fact:

1. Industrial electricity prices tend to decrease with respect to the reference case;
2. Industrial electricity demand generally increases with respect to the reference case: this is the desired effect;
3. Industries have access to base-load capacity characterized by low emission factor;
4. The fuel mix on which countries base their electricity production is a key factor in meeting the ETS target;
5. Allowance prices are quite high in both approaches: 40.22 €/ton and 30.85 €/ton respectively in the single and the nodal average cost pricing models.

Endogenous Capacity

New Assumptions (1)

Setup

1. Generation capacities are endogenous;
2. New power installations do not receive emission allowances for free;
3. New power installations are supposed to be available in the second phase of the EU-ETS;
4. New and old installations have an identical cost structure;
5. New emission cap: 358 Mio/ton. p.a[5]

[5] Source: Own computation based on data reported on *http://europa.eu/rapid/pressReleasesAction.do?reference=IP/07/1274*

New Assumptions (2)

Setup

1. **Reference case:** only power companies invest and apply identical marginal cost price to both consumer groups;
2. **CASE I:** only power companies invest, but they charge average cost to industries;
3. **CASE II:** power companies and industrial consumers invest. Industries buy at the marginal cost from generators (requirement of non discrimination)

New Assumptions (3)

	Pricing System	Emission Constraint	Transmission Constraint	Investment
Reference Case	Short-run marginal cost (both consumer groups)	Included	Included	Electricity generating companies invest
CASE I Single Average Cost Model	Short-run marginal cost (small consumers) Single average cost price (industrial consumers)	Included	Included	Electricity generating companies invest
CASE I Nodal Average Cost Model	Short-run marginal cost (small consumers) Nodal average cost price (industrial consumers)	Included	Included	Electricity generating companies invest
CASE II Single Average Cost Model	Short-run marginal cost (small and industrial consumers) Single average cost price (industrial self-production)	Included	Included	Electricity generating companies and industrial consumers invest
CASE II Nodal Average Cost Model	Short-run marginal cost (small and industrial consumers) Nodal average cost price (industrial self-production)	Included	Included	Electricity generating companies and industrial consumers invest

Reference Model

Assumptions of the Reference Model

Assumptions of the reference model

1. Electricity generating companies supply both industrial and small consumers and apply identical marginal cost based prices to both market segments;
2. No market segmentation;
3. No capacity split;
4. Electricity generating companies are the only ones to invest

Main Results

Investment Policy

The investment policy adopted by electricity generating companies is as follows:

- Without EU-ETS, power producers expand their capacity and build new nuclear (in France), lignite (in Germany) and coal (in the other nodes) stations;
- The inception of the EU-ETS pushes power companies to invest in clean technologies, namely in wind and nuclear;
- There are no investments in CCGT technologies. Without EU-ETS, power companies prefer building new coal stations since they are cheaper; while the inception of carbon regulation encourages investments in nuclear. Moreover, according to our data, CCGT are quite expensive

Main Results

Comparison with the former reference case

Like in the former reference case, the inception of the EU-ETS results in:

- An increase in consumers' electricity prices;
- A global decrease of the industrial electricity consumption

BUT

With respect to the former reference case, one has:

- A global decrease of electricity prices;
- A global increase of the industrial electricity consumption due to the reduced electricity price and the expansion of the production park;
- Although consumers' demand increases, emission allowance price is lower than before (21.24 €/ton) because power producers invest in clean technologies;
- This holds for both consumer groups

Reference Case with and without ETS

Demand Comparison (Industrial Sector)

- **Relative Changes in Industrial Consumers' Hourly Demand**

MW	Without ETS	With ETS	Relative Changes
Germany	39,389	27,916	-29%
France	27,754	27,754	0%
Merchtem	5,103	4,050	-21%
Gramme	2,425	2,223	-8%
Krimpen	3,754	2,745	-27%
Maastricht	1,282	952	-26%
Zwolle	2,380	1,738	-27%
Total	**82,087**	**67,378**	**-18%**

Reference Case with and without ETS

Demand Comparison (Small Consumers)

- **Relative Changes in Small Consumers' Hourly Demand (Summer)**

SUMMER			
MW	**Without ETS**	**With ETS**	**Relative Changes**
Germany	20,024	18,991	-5%
France	22,127	22,127	0%
Merchtem	1,344	1,311	-3%
Gramme	589	587	0%
Krimpen	3,028	2,915	-4%
Maastricht	721	695	-4%
Zwolle	1,209	1,160	-4%
Total	**49,042**	**47,784**	**-3%**

- **Relative Changes in Small Consumers' Hourly Demand (Winter)**

WINTER			
MW	**Without ETS**	**With ETS**	**Relative Changes**
Germany	49,355	48,235	-2%
France	45,866	45,866	0%
Merchtem	4,629	4,523	-2%
Gramme	1,981	1,943	-2%
Krimpen	7,549	7,359	-3%
Maastricht	1,829	1,788	-2%
Zwolle	3,065	2,994	-2%
Total	**114,275**	**112,707**	**-1%**

Reference Case with and without ETS

Electricity Price Comparison

- **Electricity Price Changes in Summer**

SUMMER			
€/MWh	Without ETS	With ETS	Relative Changes
Germany	18.00	39.78	121%
France	4.50*	4.50*	0%
Merchtem	29.49	39.78	35%
Gramme	19.51	20.49	5%
Krimpen	29.49	44.80	52%
Maastricht	29.49	44.80	52%
Zwolle	26.20	43.15	65%

- **Electricity Price Changes in Winter**

WINTER			
€/MWh	Without ETS	With ETS	Relative Changes
Germany	35.74	44.92	26%
France	35.66	35.66	0%
Merchtem	35.70	44.98	26%
Gramme	35.69	43.44	22%
Krimpen	35.71	45.89	29%
Maastricht	35.71	44.80	25%
Zwolle	35.72	45.20	27%

* Short-run marginal cost of nuclear plant

Reference Case with and without EU-ETS

Investments Without and With EU-ETS

- **Investment Without EU-ETS**

MW	Nuclear	Lignite	Coal	Total
Germany		19,584		**19,584**
France	16,604			**16,604**
Merchtem			3,293	**3,293**
Gramme				**0**
Krimpen			3,166	**3,166**
Maastricht			1,471	**1,471**
Zwolle				**0**
Total	**16,604**	**19,584**	**7,929**	**44,117**

- **Investment With EU-ETS**

MW	France	Merchtem	Total
Wind		2,596	**2,596**
Nuclear	26,642		**26,642**
Total	**26,642**	**2,596**	**29,238**

Assumptions of the Case I

We modify the reference case and suppose:

1. Market segmentation between industrial and small consumers;
2. Capacity splitting between industrial and small consumers;
3. Application of average cost based prices (single and nodal) to industrial consumers;
4. Application of short-run marginal cost prices to small consumers;
5. Old and new installations have identical cost structures

Results of the Single Average Cost Price Model

Single Average Cost Price

- **Single Average Cost Price**

Cost components	**€/MWh**
Fuel	6.63
Transmission	−4.48*
Emission	5.41
Fixed costs	20.50
Average cost price	**28.06**

∗ Transmission costs are negative because they are given by the sum of negative values. These negative values are influenced both by the PTDF signs and by flow directions (France export to Germany and Belgium which in its turn deliver power to the Netherlands).

Allowance price is 26.55 €/ton

Results of the Single Average Cost Price Model

Electricity Price Comparison (Small Consumers)

- **Relative Changes in Small Consumers' Electricity Prices (Summer)**

SUMMER			
€/MWh	**Reference case**	**Single Average cost**	**Relative change**
Germany	39.78	44.85	13%
France	4.50	4.50	0%
Merchtem	39.78	38.29	-4%
Gramme	20.49	38.29	87%
Krimpen	44.80	47.09	5%
Maastricht	44.80	47.09	5%
Zwolle	43.15	46.08	7%

- **Relative Changes in Small Consumers' Electricity Prices (Winter)**

WINTER			
€/MWh	**Reference case**	**Single Average cost**	**Relative change**
Germany	44.92	47.80	6%
France	35.66	35.66	0%
Merchtem	44.98	47.09	5%
Gramme	43.44	47.09	8%
Krimpen	45.89	67.71	48%
Maastricht	44.80	55.83	25%
Zwolle	45.20	58.19	29%

Results of the Single Average Cost Price Model

Demand Comparison (Industrial Consumers)

- **Relative Changes in Industrial Consumers' Hourly Demand**

MW	Reference case	Single Average cost	Relative Change
Germany	27,916	38,506	38%
France	27,754	24,057	-13%
Merchtem	4,050	5,591	38%
Gramme	2,223	2,403	8%
Krimpen	2,745	4,114	50%
Maastricht	952	1,405	48%
Zwolle	1,738	2,520	45%
Total	**67,378**	**78,597**	**17%**

Results of the Single Average Cost Price Model

Demand Comparison (Small Consumers)

- **Relative Changes in Small Consumers' Hourly Demand (Summer)**

SUMMER			
MW	**Reference case**	**Single Average cost**	**Relative Change**
Germany	18,991	18,750	-1.3%
France	22,127	22,127	0.0%
Merchtem	1,311	1,316	0.4%
Gramme	587	562	-4.2%
Krimpen	2,915	2,898	-0.6%
Maastricht	695	691	-0.6%
Zwolle	1,160	1,151	-0.7%
Total	**47,784**	**47,494**	**-0.6%**

- **Relative Changes in Small Consumers' Hourly Demand (Winter)**

WINTER			
MW	**Reference case**	**Single Average cost**	**Relative Change**
Germany	48,235	47,883	-1%
France	45,866	45,866	0%
Merchtem	4,523	4,499	-1%
Gramme	1,943	1,925	-1%
Krimpen	7,359	6,952	-6%
Maastricht	1,788	1,738	-3%
Zwolle	2,994	2,895	-3%
Total	**112,707**	**111,757**	**-1%**

Results of the Single Average Cost Price Model

Existing Capacity Dedicated to Industrial Consumers

- **Existing capacity dedicated to industrial consumers**

	Hydro	Wind	Nuclear	Lignite	Coal	CCGT
Germany	73%	54%	51%	51%	21%	0%
France	32%	100%	41%	0%	0%	0%
Merchtem		72%	47%		0%	0%
Gramme	100%	100%	50%		0%	0%
Krimpen		100%	52%		37%	27%
Maastricht		100%				27%
Zwolle		100%			75%	0%
Total	**41%**	**57%**	**44%**	**51%**	**18%**	**6%**

Results of the Single Average Cost Price Model

Investments under the EU-ETS

- **Investments for Small Consumers**

MW	Germany	France	Merchtem	Total
Wind	4,697		295	**4,992**
Nuclear		6,252		**6,252**
Total	**4,697**	**6,252**	**295**	**11,243**

- **Investments for Industrial Consumers**

MW	Germany	France	Merchtem	Gramme	Krimpen	Total
Wind	6,446		5,022	36		**11,504**
Nuclear		14,879				**14,879**
CCGT					14	**14**
Total	**6,446**	**14,879**	**5,022**	**36**	**14**	**26,397**

Results of the Single Average Cost Price Model

Summary

With respect to the investment reference case:

1. Industrial consumers increase their electricity consumption since electricity becomes cheaper;
2. Single average cost pricing system damages small consumers: their electricity prices slightly increase implying a reduction of their electricity consumption;
3. Emission allowance price is higher since the global market demand rises;
4. Investments in new capacity (namely wind and nuclear) are globally higher than in the reference case

Results of the Nodal Average Cost Price Model

Nodal Average Cost Price

- **Nodal Average Cost Price**

€/MWh	Fuel	Emission	Fixed	Average cost price
Germany	9.42	10.22	19.94	**39.58**
France	4.44		13.48	**17.92**
Merchtem	1.15		34.50	**35.65**
Gramme	3.69		18.19	**21.88**
Krimpen	21.47	13.55	15.26	**50.28**
Maastricht	29.02	7.74	23.03	**59.79**
Zwolle	25.73	13.48	17.11	**56.32**

Emission Allowance Price: 21.99 €/ton

Results of the Nodal Average Cost Price Model

Electricity Price Comparison (Industrial Consumers)

- **Relative Changes in Industrial Consumers' Electricity Prices**

	% *Reference**	% *Single***
Germany	-6%	41%
France	3%	-36%
Merchtem	-15%	27%
Gramme	-27%	-22%
Krimpen	11%	79%
Maastricht	33%	113%
Zwolle	28%	101%

∗ Relative changes of nodal average cost prices with respect to the average of those of reference case

∗∗ Relative changes of nodal average cost prices with respect to those of the single average cost price

Results of the Nodal Average Cost Price Model

Electricity Price Comparison (Small Consumers)

- **Relative Changes in Small Consumers' Electricity Prices (Summer)**

SUMMER			
€/MWh	Single Average Cost	Nodal Average Cost	Relative Changes
Germany	44.85	40.49	-10%
France	4.50	4.50	0%
Merchtem	38.29	39.68	4%
Gramme	38.29	29.70	-22%
Krimpen	47.09	45.12	-4%
Maastricht	47.09	39.17	-17%
Zwolle	46.08	41.68	-10%

- **Relative Changes in Small Consumers' Electricity Prices (Winter)**

WINTER			
€/MWh	Single Average Cost	Nodal Average Cost	Relative Changes
Germany	47.80	45.83	-4%
France	35.66	35.66	0%
Merchtem	47.09	45.12	-4%
Gramme	47.09	45.12	-4%
Krimpen	67.71	45.24	-33%
Maastricht	55.83	45.12	-19%
Zwolle	58.19	45.27	-22%

Results of the Nodal Average Cost Price Model

Demand Comparison (Industrial Consumers)

- **Comparison of Industrial Consumers' Hourly Demand**

MW	Reference case	Single Average cost	Nodal Average cost
Germany	27,916	38,506	29,965
France	27,754	24,057	28,755
Merchtem	4,050	5,591	4,774
Gramme	2,223	2,403	2,689
Krimpen	2,745	4,114	2,354
Maastricht	952	1,405	547
Zwolle	1,738	2,520	1,149
Total	**67,378**	**78,597**	**70,234**

Results of the Nodal Average Cost Price Model

Demand Comparison (Industrial Consumers)

- **Relative Changes in Industrial Consumers' Hourly Demand**

	% *Reference**	% *Single**
Germany	7%	-22%
France	4%	20%
Merchtem	18%	-15%
Gramme	21%	12%
Krimpen	-14%	-43%
Maastricht	-43%	-61%
Zwolle	-34%	-54%
Total	**4%**	**-11%**

∗ Relative changes in industrial demand given by the comparison between the reference and the nodal average cost cases

∗∗ Relative changes in industrial demand given by the comparison between the single and the nodal average cost pricing cases

Results of the Nodal Average Cost Price Model

Electricity Demand Comparison (Small Consumers)

- **Relative Changes in Small Consumers' Hourly Demand (Summer)**

MW	Single Average cost	Nodal Average cost	Relative changes
Germany	18,750	18,957	1.1%
France	22,127	22,127	0.0%
Merchtem	1,316	1,311	-0.3%
Gramme	562	574	2.1%
Krimpen	2,898	2,912	0.5%
Maastricht	691	704	2.0%
Zwolle	1,151	1,164	1.1%
Total	**47,494**	**47,750**	**0.5%**

- **Relative Changes in Small Consumers' Hourly Demand (Winter)**

MW	Single Average cost	Nodal Average cost	Relative changes
Germany	47,883	48,123	0.5%
France	45,866	45,866	0.0%
Merchtem	4,499	4,521	0.5%
Gramme	1,925	1,935	0.5%
Krimpen	6,952	7,371	6.0%
Maastricht	1,738	1,787	2.8%
Zwolle	2,895	2,993	3.4%
Total	**111,757**	**112,596**	**0.8%**

Results of the Nodal Average Cost Price Model

Capacity Dedicated to Industrial Consumers

- **Capacity dedicated to industrial consumers**

	Hydro	Wind	Nuclear	Lignite	Coal	CCGT
Germany	77%	98%	66%	40%	30%	0%
France	7%	0%	60%	0%	0%	0%
Merchtem		66%	59%		0%	0%
Gramme	100%	100%	100%		0%	0%
Krimpen		100%	100%		38%	16%
Maastricht		100%				15%
Zwolle		100%			100%	12%
Total	**21%**	**98%**	**63%**	**40%**	**25%**	**6%**

Results of the Nodal Average Cost Price Model

Investment under the EU-ETS

- **Investments for Small Consumers**

MW	France	Merchtem	Total
Wind		821	**821**
Nuclear	26,680		**26,680**
Total	**26,680**	**821**	**27,501**

- **Investments for Industrial Consumers**

MW	France	Merchtem	Gramme	Total
Wind		3,540	451	**3,991**
Nuclear	990			**990**
Total	**990**	**3,540**	**451**	**4,981**

Results of the Nodal Average Cost Price Model

Summary

1. Industrial demand is higher with respect to the reference investment case, but lower with regard to the single average cost case;
2. Electricity prices and consumption of the retail sector is aligned with those of the reference investment case and lower (price) and higher (consumption) in comparison with the single average cost model (small consumers profit from this policy);
3. Emission allowance price is 21.99 €/ton;
4. Investments in new capacity are lower than in the single average cost pricing scenario: this obliges electricity generating companies to exploit more already existing capacity;
5. Global consumers' annual demand is lower than in the single average investment case, but higher than in the reference investment case: this explains the allowance price trend (21.24 €/ton (reference), 26.55 €/ton (single) and 21.99 €/ton (nodal))

Assumptions of the Case II

We modify the Reference Case and suppose:

1. Electricity generating companies supply both industrial and small consumers and apply nodal marginal cost prices;
2. Both electricity and industries may invest in new installations;
3. Industrial consumers face average cost based prices (single and nodal) when they vertically integrate electricity production;
4. Old and new installations have identical cost structures

Results of the Single Average Cost Price Model

Summary

- Industries do not invest and buy electricity from power producers at the marginal cost price;
- Power producers build new wind and nuclear plants for both consumer segments;
- Emission constraint is binding and allowances price is 21.34 €/ton. This is slightly higher than in the reference case (21.24 €/ton) because there is a marginal increase in industrial demand. Small consumers require almost the same amount of electricity

We compare the results of this investment case II with those of the reference investment scenario

Results of the Single Average Cost Price Model

Industrial Consumers' Electricity Prices

- **Industrial Consumers' Electricity Prices (Marginal Prices)**

Nodes	€/MWh
Germany	41.98
France	17.39
Merchtem	41.93
Gramme	30.62
Krimpen	45.04
Maastricht	44.84
Zwolle	43.94

These price are similar (but in average lower) to the average of those of the reference investment case

Results of the Single Average Cost Price Model

Small Consumers' Electricity Prices

- **Small Consumers' Electricity Prices**

€/MWh	Summer	Winter
Germany	39.88	44.96
France	4.50	35.66
Merchtem	39.88	44.84
Gramme	20.59	44.84
Krimpen	44.84	45.33
Maastricht	44.84	44.84
Zwolle	43.21	44.99

Results of the Single Average Cost Price Model

Industrial consumers' Hourly Demand

With respect to the reference investment case, there is a slight increase of the industrial electricity demand

- **Hourly Industrial Demand (MW)**

Nodes	MW
Germany	28,187
France	28,999
Merchtem	4,098
Gramme	2,285
Krimpen	2,769
Maastricht	951
Zwolle	1,750
Total	**69,039**

Results of the Single Average Cost Price Model

Electricity Demand (Small consumers)

- **Small Consumers' Hourly Demand**

MW	Summer	Winter
Germany	18,986	48,229
France	22,127	45,866
Merchtem	1,310	4,525
Gramme	587	1,936
Krimpen	2,914	7,370
Maastricht	694	1,788
Zwolle	1,160	2,995
Total	**47,779**	**112,709**

Small consumers' demand is almost identical to that of the reference investment case

Results of the Single Average Cost Price Model

Investment

- **New capacity built by power companies for small consumers**

MW	France	Merchtem	Total
Wind		1	**1**
Nuclear	4,441		**4,441**
Total	**4,441**	**1**	**4,442**

- **New capacity built by power companies for industrial consumers**

MW	France	Merchtem	Total
Wind		2,995	**2,995**
Nuclear	23,444		**23,444**
Total	**23,444**	**2,995**	**26,439**

Results of the Nodal Average Cost Price Model

Summary

- Results are closed to those of the reference investment case and those of the nodal average cost model with fixed capacity;
- Electricity prices and demands of industrial and small consumers are identical to those of the former single average case;
- Again, industries do not invest and buy electricity from power companies at the marginal cost;
- Power producers invest in nuclear and in wind power stations. The total MW of new capacity built are identical to those of the former single investment case, but they are subdivided in a different way between small and industrial consumers;
- Emission allowance price is still 21.34 €/ton

Results of the Nodal Average Cost Price Model

Industrial Consumers' Electricity Prices

- **Industrial Consumers' Electricity Prices (Marginal Prices)**

Nodes	**€/MWh**
Germany	41.98
France	17.39
Merchtem	41.93
Gramme	30.62
Krimpen	45.04
Maastricht	44.84
Zwolle	43.94

Results of the Nodal Average Cost Price Model

Small Consumers' Electricity Prices

- **Small Consumers' Electricity Prices**

€/MWh	Summer	Winter
Germany	39.88	44.96
France	4.50	35.66
Merchtem	39.88	44.84
Gramme	20.59	44.84
Krimpen	44.84	45.33
Maastricht	44.84	44.84
Zwolle	43.21	44.99

Results of the Nodal Average Cost Price Model

Industrial Consumers' Hourly Demand

- **Industrial Consumers' Hourly Demand**

Nodes	MW
Germany	28,187
France	28,999
Merchtem	4,098
Gramme	2,285
Krimpen	2,769
Maastricht	951
Zwolle	1,750
Total	**69,039**

Results of the Nodal Average Cost Price Model

Small Consumers' Hourly Demand

- **Small Consumers' Hourly Demand**

MW	Summer	Winter
Germany	18,986	48,229
France	22,127	45,866
Merchtem	1,310	4,525
Gramme	587	1,936
Krimpen	2,914	7,370
Maastricht	694	1,788
Zwolle	1,160	2,995
Total	**47,779**	**112,709**

Results of the Nodal Average Cost Price Model

Investments

- **New capacity built by power companies for small consumers**

MW	France
Nuclear	11,379

- **New capacity built by power companies for industrial consumers**

MW	France	Merchtem	Total
Wind		2,996	**2,996**
Nuclear	16,505		**16,505**
Total	**16,505**	**2,996**	**19,502**

Conclusions

We can conclude that:

1. The introduction of the average cost based contract partially relieves industries from the additional burdens caused by the EU-ETS;
2. Investments in new generating capacity increase the efficiency of the market as highlighted by the reduced emission allowance prices.

Appendix: Endogenous Capacity Models

Reference Investment Model

Reference Model

Electricity companies' maximization problem

Each electricity generating company f maximizes its profit:

$$max. \sum_{t,i} p_i^t \cdot g_{f,i}^t \cdot hour^t - \sum_{t,i,m} cost_{f,i,m} \cdot gpc_{f,i,m}^t \cdot hour^t \quad (58)$$

$$- \sum_{t,i,m} fuel_{f,i,m} \cdot gpi_{f,i,m}^t \cdot hour^t - \sum_{i,m} FC\_annual_{f,i,m} \cdot investment_{f,i,m}$$

$$+ \lambda \cdot (NAP_f - \sum_{t,i,m} gpc_{f,i,m}^t \cdot em_m \cdot hour^t - \sum_{t,i,m} gpi_{f,i,m}^t \cdot em_m \cdot hour^t)$$

subject to:

- **Generation balance**

$$\sum_m gpc_{f,i,m}^t + \sum_m gpi_{f,i,m}^t - g_{f,i}^t \geq 0 \qquad (\eta_{f,i}^t) \quad (59)$$

- **Capacity and investment constraints**

$$Cap_{f,i,m} - gpc_{f,i,m}^t \geq 0 \qquad (\nu c_{f,i,m}^t) \quad (60)$$

$$investment_{f,i,m} - gpi_{f,i,m}^t \geq 0 \qquad (\nu i_{f,i,m}^t) \quad (61)$$

Reference Model

Consumers' surplus maximization problem

- **Industry**

$$max. \quad \sum_{t=s,w}\left[hour^t \cdot \int_0^{d_i^{t,1}} P_i^{t,1}(\epsilon)\cdot d\epsilon - hour^t \cdot p_i^t \cdot d_i^{t,1}\right] \quad (62)$$

$$d_i^{s,1} - d_i^{w,1} = 0 \quad (\alpha_i) \quad (63)$$

- **Households**

$$max. \quad hour^t \cdot \int_0^{d_i^{t,2}} P_i^{t,2}(\epsilon)\cdot d\epsilon - hour^t \cdot p_i^t \cdot d_i^{t,2} \quad (64)$$

Reference Model

Global Constraints

- **Market Balance**

$$\sum_{f,i} g^t_{f,i} - \sum_i d^{t,1}_i - \sum_i d^{t,2}_i \geq 0 \quad (phub^t) \tag{65}$$

- **Electricity Prices**

$$p^t_i = p^t + \sum_l (-\mu^{t,+}_l + \mu^{t,-}_l) \cdot PTDF_{l,i} \quad (p^t_i) \tag{66}$$

- **Transmission Constraint**

$$Linecap_l \mp (\sum_i PTDF_{l,i} \cdot (\sum_f g^t_{f,i} - d^{t,1}_i - d^{t,2}_i)) = 0 \quad (\mu^{t,\pm}_l) \tag{67}$$

- **Emission Constraint**

$$E - \sum_{t,f,i,m} gpc^t_{f,i,m} \cdot em_m \cdot hour^t - \sum_{t,f,i,m} gpi^t_{f,i,m} \cdot em_m \cdot hour^t \geq 0 \quad (\lambda) \tag{68}$$

Complementarity Conditions Form of the Reference Case

- **Generators' conditions**

This model is similar (but not identical) to the generators' one with fixed capacity

$$0 \leq -p_i^t + \eta_{f,i}^t \perp g_{f,i}^t \geq 0 \tag{69}$$

$$0 \leq cost_{f,i,m} + em_m \cdot \lambda + \nu_{f,i,m}^t - \eta_{f,i}^t \perp gp_{f,i,m}^t \geq 0 \tag{70}$$

$$0 \leq cost_{f,i,m} + em_m \cdot \lambda + \nu c_{f,i,m}^t - \eta_{f,i}^t \perp gpc_{f,i,m}^t \geq 0 \tag{71}$$

$$0 \leq fuel_{f,i,m} + em_m \cdot \lambda + \nu i_{f,i,m}^t - \eta_{f,i}^t \perp gpi_{f,i,m}^t \geq 0 \tag{72}$$

$$0 \leq Cap_{f,i,m} - gpc_{f,i,m}^t \perp \nu c_{f,i,m}^t \geq 0 \tag{73}$$

$$0 \leq investment_{f,i,m} - gpi_{f,i,m}^t \perp \nu i_{f,i,m}^t \geq 0 \tag{74}$$

$$0 \leq \sum_m gpc_{f,i,m}^t + \sum_m gpi_{f,i,m}^t - g_{f,i}^t \perp \eta_{f,i}^t \geq 0 \tag{75}$$

$$0 \leq FC\_hour_{f,i,m} - \sum_t \nu i_{f,i,m}^t \cdot proportion^t \perp investment_{f,i,m} \geq 0 \tag{76}$$

Complementarity Conditions Form of the Reference Case

- **Industry and Households' conditions (as in the former reference model)**

$$0 \leq p_i^s - \alpha_i - a_i^{s,1} + b_i^{s,1} \cdot d_i^{s,1} \cdot \perp d_i^{s,1} \geq 0 \tag{77}$$

$$0 \leq p_i^w + \alpha_i - a_i^{w,1} + b_i^{w,1} \cdot d_i^{w,1} \cdot \perp d_i^{w,1} \geq 0 \tag{78}$$

$$0 \leq d_i^{s,1} - d_i^{w,1} \perp \alpha_i \geq 0 \tag{79}$$

$$0 \leq p_i^t - a_i^{t,2} + b_i^{t,2} \cdot d_i^{t,2} \perp d_i^{t,2} \geq 0 \tag{80}$$

Complementarity Conditions Form of the Reference Model

- **Market balance equilibrium (as in the former reference model)**

$$0 \leq \sum_{f,i} g_{f,i}^{t} - \sum_{i} d_i^{t,1} - \sum_{i} d_i^{t,2} \perp \;\; phub^t \geq 0 \tag{81}$$

- **Electricity prices (as in the former reference model)**

$$0 \leq p_i^t - phub^t - \sum_{m} (-\mu_l^{t,+} + \mu_l^{t,-}) \cdot PTDF_{l,i} \perp \;\; p_i^t \geq 0 \tag{82}$$

- **Transmission constraints (as in the former reference model)**

$$0 \leq Linecap_l \mp (\sum_{i} PTDF_{l,i} \cdot (\sum_{f} g_{f,i}^{t} - d_i^{t,1} - d_i^{t,2})) \perp \mu_l^{t,\pm} \geq 0 \tag{83}$$

- **Emission constraint (similar, but not identical to the former reference model)**

$$0 \leq E - \sum_{t,f,i,m} gc_{f,i,m}^{t} \cdot em_m \cdot hour_i^t - \sum_{t,f,i,m} gi_{f,i,m}^{t} \cdot em_m \cdot hour_i^t \perp \lambda \geq 0 \tag{84}$$

Single Investment Case I

Single Average Cost Case Model

Single Average Cost Price Formulation

1. **Average production cost ($pprod^1$)**

$$pprod^1 = \frac{(\sum_{f,i,m}(gpc^1_{f,i,m} \cdot (cost_{f,i,m} + em_m \cdot \lambda) \cdot 8760))}{\sum_i d^1_i \cdot 8760} + \frac{(\sum_{f,i,m}(gpi^1_{f,i,m} \cdot (fuel_{f,i,m} + em_m \cdot \lambda) \cdot 8760))}{\sum_i d^1_i \cdot 8760} + \frac{\sum_{f,i,m} FC\_annual_{f,i,m} \cdot G^1_{f,i,m}}{\sum_i d^1_i \cdot 8760} + \frac{\sum_{f,i,m} FC\_annual_{f,i,m} \cdot investment^1_{f,i,m}}{\sum_i d^1_i \cdot 8760}$$

2. **Average transmission cost ($ptrans^1$)**

$$ptrans^1 = \frac{(\sum_{l,i} PTDF_{l,i} \cdot (\sum_f g^1_{f,i} - d^1_i) \cdot 8760 \cdot \sum_t((-\mu^{t,+}_l + \mu^{t,-}_l) \cdot proportion^t))}{\sum_i d^1_i \cdot 8760}$$

Single Average Cost Case Model

Electricity companies' maximization problem (1)

Each electricity generating company f maximizes its profit:

$$
\begin{aligned}
max.\quad & pprod^{1} \cdot \sum_{i} g^{1}_{f,i} \cdot 8760 + \sum_{t,i} p^{t,2}_{i} \cdot g^{t,2}_{f,i} \cdot hour^{t} \qquad (85) \\
& - \sum_{i,m} cost_{f,i,m} \cdot gpc^{1}_{f,i,m} \cdot 8760 - \sum_{i,m} fuel_{f,i,m} \cdot gpi^{1}_{f,i,m} \cdot 8760 \\
& - \sum_{t,i,m} cost_{f,i,m} \cdot gpc^{t,2}_{f,i,m} \cdot hour^{t} - \sum_{t,i,m} fuel_{f,i,m} \cdot gpi^{t,2}_{f,i,m} \cdot hour^{t} \\
& + \lambda \cdot (NAP_{f} - \sum_{i,m} gpc^{1}_{f,i,m} \cdot em_{m} \cdot 8760 - \sum_{i,m} gpi^{1}_{f,i,m} \cdot em_{m} \cdot 8760 \\
& - \sum_{t,i,m} gpc^{t,2}_{f,i,m} \cdot em_{m} \cdot hour^{t} - \sum_{t,i,m} gpi^{t,2}_{f,i,m} \cdot em_{m} \cdot hour^{t}) \\
& - \sum_{i,m} FC\_annual_{f,i,m} \cdot investment^{1}_{f,i,m} - \sum_{i,m} FC\_annual_{f,i,m} \cdot investment^{2}_{f,i,m}
\end{aligned}
$$

Single Average Cost Case Model

Electricity companies' maximization problem (2)

subject to:

$$\sum_m gpc^1_{f,i,m} + \sum_m gpi^1_{f,i,m} - g^1_{f,i} \geq 0 \quad (\eta^1_{f,i}) \tag{86}$$

$$\sum_m gpc^{t,2}_{f,i,m} + \sum_m gpi^{t,2}_{f,i,m} - g^{t,2}_{f,i} \geq 0 \quad (\eta^{t,2}_{f,i}) \tag{87}$$

$$G^1_{f,i,m} - gpc^1_{f,i,m} \geq 0 \quad (\nu c^1_{f,i,m}) \tag{88}$$

$$investment^1_{f,i,m} - gpi^1_{f,i,m} \geq 0 \quad (\nu i^1_{f,i,m}) \tag{89}$$

$$G^2_{f,i,m} - gp^{t,2}_{f,i,m} \geq 0 \quad (\nu c^{t,2}_{f,i,m}) \tag{90}$$

$$investment^2_{f,i,m} - gpi^{t,2}_{f,i,m} \geq 0 \quad (\nu i^{t,2}_{f,i,m}) \tag{91}$$

$$Cap_{f,i,m} - G^1_{f,i,m} - G^2_{f,i,m} \geq 0 \quad (\nu_{f,i,m}) \tag{92}$$

Single Average Cost Case Model

Consumers' surplus maximization problem

- **Industrial consumers**

$$max. \qquad 8760 \cdot \int_0^{d_i^1} P_i^1(\epsilon) \cdot d\epsilon - p^1 \cdot d_i^1 \cdot 8760 \tag{93}$$

- **Small consumers**

$$max. \qquad hour^t \cdot \int_0^{d_i^{t,2}} P_i^{t,2}(\epsilon) \cdot d\epsilon - hour^t \cdot p_i^{t,2} \cdot d_i^{t,2} \tag{94}$$

Single Average Cost Case Model

Global Constraints (1)

- **Market Balance for Small Consumers**

$$\sum_{f,i} g_{f,i}^{t,2} - \sum_{i} d_i^{t,2} = 0 \quad (phub^{t,2}) \tag{95}$$

- **Market Balance for Industrial Consumers**

$$\sum_{f,i} g_{f,i}^{1} - \sum_{i} d_i^{1} = 0 \quad (\beta^{1}) \tag{96}$$

- **Electricity Price for Small Consumers**

$$p_i^{t,2} = phub^{t,2} + (\sum_{l}(-\mu_l^{t,+} + \mu_l^{t,-}) \cdot PTDF_{l,i}) \qquad (p_i^{t,2}) \tag{97}$$

Single Average Cost Case Model

Global Constraints (2)

- **Transmission Constraints**

$$Linecap_l \mp (\sum_i PTDF_{l,i} \cdot (\sum_f g^1_{f,i} + \sum_f g^{t,2}_{f,i} - d^1_i - d^{t,2}_i)) \geq 0 \quad (\mu^{t,\pm}_l) \quad (98)$$

- **Emission Constraint**

$$E - (\sum_{f,i,m} em_m \cdot gpc^1_{f,i,m} \cdot 8760 + \sum_{f,i,m} em_m \cdot gpi^1_{f,i,m} \cdot 8760 + \quad (99)$$

$$+ \sum_{t,f,i,m} em_m \cdot gpc^{t,2}_{f,i,m} \cdot hour^t + \sum_{t,f,i,m} em_m \cdot gpi^{t,2}_{f,i,m} \cdot hour^t) \geq 0 \quad (\lambda)$$

Complementarity Conditions Form of the Single Case I

Small Consumers (1)

- **Small consumers**

$$0 \leq \eta^{t,2}_{f,i} - p^{t,2}_{i} \perp g^{t,2}_{f,i} \geq 0 \tag{100}$$

$$0 \leq cost_{f,i,m} + \lambda \cdot em_{m} + \nu c^{t,2}_{f,i,m} - \eta^{t,2}_{f,i} \perp gpc^{t,2}_{f,i,m} \geq 0 \tag{101}$$

$$0 \leq fuel_{f,i,m} + \lambda \cdot em_{m} + \nu i^{t,2}_{f,i,m} - \eta^{t,2}_{f,i} \perp gpi^{t,2}_{f,i,m} \geq 0 \tag{102}$$

$$0 \leq \sum_{m} gpc^{t,2}_{f,i,m} + \sum_{m} gpi^{t,2}_{f,i,m} - g^{t,2}_{f,i} \perp \eta^{t,2}_{f,i} \geq 0 \tag{103}$$

$$0 \leq G^{2}_{f,i,m} - gpc^{t,2}_{f,i,m} \perp \nu c^{t,2}_{f,i,m} \geq 0 \tag{104}$$

$$0 \leq investment^{2}_{f,i,m} - gpi^{t,2}_{f,i,m} \perp \nu i^{t,2}_{f,i,m} \geq 0 \tag{105}$$

Complementarity Conditions Form of the Single Case I

Small Consumers (2)

$$0 \leq \sum_{f,i} g_{f,i}^{t,2} - \sum_{i} d_i^{t,2} \perp \, phub^{t,2} \geq 0 \tag{106}$$

$$0 \leq p_i^{t,2} - a_i^{t,2} + b_i^{t,2} \cdot d_i^{t,2} \perp \, d_i^{t,2} \geq 0 \tag{107}$$

$$0 \leq p_i^{t,2} - phub^{t,2} - (\sum_{l} (-\mu_l^{t,+} + \mu_l^{t,-}) \cdot PTDF_{l,i}) \perp \, p_i^{t,2} \geq 0 \tag{108}$$

$$0 \leq v_{f,i,m} - \sum_{t} vc_{f,i,m}^{t,2} \cdot proportion^t \perp \, G_{f,i,m}^2 \geq 0 \tag{109}$$

$$0 \leq FC\_hour_{f,i,m} - \sum_{t} \nu i_{f,i,m}^{t,2} \cdot proportion^t \perp \, investment_{f,i,m}^2 \geq 0 \tag{110}$$

Complementarity Conditions Form of the Single Case I

Industrial Consumers (1)

- **Industrial consumers**

$$0 \leq \eta^1_{f,i} - \beta^1 - (\sum_{t,l} proportion^t \cdot (-\mu^{t,+}_l + \mu^{t,-}_l) \cdot PTDF_{l,i}) \perp g^1_{f,i} \geq 0 \quad (111)$$

$$0 \leq cost_{f,i,m} + \lambda \cdot em_m + \nu c^1_{f,i,m} - \eta^1_{f,i} \perp gpc^1_{f,i,m} \geq 0 \quad (112)$$

$$0 \leq fuel_{f,i,m} + \lambda \cdot em_m + \nu i^1_{f,i,m} - \eta^1_{f,i} \perp gpi^1_{f,i,m} \geq 0 \quad (113)$$

$$0 \leq \sum_m gpc^1_{f,i,m} + \sum_m gpi^1_{f,i,m} - g^1_{f,i} \perp \eta^1_{f,i} \geq 0 \quad (114)$$

$$0 \leq G^1_{f,i,m} - gpc^1_{f,i,m} \perp \nu c^1_{f,i,m} \geq 0 \quad (115)$$

$$0 \leq investment^1_{f,i,m} - gpi^1_{f,i,m} \perp \nu i^1_{f,i,m} \geq 0 \quad (116)$$

$$0 \leq \sum_{f,i} g^1_{f,i} - \sum_i d^1_i \perp \beta^1 \geq 0 \quad (117)$$

$$0 \leq p^1 - a^1_i + b^1_i \cdot d^1_i \perp d^1_i \geq 0 \quad (118)$$

Complementarity Conditions Form of the Single Case I

Industrial Consumers (2)

$$0 \le pprod^1 - \frac{(\sum_{f,i,m}(gpc^{t,1}_{f,i,m} \cdot (cost_{f,i,m} + em_m \cdot \lambda) \cdot 8760))}{\sum_i d^1_i \cdot 8760}$$
$$- \frac{(\sum_{f,i,m}(gpi^1_{f,i,m} \cdot (fuel_{f,i,m} + em_m \cdot \lambda) \cdot 8760))}{\sum_i d^1_i \cdot 8760}$$
$$- \frac{\sum_{f,i,m} FC\_annual_{f,i,m} \cdot G^1_{f,i,m}}{\sum_i d^1_i \cdot 8760}$$
$$- \frac{\sum_{f,i,m} FC\_annual_{f,i,m} \cdot investment^1_{f,i,m}}{\sum_i d^1_i \cdot 8760} \perp pprod^1 \ge 0 \quad (119)$$

Complementarity Conditions Form of the Single Case I

Industrial Consumers (3)

$$0 \leq ptrans^1 - \frac{(\sum_{l,i} PTDF_{l,i} \cdot inj_i \cdot 8760 \cdot (-\mu_l^{t,+} + \mu_l^{t,-}) \cdot proportion^t)}{\sum_i d_i^1 \cdot 8760} \perp ptrans^1 \geq 0 \quad (120)$$

$$0 \leq inj_i - \sum_f g_{f,i}^1 + d_i^1 \perp inj_i^1 \geq 0 \quad (121)$$

$$0 \leq p^1 - pprod^1 - ptrans^1 \perp p^1 \geq 0 \quad (122)$$

$$0 \leq FC\_hour_{f,i,m} - \nu i_{f,i,m}^1 \perp investment_{f,i,m}^1 \geq 0 \quad (123)$$

$$0 \leq v_{f,i,m} - vc_{f,i,m}^1 \perp G_{f,i,m}^1 \geq 0 \quad (124)$$

Complementarity Conditions Form of the Single Case I

Global Constraints (2)

- **Transmission Constraints**

$$0 \leq Linecap_l \mp (\sum_i PTDF_{l,i} \cdot (\sum_f g^1_{f,i} + \sum_f g^{t,2}_{f,i} - d^1_i - d^{t,2}_i)) \perp \mu^{t,+}_l \geq 0 \quad (125)$$

- **Global Capacity Constraint**

$$0 \leq Cap_{f,i,m} - G^1_{f,i,m} - G^2_{f,i,m} \perp \nu_{f,i,m} \geq 0 \quad (126)$$

- **Emission Constraint**

$$0 \leq E - (\sum_{f,i,m} em_m \cdot gpc^1_{f,i.m} \cdot 8760 + \sum_{f,i,m} em_m \cdot gpi^1_{f,i.m} \cdot 8760 + \quad (127)$$

$$\sum_{t,f,i,m} em_m \cdot gpc^{t,2}_{f,i.m} \cdot hour^t + \sum_{t,f,i,m} em_m \cdot gpi^{t,2}_{f,i.m} \cdot hour^t) \perp \lambda \geq 0$$

Nodal Investment Case I

Nodal Average Cost Case Model

Nodal Average Cost Price Formulation

The nodal version of the investment Case I is similar to the correspondent single average cost case. We present only the modified formulas:

- **Nodal Average Cost Price**

$$p_i^1 = \frac{(\sum_{f,m}(gpc_{f,i,m}^1 \cdot (cost_{f,i,m} + em_m \cdot \lambda) \cdot 8760))}{d_i^1 \cdot 8760} + \frac{(\sum_{f,m}(gpi_{f,i,m}^1 \cdot (fuel_{f,i,m} + em_m \cdot \lambda) \cdot 8760))}{d_i^1 \cdot 8760} + \frac{\sum_{f,m} FC_{f,m,i} \cdot investment_{f,i,m}^1}{d_i^1 \cdot 8760} + \frac{\sum_{f,m} FC_{f,m,i} \cdot G_{f,i,m}^1}{d_i^1 \cdot 8760}$$

Nodal Average Cost Case Model

Nodal Average Cost Price Model

It is similar to the single average cost pricing model already presented. One has a nodal balance instead of a market balance for the industrial sector as stated by the following equation:

$$\sum_{f} g^{1}_{f,i} - d^{1}_{i} = 0 \quad (\beta^{1}_{i}) \tag{128}$$

Single Investment Case II

Single Average Cost Case Model

Definitions

Specifications

- Industries may buy electricity from power companies paying a marginal price $gen.p_i^1$ in order to cover an amount d_i^1 of their demand;
- Industries may self-produce electricity at the average cost $ind.p^1$ in order to satisfy the proportion $ind.d_i^1$ of their demand;
- All variable defining the industrial consumers' optimization problem have the suffix "*ind*";
- The set "*ii*" used for the variables of industrial problem indicates the node where industries invest in new capacity

Single Average Cost Case Model

Electricity companies' maximization problem

Each electricity generating company f maximizes its profit:

$$
\begin{aligned}
max. \ & \sum_{i} gen.p_i^1 \cdot g_{f,i}^1 \cdot 8760 + \sum_{t,i} p_i^{t,2} \cdot g_{f,i}^{t,2} \cdot hour^t \qquad (129) \\
& - \sum_{i,m} cost_{f,i,m} \cdot gpc_{f,i,m}^1 \cdot 8760 - \sum_{i,m} fuel_{f,i,m} \cdot gpi_{f,i,m}^1 \cdot 8760 \\
& - \sum_{t,i,m} cost_{f,i,m} \cdot gpc_{f,i,m}^{t,2} \cdot hour^t - \sum_{t,i,m} fuel_{f,i,m} \cdot gpi_{f,i,m}^{t,2} \cdot hour^t \\
& + \lambda \cdot (NAP_f - \sum_{i,m} gpc_{f,i,m}^1 \cdot em_m \cdot 8760 - \sum_{i,m} gpi_{f,i,m}^1 \cdot em_m \cdot 8760 \\
& - \sum_{t,i,m} gpc_{f,i,m}^{t,2} \cdot em_m \cdot hour^t - \sum_{t,i,m} gpi_{f,i,m}^{t,2} \cdot em_m \cdot hour^t) \\
& - \sum_{i,m} FC\_annual_{f,i,m} \cdot investment_{f,i,m}^1 - \sum_{i,m} FC\_annual_{f,i,m} \cdot investment_{f,i,m}^2
\end{aligned}
$$

Single Average Cost Case Model

Electricity companies' maximization problem (2)

subject to:

$$\sum_m gpc^1_{f,i,m} + \sum_m gpi^1_{f,i,m} - g^1_{f,i} \geq 0 \quad (\eta^1_{f,i}) \tag{130}$$

$$\sum_m gpc^{t,2}_{f,i,m} + \sum_m gpi^{t,2}_{f,i,m} - g^{t,2}_{f,i} \geq 0 \quad (\eta^{t,2}_{f,i}) \tag{131}$$

$$G^1_{f,i,m} - gpc^1_{f,i,m} \geq 0 \quad (\nu c^1_{f,i,m}) \tag{132}$$

$$investment^1_{f,i,m} - gpi^1_{f,i,m} \geq 0 \quad (\nu i^1_{f,i,m}) \tag{133}$$

$$G^2_{f,i,m} - gp^{t,2}_{f,i,m} \geq 0 \quad (\nu c^{t,2}_{f,i,m}) \tag{134}$$

$$investment^2_{f,i,m} - gpi^{t,2}_{f,i,m} \geq 0 \quad (\nu i^{t,2}_{f,i,m}) \tag{135}$$

$$Cap_{f,i,m} - G^1_{f,i,m} - G^2_{f,i,m} \geq 0 \quad (\nu_{f,i,m}) \tag{136}$$

Single Average Cost Case Model

Single Average Cost Price

This is the single average cost price faced by industries when they self-produce electricity

- **Average Production Cost**

$$ind.pprod^1 = \frac{8760 \cdot (\sum_{i,ii,m}(ind.gp^1_{i,ii,m} \cdot (fuel_{i,ii,m} + em_m \cdot \lambda)))}{\sum_i ind.d^1_i \cdot 8760} + \frac{\sum_{i,ii,m} FC\_annual_{i,ii,m} \cdot ind.investment^1_{i,ii,m}}{\sum_i ind.d^1_i \cdot 8760}$$

- **Average Transmission Cost**

$$ind.ptrans^1 = \frac{(\sum_{l,ii} PTDF_{l,ii} \cdot (ind.inj_{ii} \cdot 8760) \cdot (\sum_t(-\mu_l^{t,+} + \mu_l^{t,-}) \cdot proportion^t))}{\sum_i ind.d^1_i \cdot 8760}$$

- **Single Average Cost Price**

$$ind.p^1 = ind.pprod^1 + ind.ptrans^1$$

Single Average Cost Case Model

Industrial consumers' optimization problem

- **Industrial consumers' optimization problem**

$$max. \sum_{t,ii} 8760 \cdot ind.pprod^1 \cdot ind.g^1_{i,ii} - \sum_{ii,m} fuel_{i,ii,m} \cdot ind.gp^1_{i,ii,m} \cdot 8760 \qquad (137)$$

$$- \sum_{ii,m} ind.gp^1_{i,ii,m} \cdot em_m \cdot \lambda \cdot 8760 - \sum_{ii,m} FC\_annual_{i,ii,m} \cdot ind.investment^1_{i,ii,m}$$

subject to:

$$\sum_{m} ind.gp^1_{i,ii,m} - ind.g^1_{i,ii} \geq 0 \quad (ind.\eta^1_{i,ii}) \qquad (138)$$

$$ind.investment^1_{i,ii,m} - ind.gp^1_{i,ii,m} \geq 0 \quad (ind.\nu^1_{i,ii,m}) \qquad (139)$$

Single Average Cost Case Model

Consumers' surplus optimization problem (1)

- **Small consumers:**

$$max. \qquad hour^t \cdot \int_0^{d_i^{t,2}} P_i^{t,2}(\epsilon) \cdot d\epsilon - hour^t \cdot p_i^{t,2} \cdot d_i^{t,2} \tag{140}$$

Single Average Cost Case Model

Consumers' surplus optimization problem (2)

- **Industrial consumers:**

$$max. \qquad 8760 \cdot \int_0^{tot.d_i^1} P_i^1(\epsilon) \cdot d\epsilon - 8760 \cdot tot.p_i^1 \cdot tot.d_i^1 \quad (tot.d_i^1) \tag{141}$$

where

$$tot.d_i^1 = ind.d_i^1 + d_i^1 \tag{142}$$

$$tot.p_i^1 - ind.p^1 = 0 \tag{143}$$

$$tot.p_i^1 - gen.p_i^1 = 0 \tag{144}$$

Single Average Cost Case Model

Global constraints (1)

- **Market balance equilibrium for small consumers (supplied by power producers)**

$$\sum_{f,i} g_{f,i}^{t,2} - \sum_{i} d_i^{t,2} = 0 \quad (phub^{t,2}) \tag{145}$$

- **Small consumers' electricity prices (set by power producers)**

$$p_i^{t,2} = phub^{t,2} + (\sum_{l} (-\mu_l^{t,+} + \mu_l^{t,-}) \cdot PTDF_{l,i}) \tag{146}$$

Single Average Cost Case Model

Global constraints (3)

- **Market balance equilibrium for industrial consumers (supplied by power producers)**

$$\sum_{f,i} g^1_{f,i} - \sum_i d^1_i = 0 \quad (gen.phub^1) \tag{147}$$

- **Industrial consumers' electricity prices (set by power producers)**

$$gen.p^1_i = gen.phub^1 + (\sum_{t,l} proportion^t \cdot (-\mu^{t,+}_l + \mu^{t,-}_l) \cdot PTDF_{l,i}) \tag{148}$$

- **Market balance equilibrium (industrial self-production)**

$$\sum_{ii,i} ind.g^1_{ii,i} - \sum_i ind.d^1_i = 0 \quad (ind.\beta^1) \tag{149}$$

Single Average Cost Case Model

Global constraints (3)

- **Transmission constraints**

$$Linecap_l \mp (\sum_i PTDF_{l,i} \cdot (\sum_f g_{f,i}^1 + \sum_{ii} ind.g_{ii,i}^1 + \sum_f g_{f,i}^{t,2} + -d_i^1 - ind.d_i^1 - d_i^{t,2})) \geq 0 \quad (\mu_l^{t,\pm}) \tag{150}$$

- **Emission constraint**

$$E - (\sum_{f,i,m} em_m \cdot gpc_{f,i,m}^1 \cdot 8760 + \sum_{f,i,m} em_m \cdot gpi_{f,i,m}^1 \cdot 8760 + \sum_{t,f,i,m} em_m \cdot gpc_{f,i,m}^{t,2} \cdot hour^t + \sum_{t,f,i,m} em_m \cdot gpi_{f,i,m}^{t,2} \cdot hour^t + \sum_{i,ii,m} em_m \cdot ind.gp_{i,ii,m}^1 \cdot 8760) \geq 0 \quad (\lambda) \tag{151}$$

Complementarity Conditions Form of the Single Case II

Specification

Specification

- Complementarity conditions of small consumers' problem in investment Case I and II are identical. We omit to report them;
- The same reasoning holds for power companies. One has just to replace the average cost based cost with the marginal one;
- We focus our attention on industrial consumers' problem and global constraints

Complementarity Conditions Form of the Single Case II

Industrial Consumers' Optimization Problem (1)

- **Industries self-produce electricity**

$$0 \leq -ind.\beta^1 - (\sum_{t,l}(-\mu_l^{t,+} + \mu_l^{t,-}) \cdot proportion_t \cdot PTDF_{l,i}) + ind.\eta^1_{i,ii} \perp ind.g^1_{i,ii} \geq 0 \quad (152)$$

$$0 \leq fuel_{i,ii,m} + \lambda \cdot em_m + ind.\nu^1_{i,ii,m} - ind.\eta^1_{i,ii} \perp ind.gp^1_{i,ii,m} \geq 0 \quad (153)$$

$$0 \leq ind.investment^1_{i,ii,m} - ind.gp^1_{i,ii,m} \perp ind.\nu^1_{i,ii,m} \geq 0 \quad (154)$$

$$0 \leq \sum_m ind.gp^1_{i,ii,m} - ind.g^1_{i,ii} \perp ind.\eta^1_{i,ii} \geq 0 \quad (155)$$

$$0 \leq \sum_{ii} ind.g^1_{i,ii} - \sum_i ind.d^1_i \perp ind.\beta^1 \geq 0 \quad (156)$$

Complementarity Conditions Form of the Single Case II

Industrial Consumers' Optimization Problem (2)

- **Single Average Cost Price**

$$0 \leq ind.pprod^1 - \frac{(\sum_{i,ii,m}(8760 \cdot ind.gp^1_{i,ii,m} \cdot (fuel_{i,ii,m} + em_m \cdot \lambda)))}{\sum_i ind.d^1_i \cdot 8760} - \frac{\sum_m FC\_annual_{i,ii,m} \cdot ind.investment^1_{i,ii,m})}{ind.d^1_i \cdot 8760} \perp \sum_i ind.pprod^1 \geq 0 \quad (157)$$

$$0 \leq ind.ptrans^1 - \frac{(\sum_{t,l,ii}(-\mu_l^{t,+} + \mu_l^{t,-}) \cdot proportion^t \cdot PTDF_{l,ii} \cdot ind.inj^1_{ii}) \cdot 8760}{\sum_i ind.d^1_i \cdot 8760} \perp ind.ptrans^1 \geq 0 \quad (158)$$

$$0 \leq ind.p^1 - ind.pprod^1 - ind.ptrans^1 \perp ind.p^1_i \geq 0$$

$$ind.inj^1_{ii} = \sum_i ind.g^1_{i,ii} - ind.d^1_{ii} \quad (159)$$

$$0 \leq FC\_hour\_i, ii, m - ind.\nu^1_{i,ii,m} \perp ind.investment^1_{i,ii,m} \geq 0 \quad (160)$$

Complementarity Conditions Form of the Single Case II

Industrial Demand

- **Global Industrial Demand**

$$0 \leq tot.d_i^1 - ind.d_i^1 - d_i^1 \perp tot.p_i^1 \geq 0 \tag{161}$$

$$0 \leq tot.p_i^1 - a_i^1 + b_i^1 \cdot tot.d_i^1 \perp tot.d_i^1 \geq 0 \tag{162}$$

$$0 \leq tot.p_i^1 - ind.p^1 \perp ind.d_i^1 \geq 0 \tag{163}$$

$$0 \leq tot.p_i^1 - p_i^1 \perp d_i^1 \geq 0 \tag{164}$$

Complementarity Conditions Form of the Single Case II

Global Constraints

- **Transmission Constraints**

$$0 \leq Linecap_l \mp (\sum_i PTDF_{l,i} \cdot (\sum_f g^1_{f,i} + \sum_{ii} ind.g^1_{i,ii} + \sum_f g^{t,2}_{f,i} \tag{165}$$

$$-d^1_i - ind.d^1_i - d^{t,2}_i) \perp \mu^{t,+\pm}_l \geq 0$$

- **Emission Constraint**

$$0 \leq E - (\sum_{f,i,m} em_m \cdot gpc^1_{f,i,m} \cdot 8760 + \sum_{f,i,m} em_m \cdot gpi^1_{f,i,m} \cdot 8760 + \tag{166}$$

$$\sum_{t,f,i,m} em_m \cdot gpc^{t,2}_{f,i,m} \cdot hour^t + \sum_{t,f,i,m} em_m \cdot gpi^{t,2}_{f,i,m} \cdot hour^t +$$

$$\sum_{i,ii,m} em_m \cdot ind.gp^1_{i,ii,m} \cdot 8760) \perp \lambda \geq 0$$

Nodal Investment Case II

Nodal Average Cost Case Model

Nodal Average Cost Price Formulation

This nodal average cost scenario is similar to the single investment Case II model. We show only the changed conditions:

- **Nodal Average Cost Price**

$$ind.p_i^1 = \frac{(\sum_m (ind.gp_{i,m}^1 \cdot (fuel_{i,m} + em_m \cdot \lambda)))}{ind.d_i^1 \cdot 8760} +$$

$$\frac{\sum_m FC\_annual_{i,m} \cdot ind.investment_{i,m}^1)}{ind.d_i^1 \cdot 8760}$$

Nodal Average Cost Case Model

Industrial Consumers' Optimization Problem

- **Industrial consumers' optimization problem**

$$max. \sum_m 8760 \cdot p_i^1 \cdot gp_{i,m}^1 - \sum_m fuel_{i,m} \cdot ind.gp_{i,m}^1 \cdot 8760 \tag{167}$$

$$- \sum_m gp_{i,m}^1 \cdot em_m \cdot 8760 - \sum_{ii,m} FC\_annual_{i,m} \cdot ind.investment_{i,m}^1$$

subject to:

$$ind.investment_{i,m}^1 - ind.gp_{i,m}^1 \geq 0 \quad (ind.\nu_{i,m}^1) \tag{168}$$

Nodal Average Cost Case Model

Consumers' surplus optimization problem

- **Industrial consumers:**

$$max. \qquad 8760 \cdot \int_0^{tot.d_i^1} P_i^1(\epsilon) \cdot d\epsilon - 8760 \cdot tot.p_i^1 \cdot tot.d_i^1 \quad (tot.d_i^1) \tag{169}$$

where

$$tot.d_i^1 = ind.d_i^1 + d_i^1 \tag{170}$$

$$tot.p_i^1 - ind.p_i^1 = 0 \tag{171}$$

$$tot.p_i^1 - gen.p_i^1 = 0 \tag{172}$$

Nodal Average Cost Case Model

Global Constraints

- **Market balance equilibrium (industrial self-production)**

$$\sum_{m} ind.gp^{1}_{i,m} - ind.d^{1}_{i} = 0 \quad (ind.\beta^{1}_{i}) \tag{173}$$

- **Transmission constraints**

$$Linecap_{l} \mp (\sum_{i} PTDF_{l,i} \cdot (\sum_{f} g^{1}_{f,i} + \sum_{f} g^{t,2}_{f,i} - d^{t,1}_{i} - d^{t,2}_{i})) \geq 0 \quad (\mu^{t,\pm}_{l}) \tag{174}$$