# Developments in network charging: Generalized merit order and locational pricing

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# Motivation

Two lines of institutional reforms can be observed in European energy policy:

(1) market liberalization and competitive decentralized electricity generators. Market liberalization opens up possibilities for decentralized, competitive generators of renewable energy.

(2) Changes in the architecture of smart electricity systems encompass the growing importance of the interaction of distribution networks with microgrids. Make or buy decisions to build and operate a smart grid platform as well as decisions to extract and inject electricity from an electricity network should take into account the node-specific opportunity costs imposed on electricity networks by injection or extraction.

# Disaggregated nodal pricing (1)

In contrast to integrated nodal pricing reflecting the total value of electricity consisting of generation and transmission costs at different nodes, disaggregated nodal pricing consists of three separate elements:

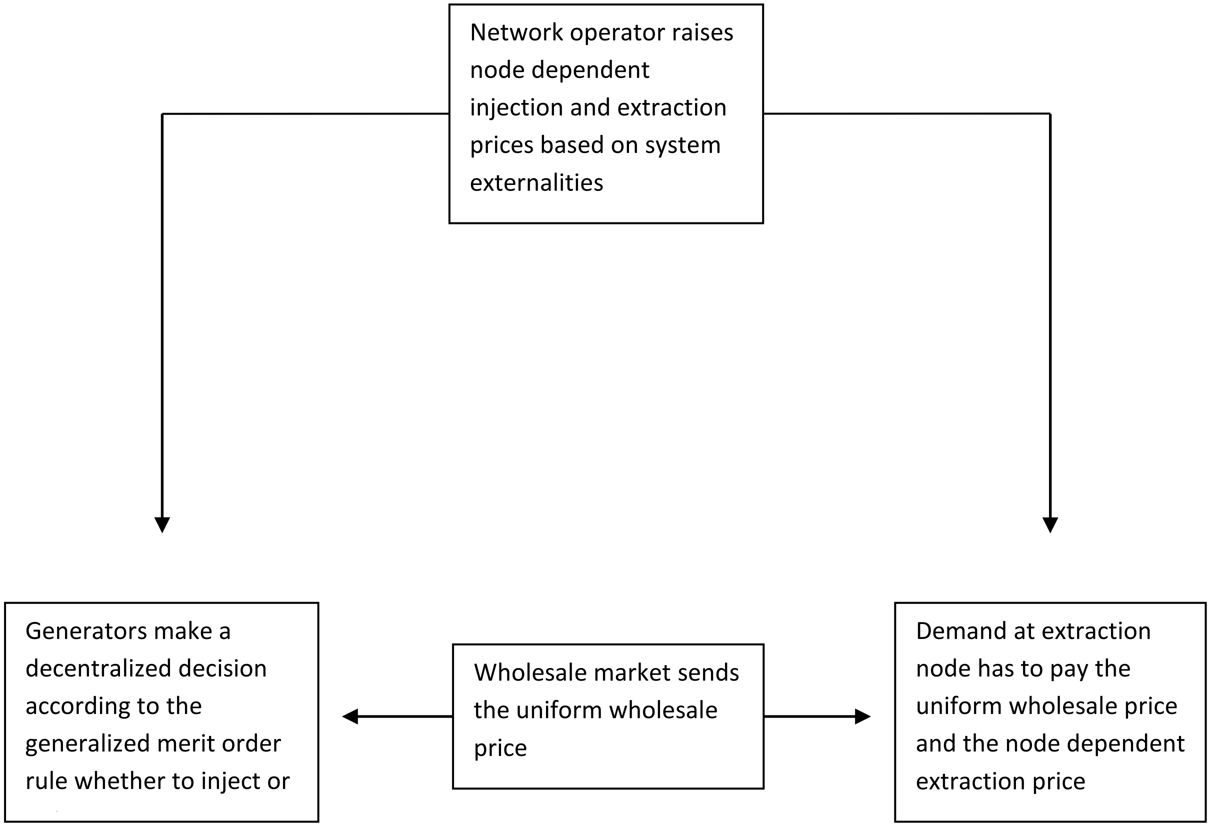
Firstly: electricity transmission prices raised by the network carrier, consisting of node-dependent injection and extraction prices based on system externalities. System externalities changing power loss and network scarcity are the opportunity costs of electricity injection or extraction depending on the node (location) where generation or extraction takes place.

# Disaggregated nodal pricing (2)

Secondly: the generalized merit order indicating at which nodes injection is worthwhile so that generation costs and injection price do not exceed marginal willingness to pay on the wholesale market.

Thirdly: nodal prices at extraction nodes reflecting the sum of the (uniform) wholesale price and node-dependent extraction price.

# Disaggregated nodal pricing framework



# The principle of decentralized interaction between different network levels

| Injection on different levels | | Wholesale markets | Retail market |
|---|---|---|---|
| → | Transmission network | High voltage electricity | |
| | ↓↑ | | |
| → | Distribution network | Medium voltage electricity | |
| | ↓↑ | | |
| → | Microgrid/ local network | | Low voltage electricity |

# Incentives for microgrids

- If willingness to pay within a microgrid is lower than the wholesale market price of the distribution network, it is worthwhile for the microgrid to sell electricity to the wholesale market.
- If microgrid demand exceeds microgrid generation, it is worthwhile to import electricity from the distribution wholesale market, as long as willingness to pay exceeds the distribution wholesale market price plus the injection charge at the microgrid node.
- Import into the microgrid only takes place if microgrid demand exceeds microgrid generation. Otherwise, due to arbitrage conditions, it is possible to use microgrid generated electricity at opportunity costs equal to the distribution wholesale price thereby saving the injection charge at the microgrid node.

# Disaggregated nodal pricing and market power regulation

A natural behavioral assumption is that electricity transmission network carriers do not maximize social welfare but maximize their monopolistic profit.

Disaggregated nodal pricing is considered under the profit maximizing objective function. The network owner provides disaggregated nodal pricing signals to two sides: to the different generators located at the (net) injection nodes and to the different consumers located at the (net) extraction nodes. Since the consumers, via the wholesale market price, (implicitly) also pay the injection price, the network monopolist will avoid the fallacy of double marginalization.

# Regulatory fallacies

Regulation of network-specific market power due to the monopolistic bottleneck of electricity networks should be based on incentive regulation. Price cap regulation of transmission price levels should be applied, with entrepreneurial flexibility regarding injection and extraction pricing structures.

Market power regulation of electricity transmission networks should not intervene in disaggregated nodal pricing structures.

Regulation of network pricing structures (in particular the legal prohibition of electricity injection prices) or regulatory obligations to invest in network capacities should be avoided.

# References

Knieps, G. (2013), Renewable energy, efficient electricity networks and sector-specific market power regulation in: F.P. Sioshansi (Ed.), Evolution of Global Electricity Markets: New Paradigms, New Challenges New Approaches, Elsevier, Amsterdam et al.,147-168

Knieps, G. (2016), The Evolution of Smart Grids Begs Disaggregated Nodal Pricing, in: F. Sioshansi (Ed.), Future of Utilities - Utilities of the Future: How Technological Innovations in Distributed Energy Resources will Reshape the Electric Power Sector, Academic Press/Elsevier, Amsterdam et al., 267-280

# Appendix

The model

# The disaggregated model framework (1)

It is assumed that the electricity transmission network of a typical network provider consists of an exogenously given number of *H* lines. All lines are connected, building a transmission network between all nodes (net injection nodes and net extraction nodes).

# The disaggregated model framework (2)

Marginal generation costs at net injection node *j* are assumed to be constant

| | | |
|---|---|---|
| $\lambda_j$ | $j = 1, \dots, J$ | exogenously given |
| $w_i$ | | infrastructure size (capacity) of each line *i*, *i* = 1, …, *H* |
| $w = (w_1, \dots, w_H)$ | | vector of transmission network infrastructure investment |
| $g_t = (g_{1t}, \dots, g_{Jt})$ | | net injection in node *j* = 1, …, *J* |
| $d_t = (d_{1t}, \dots, d_{Kt})$ | | net extraction in node *k* = 1, …, *K* |
| $z_{it}(g_t, d_t, w)$ | | power flow on line *i* in period *t*, *i = 1, …, H* |

# The disaggregated model framework (3)

Electricity injection in nodes *j* may increase or decrease the power flows on different lines, because opposing flows are cancelling each other out, the same holds also for electricity extraction in nodes *k*:

$\frac{\partial z_{it}}{\partial g_{jt}} > 0$ increasing injection results in increased power flow on line *i*

$\frac{\partial z_{it}}{\partial g_{jt}} < 0$ increasing injection results in decreased power flow on line *i*

$\frac{\partial z_{it}}{\partial d_{kt}} > 0$ increasing extraction results in increased power flow on line *i*

$\frac{\partial z_{it}}{\partial d_{kt}} < 0$ increasing extraction results in decreased power flow on line *i*

# The disaggregated model framework (4)

$z_t = (z_{1t}, \ldots, z_{Ht})$ vector of power flows along each line in period *t*

$w_i$ is assumed to be a continuous variable (scalar), with no indivisibilities

$\rho(w_i)$ investment costs of $w_i$

$T$ life time of investment in lines, *t* = 1, …, *T* periods

$\hat{z}_i(w_i) \quad i = 1, \ldots, H$ maximal capacity of line *i* depending on the size of the line

$\frac{\partial \hat{z}_i}{\partial w_i} > 0$ maximal power flow increases with the size of the line (infrastructure capacity)

# The disaggregated model framework (5)

A change in the power flow on line *i* does not only depend on a change in investments on line *i*, but also on a change in investments on all other lines. It is assumed that an increase in investment increases network capacity. The underlying assumption typically applied in network industries is that additional incremental investment is beneficial by reducing congestion externalities and capacity constraints (Schweppe et al., 1988, p. 247).

# The disaggregated model framework (6)

$$\frac{\partial z_{it}}{\partial w_i} < 0; \quad \frac{\partial z_{it}}{\partial w_j} \neq 0 \quad i = 1,\ldots, H$$

$V_t\left(z_{it}(g_t, d_{t,} w)\right)$ power loss on line *i* in period *t*

$V_t(z_t) = \sum_{i=1}^{H} V_t\left(z_{it}(g_t, d_{t,} w)\right)$ power loss of flow $z_t$

$$\frac{\partial V_t(z_t)}{\partial w_i} = \sum_{i=1}^{H} \frac{\partial V_t\left(z_{it}(g_t, d_{t,} w)\right)}{\partial w_i} < 0$$

A marginal increase of investments on line *i* reduces power loss on all lines (electricity always searches the way of lowest resistance).

# The disaggregated model framework (7)

$S(d_{kt}) = \int_0^{d_{kt}} p_{kt}\,\mathrm{d}\widetilde{d_{kt}}$ thus, $\frac{\partial S}{\partial d_{kt}} = p_{kt}$ , $k$ = 1, …, $K$ (exogenously given),

and total consumer surplus of demand on different extraction nodes in period $t$ is :

S($d_t$) = $\sum_{k=1}^{K} S(d_{kt})$, $t$ = 1, …, $T$

# Socially optimal network investments and disaggregated nodal pricing (1)

*(1)* $\max\limits_{g_{kt},d_{jt},w_i} \sum_{t=1}^{T}\left(S(d_t) - \sum_{j=1}^{K} \lambda_j\, g_{jt}\right) - \sum_{i=1}^{L} \rho_i(w_i)$

(2) $z_{it}(g_t, d_t, w) \leq \hat{z}_{it}(w) \qquad i = 1, \ldots L, \quad t = 1, \ldots, \overline{1}$ $\quad | \; \mu_{z_i}(w)$ shadow value of line constraints

(3) $g_t = d_t + V_t(z_t)$ $\quad | \; \theta_{\mathrm{t}}$ shadow value of system balance equation

(4) $L = \sum_{t=1}^{T}\left(S(d_t) - \sum_{j=1}^{K} \lambda_j g_{jt}\right) - \sum_{i=1}^{H} \rho_i(w_i) -$

$\sum_{t=1}^{T}\left(\sum_{i=1}^{H} \mu_{z_{it}}\left(z_{it}(g_t, d_t, w) - \hat{z}_{it}(w)\right) - \theta_t\left(d_t + V_t(z_t) - g_t\right)\right)$

(5) $\frac{\partial L}{\partial g_{jt}} = -\lambda_j - \sum_{i=1}^{H} \mu_{z_{it}} \frac{\partial z_{it}(\cdot, w)}{\partial g_{jt}} - \theta_t\left(-1 + \frac{\partial V_t(z_t)}{\partial g_{jt}}\right) = 0 \qquad j = 1, \ldots, J$

$t = 1, \ldots, T$

# Socially optimal network investments and disaggregated nodal pricing (2)

(6) $$\frac{\partial L}{\partial d_{kt}} = \frac{\partial S}{\partial d_{kt}} - \sum_{i=1}^{H} \mu_{z_{it}} \frac{\partial z_{it}(\ ,w)}{\partial d_{kt}} - \theta_t \left(+1 + \frac{\partial V_t(z_t)}{\partial d_{kt}}\right) = 0 \qquad k = 1, \dots, K \quad t = 1, \dots, T$$

(7) $$\frac{\partial L}{\partial w_i} = -\frac{\partial \rho_i}{\partial w_i} - \sum_{t=1}^{T} \left[\sum_{j=1}^{H} \left(\mu_{z_{it}} \left(\frac{\partial z_{jt}}{\partial w_i} - \frac{\partial \hat{z}_{jt}}{\partial w_i}\right) + \theta_t \frac{\partial V_t(z_t)}{\partial w_i}\right)\right] = 0 \quad i = 1, \dots, H$$

From simultaneous solution of equations (5), (6) and (7) follows:

$g_t^* = (g_{1t}^*, \dots, g_{Kt}^*)$ socially optimal net injection in node *j*, *j* = 1, …, *J*

$d_t^* = (d_{1t}^*, \dots, d_{Jt}^*)$ socially optimal net extraction in node *k*, *k* = 1, …, *K*

$w^* = (w_1^*, \dots, w_L^*)$ socially optimal infrastructure level in line *i*, *i* = 1, …, *H*

# Socially optimal investment rule in electricity networks (1)

From (7) follows:

(8) $$\frac{\partial \rho_i}{\partial w_i} = -\sum_{t=1}^{T}\left[\sum_{j=1}^{H}\left(\mu_{z_{it}}\left(\frac{\partial z_{jt}}{\partial w_i} - \frac{\partial \hat{z}_{jt}}{\partial w_i}\right) + \quad \theta_t \frac{\partial V_t(z_i)}{\partial w_i}\right)\right] \quad i = 1, \ldots H$$

The infrastructure capacity of each line should be extended to the point where the marginal costs of an extra unit of capacity are equal to the marginal benefit through reductions of system externalities (reductions of power loss and alleviations of line flow constraints) on all lines.

# Socially optimal injection and extraction pricing rules at optimal investment level (1)

System externality of injection at node *j* :

$\sum_{i=1}^{H} \mu_{z_{it}} \frac{\partial z_{it}}{\partial g_{jt}}$ impact of marginal increase of injection at node *j* on scarce transmission capacity plus

$\frac{\partial \theta_t V_t(z)}{\partial g_{jt}}$ impact of marginal increase of injection at node *j* on power loss

# Socially optimal injection and extraction pricing rules at optimal investment level (2)

System externalities of extraction at node *k*:

$\sum_{i=1}^{H} \mu_{z_{it}} \frac{\partial z_{it}}{\partial d_{kt}}$ impact of marginal increase of extraction at node *k* on scarce transmission capacity plus

$\frac{\partial \theta_t V_t(z)}{\partial d_{kt}}$ impact of marginal increase of extraction at node *d* on power loss.

Socially optimal injection pricing rule at optimal investment level:

(9) $$\tau_{jt} = \sum_{i=1}^{H} \mu_{z_{it}} \frac{\partial z_{it}(\cdot, w^*)}{\partial g_{jt}} + \theta_t \left( \frac{\partial V_t(z_t)}{\partial g_{jt}} \right) \qquad j = 1, \ldots, J, \qquad t = 1, \ldots, T$$

Socially optimal extraction pricing rule at optimal investment level:

(10) $$\tau_{kt} = \sum_{i=1}^{H} \mu_{z_{it}} \frac{\partial z_{it}(\cdot, w^*)}{\partial d_{kt}} + \theta_t \left( \frac{\partial V_t(z)}{\partial d_{kt}} \right) \qquad k = 1, \ldots, K \qquad t = 1, \ldots, T$$

# The generalized merit order rule and the optimal consumption rule (1)

The network carrier requires injection prices according to opportunity costs of injection

$\tau_{jt}, \qquad j = 1, \ldots, J, \qquad t = 1, \ldots, T$

The wholesale market sends $\theta_t$: Marginal willingness to pay at the system limit (last marginal unit which is served (or just not served)).

From (5) and (9) follows for the marginal most expensive generator:

$$-\lambda_j - \tau_{jt} + \theta_t = 0$$

$$\Rightarrow \quad \theta_t = \lambda_j + \tau_{jt}$$

# The generalized merit order rule and the optimal consumption rule (2)

The generators at a net injection node make a decentralized decision according to the generalized merit order rule, whether to inject or not inject.

$\lambda_1 + \tau_{1t}, \lambda_2 + \tau_{2t}, \ldots, \lambda_J + \tau_{Jt}$

If $\lambda_j + \tau_{jt}, \leq \theta_t$ inject

If $\lambda_j + \tau_{jt}, > \theta_t$ do not inject

# The generalized merit order rule and the optimal consumption rule (3)

Consumers at extraction nodes have to pay the uniform wholesale price and the node-dependent opportunity costs of extraction. The network carrier requires extraction prices according to the opportunity costs of extraction

$\tau_{kt}, \qquad k = 1, \ldots, K\ , \qquad t = 1, \ldots, T$

From (6) follows:

$\frac{\partial S(d_t)}{\partial d_{kt}} - \tau_{kt} - \theta_t = 0 \qquad \frac{\partial S}{\partial d_{kt}}$ exogenously given $k$ = 1, …, $K$

$\Rightarrow \quad p_{kt} \quad = \quad \theta_t \quad + \quad \tau_{kt}$

| $p_{kt}$ | $\theta_t$ | $\tau_{kt}$ |
|---|---|---|
| price for demand in node *k* in period *t* | wholesale price (irrespective at which node generation takes place) | extraction price at node *k* |

# The financial viability problem (1)

Revenues from the socially optimal injection price at optimal investment level:

$$\sum_{j=1}^{J} R\left(\tau_{jt}\right) = \sum_{j=1}^{J} \tau_{jt} g_{jt} =$$

$$\sum_{j=1}^{J} \left[\sum_{i=1}^{H} \mu_{z_{it}} \frac{\partial z_{it}(g_t, d_t, w^*)}{\partial g_{kt}} g_{jt} + \theta_t \left(\frac{\partial V_t(z_t)}{\partial g_{jt}}\right) g_{jt}\right] \quad t = 1, \dots, T$$

Revenues from the socially optimal extraction price at optimal investment level:

$$\sum_{k=1}^{K} R(\tau_{kt}) = \sum_{k=1}^{K} \tau_{kt} d_{kt} =$$

$$\sum_{k=1}^{K} \left[\sum_{i=1}^{H} \mu_{z_{it}} \frac{\partial z_{it}(g_t, d_t, w^*)}{\partial d_{kt}} d_{kt} + \theta_t \left(\frac{\partial V_t(z_t)}{\partial d_{kt}}\right) d_{kt}\right] \quad t = 1, \dots, T$$

# The financial viability problem (2)

Under the assumption that $z_{it}$ and subsequently $V_t$ are homogeneous of degree zero, such that the Euler theorem can be applied, and taking into account the optimal investment rule (8), we obtain :

$$\sum_{t=1}^{T} \sum_{j=1}^{J} \left[ \sum_{i=1}^{H} \mu_{z_{it}} \frac{\partial z_{it}(g_t, d_t, w^*)}{\partial g_{jt}} g_{jt} + \theta_t \left( \frac{\partial V_t(z_t)}{\partial g_{jt}} \right) g_{jt} \right] +$$

$$\sum_{t=1}^{T} \sum_{k=1}^{K} \left[ \sum_{i=1}^{H} \mu_{z_{it}} \frac{\partial z_{it}(g_t, d_t, w^*)}{\partial d_{kt}} d_{kt} + \theta_t \left( \frac{\partial V_t(z_t)}{\partial d_{kt}} \right) d_{kt} \right]$$

$$= - \sum_{t=1}^{T} \left[ w_i^* \sum_{j=1}^{H} \left( \mu_{z_{it}} \left( \frac{\partial z_{jt}}{\partial w_i} - \frac{\partial \hat{z}_{jt}}{\partial w_i} \right) - \theta_t \frac{\partial V_t(z_i)}{\partial w_i} \right) \right] =$$

$$\sum_{i=1}^{H} \frac{\partial \rho_i}{\partial w_i} w_i^*$$

# The financial viability problem (3)

If there are constant returns to scale in infrastructure construction,

then: $\sum_{i=1}^{H} \frac{\partial \rho_i}{\partial w_i} w_i^* = \sum_{i=1}^{H} \rho_i \, (w_i^*)$

With decreasing returns in infrastructure construction:

$$\sum_{i=1}^{H} \frac{\partial \rho_i}{\partial w_i} w_i^* > \sum_{i=1}^{H} \rho_i \, (w_i^*)$$

For increasing returns in infrastructure construction of electricity

transmission networks: $\sum_{i=1}^{H} \frac{\partial \rho_i}{\partial w_i} w_i^* < \sum_{i=1}^{H} \rho_i \, (w_i^*)$

# The profit maximizing transmission network carrier (1)

11) $\max_{g_{kt}, d_{kt}, w_i} \sum_{t=1}^{T} \left( \sum_1^K p_{kt}(d_{kt}) d_{kt} - \sum_{j=1}^{J} \lambda_j \, g_{jt} \right) - \sum_{i=1}^{H} \rho_i(w_i)$

(12) $z_{it}(g_t, d_t, w) \leq \hat{z}_{it}(w) \qquad i = 1, \ldots H, \quad t = 1, \ldots, T \qquad | \; \mu_{z_i}(w)$

(13) $g_t = d_t + V_t(z) \qquad | \; \theta_{\mathrm{t}}$ but only $_{w_i}$ can be influenced

(14) $L = \sum_{t=1}^{T} \left( \sum_1^K p_{kt}(d_{kt}) d_{kt} - \sum_{j=1}^{J} \lambda_j \, g_{jt} \right) - \sum_{i=1}^{H} \rho_i(w_i) -$

$\sum_{t=1}^{T} \sum_{i=1}^{H} \mu_{z_{it}} \big( z_{it}(g_t, d_t, w) - \hat{z}_{it}(w) \big) - \theta_t \left( d_t + V_t(z_t) - g_t \right) \quad t = 1, \ldots, T$

(15) $\frac{\partial L}{\partial g_{jt}} = \lambda_j - \sum_{i=1}^{H} \mu_{z_i} \frac{\partial z_{it}(\cdot, w)}{\partial g_{jt}} - \theta_t \left( -1 + \frac{\partial V_t(z_t)}{\partial g_{jt}} \right) = 0 \qquad j = 1, \ldots, J \quad t = 1, \ldots, T$

(16) $\frac{\partial L}{\partial d_{kt}} = p_{kt} + \frac{\partial p_{kt}}{\partial d_{kt}} d_{kt} - \sum_{i=1}^{H} \mu_{z_{it}} \frac{\partial z_{it}(\;, w)}{\partial d_{kt}} - \theta_t \left( +1 + \frac{\partial V_t(z_t)}{\partial d_{kt}} \right) = 0 \qquad k = 1, \ldots, K$

$t = 1, \ldots, T$

(17) $\frac{\partial L}{\partial w_i} = -\frac{\partial \rho_i}{\partial w_i} - \sum_{t=1}^{T} \left[ \sum_{j=1}^{H} \left( \mu_{z_{it}} \left( \frac{\partial z_{jt}}{\partial w_i} - \frac{\partial \hat{z}_{jt}}{\partial w_i} \right) + \theta_t \frac{\partial V_t(z_t)}{\partial w_i} \right) \right] = 0 \qquad i = 1, \ldots, H$

# The profit maximizing transmission network carrier (2)

Monopolistic mark-up: $a_{kt}^{m} = -\frac{\partial p_{kt}}{\partial d_{kt}} d_{kt}$

The gross monopoly price $p_{k}^{m}$ at the extraction nodes *k* at time *t* can be derived from equation (16) as follows:

$$MR_{kt} = p_{kt} + \frac{\partial p_{kt}}{\partial d_{kt}} d_{kt} = \theta_t + \tau_{kt} = MC_{kt}$$

Thus:

$$\frac{p_{kt}^{m} - MC_{kt}}{p_{kt}^{m}} = -\frac{1}{\varepsilon_{kt}} \quad \text{with } \varepsilon_{kt} = \frac{\partial d_{kt}}{\partial p_{kt}} \frac{p_{kt}}{d_{kt}}$$

$$p_{k}^{m} = \theta_t + \tau_{kt} + a_{kt}^{m} = \theta_t + \tau_{kt}^{m}$$

$\tau_{kt}^{m} = \tau_{kt} + a_{kt}^{m}$ is the monopolistic extraction charge at node *k* in period *t*, characterized by a monopolistic mark-up.

# The profit maximizing transmission network carrier (3)

Compared to social welfare maximization the pricing rule for electricity injection (equation 15) and the investment rule (equation 17) remain unchanged.

From simultaneous solution of equations (15), (16) and (17) follows:

$g_t^m = (g_{1t}^m, \ldots, g_{Kt}^m)$ profit maximizing net injection in node *j*, *j* = 1, …, *J*

$d_t^m = (d_{1t}^m, \ldots, d_{Jt}^m)$ profit maximizing net extraction in node *k*, *k* = 1, …, *K*

$w^m = (w_1^m, \ldots, w_H^m)$ profit maximizing infrastructure level in line *i*, *i* = 1, …, *H*

# The fallacies of investment obligations (1)

Assuming again that the functions $z_t$ (and therefore $V_t$ ) are homogeneous of degree zero, such that Euler´s theorem can be applied, it follows

$$\sum_{t=1}^{T}\sum_{j=1}^{J}\left[\sum_{i=1}^{H}\mu_{z_{it}}\frac{\partial z_{it}(g_t,d_t,w^*)}{\partial g_{jt}}g_{jt}+\ \theta_t\left(\frac{\partial V_t(z_t)}{\partial g_{jt}}\right)g_{jt}\right]+$$

$$\sum_{t=1}^{T}\sum_{k=1}^{K}\left[\sum_{i=1}^{H}\mu_{z_{it}}\frac{\partial z_{it}(g_t,d_t,w^*)}{\partial d_{kt}}d_{kt}+\ \theta_t\left(\frac{\partial V_t(z_t)}{\partial d_{kt}}\right)d_{kt}\right]=\ \sum_{i=1}^{H}\frac{\partial\rho_i}{\partial w_i}\ w_i^*$$

>

$$\sum_{t=1}^{T}\sum_{j=1}^{J}\left[\sum_{i=1}^{H}\mu_{z_{it}}\frac{\partial z_{it}(g_t,d_t,w^m)}{\partial g_{jt}}g_{jt}+\ \theta_t\left(\frac{\partial V_t(z_t)}{\partial g_{jt}}\right)g_{jt}\right]+$$

$$\sum_{t=1}^{T}\sum_{k=1}^{K}\left[\sum_{i=1}^{H}\mu_{z_{it}}\frac{\partial z_{it}(g_t,d_t,w^m)}{\partial d_{kt}}d_{kt}+\ \theta_t\left(\frac{\partial V_t(z_t)}{\partial d_{kt}}\right)d_{kt}\right]=\ \sum_{i=1}^{H}\frac{\partial\rho_i}{\partial w_i}\ w_i^m$$