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Implementation of the Nodal Pricing Regime for Distribution Network Pricing: A Benchmark Model

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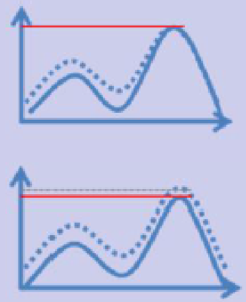
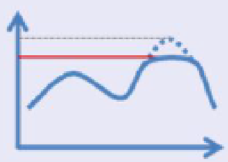
Contents

Current Distribution Pricing Types

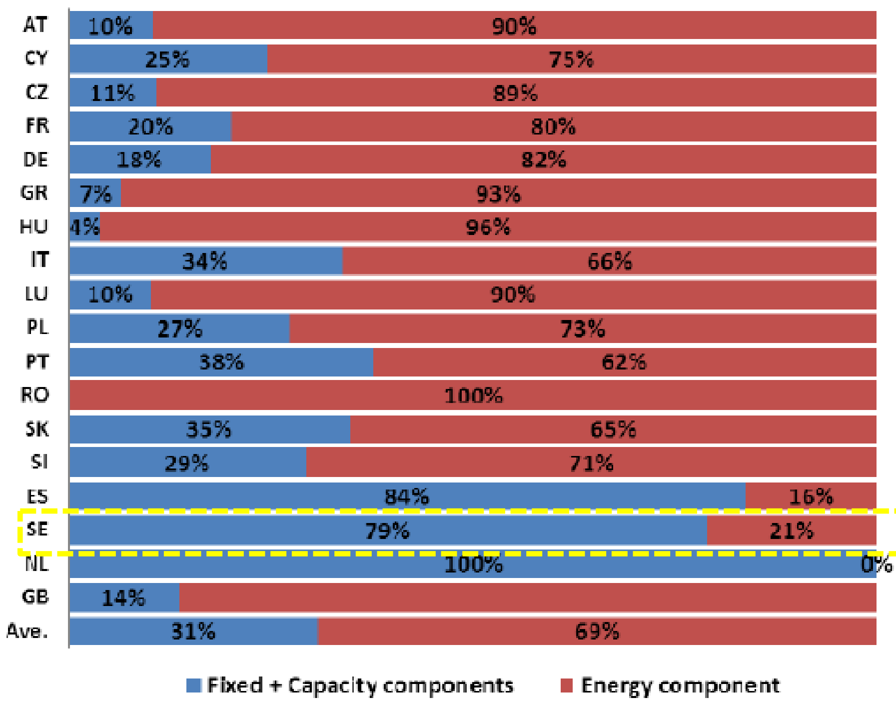
Network tariff type	Options within this approach:
Volumetric tariffs (€/kWh)	1. Flat (fixed price for a fixed amount of energy) 2. Fixed (fixed price per unit of energy/kWh) 3. ToU (price per kWh depends on time of consumption) 4. Event driven including critical peak pricing (higher prices if peak occurs) 5. Dynamic including real time (dynamic prices e.g. depending on wholesale prices)
Capacity tariffs (€/kW)	1. Flat (fixed price for a predefined capacity) 2. Variable – e.g. two capacity levels (different capacity levels defined, one price for each level) 3. ToU (price per kW depends on time of consumption)
Two part tariffs (€/kW) + (€/kWh)	Combination of the above options (for example ToU, event driven, dynamic options possible within the energy component)
One of the above + System services contracts	1. Interruptible tariff options (e.g. lower network tariffs for giving the option to control a predefined amount of load) 2. Other

Impact of Different Pricing Approach

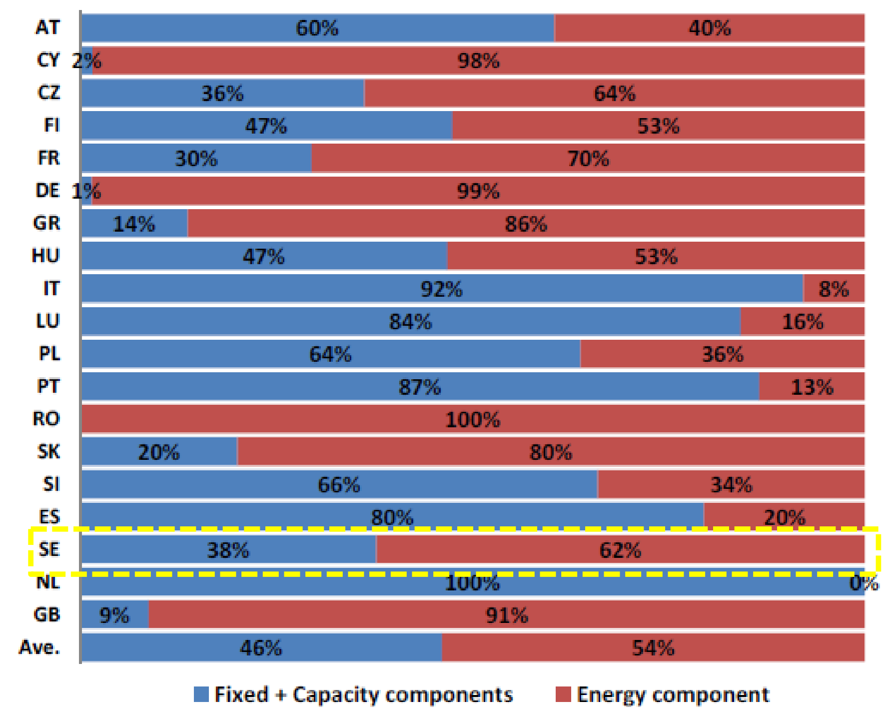
Network Tariff Type	Incentive	Possible Effects on Load	Impact on overall energy consumption reduction	Impact on network costs reduction (losses excluded)	Regulatory trade-off criteria
A. Fixed volumetric (€/kWh)	Reduce overall consumption, regardless of the time		✔ Medium to high – provides incentives for reducing overall consumption, but price signal is lower than time-of-use tariffs	✘ Low	✔ Intelligibility / Acceptability ✘ Economic efficiency ✘ Cost reflectiveness ✘ Revenue adequacy (for DSOs with no ex post adjustment)
B. Capacity based (€/kW)	Reduce peak usage (e.g. not switching multiple appliances at the same time) Shift consumption to off-peak hours		✔ Medium* – incentive is for reducing customer's peak demand, which may also induce reduction of overall consumption **Medium to high for ToU capacity based tariffs*	✔ High – peak demand (consumption during peak-hours) is the major driver for network costs	✔ Intelligibility / Acceptability ✔ Economic efficiency ✔ Cost reflectiveness ✔ Revenue adequacy (for DSOs with no ex post adjustment)
C. Time-of-use volumetric • High €/kWh (peak hours) • Low €/kWh (off-peak hours)	Reduce consumption during peak-hours Shift consumption to off-peak hours		✔ Medium to high – allows for higher prices during peak-hours which encourages higher overall consumption reduction		✔ Economic efficiency ✔ Cost reflectiveness ✘ Revenue adequacy (for DSOs with no ex post adjustment) ✘ Higher tariff complexity
D. Two-part tariff • Power component (€/kW) and • Energy component (€/kWh) (with flat or ToU energy charge)	Reduce peak usage/ Reduce consumption during peak-hours Shift consumption to off-peak hours				✔ Economic efficiency ✔ Cost reflectiveness ✔ Revenue adequacy (for DSOs with no ex post adjustment) ✘ Higher tariff complexity

EU Distribution Tariff Component Weight

Household



Small Industrial

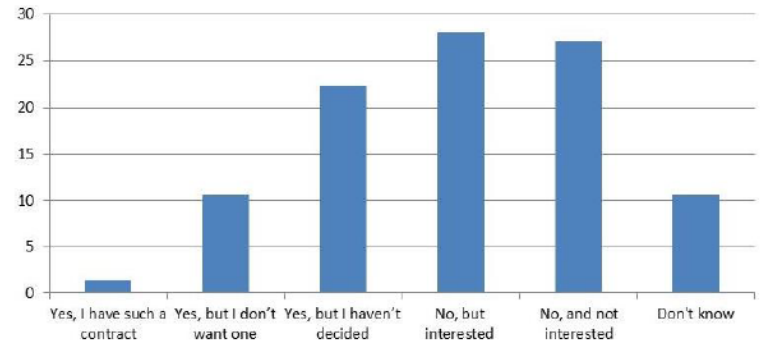


Source: EU energy report

- Capacity component may not support demand shift to off-peak hours

Proved Large Peak Load Reduction vs Small Share of Flexible Consumer

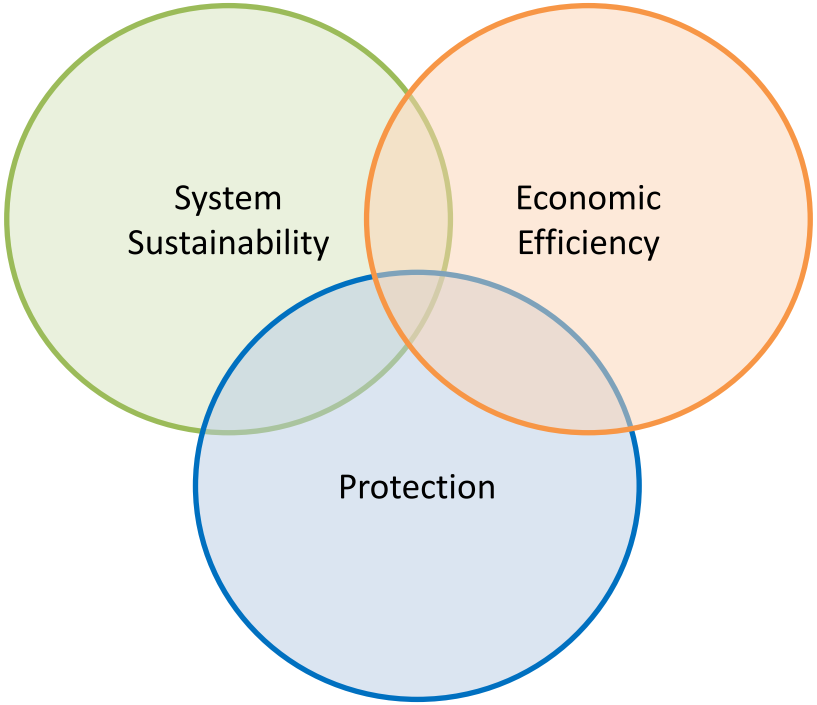
US Load Management - Actual Peak Load Reduction (MW) Data From US Energy Agency					
Year	Residential	Commercial	Industrial	Transportation	Total
2003	3,524	1,864	3,899	11	9,298
2004	3,014	1,652	4,588	9	9,263
2005	3,407	1,544	5,388	2	10,341
2006	3,863	1,730	5,643	32	11,268
2007	4,949	1,837	5,749	10	12,545
2008	4,158	3,270	4,625	12	12,064
2009	3,899	3,464	4,606	3	11,972
2010	4,726	2,854	4,819	137	12,536
2011	4,105	2,808	5,108	105	12,126
2012	4,152	3,208	5,732	108	13,200



Share of households with real-time contracts and if they know that such contracts exist (Data from Ei Report)

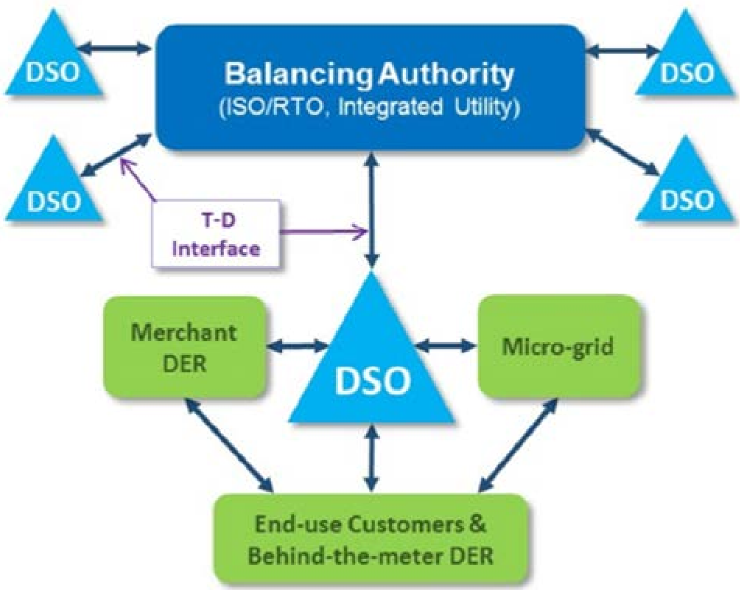
The Energy Efficiency Directive (2012/27/EU, art. 15.4) requires that network tariffs contribute to overall efficiency by providing signals for power saving/optimal utilisation of energy infrastructure assets, including demand side participation.

Principles of Tariff Regulation

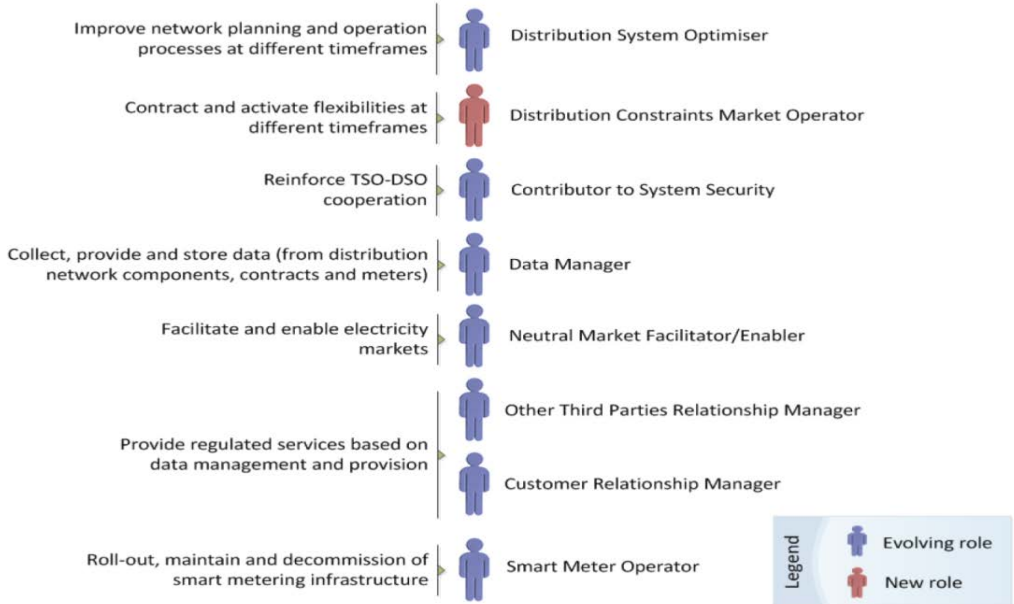


Distribution Grid in Transition

Future Integrated Power System



DSO Roles



- Cooperation between TSO and DSO
- Activate flexibilities of distributed energy resources (DER)

Why Nodal Pricing for Distribution Network?

Nodal Price = marginal energy cost + marginal loss cost + marginal congestion cost

- **Proved economical efficiency for transmission systems** - implemented in New York, New England, PJM, New Zealand, Argentina, and Chile.
- **Solid Theory Foundation** - Efficient consumption and investment decisions require efficient prices reflecting marginal costs.
- **Future Distribution Challenge** - Distribution congestion management due to DG, EV penetration.
- **Combined with RTP** - Convey locational economical signals combined with real time pricing (RTP). RTP is estimated to give 1541 to 1989 million SEK benefits for Sweden.
- **Deploy the Demand Side Flexibility** - Increased demand flexibility can reduce system operating capacity reserve (cost 130 million SEK in 2013, planned to phase out in 2020). Incentives for services from distributed energy resources (production, storage and demand response) in distribution network.
- **Reduce network infrastructure investment.**

Challenges of Nodal Pricing for Distribution Network

- **Computation** – DC optimal power flow (OPF) is not valid for distribution network.
  Solution – Convex AC OPF.

- **Data Management** – Large amount of nodes in distribution network.
  Solution – Generalized Supply Function.

- **Dispatch complexity** – Distributed energy resources.
  Solution – Hierarchical Economic Dispatch.

Convex AC Economic Dispatch

Non-convex Branch Flow Model

$$\text{Minimize} \quad \sum Cost(P_G)$$

$$\text{Subject to} \quad P_G - P_D = A_{nl}P_l - A_{nl}^{'}P_{loss,l}$$

$$Q_G - Q_D = A_{nl}Q_l - A_{nl}^{'}Q_{loss,l}$$

$$V_{sl}^2 - V_{rl}^2 = 2R_lP_{sl} + 2X_lQ_{sl} - R_lP_{loss,l} - X_lQ_{loss,l}$$

$$V_{sl}V_{rl}\sin(\theta_l) = X_lP_{sl} - R_lQ_{sl}$$

$$P_{loss,l} = \frac{P_{sl}^2 + Q_{sl}^2}{V_{sl}^2}R_l$$

$$Q_{loss,l} = \frac{P_{sl}^2 + Q_{sl}^2}{V_{sl}^2}X_l$$

Convex Branch Flow Model

$$\text{Minimize} \quad \sum Cost(P_G)$$

$$\text{Subject to} \quad P_G - P_D = A_{nl}P_l - A_{nl}^{'}P_{loss,l}$$

$$Q_G - Q_D = A_{nl}Q_l - A_{nl}^{'}Q_{loss,l}$$

$$V_{sl}^2 - V_{rl}^2 = 2R_lP_{sl} + 2X_lQ_{sl} - R_lP_{loss,l} - X_lQ_{loss,l}$$

$$\theta_l = X_lP_{sl} - R_lQ_{sl}$$

$$P_{loss,l} \geq \frac{P_{sl}^2 + Q_{sl}^2}{V_{sl}^2}R_l$$

Rotated Cone

$$Q_{loss,l} \geq \frac{P_{sl}^2 + Q_{sl}^2}{V_{sl}^2}X_l$$

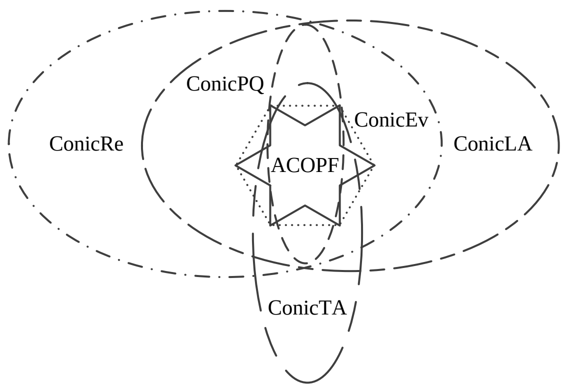
Rotated Cone

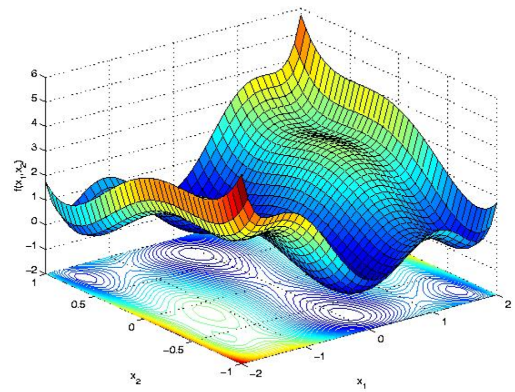
Convex Model Gives Global Optimal Solutions

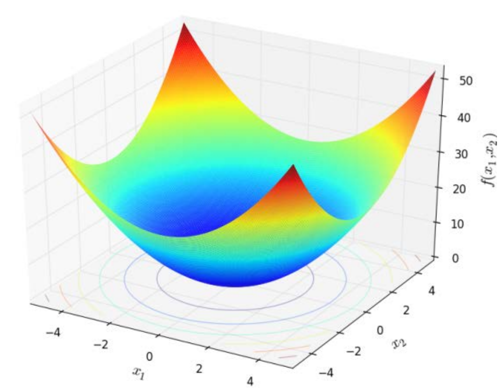
Convex AC Economic Dispatch for Distribution Network

Approach	Advantage
A	Voltage Not Limited to 1 p.u
B	Improved Reactive Power Dispatch
C	Controllable Error
D	Controllable Error
E	Less Parameter Setting Requirement
F	Complete Relaxations

Feasible Region Relationship

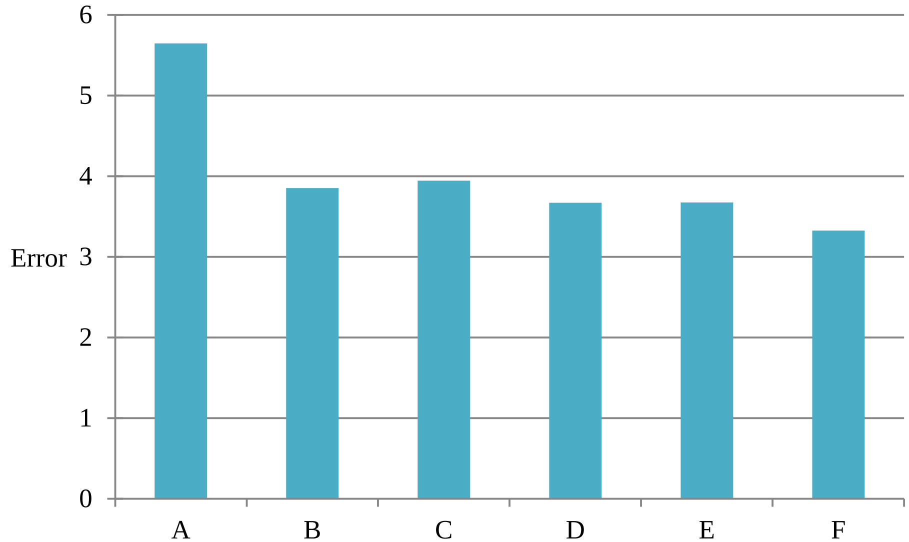






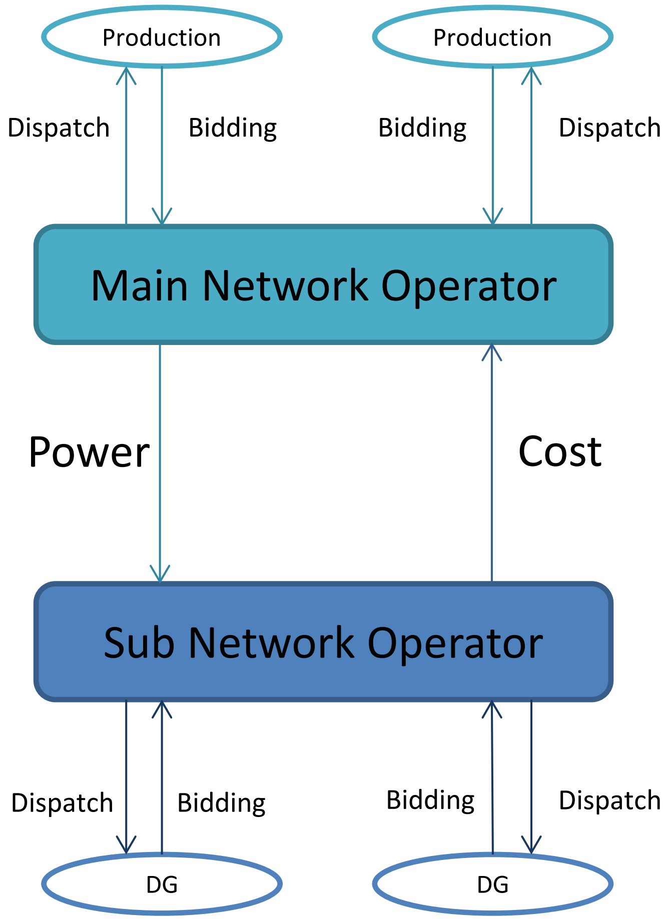
- Convex AC economic dispatch methods are relaxations of AC OPF
- Feasible solution means global optimization achieved
- No feasible solution means not solvable AC OPF.

Convex AC Economic Dispatch Performance

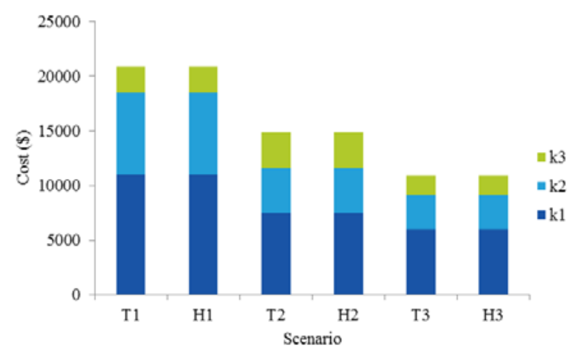


Test Cases : IEEE13, 69, 57, 118, 300.
Bench marked by matlab power system analysis tool (PSAT).
Error is Normalized for results of active power, reactive power, nodal price and final dispatch cost.
All errors of active power are less than 10^{-8}

Hierarchical Economic Dispatch



- TSO and DISO Coordination
- Active Distribution System Management
- Increasing DG
- Growing Prosumers, EV
- Dispatch Complexity
- Locational Marginal Prices for Distribution Network



Same Results with Centralized Dispatch [1]

[1] Zhao Yuan and Mohammad Reza Hesamzadeh, A Hierarchical Dispatch Structure for Distribution Network Pricing, 15 IEEE International Conference on Environment and Electrical Engineering

Bender's Decomposition

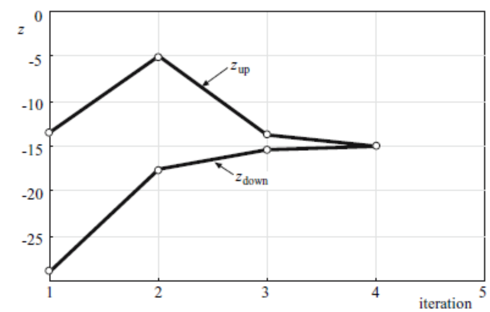
Main-Network
Minimize f(x)+z
Subject to x∈X, z>g(x, y)

Minimize f(x, y)
Subject to x∈X, y∈Y

x'

y

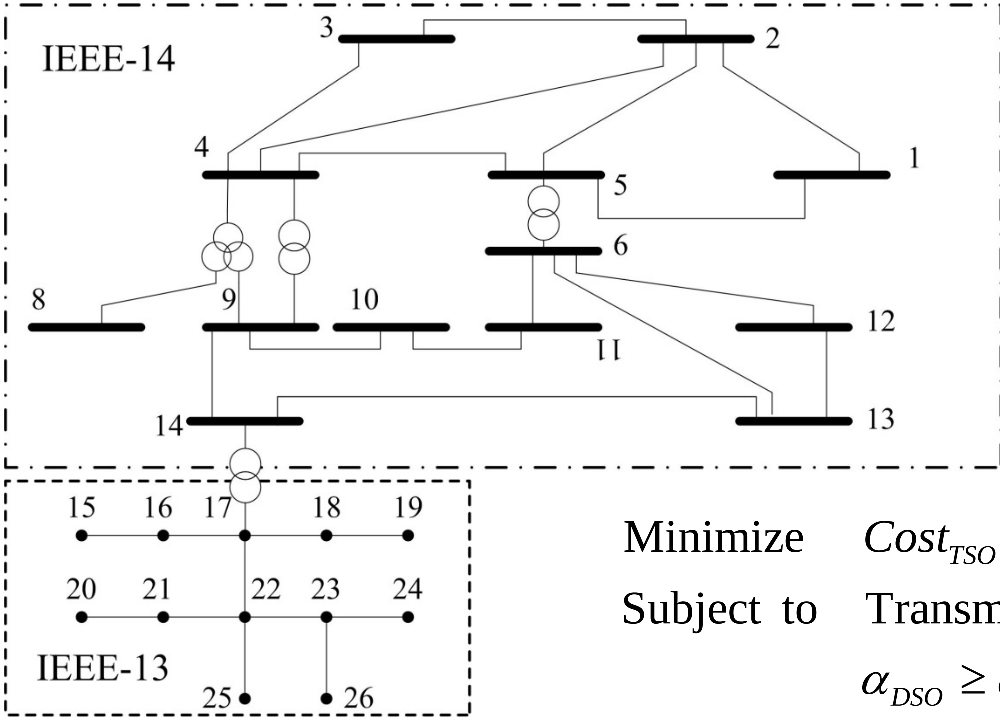
Sub-Network
Minimize z
Subject to x=x', y∈Y



Upper and lower bounds

Breaking down centralized dispatch into hierarchical dispatch

Bender's Cuts as Generalized Supply Functions



DSO Cost (a_k) [€]	DSO Bidding (P_k) [MW]	C_k [€/MWh]
940.49	10	85
780.62	10.05	39
640.94	10.1	40
640.65	6.9	44

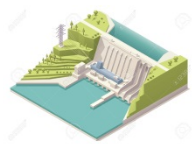
DISO has strong incentive to correctly bidding

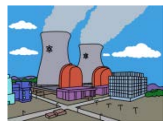
Minimize $\quad Cost_{TSO} + \alpha_{DSO}$

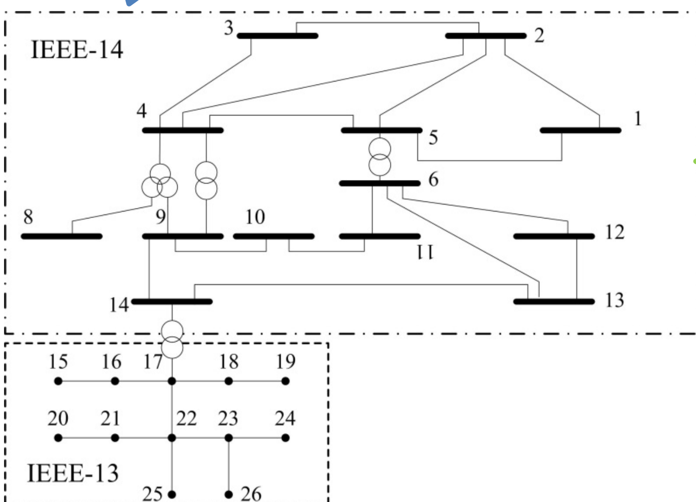
Subject to $\quad$ Transmission Network Constraints

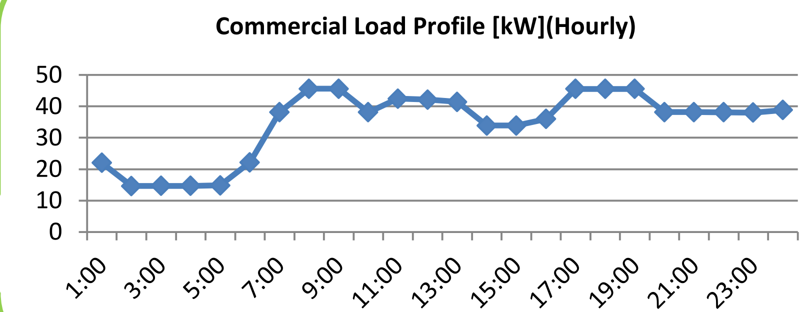
$$\alpha_{DSO} \geq \alpha_k + c_k (p - p_k)$$

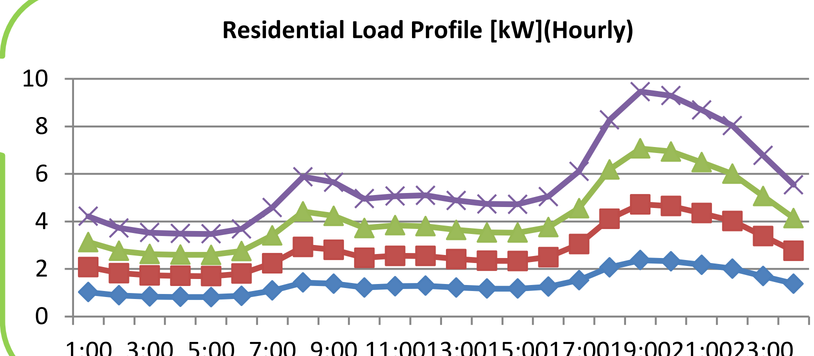
Efficiency of Nodal Pricing



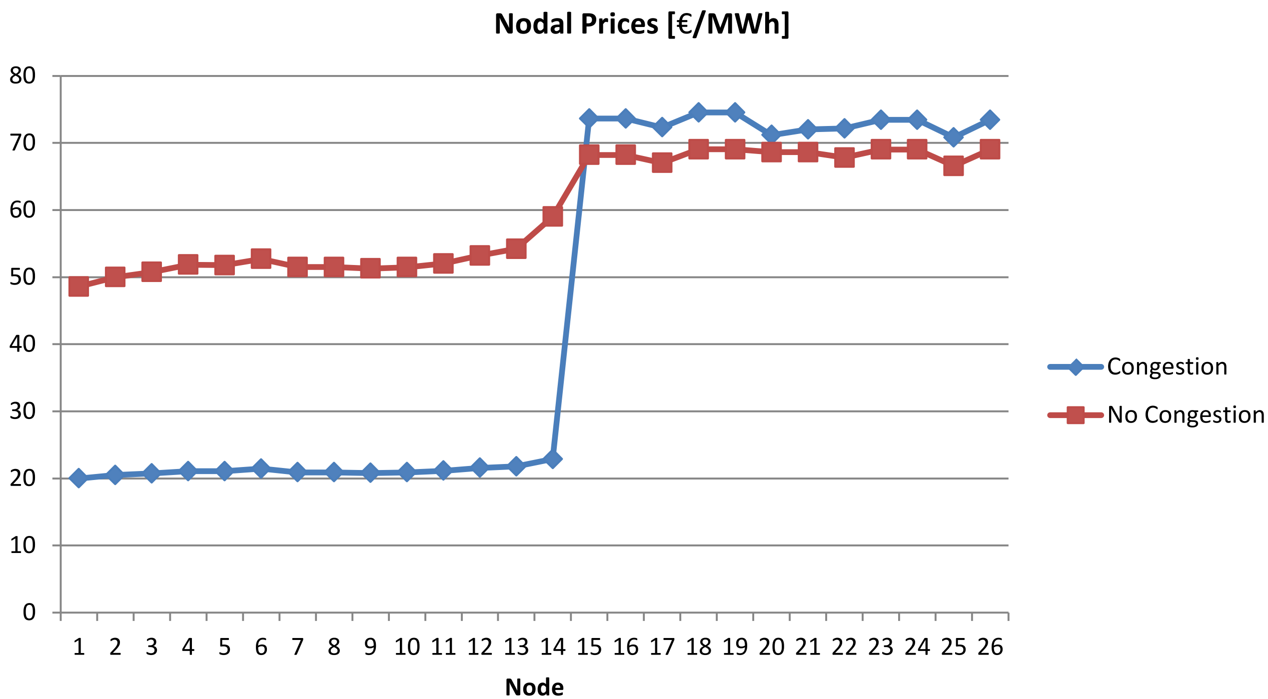






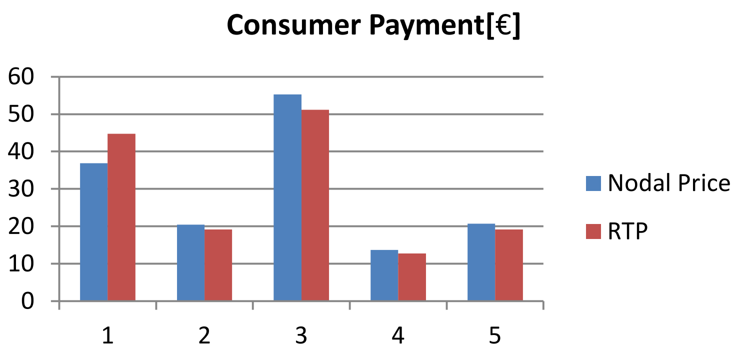


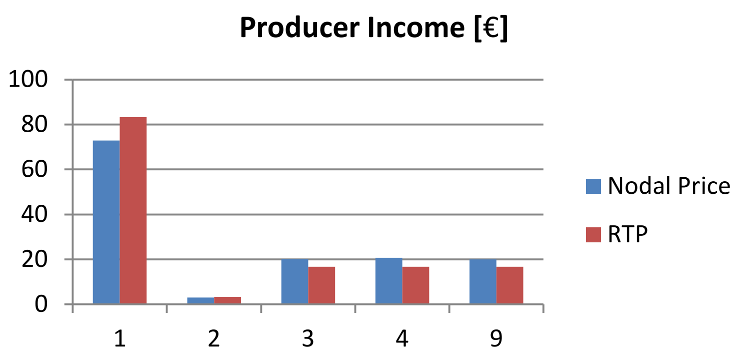
Congestion Management



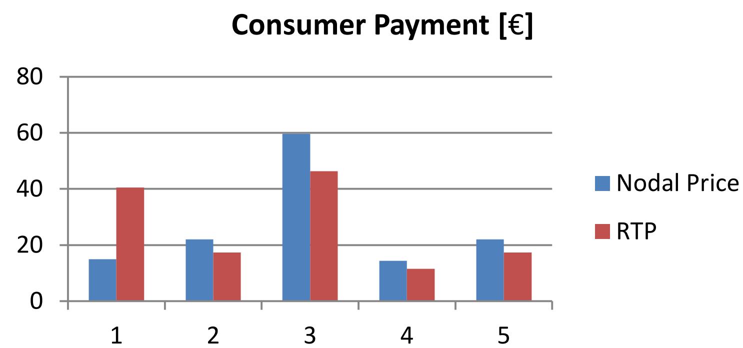
Congestion Management

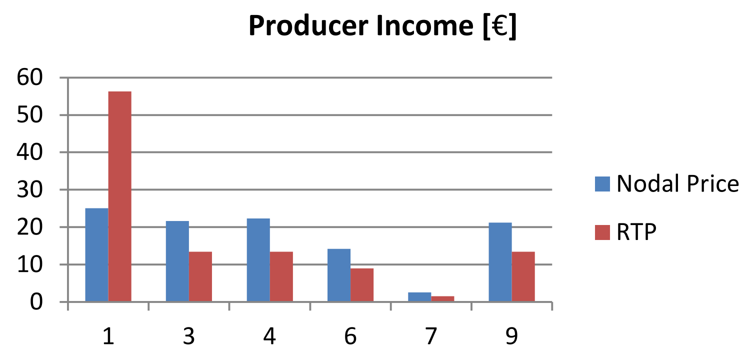
No Congestion



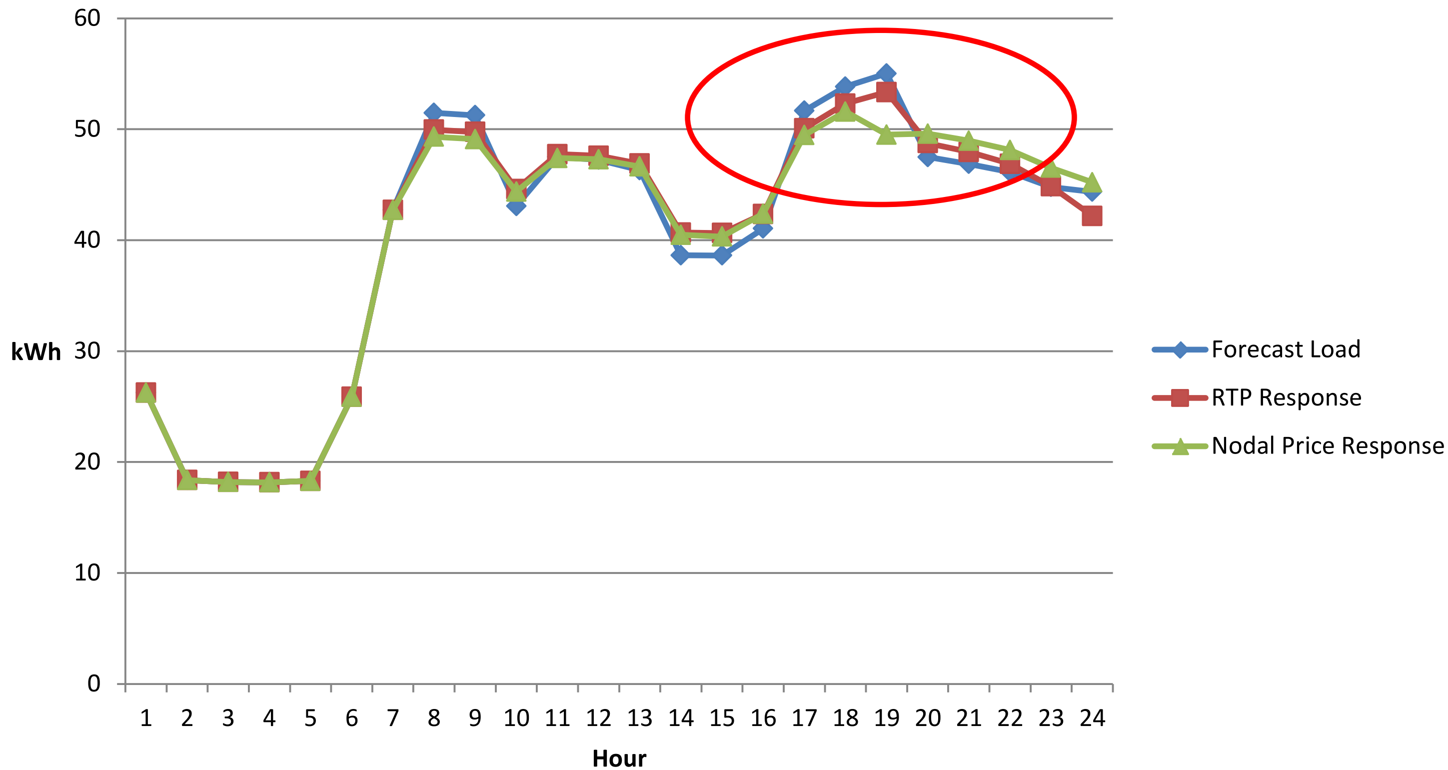


Congestion





Demand Side Management by Pricing



Price Elasticity of Sweden Consumers is -0.68~-1 (Krishnamurthy and Kriström, 2013)

Nodal Pricing provides more efficient load shift

Conclusions

- Current distribution pricing lacks locational information.
- Convex AC OPF is more accurate for distribution network than DC power flow approach.
- TSO and DSO dispatch can be coordinated by hierarchical dispatch.
- Generalized supply functions are the information that should be communicated from DSO to TSO to achieve global optimization.
- Distribution Network Nodal Pricing complexity is relaxed by hierarchical dispatch.
- Nodal Pricing is more efficient for congestion management and demand side response.

Some Further Issues

- DSO Long Run Incremental Cost (LRIC) pricing model.
- Common Distribution Charging Model (CDCM).
- Pricing by long run investment and short run operation.
- Sweden distribution network data. Media-high voltage and low voltage.
- Demand side flexibility market.