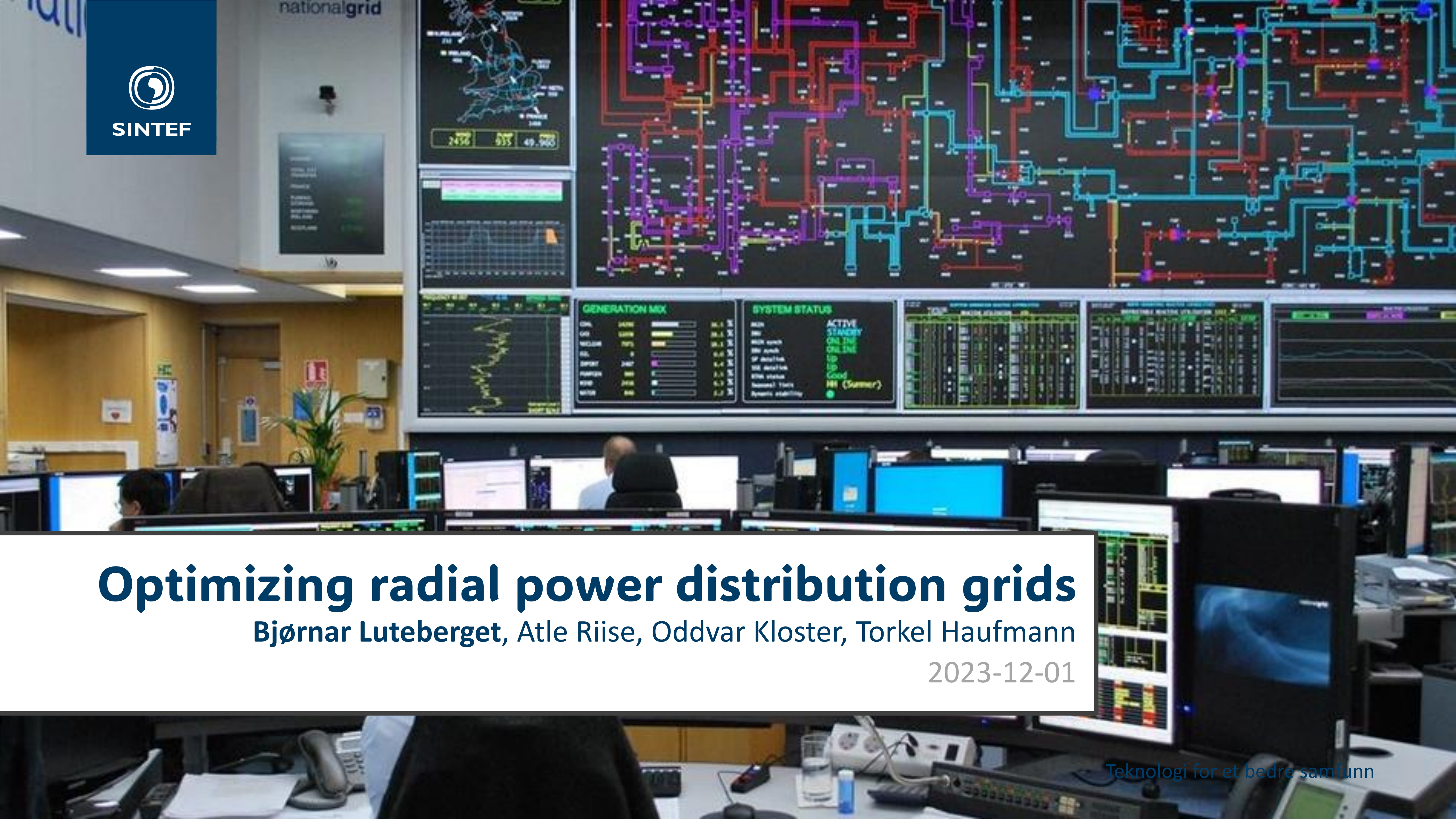
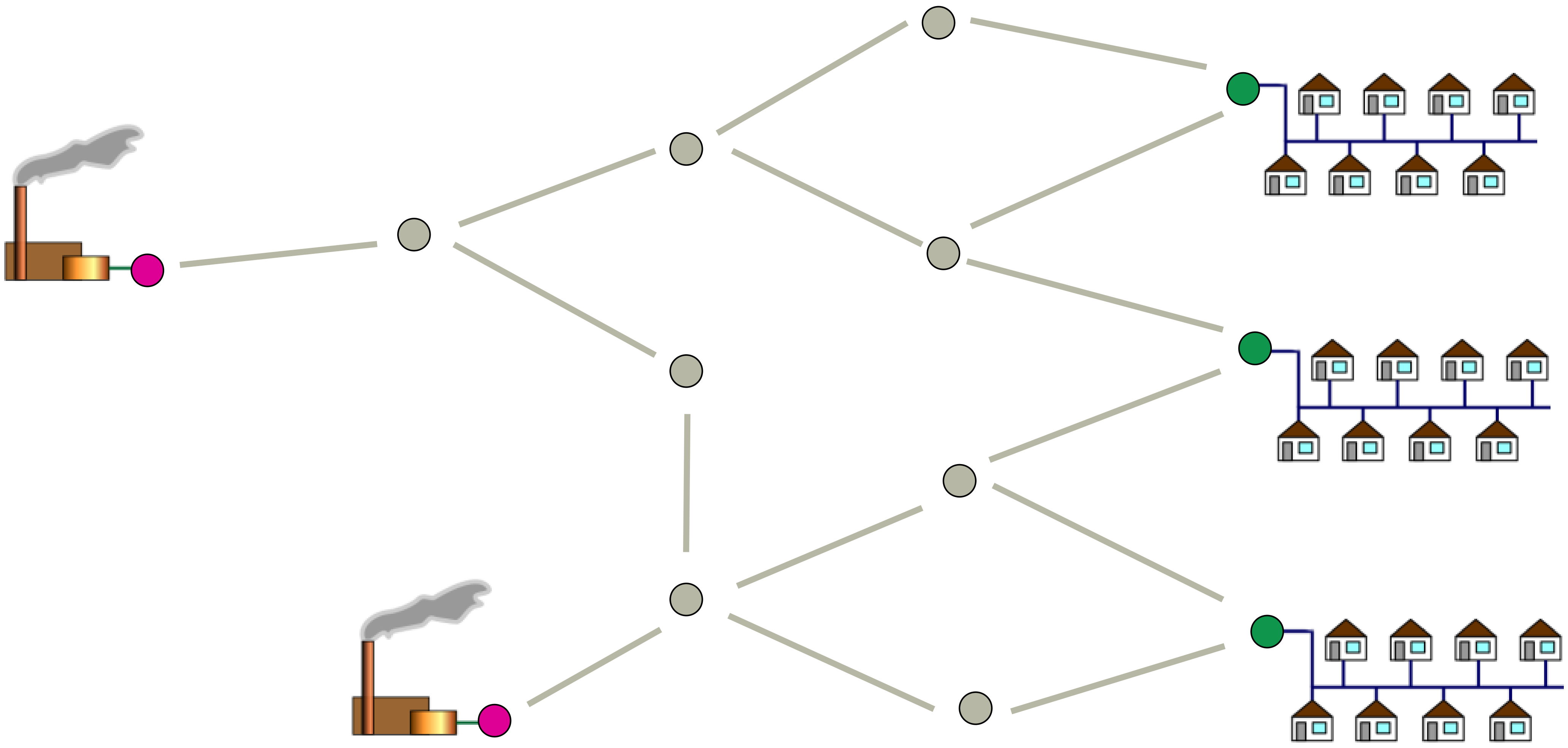


Optimizing radial power distribution grids

Bjørnar Luteberget, Atle Riise, Oddvar Kloster, Torkel Haufmann

2023-12-01

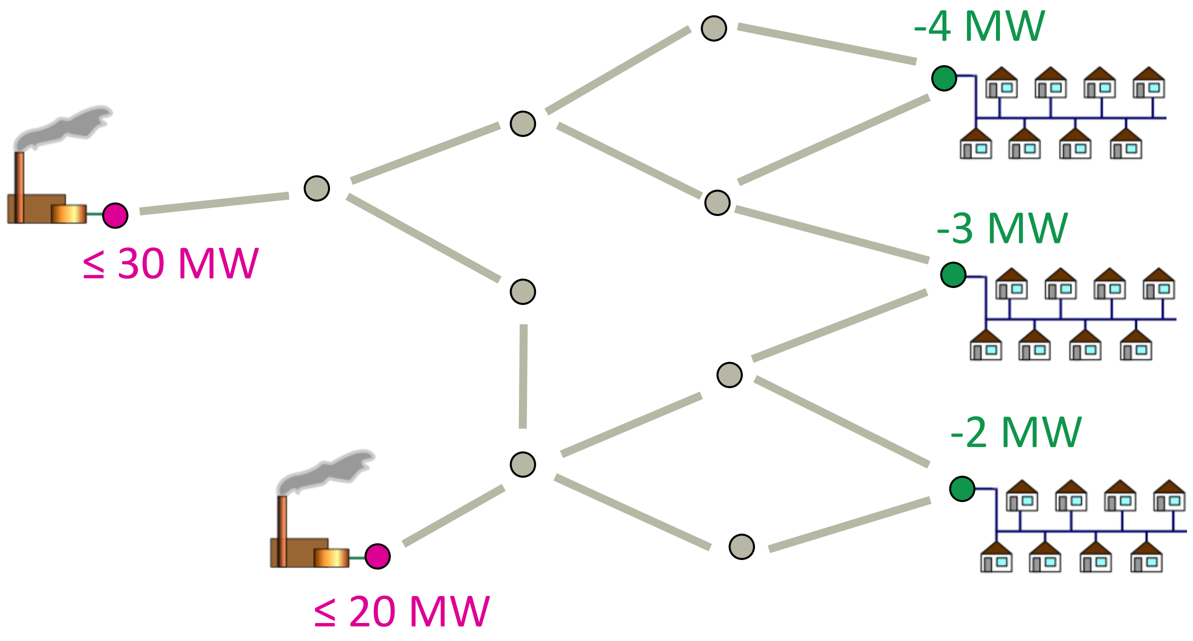
Optimal Power Flow



Optimal Power Flow

- Consumers have a specified energy demand
- Producers need a specification of how much energy to produce
- Minimize the total cost of production
  - Each producer has a cost curve
- Alternating current (AC) Power flow given by

$$\tilde{S} = \tilde{V} \circ \left(\tilde{Y}\,\tilde{V}\right)^{*}$$



(Conventional) Power Flow

- Power flow given by complex matrix equation:

$$\tilde{\boldsymbol{S}} = \tilde{\boldsymbol{V}} \circ \left(\tilde{\boldsymbol{Y}}\,\tilde{\boldsymbol{V}}\right)^*$$

- Using power $\tilde{\boldsymbol{S}} = \boldsymbol{P} + \boldsymbol{jQ}$ instead of current.
- Typically with polar coords for voltage and rectangular coords for admittance ($\tilde{Y}$):

$$P_i(V,\delta) = V_i \sum_{k=1}^{N} V_k(G_{ik}\cos(\delta_i - \delta_k) + B_{ik}\sin(\delta_i - \delta_k))$$

$$Q_i(V,\delta) = V_i \sum_{k=1}^{N} V_k(G_{ik}\,sin(\delta_i - \delta_k) + B_{ik}\,cos(\delta_i - \delta_k))$$

See: Frank, S., & Rebennack, S. (2016). An introduction to optimal power flow: Theory, formulation, and examples. IIE transactions, 48(12), 1172-1197.

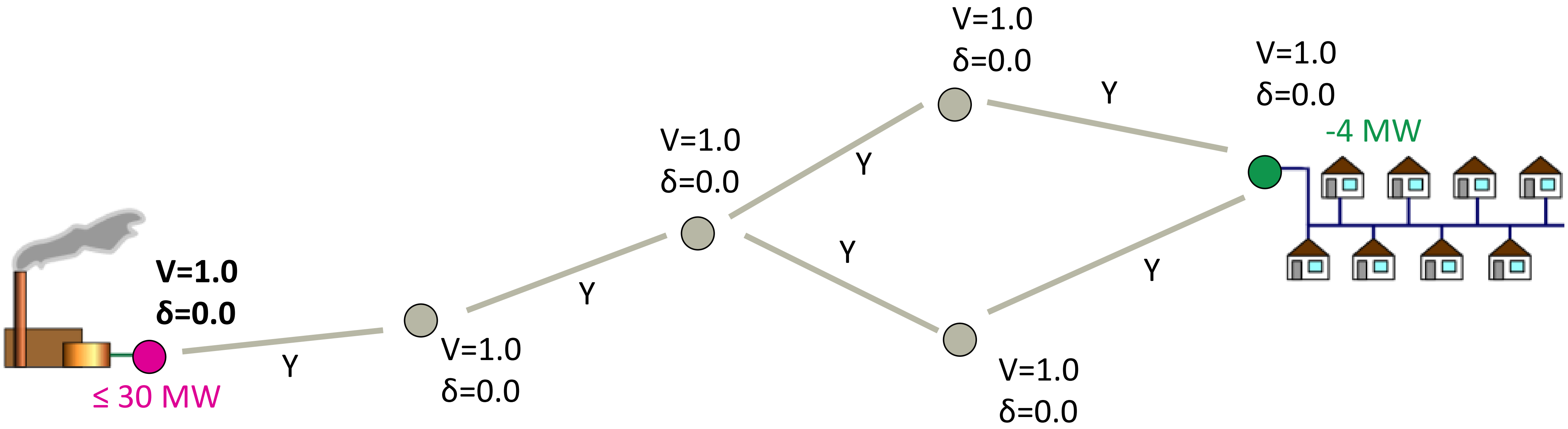
(Conventional) Power Flow

- Solving (conventional) power flow by the Newton-Raphson method

$$\begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix} \approx \begin{pmatrix} \frac{\delta P}{\delta \delta} & \frac{\delta P}{\delta V} \\ \frac{\partial Q}{\partial \delta} & \frac{\delta Q}{\delta V} \end{pmatrix} \begin{pmatrix} \Delta \delta \\ \Delta V \end{pmatrix}$$

$$\Delta P_i = \left(P_i^G - P_i^L\right) - P_i(V, \delta)$$
$$\Delta Q_i = \left(Q_i^G - Q_i^L\right) - Q_i(V, \delta)$$

(Conventional) Power Flow



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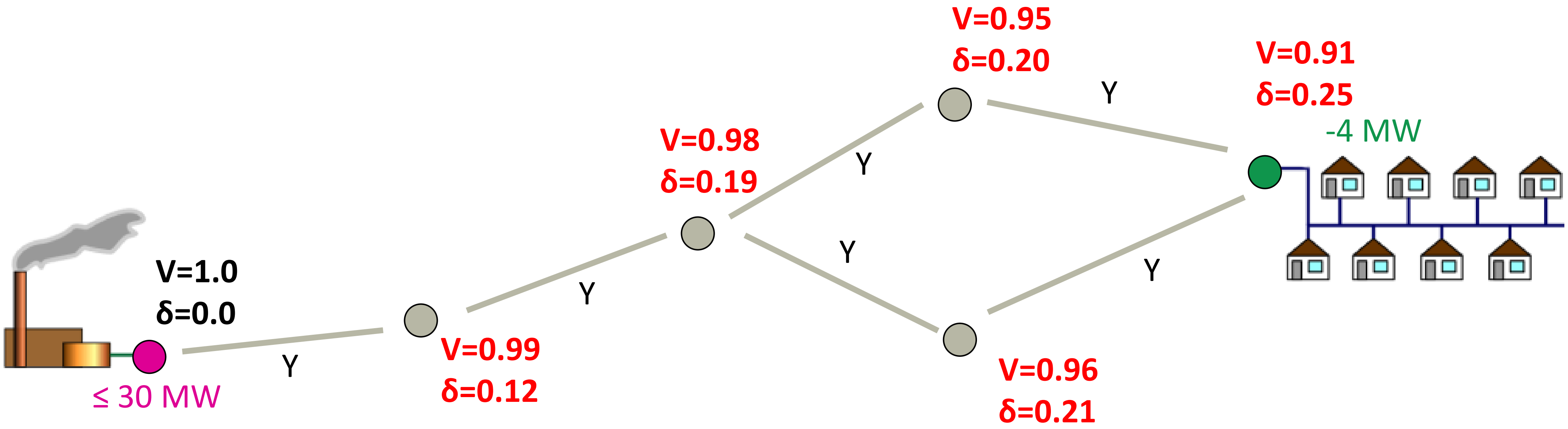


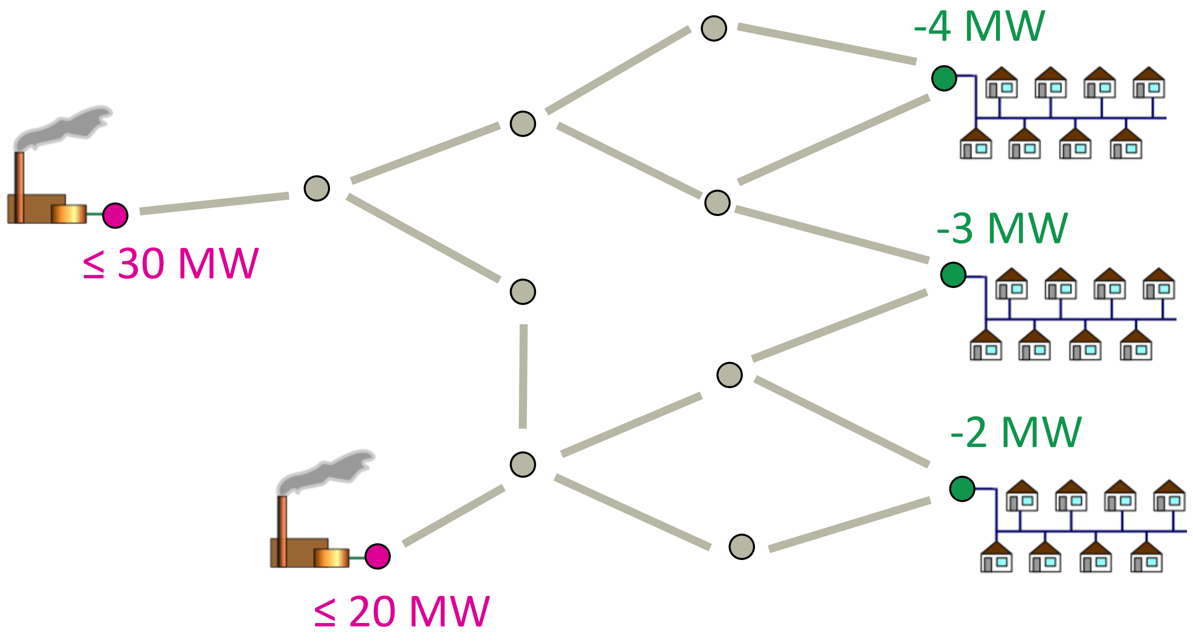
Note:

- The power plant produces >4 MW because of loss (determined by Y)
- This is "just" a feasibility problem.
- Each iteration solves a matrix equation with $O(|E|)$ nonzeros
- Open-source implementations available:
  - MATPOWER (Matlab), PyPower, PandaPower (Python)

Optimal Power Flow

Variants of optimization problems:

- Minimize cost of production
- Unit commitment
- Security-constrained
  (or reliability objectives)
- Topology (switches)

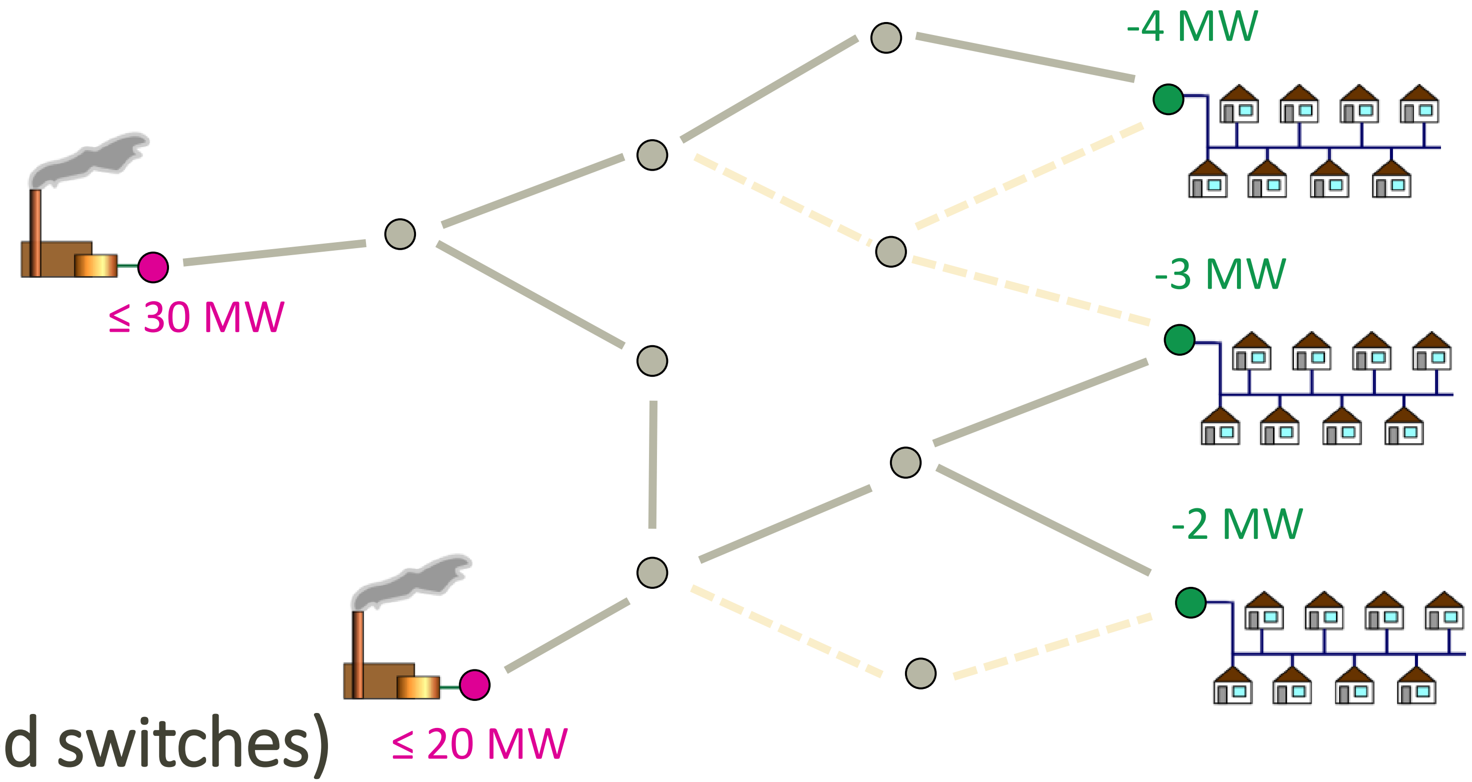


An economicly significant problem

Optimal Power Flow

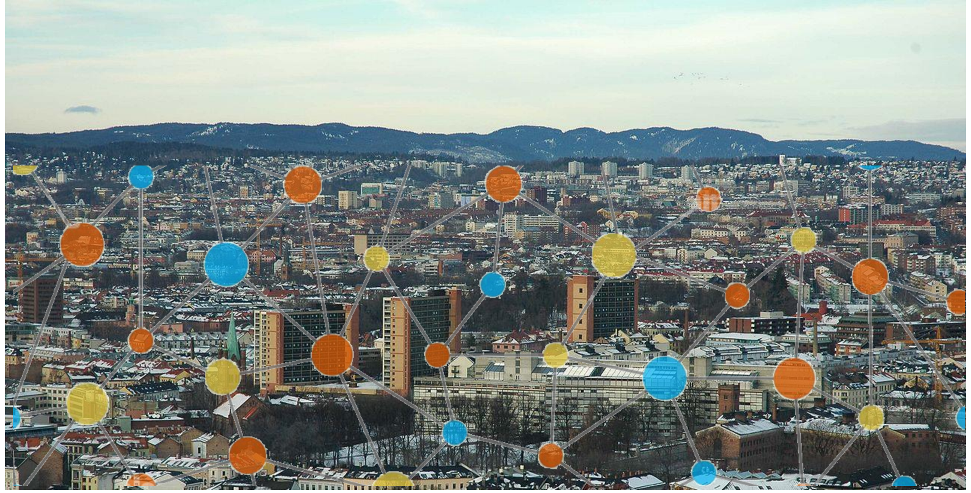
Variants of optimization problems:

- Minimize cost of production
- Unit commitment
- Security-constrained (or reliability objectives)
- Topology (switches)
  - Grid topology (all lines)
  - Operating topology (closed switches)



Distribution network

- Transmission network: high voltage, long distances
- Distribution networks: medium/low voltage, short distances
- Typically required to be operated radially
  - Switches are opened to make the operating topology radial



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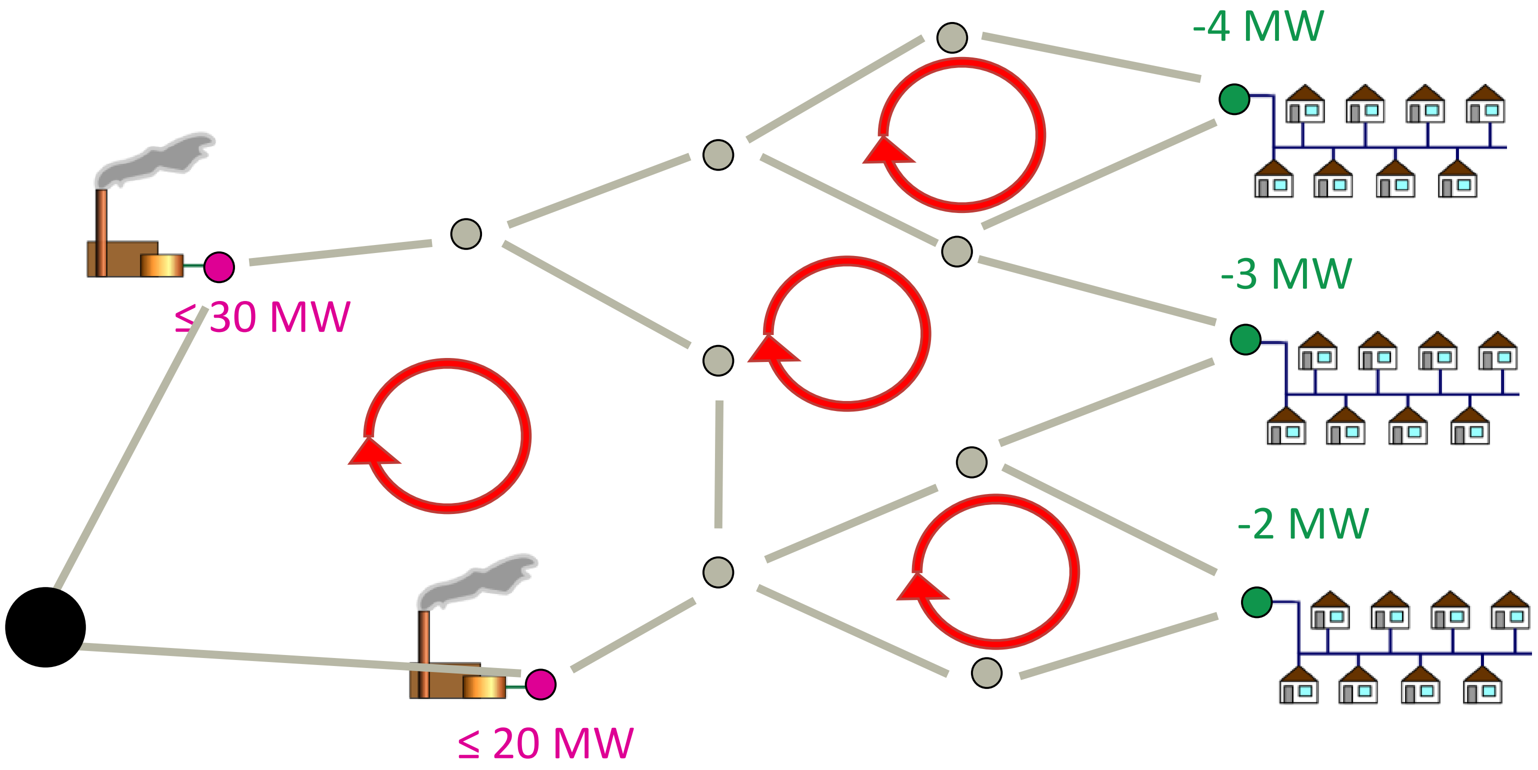

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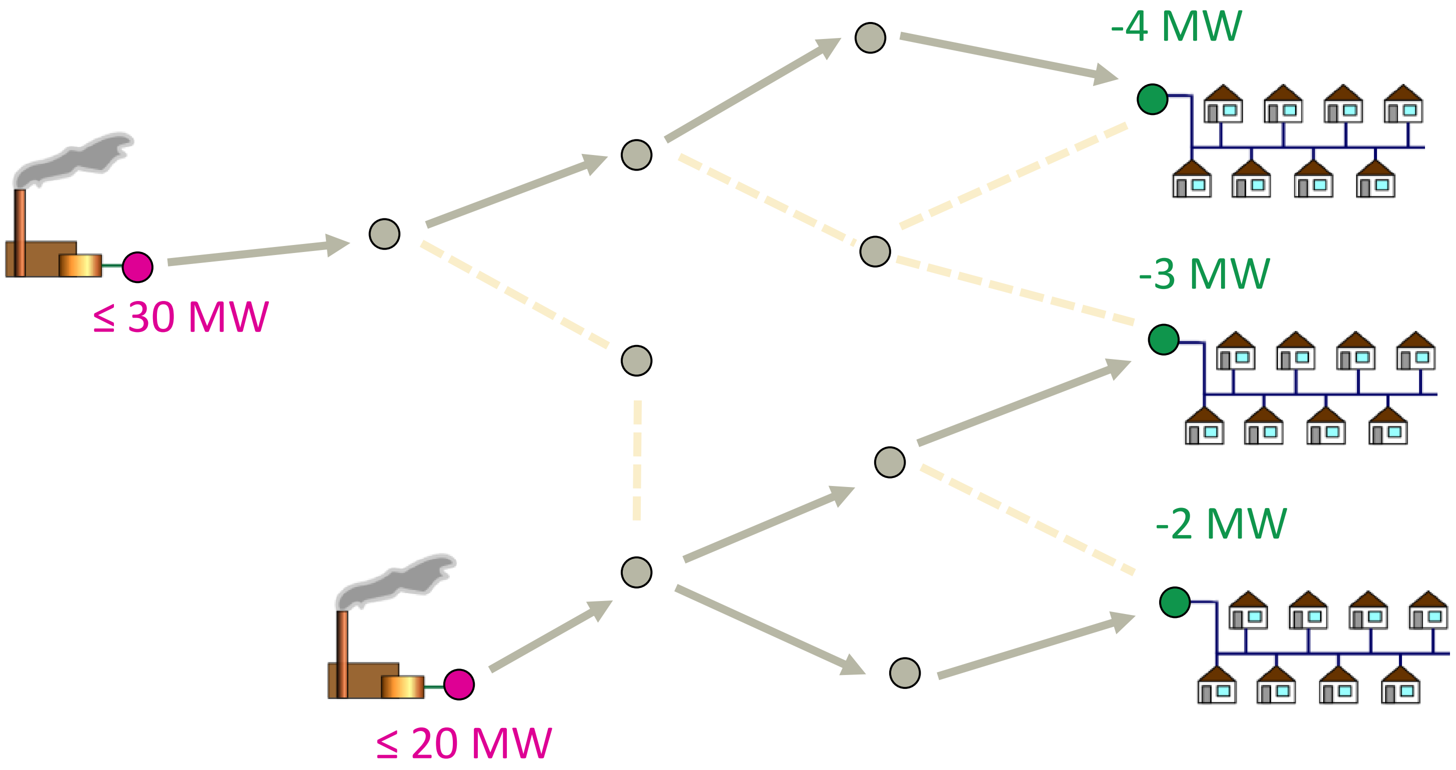

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- Why radiality?
  - Easier to locate faults
  - Smaller currents when short-circuiting
  - Simpler design and operation
  - Engineering convention

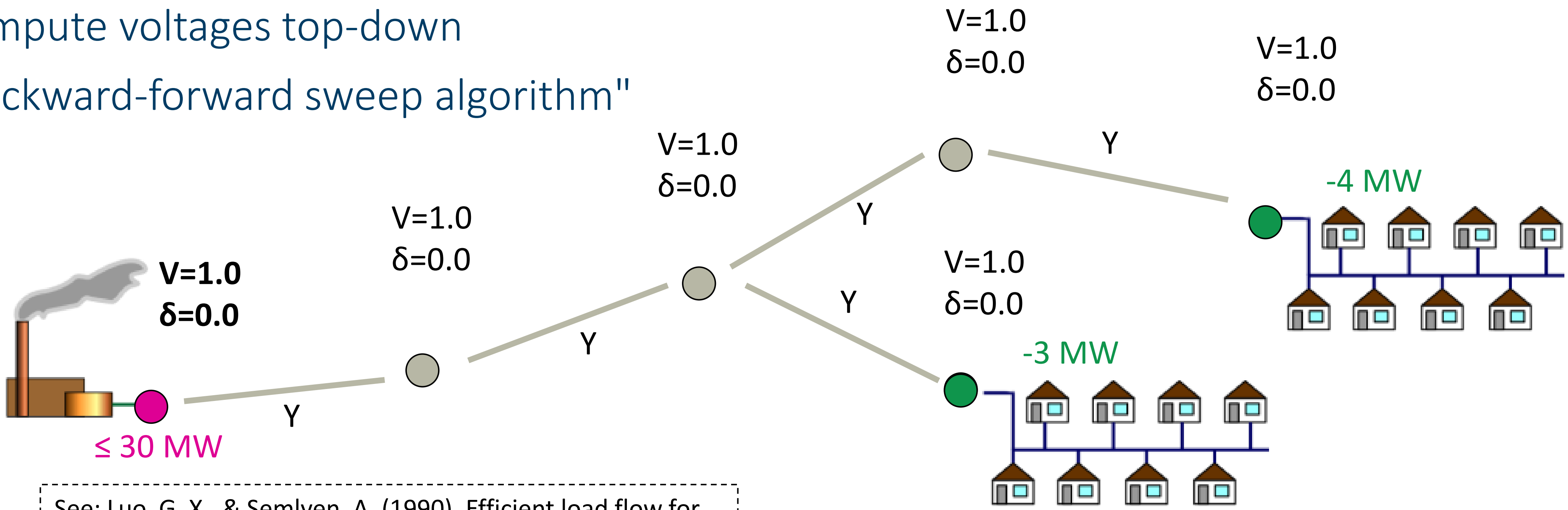
- SINTEF Power Grid Optimizer software

1. Efficient **radial** (conventional) power flow
2. Optimization by **local search** over radial configurations

Joint work with Atle Riise, Oddvar Kloster and Torkel Haufmann

Radial power flow

- (Conventional) power flow is easier on radial topology!
- Sum powers bottom-up
- Compute voltages top-down
- "Backward-forward sweep algorithm"



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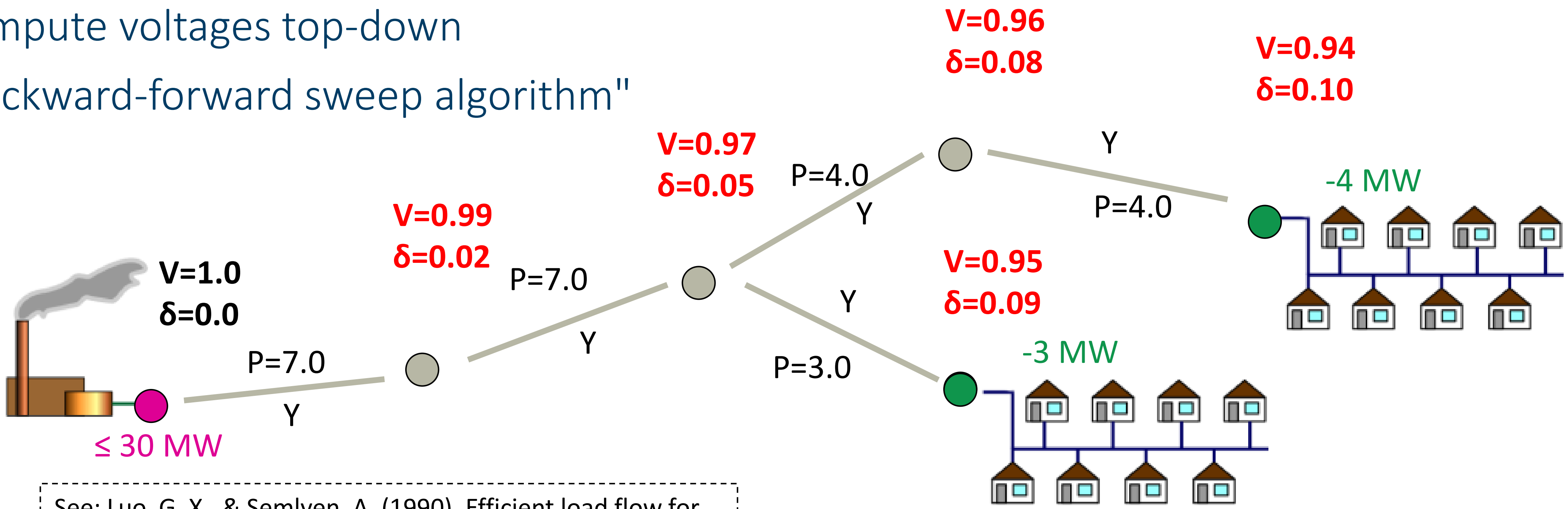

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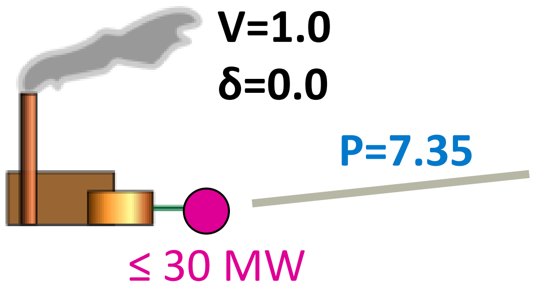
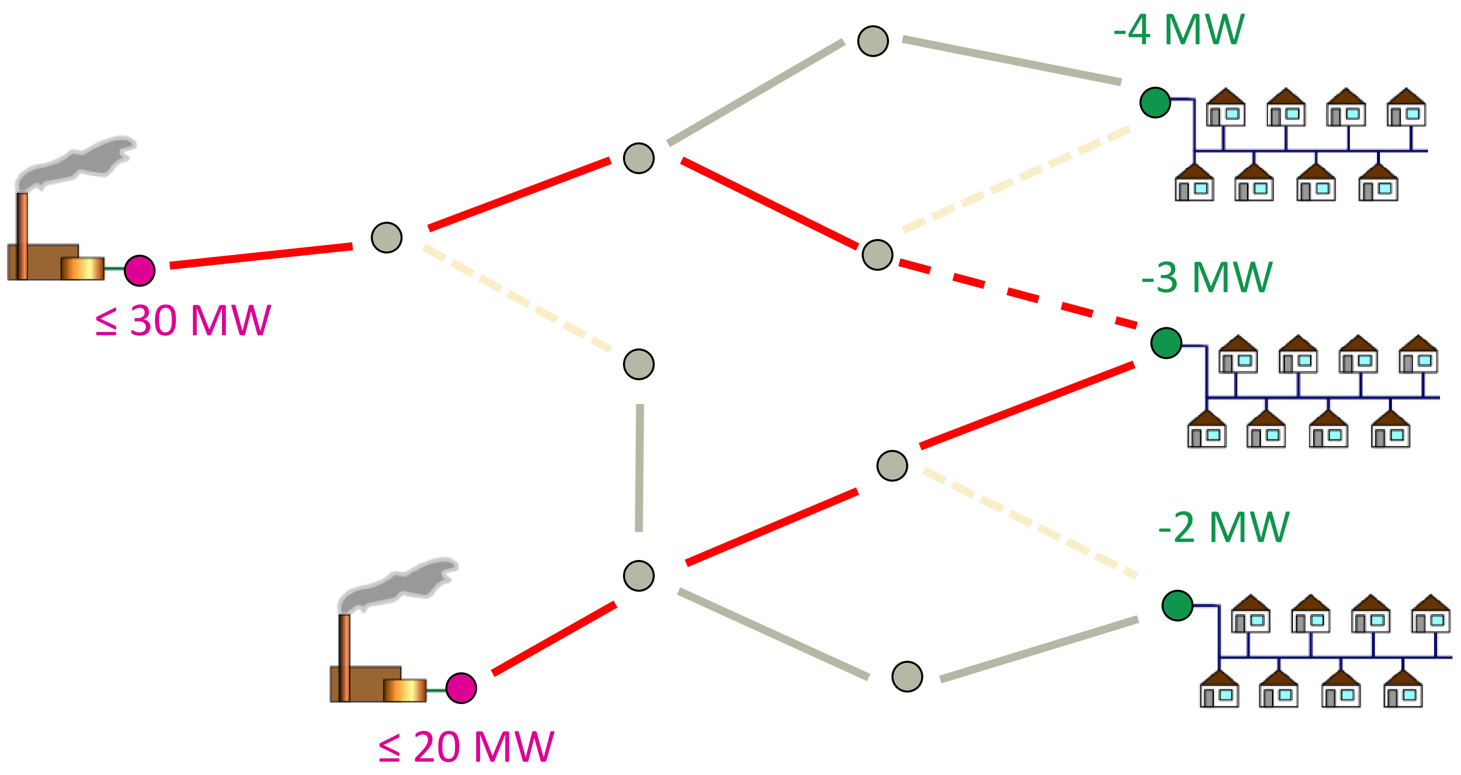
Local search over configurations

- In a grid with N lines, let $c = [c_0, c_1, \dots, c_N] \in \{0,1\}^N$ describe which lines are switched out ($c_i = 0$) or in (c_i =1) (the configuration).
- For a given c, we can evaluate the conventional power flow to evaluate the objective $\mathrm{cost}(\mathrm{c})$
  - (typically total power produced)



Neighborhood

- Assume the edges defined by c define a spanning tree (radial and connected configuration)
- Connecting any unconnected line will create a cycle
- Disconnect any other line on the cycle



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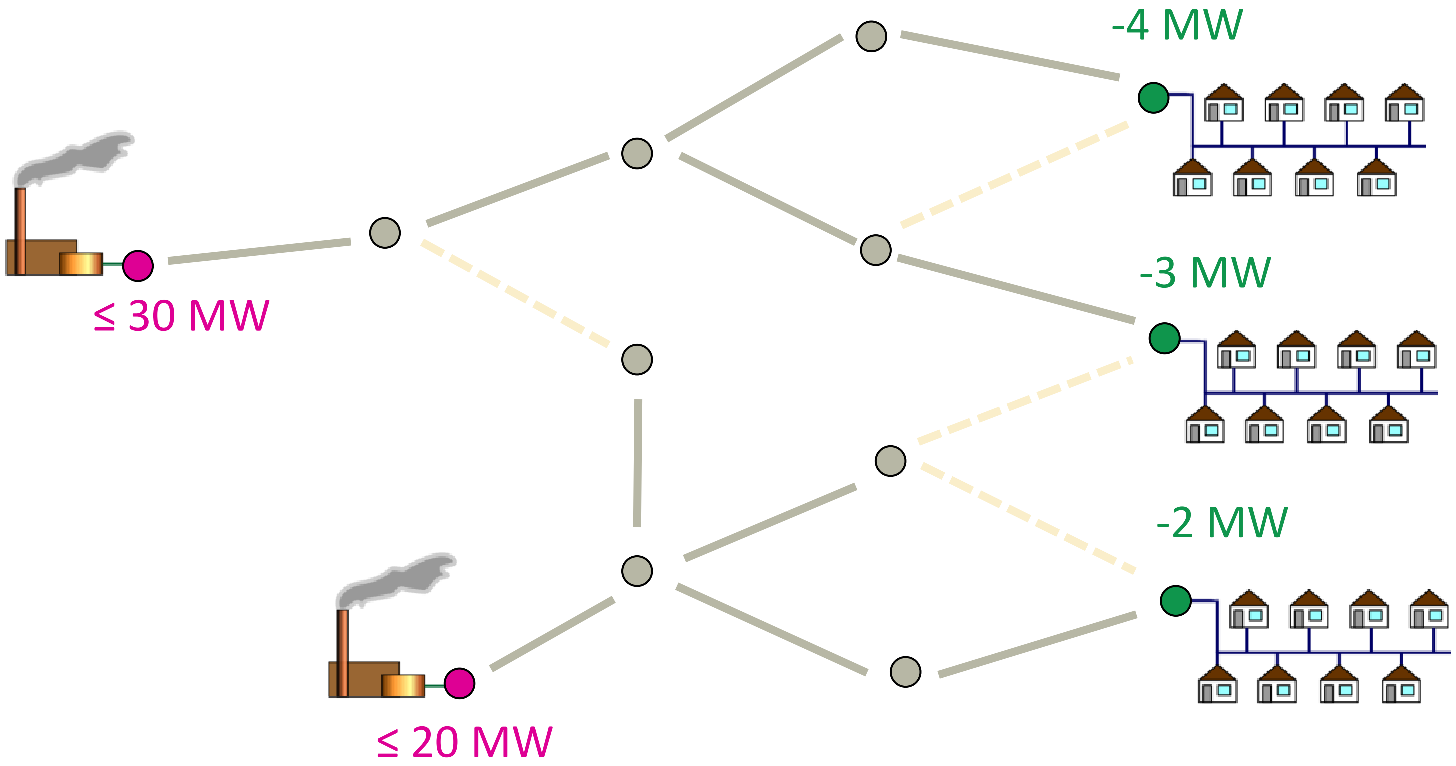

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Local search over configurations

- With this neighborhood $N(c)$ of other configurations
- As long as

  $$\exists c^* \in N(c) \text{ s.t. } \mathrm{cost}(c^*) < \mathrm{cost}(c)$$

  – … let $c \coloneqq c^*$ and repeat

Summary

In radially operated networks:

- **Decomposing** the configuration from the power flow allows:
  - Local search over a neighborhood defined by connecting one line and disconnecting another
  - Efficient power flow computation as a subproblem determining the cost

- Additional tricks:
  - Incremental power flow (update only the changed part)
  - Ruin-and-recreate meta-heuristic
  - … much more

Reality bites

- Academic studies often demonstrate on 10-100 node grids
- **Lede**, our most advanced industry partner, wants to use their infrastructure database with 100 000s of nodes
- ... optimizing directly from their proprietary database
- ... integrated with their work flow and control systems

SINTEF

Industrial deployment

Local search in itself is often very scalable.

But also, engineering efforts are required to handle large networks:

- Converting from infrastructure databases
- Converting from the infamously complicated CIM (common interchange format)
- Preprocessing, aggregation, simplification
- Code optimization, parallelization
- Correctness tests, performance regression tests
- Integrating with control systems
- Extension to multi-period problems, network design problems

It will be worth it

- On a portion of Lede's network (a small city) we found configurations using 3.29 MW less power
- There are practical obstacles to implementing large changes, but Lede are developing software to suggest smaller changes in operating topology to operators
- Not limited to one static configuration -- with efficient optimization and remote-controlled switches, you can dynamically change configuration as the consumption changes throughout the day!

Teknologi for et bedre samfunn