Distributed supply-demand balancing and the physics of smart energy systems

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Joint work with a.o. Gunn K.H. Larsen, Nicky van Foreest, Desti Alkano, Bao Nguyen, Arjan van der Schaft, Fiaz Shaik, Daniele Zonetti, Romeo Ortega,....

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Topic

- Supply demand matching at an economic level: distributed optimal control via dual decomposition.

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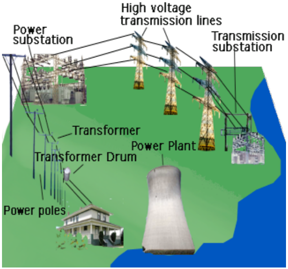
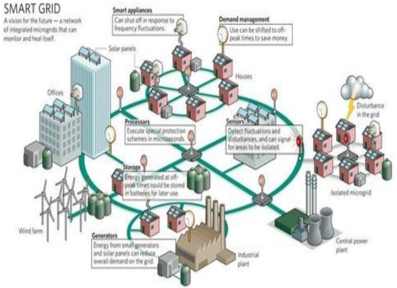
Two decoupled layers?

Past and future power grid





Outline

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1. Distributed optimal control of the power grid
   - The production side
   - Demand side control
2. Market embedding
3. Grid integration
   - Distributed control of the gas grid
   - Distributed control with power to gas facilities
4. The physics of the power grid

An example project: The Flexines Project

Flexines

Gas important in Groningen area, micro-CHP of interest for distributed generation.

- **Business case**: Estimation that in 2020 1 million μCHP units in the Netherlands, in 2030 4 million.

provincie groningen

Gemeente Groningen

Ministerie van Economische Zaken

Naast de provincie en de gemeente Groningen, wordt dit project medegefinancierd door het Ministerie van EZ en het Europees fonds voor regionale ontwikkeling

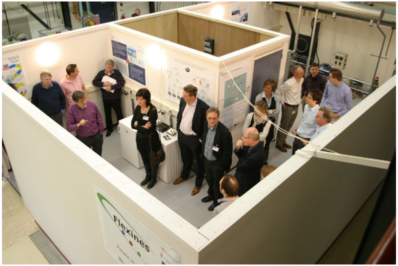
rijksuniversiteit groningen

The Flexines Project

Goal Develop Energy Management System (EMS) based on prices, helping user to regulate costs.

Role Network balance and prices.

Flexines

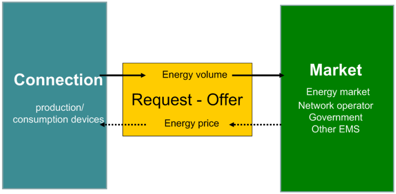


The Flexines Project

Goal Develop Energy Management System (EMS) based on prices, helping user to regulate costs.

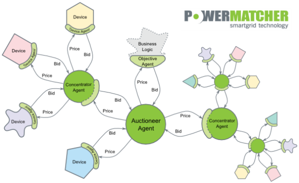
Role Network balance and prices.

- Local production, lower transmission losses.
- No longer centralized top-down control.
- End users also producers, prosumers.
- Stability of the network.
- Need for coordination.

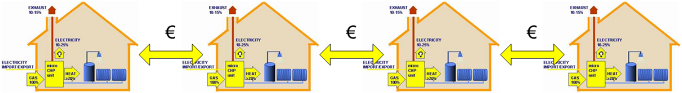


Smart grid experiment in suburb Groningen

- Place: An area in Groningen.
- Field test with Power-Matcher concept.
- Households with controllable devices (washing machines, heat pump, μCHP, batteries, solar panels, etc.)
- Multi-agent accumulating bid curves in a tree structure. Microeconomics used to determine equilibrium price.
- No forecasting included.



Another alternative: Distributed control



- Interested in an alternative way of coordination.
- Distributed control $\rightarrow$ Local price communication between neighbors.

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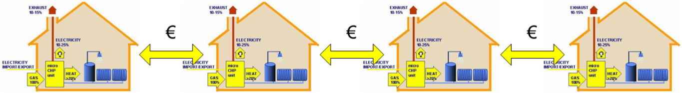
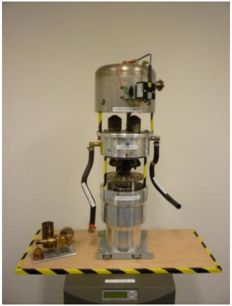


- Interested in an alternative way of coordination.
- Distributed control → Local price communication between neighbors.
- The micro Combined Heat Power (μCHP) system is an option for local production (e.g., Houwing et al. 2011).
  - Overall efficiency of the μCHP can be as high as 90%.
  - Electrical output is typical 1kWh.



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Network control issues

- Imbalance zero.
- Avoid peaks $\rightarrow$ may allow more connections on one transformer.
- Lower transmission losses $\rightarrow$ local delivery.
- Delivery certainty.
- Local optimization versus global optimization.

Problem formulation

Minimize imbalance and costs of production given the imbalance equations per household, i.e., $\min_u \Sigma x^T x + u^T u$.

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$x_i[k]$ is imbalance *information* household i at time k. Then

$$x_i(k+1) = A_{ii} x_i(k) + \sum A_{ij} x_j(k) + u(k) + w_i(k)$$

x_i imbalance information, w_i change in demand (white noise), u_i change in production. NB: real imbalance $\tilde{x}_i$: $A_{ij} = 0$, $A_{ii} = 1$.

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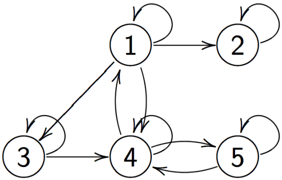

$$A = \begin{bmatrix} * & 0 & 0 & * & 0 \\ * & * & 0 & 0 & 0 \\ * & 0 & * & 0 & 0 \\ * & 0 & * & * & * \\ 0 & 0 & 0 & * & * \end{bmatrix}$$

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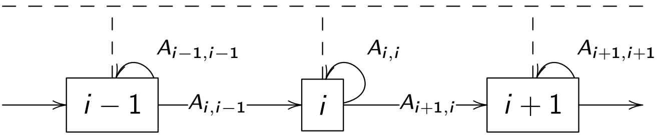
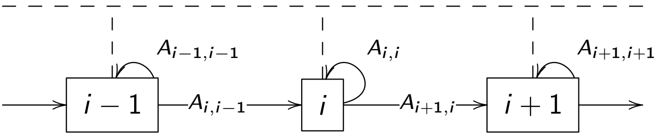


- R1 $A_{ij} \neq 0$ if and only if information is exchanged from agent j to agent i.
- R2 All weights are non-negative: $A_{ij} \geq 0, \ i,j = 1,\ldots,n$.
- R3 All columns sum up equal to one: $\sum_{i=1}^{n} A_{ij} = 1, \ j = 1,\ldots,n$.
- R4 The graph corresponding to information matrix A is strongly connected.

Network model - Information weights



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Consequence, if $\tilde{x}(0) = x(0)$, then

$$\sum_{i=1}^{n} x_i(k) = \sum_{i=1}^{n} \tilde{x}_i(k),\ \forall\ k \geq 0,$$

where $\tilde{x}$ is the real imbalance, and x the imbalance information.

Dual-decomposition and sub-gradient iterations

- Game theoretic interpretation from economics literature, dual decomposition in optimization treated in e.g.
  (Boyd and Vandenberghe 2004).
- Based on price mechanisms in linear quadratic team theory and dynamic dual decomposition for distributed control,
  (Rantzer 2007,2009).
- "Distributed model predictive control with suboptimality and stability guarantees" (Giselsson and Rantzer 2013).
- Recently applied to production side control with micro CHP's and heat pumps, (Larsen, van Foreest, Scherpen, 2013, 2014).

From a centralized MPC to a distributed MPC

Central MPC

$$\min_{\hat{u},\hat{x}} \sum_{\tau=k}^{k+N} \sum_{i=1}^{n} l_i(\hat{x}_i(\tau), \hat{u}_i(\tau))$$

s.t. for all i, τ

$$\hat{x}_i(\tau+1) = A_{ii}\hat{x}_i(\tau) + \sum_{j\in N_i} A_{ij}\hat{x}_j(\tau) + B_{ii}\hat{u}_i(\tau),$$

$$\hat{x}_i(\tau)_{\tau=k} = x_i(k),$$

$$\hat{x}_i(\tau) \in X_i, \quad \hat{u}_i(\tau) \in U_i,$$

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Distributed MPC

$$\min_{\hat{u}_i,\hat{x}_i,\hat{v}_i} \sum_{\tau=k}^{k+N} V^i_{\text{agent}}$$

s.t. for all τ it holds:

$$\hat{x}_i(\tau+1) = A_{ii}\hat{x}_i(\tau) + \hat{v}_i(\tau) + B_{ii}\hat{u}_i(\tau)$$

$$\hat{x}_i(\tau)_{\tau=k} = x_i(k),$$

$$\hat{x}_i(\tau) \in X_i, \;\; \hat{u}_i(\tau) \in U_i,$$

with sub-gradient iterations

$$\hat{\lambda}_{i,r+1}(\tau) =$$
$$\hat{\lambda}_{i,r}(\tau) + \gamma_{i,r}[\hat{v}_{i,r}(\tau) - \textstyle\sum_{j\in N_i} A_{ij}\hat{x}_{j,r}(\tau)]$$

$$V^i_{\text{agent}} = \Big(l_i(\hat{x}_i(\tau), \hat{u}_i(\tau)) + \hat{\lambda}_i(\tau)\hat{v}_i(\tau) - \textstyle\sum_{j\in N_i} \hat{\lambda}_j(\tau) A_{ji}\hat{x}_i(\tau)\Big)$$

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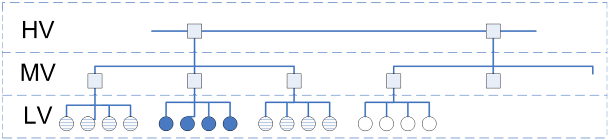
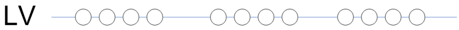
Our electricity grid

Current grid:



Possible fully distributed topology:



Networks of households with μCHP and heat pumps

- Heat demand is leading, i.e., it is a constraint that the heat demand has to be met with local devices.
- Constraints on production side, i.e., μCHP, and heat pump (off-time, not on for very small demand, maximum production level, etc.), of which some are non-convex.
- Information exchange with neighbors.

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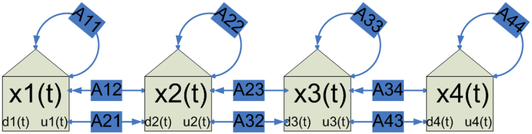
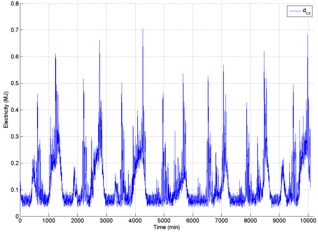
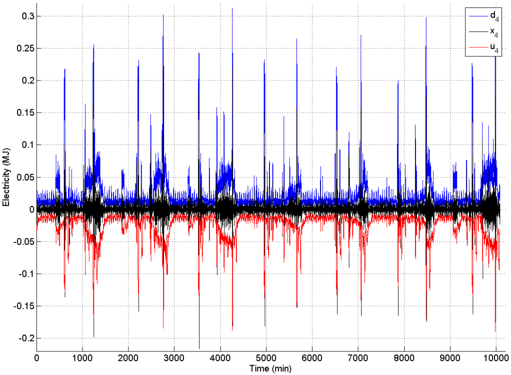
- Constraints on production side, i.e., μCHP, and heat pump (off-time, not on for very small demand, maximum production level, etc.), of which some are non-convex.
- Information exchange with neighbors.
- Via game theory and dual decomposition price mechanism interpretation.
- Control of the imbalance can be done fully distributed at each household with only information of the neighbors.
- Implementation feasible, imposing constraints.

Realistic electrical demand obtained from field tests





Optimal control $u(k)$



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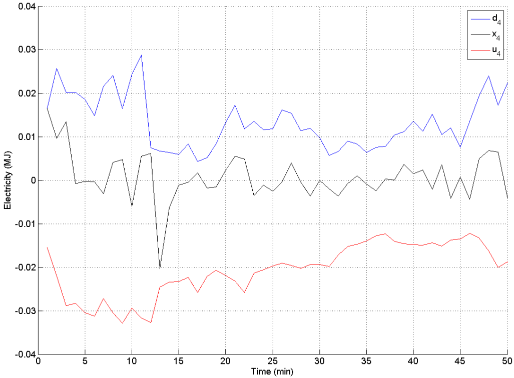


Zoom

Summary of production side

- By embedding the electrical power grid in the dual decomposition framework distributed suboptimal control of decentralized power generation can be achieved.
- Method can also capture current network structure.
- Information from physical far away neighbours set to zero. This is promising with respect to computational complexity, and reduces transportation costs.

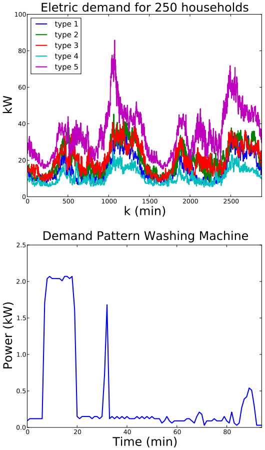
Summary of production side

- By embedding the electrical power grid in the dual decomposition framework distributed suboptimal control of decentralized power generation can be achieved.
- Method can also capture current network structure.
- Information from physical far away neighbours set to zero. This is promising with respect to computational complexity, and reduces transportation costs.
- Propose that the structure of the network in the future may change when there is a high share of controllable decentralized generation present.
- Published in IEEE Transactions on Smart Grid (2013, 2014), and Applied Mathematical Modelling (2014).

Extensions

- To do: feasible, and optimal storage topology to be incorporated in the modeling.
- To do: price interpretation. Shadow prices are marginal costs made to decrease limitations and circumvent bottle necks. What are real prices?
- How to involve demand control? Include additional models.
- Example: demand side control with a washing machine (Larsen et al., 2013).

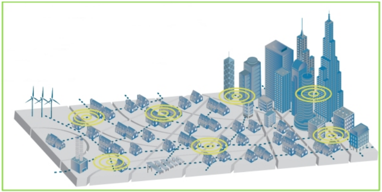
A network of households with Washing Machines



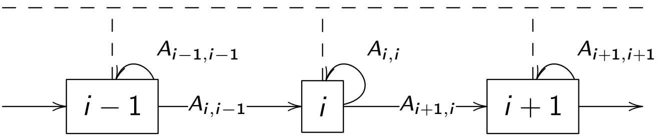
Decide about best starting time for washing machine:

- Suppose 50 % of the households do one wash per day
- Explore flexibility
- The household specifies end time T_{finish}
- Flatten net power load

Goal



- The households in the network is a subset of all households in the Power Network
- Two-way communication
- **Global goal:** flatten total power demand in the network
- **Local decision:** when to turn on the Washing Machine



- n households
- **Demand:** $d_i(k) = f_i(k) + g_i(k)$
- **Dynamics of Demand:** $d_i(k+1) = d_i(k) + u_i(k) + w_i(k)$
- Change in washing machine demand: $u_i(k) = f_i(k+1) - f_i(k)$
- Change in rest of demand: $w_i(k) = g_i(k+1) - g_i(k)$
- **Demand information:**
  $x_i(k+1) = A_{ii}x_i(k) + \sum_{æ \in N_i} A_{ij}x_j(k) + u_i(k) + w_i(k)$

Washing machine model - constraints $u_i(k)$

1. not loaded $\rightarrow$ can not run
2. not running $\rightarrow$ electric demand equals zero
3. starting $\rightarrow$ run until end of cycle
4. running $\rightarrow$ follow the demand pattern
5. at end of cycle $\rightarrow$ it stops and gets unloaded
6. loaded $\rightarrow$ forced to be finished within T_{finish} time-steps

Introduce binary variables and IF AND statements

$$\delta_i(k) = \begin{cases} 1 & \text{running}, \\ 0 & \text{otherwise}, \end{cases}$$

Num 3 as an example:

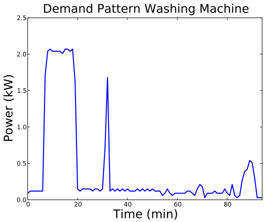
$$\delta_i(k) = 1 \bigwedge t_{i,\mathrm{on}}(k) < T_{program} \Rightarrow \delta_i(k+1) = 1$$

Implemented as:

$$\hat{\delta}_i(\tau)\, T_{program} - \hat{t}_{i,\mathrm{on}}(\tau) \le \hat{\delta}_i(\tau+1)\, T_{program}$$

Settings

- 50 % load a wash
- Wash must finish before: $T_{i,\mathrm{f}} = 4$ h 40 minutes
- Wash: 1h 30 minutes
- $\Delta k = 7$ minutes
- Simulation-time: $T_{\mathrm{end}} = 7$h
- $V = \sum_{k=0}^{T_{\mathrm{end}}} \sum_{i=1}^{n} [x_i(k) - a]^2$
- a = 0.5 kW
- $\gamma_{i,r} = 0.001$
- $|\lambda_{i,r}(\tau) - \lambda_{i,r-1}(\tau)| < 0.05$



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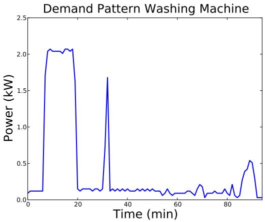

- $A = \begin{bmatrix} 0.6 & 0.2 & 0 & 0 & \cdots & 0.2 \\ 0.2 & 0.6 & 0.2 & 0 & \cdots & 0 \\ 0 & 0.2 & 0.6 & 0.2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & 0.2 & 0.6 & 0.2 \\ 0.2 & \cdots & 0 & 0 & 0.2 & 0.6 \end{bmatrix}$
- **NB:** non-convexity!

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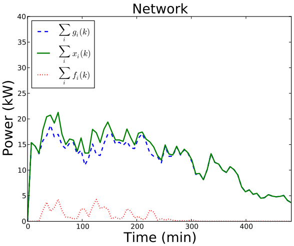
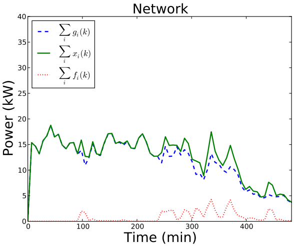
20 households - 10 washing machines





- V = 457.2 kW^2
- V = 403.6 kW^2

Green line: total demand. Blue dotted line: non-shiftable demand. Red dotted line: demand from washing machines.

Computations are well scalable.

Demand side control for washing machine feasible

Further study

- Must choose information exchange matrix A wisely.
- Multiple types of devices.
- Connect to local production of power as presented before. Ongoing work.

Demand side control for washing machine feasible

Further study

- Must choose information exchange matrix A wisely.
- Multiple types of devices.
- Connect to local production of power as presented before. Ongoing work.
- Scalability of simulations, so far simulations up to 10.000 households via parallel implementation goes well.
- Combination of hierarchical scheduling methods with distributed control, embedding in market structure $\rightarrow$ fit in Universal Smart Energy Framework.

Outline

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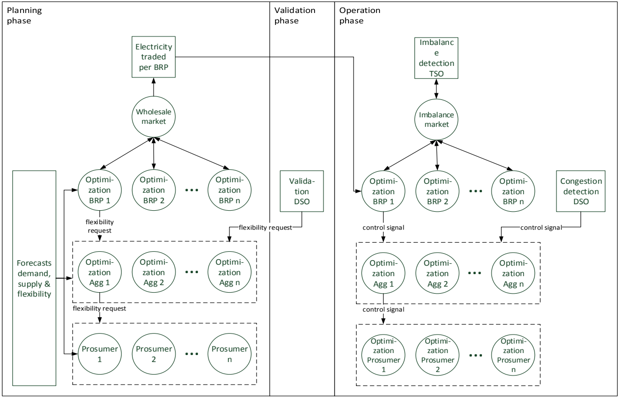
Market embedding

- Market in the Netherlands deregulated, separate price for network transport and energy delivery.
- Transport can be accounted for by choices in A matrix, i.e., low weight corresponds to expensive transport.
- However, supplier market is deregulated, physical neighbors may have different suppliers $\rightarrow$ how to embed distributed control algorithms?

Market embedding

Ongoing work to embed distributed algorithms in USEF (Universal Smart Energy Framework) → Collaboration within a consortium.



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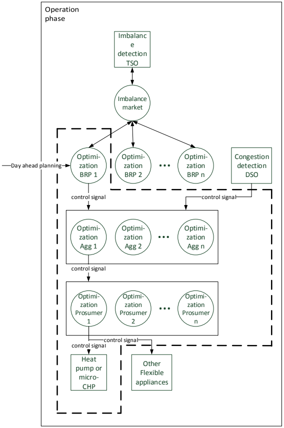
USEF in the operation phase



Ongoing work:

- Extra aggregator layer. Distributed control per layer, combined distributed and hierarchical control, how to guarantee performance?

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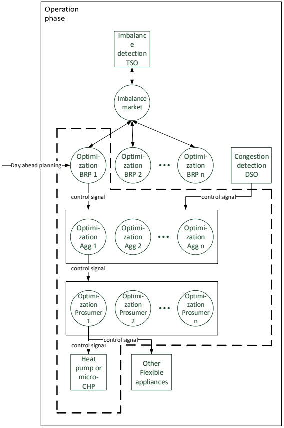

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- Goal function initialized from day ahead planning, and then adapted in the operation phase depending on the real loads. Depends on both fixed and flexible load. How to embed?

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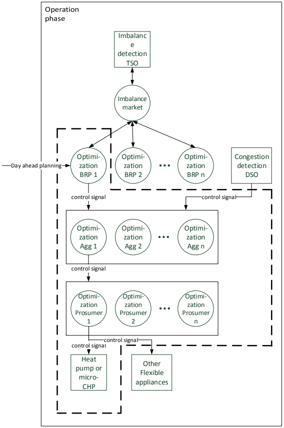

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- Role of DSO, put capacity limitations in constraints. Feasibility analysis needed.

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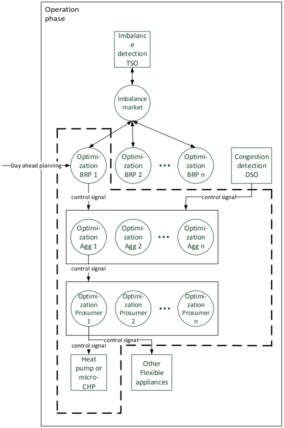

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- Role of DSO, put capacity limitations in constraints. Feasibility analysis needed.
- Collaboration between market parties?

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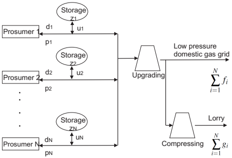
Outline

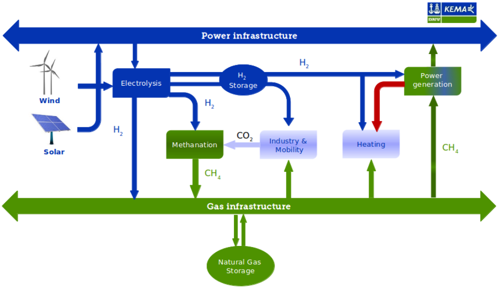
Smart gas grid project.

- Local farmers produce biogas.
- Optimize real costs.
- High, medium and low pressure gas grid.
- What is the optimal size of storage?
- Inclusion of lorry's picking up gas from farmers.
- Micro-grid for farmers, and connection to low pressure grid plus lorry's to control capacity. Alkano et al., 2014.



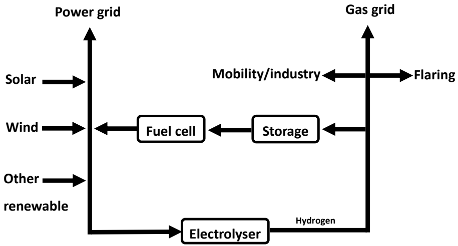
Distributed control with power to gas facilities

- Power to gas offers opportunities for storage of power in the form of hydrogen.
- Can be done locally.
- Hydrogen can be used for mobility/industry, injected into the natural gas grid (limited), or reconverted into electrical power.



Distributed control with power to gas facilities

Schematically, with distributed PtG facilities:



- Presentation tomorrow. Two layer optimization problem: maximize PtG's profit, and DSO's of three grids have to avoid overloading of grids. Builds on Biegel et al. 2012.

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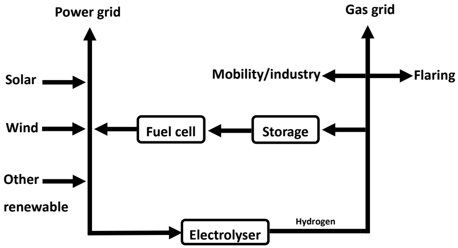

- Presentation tomorrow. Two layer optimization problem: maximize PtG's profit, and DSO's of three grids have to avoid overloading of grids. Builds on Biegel et al. 2012.
- Ongoing: asynchronous information exchange.

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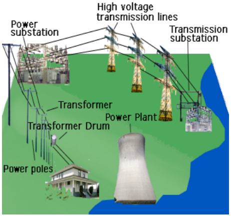
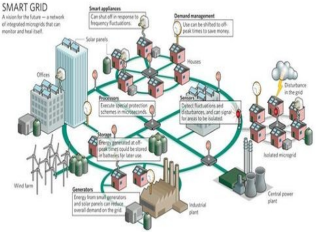
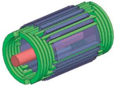
Two decoupled layers?

Outline

The grid and the synchronous machine







Future power grid,
EJC special issue
paper 2013.

The physics of the grid

From a power systems perspective:

- Models of the power systems (synchronous generators), interconnected via transmission lines (often approximated by pi models, a resistor, inductor and two grounded capacitors).

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- Models of the power systems (synchronous generators), interconnected via transmission lines (often approximated by pi models, a resistor, inductor and two grounded capacitors).
- Classical models used by power systems engineers not always suitable to study the embedding of renewables.
- Renewables embedding are known to cause large fluctuations, sometimes causing large, and not always predictable power outages.

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- Also, frequency deviations coupled to pricing mechanisms and stability for the swing equations (Jokic 2009, Bürger, De Persis, 2013, 2014).

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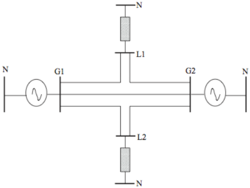
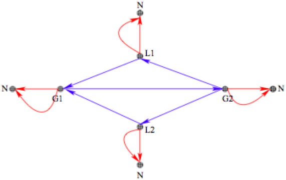
Power systems in the grid

Example network:



Corresponding graph:



The incidence matrix and the Kirchhof laws, together with the 8th order models of the synchronous generators provide a port-Hamiltonian model of the overall system.

A Port Hamiltonian model of the grid

States of a synchronous generator:

- 3 phase rotor and stator flux linkages (6 in total) ψ_r, ψ_s.
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Inputs:

- Electrical field E_f.
- Mechanical torque T_m.

Together with the incidence matrix, a PH model is obtained.

Equilibrium points and stability analysis

- No equilibrium points, i.e., angle constantly changes for a fixed frequency.
- Angle difference between generators.
- Stability analysis not straightforward from Hamiltonian, also not after Park-Blondel transformation.
- Possible for synchronous machine connected to an infinite bus (SMIB) under assumptions that some losses are zero, with help of forced Hamiltonian systems analysis (Maschke et al., 2000).

Lyapunov function

$$V(x) = H(x) - \left(\frac{E_f \psi_f}{r_f} + T_m \tan^{-1}\left(\frac{\psi_q}{\psi_d}\right)\right)$$

with ψ_q, ψ_d, ψ_f transformed fluxes.

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Only valid for SMIB case. Ongoing investigation how to use Hamiltonian for multi-machine case. Under restrictive assumptions studied by Caliskan, Tabuada, 2014.

Utility optimization

Model is rather complex.

- To consider utility optimization, a PH model can also be made of the swing equations, only taking the mechanical structure into account. Inverters (for e.g. the coupling of solar panels to the AC grid) and load models can be added as well (Monshizadeh, De Persis 2015, Stegink et al. 2015).

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However, all static optimizations, dynamics not taken into account yet. Topic of ongoing work.

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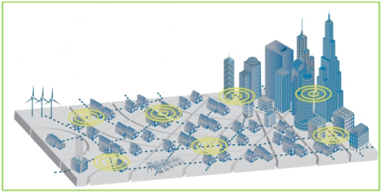

QUESTIONS?