Eidgenössische Technische Hochschule Zürich
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Evaluation of Benefits from Flexibility Measures and their Integration in Power Systems Operation and Markets

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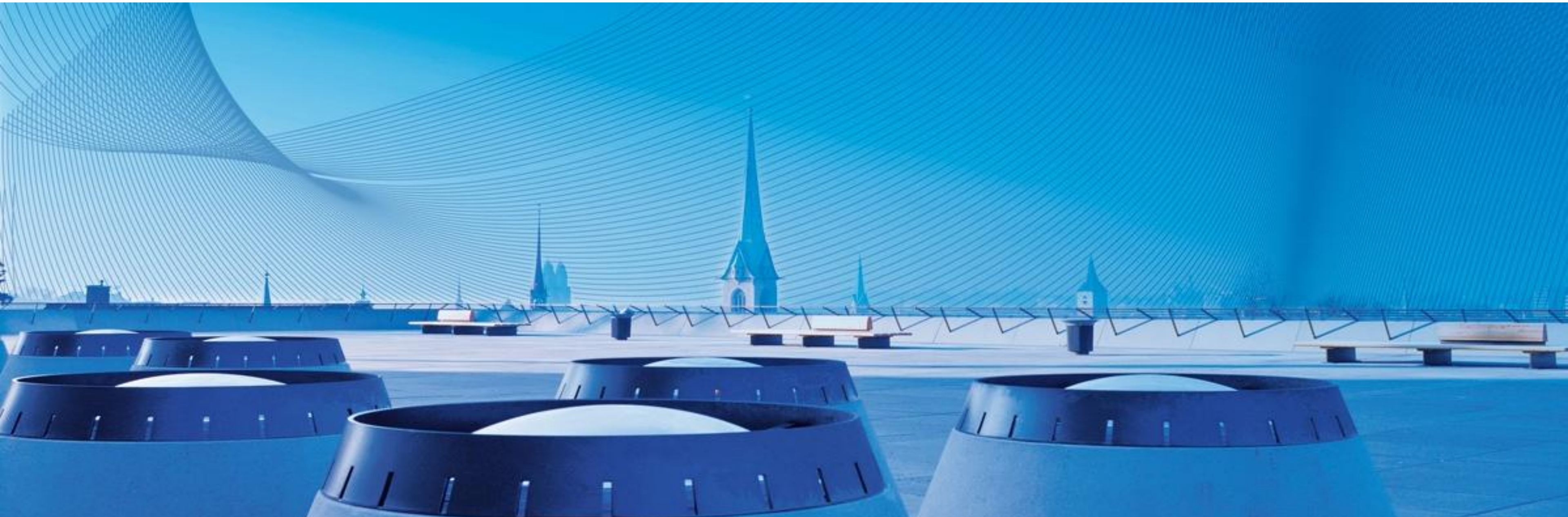


11th International Workshop on Electric Power Control Centers (EPCC 2011), Altea, Spain, 22-25 May 2011

Introduction

- Presentation of on-going research work done at the Power Systems Laboratory (PSL) of the Swiss Federal Institute of Technology (ETH Zurich)

- Research work financed through the EU FP7 Research Project „Infrastructure Roadmap for Energy Networks in Europe (IRENE-40)“
  - 4-year project (2009-2012)
  - Several partners from academia and power system manufacturers

IRENE-40.eu
Future European Energy Networks

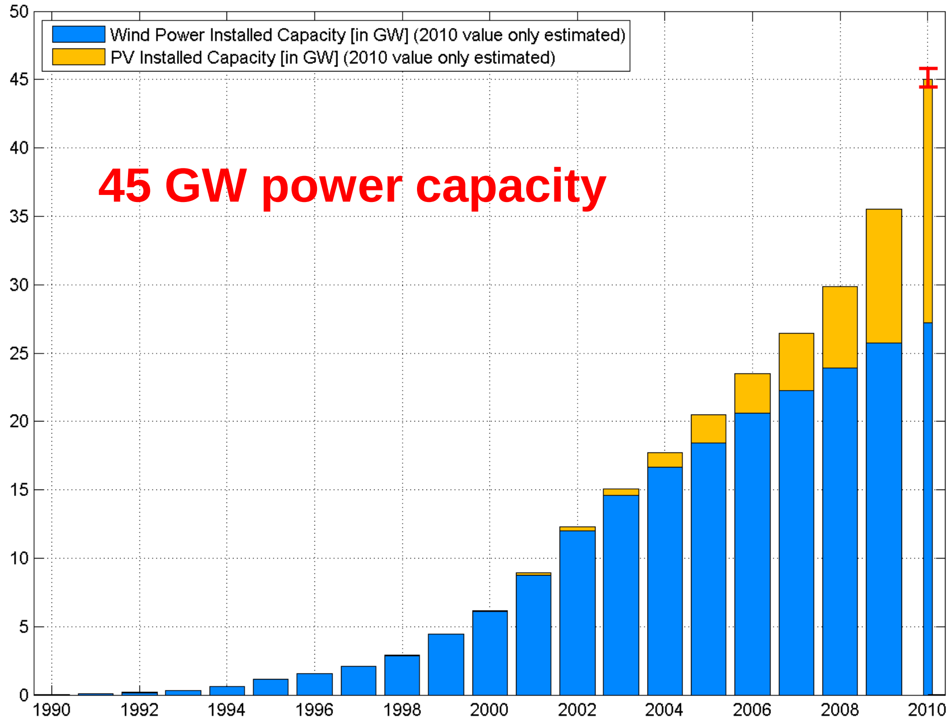
Topics of this talk

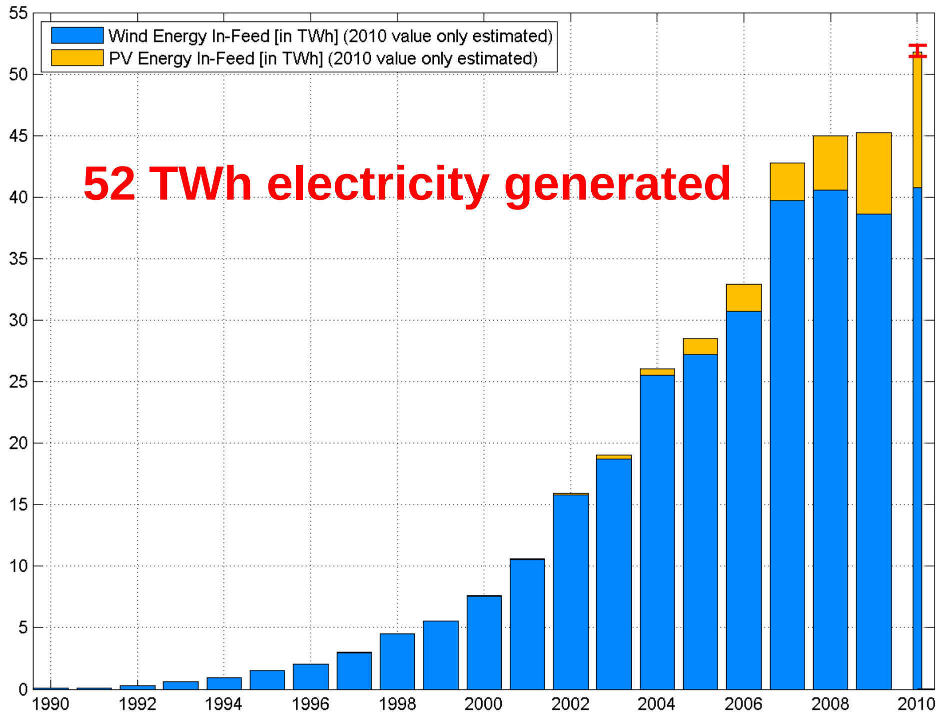
- Rapid growth of (from TSO side) non-controlled processes in transmission grid:
  - Increasing RES deployment (= stochastic power in-feed)
    - Issues: non-deterministic power imbalances, power flow changes
    - Indirectly: must-run generation (ancillary services)
  - Increasing power market activities (on European level)
    - Issues: deterministic (transient) power imbalances, more frequent power flow changes.

- Slow grid capacity expansion for coping with the increasing demands.

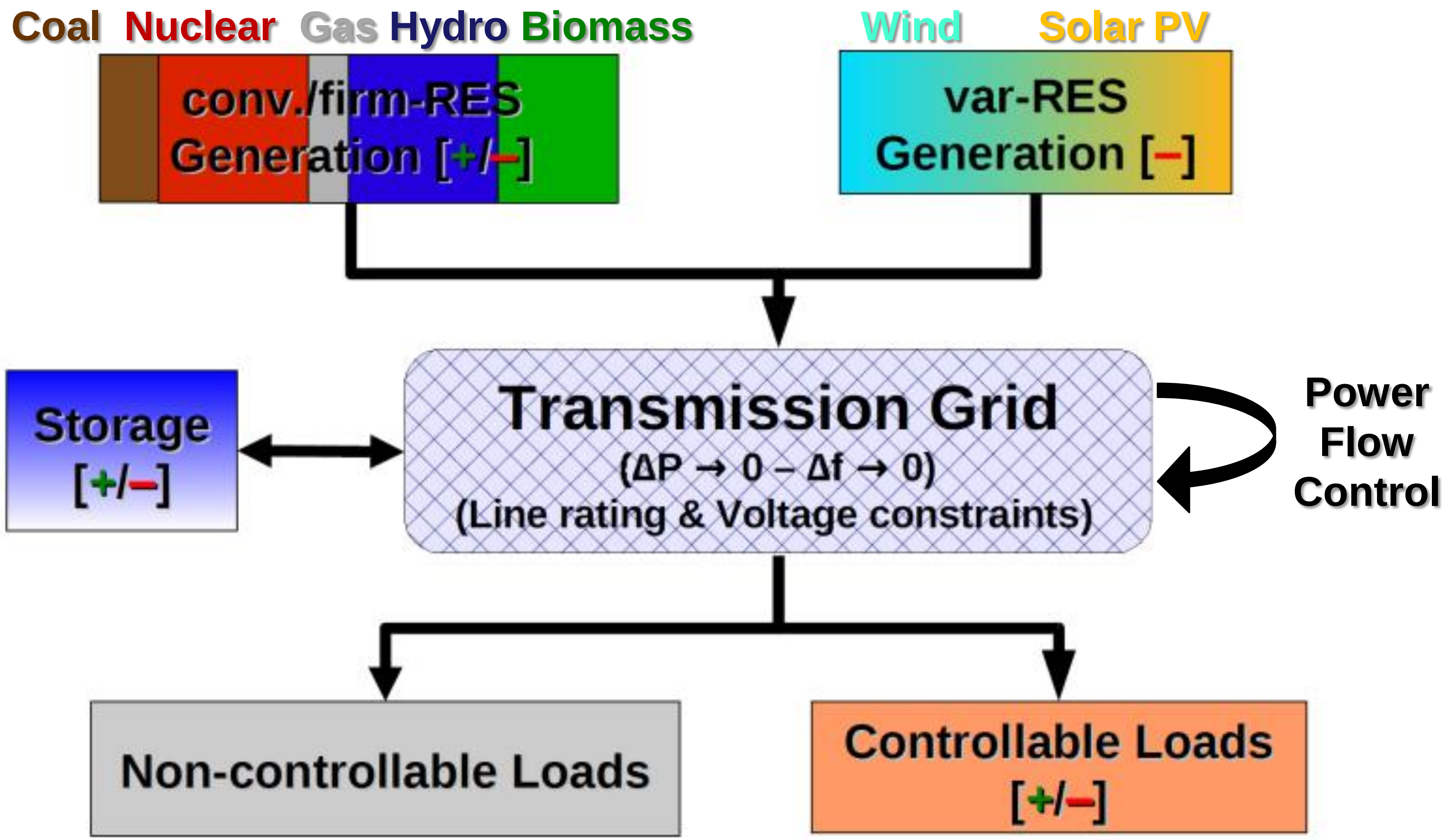
Topics of this talk

- Rapid growth of (from TSO side) non-controlled processes in transmission grid
    - Increasing RES deployment (= stochastic power in-feed)
    - Germany 2010: (45GW, 52TWh ≈ 10% of total gen.)

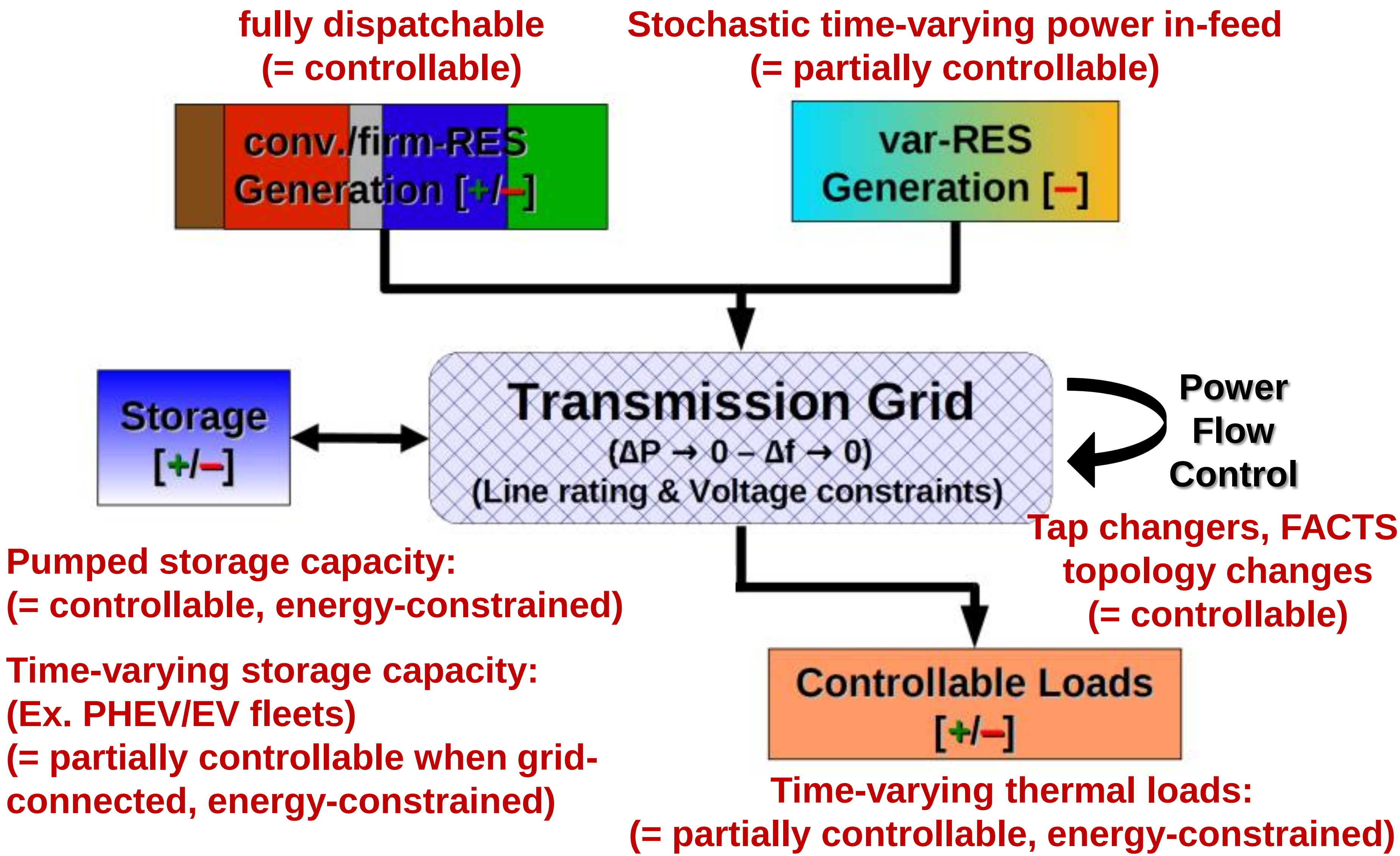




Transmission Grid as Control Problem



Transmission Grid as Control Problem



Controllability/Flexibility in Power System Operation

- Increased controllability over power system processes (electricity generation and demand) beneficial for TSOs.
- Means higher flexibility for TSOs for coping with disturbances in system operation („*more knobs that can be turned*")

- Examples:
  - Ability to curtail stochastic RES in-feed (Wind, PV).
  - Ability to modulate electricity demand of controllable loads (DSM)
  - Ability to use time-varying storage capacity (PHEV/EVs)

- Enabling such control abilities constitutes an ancillary service (AS) of the power system unit operator for the TSO.

Important Questions to Ask

- How can such control abilities over formally non-controlled power system processes be realised? Technically and within legal frameworks …?

  ⟶ **aggregator concept / ancillary service manager**

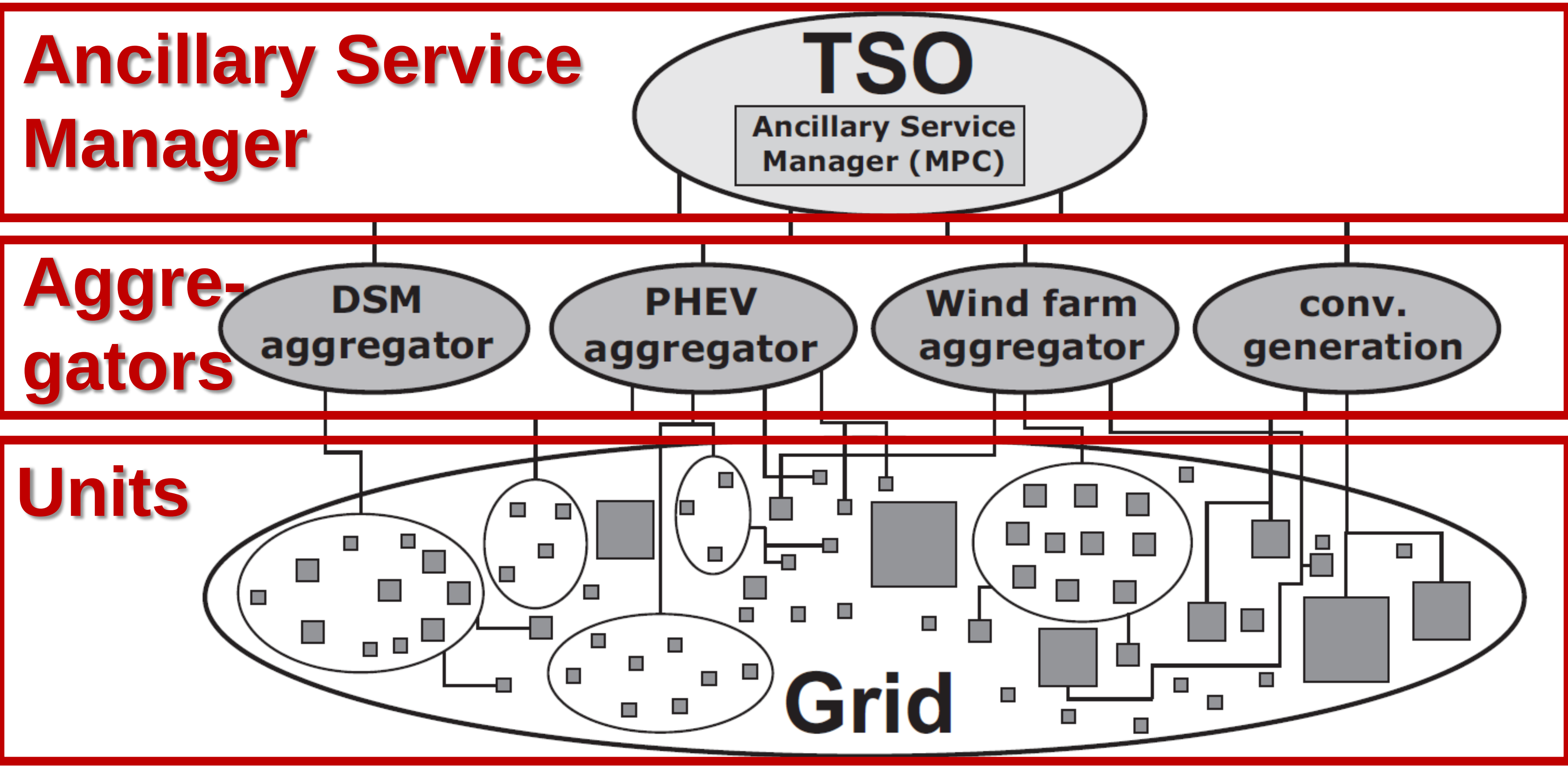
- How can such controllability services (needing short-term predictions, offering only time-varying controllability) be integrated into existing AS frameworks?

  ⟶ **some suggestions for AS auctioning schemes**

- What is the value of such controllability services for power system operation, i.e. for the TSO?

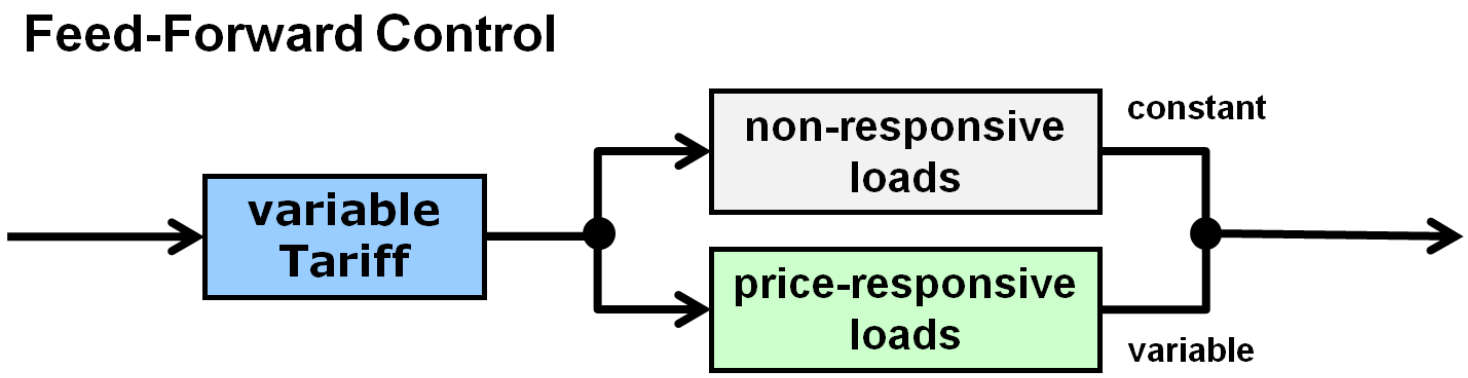
  ⟶ **Power Nodes modelling and evaluation framework**

Ancillary Service Manager – Communication Structure



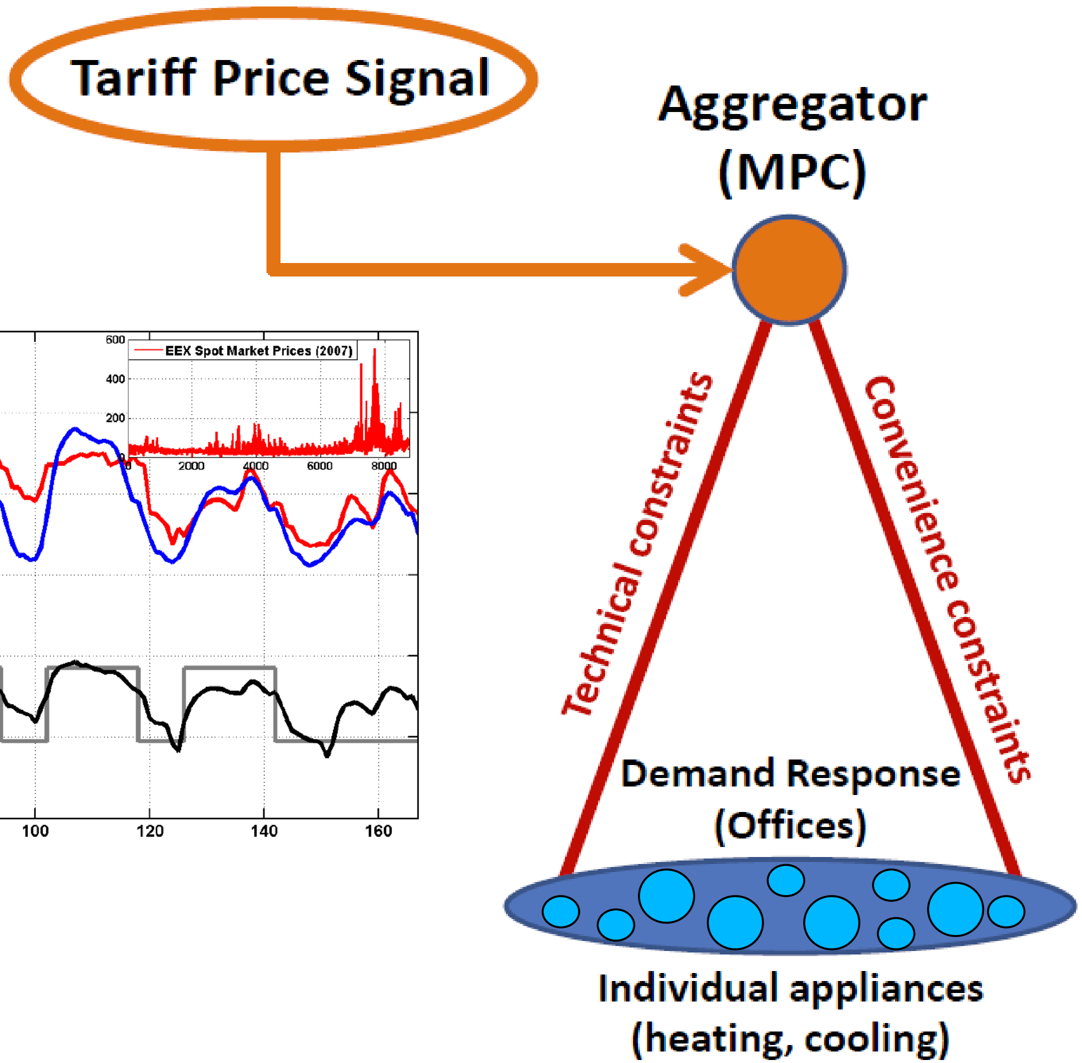
Aggregator Examples: Demand Side Management

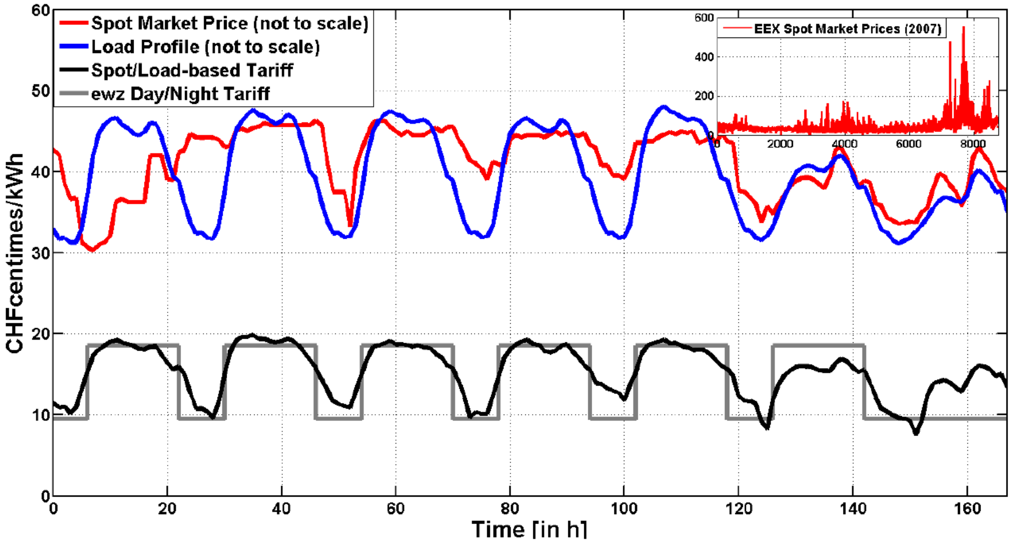
- Variable tariff is needed to induce incentive for load shifting (= control signal for price-responsive loads)



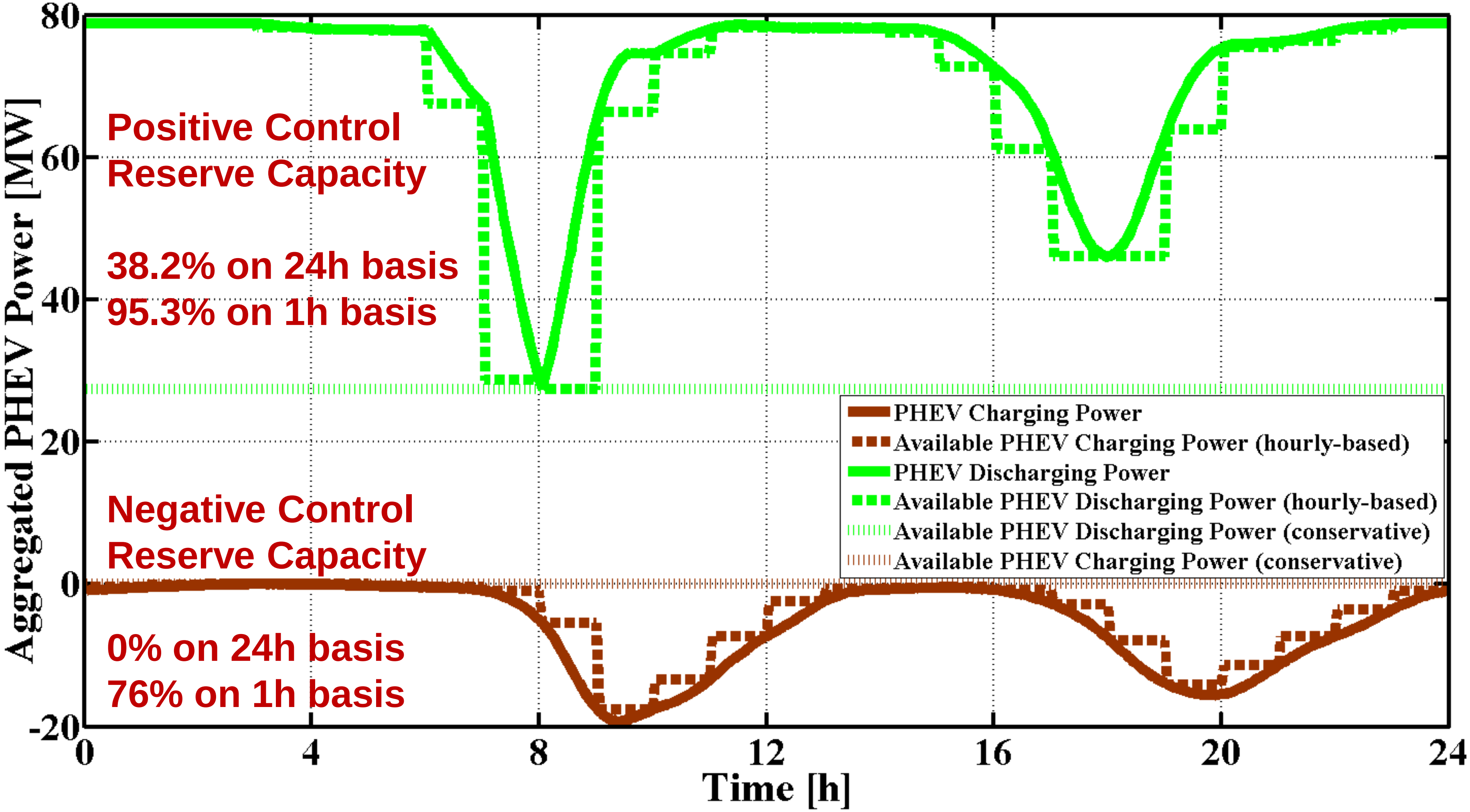
- Using different benchmark tariffs for studying DR (load shifting, peak load reduction)

Aggregator Examples: Demand Side Management





Aggregator Example: Fluctuating Availability of PHEV/EV Charging/Discharging Power (25,000 cars)



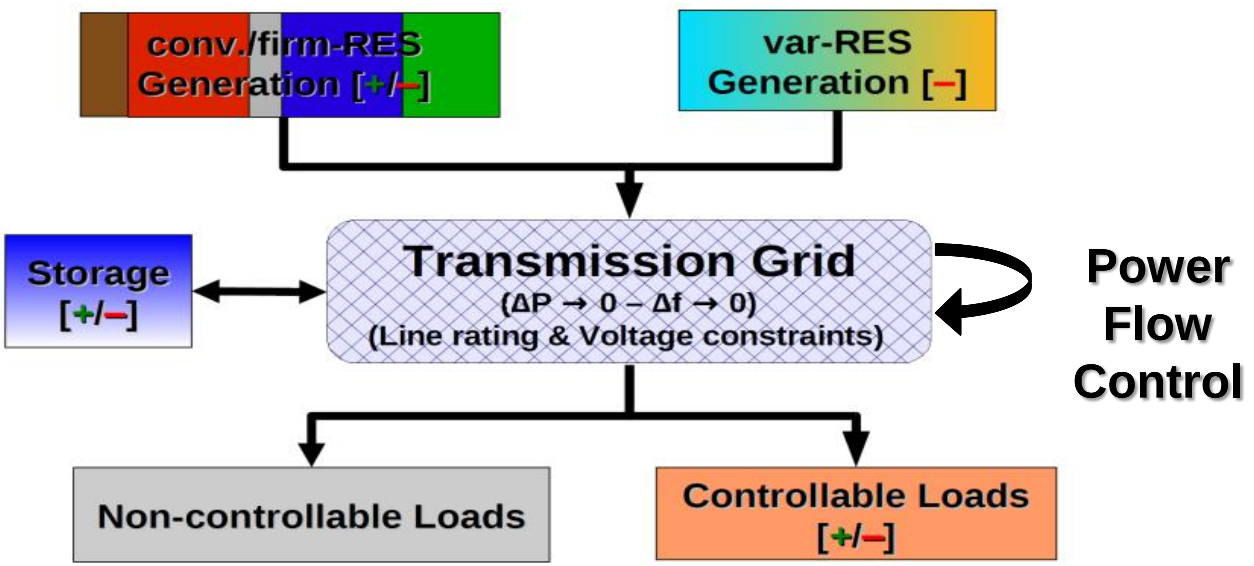
Ulbig, Galus, Chatzivasileiadis, Andersson, IREP 2010

Integration of Supplementary Control Reserves

- **Today&Future:** Growing shares of
  - fluctuating power in-feed, i.e. wind turbines, PV panels
  - controllable thermal loads, i.e. heat pumps, water heaters,
  - fluctuating storage capacity, i.e. battery capacity of PHEV/ EV fleets (predicted).
- **Beneficial:** If yet untapped control reserve capacities could be integrated into ancillary services (AS) schemes, i.e.
  - increasing TSO controllability over power in-feed and out-feed processes.
- **Prerequisite:** Flexible ancillary services schemes.
  - daily/hourly-based ancillary service (AS) procurement (instead of weekly/monthly-based AS auctions)
  - AS auctions closer to real-time (day-ahead / hour-ahead)

Power Nodes Modelling and Evaluation Framework

- In order to evaluate the benefits of additional control abillities (=flexibility measures), a framework is needed for modelling the relevant controlled&non-controlled processes in power systems operation

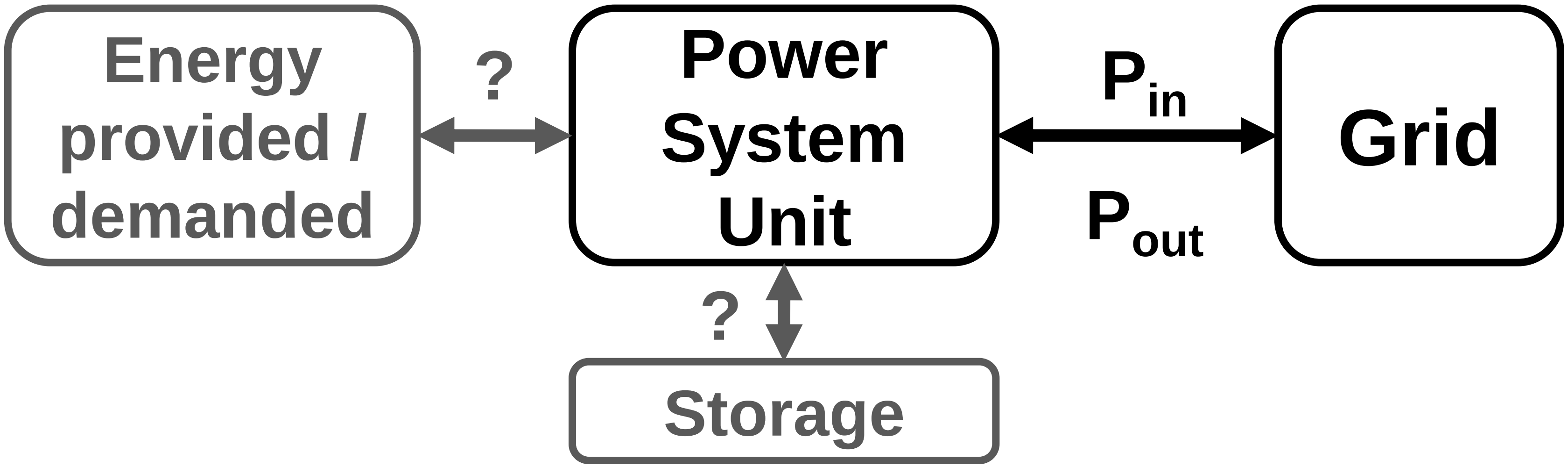


Status Quo in Power Systems Modelling

- Traditional power system modeling is „fractional“
- Separate models are used for capturing information of
  - Transmission & distribution grid (topology, voltage & frequency dynamics, voltage & line limits)
  - Power generation (generator dynamics, ramp constraints, wind and PV in-feed predictions)
  - Load models (dynamics, load demand predictions)
  - Storage models (capacity, storage levels, dynamics)
- Modelled interaction between individual power system units and grid does not necessarily capture all relevant aspects

Status Quo in Power Systems Modelling

- Example: optimal power dispatch simulations do consider units that inject or absorb power from the grid.
  - Which of these units are storages (energy-constrained)?
  - Which of these units provide stochastic power in-feed?
  - What controllability (full / partial / none) does the operator have over stochastic generation and demand processes?



Motivation for Power Nodes Modelling Framework

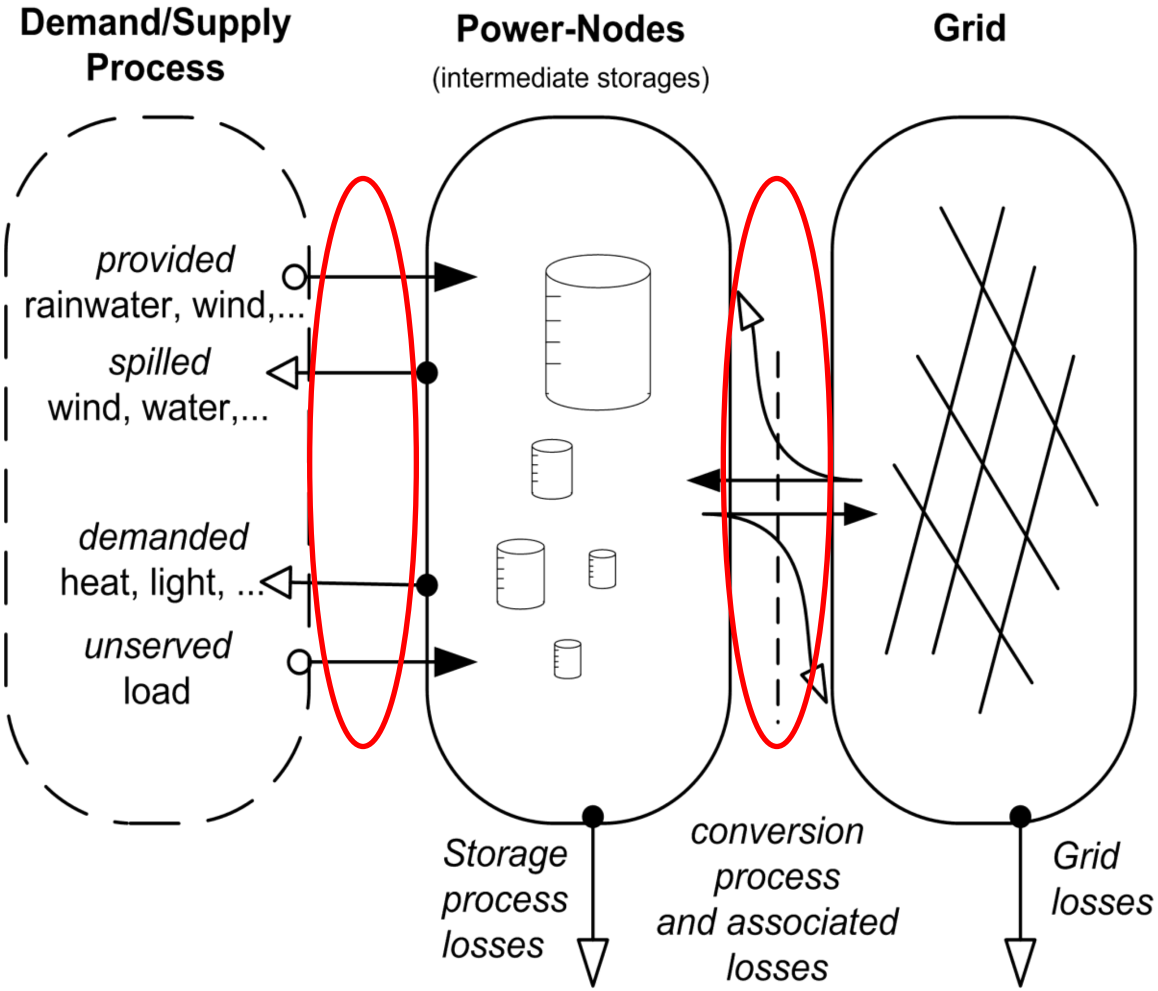
- Create unified framework for modelling power system units (incl. relevant operation constraints, power supply and demand processes and the controllability)
  - Diverse storage units (battery, pumped hydro, …)
  - Diverse generation units (fully dispatchable conventional generators, stochastic in-feed of wind turbines and PV)
  - Diverse load units (conventional, interruptible, thermal, ...)
- **Operation constraints:** ramp rates, storage capacity, current storage level (SOC)
- **Controllability over power system processes (=“flexibility“):** A given process is either fully controllable, curtailable / sheddable, non-controllable or has time-varying controllability.

Goals of Power Node Approach

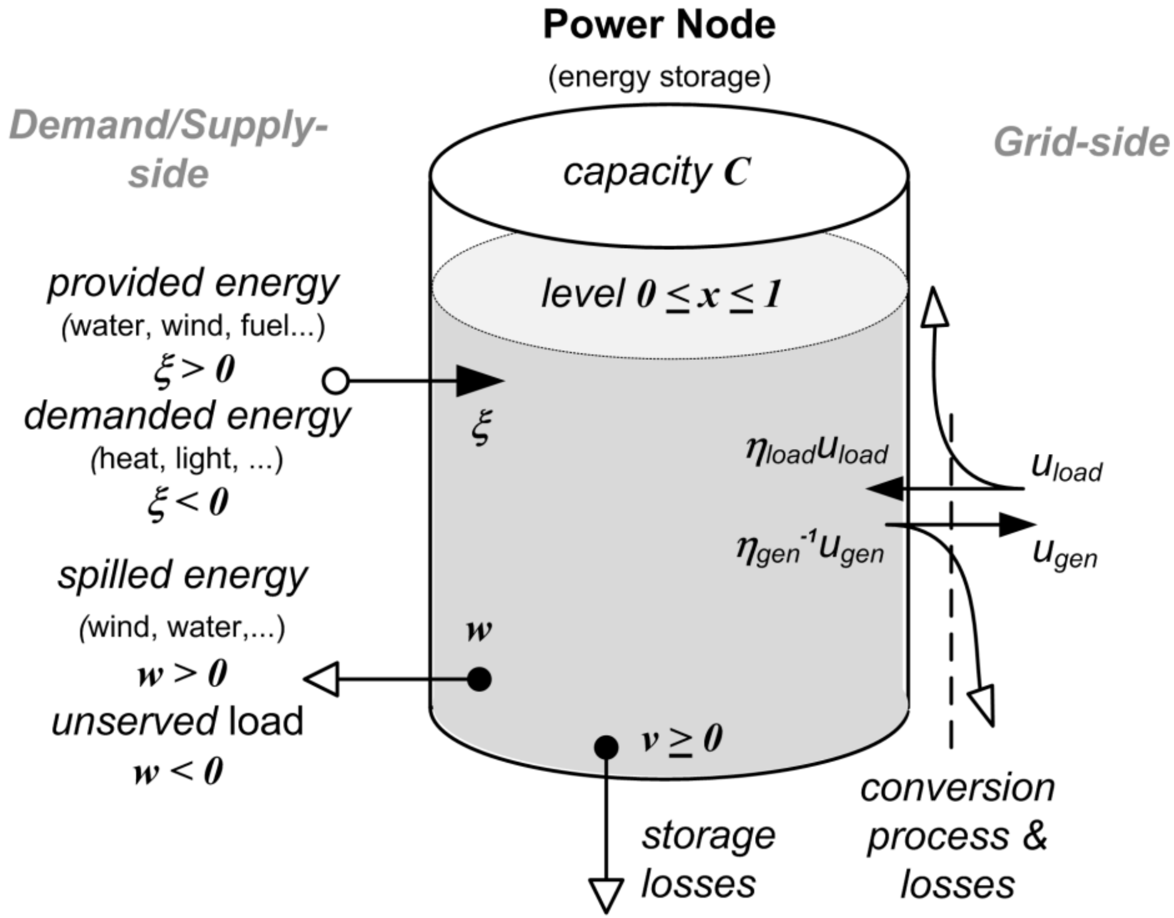
- Goal is to better evaluate performance of power system operation and to improve performance
  - Storage utilisation (What is its best use?)
  - Integrating stochastic power in-feed
  - Integrating demand-side management (DSM)
  - Reduce forced ramping of conventional generators for load following and balancing of stochastic power in-feed
  - Performance criteria
    - power system operation cost
    - curtailment of RES in-feed
    - Power system CO_2 emissions

The Power Nodes Framework

- Modelling of three domains and their interactions

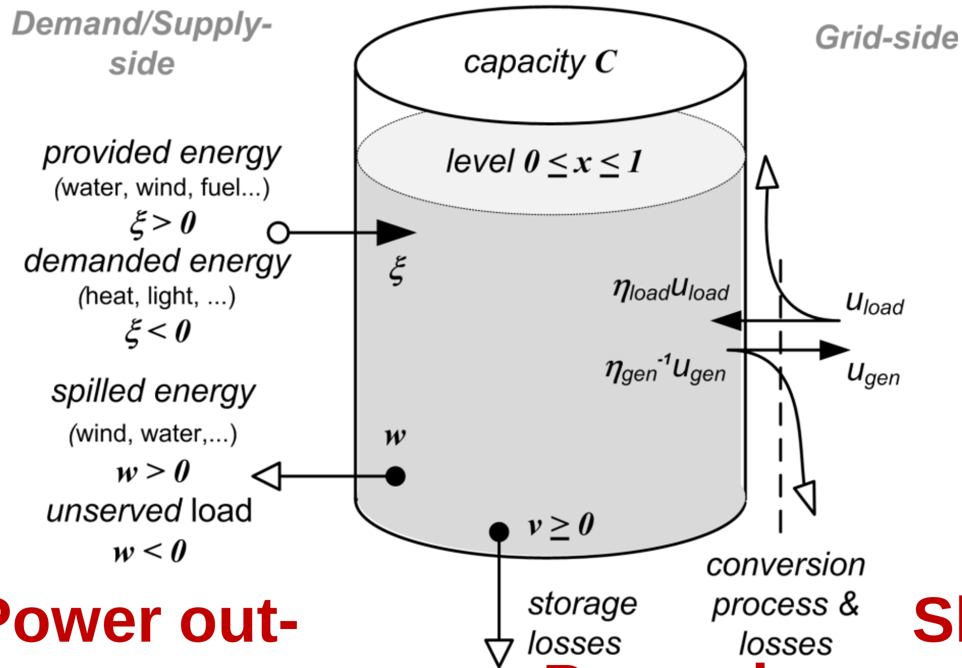


One Power Node



$$C_i \dot{x}_i = \eta_{load_i} u_{load_i} - \eta_{gen_i}^{-1} u_{gen_i} + \xi_i - w_i - v_i$$

One Power Node



Storage capacity × state-of-charge

Power out-feed from grid

Power in-feed to grid

Shedding term

Internal losses

$$C_i \dot{x}_i = \eta_{load_i} u_{load_i} - \eta_{gen_i}^{-1} u_{gen_i} + \xi_i - w_i - v_i$$

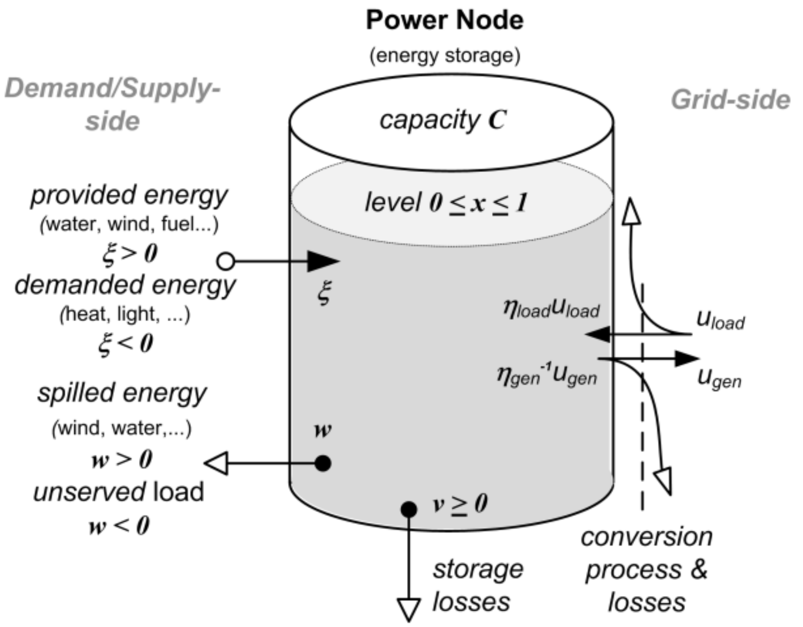
Efficiency factors

Provided / demanded power

One Power Node (including constraints)

$$C_i\,\dot{x}_i \quad = \quad \eta_{\mathrm{load},i}\,u_{\mathrm{load},i} - \eta_{\mathrm{gen},i}^{-1}\,u_{\mathrm{gen},i} + \xi_i - w_i - v_i,$$

$$\begin{aligned} \text{s.t. } & 0 \leq x_i \leq 1 \quad , \\ & 0 \leq u_{\mathrm{gen},i}^{\min} \leq u_{\mathrm{gen},i} \leq u_{\mathrm{gen},i}^{\max} \\ & 0 \leq u_{\mathrm{load},i}^{\min} \leq u_{\mathrm{load},i} \leq u_{\mathrm{load},i}^{\max} \\ & 0 \leq \xi_i \cdot w_i \quad , \\ & 0 \leq |\xi_i| - |w_i| \quad , \\ & 0 \leq v_i \quad \forall\, i = 1, \ldots, N \quad . \end{aligned}$$



- Power constraints defined by: min/max power, ramp rates, storage capacity
- Operation flexibility defined by: shedding term w_i, storage term $C_i\, x_i$, ξ_i

Power Node Modelling Example:

Joint Provision of Load Frequency Control

Convenient representation: Control signal modelled as a load to be served

Battery storage

$$C_{\text{Bat}}\Delta\dot{x}_{\text{Bat}} = \eta_{\text{load,Bat}}\Delta u_{\text{load,Bat}} - \eta^{-1}_{\text{gen,Bat}}\Delta u_{\text{gen,Bat}}$$

Controllable Thermal Load

$$C_{\text{CL}}\Delta\dot{x}_{\text{CL}} = \eta_{\text{load,CL}}\Delta u_{\text{load,CL}} - a(\Delta x_{\text{CL}} - \Delta x_{\text{CL,0}}) + \Delta\zeta_{\text{CL}}$$

Controllable Generator

$$\eta^{-1}_{\text{gen,CG}}\Delta u_{\text{gen,CG}} = \Delta\xi_{\text{gen,CG}}$$

$\Delta u_{\text{load, Bat}}$, $\Delta u_{\text{gen, Bat}}$, $\Delta u_{\text{load, CL}}$, $\Delta u_{\text{gen, CG}}$, $\Delta u_{\text{load, LFC}}$

Secondary Frequency Controller

$$\Delta u_{\text{load,LFC}} = \hat{P}_{\text{LFC}} \cdot Y_{\text{LFC}}$$

Y_{LFC} : control signal [-100%, +100%]

$\hat{P}_{\text{LFC}}$: offered control band [MW]

Power Balance:

$$\Delta u_{\text{gen, Bat}} + \Delta u_{\text{gen, CG}} - \Delta u_{\text{load, Bat}} - \Delta u_{\text{load, CL}} = \Delta u_{\text{load, LFC}}$$

Power Node Modelling Examples

PV with local storage unit, RES feed-in tariff

PV Panel

$$\eta_{\mathrm{gen,PV}}^{-1} u_{\mathrm{gen,PV}} = \xi_{\mathrm{gen,PV}}$$

$u_{\mathrm{gen,PV}}$

$u_{\mathrm{load,Grid,RES}}$ (subject to RES FIT)

Node 1

P_{12}

Node 2

Battery storage

$$C_{\mathrm{Bat}} \dot{x}_{\mathrm{Bat}} = \eta_{\mathrm{load,Bat}} u_{\mathrm{load,Bat}} - \eta_{\mathrm{gen,Bat}}^{-1} u_{\mathrm{gen,Bat}}$$

$u_{\mathrm{load,Bat}}$

$u_{\mathrm{gen,Bat}}$

Controllable Thermal Load

$$C_{\mathrm{CL}} \dot{x}_{\mathrm{CL}} = \eta_{\mathrm{load,CL}} u_{\mathrm{load,CL}} - a(x_{\mathrm{CL}} - x_{\mathrm{CL,0}}) + \zeta_{\mathrm{CL}}$$

$u_{\mathrm{load,CL}}$

Non-Controllable Local Load

$$\eta_{\mathrm{load,NCL}} u_{\mathrm{load,NCL}} = -\xi_{\mathrm{load,NCL}}$$

$u_{\mathrm{load,NCL}}$

Power Grid

$$u_{\mathrm{gen,Grid}} - u_{\mathrm{load,Grid}} - u_{\mathrm{load,Grid,RES}} = \xi_{\mathrm{Grid}}$$

(additional variable for FIT energy)

$u_{\mathrm{gen,Grid}}$

$u_{\mathrm{load,Grid}}$

This enables the modelling of differentiated feed-in tariffs incl. options for local PV energy usage (e.g. Germany).

Power Node Modeling Example: Predictive Dispatch

- Conventional generation unit [6]
- Conventional (uncontrolled) load [1] + load predictions
- Pumped-hydro storage units [4+5] and flexible loads (DSM) [7]
- Wind/PV units (curtailable) [2-3] + Wind/PV power in-feed predictions

$$\xi_1 - w_1 = -\eta_{load,1}\, u_{load,1}$$

$$\xi_2 - w_2 = \eta_{gen,2}^{-1}\, u_{gen,2}$$

$$\xi_3 - w_3 = \eta_{gen,3}^{-1}\, u_{gen,3}$$

$$C_4\, \dot{x}_4 = \eta_{load,4}\, u_{load,4} - \eta_{gen,4}^{-1}\, u_{gen,4}$$

$$C_5\, \dot{x}_5 = \eta_{load,5}\, u_{load,5} - \eta_{gen,5}^{-1}\, u_{gen,5}$$

$$\xi_6 = \eta_{gen,6}^{-1}\, u_{gen,6}$$

$$C_7\, \dot{x}_7 = \eta_{load,7}\, u_{load,7} + \xi_7 - a_7\, (x_7 - x_{ss,7})$$

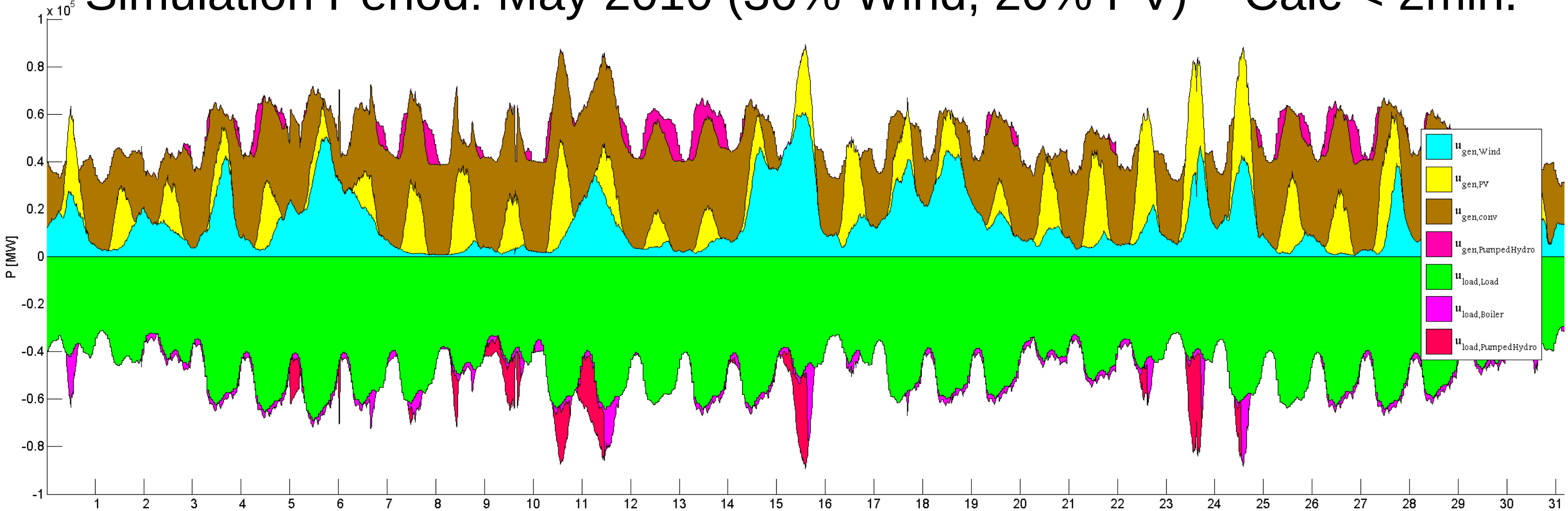
Power Node Modeling Example: Predictive Dispatch

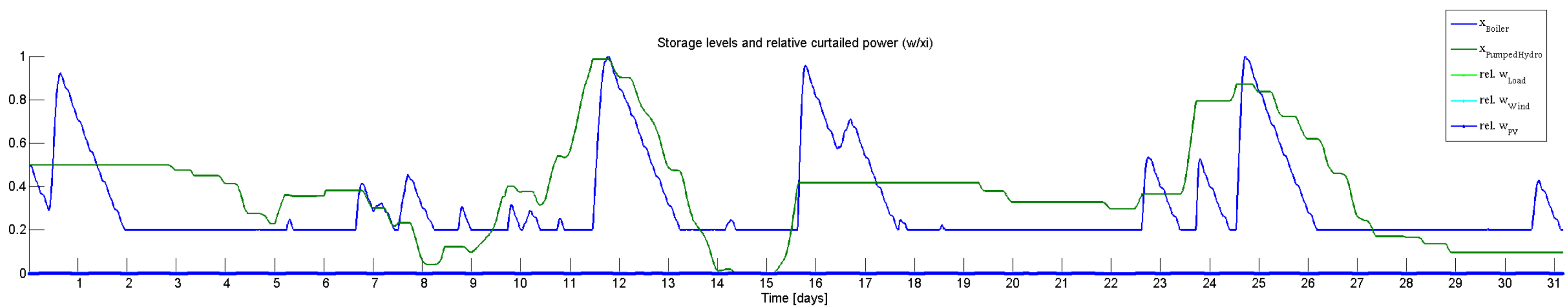
$$\begin{aligned}
\min J(k) \quad = \quad & \sum_{l=k}^{l=k+N-1} (x(l) - x_{ref})^T \cdot Q_x \cdot (x(l) - x_{ref}) \\
& + u(l)^T \cdot Q_u \cdot u(l) + R_u \cdot u(l) \\
& + \delta u(l)^T \cdot \delta Q_u \cdot \delta u(l) \\
\text{s.t.} \quad (a) \quad & x(l+1) = A \cdot x(l) + B \cdot u(l) \\
(b) \quad & 0 \le x^{min} \le x(l) \le x^{max} \le 1 \\
(c) \quad & 0 \le u^{min} \le u(l) \le u^{max} \\
(d) \quad & \delta u^{min} \le \delta u(l) \le \delta u^{max} \\
(e) \quad & \xi_1(l) = \xi_{drv,1}(l \cdot T) \\
(f) \quad & \xi_2(l) = \xi_{drv,2}(l \cdot T) \\
(g) \quad & \xi_3(l) = \xi_{drv,3}(l \cdot T) \\
(h) \quad & \xi_7(l) = \xi_{drv,7}(l \cdot T) \\
(i) \quad & u_{gen,4}(l) \cdot u_{load,4}(l) = 0 \\
(j) \quad & u_{gen,5}(l) \cdot u_{load,5}(l) = 0 \\
(k) \quad & \sum_{i=\{2,3,4,5,6\}} u_{gen,i}(l) - \sum_{i=\{1,4,5,7\}} u_{load,i}(l) = 0 \\
(a\text{-}k) \quad & \forall l = \{k, \ldots, k+N-1\}
\end{aligned}$$

- Power balance at all times
- Demand and RES power in-feed forecasts: 72h ahead
- Optimisation based on marginal generation costs (including ramping costs)
- For now: Copperplate simplification
- Representation of transmission and distribution grid constraints (line capacity, voltage): *work in progress*

Optimal predictive power dispatch (Germany)

- $T_{pred.}$ = 72h, $T_{upd.}$ = 4h, T_{sample}= 15min.
- Simulation Period: May 2010 (30% Wind, 20% PV) – Calc < 2min.

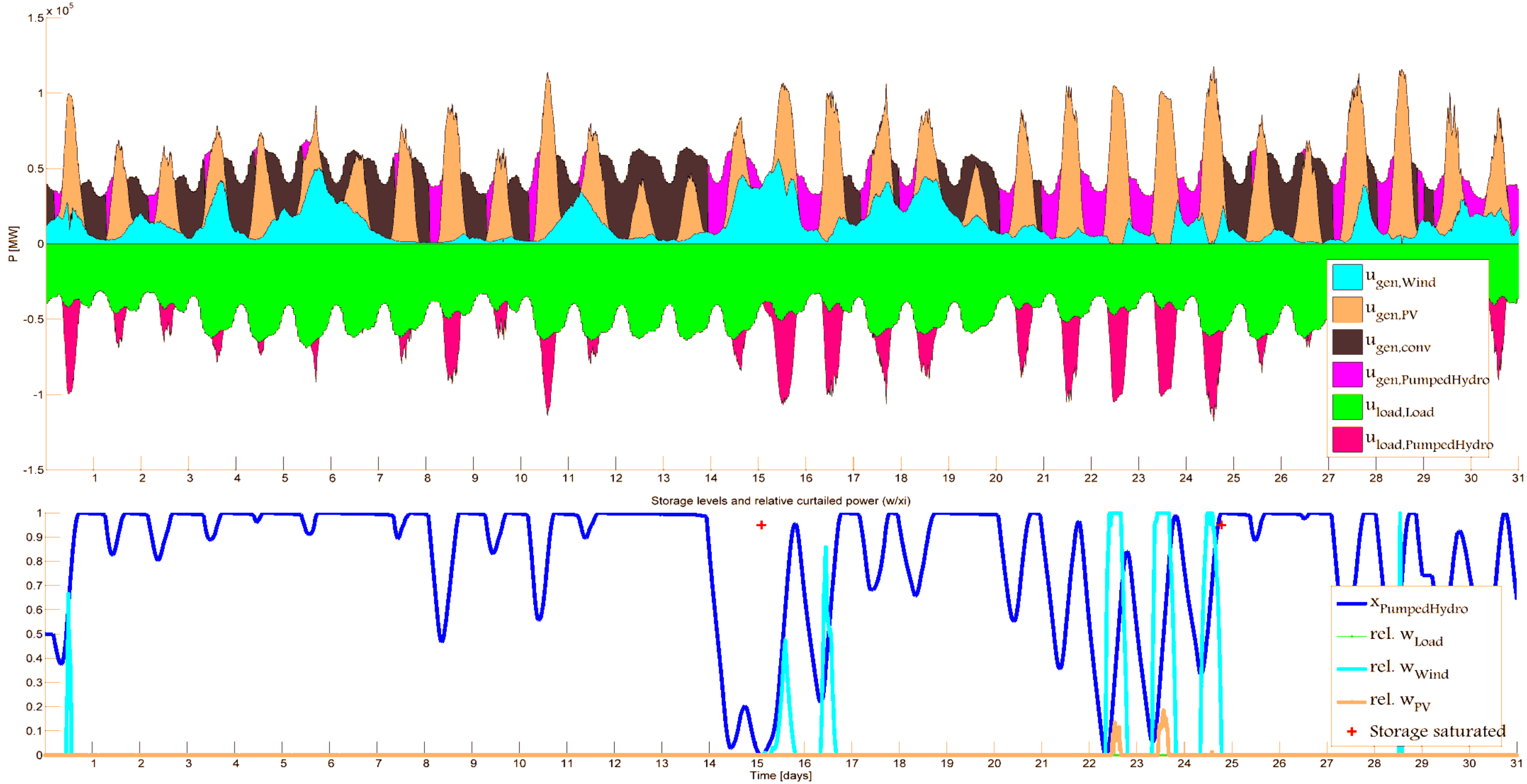




- Evaluation of balance terms (May 2010)

Balance Term	Value [GWh]
Electricity consumed by loads	36440.1
Electricity produced by conventional generator	19808.1
Wind generation – fed into grid	10935.4
Wind generation – curtailed	0.00002
PV generation – fed into grid	7290.2
PV generation – curtailed	0.00001
Warm-water heater – Load	1515.7
Pumped hydro storage – Generation	1134.0
Pumped hydro storage – Load	1211.9

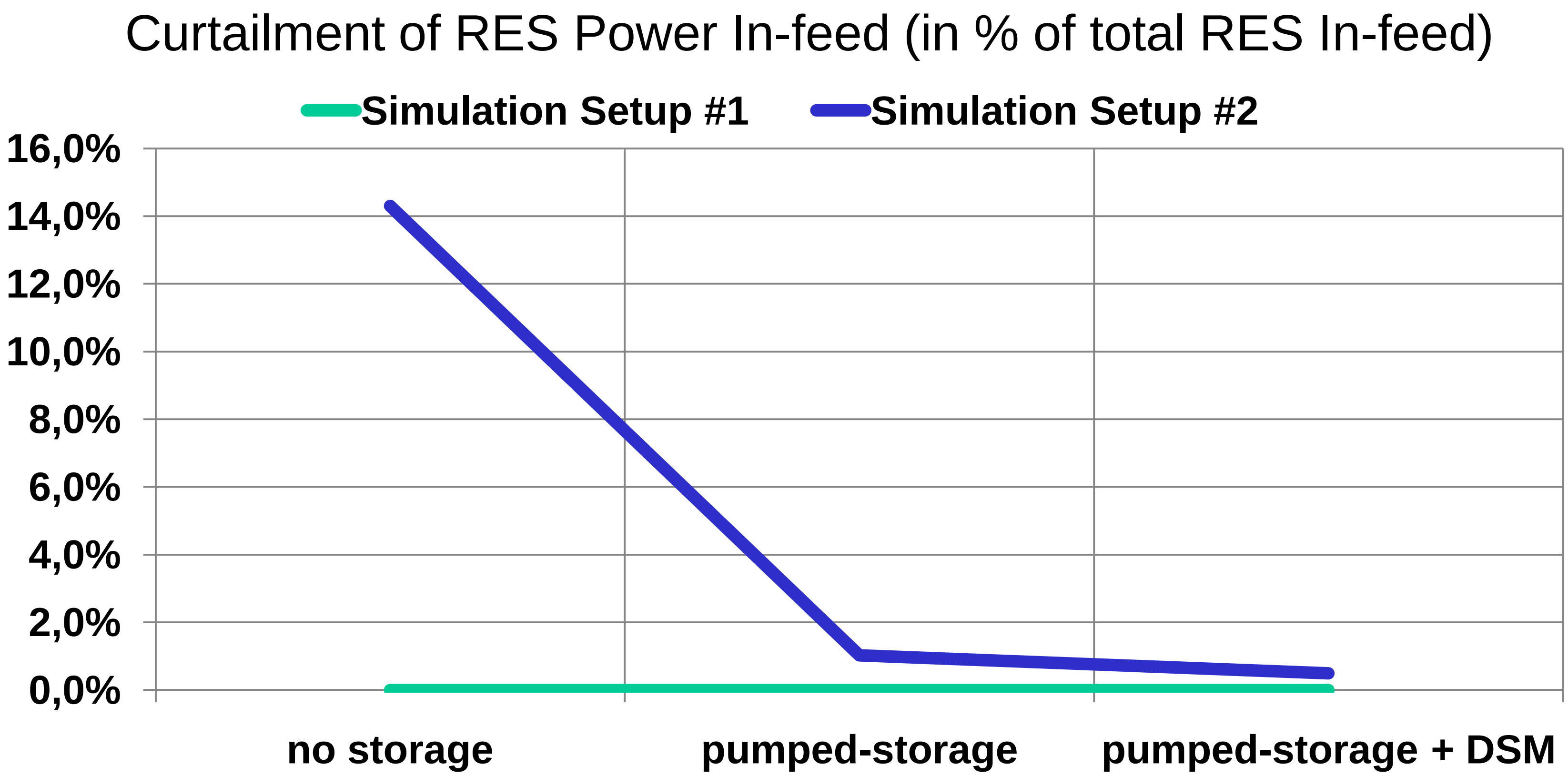
- Optimal predictive power dispatch (Germany, **high PV**)
- $T_{pred.}$ = 72h, $T_{upd.}$ = 4h, T_{sample}=15min.
- Simulation Period: May 2010 (30% Wind, **50% PV no DSM**)



- Evaluation of balance terms (May 2010)
- Case: 30%Wind, **50% PV**, **no DSM**

Balance Term	Value [GWh]
Electricity consumed by loads	36450.0
Electricity produced by conv. generator	9482.4 (≈48%)
Wind generation – fed into grid	10062.8
Wind generation – curtailed	**872.6**
PV generation – fed into grid	18111.9 (≈248%)
PV generation – curtailed	**113.1**
Warm-water heater – Load	not available
Pumped hydro storage – Generation	4810.1 (≈424%)
Pumped hydro storage – Load	6017.2 (≈496%)

- Optimal predictive power dispatch (Germany)
- Sim. Setup #1: full year 2010 (8.5% Wind, 1.5% PV) – Calc: <20min.
- Sim. Setup #2: full year 2010 (30% Wind, 20% PV) – Calc: <20min.
- Pumped storage (7GW, 40GWh) and warm water heater (24GW, 9GWh)



Thank you for your interest.

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