Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

eeh power systems laboratory

A Modeling Framework for Future Energy Systems

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Content

- Energy Hub

  - Multi energy-carrier systems

- Power Node

  - Incorporation of fluctuating power sources
  - Incorporation of demand side participation
  - Incorporation of storage

The Energy Hub

$$\mathbf{L}+\mathbf{M}=\mathbf{C}\left[\ \mathbf{P}-\mathbf{Q}\ \right]$$

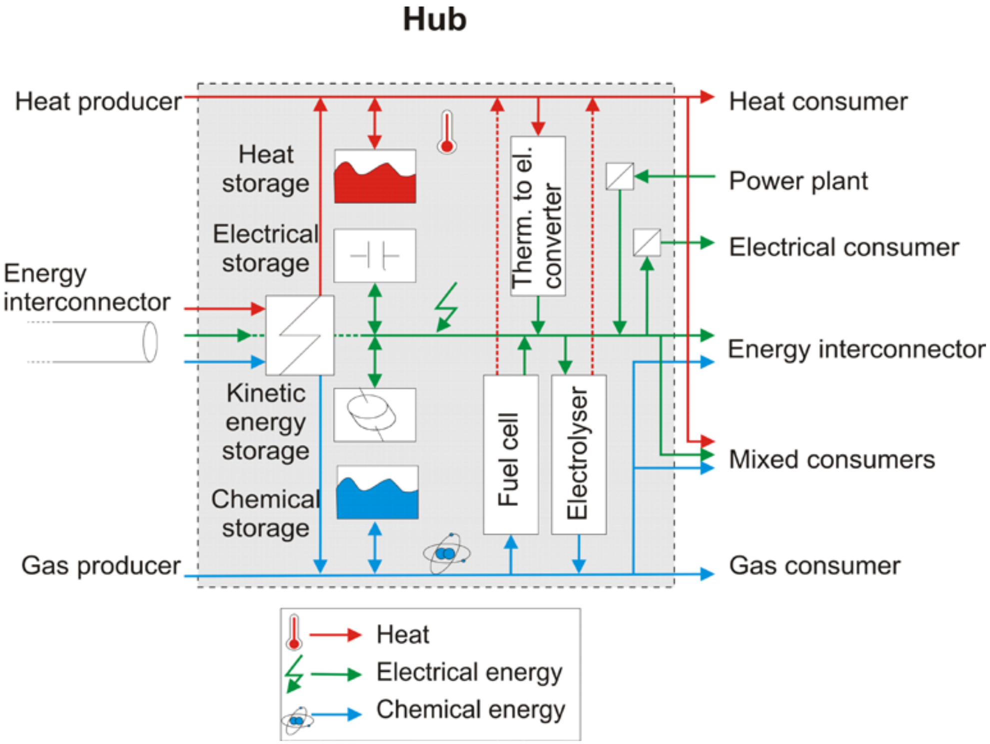
L = Loads (Output)

M = Output side storage flows

C = Coupling matrix

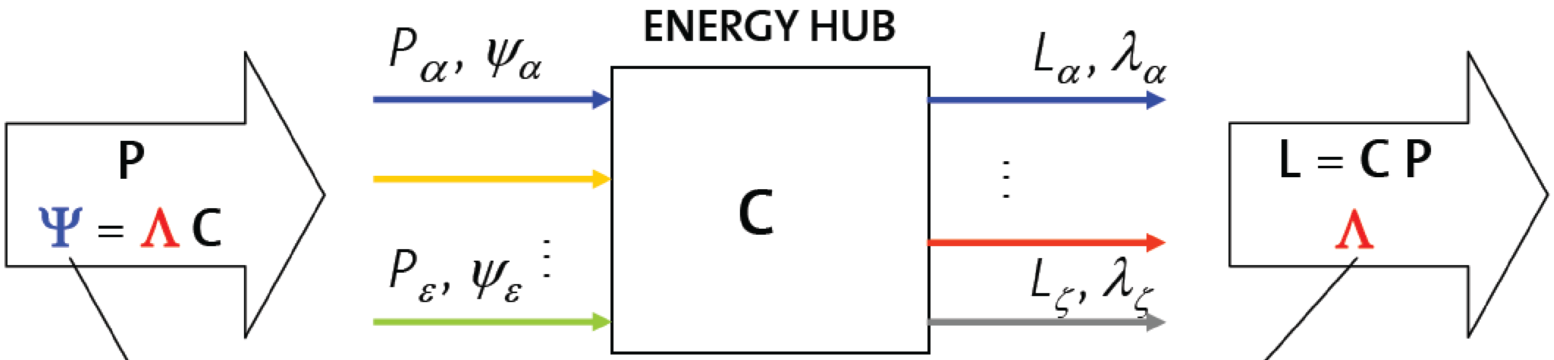
P = Input power flows

Q = Input storage flows



Hub Equations and Results

- Power conversion ⇔ price conversion



P

$\Psi = \Lambda C$

$L = C P$

Λ

system marginal prices

hub marginal prices

Applications (so far)

- Long term energy planning of the city of Bern
- Energy planning of several Swiss municipalities
- Analysis of e-mobility
- Energy/Exergy analysis of city of Zürich
- …

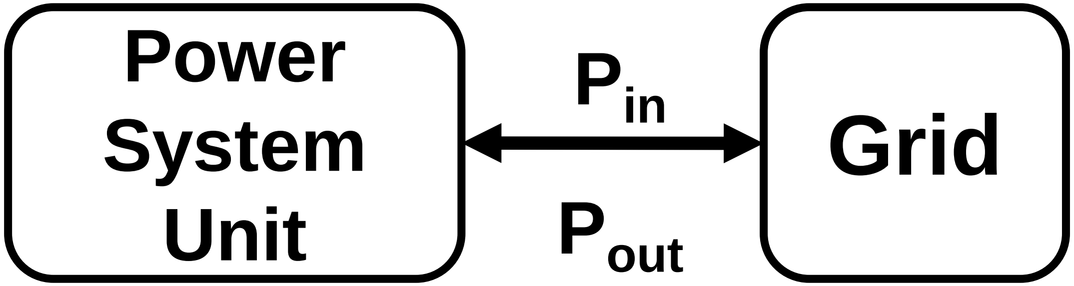
Status Quo in Power Systems Modelling

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
- No interaction with other energy carriers modeled (cf Energy Hub)

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 fluctuating power in-feed?
    - What controllability (full / partial / none) does the operator have over fluctuating generation and demand processes?



Status Quo in Power Systems Modelling

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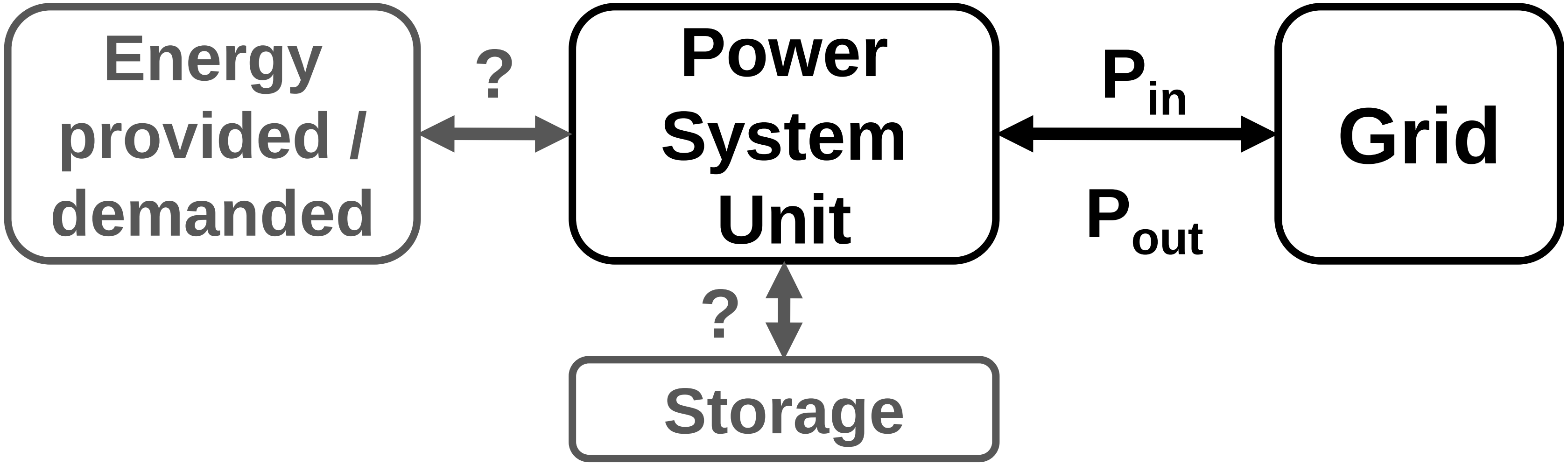
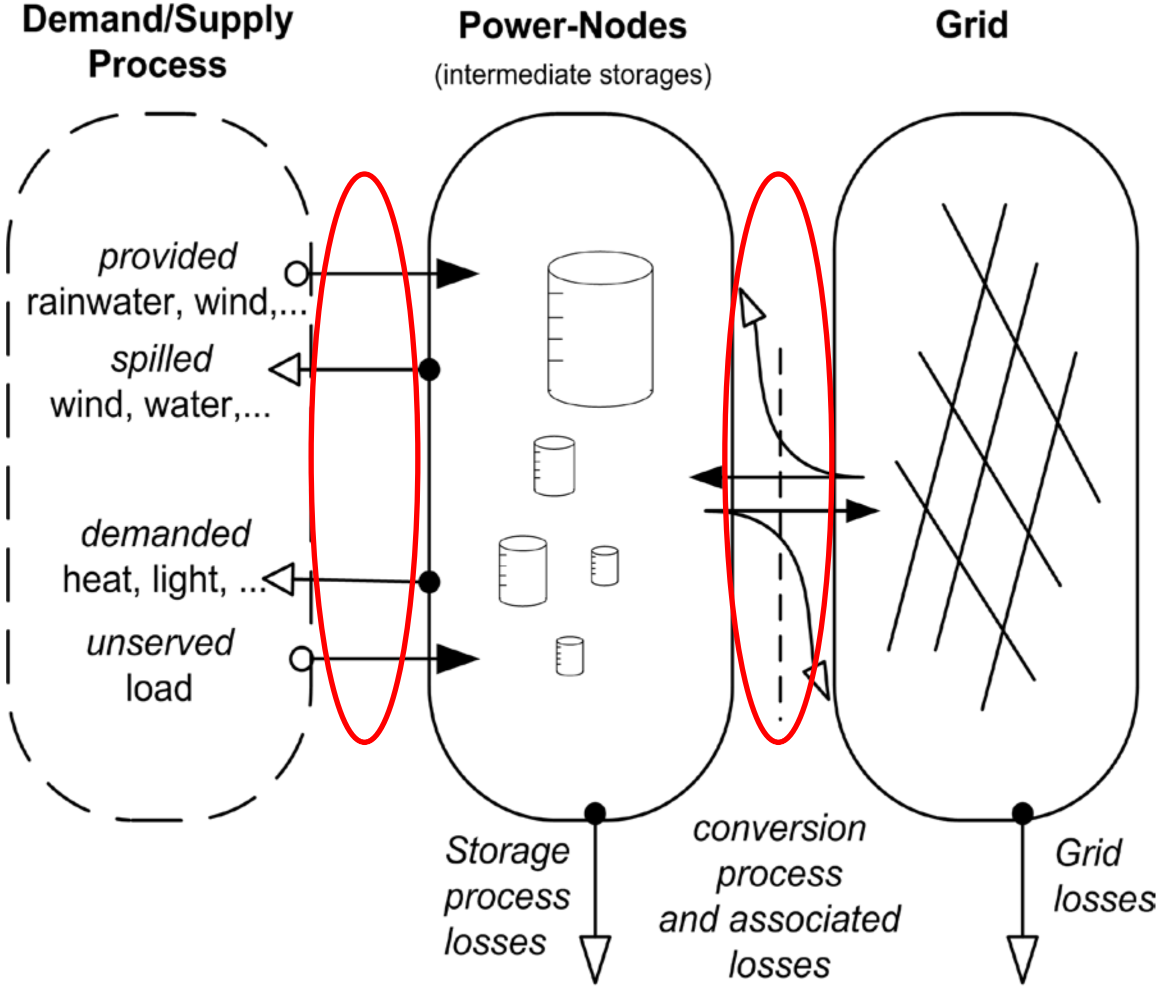


Motivation for Power Nodes Modeling Framework

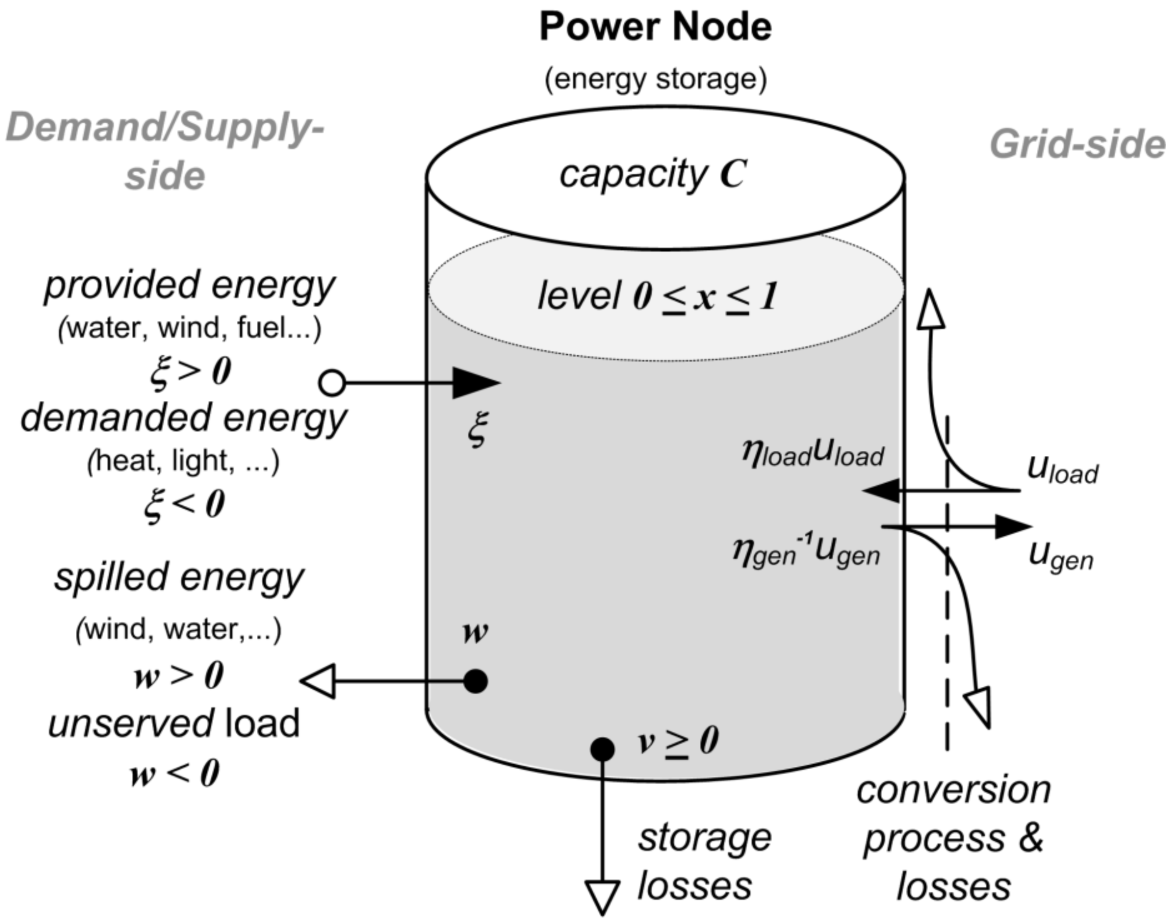
- Create unified framework for modeling power system units (incl. relevant operation constraints, power supply and demand processes and the controllability)
    - Diverse storage units (battery, pumped hydro, …)
    - Diverse generation units (fully dispatchable conventional generators, fluctuating in-feed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

The Power Nodes Framework

- Modeling of three domains and their interactions

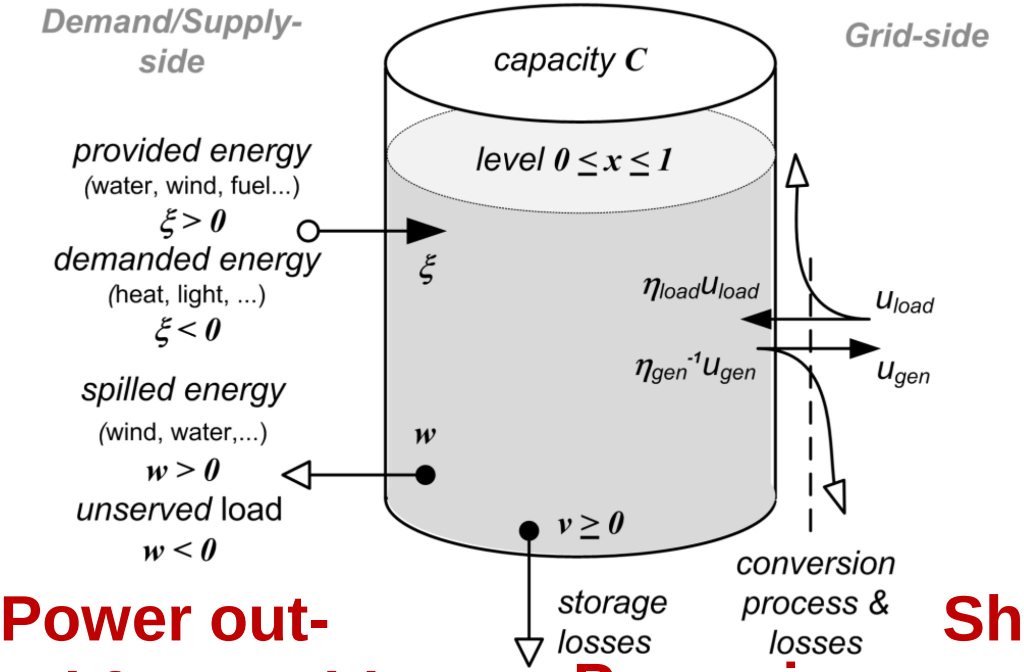


One Power Node



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

One Power Node



Storage capacity × state-of-charge

Internal losses

Power out-feed from grid

Shedding term

Power in-feed to grid

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

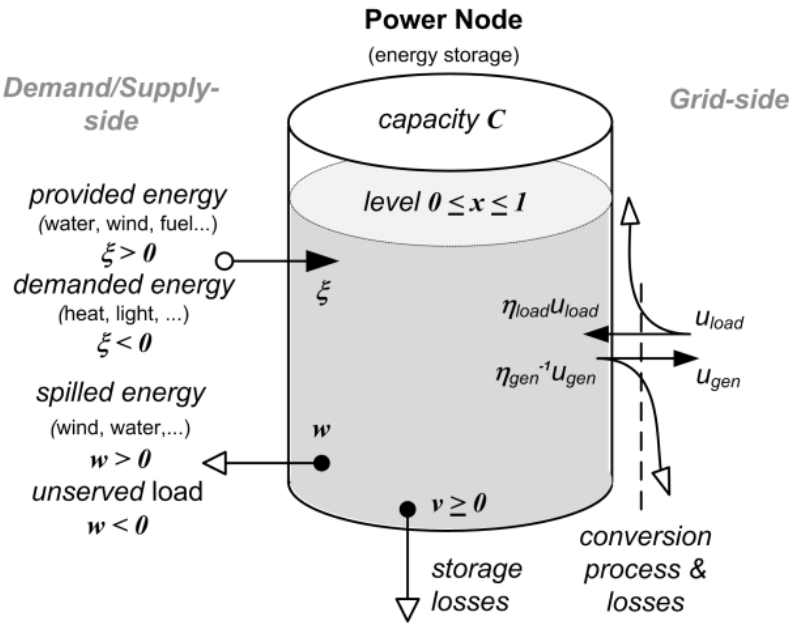
Efficiency factors

Provided / demanded power

One Power Node (including constraints)

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

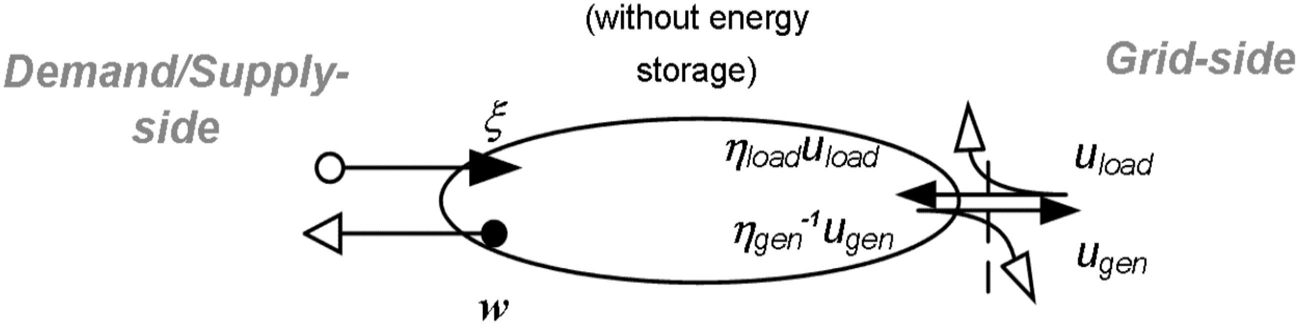
$$\begin{aligned}
\text{s.t. } & 0 \le x_i \le 1 \quad , \\
& 0 \le u_{\text{gen},i}^{\min} \le u_{\text{gen},i} \le u_{\text{gen},i}^{\max} \\
& 0 \le u_{\text{load},i}^{\min} \le u_{\text{load},i} \le u_{\text{load},i}^{\max} \\
& 0 \le \xi_i \cdot w_i \quad , \\
& 0 \le |\xi_i| - |w_i| \quad , \\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



- 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

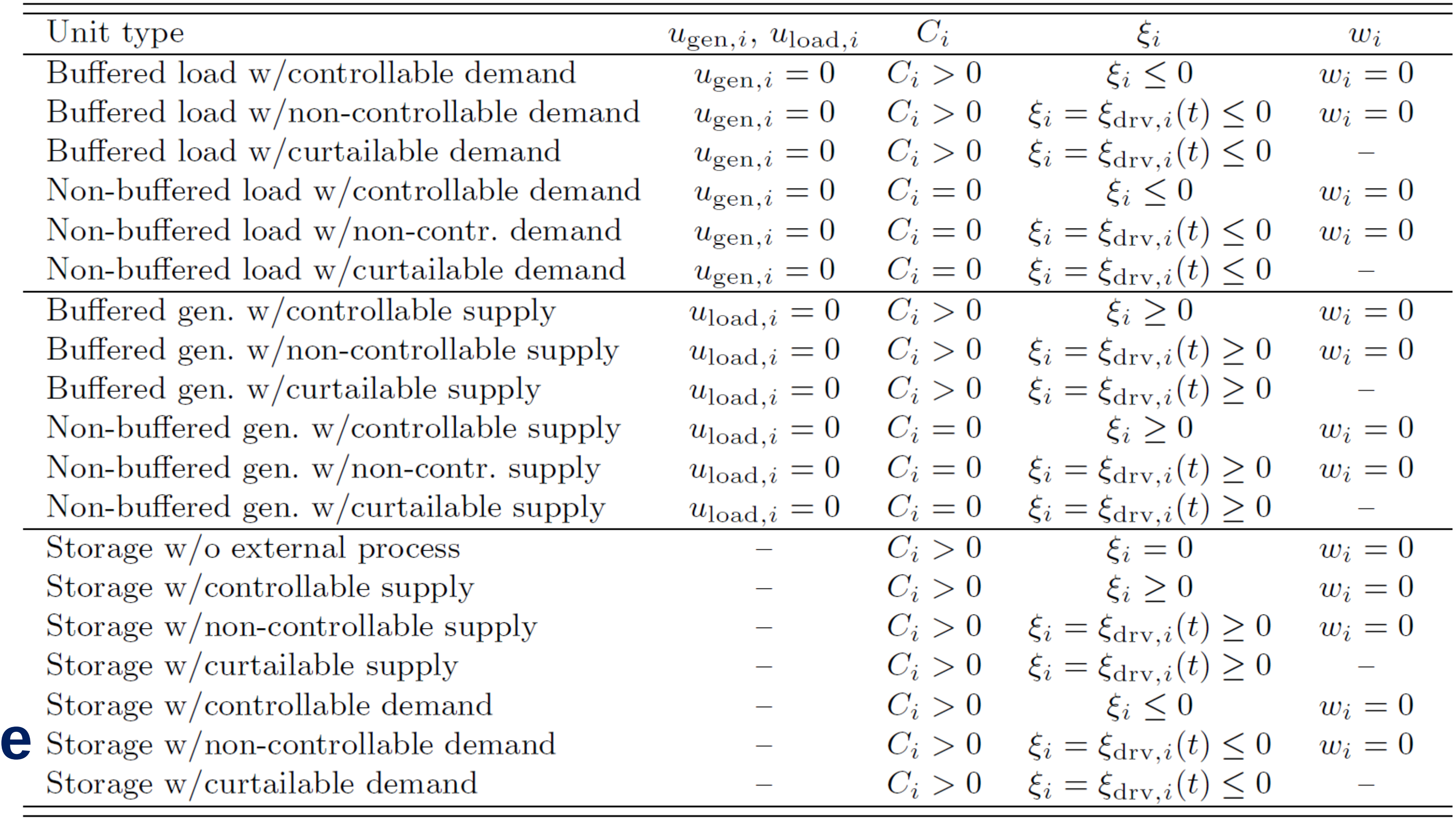
Power Node without storage (e.g. non-controllable load)

$$\xi_i - w_i = \eta_{\mathrm{gen},i}^{-1} u_{\mathrm{gen},i} - \eta_{\mathrm{load},i} u_{\mathrm{load},i}$$



- Power node equation degenerates to algebraic equality constraint (for classical load: $u_{\mathrm{gen},i} = 0$)
- Power node's power in-feed / out-feed is
  - Partially controllable, if shedding term adjustable ($w_i(k) > 0$)
  - Non-controllable, if shedding term is zero ($w_i(k) = 0$)

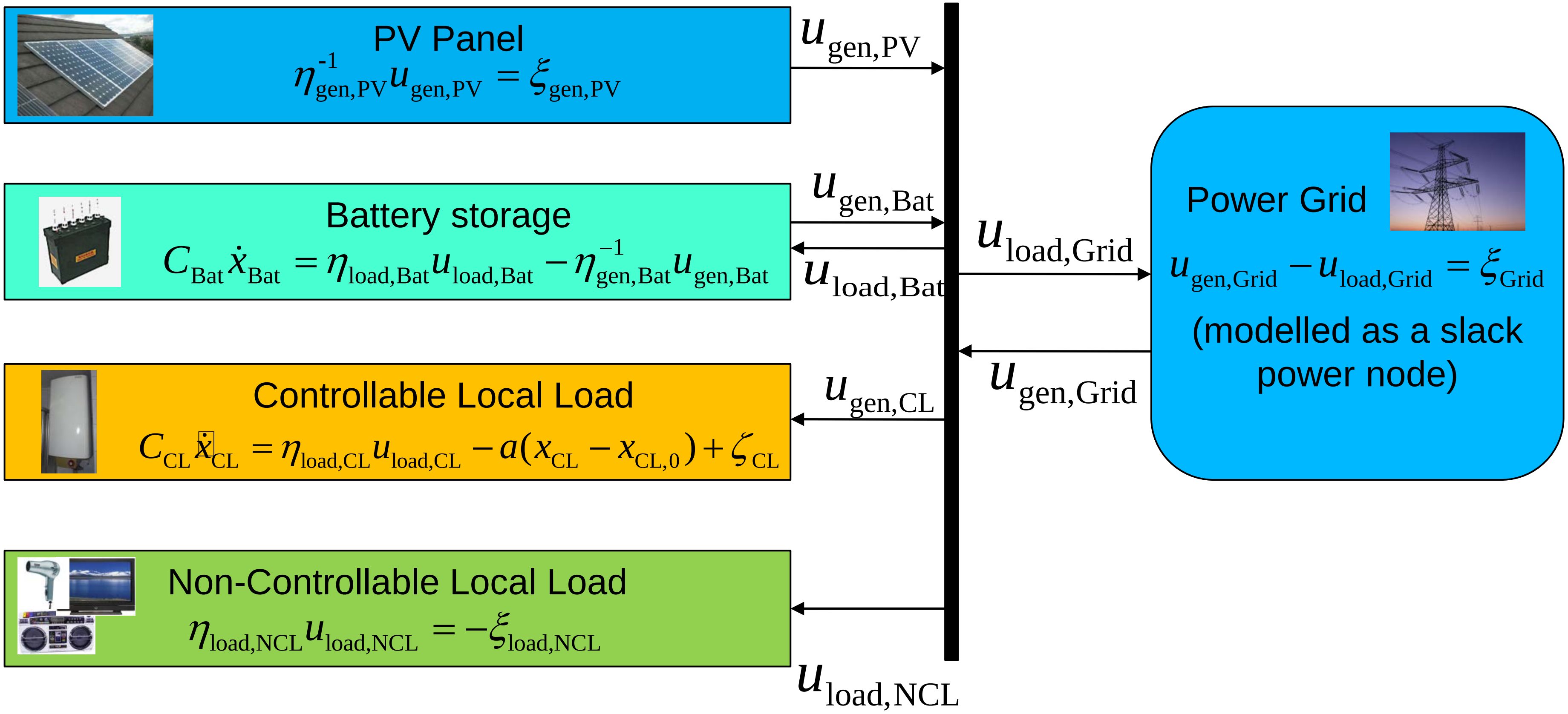
Variety of Power Node modelling definitions



	Unit type	$u_{\text{gen},i}$, $u_{\text{load},i}$	C_i	ξ_i	w_i
Load	Buffered load w/controllable demand	$u_{\text{gen},i} = 0$	$C_i > 0$	$\xi_i \leq 0$	$w_i = 0$
	Buffered load w/non-controllable demand	$u_{\text{gen},i} = 0$	$C_i > 0$	$\xi_i = \xi_{\text{drv},i}(t) \leq 0$	$w_i = 0$
	Buffered load w/curtailable demand	$u_{\text{gen},i} = 0$	$C_i > 0$	$\xi_i = \xi_{\text{drv},i}(t) \leq 0$	–
	Non-buffered load w/controllable demand	$u_{\text{gen},i} = 0$	$C_i = 0$	$\xi_i \leq 0$	$w_i = 0$
	Non-buffered load w/non-contr. demand	$u_{\text{gen},i} = 0$	$C_i = 0$	$\xi_i = \xi_{\text{drv},i}(t) \leq 0$	$w_i = 0$
	Non-buffered load w/curtailable demand	$u_{\text{gen},i} = 0$	$C_i = 0$	$\xi_i = \xi_{\text{drv},i}(t) \leq 0$	–
Gener-ation	Buffered gen. w/controllable supply	$u_{\text{load},i} = 0$	$C_i > 0$	$\xi_i \geq 0$	$w_i = 0$
	Buffered gen. w/non-controllable supply	$u_{\text{load},i} = 0$	$C_i > 0$	$\xi_i = \xi_{\text{drv},i}(t) \geq 0$	$w_i = 0$
	Buffered gen. w/curtailable supply	$u_{\text{load},i} = 0$	$C_i > 0$	$\xi_i = \xi_{\text{drv},i}(t) \geq 0$	–
	Non-buffered gen. w/controllable supply	$u_{\text{load},i} = 0$	$C_i = 0$	$\xi_i \geq 0$	$w_i = 0$
	Non-buffered gen. w/non-contr. supply	$u_{\text{load},i} = 0$	$C_i = 0$	$\xi_i = \xi_{\text{drv},i}(t) \geq 0$	$w_i = 0$
	Non-buffered gen. w/curtailable supply	$u_{\text{load},i} = 0$	$C_i = 0$	$\xi_i = \xi_{\text{drv},i}(t) \geq 0$	–
Storage	Storage w/o external process	–	$C_i > 0$	$\xi_i = 0$	$w_i = 0$
	Storage w/controllable supply	–	$C_i > 0$	$\xi_i \geq 0$	$w_i = 0$
	Storage w/non-controllable supply	–	$C_i > 0$	$\xi_i = \xi_{\text{drv},i}(t) \geq 0$	$w_i = 0$
	Storage w/curtailable supply	–	$C_i > 0$	$\xi_i = \xi_{\text{drv},i}(t) \geq 0$	–
	Storage w/controllable demand	–	$C_i > 0$	$\xi_i \leq 0$	$w_i = 0$
	Storage w/non-controllable demand	–	$C_i > 0$	$\xi_i = \xi_{\text{drv},i}(t) \leq 0$	$w_i = 0$
	Storage w/curtailable demand	–	$C_i > 0$	$\xi_i = \xi_{\text{drv},i}(t) \leq 0$	–

Power Node Modelling Examples

PV with local storage unit, no RES feed-in tariff



PV Panel

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

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

Battery storage

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

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

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

Controllable Local Load

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

$u_{\text{gen,CL}}$

Non-Controllable Local Load

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

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

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

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

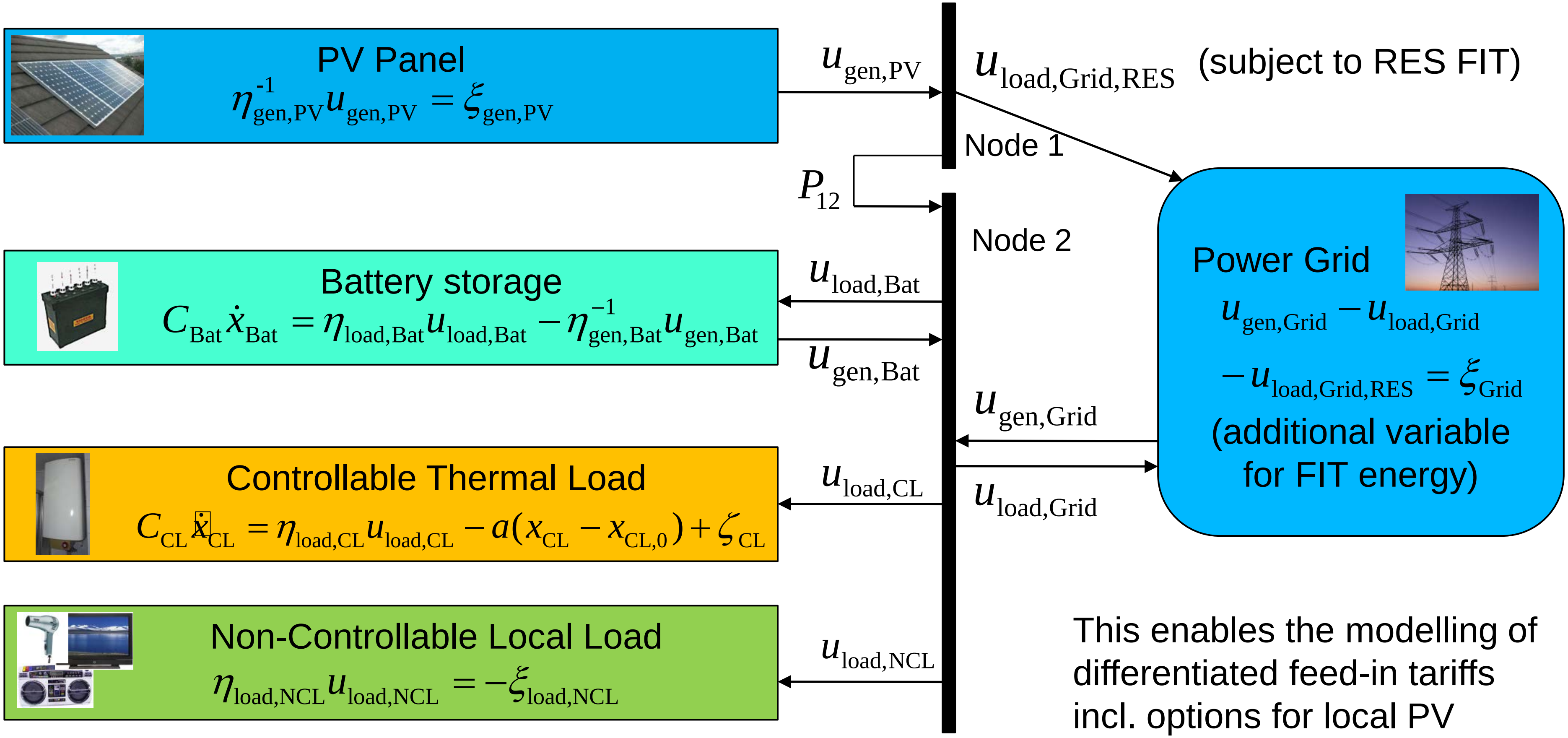
Power Grid

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

(modelled as a slack power node)

Power Node Modelling Examples

PV with local storage unit, RES feed-in tariff

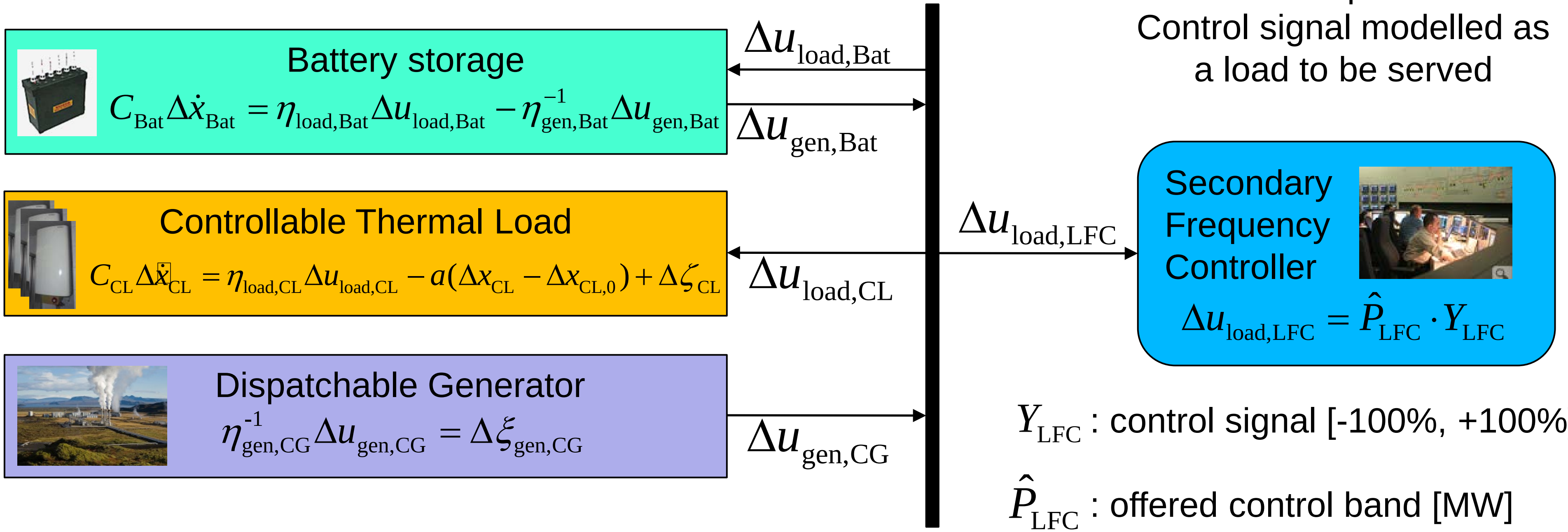


This enables the modelling of differentiated feed-in tariffs incl. options for local PV energy usage (e.g. Germany).

Power Node Modelling Examples

Joint Provision of Load Frequency Control

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



Battery storage

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

Controllable Thermal Load

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

Dispatchable Generator

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

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

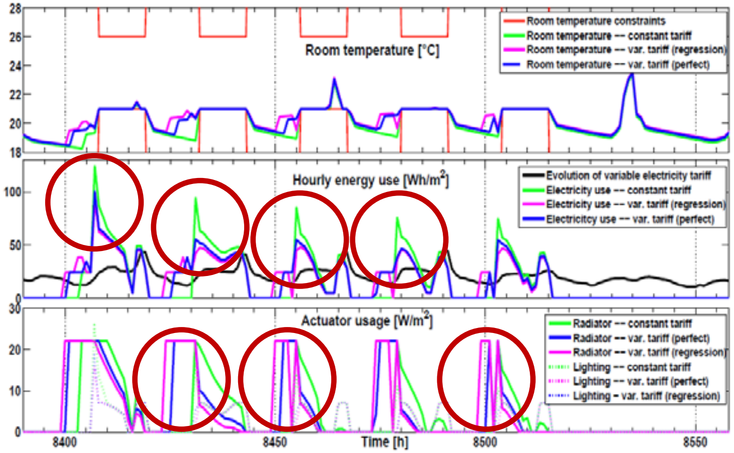
Demand response (driven by dynamic electricity tariff)

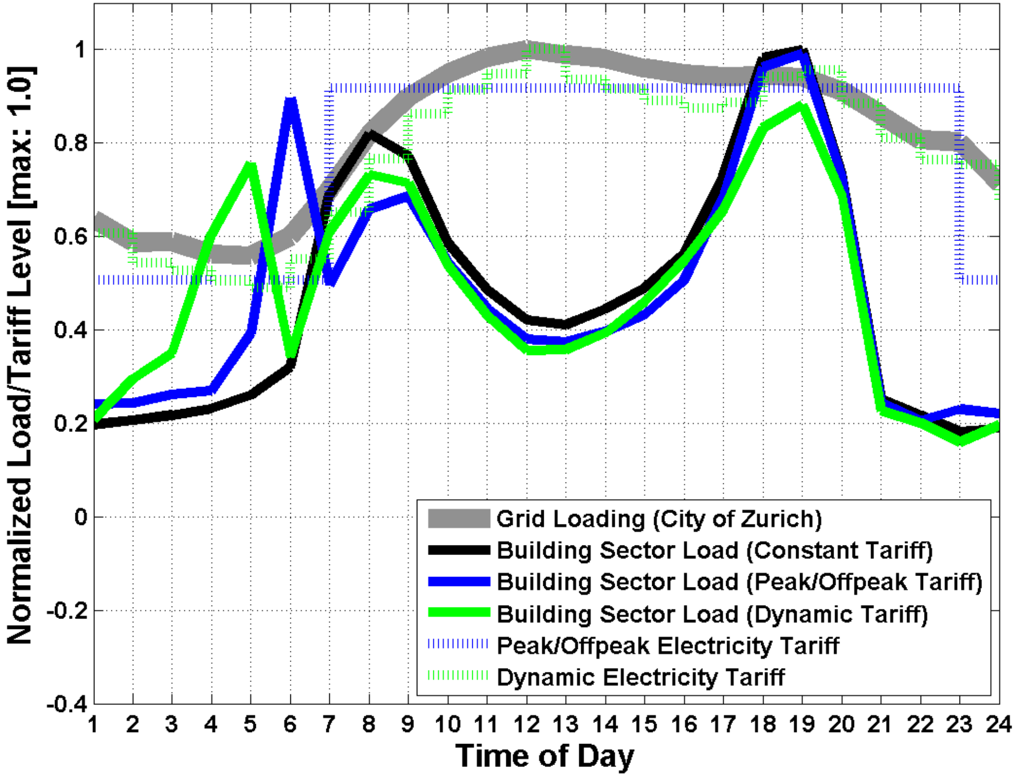
$$u^* = \min \sum_{k=0}^{k=N-1} elec.tariff(k) \cdot \left[u_{load\,i}(k) + v_{losses_i}(k) \right]$$

$$s.t. \quad C_i \dot{x}_i = \eta_{load_i} u_{load_i} + \xi_{demand_i} - v_{losses_i}(x_i),$$

$$0 \leq x_i \leq 1$$

$$u_{load_i} \geq 0,$$





Power Node Modeling Example: Predictive power 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

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

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

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

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

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

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

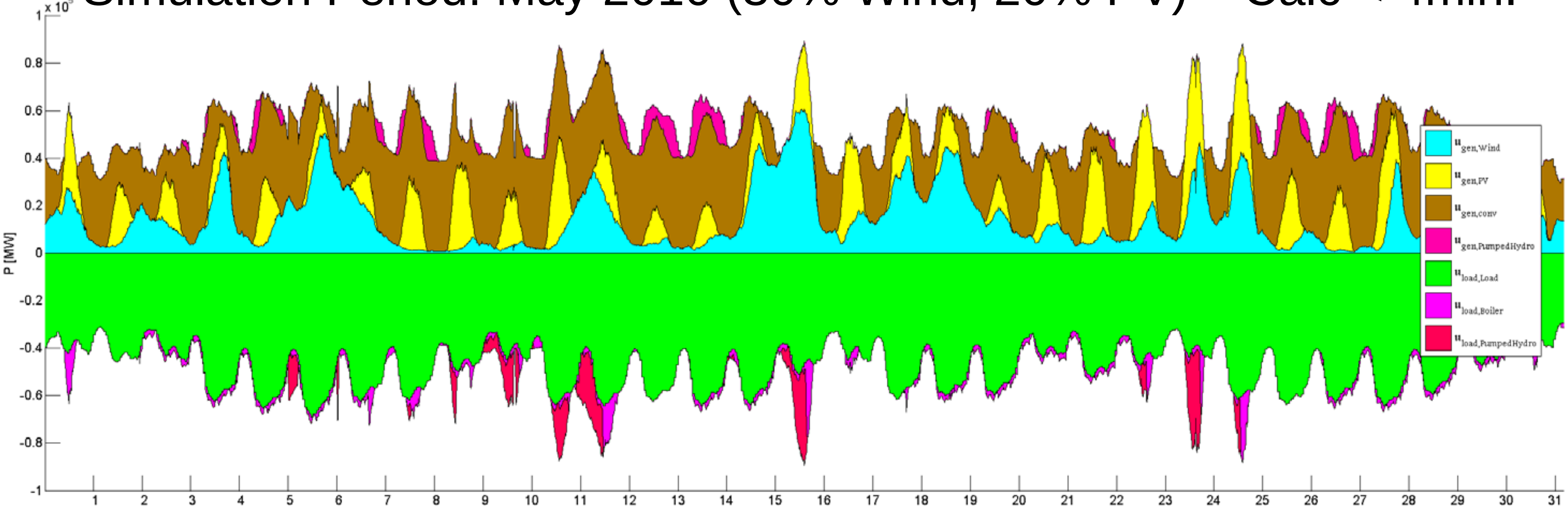
$$C_7\, \dot{x}_7 = \eta_{load,7}\, u_{load,7} + \xi_7 - a_7\,(x_7 - x_{ss,7})$$

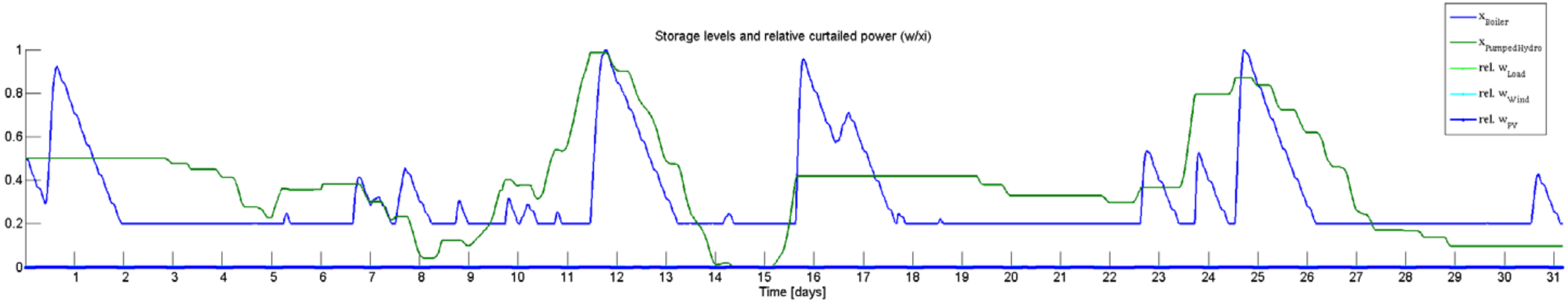
Power Node Modeling Example: Predictive power dispatch

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

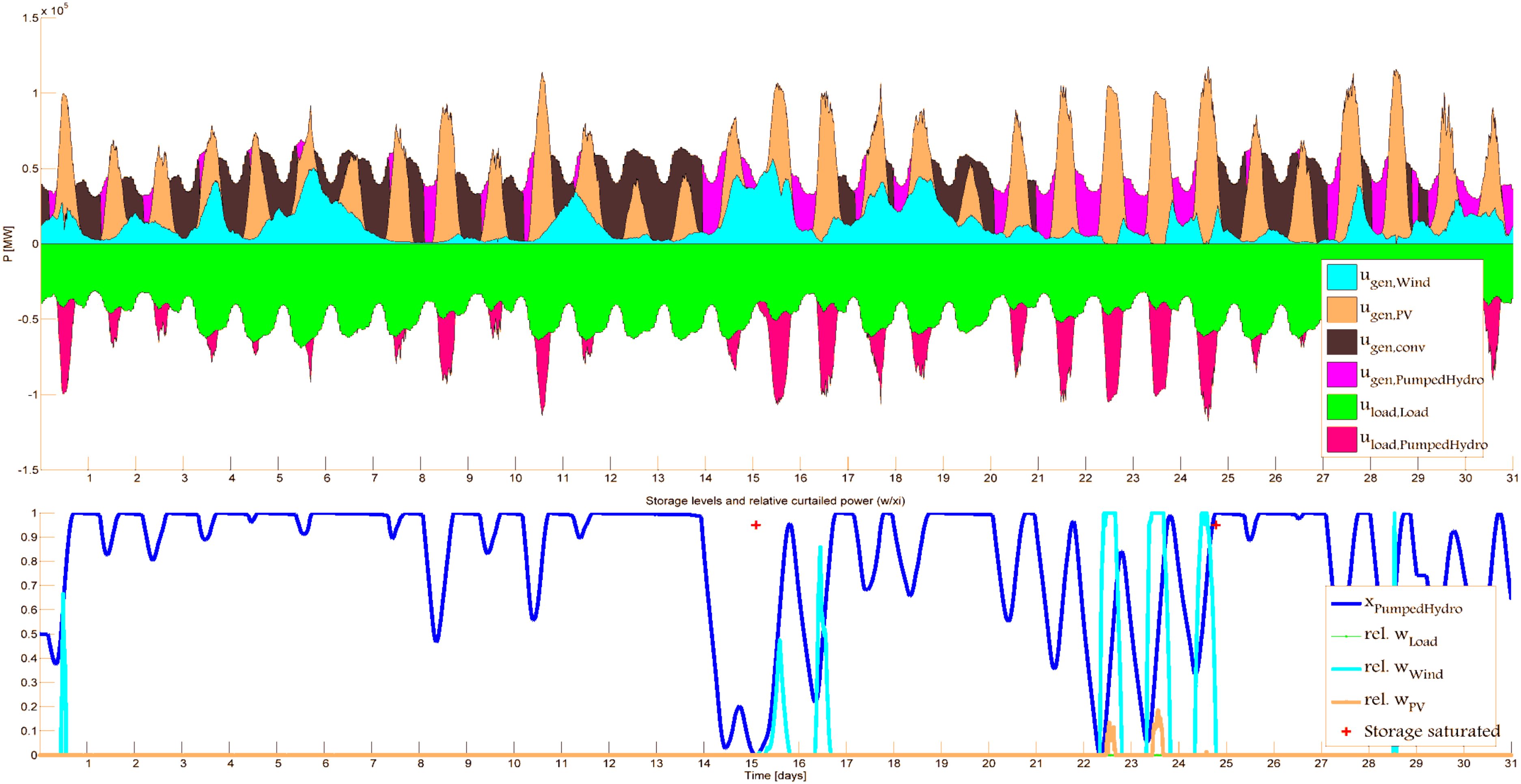
Optimal predictive power dispatch (Germany)

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





- 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**)

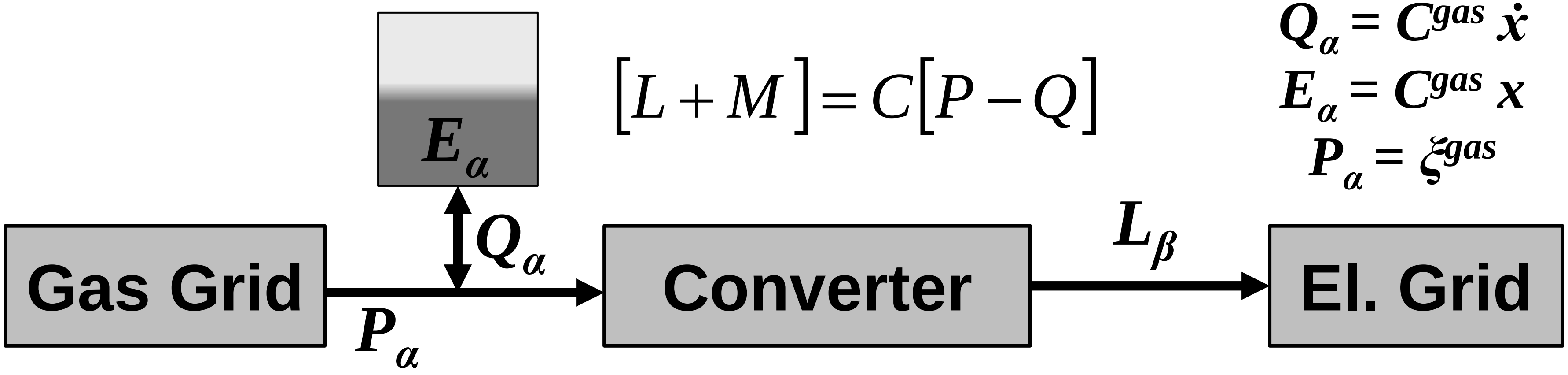


Power Nodes and Energy Hubs

- Partial transformation between Power Nodes and Energy Hubs is possible
  - Converter: natural gas → electricity ($\boldsymbol{u_{load} = 0, M_\beta = 0}$)

$$C^{gas}\dot{x} = \eta_{load} u^{el}_{load} - \eta^{-1}_{gen} u^{el}_{gen} + \xi^{gas}_{in} = -\eta^{-1}_{gen} u^{el}_{gen} + \xi^{gas}_{in}$$

$$u^{el}_{gen} = \eta_{gen}\left(\xi^{gas}_{in} - C^{gas}\dot{x}\right) \Leftrightarrow \underline{L_\beta = c_{\alpha\beta}\left(P_\alpha - Q_\alpha\right)}$$



$$\left[L + M\right] = C\left[P - Q\right]$$

$$\boldsymbol{Q_\alpha = C^{gas}\,\dot{x}}$$
$$\boldsymbol{E_\alpha = C^{gas}\,x}$$
$$\boldsymbol{P_\alpha = \xi^{gas}}$$

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 fluctuating power in-feed
    - Integrating demand-side management (DSM)
    - Reduce forced ramping of conventional generators for load following and balancing of fluctuating power in-feed
    - Examples of performance criteria
        - power system operation cost
        - curtailment of RES in-feed
        - Power system CO_2 emissions

Contributions from

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