ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

eeh power systems laboratory

Grid Integration Challenges of Renewable Energy Sources and Prospective Solutions

Andreas Ulbig
Power Systems Laboratory
ETH Zurich, Switzerland

Frontiers in Energy Research, ETH Zurich, 30 October 2013

Topics and Questions of this Talk

- Complexity of Power System Processes

- On-Going Transformation of Power Systems (CH, DE, Europe)
  - Impacts of Renewable Energies
  - Energy Transformation («Energiewende»)
  - Impacts of Liberalization and Power Markets

- Grid Integration Challenges for Power Systems with High Shares of Fluctuating Renewable Energy Sources (RES)

→ What are the challenges for grid integration of wind & PV units?
→ What are the opportunities of RES deployment?
→ What are the opportunities for control engineering («smartness»)?
→ What is the role of energy storage?
→ Power System Planning: «Hard Paths versus Soft Paths» (A. Lovins)

- Prospective Solutions

Structure of this Talk

- Complexity of Power System Processes
- Trends & Challenges in Power System Operation
- Role of Operational Flexibility in Power Systems
- Modeling and Analysis of Power Systems and their Operation
- Conclusion

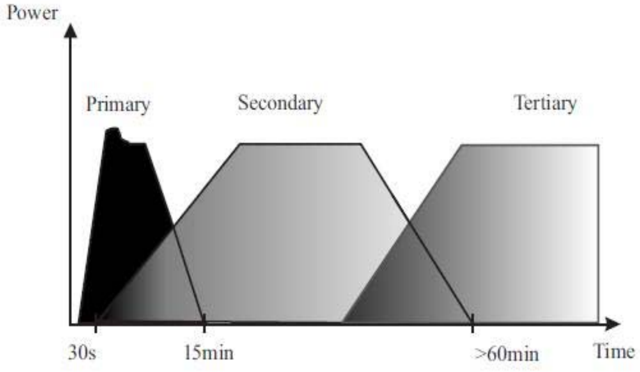
Structure of this Talk

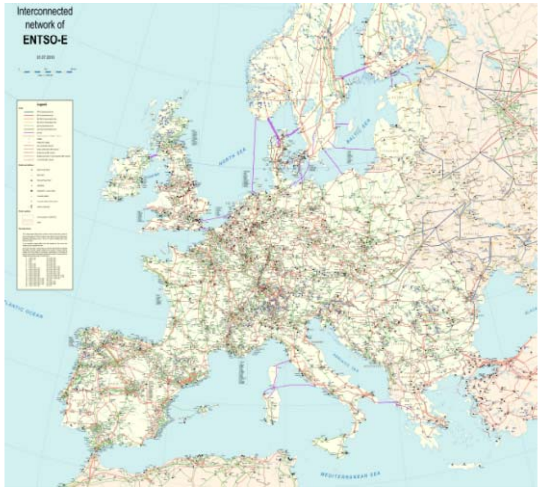
- **Complexity of Power System Processes**
- Trends & Challenges in Power System Operation
- Role of Operational Flexibility in Power Systems
- Modeling and Analysis of Power Systems and their Operation
- Conclusion

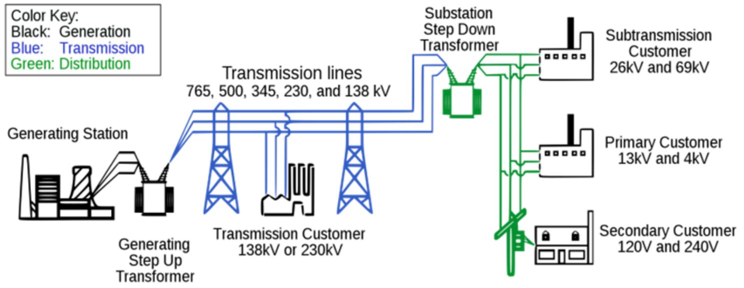
Complexity of Power Systems

Complexity along several dimensions

- **Time** **(milli)seconds** (e.g. frequency inertia, frequency&voltage control),
  minutes (e.g. secondary/tertiary frequency&voltage control),
  hours/days (e.g. spot market-based plant/storage scheduling),
  months/years (e.g. seasonal storage, infrastructure planning).
- **Space** **1‘000+ km**, e.g. interconnected continental European grid
  (Portugal – Poland: 3‘600 km, Denmark – Sicily: 3‘000 km).
- **Hierarchy** **from distribution grid** (e.g. 120/240 V, 10 kV) **to**
  high-voltage transmission grid (e.g. 220/380 kV).



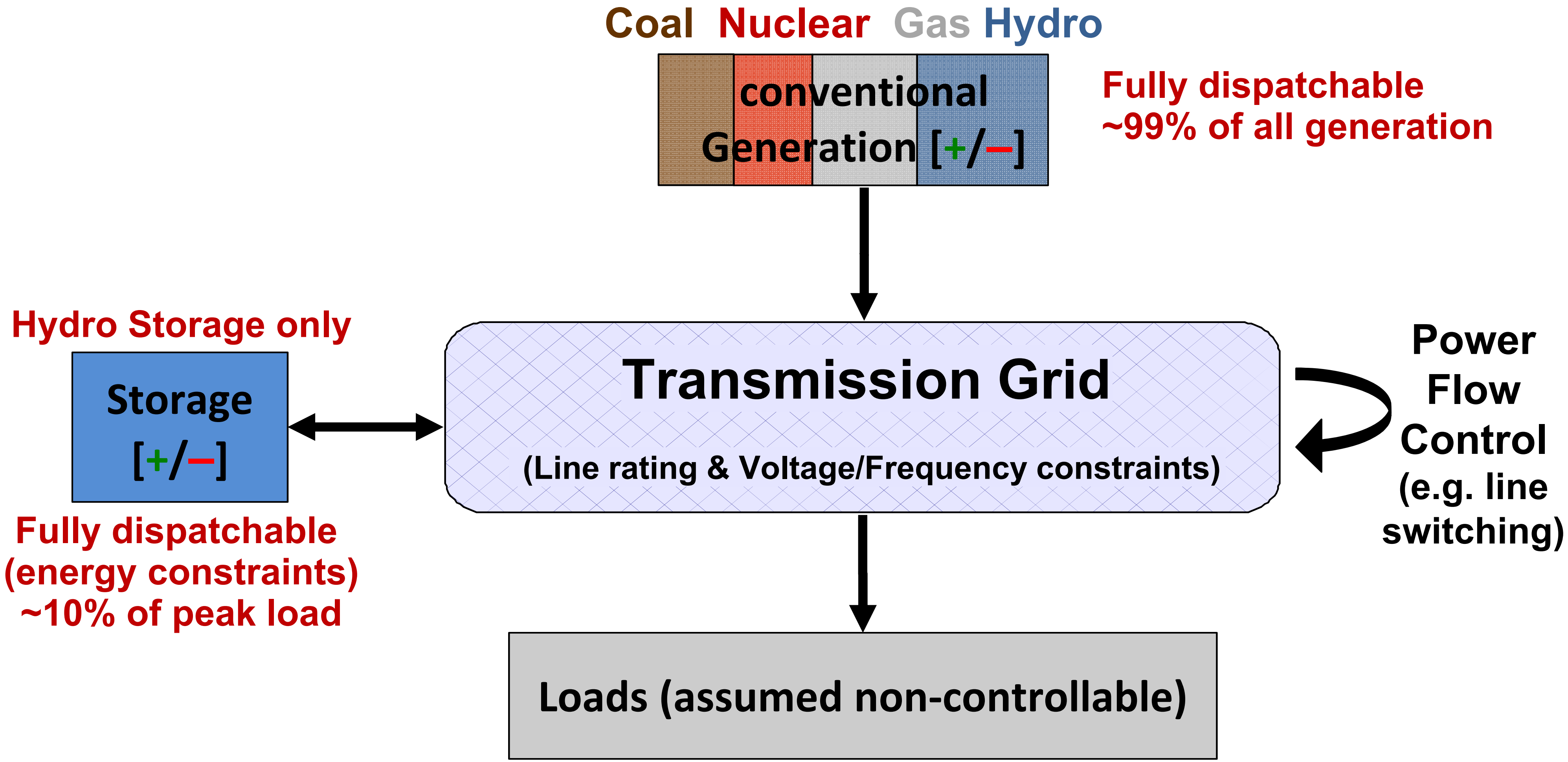




Complexity of Power Systems

PAST – Traditional view

(DE capacity values of around year 2000)



Coal Nuclear Gas Hydro

conventional Generation [+/–]

Fully dispatchable
~99% of all generation

Hydro Storage only

Storage [+/–]

Fully dispatchable
(energy constraints)
~10% of peak load

Transmission Grid

(Line rating & Voltage/Frequency constraints)

Power Flow Control
(e.g. line switching)

Loads (assumed non-controllable)

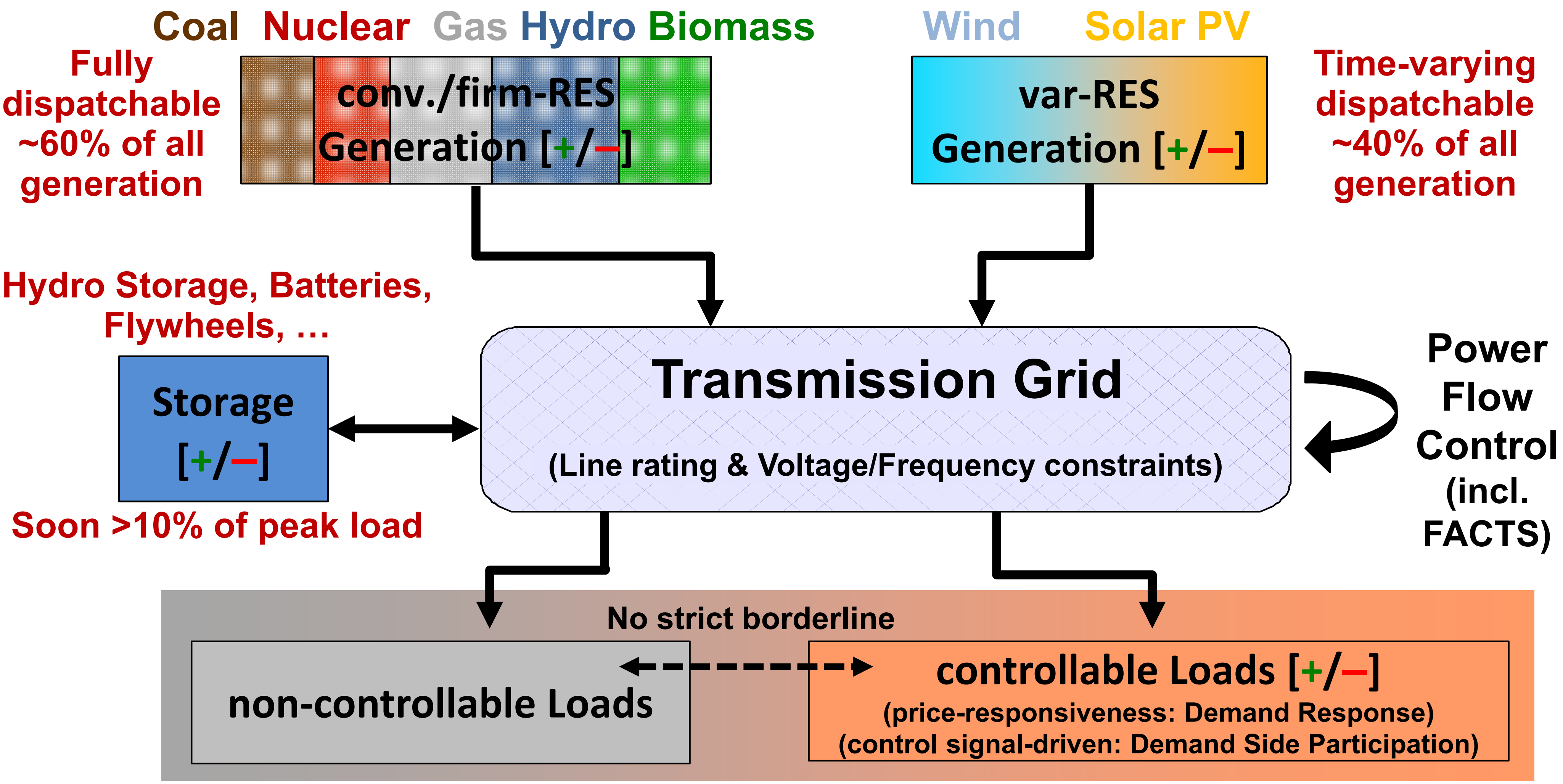
Observable & well predictable
Interruptible loads by manual or static control means
(large industrial loads, hot water boilers)

[+/–]: Power regulation up/down possible.

Complexity of Power Systems

PRESENT & FUTURE – high RES shares & *Smart Grid Vision*

(DE capacity values of year 2011)



Coal Nuclear Gas Hydro Biomass

conv./firm-RES Generation [+/–]

Fully dispatchable ~60% of all generation

Wind Solar PV

var-RES Generation [+/–]

Time-varying dispatchable ~40% of all generation

Hydro Storage, Batteries, Flywheels, …

Storage [+/–]

Soon >10% of peak load

Transmission Grid

(Line rating & Voltage/Frequency constraints)

Power Flow Control (incl. FACTS)

No strict borderline

non-controllable Loads

controllable Loads [+/–]

(price-responsiveness: Demand Response)
(control signal-driven: Demand Side Participation)

Increase of controllable loads (faster response times, automatic control)

[+/–]: Power regulation up/down possible.

Structure of this Talk

- Complexity of Power System Processes
- **Trends & Challenges in Power System Operation**
- Role of Operational Flexibility in Power Systems
- Modeling and Analysis of Power Systems and their Operation
- Conclusion

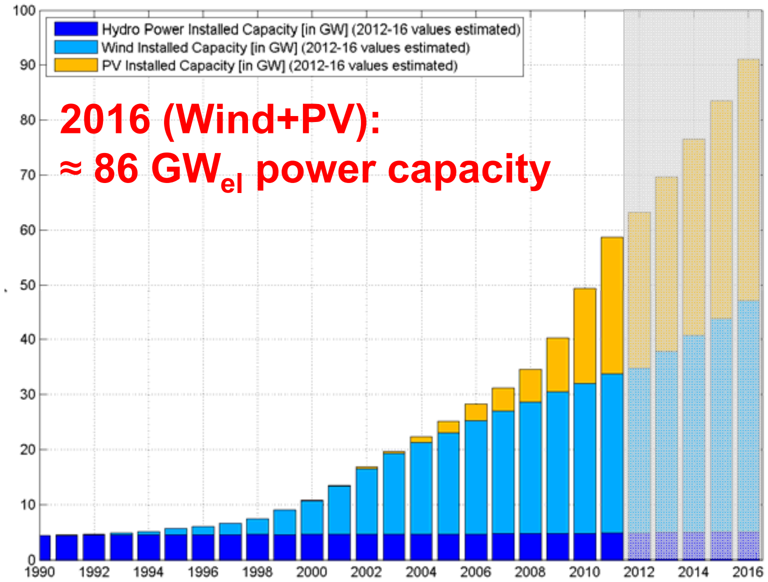
Trends and Challenges

Increasing fluctuating RES deployment = Stochastic power in-feed

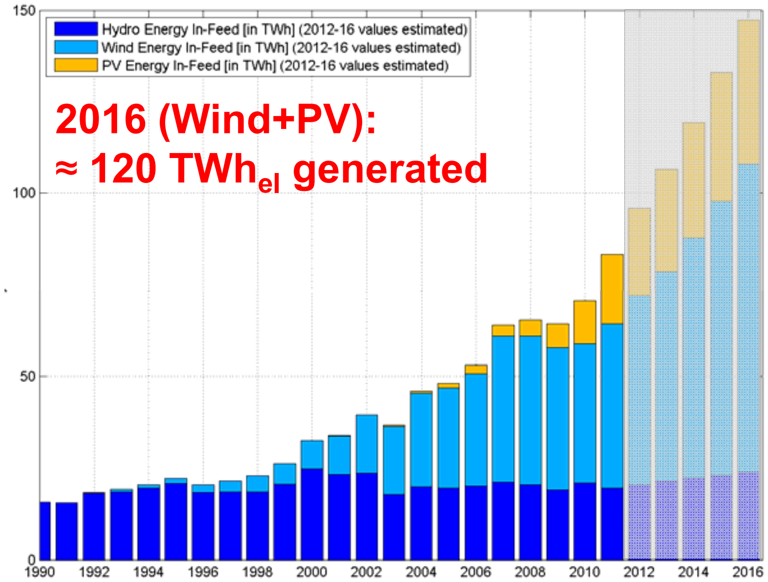
- Germany 2011: **53.9 GW power capacity** ≈ 63% of fully dispatchable fossil generation.
  (Wind+PV) **63.6 TWh energy produced** ≈ 12.5% of final electricity consumption.
- Wind+PV: *Still* mostly uncontrolled power in-feed – Hydro: well-predictable power in-feed.

Mitigation Options

- Improvement of Controllability: Wind/PV unit curtailment implemented in some countries.
- Improvement of Observability: More measurements and better predictions of PV and wind power in-feed (state estimation & prediction).



2016 (Wind+PV):
≈ 86 GW_{el} power capacity



2016 (Wind+PV):
≈ 120 TWh_{el} generated

Data: P_{el}: Wind 29.1GW, PV 24.8GW, Hydro 4.8GW – E_{el}: Wind 44.8TWh, PV 18.8TWh, Hydro 19.6TWh –
Germany Final Electricity Consumption (2011): ≈510TWh estimated – Fully dispatchable (fossil+nuclear) generation: ≈ 85GW

Sources: BaSt 2012, IEA Electricity Information 2011, own calculations

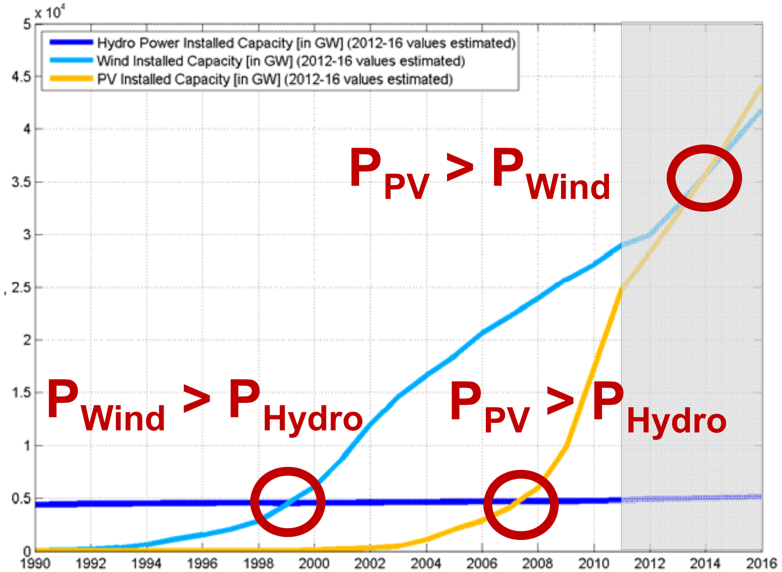
Trends and Challenges

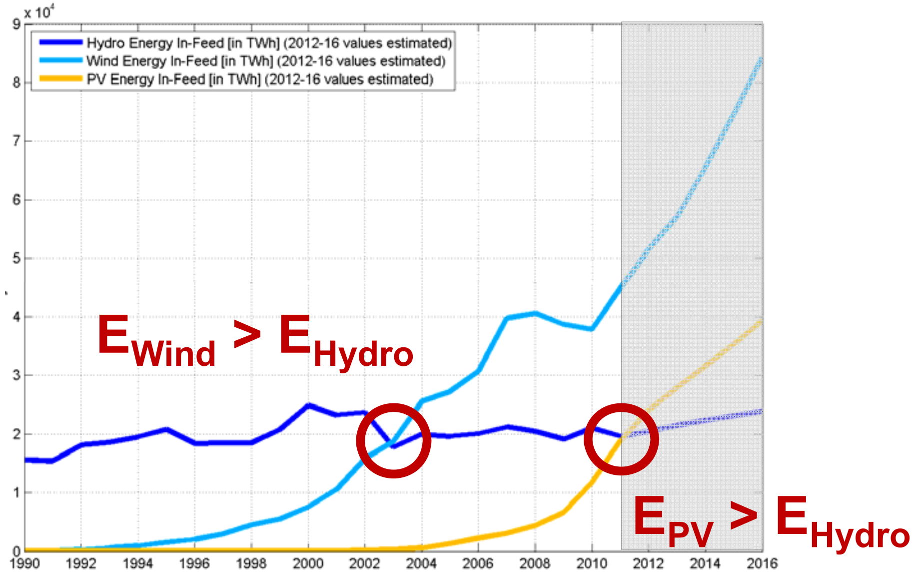
Increasing fluctuating RES deployment = Stochastic power in-feed

- Germany 2011: **53.9 GW power capacity** ≈ 63% of fully dispatchable fossil generation.
  (Wind+PV) **63.6 TWh energy produced** ≈ 12.5% of final electricity consumption.
- Wind+PV: *Still* mostly uncontrolled power in-feed – Hydro: well-predictable power in-feed.

Mitigation Options

- Improvement of Controllability: Wind/PV unit curtailment implemented in some countries.
- Improvement of Observability: More measurements and better predictions of PV and wind power in-feed (state estimation & prediction).





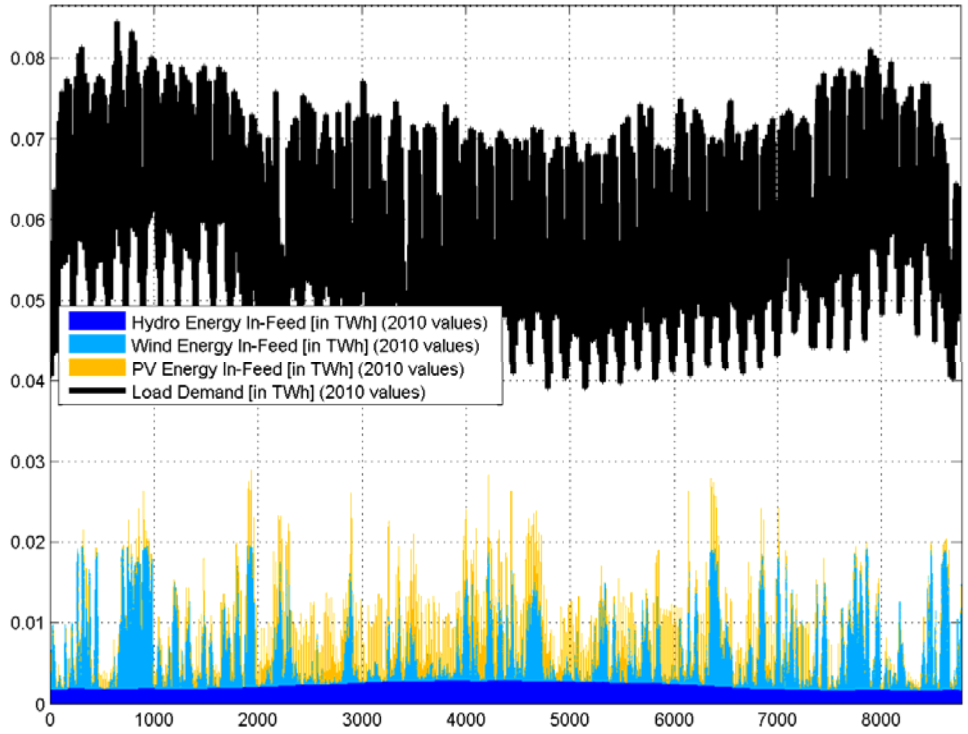
Data: P_{el}: Wind 29.1GW, PV 24.8GW, Hydro 4.8GW – E_{el}: Wind 44.8TWh, PV 18.8TWh, Hydro 19.6TWh –
Germany Final Electricity Consumption (2011): ≈510TWh estimated – Fully dispatchable (fossil+nuclear) generation: ≈ 85GW

Sources: BaSt 2012, IEA Electricity Information 2011, own calculations

Trends and Challenges

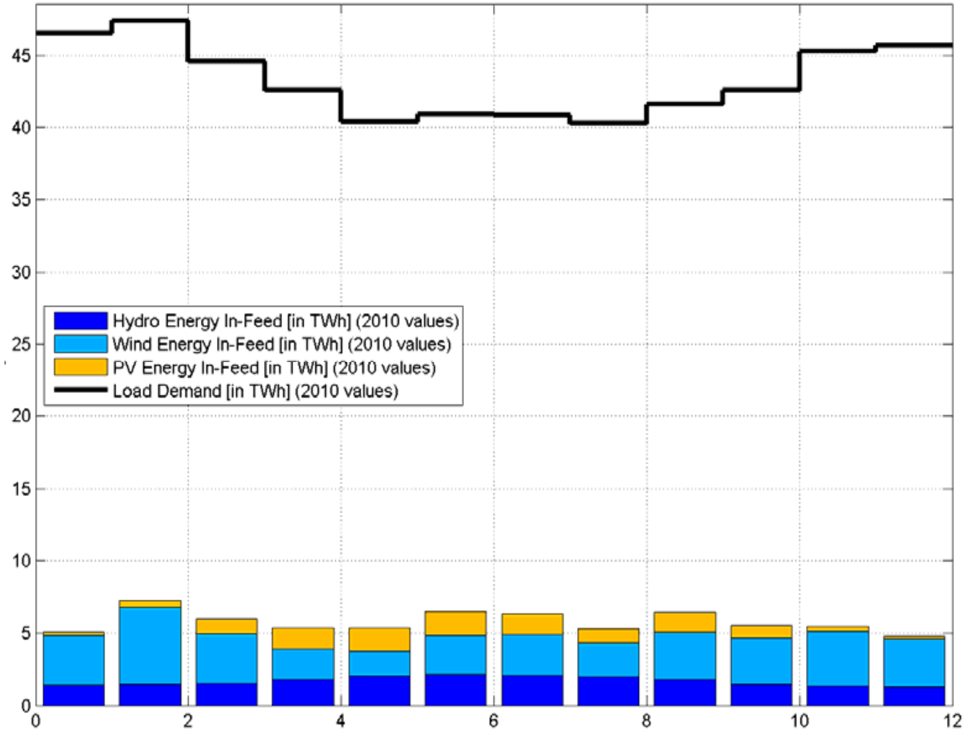
RES Integration challenges are on different time-scales (Germany, 2010)

Hourly Power Infeed Profile



- Buffering of RES In-feed and Load Demand Peaks
- Requires fast ramping capability

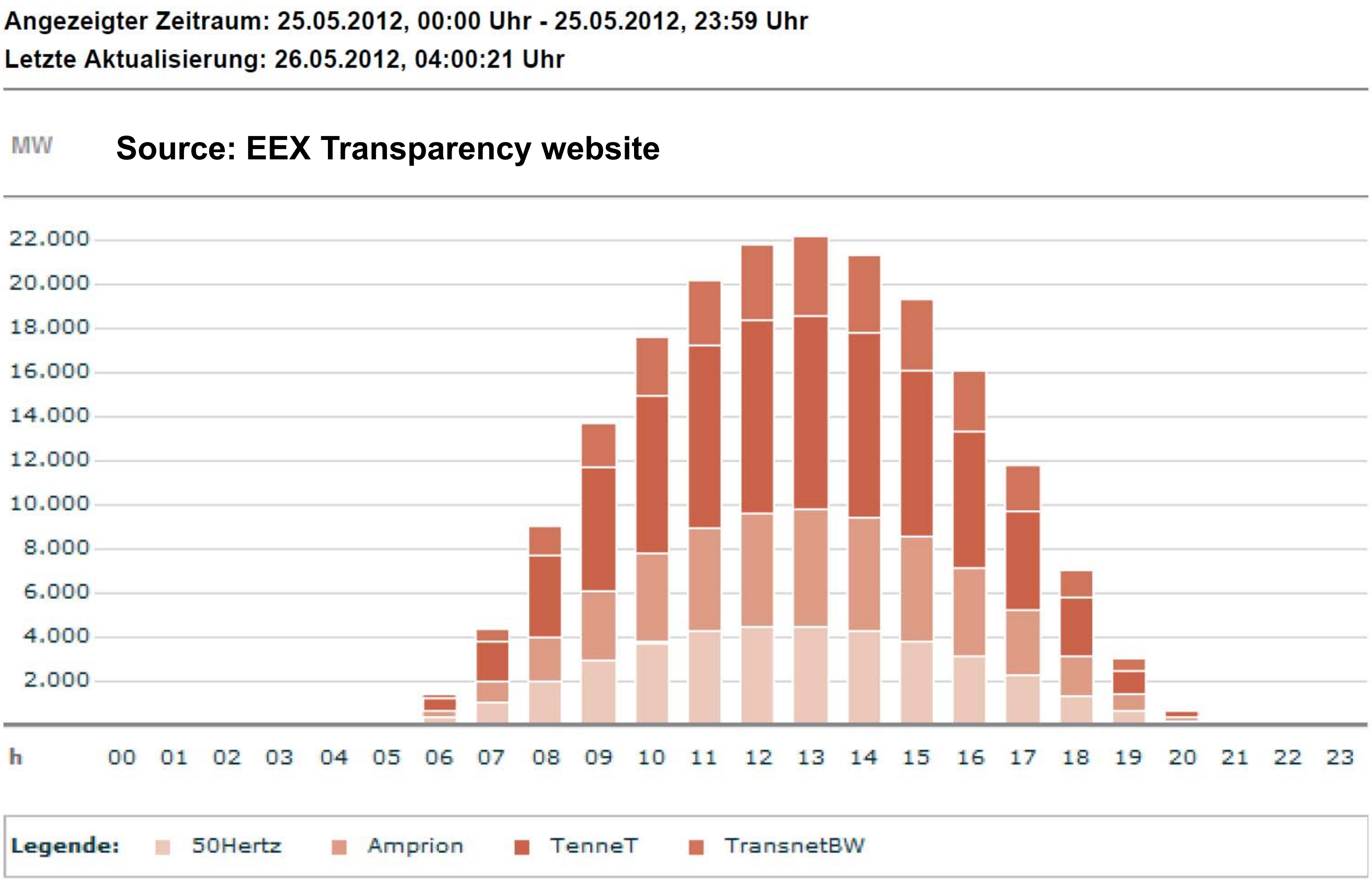
Monthly Power Infeed Profile



- Accomodation of seasonal changes in RES in-feed and Load demand
- Requires back-up capacity (and some day seasonal storage)

Trends and Challenges

Recent record: 22GW PV peak on 25 May 2012 (>33% of average load demand)



Angezeigter Zeitraum: 25.05.2012, 00:00 Uhr - 25.05.2012, 23:59 Uhr

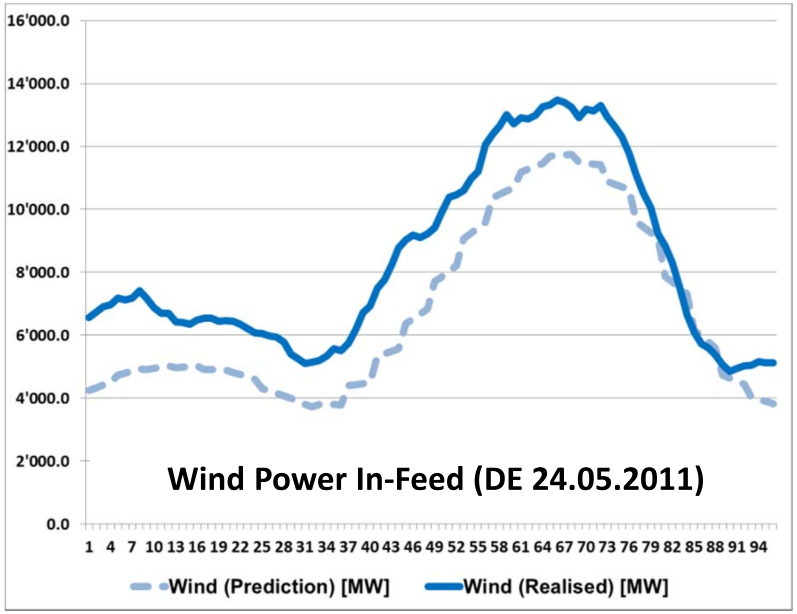
Letzte Aktualisierung: 26.05.2012, 04:00:21 Uhr

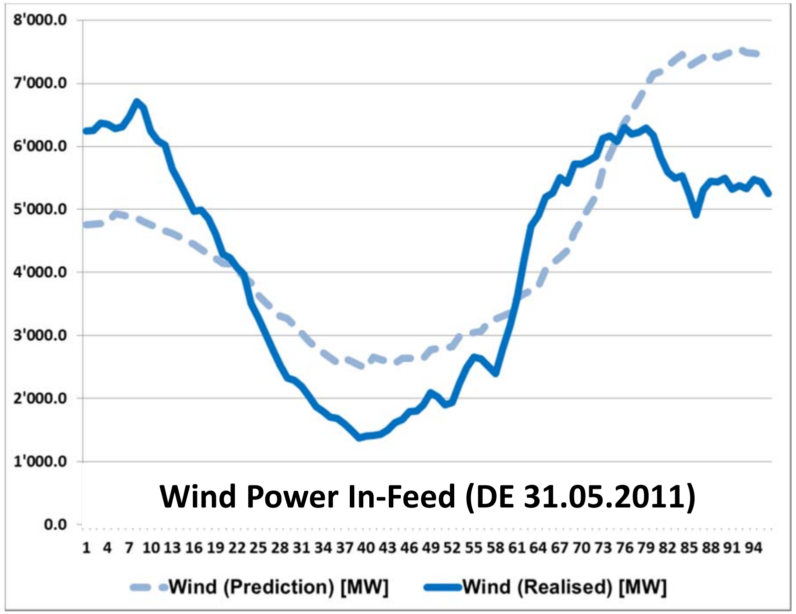
Source: EEX Transparency website

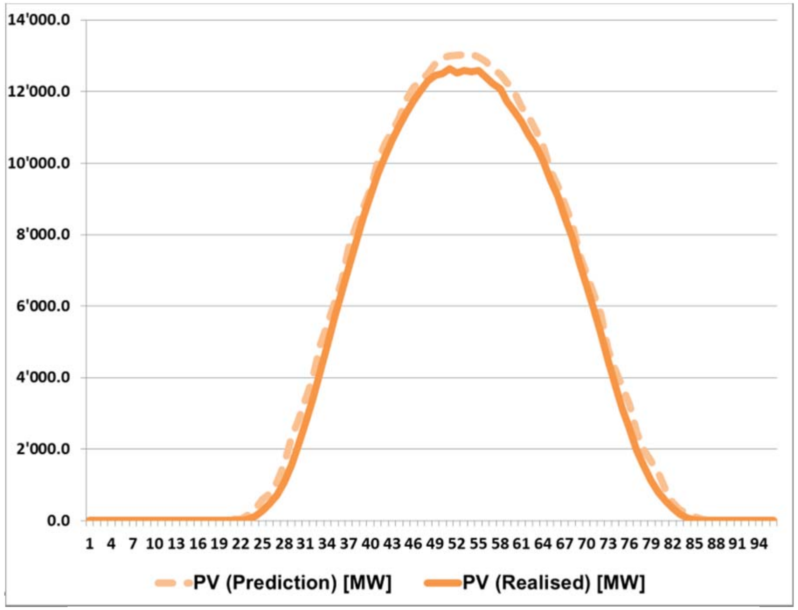
Grid integration becomes more challenging as wind and PV deployment continous.

Trends and Challenges

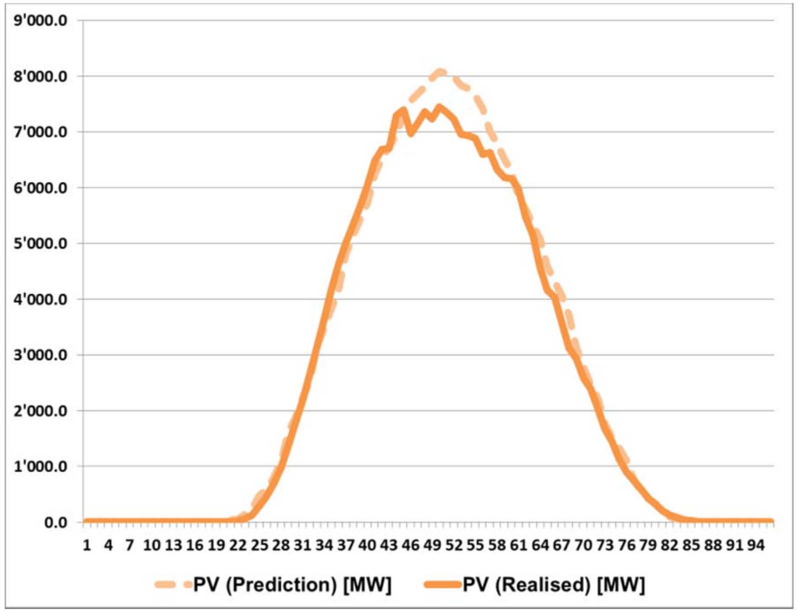
Challenges of Wind & PV (but also Load Demand) Forecasts


Wind Power In-Feed (DE 24.05.2011)


Wind Power In-Feed (DE 31.05.2011)



PV Power In-Feed (DE 30.05.2011)



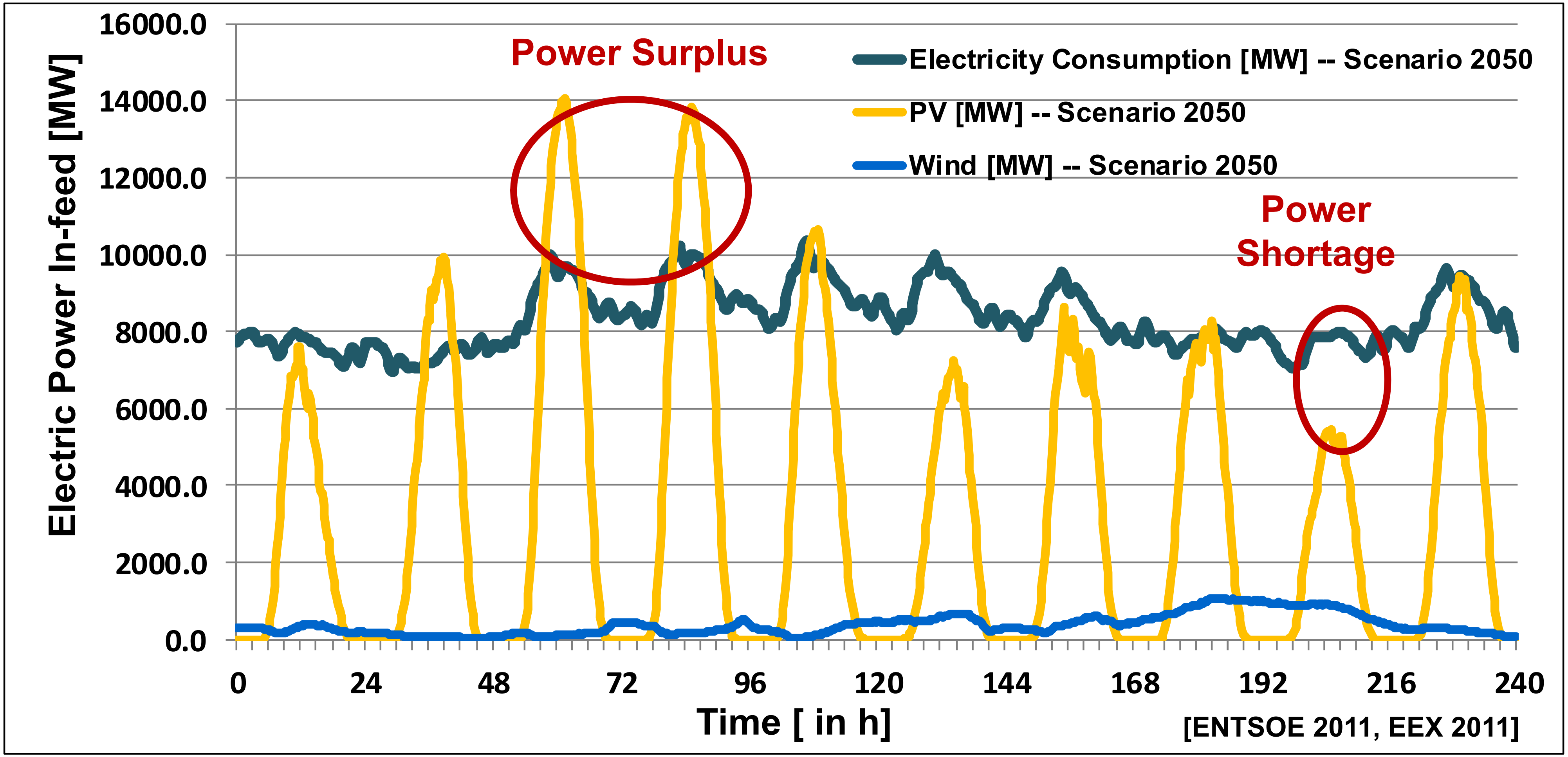
PV Power In-Feed (DE 31.05.2011)

Trends and Challenges

RES Integration challenges in Switzerland (ETH Scenario 2050)

Fluctuating Power In-Feed:

1. **Generation Capacities?**
2. **Energy Storage Capacities?**
3. ***Invisible Ceiling* for Operational Flexibility?**

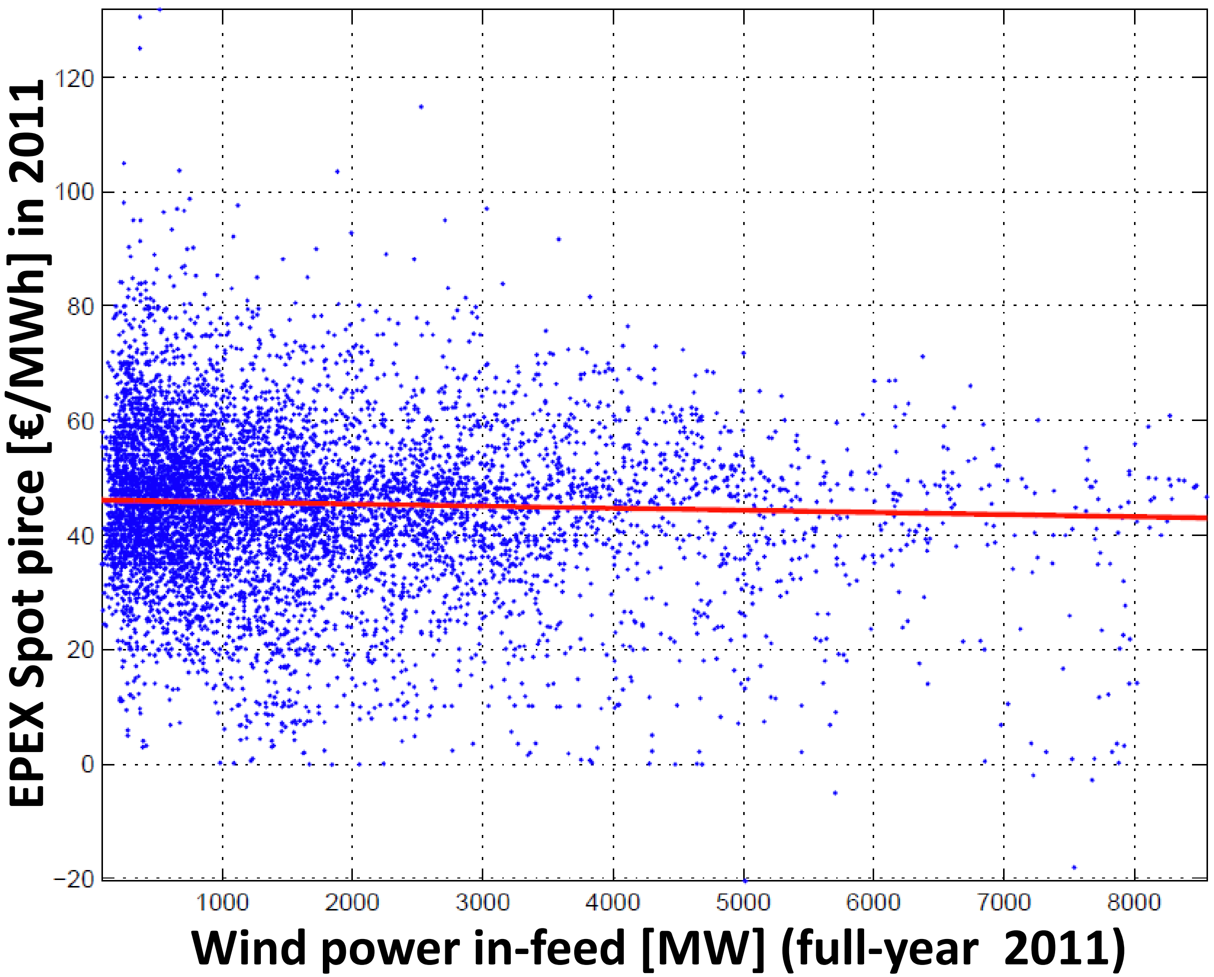


[ENTSOE 2011, EEX 2011]

ETH Zurich Energy Scenario 2050: Potential Swiss Load Demand, Wind and PV In-feed using (June/July-Week).

Trends and Challenges

Impacts on Power Markets (Merit-Order Effect of RES Generation)



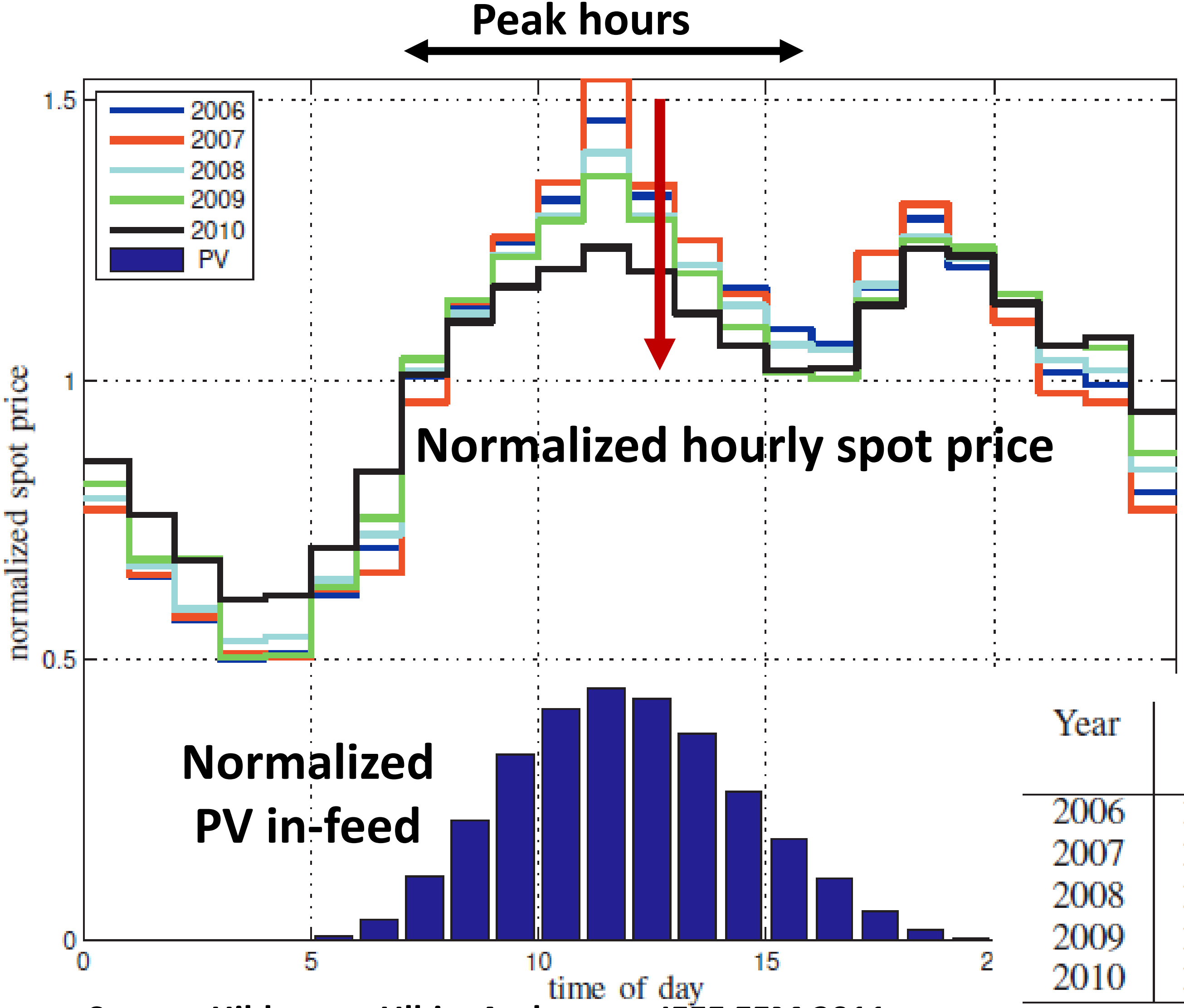
- **Wind power in-feed** (zero marginal cost) shifts supply curve to the right
- **Result** Reduction of average spot price level
- **Long-term impact** Risk for conventional generators (recovery of investment)

Source: Hildmann, Ulbig, Andersson, IEEE EEM 2011

Wind in-feed reduces spot prices (neg. correlation between wind in-feed and spot price).

Trends and Challenges

Impacts on Power Markets (Merit-Order Effect of RES Generation)



Source: Hildmann, Ulbig, Andersson, IEEE EEM 2011

- **PV power in-feed** causes reduction of spot price spread ζ (zero marginal cost, zero price bid in supply curve)
- **Net energy arbitrage potential Δ_{net}** between peak and off-peak hours **significantly reduced**

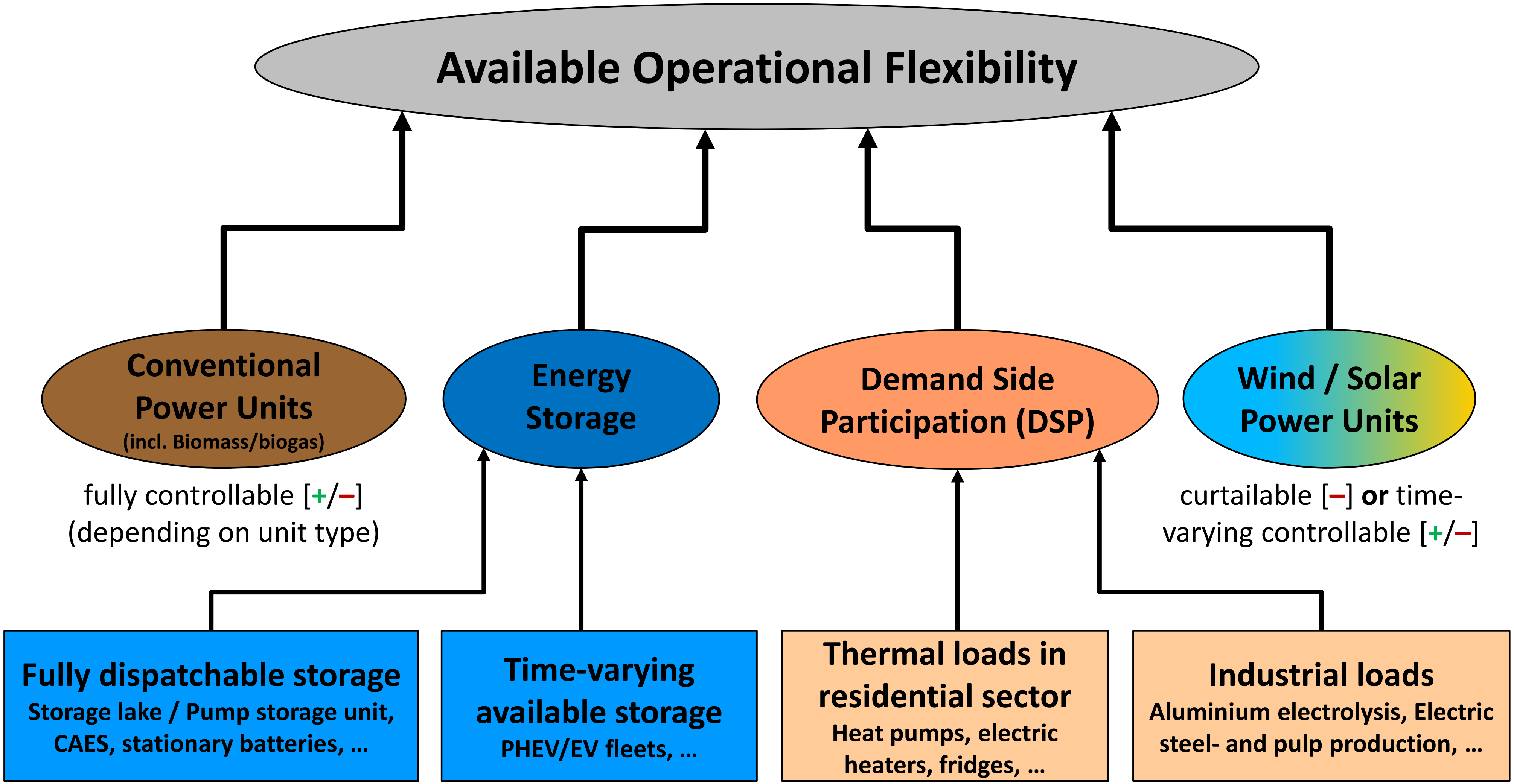
Year	ζ	Δ_{net} $[\frac{€}{MWh}]$	P_{spot}^{base} $[\frac{€}{MWh}]$
2006	1.59	17.06	50.79
2007	1.64	15.00	37.99
2008	1.51	17.12	65.76
2009	1.46	8.09	38.85
2010	1.33	3.71	44.49

PV in-feed flattens spot price curve during peak hours, reducing energy arbitrage yield.

Structure of this Talk

- Complexity of Power System Processes
- Trends & Challenges in Power System Operation
- **Role of Operational Flexibility in Power Systems**
- Modeling and Analysis of Power Systems and their Operation
- Conclusion

Sources of Operational Flexibility in Power Systems



Available Operational Flexibility

Conventional Power Units
(incl. Biomass/biogas)

fully controllable [+/–]
(depending on unit type)

Energy Storage

Demand Side Participation (DSP)

Wind / Solar Power Units

curtailable [–] **or** time-varying controllable [+/–]

Fully dispatchable storage
Storage lake / Pump storage unit, CAES, stationary batteries, …

fully controllable [+/–]
(energy constraint, hydro power: seasonal effects)

Time-varying available storage
PHEV/EV fleets, …

fully controllable [+/–]
if grid-connected
(energy constraint)

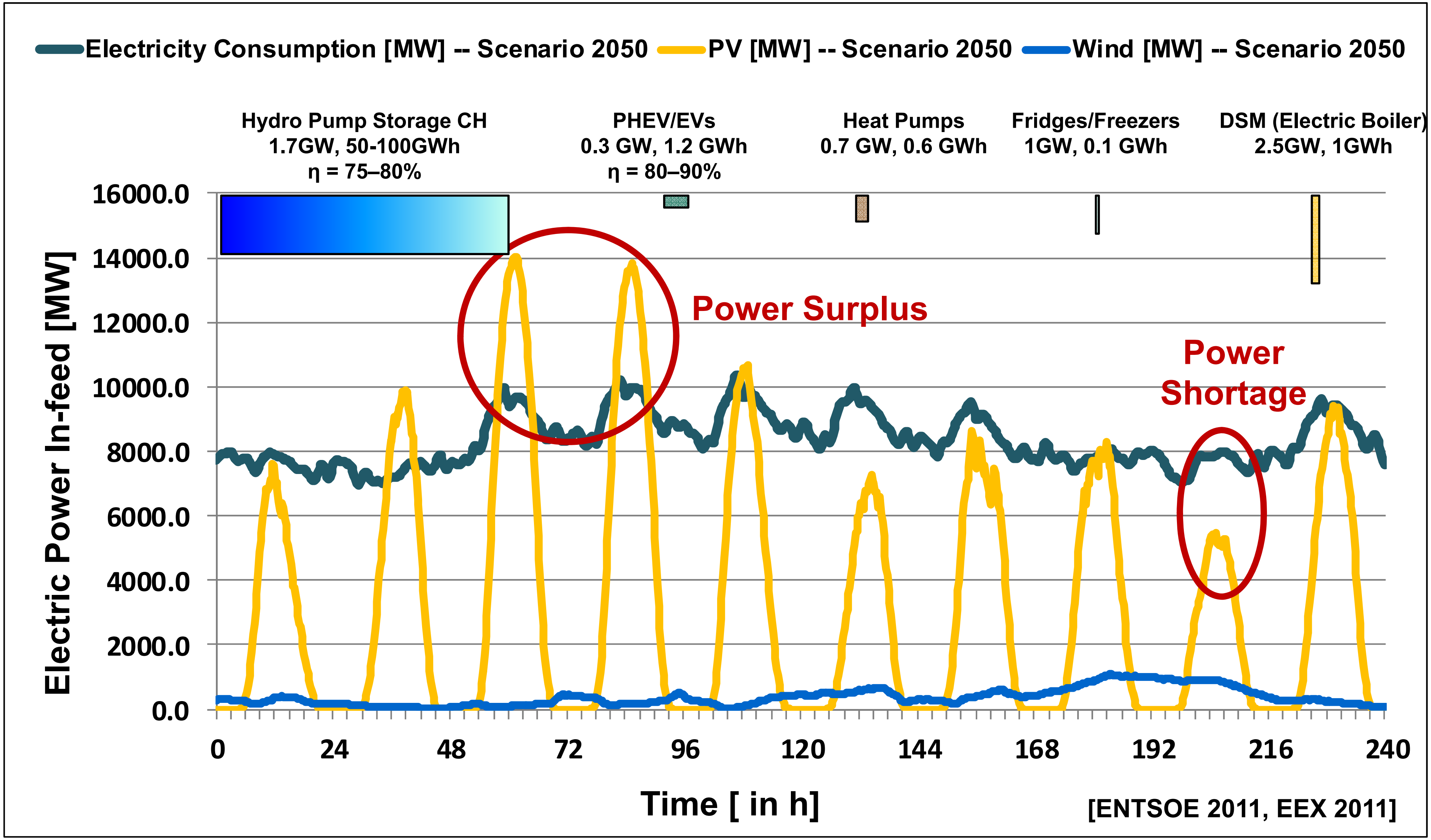
Thermal loads in residential sector
Heat pumps, electric heaters, fridges, …

curtailable [–] **or**
fully controllable [+/–]
(energy constraint)

Industrial loads
Aluminium electrolysis, Electric steel- and pulp production, …

curtailable [–] **or**
fully controllable [+/–]
(production dependent)

Sources of
Operational Flexibility in Power Systems



[ENTSOE 2011, EEX 2011]

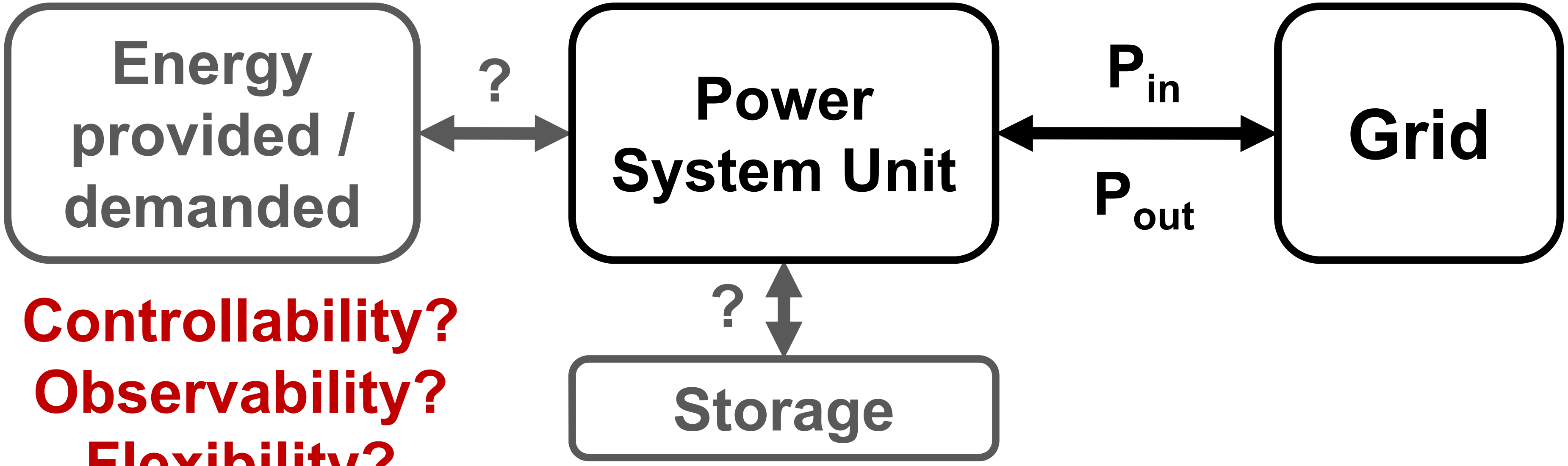
ETH Zurich Energy Scenario 2050: Potential Swiss Load Demand, Wind and PV In-feed using (June/July-Week).

Structure of this Talk

- Complexity of Power System Processes
- Trends & Challenges in Power System Operation
- Role of Operational Flexibility in Power Systems
- **Modeling and Analysis of Power Systems and their Operation**
- Conclusion

Motivation for Power Nodes Modeling Framework

- **Consideration of interactions of power system units and the electricity grid**, i.e. power injected into the grid or power demanded from the grid, is not giving the whole picture.
    - Which of these units are storages (and thus energy-constrained)?
    - Which of these units provide fluctuating power in-feed?
    - What controllability and observability (full / partial / none) does an operator have over fluctuating generation and demand processes?



Energy provided / demanded

?

Power System Unit

P_{in}

P_{out}

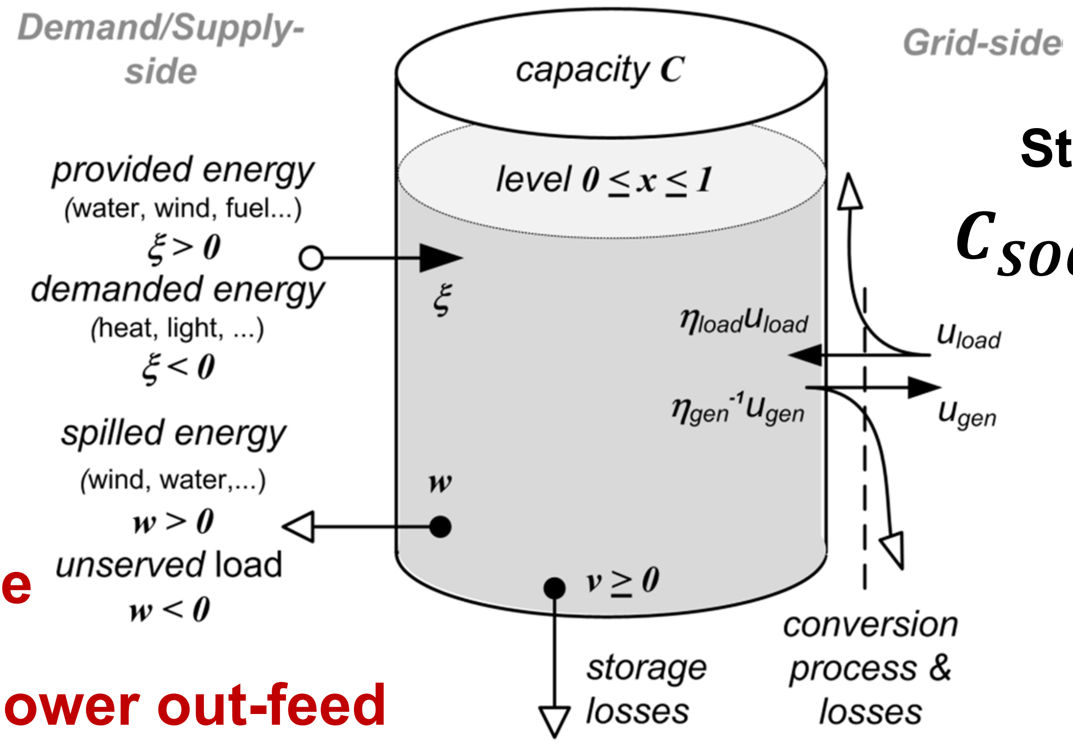
Grid

?

Storage

Controllability? Observability? Flexibility?

One Power Node



State-Descriptor Form

$$C_{SOC,i}\dot{x}_i = a_i x_i + b_i^T \underline{u}$$

Storage capacity × state-of-charge (SOC)

Power out-feed from grid

Power in-feed to grid

Internal storage losses v(x)

Shedding term

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

Efficiency factors

Provided / demanded power

Examples of Power Node Definitions

General formulation: $C_i \dot{x}_i = \eta_{\mathrm{load}_i} u_{\mathrm{load}_i} - \eta_{\mathrm{gen}_i}^{-1} u_{\mathrm{gen}_i} + \xi_i - w_i - v_i$

Combined Heat/ Power Plant (CHP), Berlin-Mitte

- Fully dispatchable generation
- No load, no storage (C)
- Fuel: natural gas ($\xi>0$)

$$\eta_{\mathrm{gen}_i}^{-1} u_{\mathrm{gen}_i} = \xi_i$$

Offshore Wind Farm, Denmark

- Time-dependent dispatchable generation, if wind blows, $\xi \geq 0$, and if energy waste term $w \geq 0$
- No load, no storage (C)
- Fuel: wind power ($\xi>0$)

$$\eta_{\mathrm{gen}_i}^{-1} u_{\mathrm{gen}_i} = \xi_i - w_i$$

Examples of Power Node Definitions

General formulation: $C_i \dot{x}_i = \eta_{\text{load}_i} u_{\text{load}_i} - \eta_{\text{gen}_i}^{-1} u_{\text{gen}_i} + \xi_i - w_i - v_i$

Goldisthal Hydro Pumped Storage, Germany

- Fully dispatchable generation (turbine) and load (pump)
- Constrained storage ($C \approx 8$ GWh)
- Fuel: almost no water influx ($\xi \approx 0$)

$$C_i \dot{x}_i = \eta_{\text{load}_i} u_{\text{load}_i} - \eta_{\text{gen}_i}^{-1} u_{\text{gen}_i}$$

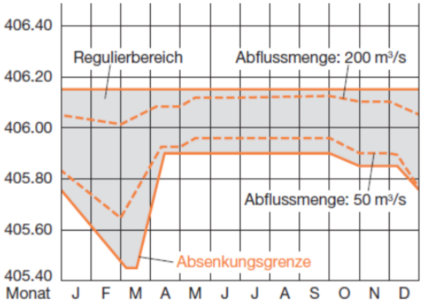
Emosson Storage Lake, Switzerland

- Fully dispatchable generation (turbine), but no load (pump)
- Large storage ($C \approx 1000$ GWh)
- Fuel supply: rain, snow melting ($\xi > 0$)

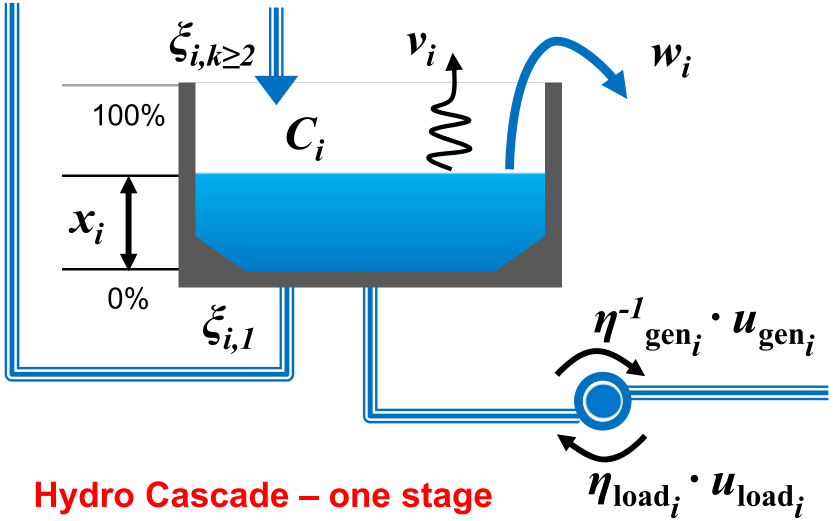
$$C_i \dot{x}_i = -\eta_{\text{gen}_i}^{-1} u_{\text{gen}_i} + \xi_i$$

Examples of Power Node Definitions

General formulation: $$C_i\dot{x}_i = \eta_{\text{load}_i} u_{\text{load}_i} - \eta_{\text{gen}_i}^{-1} u_{\text{gen}_i} + \xi_i - w_i - v_i$$




Run-of-River Plant, Zurich



Hydro Cascade – one stage

- **Dispatchable generation, but no load**
- **Storage function dependent on geography, $C \in [0, \dots, GWh, TWh]$**
- **Fuel (ξ): water influx from river, ($\xi>0$)**
- **Waste (w): water flow over barrage (high water-level) or intentional water diversion**

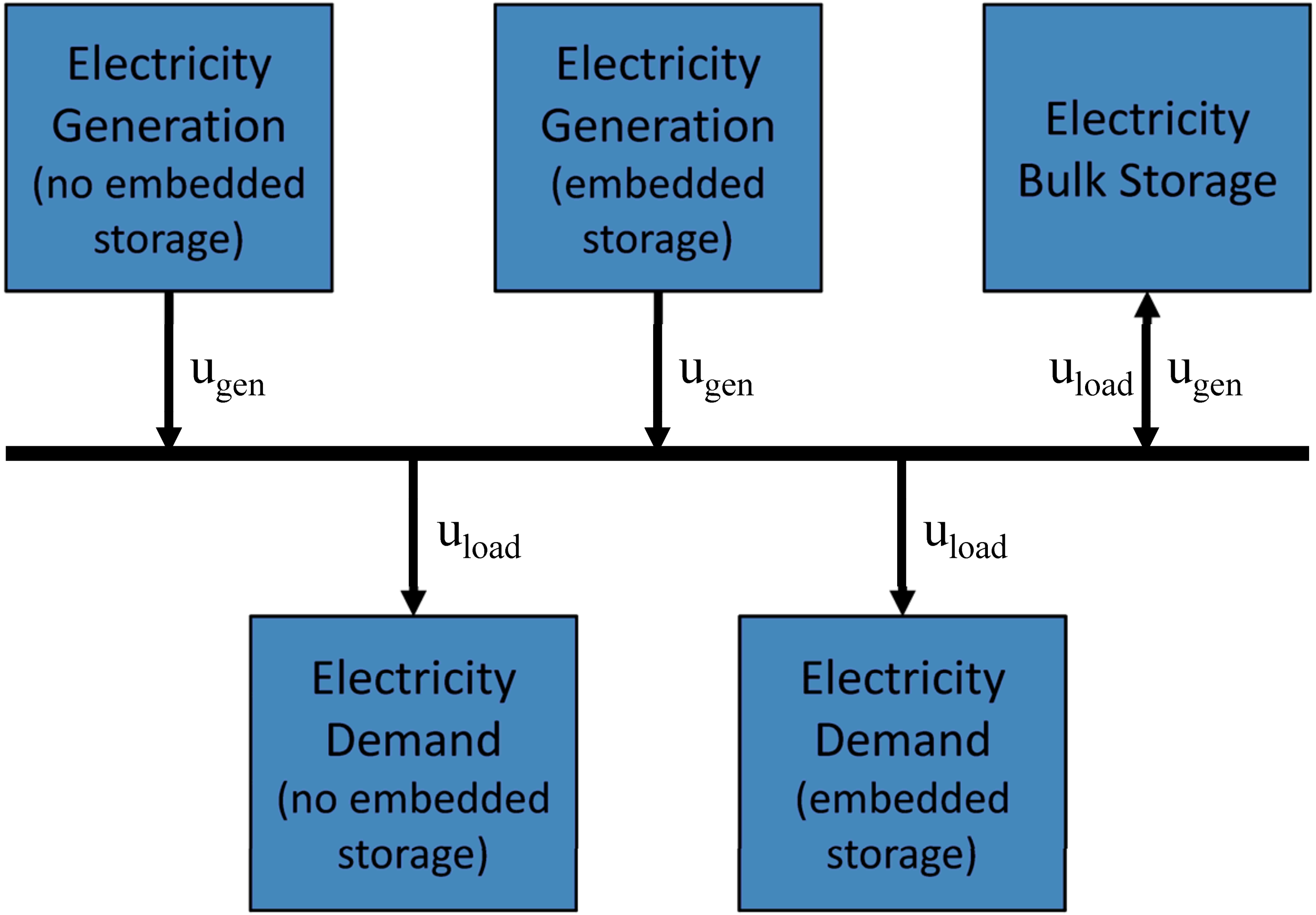
$$C_i\dot{x}_i = -\eta_{\text{gen}_i}^{-1} u_{\text{gen}_i} + \xi_i^{\text{water inflow}} - w_i$$

- **Dispatchable generation and load**
- **Constrained storage ($C \approx GWh$ range)**
- **Fuel ($\xi_{i,k}$): water influx from upper basin and other inflows ($\xi_{i,k\geq2}$)**
- **Waste (w): water discharge into lower basin (or river)**
- **Loss (v): evaporation from bassin**

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

Simplified
Functional Representation of a Power System

Modeling of Interaction with Electricity Grid only



Electricity Generation (no embedded storage)

Electricity Generation (embedded storage)

Electricity Bulk Storage

u_{gen}

u_{gen}

u_{load} u_{gen}

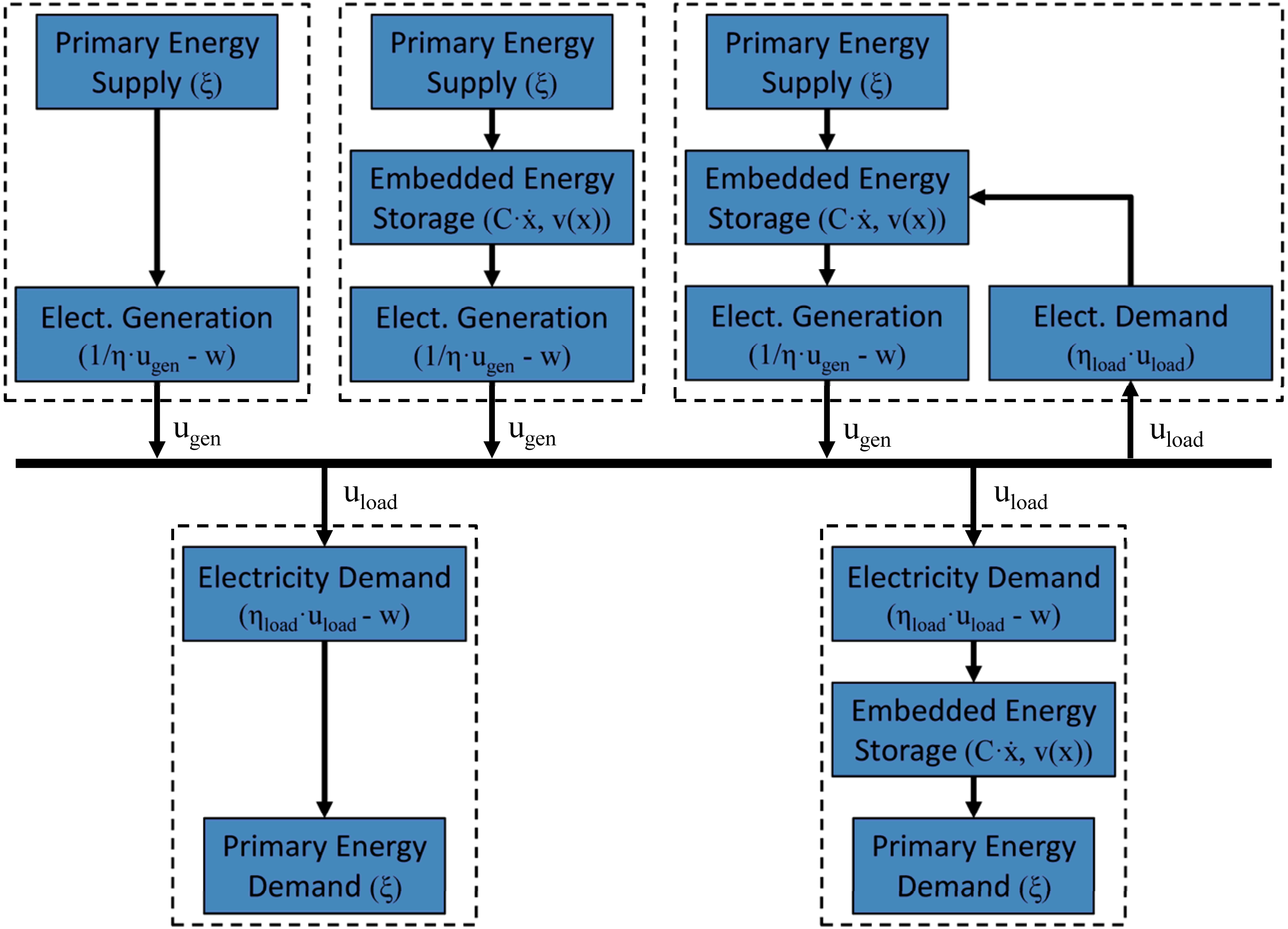
u_{load}

u_{load}

Electricity Demand (no embedded storage)

Electricity Demand (embedded storage)

(More) Complete
Functional Representation of a Power System



Primary Energy Supply (ξ)

Elect. Generation $(1/\eta\cdot u_{gen} - w)$

u_{gen}

Primary Energy Supply (ξ)

Embedded Energy Storage ($C\cdot\dot{x}$, $v(x)$)

Elect. Generation $(1/\eta\cdot u_{gen} - w)$

u_{gen}

Primary Energy Supply (ξ)

Embedded Energy Storage ($C\cdot\dot{x}$, $v(x)$)

Elect. Generation $(1/\eta\cdot u_{gen} - w)$

Elect. Demand $(\eta_{load}\cdot u_{load})$

u_{gen}

u_{load}

u_{load}

Electricity Demand $(\eta_{load}\cdot u_{load} - w)$

Primary Energy Demand (ξ)

u_{load}

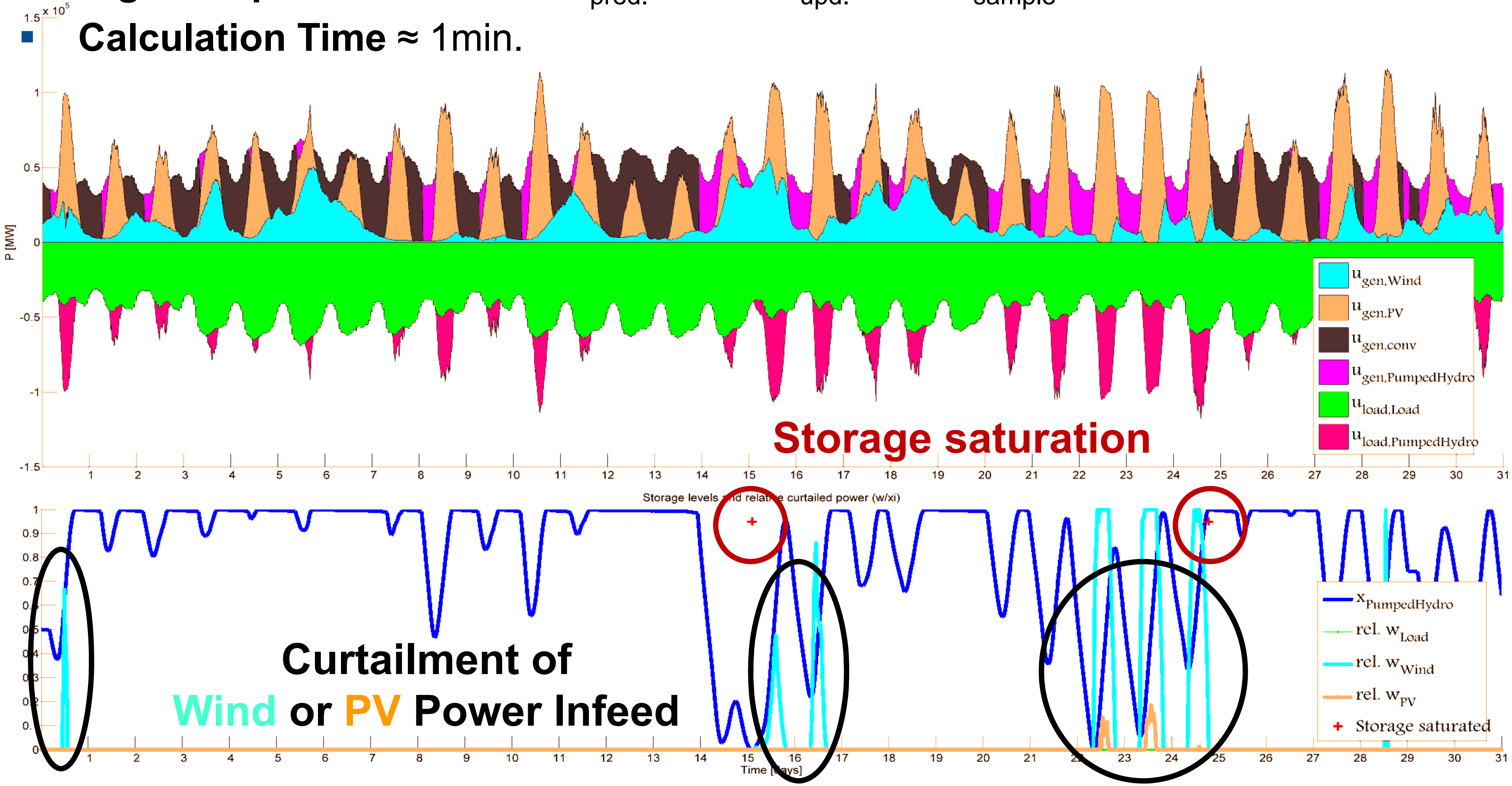
Electricity Demand $(\eta_{load}\cdot u_{load} - w)$

Embedded Energy Storage ($C\cdot\dot{x}$, $v(x)$)

Primary Energy Demand (ξ)

Simulation Results – Predictive Power Dispatch (Case Study Germany)

- **Simulation Period** May 2010 (30% Wind, **50% PV, no DSP**)
- **High Temporal Resolution** $T_{pred.} = 72h$, $T_{upd.} = 4h$, $T_{sample} = 15min.$
- **Calculation Time** ≈ 1min.

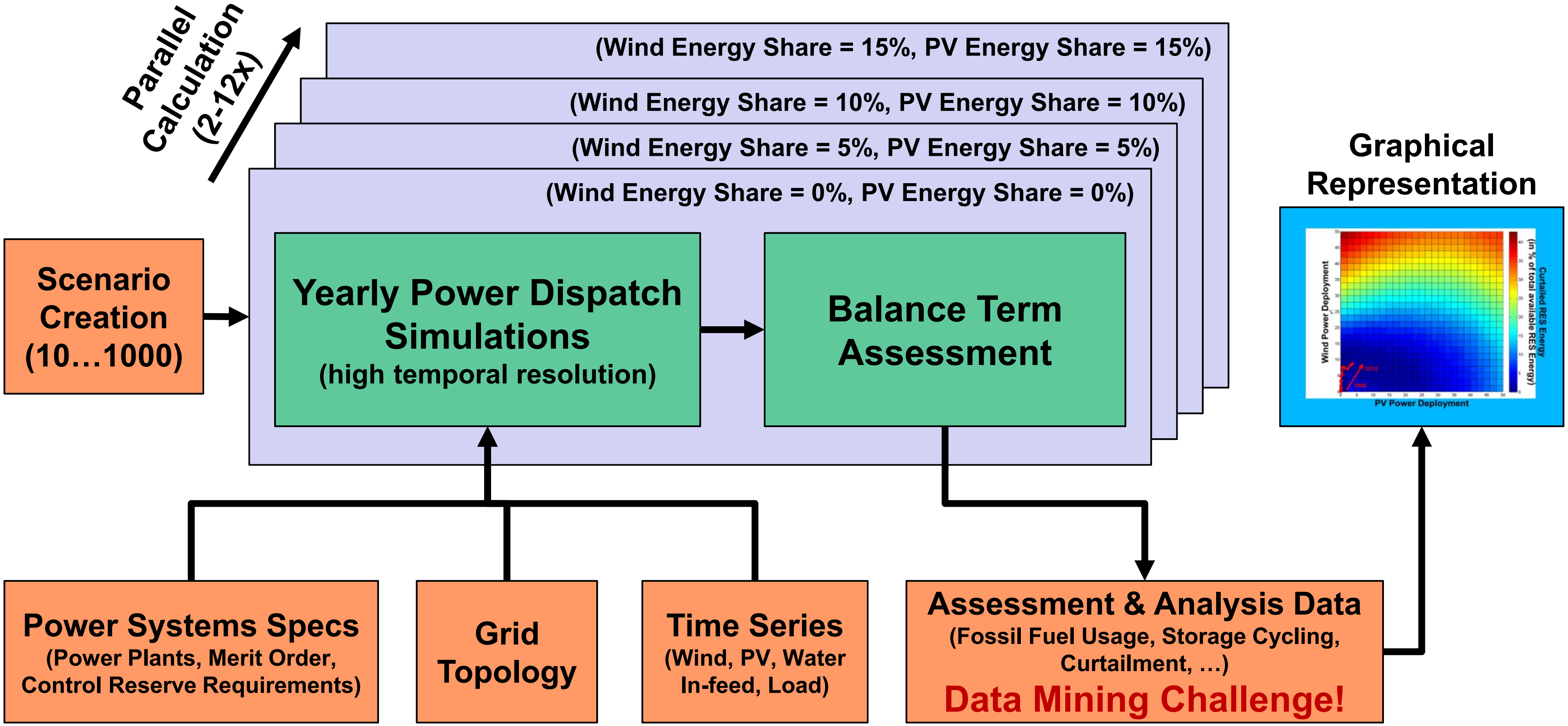


Storage saturation

Curtailment of Wind or PV Power Infeed

Assessment of Flexibility
General Simulation Approach

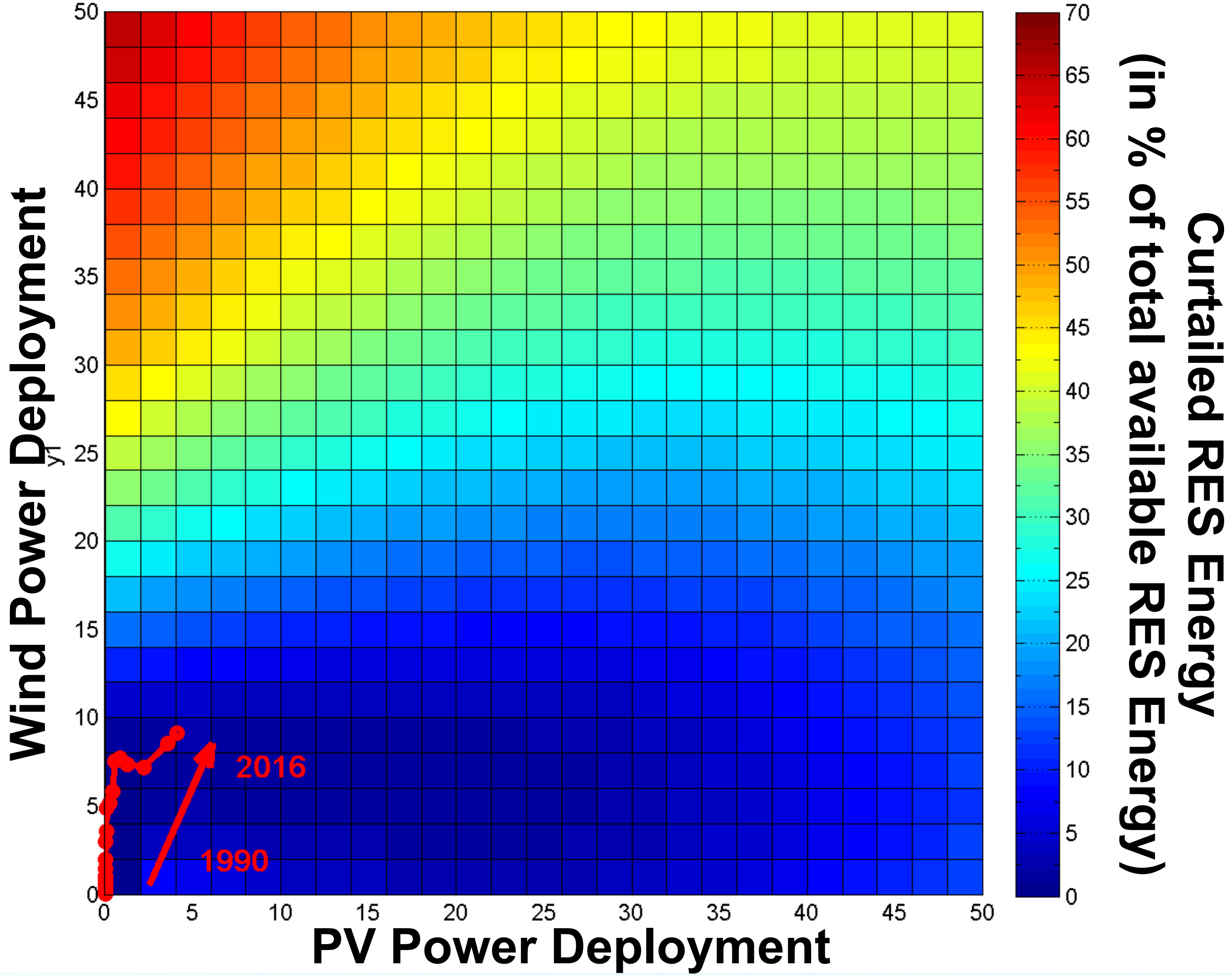
- Predictive power dispatch for full-year simulations
- High temporal resolution (15min.) – 1 year / 15min. ≈ 35’000 sim. steps
- Parallel calculation of 10-1000s scenarios (*perfectly parallel* task)



Assessment of Flexibility – Curtailed Renewable Energy in Germany

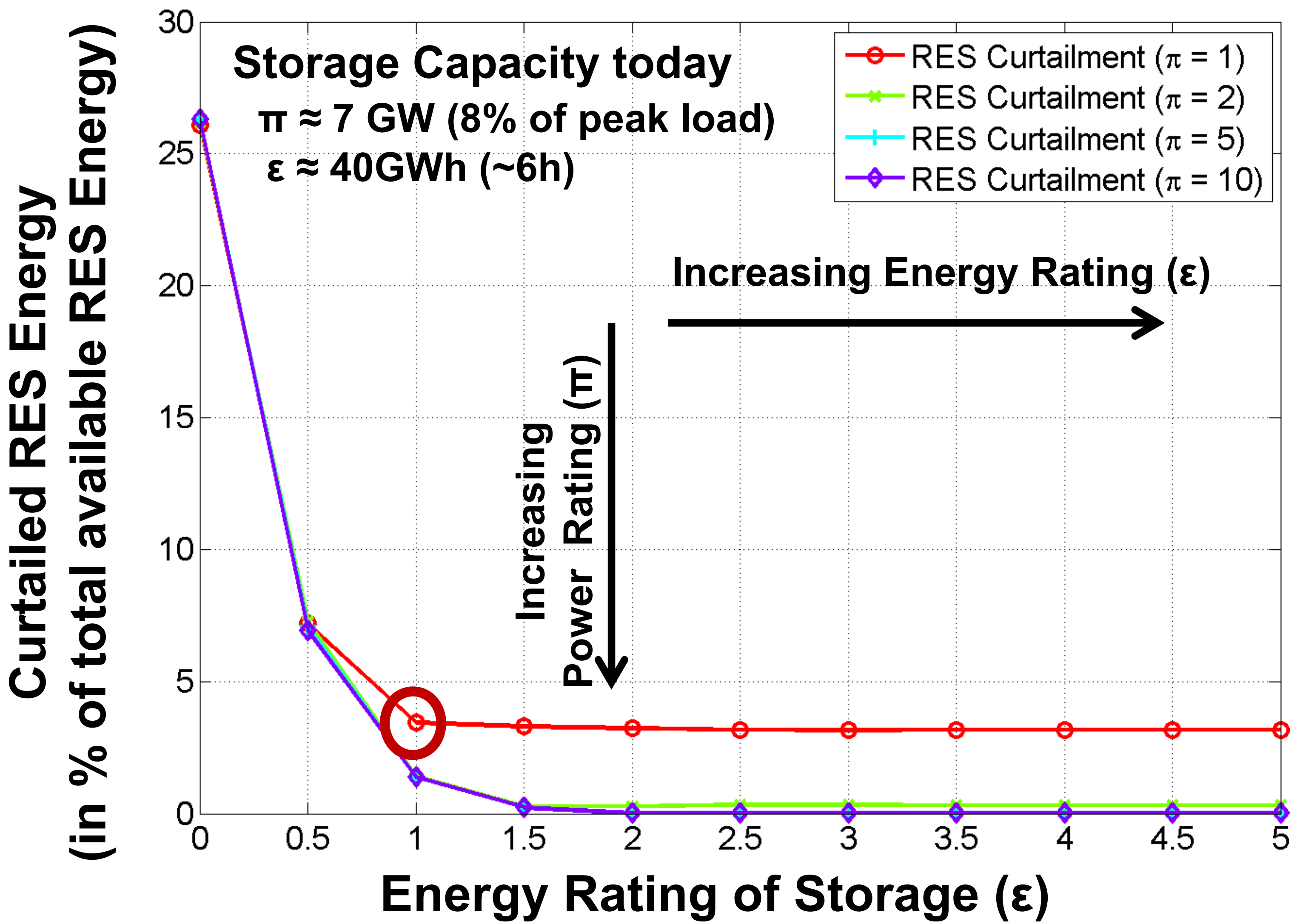
0-50% Wind Energy, 0-50% PV Energy, Full-Year 2011 simulations

only existing hydro storage, copperplate grid model, no export, no DSP



Assessment of Flexibility – Curtailed Renewable Energy in Germany

20% Wind Energy, 10% PV Energy (EU-NREAP Goals), Full-Year 2011 simulations
only existing hydro storage, copperplate grid model, no export *yet*, no DSP

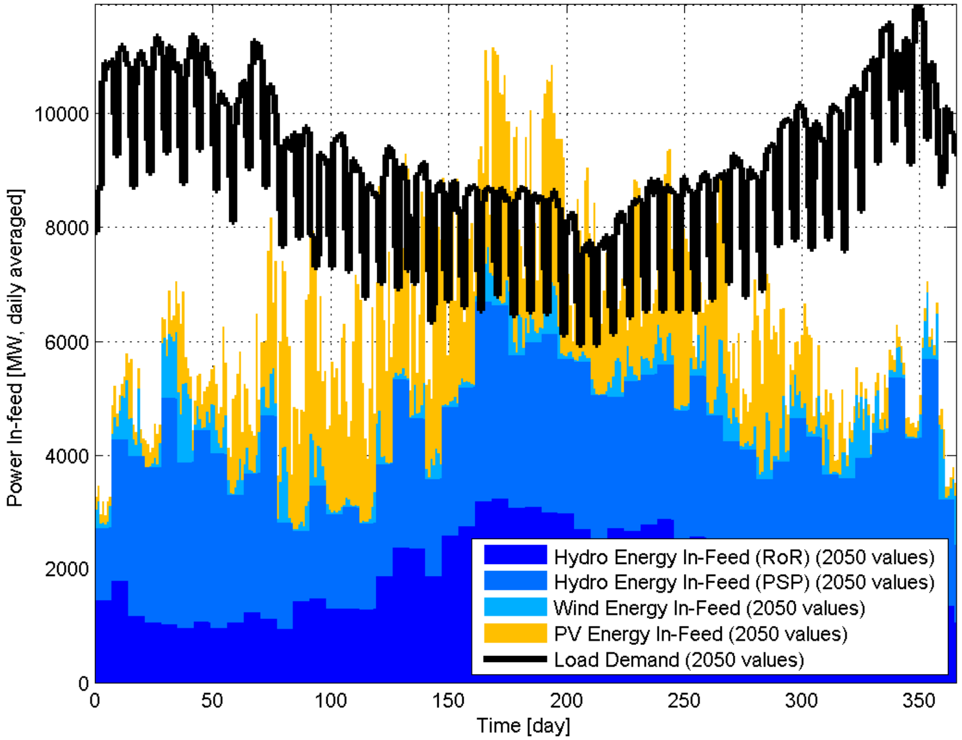


Simulations of Swiss Power System

Modeling and Simulation of Swiss Power System using Power Nodes

- **Full-Year Simulations based on ETH 2050 Scenario** (14 TWh PV, 3 TWh Wind, 39 TWh Storage Lake and Run-of-River Hydro, 78 TWh Load demand)

- Aggregation of 7 different Power Node types (load demand, wind & PV units, hydro storage lakes, run-of-river, pumped hydro storage, backup generation)



Simulations of Swiss Power System

Flexibility Electricity Production from Hydro Units

- Some flexibility for run-of-river plants observable (higher production levels during peak hours).
- Storage lakes are highly flexible producers when lakes are (energywise) neither empty nor full.

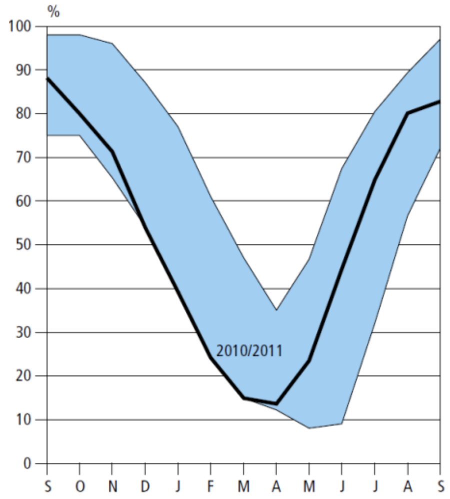
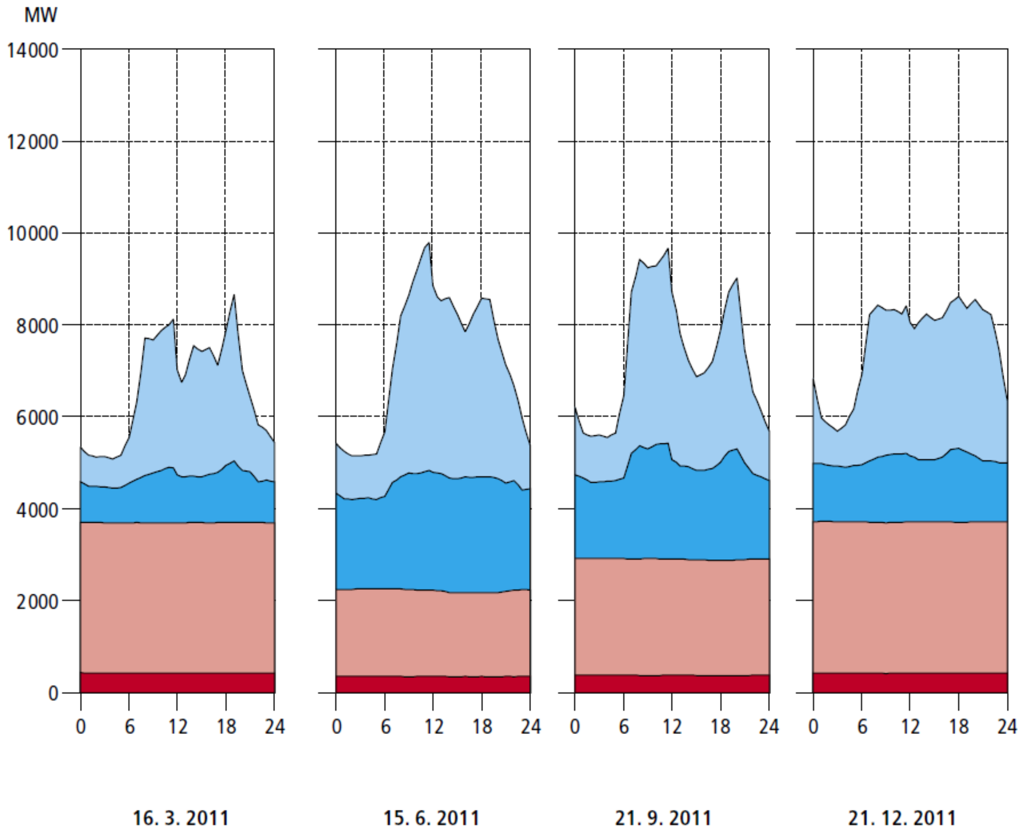


Fig. 13
Verlauf des Speicherinhalts (Stand Ende Monat)

Fig. 13
Variation du contenu des bassins d'accumulation (à la fin du mois)

Schwankungsbreite der hydrologischen Jahre 1972/1973–2010/2011

Ecarts au cours des années hydrologiques 1972/1973–2010/2011



Speicherkraftwerke
Centrales à accumulation

Laufkraftwerke
Centrales au fil de l'eau

Kernkraftwerke
Centrales nucléaires

Konventionell-thermische und andere Kraftwerke
Centrales thermiques classiques et divers

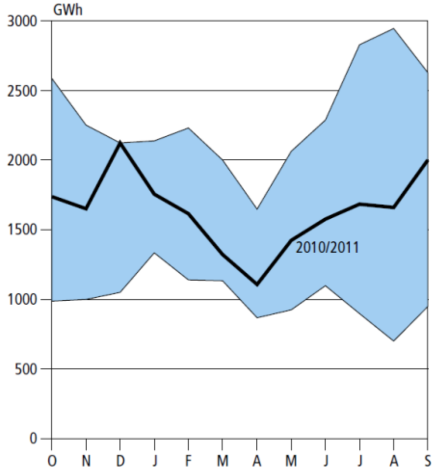


Fig. 12
Tatsächliche Erzeugung in den Speicherkraftwerken

Fig. 12
Production effective dans les centrales à accumulation

Schwankungsbreite der hydrologischen Jahre 1972/1973–2010/2011

Ecarts au cours des années hydrologiques 1972/1973–2010/2011

Simulations of Swiss Power System using Power Nodes

Modeling and Simulation of Swiss Power System (PHS: 1.7 GW, 50GWh)

- **Full-Year Simulations based on ETH 2050 Scenario (Base Case)**

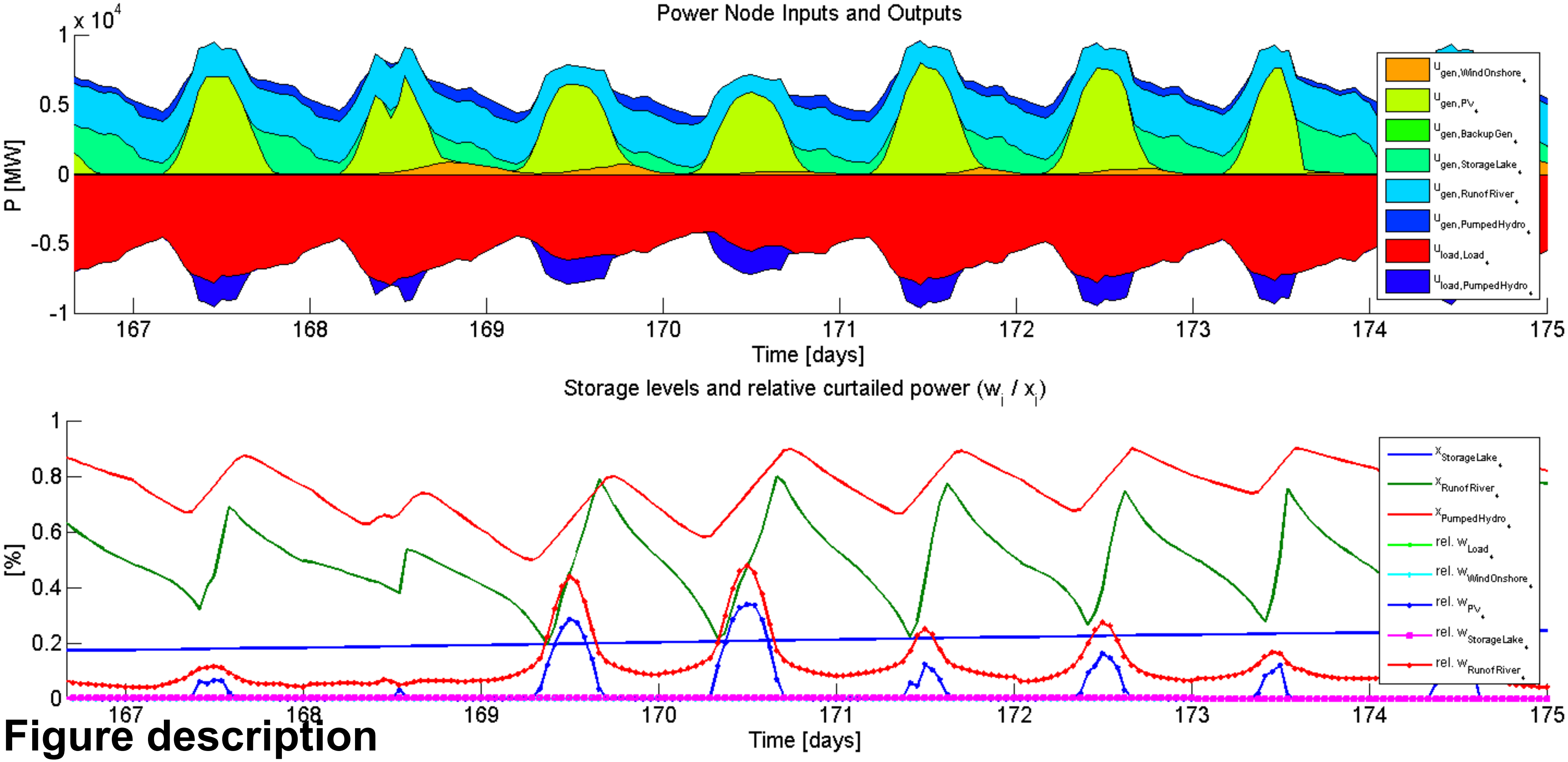
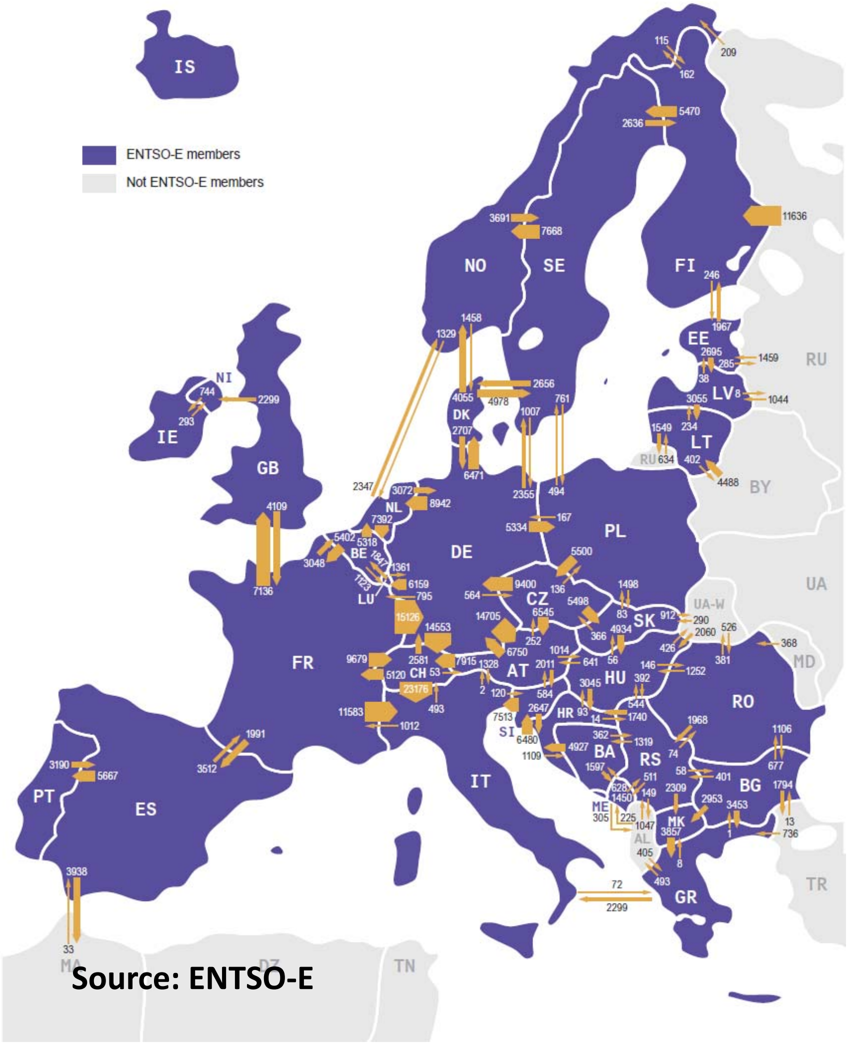


Figure description

- x-axis: One Summer Week (Hours 4000-4200)
- y-axis: Power In-feed (positive) / Outfeed (negative)

Assessment of Flexibility – Curtailed Renewable Energy in Europe



Source: ENTSO-E

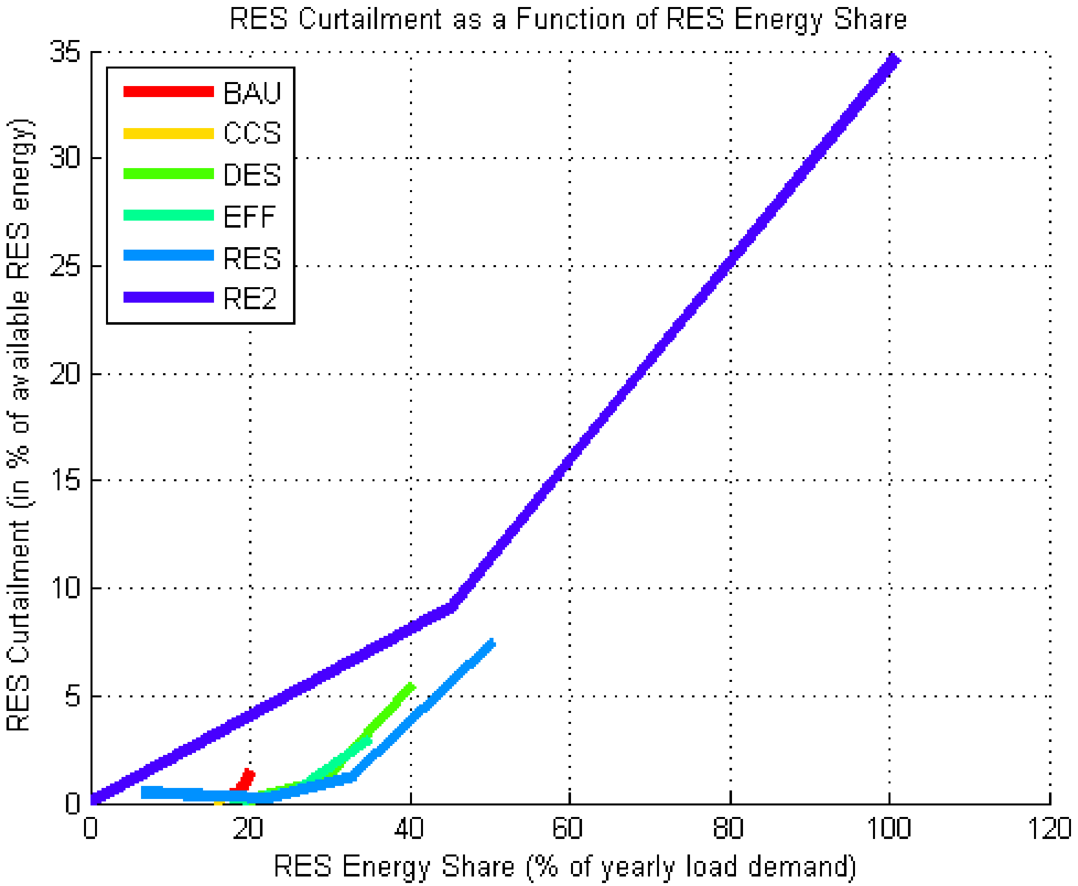
Modeling and Simulation of European Power System using Power Nodes

- **Power System** – 29 countries x up to 8 different aggregated Power Node types (load, wind, PV, hydro storage, fast/slow generation, CSP, DSP)
  → **up to 232 Power Node units**
- **Full-Year Simulations** with high temporal resolution (= 8’760 hourly steps)
- **Grid Topology** – 29 Node energy transfer model (using real Net Transfer Capacities)

Assessment of Flexibility – Curtailed Renewable Energy in Europe

There will soon be limits to RES integration without

- **Hardware-based Adaptation (transmission and/or storage capacities) and**
- **Control-based Adaptation (DSM, DLR, other smart grid measures)**

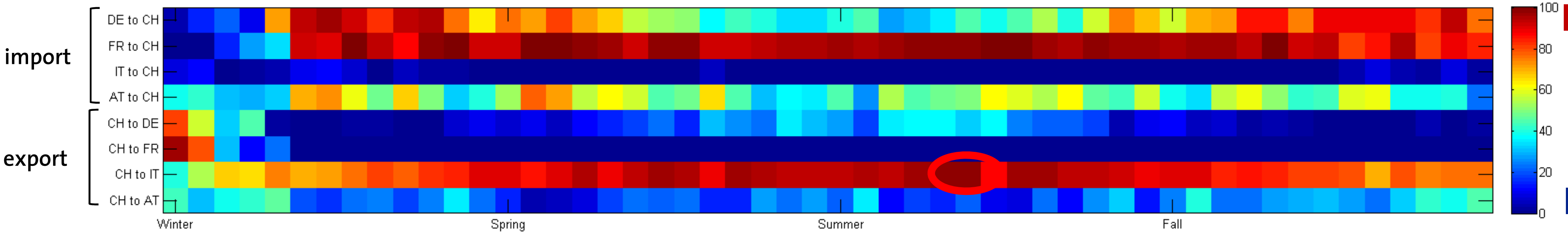


Performance Benchmark (central dispatch optimisation, no grid bottlenecks within countries, perfect prediction of wind/PV/load time-series, RES integration has priority)

Change of Load Flow Patterns around Switzerland

Master Thesis of Farid Comaty

Weekly NTC loading of the Swiss power system (Year 2010)



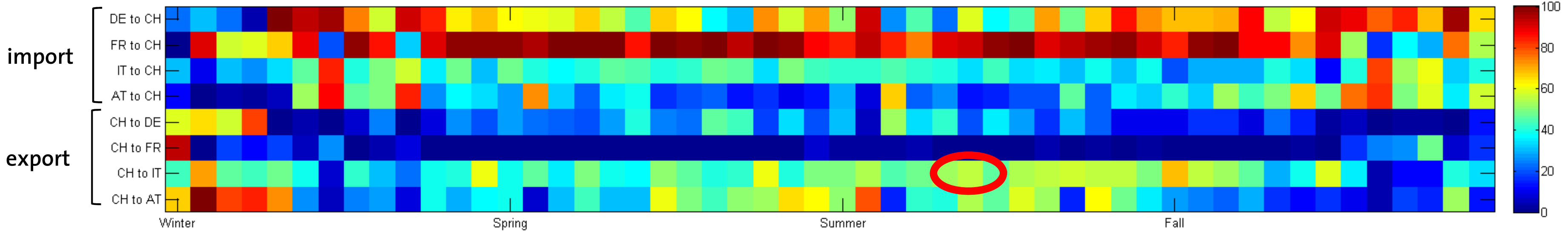
🟥 100% = fully loaded NTC, on a weekly basis

🟦 0 % = no loading , on a weekly basis

ENTSO-E NTC 2010			
FROM	**TO**	**MW**	**MW**
CH	AT	-505	1100
CH	DE	-1780	3800
CH	FR	-3100	1700
CH	IT	-1625	3850

First week of August		
CH → IT (3850MW)	**Low-RES (2010)**	**High-RES (2050)**
Weekly NTC loading	~100%	~50%
Energy export (GWh/week)	647	324

Weekly NTC loading of the Swiss power system with (Year 2050 with 50% RES)



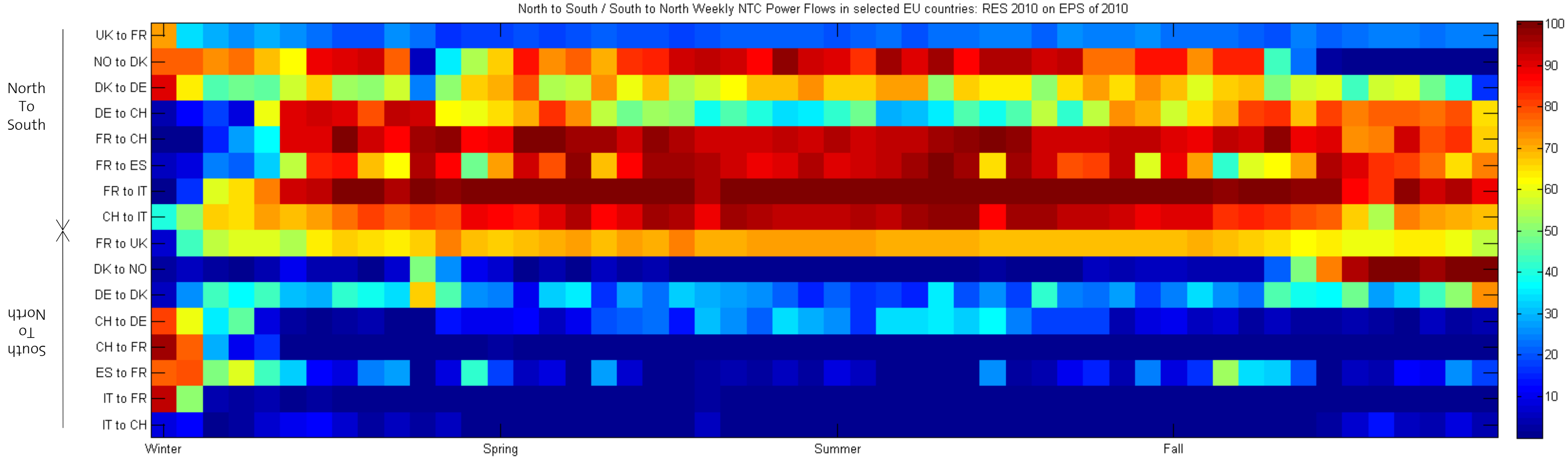
🟥 100% = fully loaded NTC, on a weekly basis

🟦 0 % = no loading , on a weekly basis

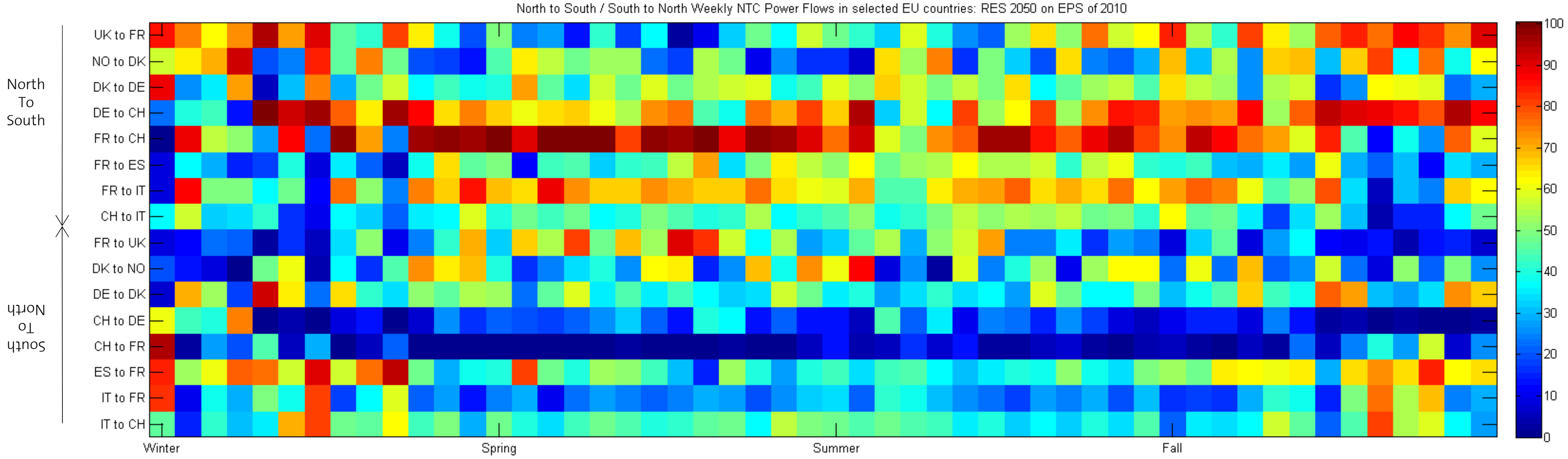
Change of Load Flow Patterns in European Power System

Master Thesis of Farid Comaty

Year 2010



Year 2010 (50% RES)



Structure of this Talk

- Complexity of Power System Processes
- Trends & Challenges in Power System Operation
- Role of Operational Flexibility in Power Systems
- Modeling and Analysis of Power Systems and their Operation
- **Conclusion**

Conclusion

- RES integration challenges are manyfold but – in principal – managable.
- Also other challenges (power markets, consumption growth, …).

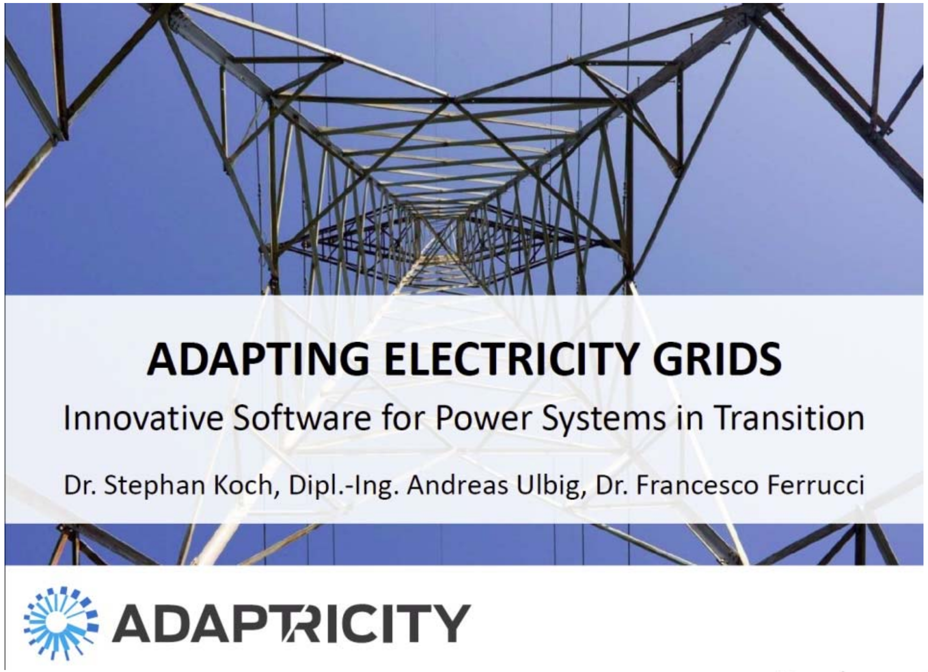
- Accurate modeling, simulation and analysis tools necessary for studying power systems and derive **adaptation strategies** from such decision support tools.
    - **Hard Paths** – Solve problems simply by oversizing everything. (= oversized, expensive, inefficiently operated power system)
    - **Soft Paths** – Solve problems via more control & optimal operation. (= right sized, less expensive, efficiently operated power system)

- **Trade-Off** Computation is cheap (and getting cheaper), physical grid investments are expensive.

Some References on Power Nodes

- **Heussen, Koch, Ulbig and Andersson, IEEE ISGT Europe Conference 2010.**
- **Heussen, Koch, Ulbig and Andersson, IEEE Systems Journal 2011.**
- **Ulbig and Andersson, IEEE PES General Meeting 2012.**
- **Ulbig and Andersson, IEEE Transactions on Sustainable Energy 2014 (in preparation).**

Outlook – ETH Spin-Off Project

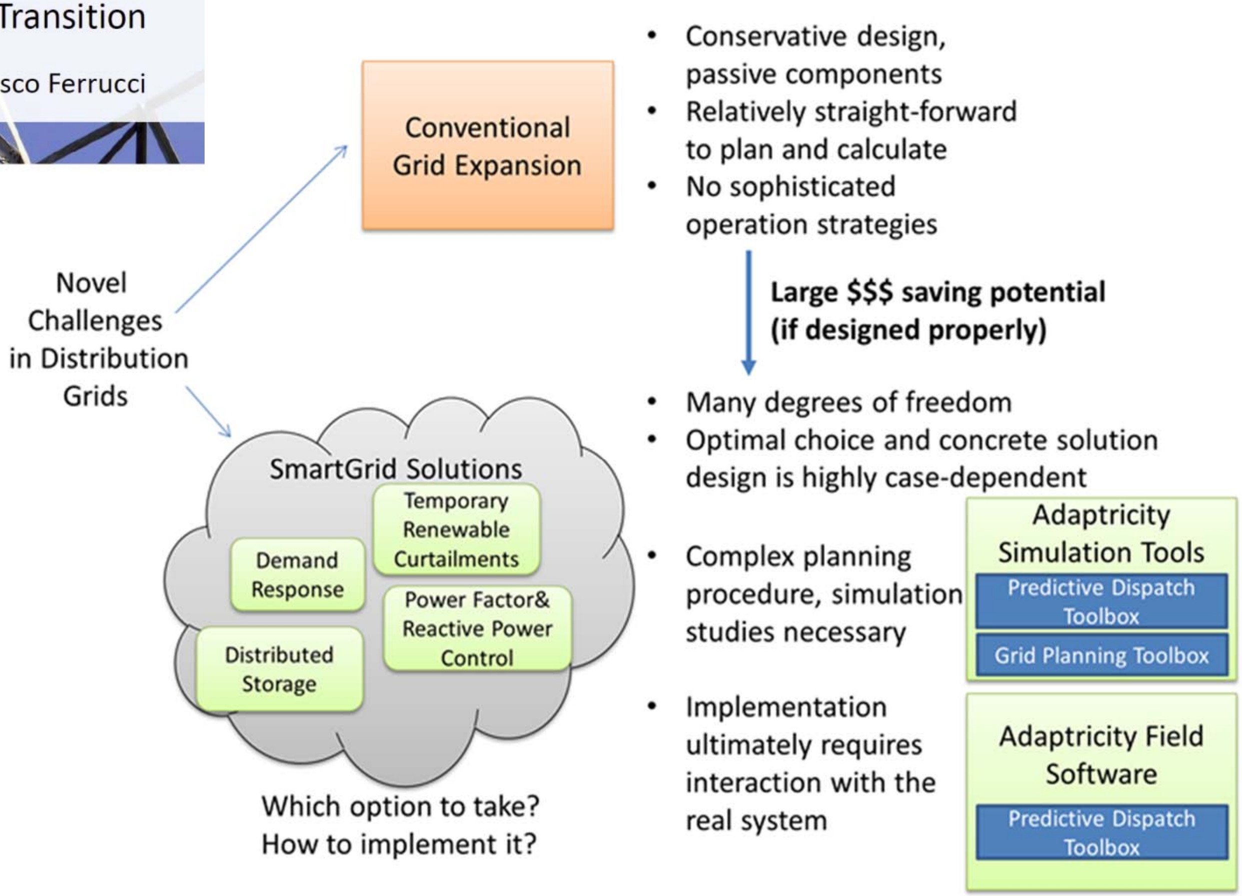


ADAPTING ELECTRICITY GRIDS

Innovative Software for Power Systems in Transition

Dr. Stephan Koch, Dipl.-Ing. Andreas Ulbig, Dr. Francesco Ferrucci

ADAPTRICITY



Novel Challenges in Distribution Grids

Conventional Grid Expansion

- Conservative design, passive components
- Relatively straight-forward to plan and calculate
- No sophisticated operation strategies

Large $$$ saving potential (if designed properly)

SmartGrid Solutions

Which option to take?
How to implement it?

- Many degrees of freedom
- Optimal choice and concrete solution design is highly case-dependent
- Complex planning procedure, simulation studies necessary
- Implementation ultimately requires interaction with the real system

Adaptricity Simulation Tools

Adaptricity Field Software

Questions or Comments?

Contact details:

Andreas Ulbig, Göran Andersson
ETH Zürich – Power Systems Laboratory

ulbig @eeh.ee.ethz.ch

www.eeh.ee.ethz.ch/en/power/power-systems-laboratory.html