Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

eeh power systems laboratory

Unified System-Level Modeling and Predictive Optimization of Virtual Power Plants for Control Services

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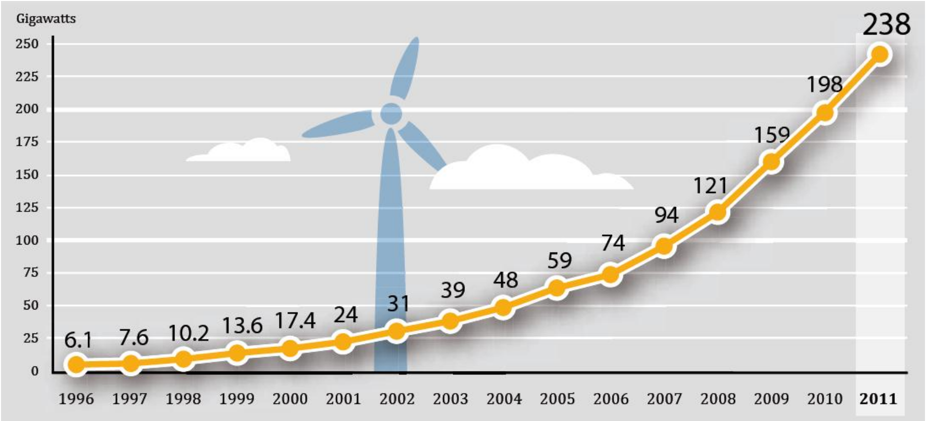
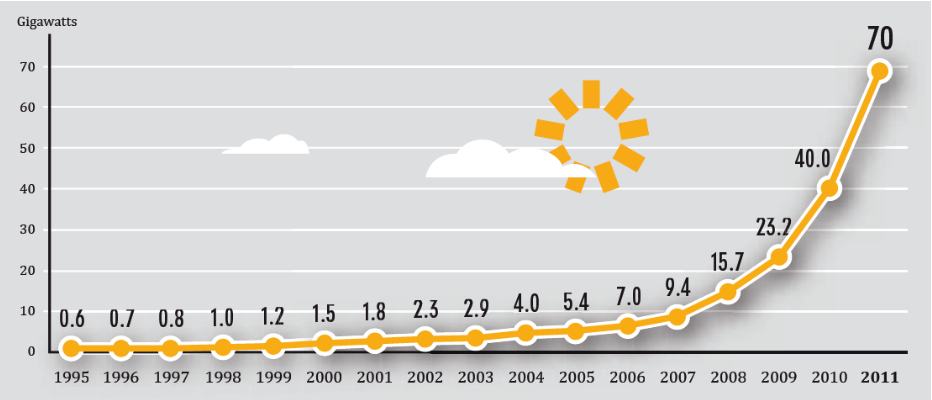
Outline

- Introduction and Motivation
  - Renewable Energy Expansion
  - Challenges for the Power System and Mitigation Options
- Leveraging Demand-Side Flexibility
- Modeling Virtual Power Plants by "Power Nodes"
- Dispatch Strategies for Control Services
- Application Potential for Advanced Optimization and Control

Introduction and Motivation

Renewable Energy Expansion



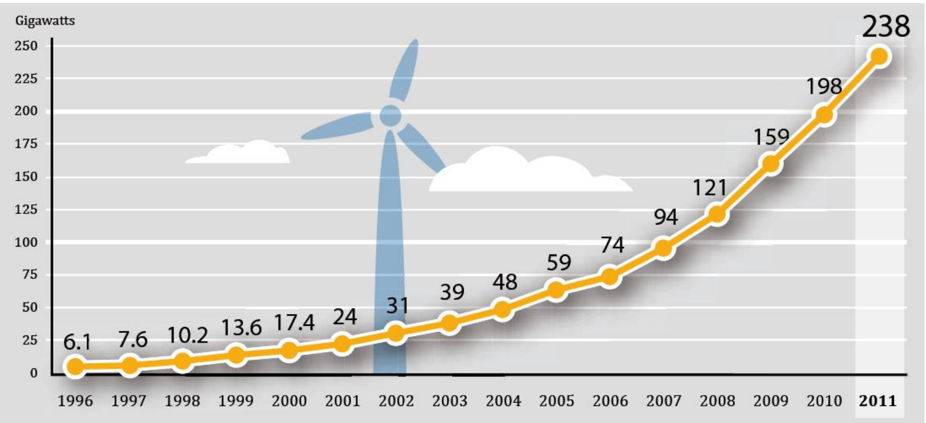


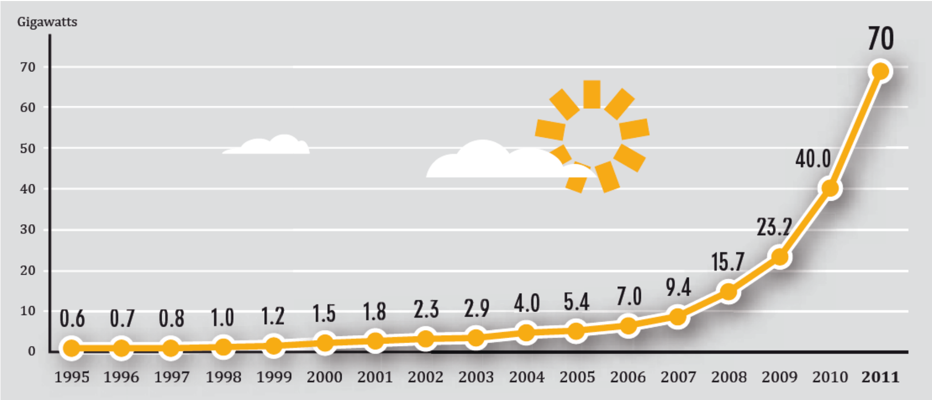
Source: Renewables Global Status Report, 2012

- Sustained high growth rates of intermittent renewable energy worldwide (mainly wind and solar)
- Certain European countries with highly above-average contributions of one specific technology
  - Denmark, Spain, Germany (wind)
  - Germany, Italy (solar PV)

Introduction and Motivation

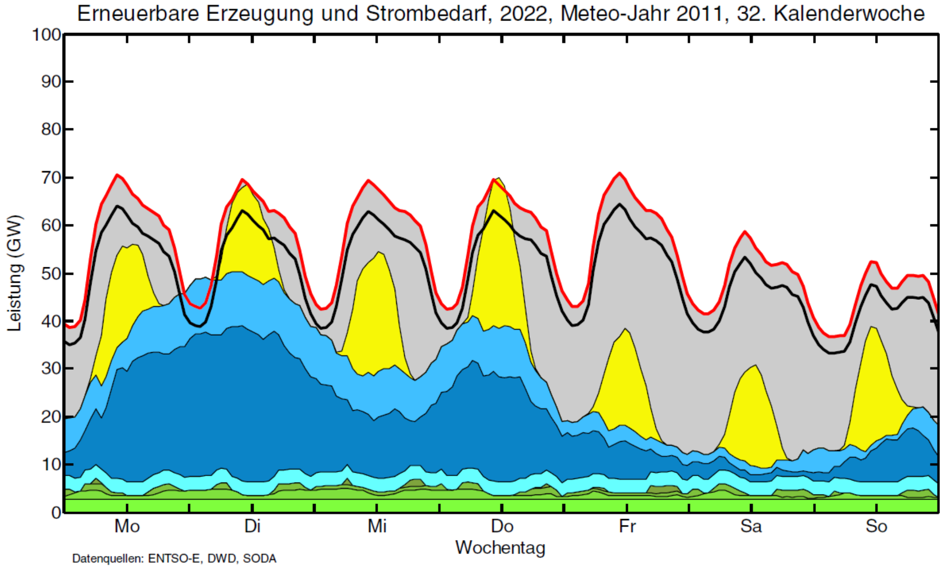
Renewable Energy Expansion





Source: Renewables Global Status Report, 2012

- Low capacity factor of RES (wind: ~20-30%, PV ~10-20%)
- “Large” contributions in **energy** imply “huge” contributions in **power** (at certain times)



Source: Agora Energiewende, 2012

Introduction and Motivation

Challenges for the Power System

Lack of energy in some instants, large excess in others

Increased ramp rate of the residual load

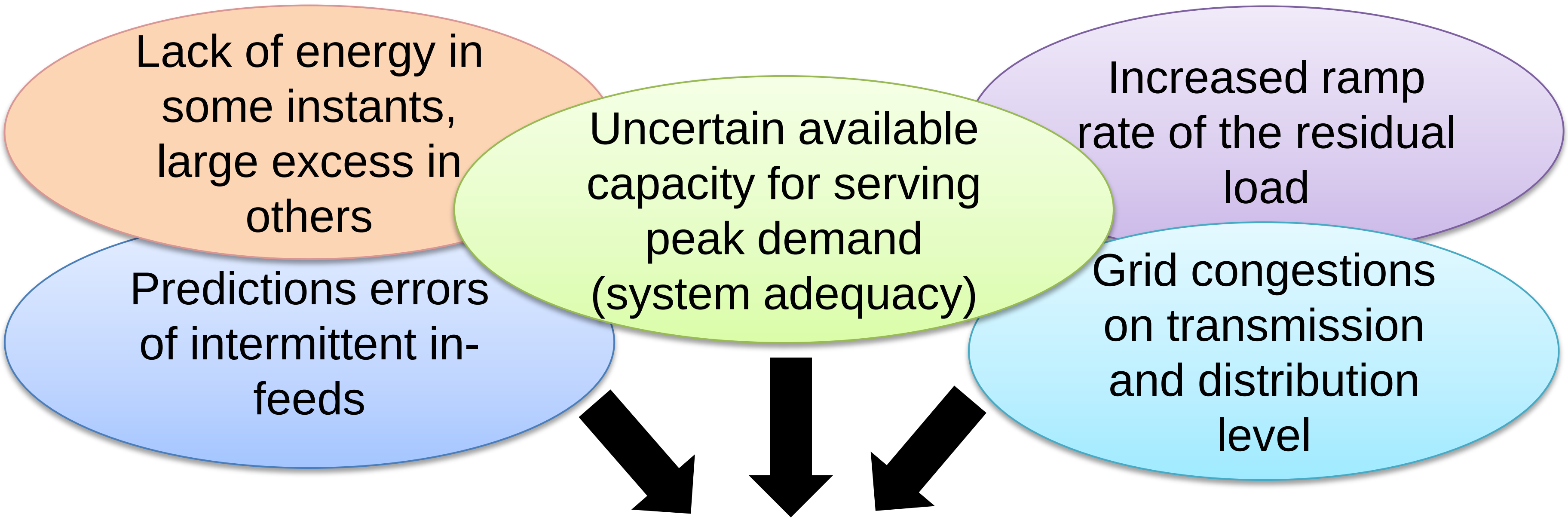
Uncertain available capacity for serving peak demand (system adequacy)

Predictions errors of intermittent in-feeds

Grid congestions on transmission and distribution level

Introduction and Motivation

Challenges for the Power System – Mitigation Options



- → Dispatchability of previously non-dispatchable resources (intermittent renewables, flexible demand)
- → Increased system flexibility (generation, load, storage), close coordination and co-optimization of resources (e.g. in Virtual Power Plants)
- → Transmission and distribution grid expansion or "smarter" utilization leveraged by advanced control and ICT

Leveraging Demand-Side Flexibility

What kind of demand is flexible, and in which way?

- Residential and commercial thermal loads

  (water heaters, heat pumps, A/C

  refrigerators, refrigeration warehouses)

  → Controlled deactivation (+energy shift)

  → Controlled activation (+energy shift)

- Manually shiftable residential demand

  (dish washer, washing machine, tumbler)

  → Deferred utilization

Interruptible industrial processes

(steel and concrete mills, industrial heating, …)

→ Deferred utilization

Leveraging Demand-Side Flexibility

Traditional Views on Demand Response

Perspective 1

Defer the load of electric heating etc. to the night hours. Main motivation: peak shaving for distribution infrastructure protection

- Manually or automatically activate electric heating and electric water heaters at night, take advantage of heat storage capacity

  → controlled activation of load in larger groups

Perspective 2

Shave the peaks if necessary by manual demand response

- Manual curtailment (possibly disruptive) of load during hours of extremely high demand (e.g. hot summer in California)

  → selective curtailment only

Perspective 3

Balance 15-minute energy values

- Selectively activate and deactivate switchable loads for balancing 15-minute energy schedules

  → controlled deactivation and activation on shorter time scales

Leveraging Demand-Side Flexibility

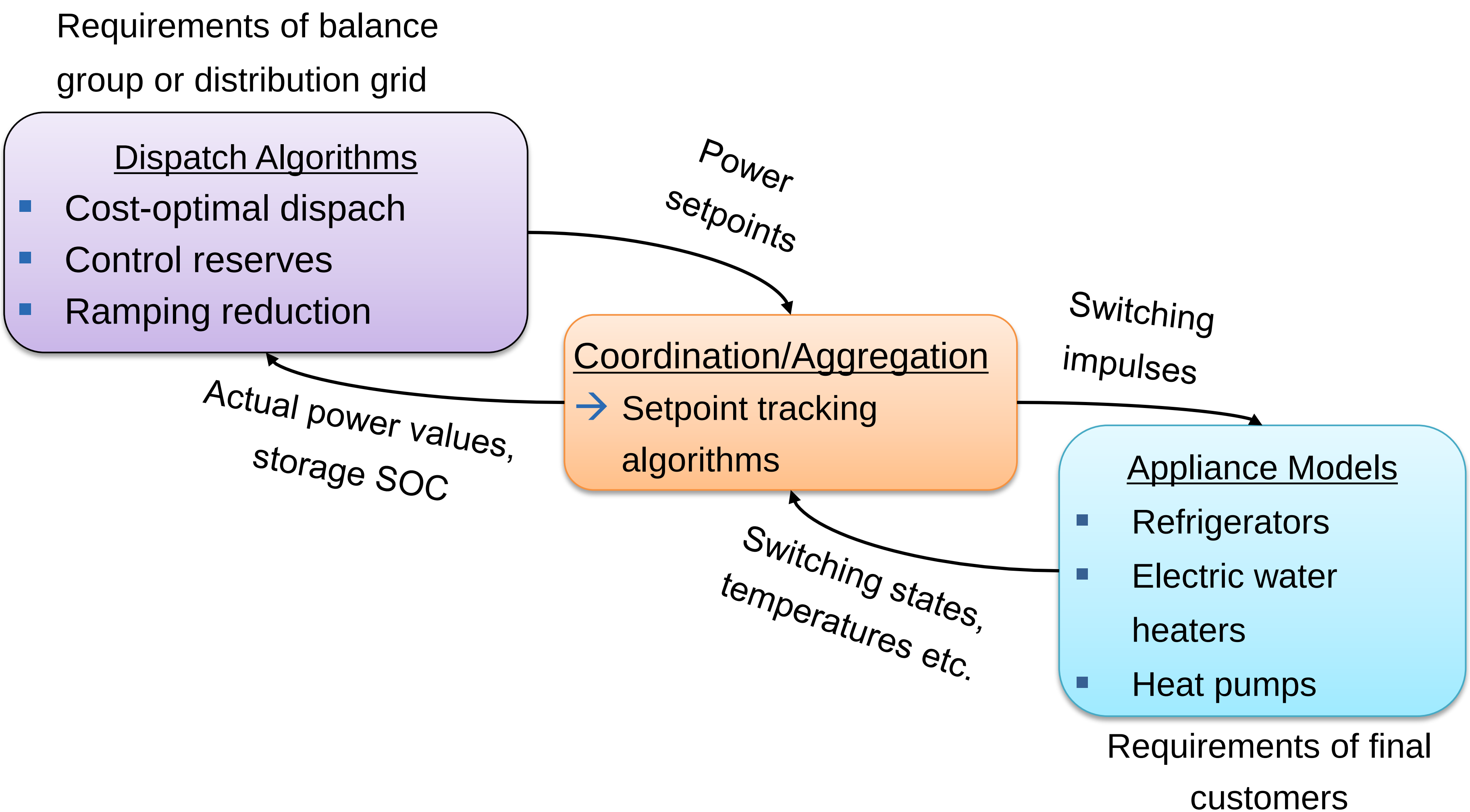
Recent Perspectives

Demand Response

Incentive-based decentralized decision	**Market participation by final customer**	**Frequency-based decentralized decision**	**Aggregation and direct control**
Rationale of the approach:			
Send price signals to customers, try to anticipate their reaction	Use automated agents to negotiate supply and demand by bidding	Measure frequency in appliances and adapt consumption behavior	Achieve setpoint tracking and derive setpoint from pursued control goal
Time scale of influence:			
(Mainly) Day-ahead	(Mainly) Day-ahead	Real-time operation	Close-to-real-time
Main purpose:			
Influence on daily load curve (shifting)	Influence on daily load curve (shifting)	Primary control or disturbance reaction	Shifting, balancing, frequency control
Unit types:			
Shiftable load, generation, storages	Shiftable load, generation, storages	Thermal load for primary, all load for dist.	Thermal load, controllable generation, storage

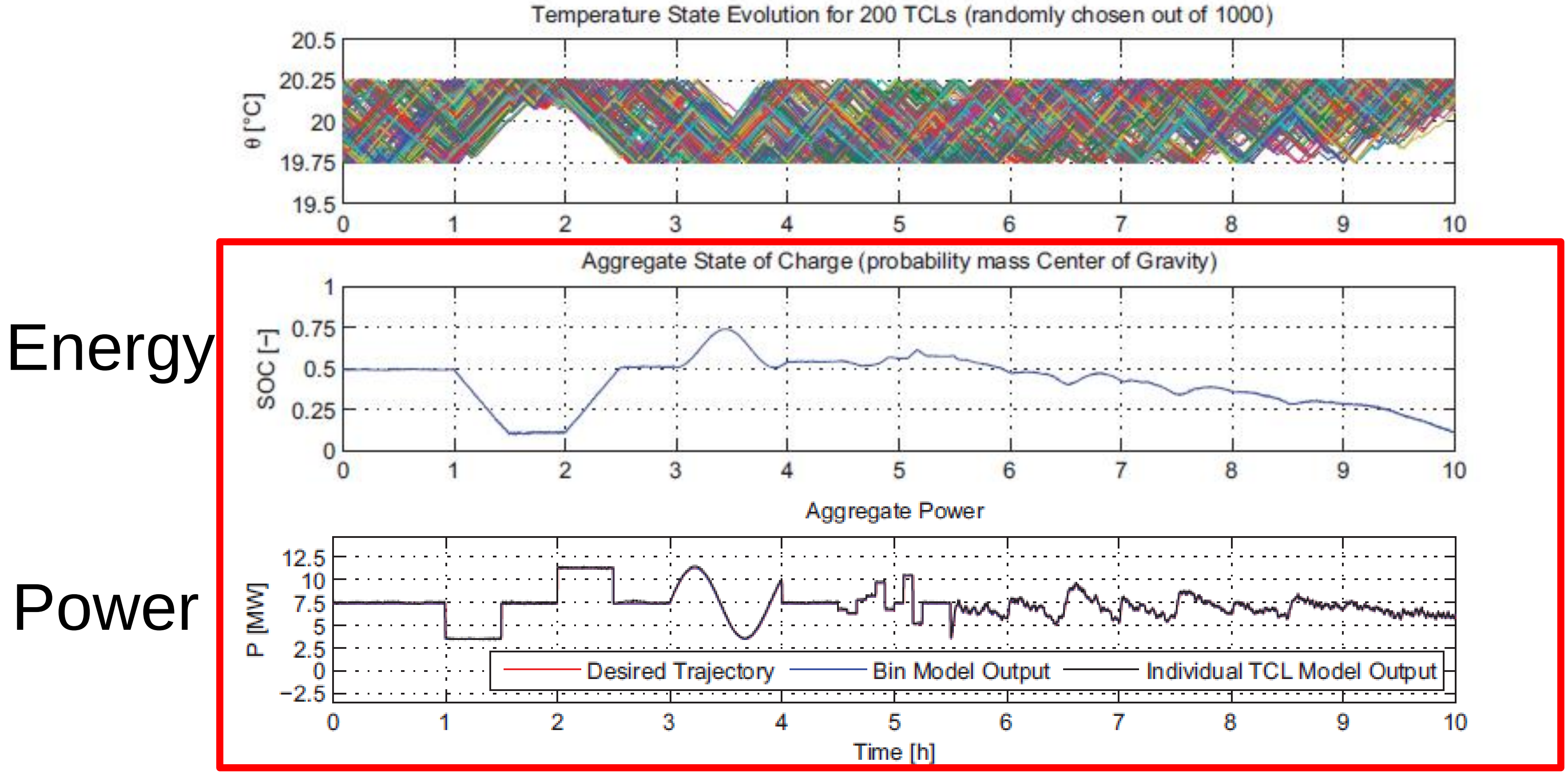
Leveraging Demand-Side Flexibility

Hierarchical Coordination and Control Concept



Leveraging Demand-Side Flexibility

Setpoint Tracking Algorithms – Example: 1’000 air conditioning units



→ Storage characteristics

Modeling Virtual Power Plants by “Power Nodes“

Virtual Power Plants

- ICT-linked pools of diverse units operated in a coordinated way
- Joint participation in energy and ancillary services markets

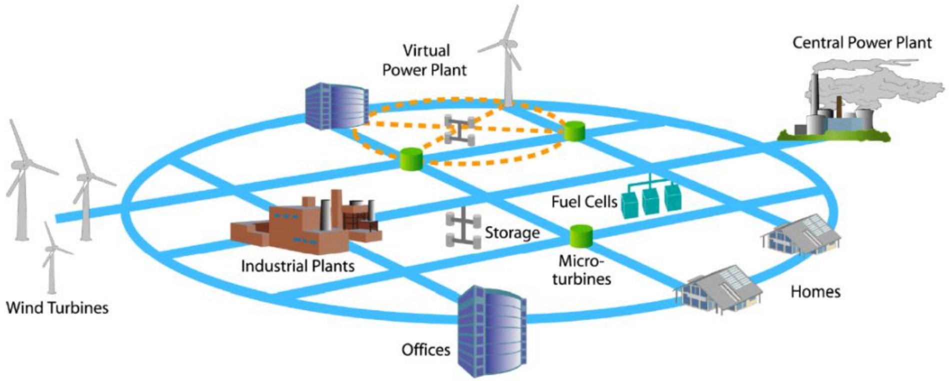


Image source: Open Systems International

Challenges

- Partial or no controllability of certain units
- Power and ramp-rate constraints
- Ability to store energy (→ State of Charge constraints)
- Diverse efficiency, operational requirements, optimal working points, cost structure, …

→

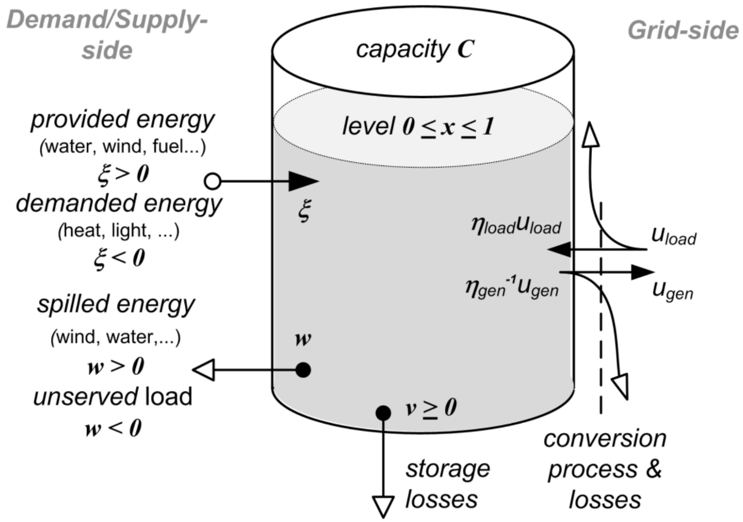
WANTED

A unified concept to model generation / load / storage portfolios consisting of diverse units from a system (→ network) perspective

Modeling Virtual Power Plants by “Power Nodes“

The Power Node

Modeling Framework



Storage capacity × state-of-charge

Power out-feed from grid

Power in-feed to grid

Shedding term

Internal losses

$$C\dot{x} = \eta_{\mathrm{load}} u_{\mathrm{load}} - \eta_{\mathrm{gen}}^{-1} u_{\mathrm{gen}} + \xi - w - v$$

Efficiency factors

Provided / demanded power

Modeling Virtual Power Plants by “Power Nodes“

General power node: $C\dot{x} = \eta_{\text{load}} u_{\text{load}} - \eta_{\text{gen}}^{-1} u_{\text{gen}} + \xi - w - v$

Electric water heaters

- Time-dependent dispatchable load (heating element)
- Constrained ”storage” ($C \approx 10\ kWh$)
- Demand: hot water, daily pattern ($\xi < 0$), internal heat loss ($v > 0$)

$$C\dot{x} = \eta_{load} u_{load} + \xi - v$$

Conventional power plant

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

$$\eta_{\text{gen}}^{-1} u_{\text{gen}} = \xi$$

Wind power plant

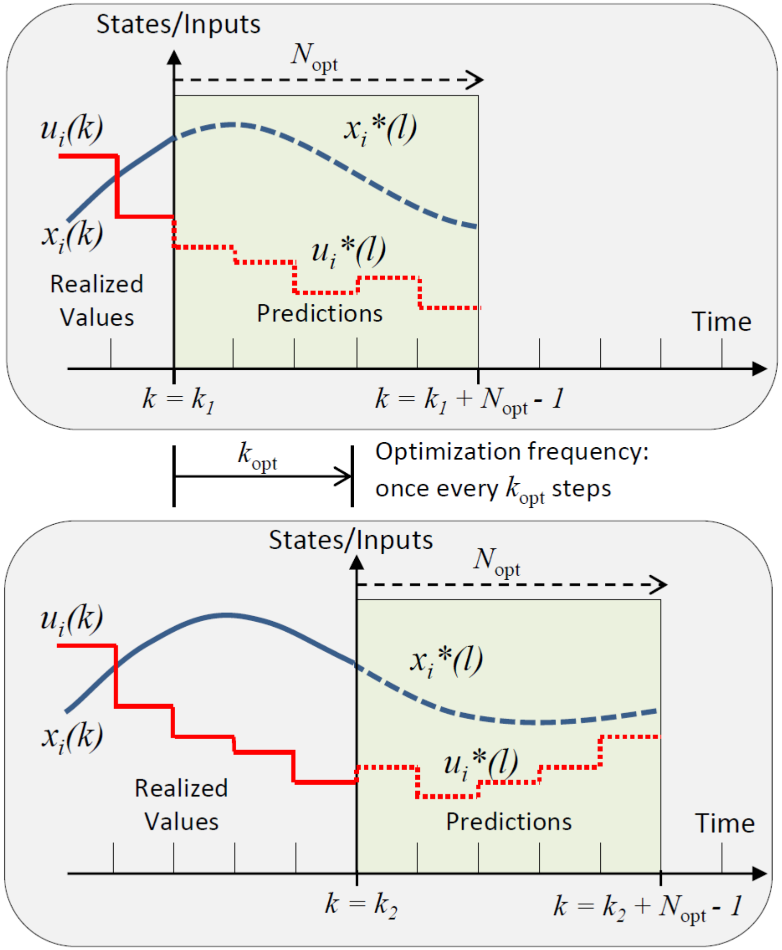
- Time-dependent dispatchable generation, if wind blows, $\xi \geq 0$, and if energy waste term $w \geq 0$
- No load, no storage (C)
- Fuel: wind power ($\xi > 0$)

$$\eta_{\text{gen}}^{-1} u_{\text{gen}} = \xi - w$$

Dispatch Strategies for Control Services

Dispatch with Model Predictive Control

- Joint predictive optimization of a power node portfolio
- Cost function and constraint design allows to cover a variety of use cases:
  - Least-cost dispatch
  - Market-based VPP operation
  - Balancing of schedule deviations
  - Provision of frequency control reserves
  - Capacity firming of intermittent generation
  - Peak shaving
  - Residual load ramp-rate reduction
  - Distribution grid optimization

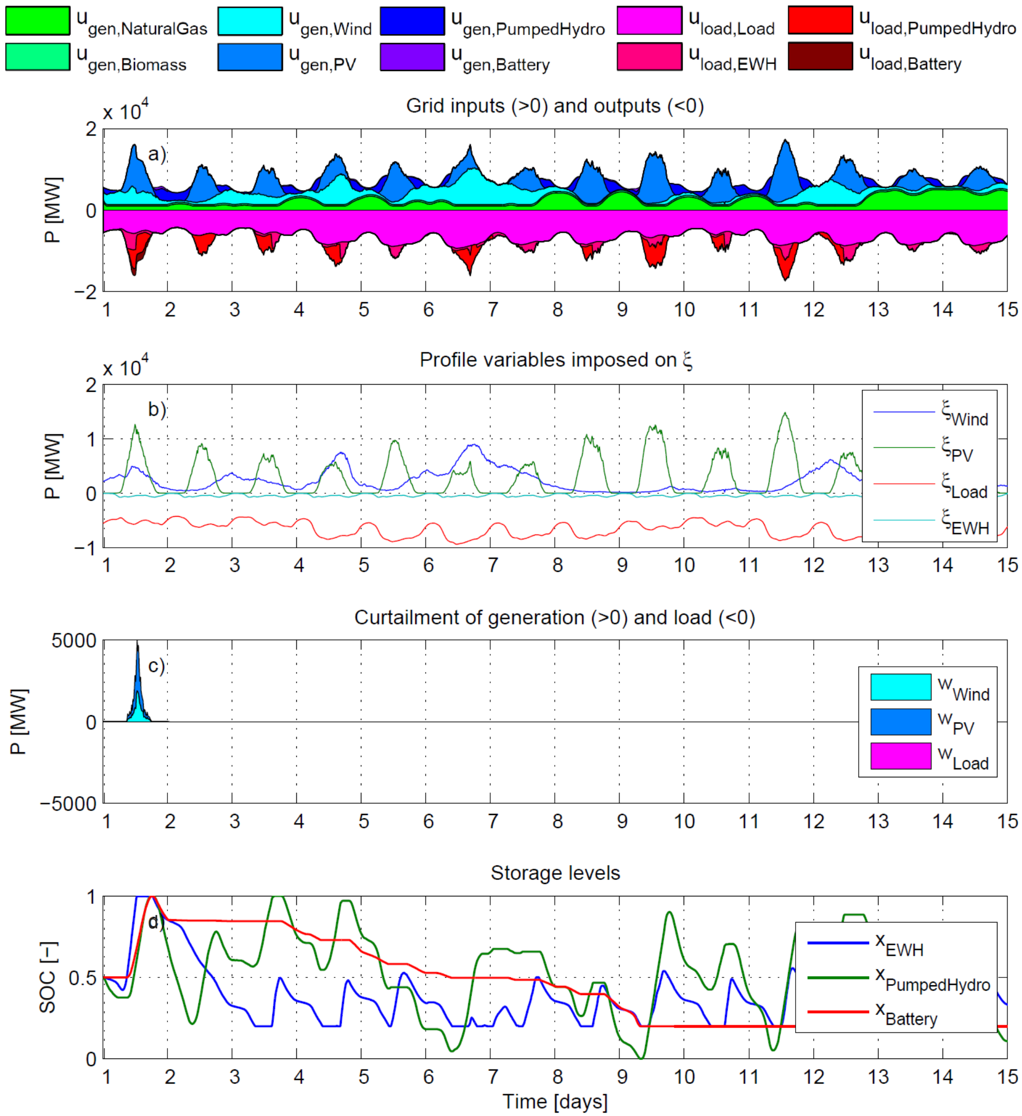


Dispatch Strategies for Control Services

Least-cost dispatch

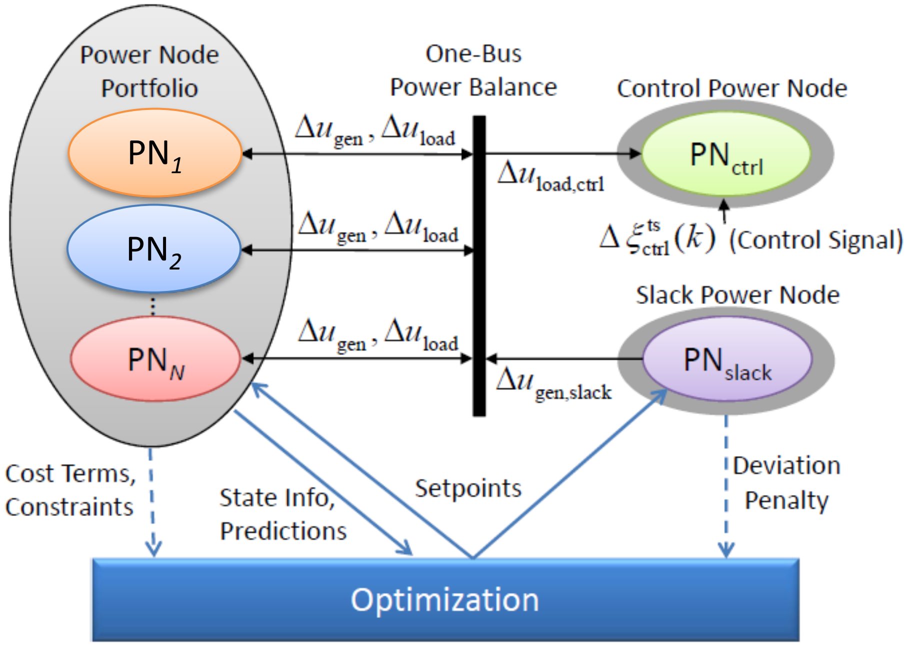
- Minimize endogenous operation cost based on predictions:

$$J_k = \sum_{l=k}^{k+N_{\text{opt}}-1} J^*_{\text{endo}}(l)$$

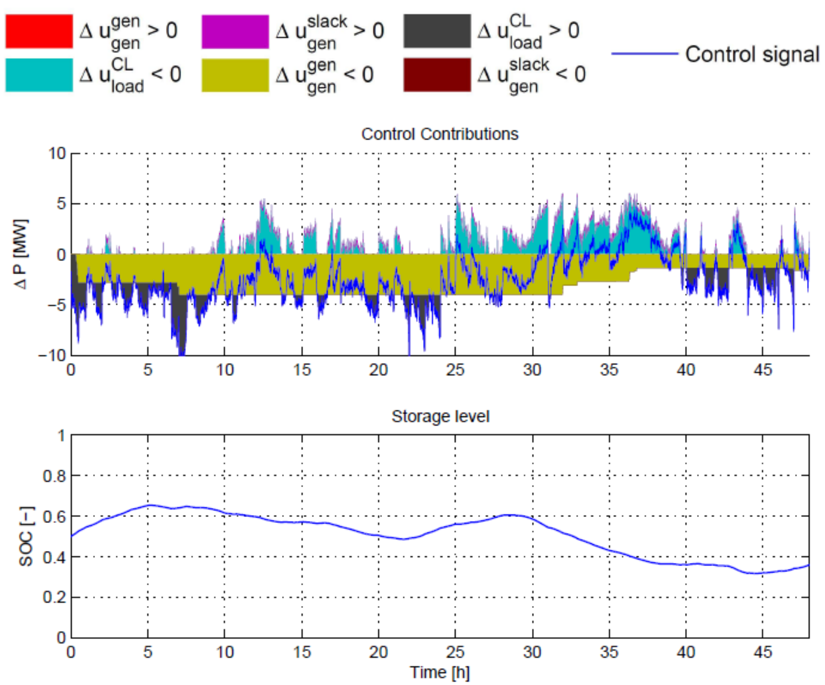


Dispatch Strategies for Control Services

Frequency Control Reserves

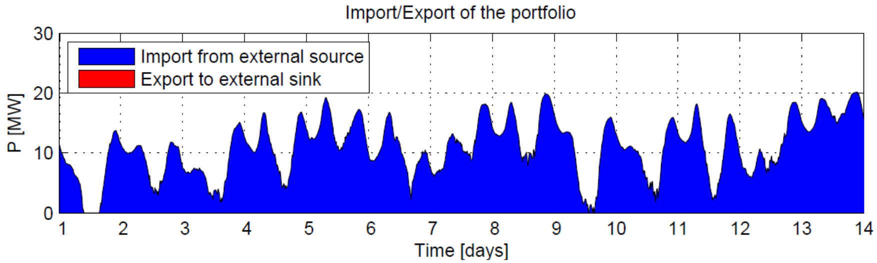


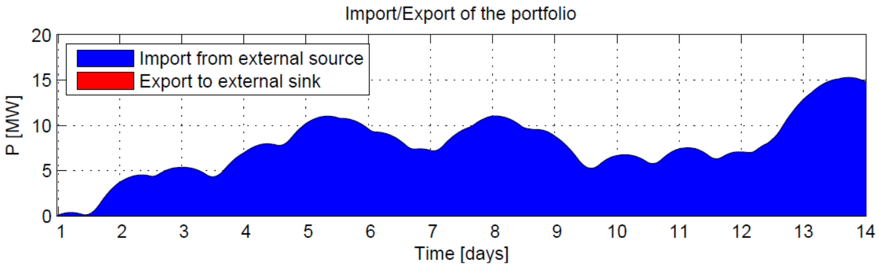
- Introduction of auxiliary power nodes
- Optimize for coverage of the control signal with minimal cost



- Cover (most of) control signal by flexible load
- Utilize generator to refill storage

Dispatch Strategies for Control Services





- Residual load can exhibit high ramps
  → high strain on conventional generation assets

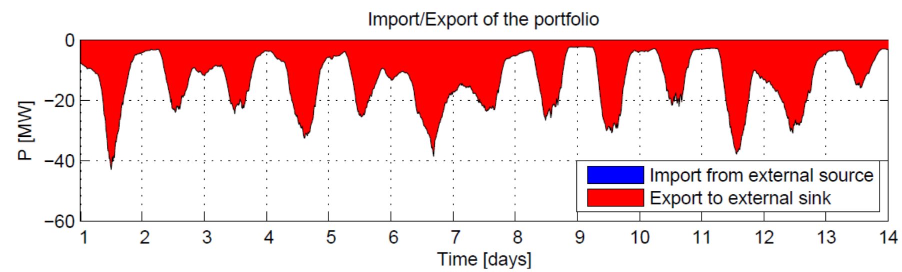
- Smoothing via dispatch of flexible units:

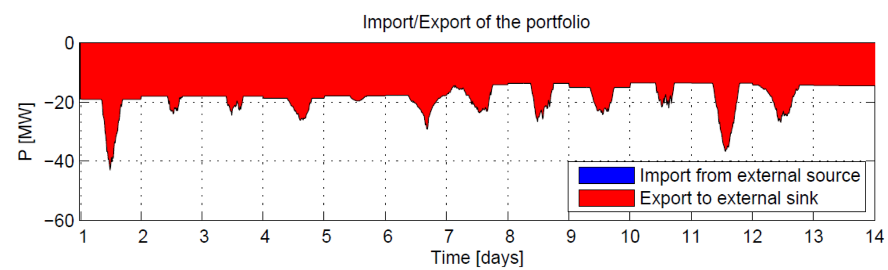
$$J_k = \sum_{l=k}^{k+N_{opt}-1} \pi^{slack}_{ramp} \frac{1}{t_s} \left(\delta \overset{*}{u}^{slack}_{load}(l)\right)^2 + \sum_{l=k}^{k+N_{opt}-1} \overset{*}{J}_{endo}(l)$$

- In-feed of intermittent generation can attain low values
  → lack of reliably available capacity

- Increasing the minimum in-feed by dispatching flexible units accordingly:

$$J_k = \sum_{l=k}^{k+N_{opt}-1} \overset{*}{J}_{endo}(l) - \pi_{cap} \cdot \min_{l\in[k,k+N_{opt}-1]} \overset{*}{u}^{slack}_{load}(l)$$





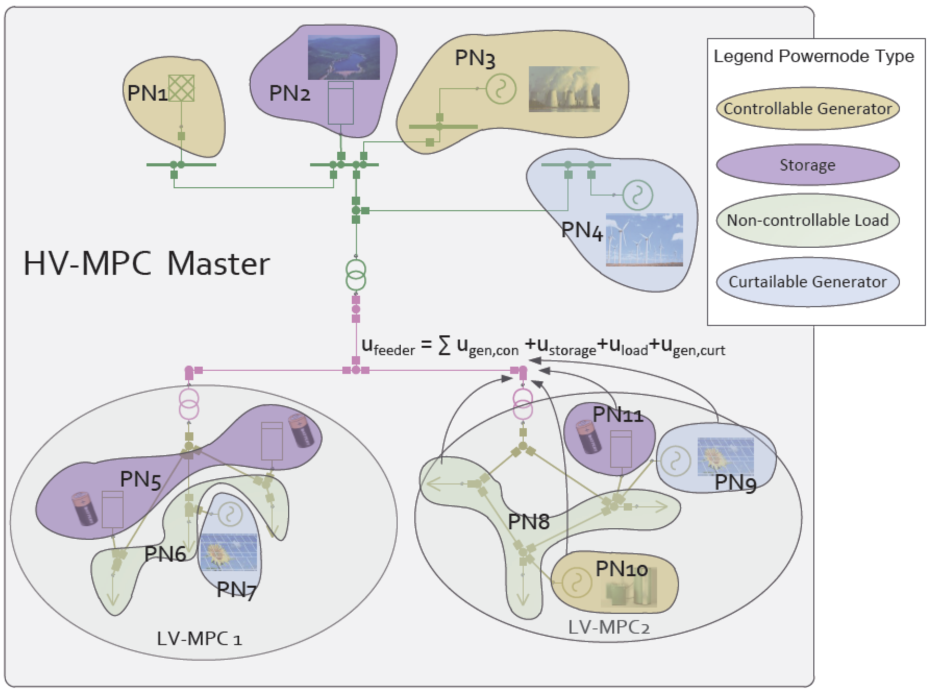
Dispatch Strategies for Control Services

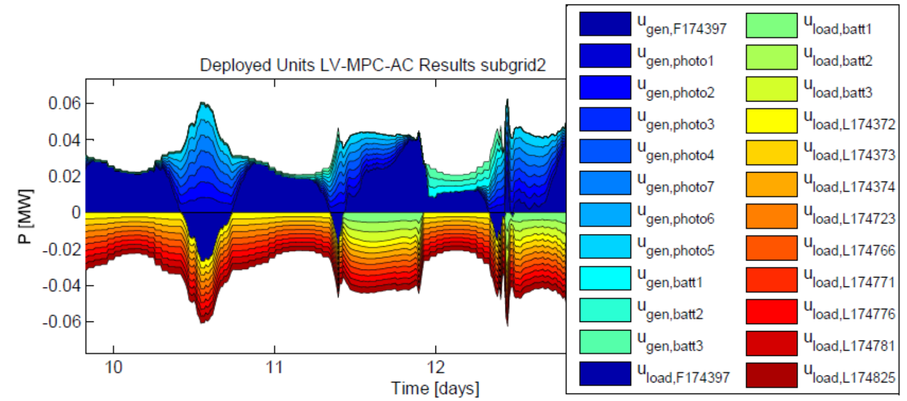
Distribution Grid Optimization

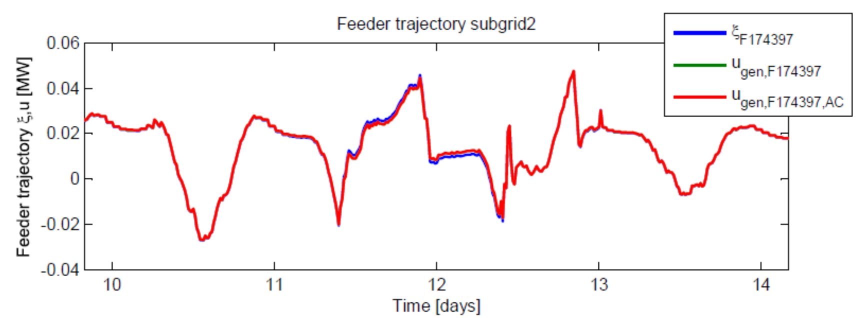
Approach:

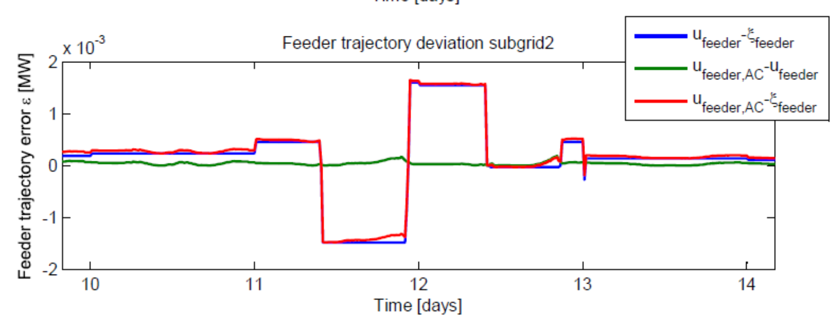
Setpoint given by MPC master

Setpoint followed by underlying MicroGrid MPC controllers







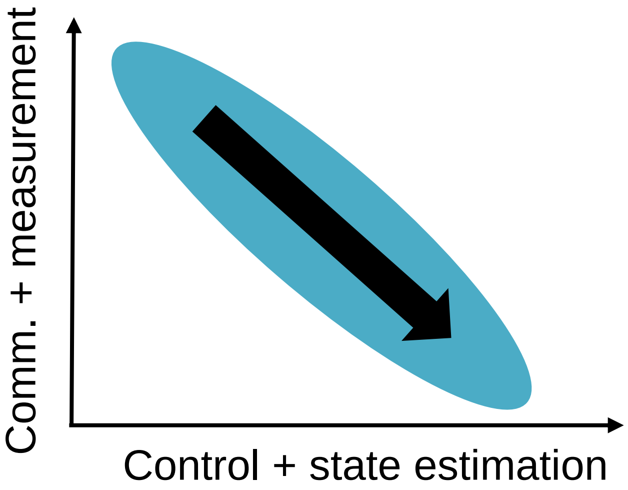


(Master‘s Thesis Philipp Fortenbacher, PSL, October 2011)

Application Potential for Advanced Optimization and Control

- Modeling unit nonlinearities
  - Battery models
  - Non-constant generation efficiencies
- and discrete state events
  - Plant start-up and shut-down
  - Network topology switching

- Large appliance populations: Saving measurements and communication requirements by
  - Sophisticated control algorithms
  - State estimation techniques



Application Potential for Advanced Optimization and Control

- Explicit consideration of prediction uncertainties
  - Robust MPC, e.g. for worst-case in-feed scenario consideration
  - Chance constraints, e.g. applied to thermal comfort zone in buildings

- Modeling unit nonlinearities
  - Battery models
  - Non-constant generation efficiencies
- and discrete state events
  - Plant start-up and shut-down
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- Large appliance populations: Saving measurements and communication requirements by
  - Sophisticated control algorithms
  - State estimation techniques

- Application of extremely fast code-generating optimization solvers for extensive Monte-Carlo-type scenario simulation
  - Infrastructure sizing
  - Economic viability assessment

Thank you for your attention!

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