ETH zürich

Automated Demand Response Strategies for Market Participation and Grid Management

Dr. Stephan Koch
Power Systems Laboratory
ETH Zurich, Switzerland

Outline

- General Aspects of Automated Demand Response
- Exemplary DR Strategies
    - Coordination & Dispatch of Thermostatically Controlled Loads (TCLs)
    - PV Self-Consumption Optimization
- Development of a Smart Distribution Grid Simulator
- Conclusions

General Aspects of Automated Demand Response

Our Definition of Automated DR:

→ A directed influence on inherently flexible loads on the customers‘ premises triggered by externally or internally computed signals.

Possible Objectives:

→ To shape the load curve in a desired way (e.g., peak shaving)

→ To trade portions of energy on the market (day-ahead, intra-day)

→ To balance prediction errors

→ To deliver ancillary services from the demand side

→ To protect the local grid infrastructure

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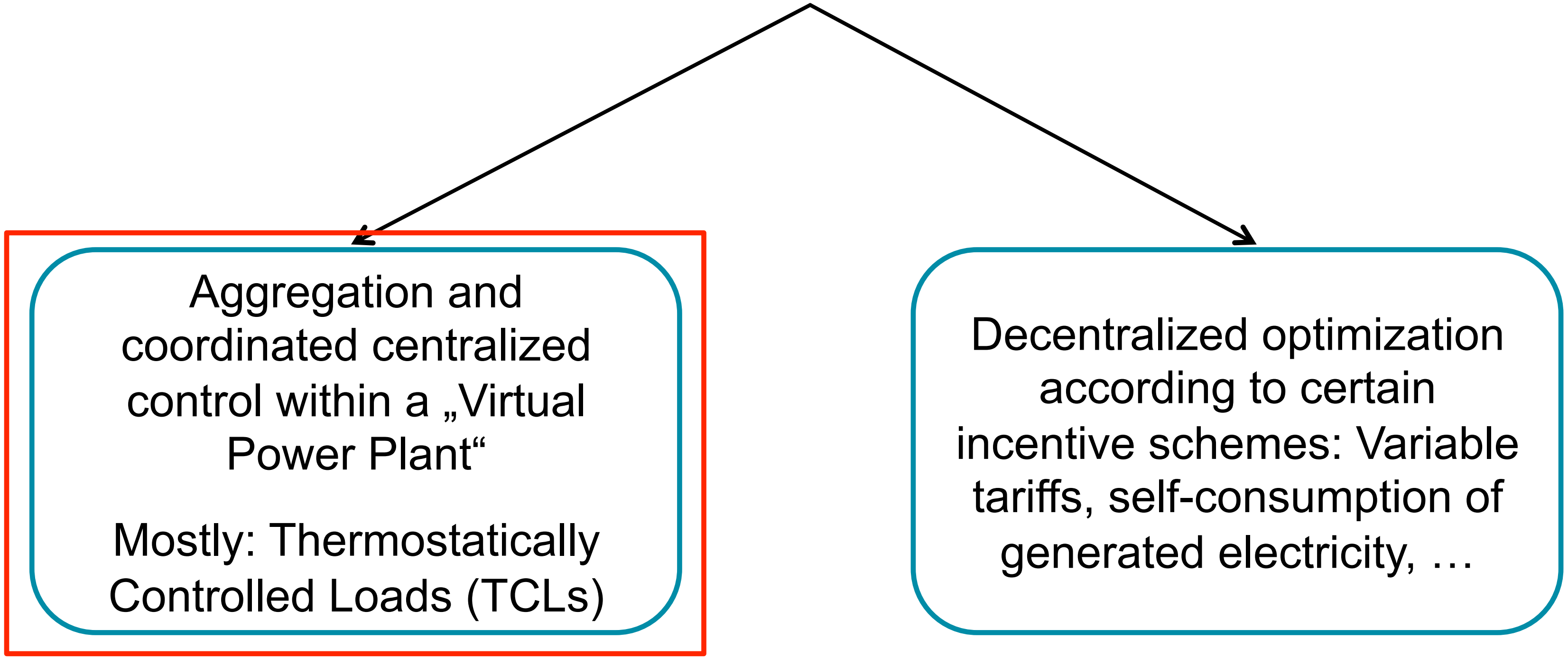


Aggregation and coordinated centralized control within a „Virtual Power Plant“

Mostly: Thermostatically Controlled Loads (TCLs)

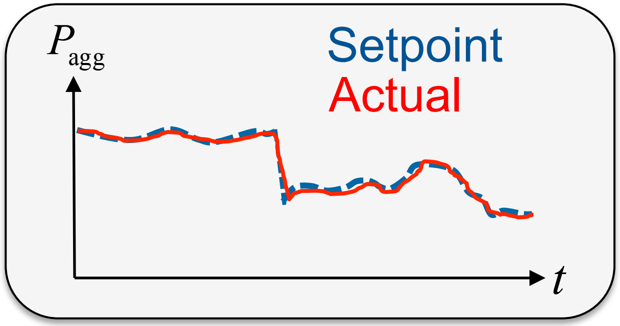
Decentralized optimization according to certain incentive schemes: Variable tariffs, self-consumption of generated electricity, …

Coordination and Dispatch of TCLs

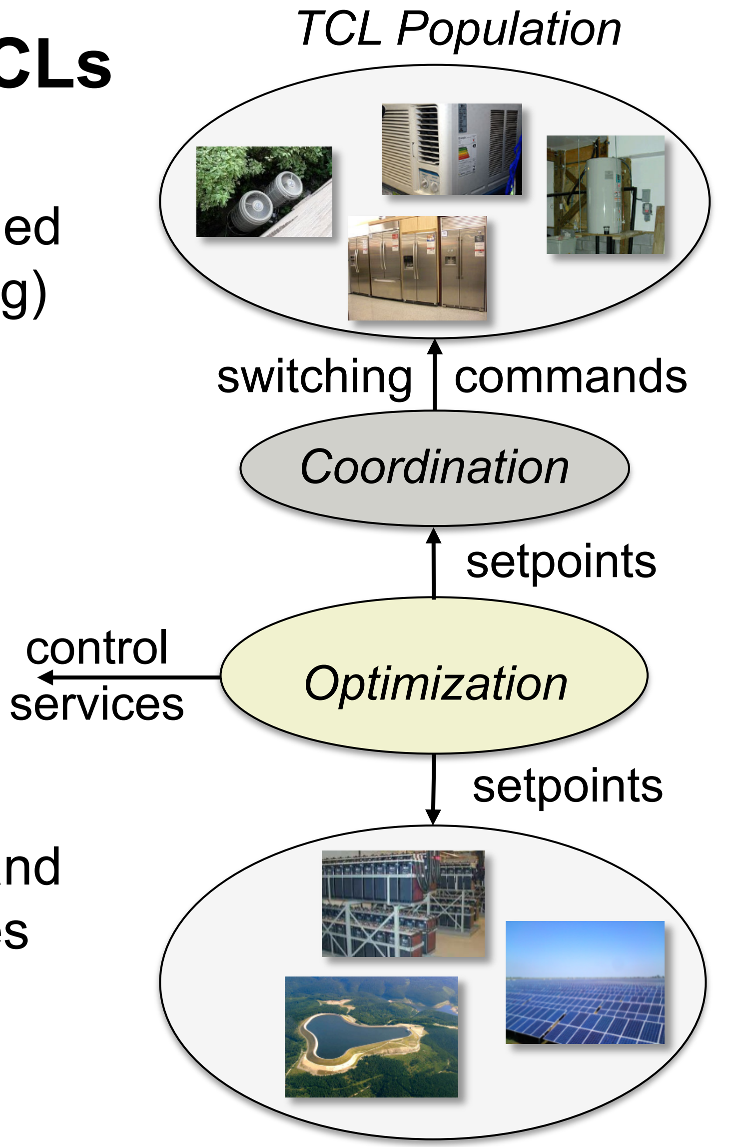
Project: Local Load Management (2008 – 2012)
Partners: FHNW, Alpiq, Landis+Gyr
Researcher: Stephan Koch
Funding: Swisselectric Research

Coordination and Dispatch of TCLs

- Make aggregated thermostatically controlled loads (TCLs) controllable (setpoint tracking)



- Integrate controllable loads with storage and generation units to provide control services



TCL Population

switching commands

Coordination

setpoints

control services

Optimization

setpoints

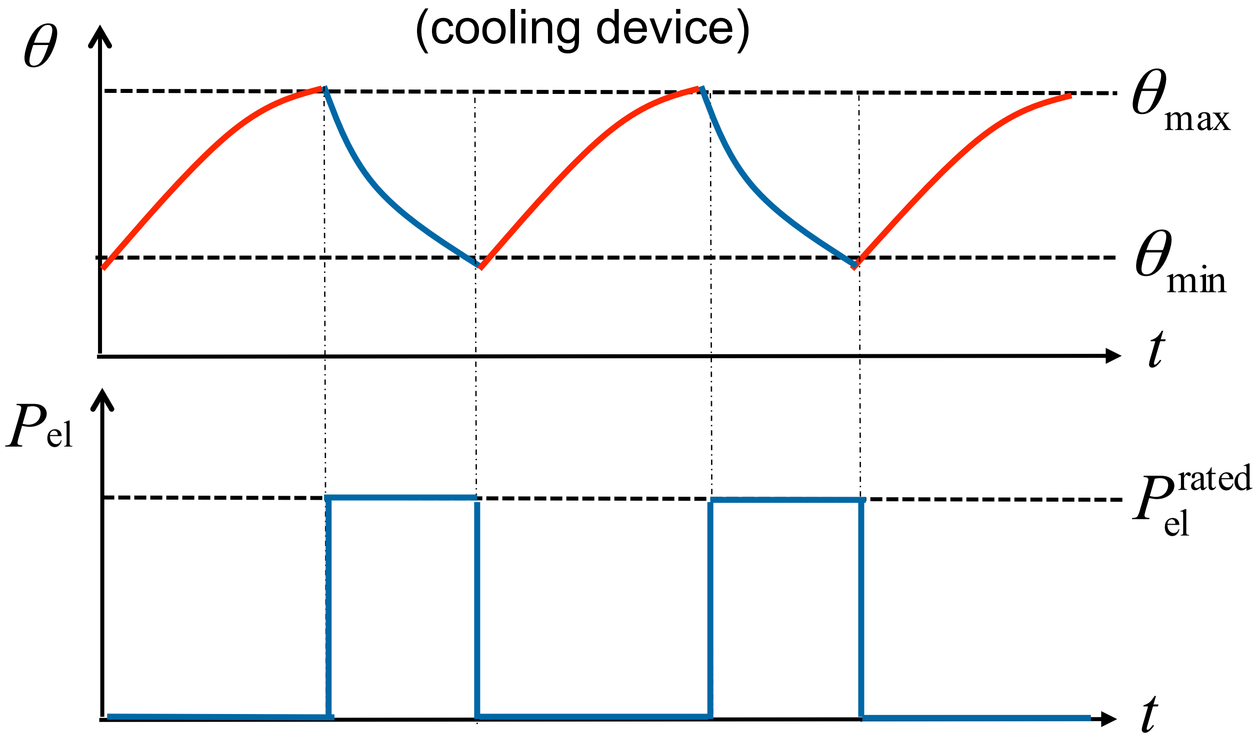
Generation and Storage Units

TCL Modeling Approach

- First-order differential equation for temperature dynamics of single TCL:

$$\theta_{i,t+1} = a_i \theta_{i,t} + (1 - a_i)(\theta_{\mathrm{a},i} - m_{i,t}\theta_{\mathrm{g},i}) + \omega_{i,t}$$

- Hysteretic thermostat controller produces characteristic cycling:



TCL Modeling Approach

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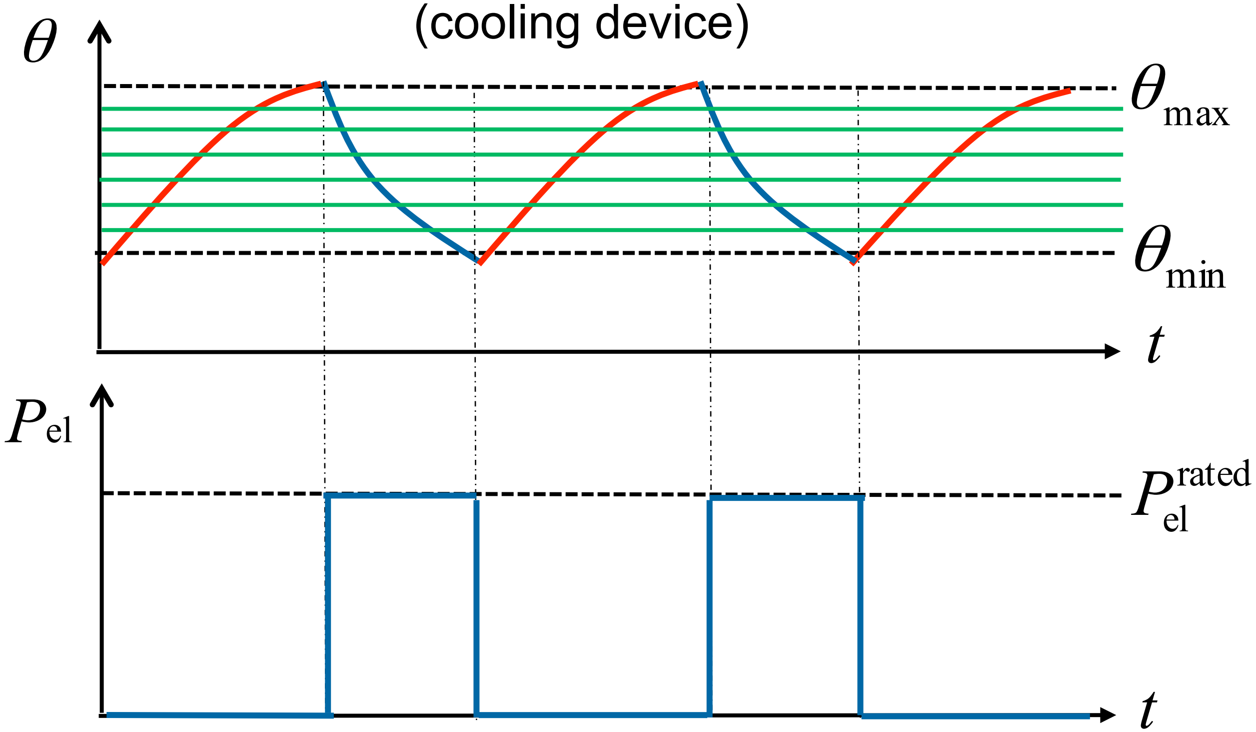
- Discretization of the temperature space into “bins”:



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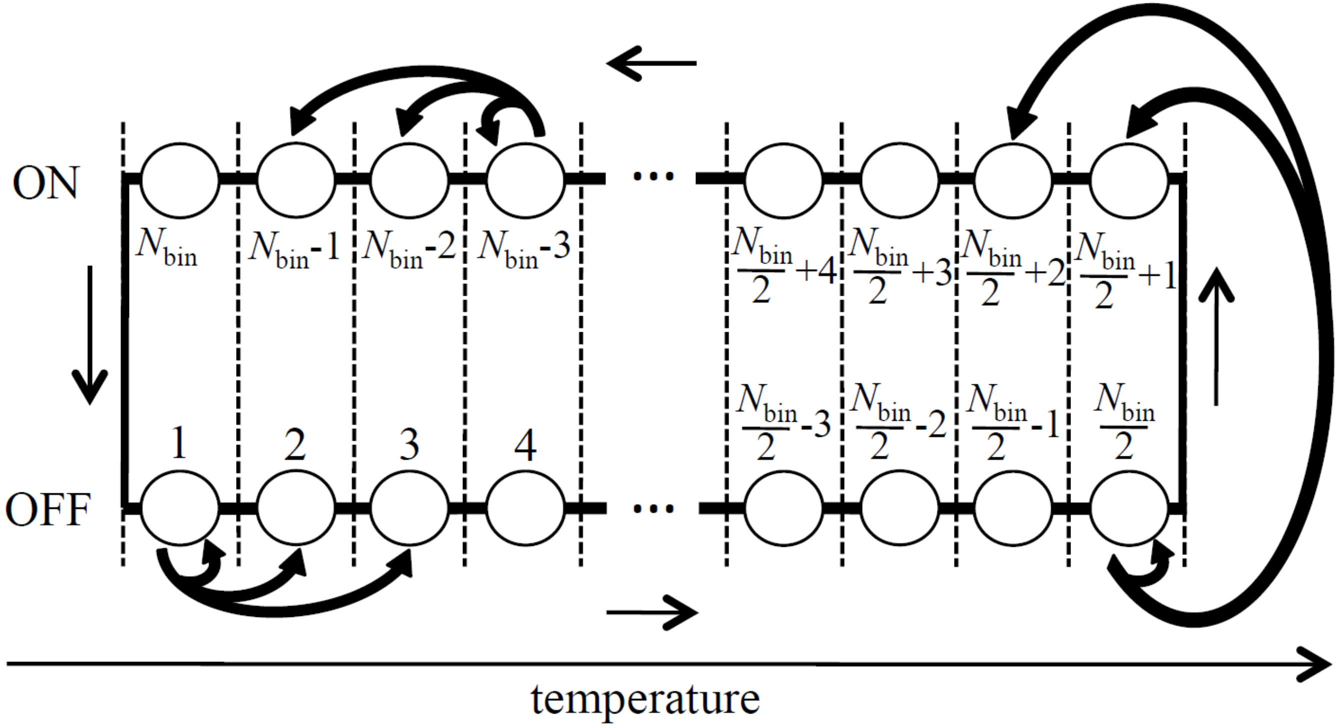
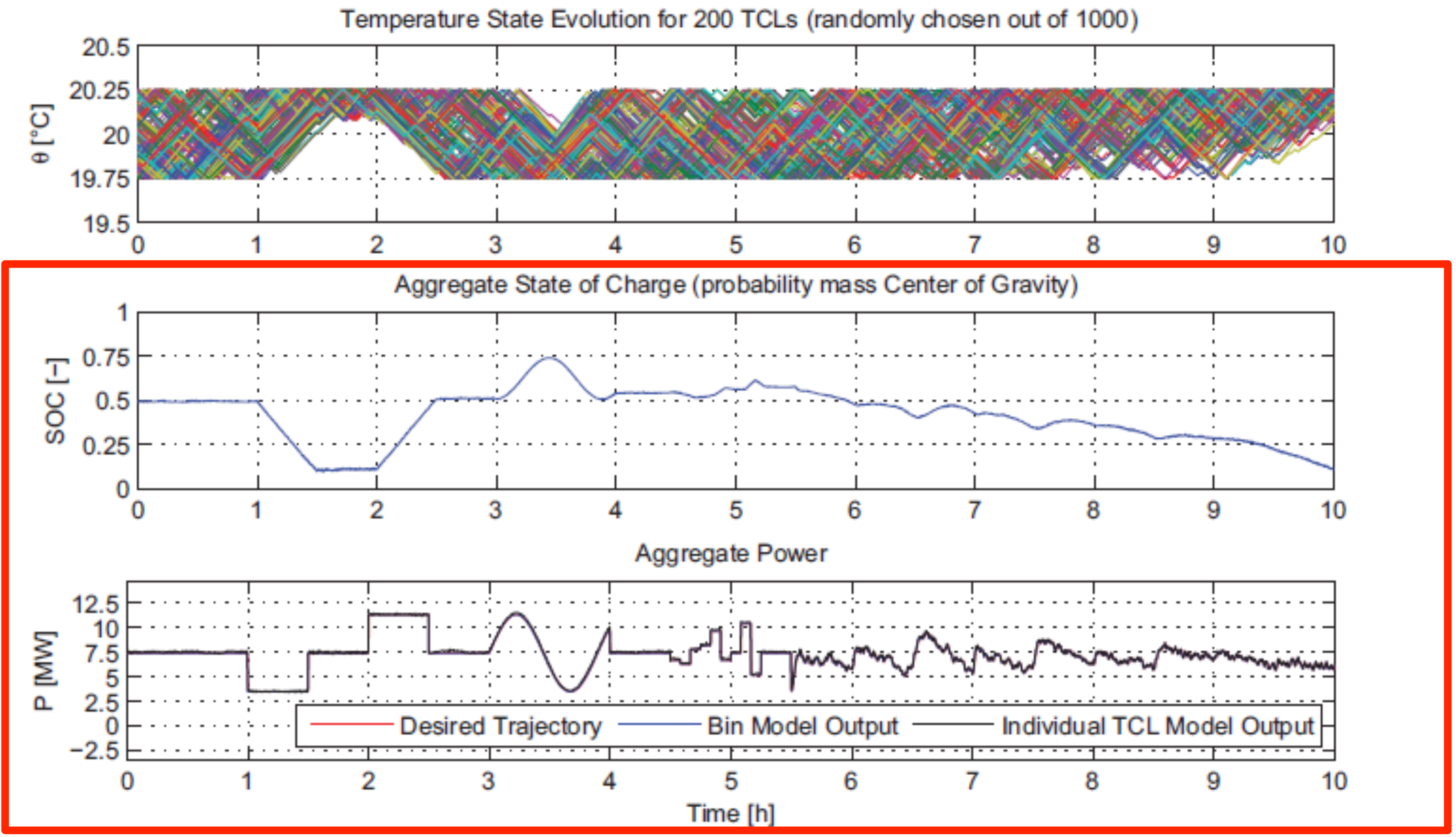


Control Strategy for TCL Setpoint Tracking

Simulation example: 1,000 air conditioning units



Energy

Power

→ Storage characteristics

Integration into a Dispatch Framework

Coordinated Groups of TCLs can track a time-varying setpoint.

But where does the setpoint come from?

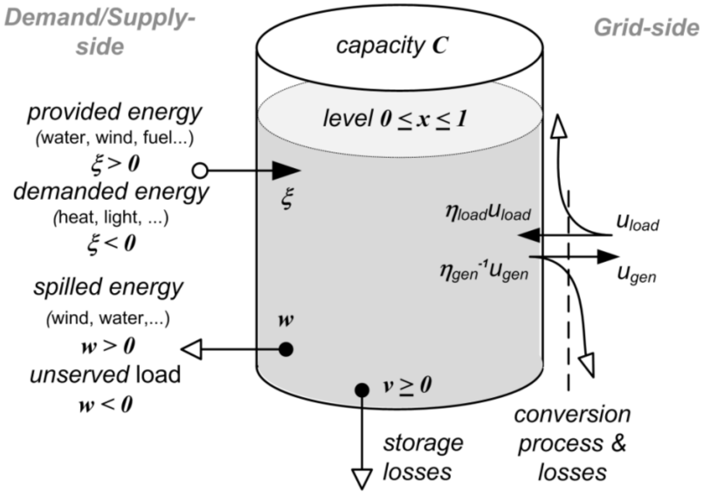
Idea: → Unify the modeling of load, storage, and generation units

→ Jointly optimize a flexible unit portfolio for a common goal

Integration into a Dispatch Framework

The Power Nodes

Modeling Framework



Storage capacity × state-of-charge

Power out-feed from grid

Power in-feed to grid

Shedding term

Internal losses

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

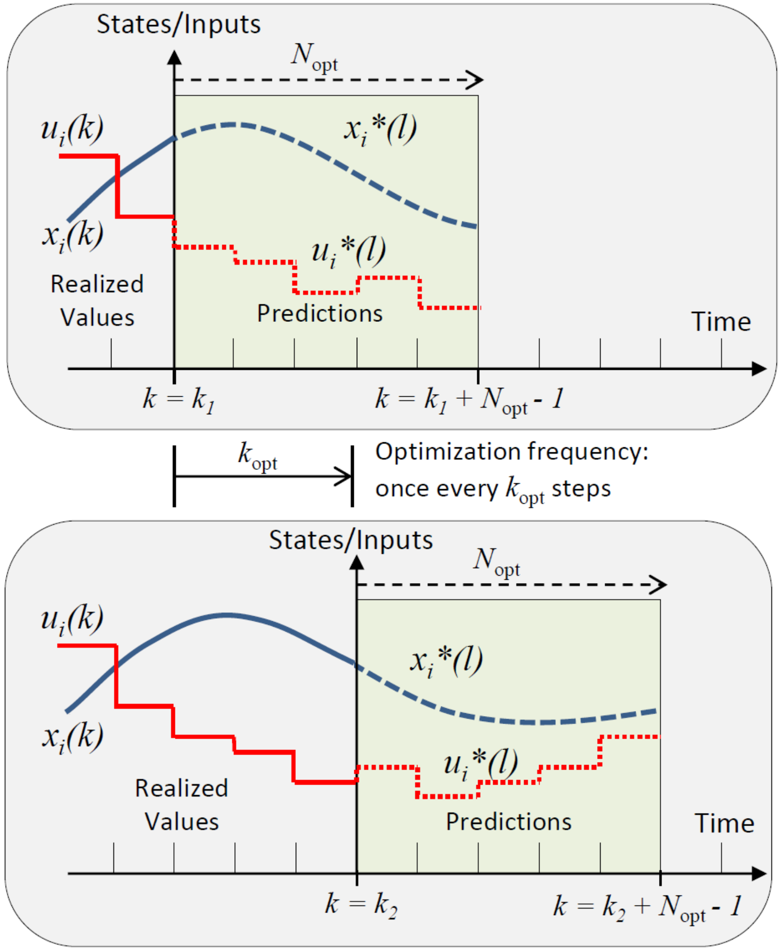
Efficiency factors

Provided / demanded power

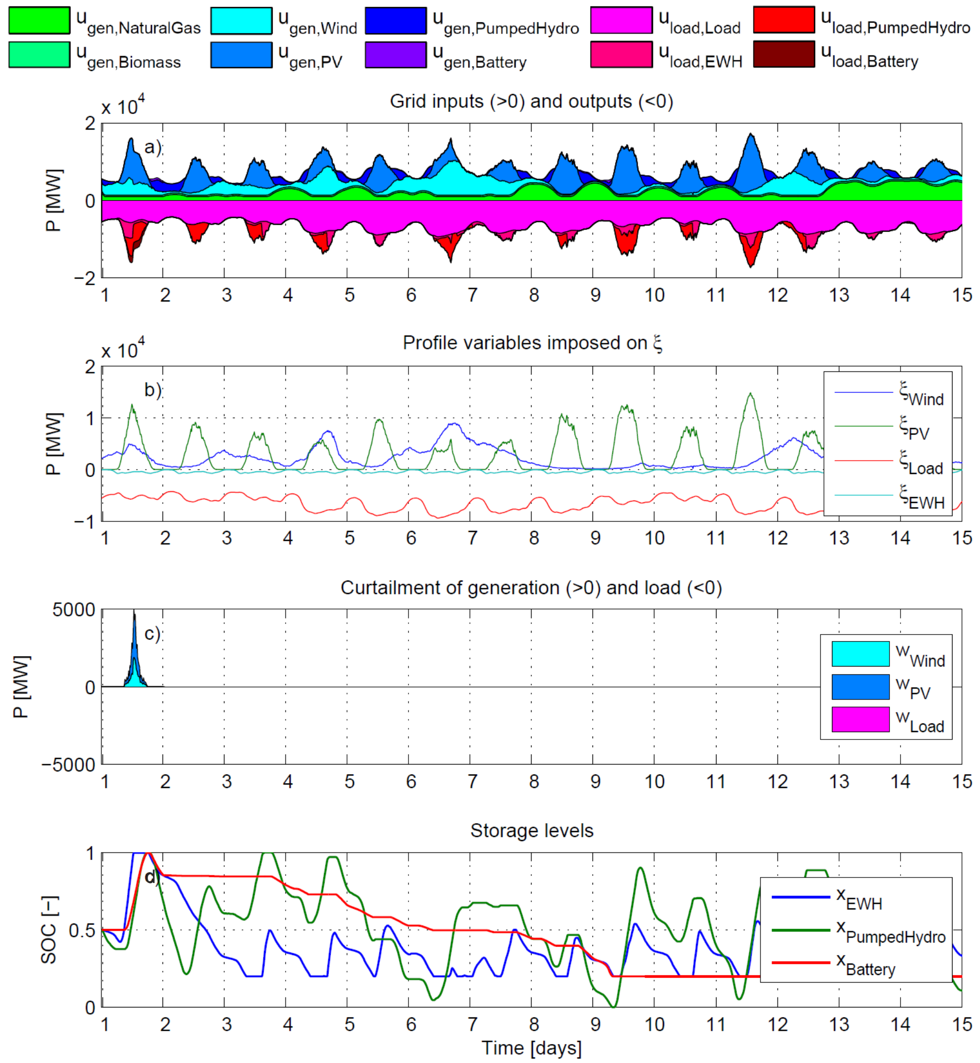
Integration into a Dispatch Framework

Dispatch with Model Predictive Control

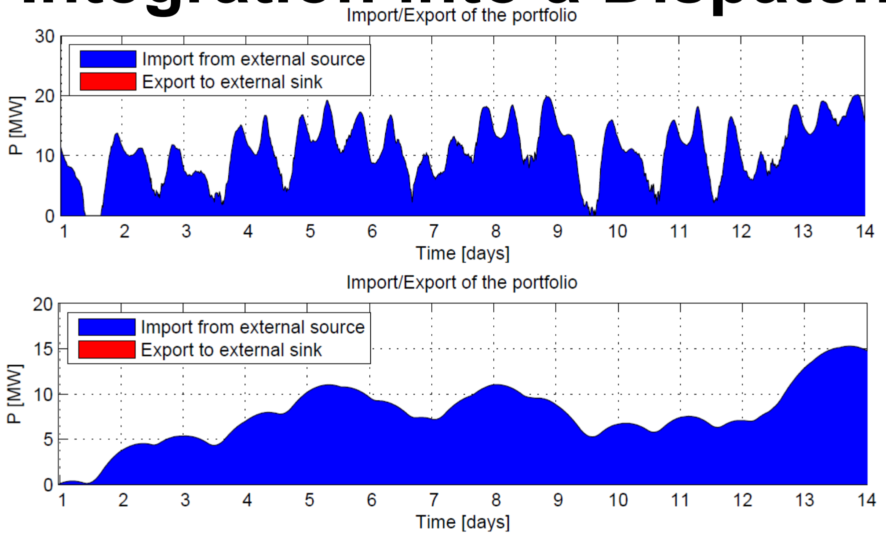
- Joint predictive optimization of a power node portfolio
- Cost function and constraint design allows to cover a variety of use cases:
  - Least-cost dispatch
  - Market-based VPP operation
  - Balancing of schedule deviations
  - Provision of frequency control reserves
  - Capacity firming of intermittent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



Integration into a Dispatch Framework



Integration into a Dispatch Framework



- Residual load can exhibit high ramps

  → high strain on conventional generation assets

- Smoothing via dispatch of flexible units:

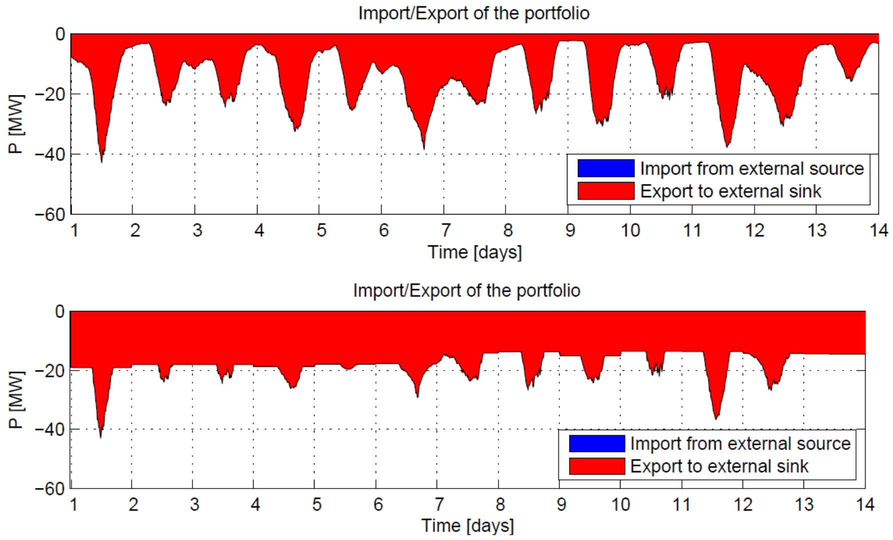
$$J_k = \sum_{l=k}^{k+N_{\text{opt}}-1} \pi_{\text{ramp}}^{\text{slack}} \frac{1}{t_s} \left(\delta \overset{*}{u}_{\text{load}}^{\text{slack}}(l)\right)^2 + \sum_{l=k}^{k+N_{\text{opt}}-1} \overset{*}{J}_{\text{endo}}(l)$$

- In-feed of intermittent generation can attain low values

  → lack of reliably available capacity

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

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



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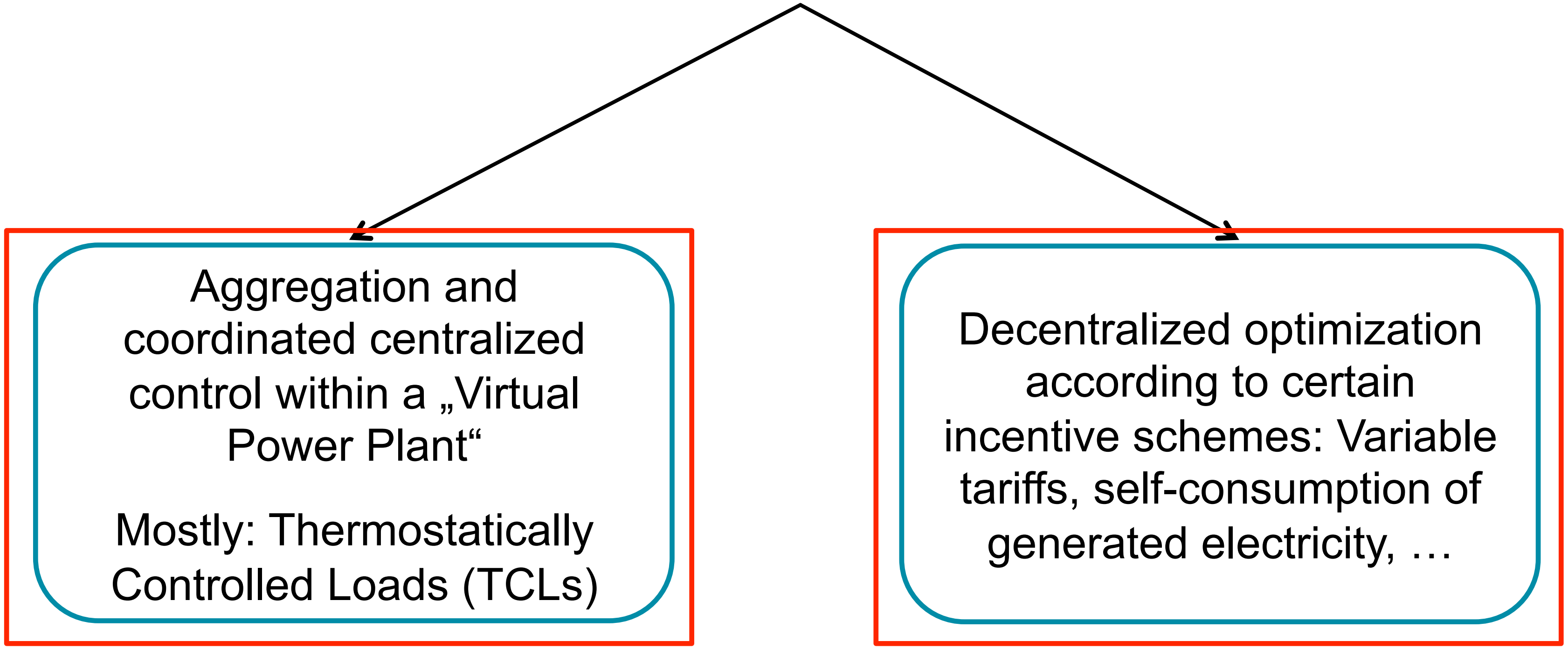


Aggregation and coordinated centralized control within a „Virtual Power Plant“

Mostly: Thermostatically Controlled Loads (TCLs)

Decentralized optimization according to certain incentive schemes: Variable tariffs, self-consumption of generated electricity, …

PV Self-Consumption Optimization

Project: SmartGrid-Polysun – Design Tool for Local Load Management
Funding: Federal Office of Energy, Swisselectric Research

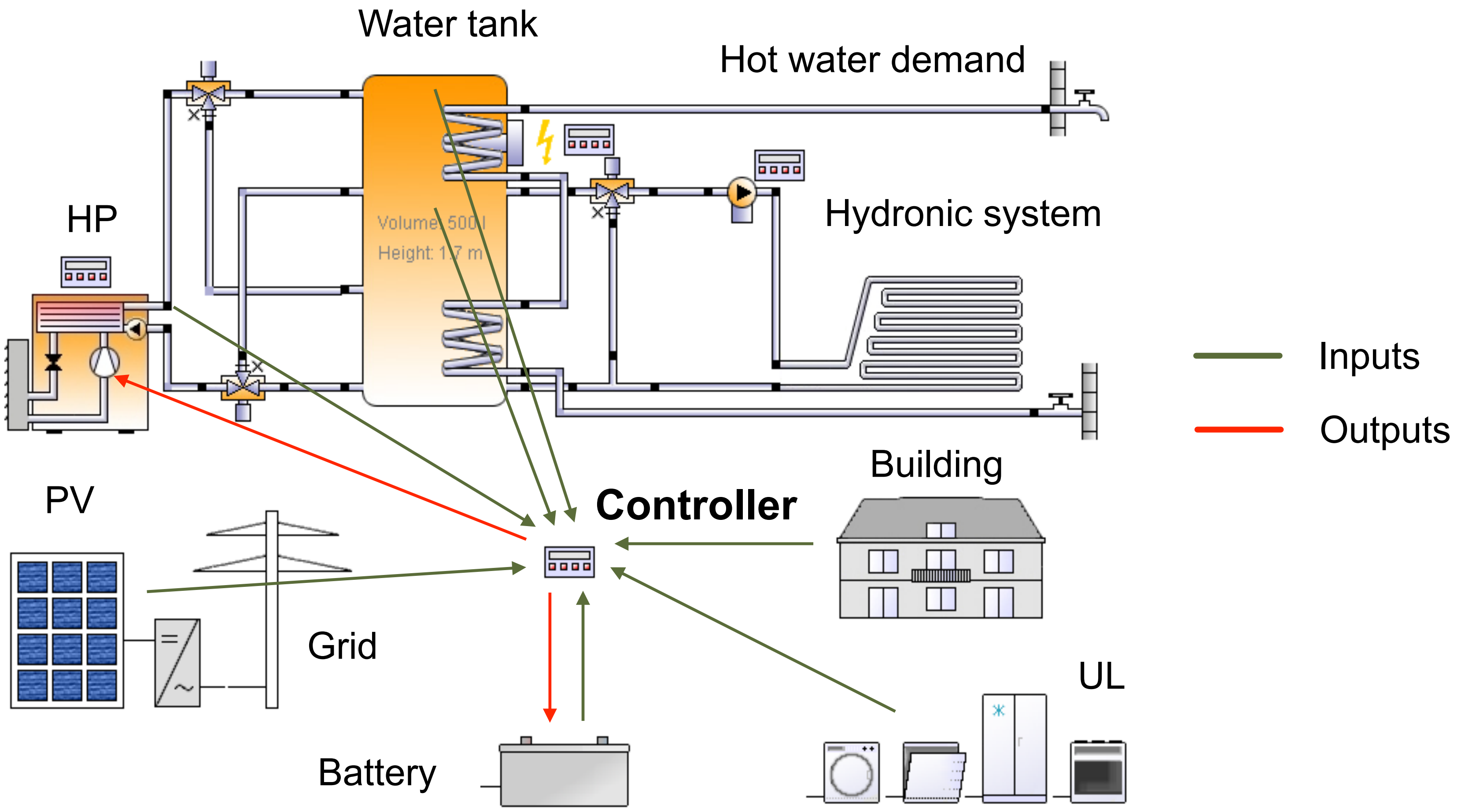
Researcher:

Evangelos Vrettos
PhD student
Power Systems Laboratory
ETH Zurich

Project Partner:

vela solaris Software for the Renewable Energy Sector
polysun®
SIMULATION SOFTWARE

Modeling of a Residential Building

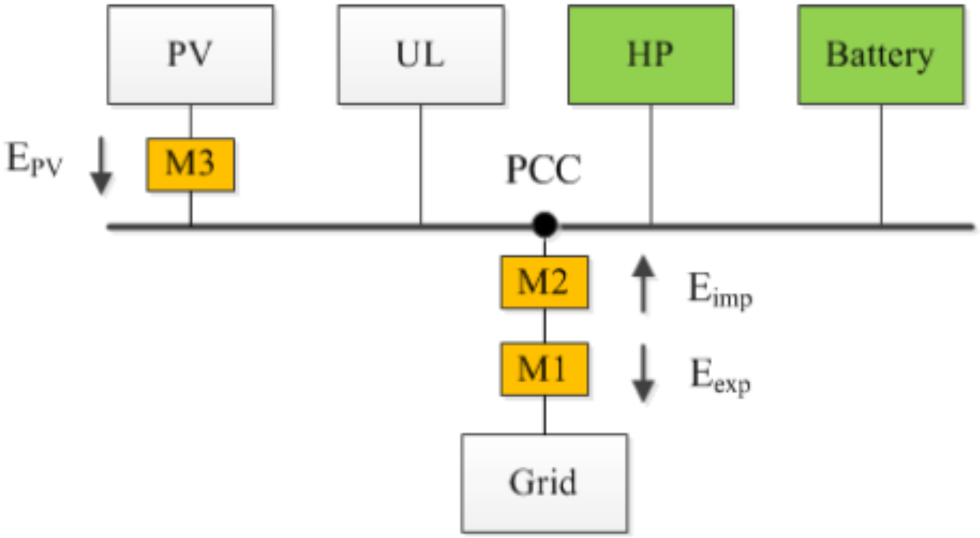


PV Self-Consumption Problem Setup

- Goals: (a) shift HP operation towards hours with high PV production
  (b) charge battery when PV surpluses exist
  (c) discharge battery to cover load in evening / at night

- Definitions: PV self-consumption ratio (ξ), total electricity cost (E_{cost})

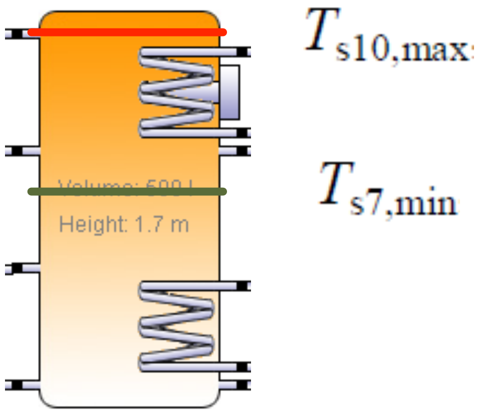
$$\xi = \frac{E_{\text{PV}\rightarrow\text{bld}}}{E_{\text{PV}}} = \frac{E_{\text{PV}} - E_{\text{exp}}}{E_{\text{PV}}} \qquad E_{\text{cost}} = C_{\text{FIT}} \cdot E_{\text{exp}} - C_{\text{el}} \cdot E_{\text{imp}}$$



PV Self-Consumption Optimization

Base case (A0)

- HP operates based on internal thermostat
- No battery



Algorithm (A1)

- Smart HP operation
- No battery

Algorithm (A2)

- HP operates based on internal thermostat
- Battery is present

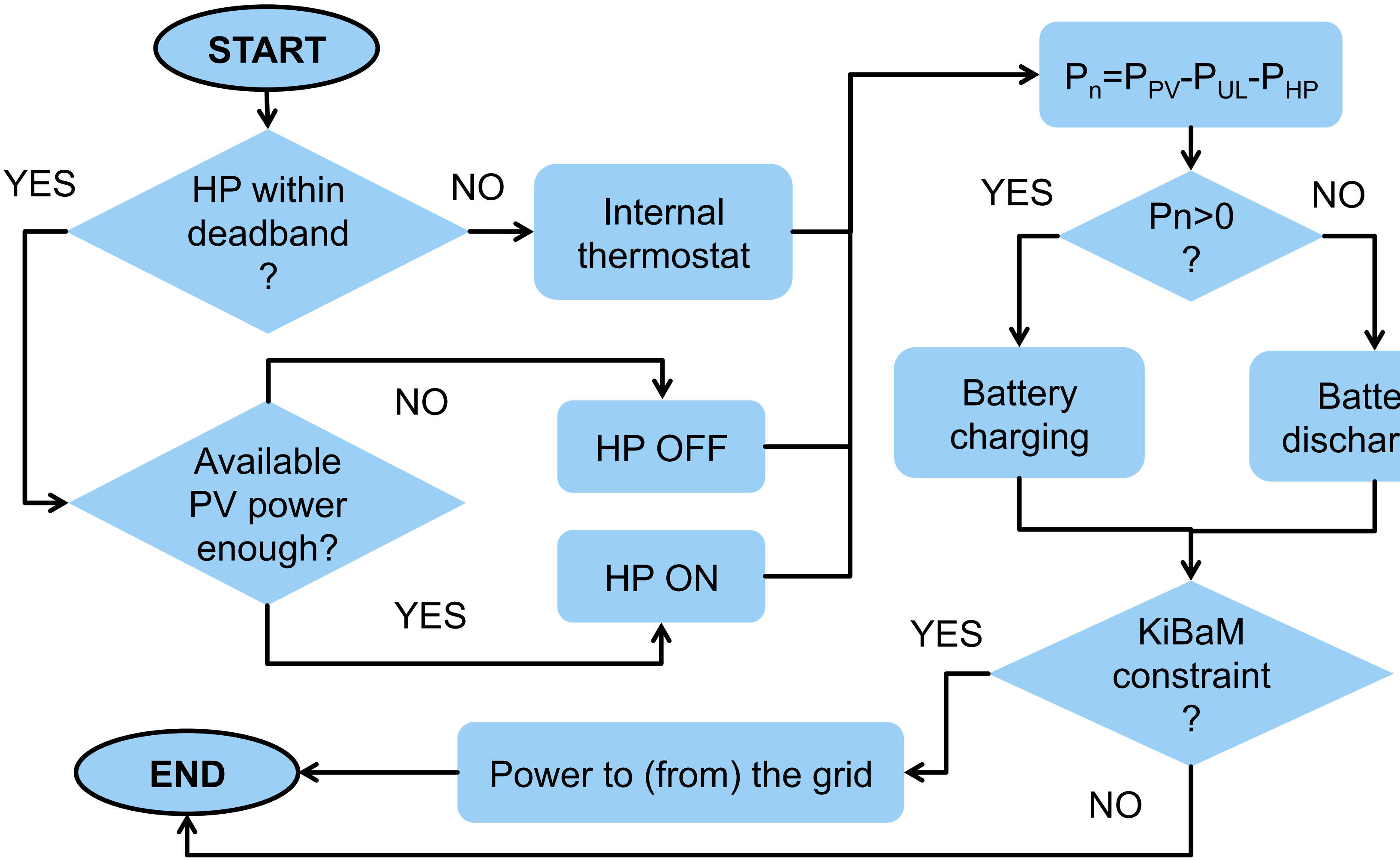
Algorithm (A3)

- Smart HP operation
- Battery is present
- **Priority to HP**

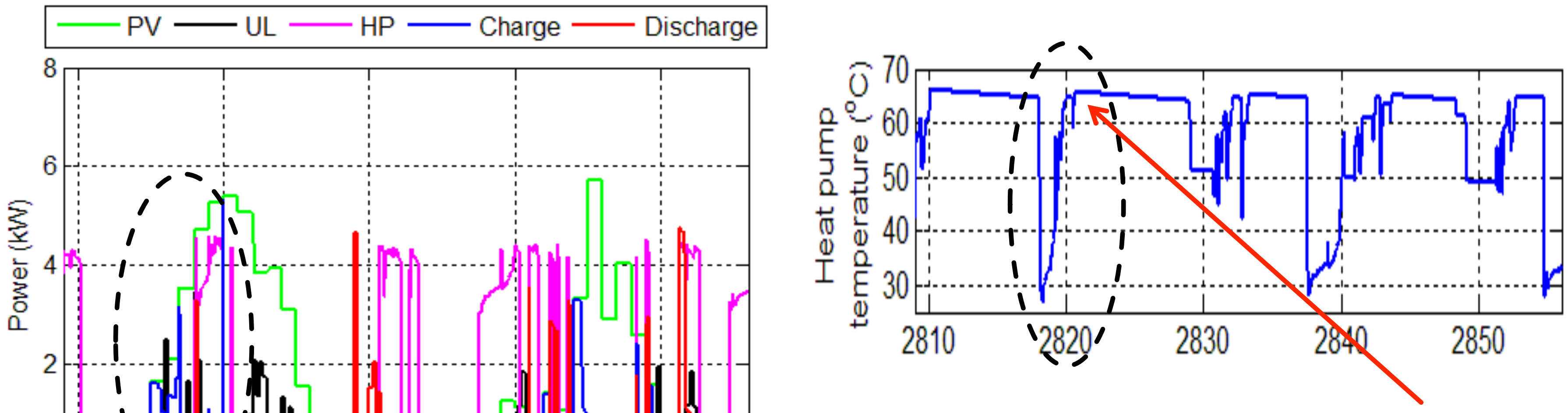
Algorithm (A4)

- Smart HP operation
- Battery is present
- **Priority to battery**

PV Self-Consumption Optimization: Algorithm A3



Simulation Results



HP temperature constraint

- **Highest potential:** in spring when both PV energy and heat demand are significant
- **Charging priority:** when $P_{PV}>P_{HP}+P_{UL}$, the HP turns on
- **HP limited potential:** after a few hours the HP gets overheated and turns off
- **Barrier for HP:** temperature constraints of HP, rather than building thermal inertia

Simulation Results

Yearly Simulation

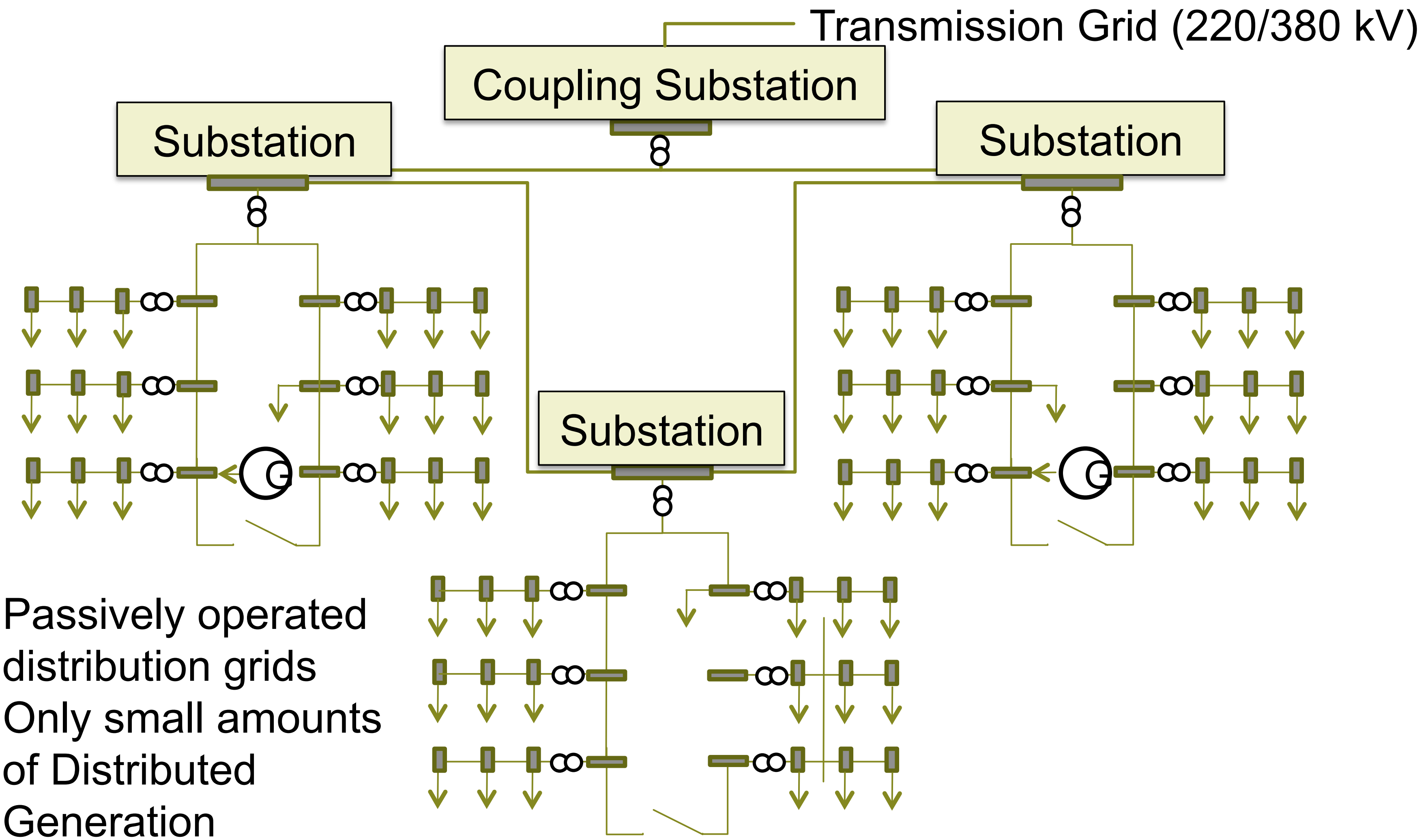
Algorithm	PV self-consumption (%)	Electricity bill (€)
Base case (A0)	19.71	1248.63
smart HP (A1)	21.14	1249.24
Battery (A2)	35.19	1169.32
Both (A3)	**36.46**	**1162.98**
Both (A4)	35.49	1163.36

- **HP only:** limited potential for PV self-consumption, cost can increase due to losses
- **Battery only:** (a) high potential for PV self-consumption, and savings of ~79 € per year
  (b) with current electricity tariffs, pays off only if battery cost < 60 €/kWh
- **Both:** priority to HP achieves highest self-consumption and savings of ~85 € per year
- HP saves additionally only ~6 € per year, but at virtually zero investment cost

Development of a *Smart Distribution Grid* Simulator

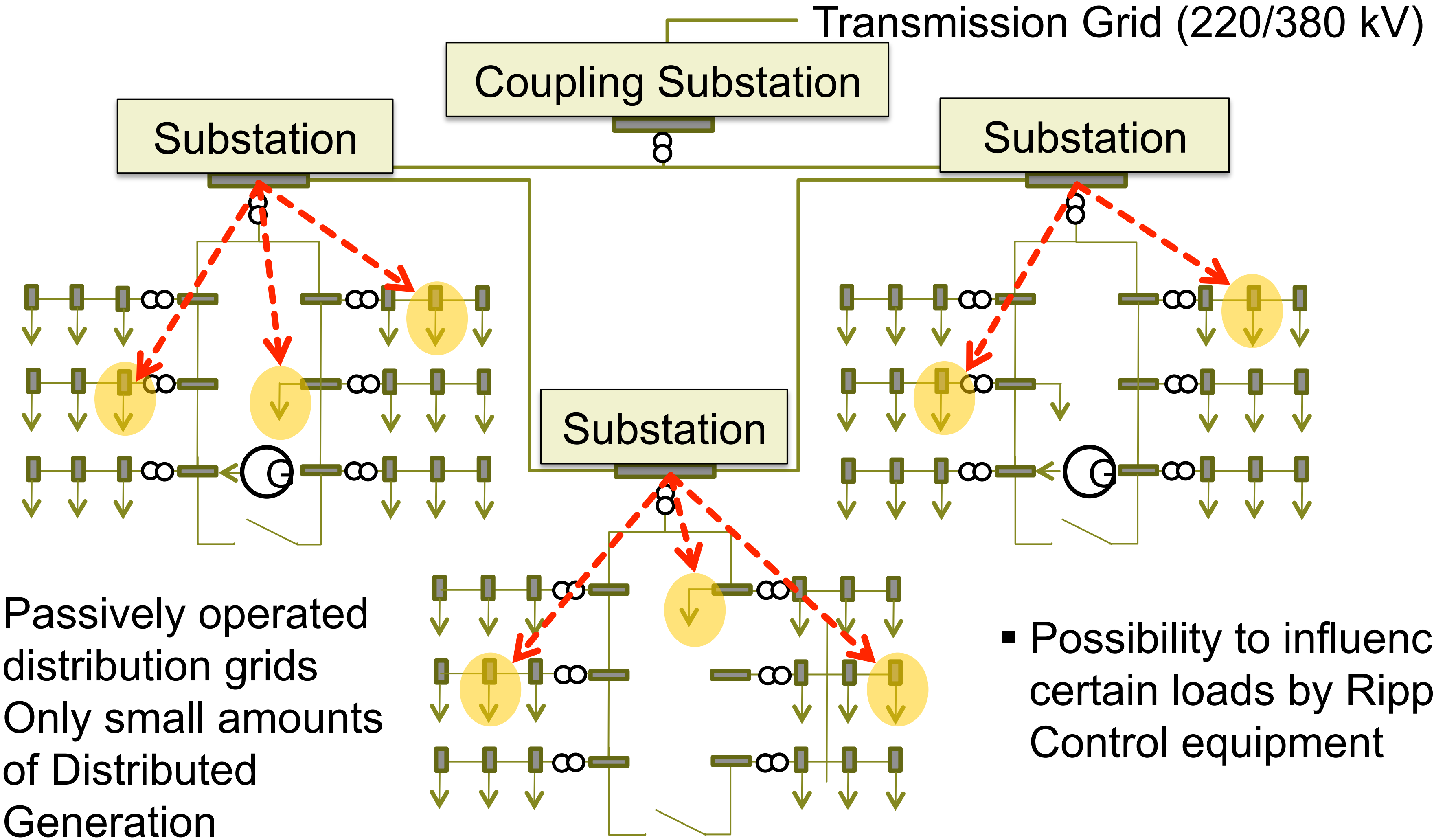
Project: “Pioneer Fellowship“ at ETH Zurich (PostDoc Employment)
Researcher: Stephan Koch
Funding: ETH Zurich

The Challenge: Distribution Grid Operation (present)



- Passively operated distribution grids
- Only small amounts of Distributed Generation

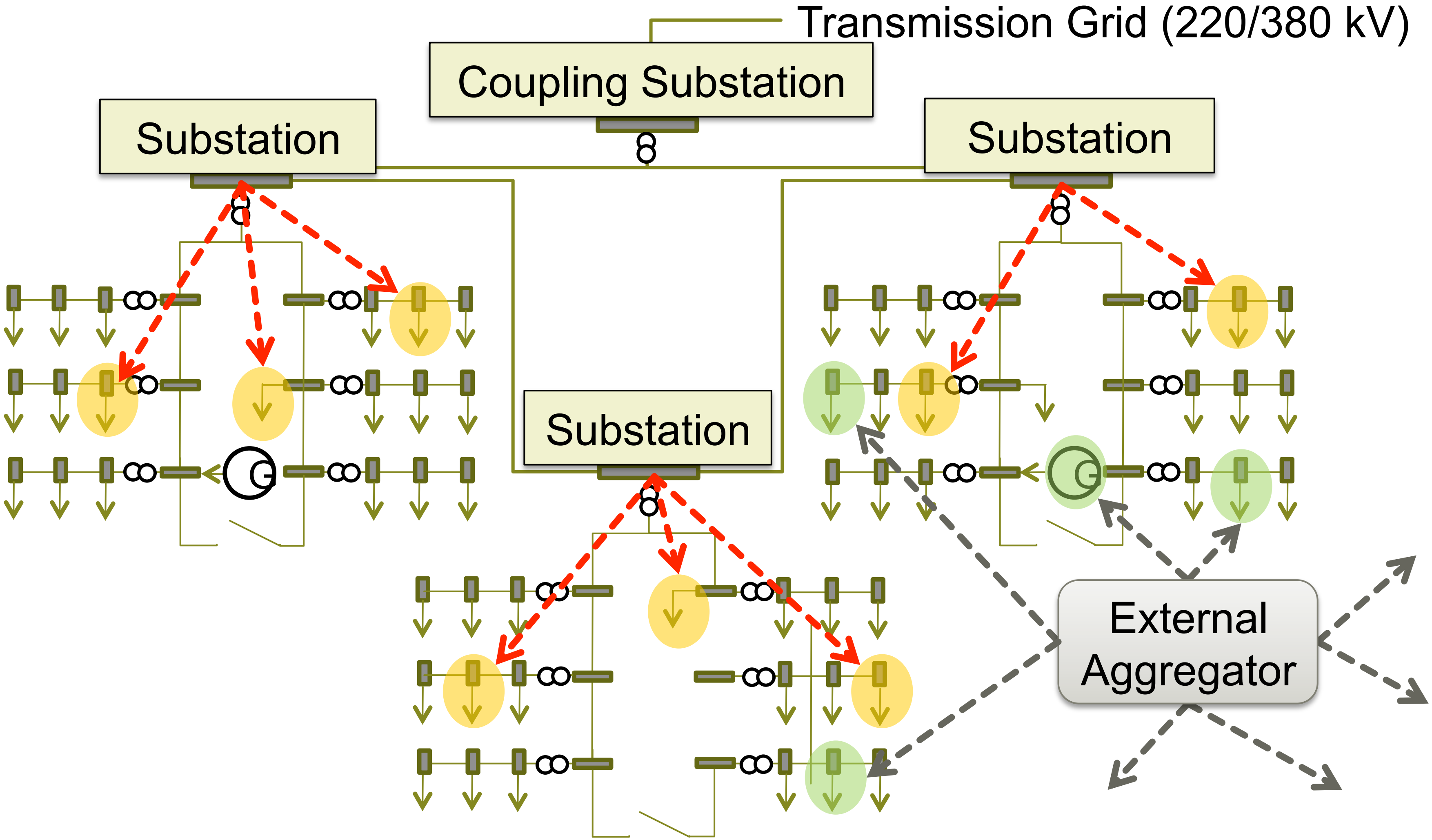
The Challenge: Distribution Grid Operation (present)



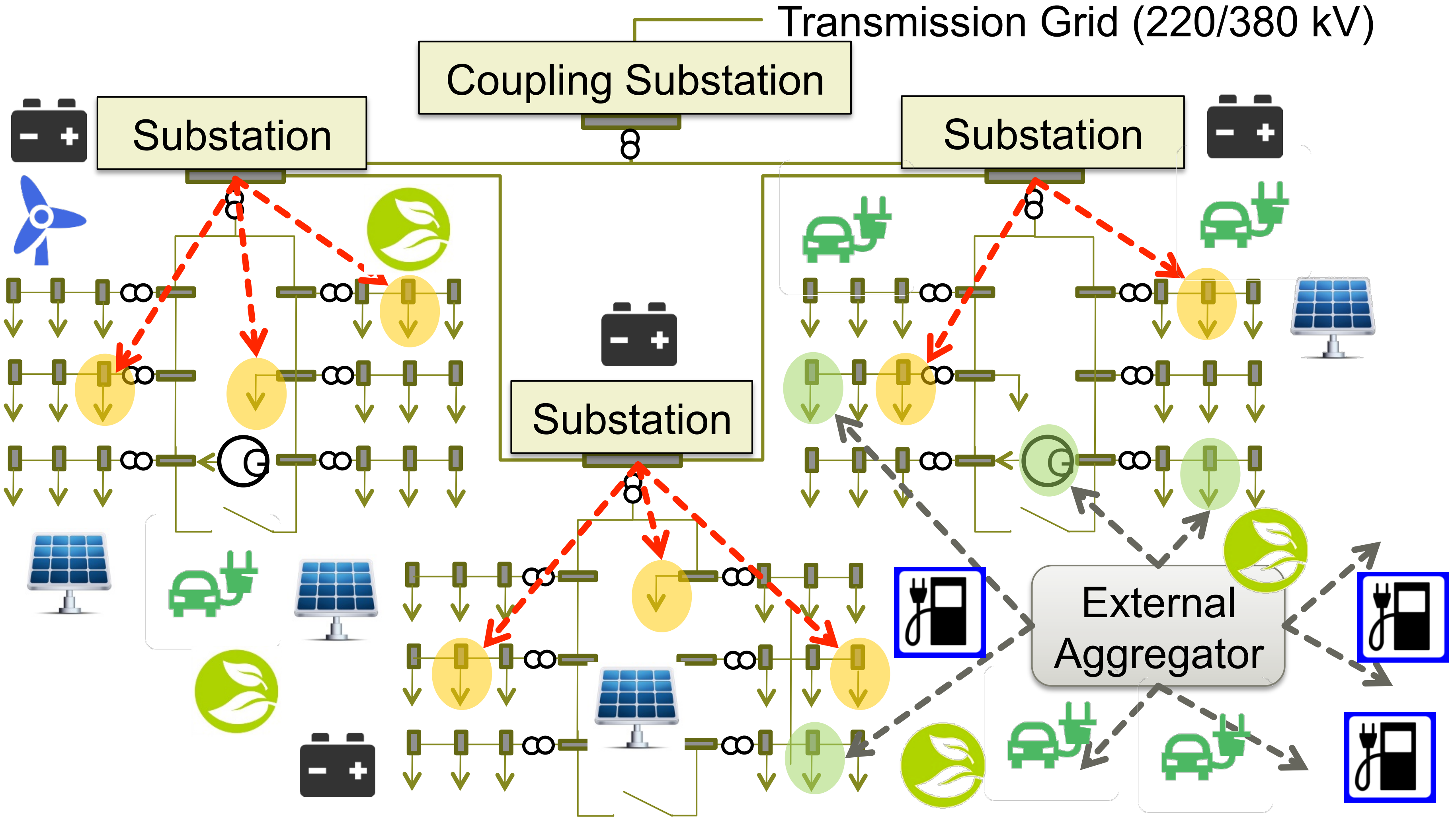
- Passively operated distribution grids
- Only small amounts of Distributed Generation

- Possibility to influence certain loads by Ripple Control equipment

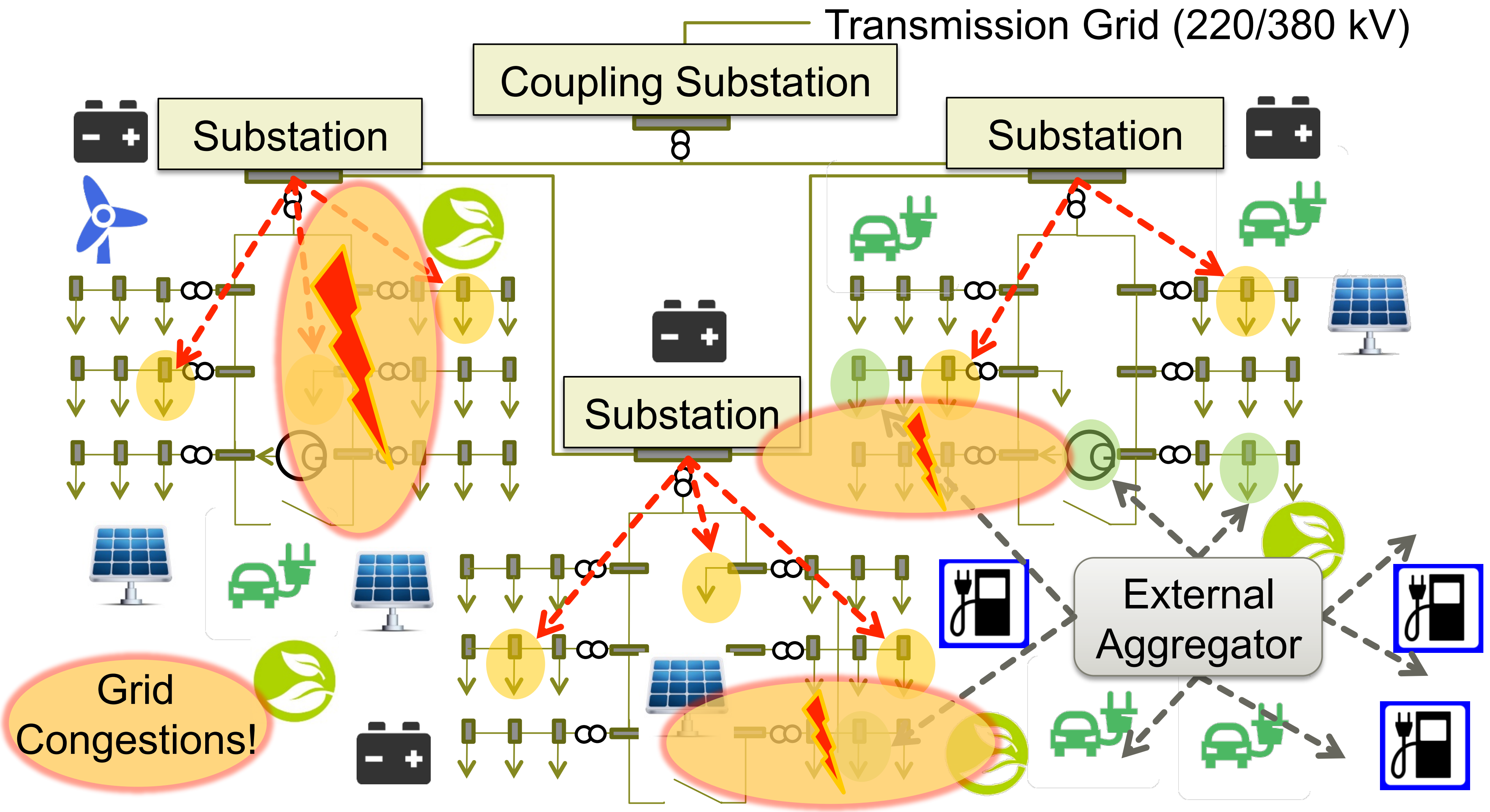
The Challenge: Distribution Grid Operation (future)



The Challenge: Distribution Grid Operation (future)



The Challenge: Distribution Grid Operation (future)



Distribution Grid Challenges

- Keeping all voltages within permissible limits in all operational situations
- Avoiding component overloadings
- Being aware of the current grid condition and taking correct countermeasures in case of disturbances

↓

Investments in even more copper and steel?

Distribution Grid Challenges

- Keeping all voltages within permissible limits in all operational situations
- Avoiding component overloadings
- Being aware of the current grid condition and taking correct countermeasures in case of disturbances

↓

The electricity grids need to become *smarter.*

↓

This requires novel software tools.

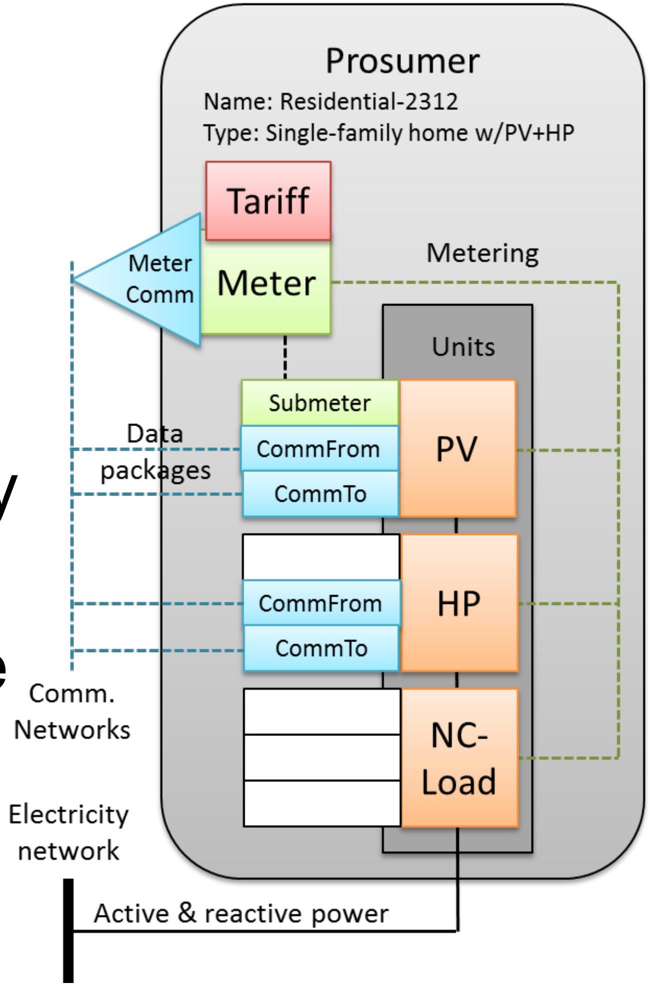
The Solution Approach

- Simulation of a *smart* distribution grid including the representation of the new physical reality in the grid
- Novel analysis and planning methods
- Innovative operation and control strategies

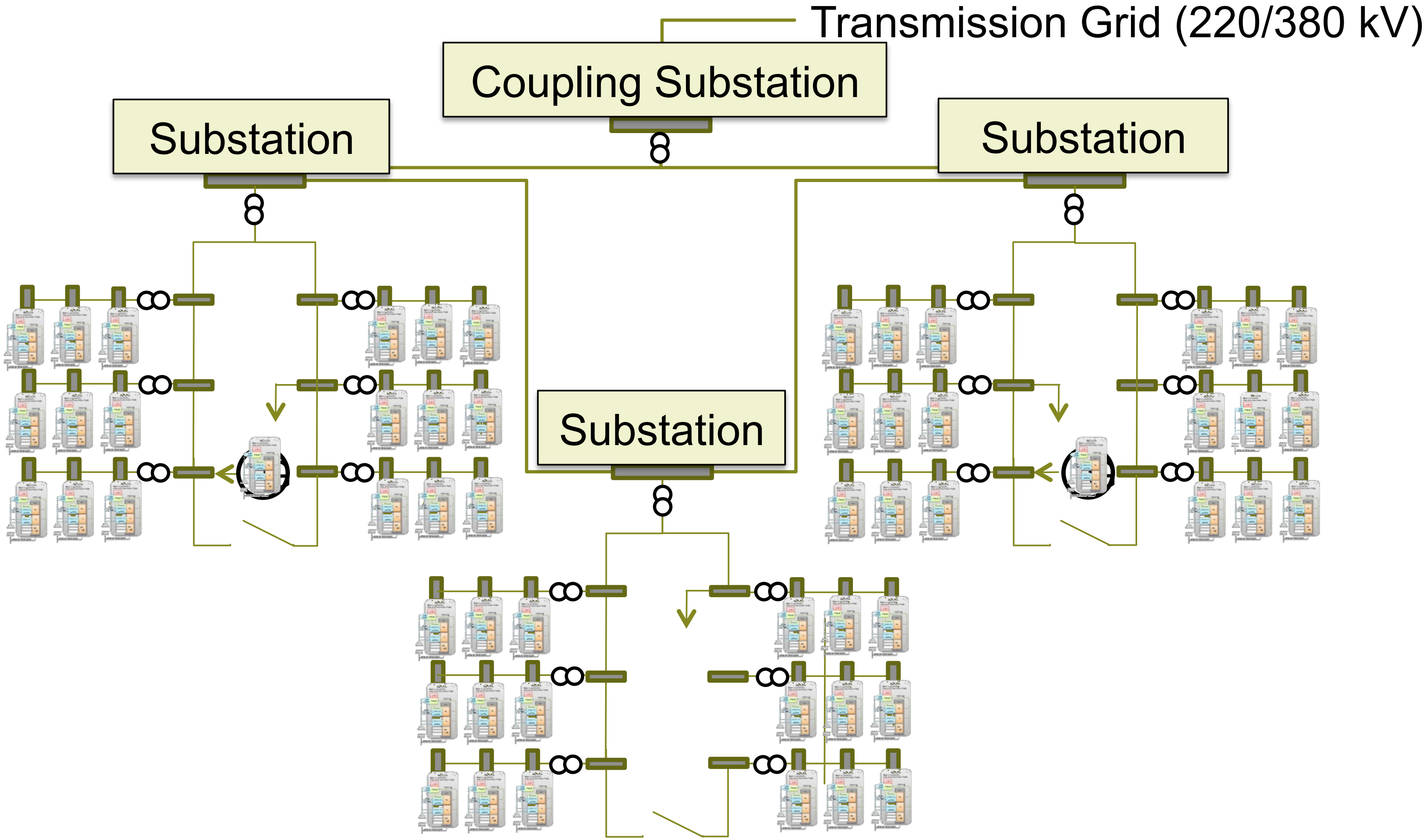
The Software DPG.sim – Basic Data Model

New Paradigm: **Active Prosumers**

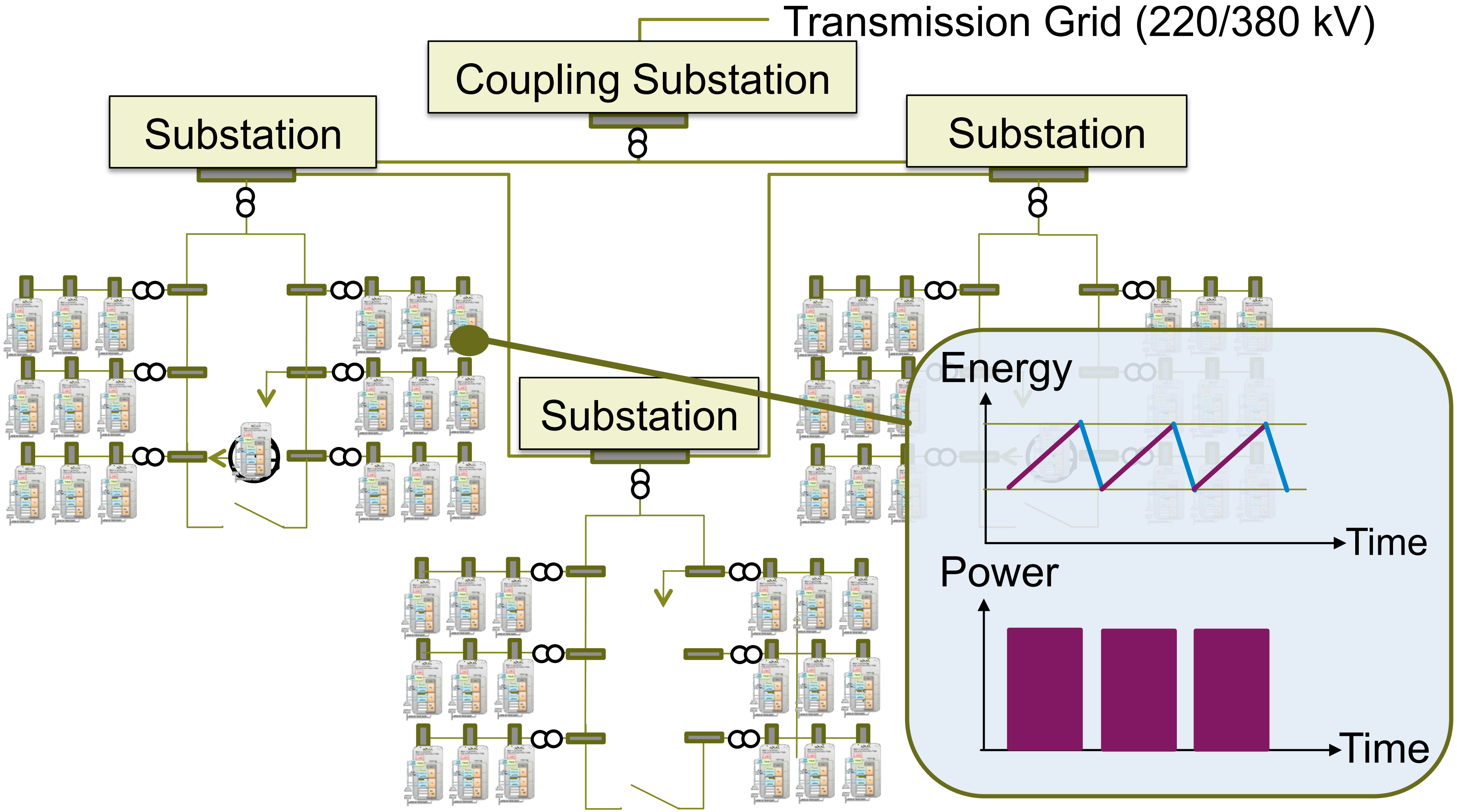
- Consumers can be producers at the same time → **Prosumers**
- Prosumers can locally optimize their interactions with the electricity grid
- External aggregators can bring the pooled capacity of decentralized units to the market



DPG.sim: Prosumer Dispersion on Grid Topology



DPG.sim: Simulation of Individual Units



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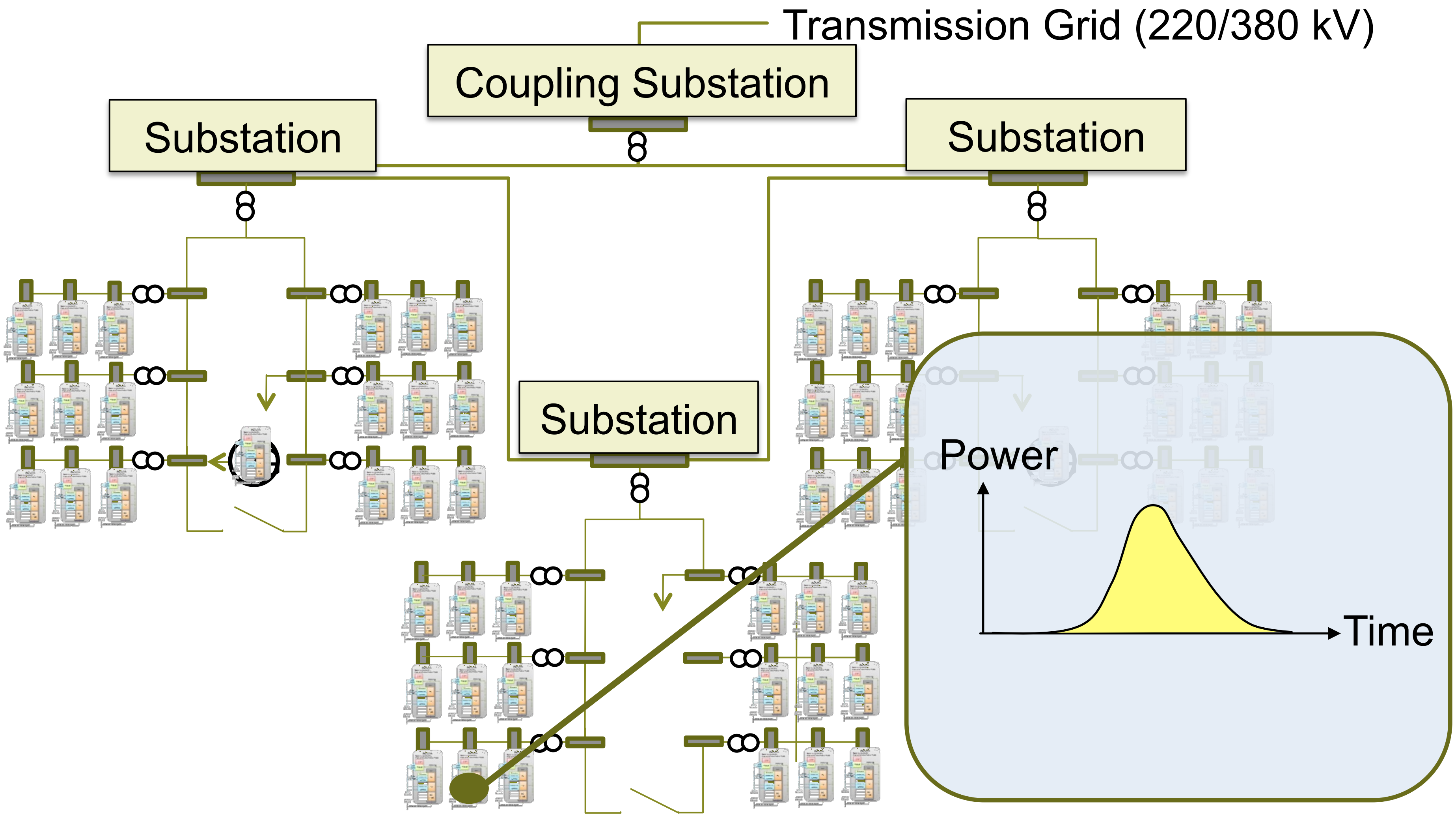
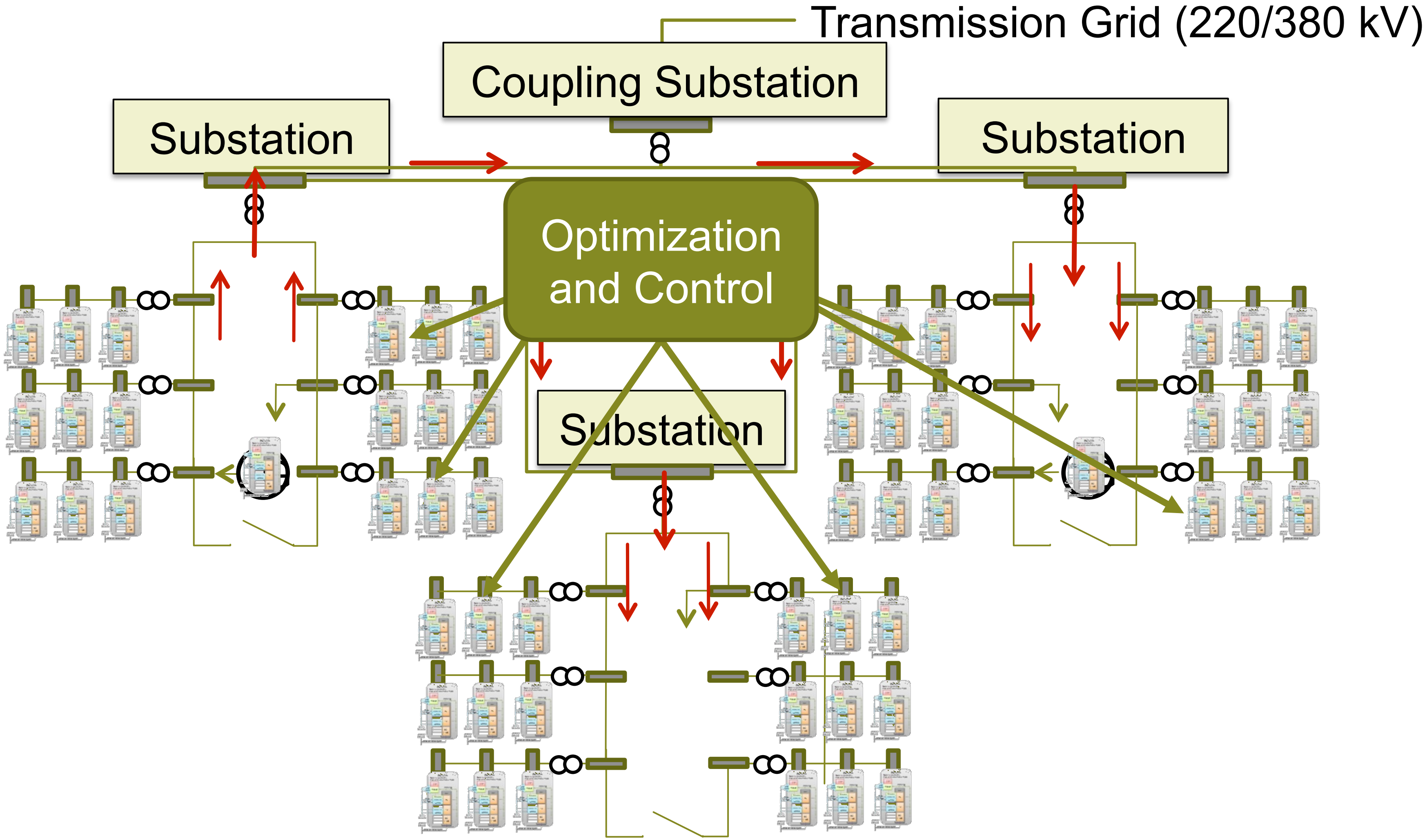


DPG.sim: Optimization and Control



Transmission Grid (220/380 kV)

Coupling Substation

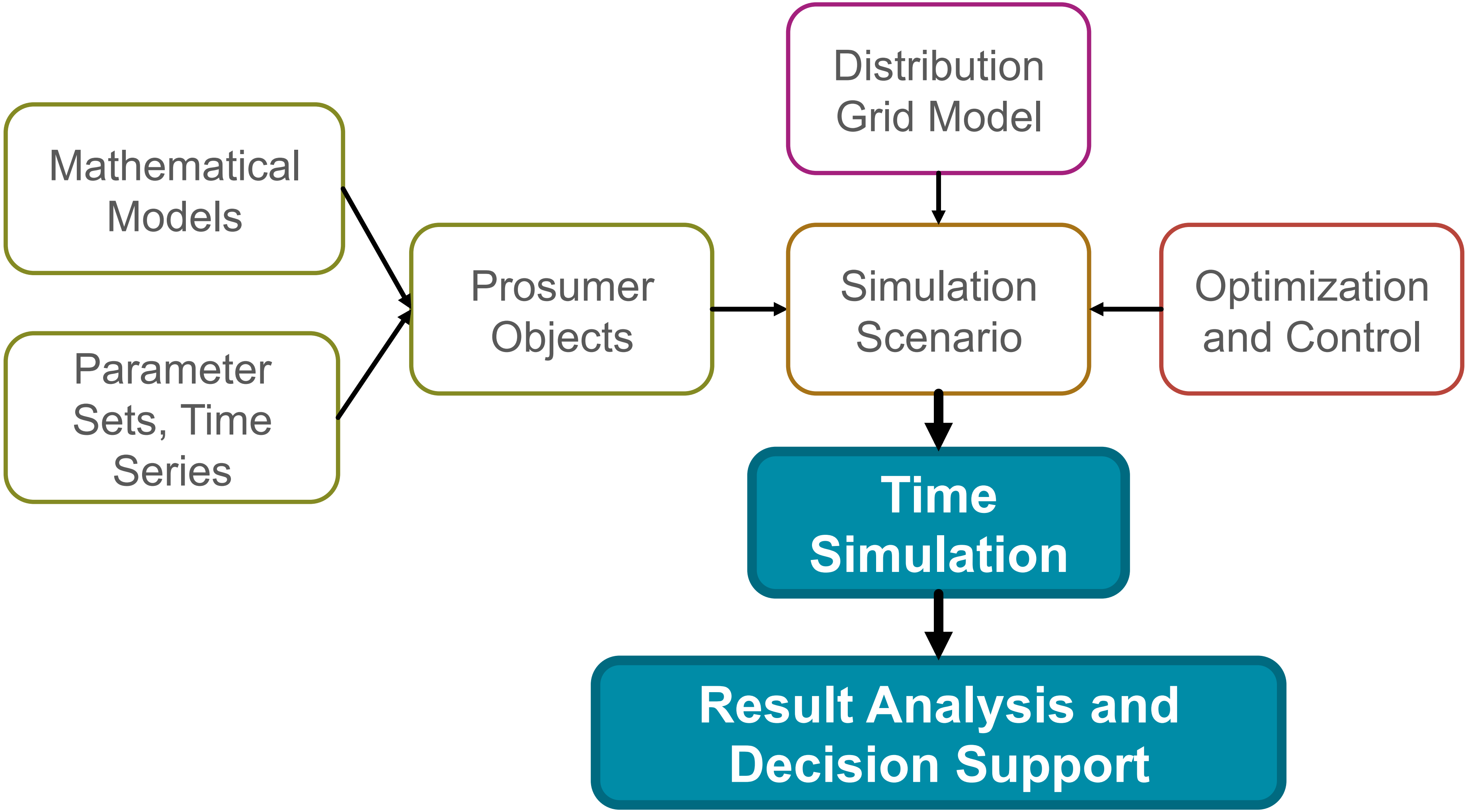
Substation

Substation

Optimization and Control

Substation

DPG.sim: Structure of the Simulation Tool



Distribution Grid Model

Mathematical Models

Parameter Sets, Time Series

Prosumer Objects

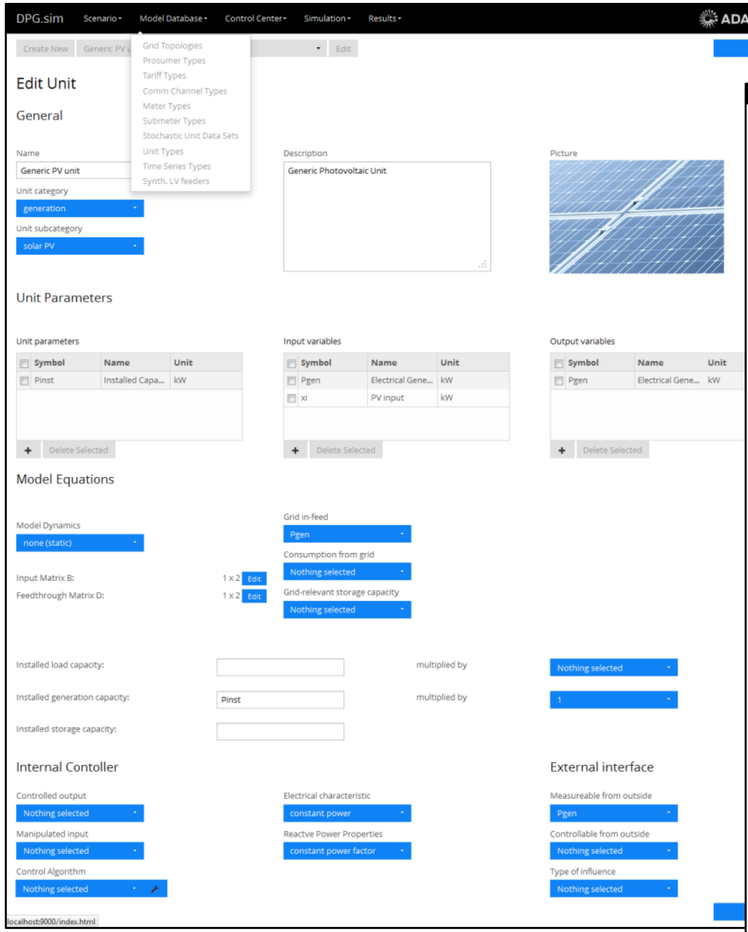
Simulation Scenario

Optimization and Control

Time Simulation

Result Analysis and Decision Support

DPG.sim: Exemplary Screenshots



Edit Unit

General

Name: Generic PV unit
Unit category: generation
Unit subcategory: solar PV
Description: Generic Photovoltaic Unit
Picture

Unit Parameters

Unit parameters

Symbol	Name	Unit
Pinst	Installed Capa...	kW

Input variables

Symbol	Name	Unit
Pgen	Electrical Gene...	kW
xi	PV input	kW

Output variables

Symbol	Name	Unit
Pgen	Electrical Gene...	kW

Model Equations

Model Dynamics: none (static)
Input Matrix B: 1 x 2 Edit
Feedthrough Matrix D: 1 x 2 Edit
Grid in-feed: Pgen
Consumption from grid: Nothing selected
Grid-relevant storage capacity: Nothing selected
Installed load capacity: multiplied by Nothing selected
Installed generation capacity: Pinst multiplied by 1
Installed storage capacity:

Internal Contoller

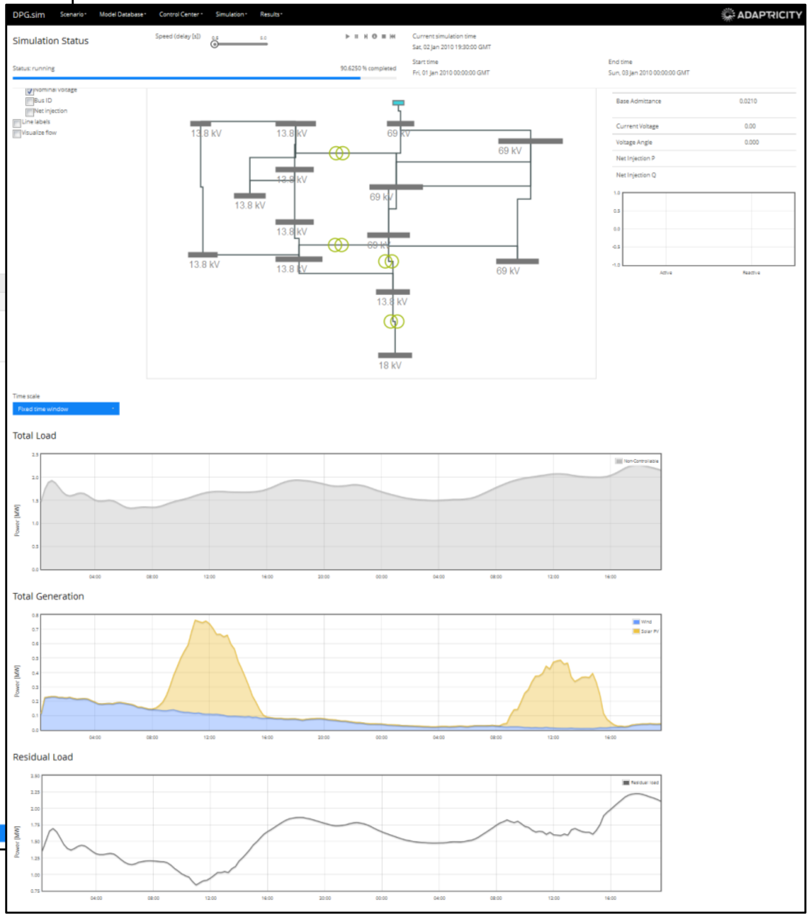
Controlled output: Nothing selected
Manipulated input: Nothing selected
Control Algorithm: Nothing selected
Electrical characteristic: constant power
Reactve Power Properties: constant power factor

External interface

Measureable from outside: Pgen
Controllable from outside: Nothing selected
Type of influence: Nothing selected

localhost:9000/index.html

functional prototype



Simulation Status

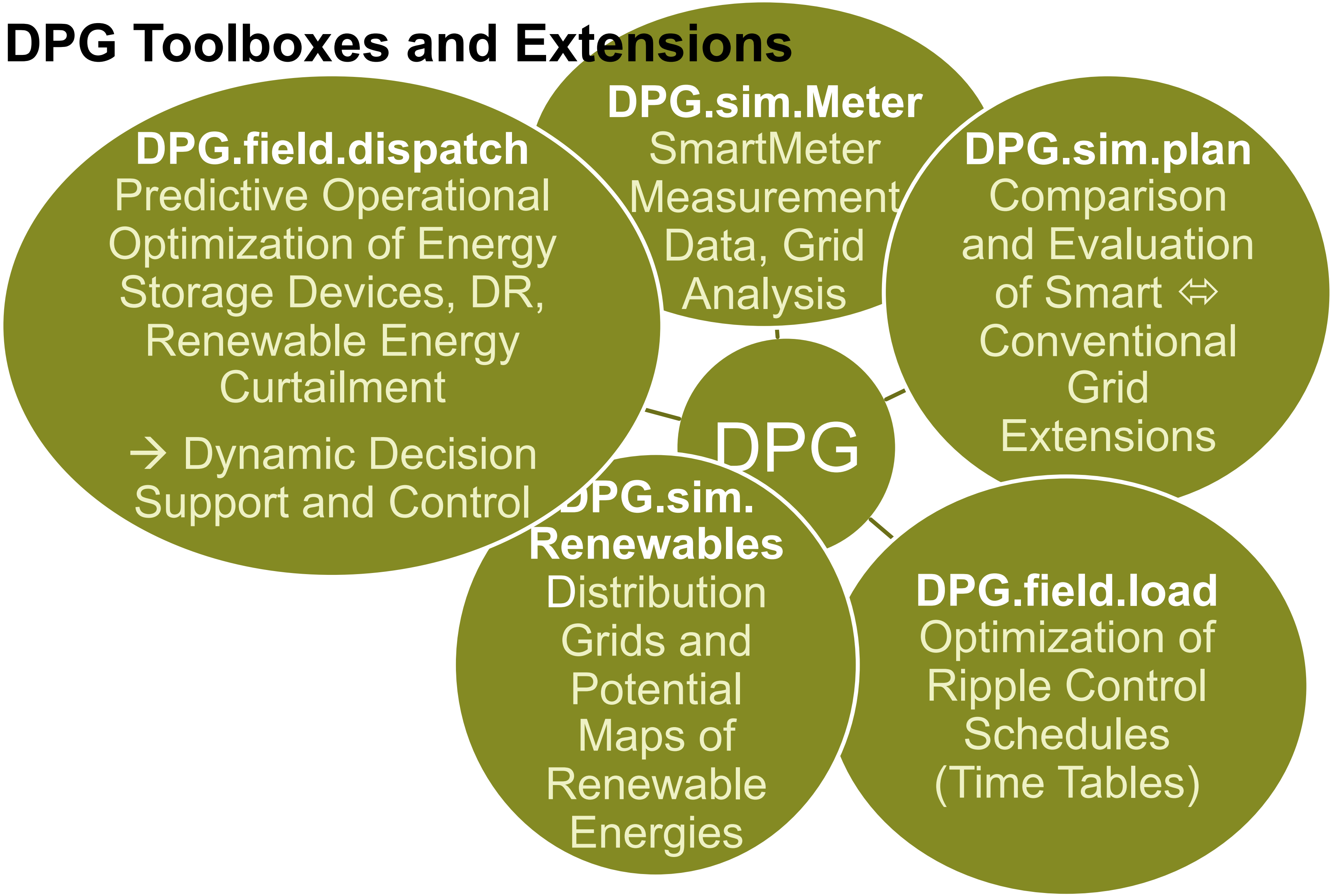
Status: running
90.6250 % completed
Current simulation time: Sat, 02 Jan 2010 19:30:00 GMT
Start time: Fri, 01 Jan 2010 00:00:00 GMT
End time: Sun, 03 Jan 2010 00:00:00 GMT
Time scale: Fixed time window

Total Load

Total Generation

Residual Load

DPG Toolboxes and Extensions



DPG.field.dispatch
Predictive Operational Optimization of Energy Storage Devices, DR, Renewable Energy Curtailment

→ Dynamic Decision Support and Control

DPG.sim.Meter
SmartMeter Measurement Data, Grid Analysis

DPG.sim.plan
Comparison and Evaluation of Smart ⇔ Conventional Grid Extensions

DPG

DPG.sim. Renewables
Distribution Grids and Potential Maps of Renewable Energies

DPG.field.load
Optimization of Ripple Control Schedules (Time Tables)

Conclusions

Aggregating DR approaches represent an important factor for system flexibility in a power system with high renewable energy shares.

Local optimization and control on the customers‘ premises can increase self-consumption of generated power and alter the aggregate customers‘ behavior.

Both aggregating and local control approaches have an impact on distribution grids that needs to be properly managed.

Thank you for your attention!
Questions?