Demand Response

Intelligence at the load side

Peter Palensky
Principal Scientist
Complex Energy Systems
AIT Austrian Institute of Technology / Energy Department

Example Project: EcoGrid EU

- New energy market design and implementation
- Model-predictive load shed/shift
- Interoperability of equipment
- Information security
- System integration
  - PowerMatcher, DEMS, grid plausibility, market platform, CellControler, etc.
  - OpenADR
- Fine grained distribution grid model parameters
- Intelligent demand side

DEMS: Decentralized Energy Management System (Siemens)
OpenADR: Open Automated Demand Response

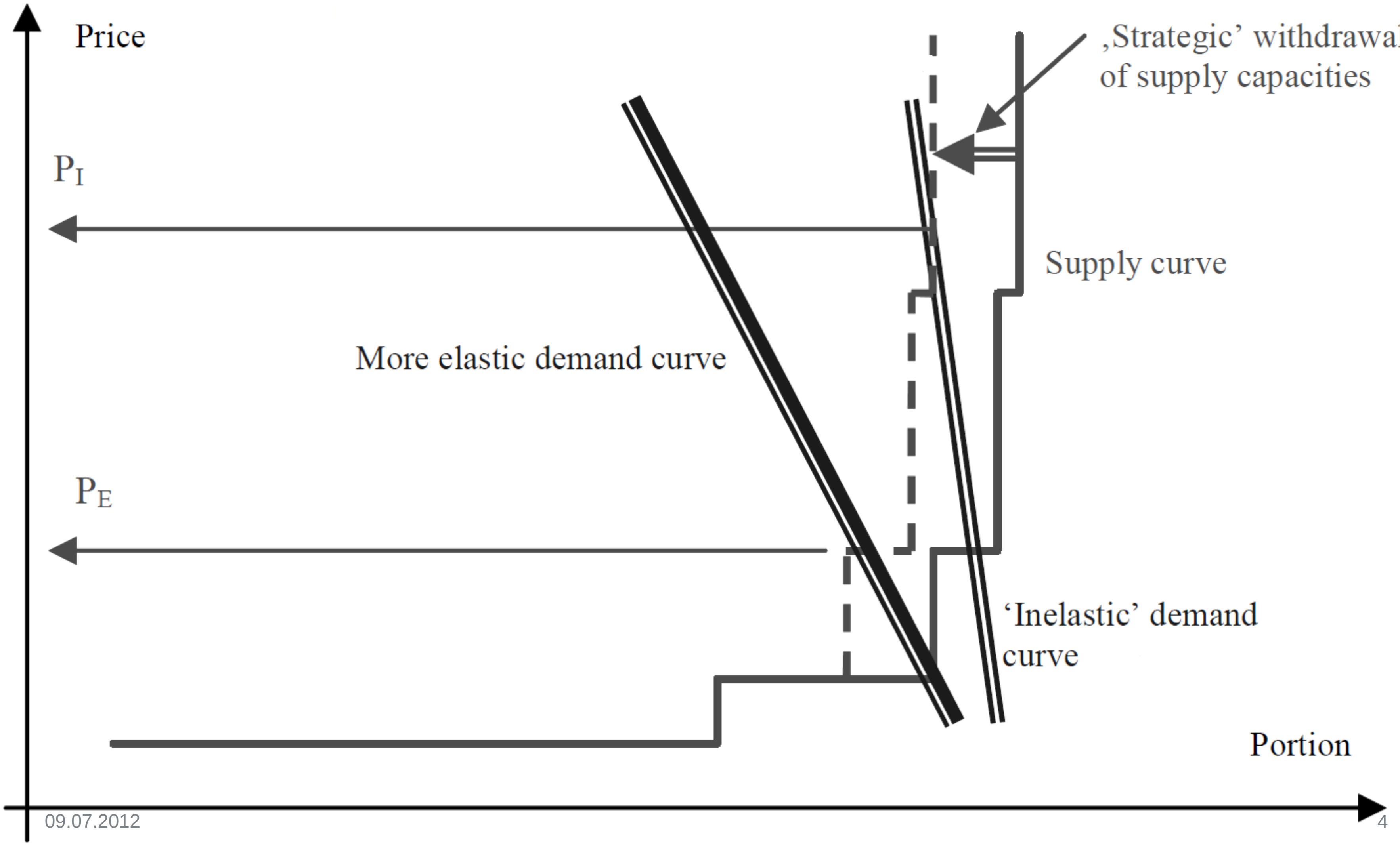
An intelligent demand side

- GRID: Frequency/Voltage support via
  - Reactive power in DG
  - Fair generation shed
  - Cooperative loads

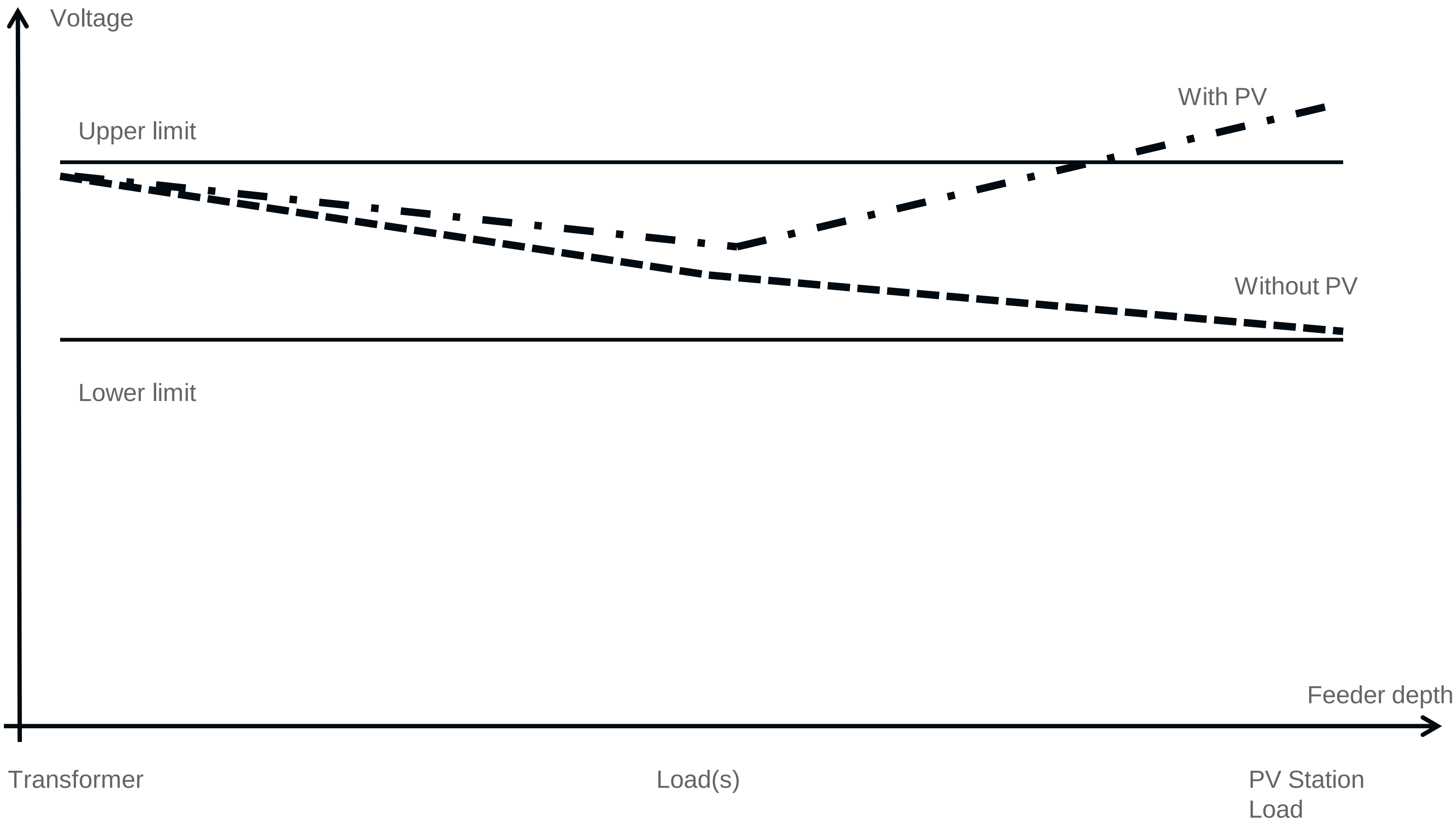
- MARKET:
  - Reduce consumption peaks / end user costs
  - Increase renewable generation
  - Demand elasticity

DG: Distributed Generation

Example: elastic demand

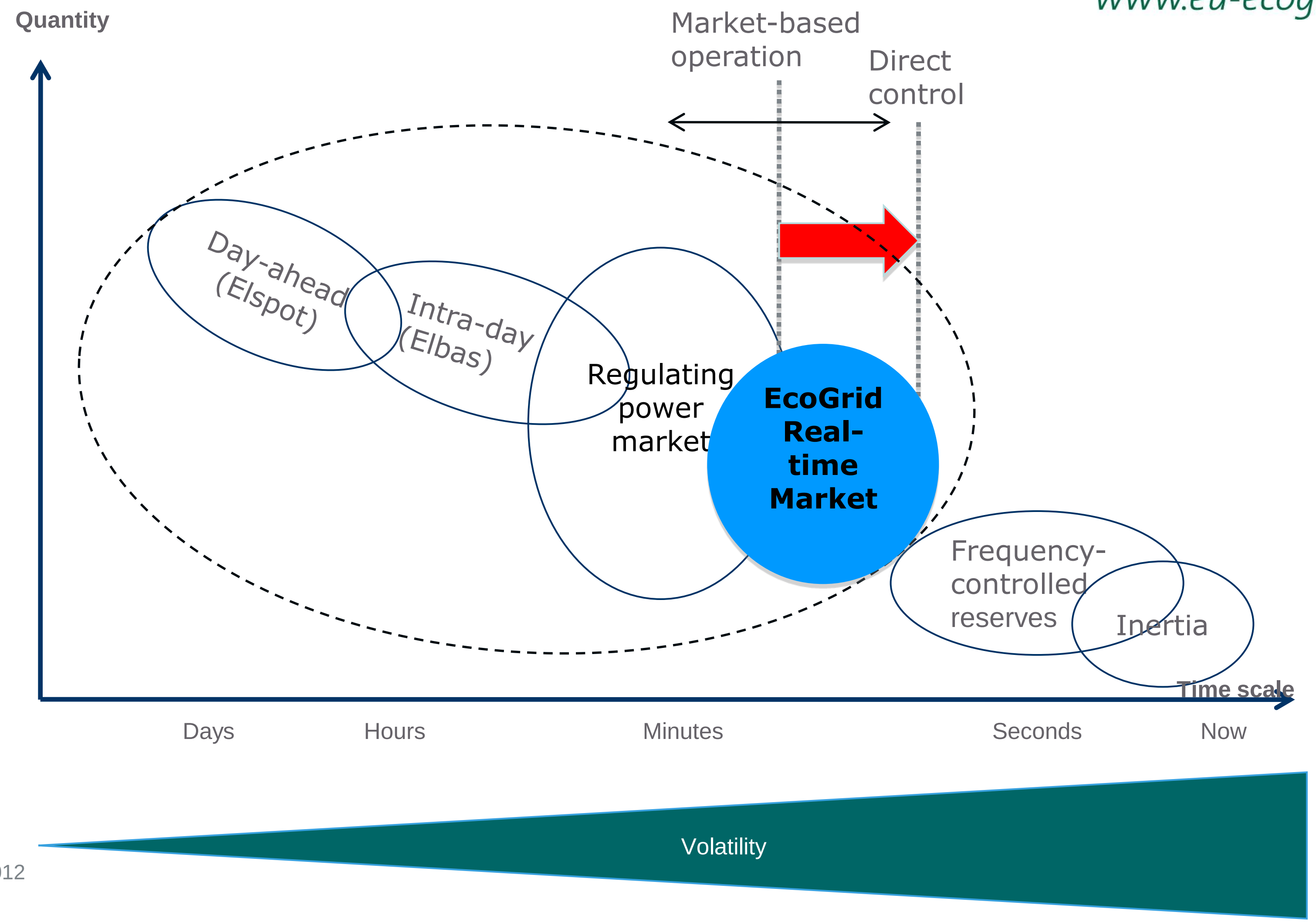


Example: Voltage Support

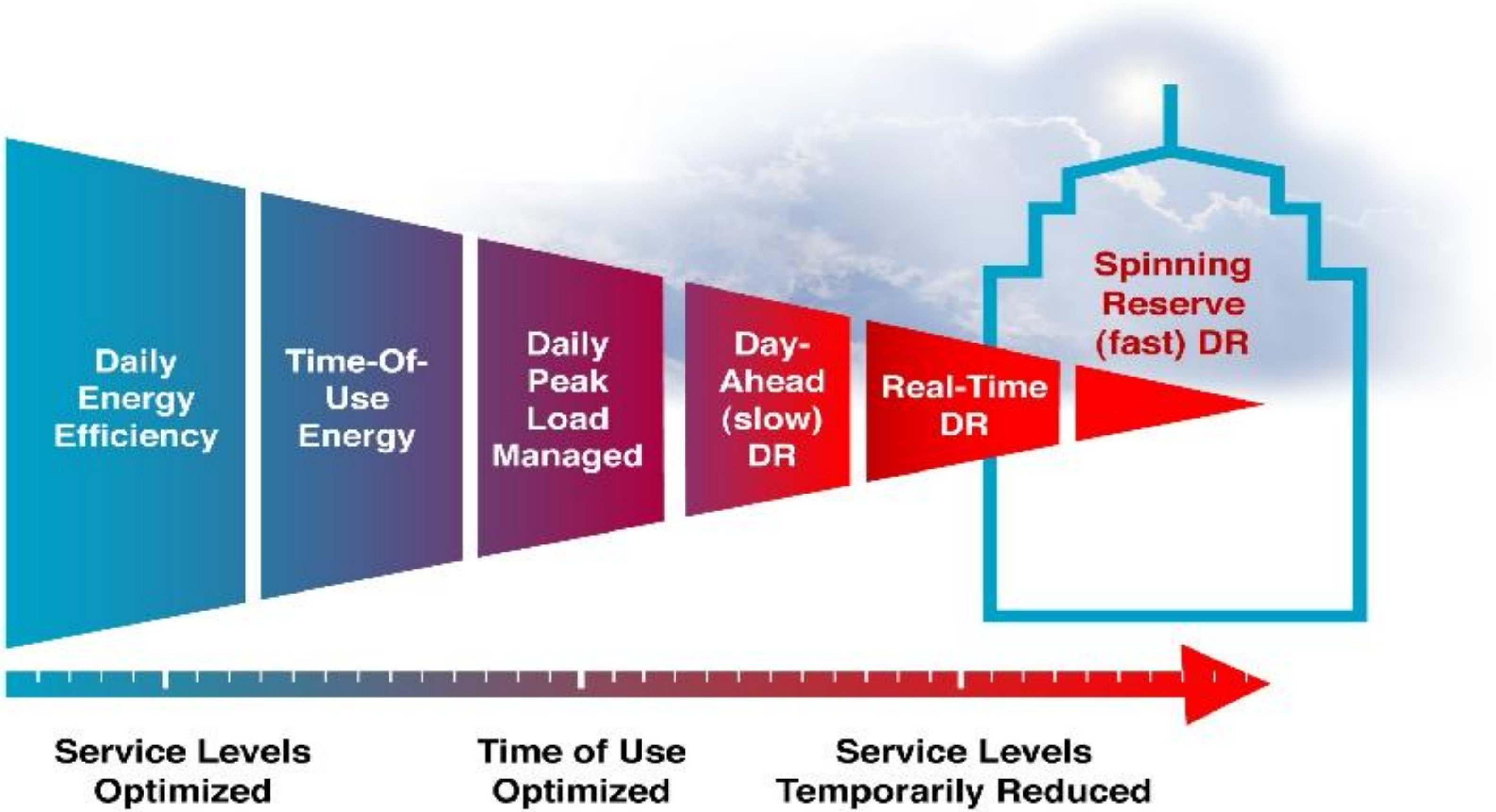


PV: Photovoltaics

EcoGrid EU Markets



DSM Time Scales



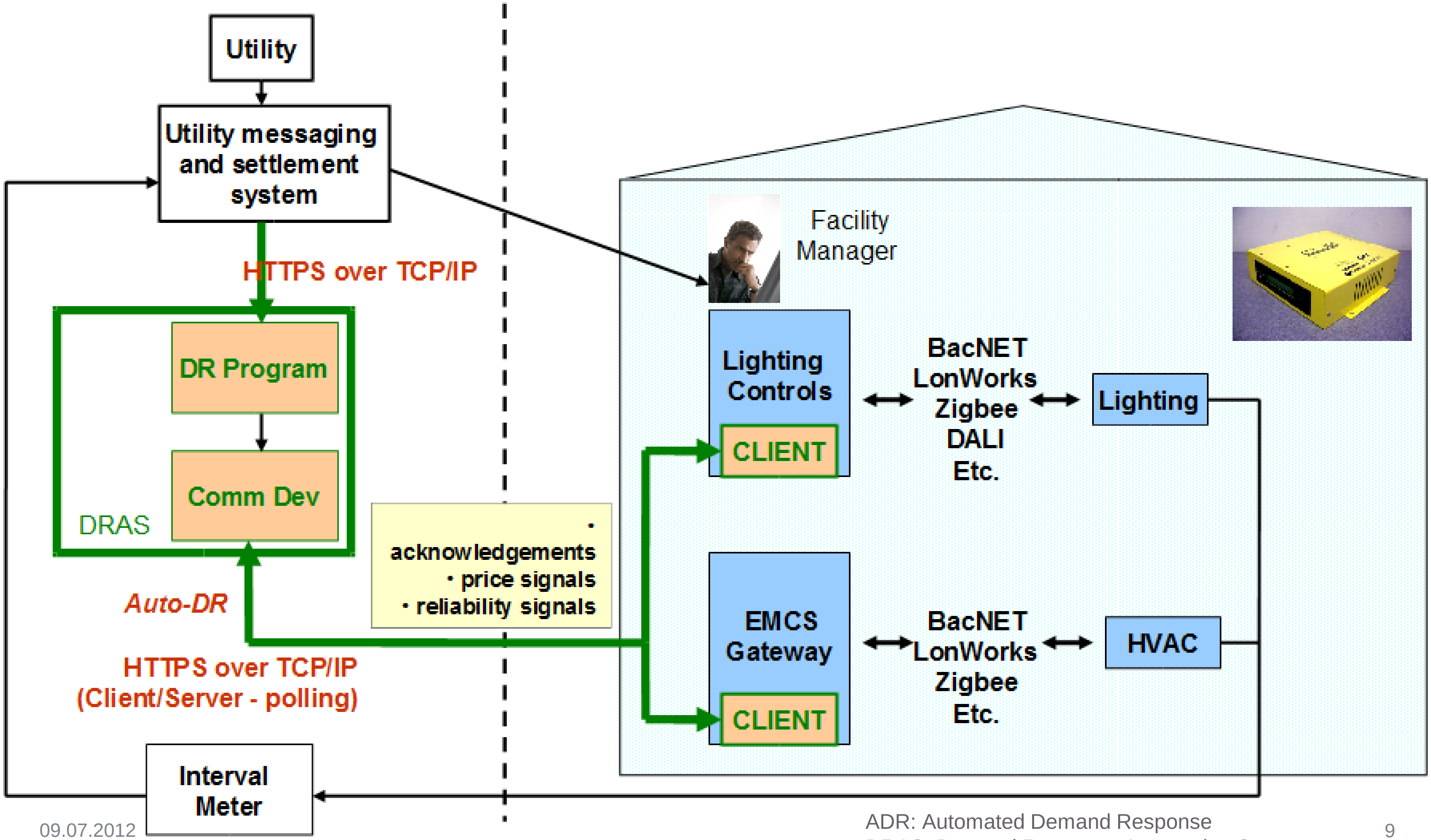
DSM: Demand Side Management
DR: Demand Response

Types of Demand Response

- Price Response:
  - Triggered by wholesale market prices (e.g. Real-time Pricing)
  - Goal: Peak load reduction
  - Measure of Success: CO_2 / Utility bill savings
- Reliability Response:
  - Triggered by the conditions of the grid
  - Goal: Peak load reduction upon request from Utilities or DSO/TSO
  - Measure of success: Financial incentive based on how much electric load (kW) is reduced

DSO/TSO: Distribution/Transmission System Operator

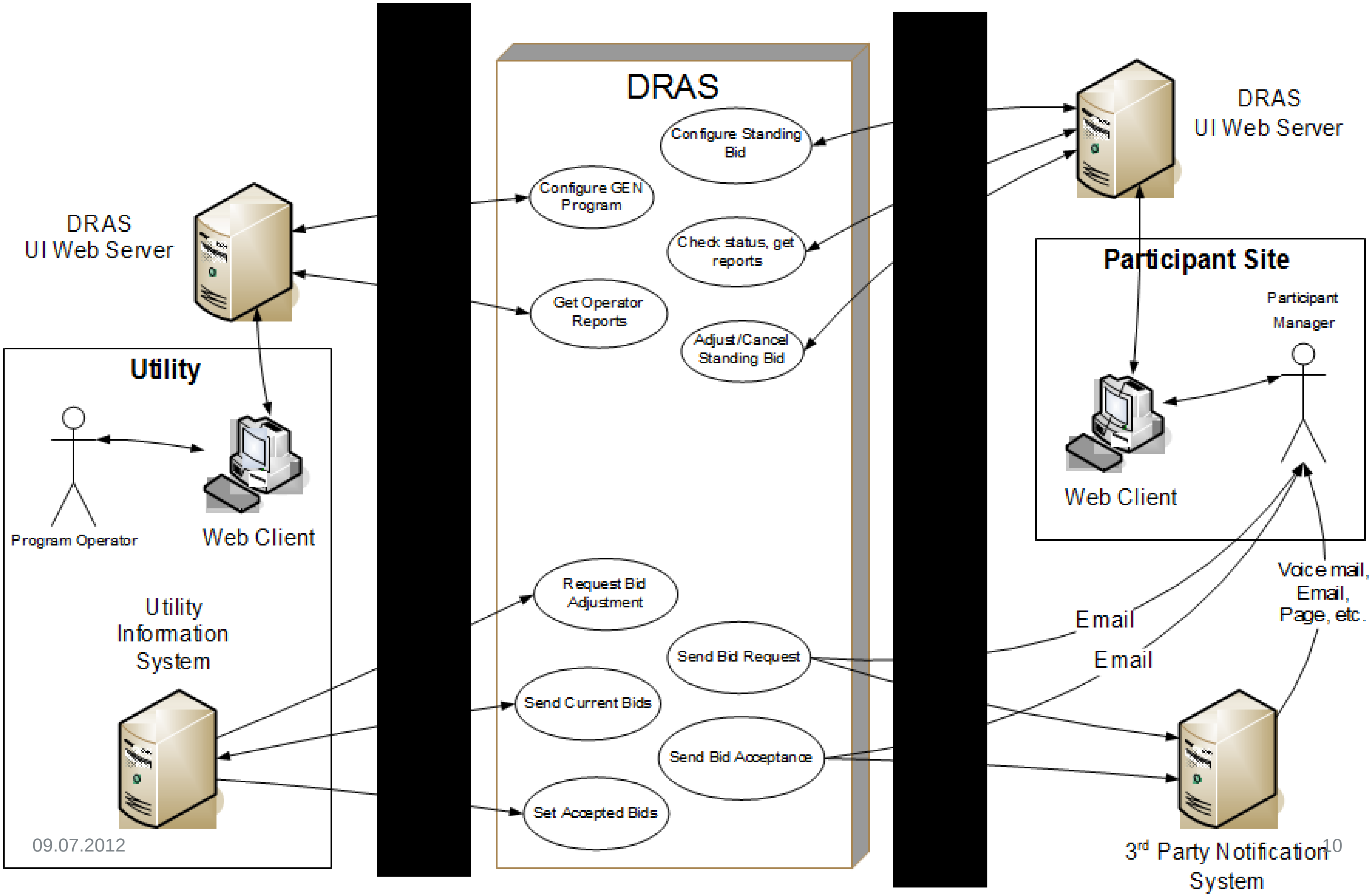
Automated Demand Response: OpenADR



HVAC: Heating Ventilation, Air Conditioning

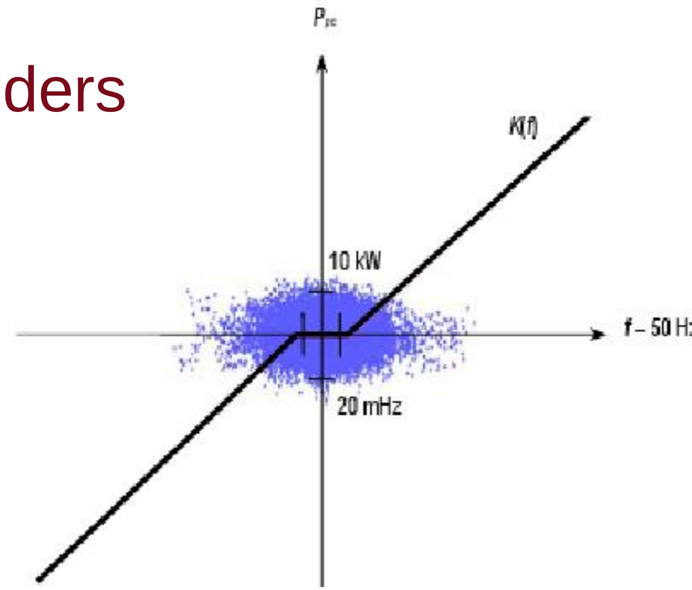
ADR: Automated Demand Response
DRAS: Demand Response Automation Server
EMCS: Energy Management Control System

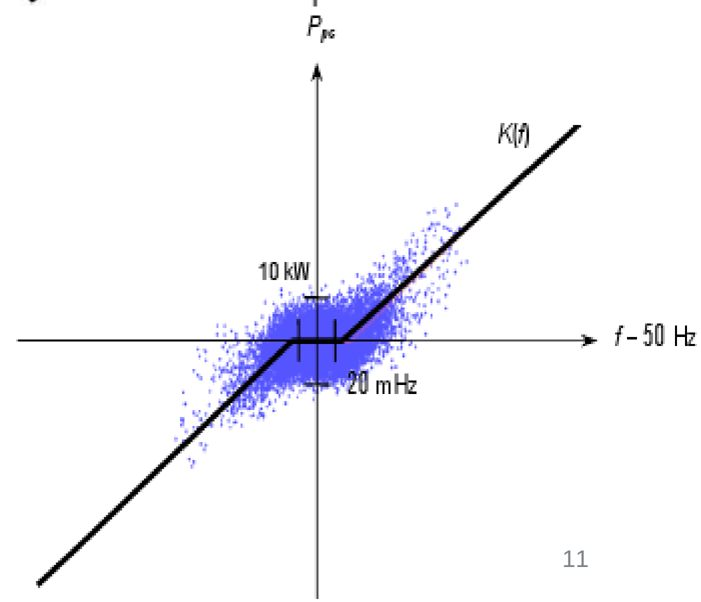
OpenADR Bidding Example



Refrigerators as regulation power providers

- 2-point controllers
- Setpoint adjustment
- Frequency-dependent
- Fairness via central registry

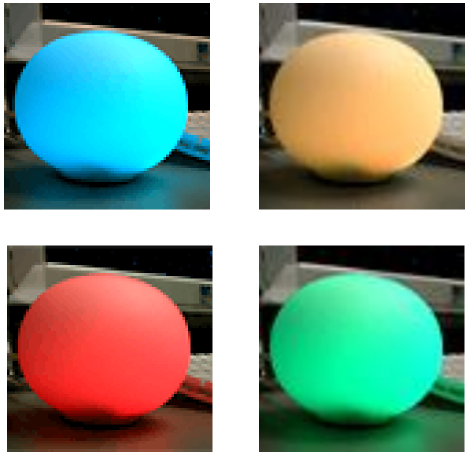




Distributed Grid Control Examples

- “GridFriendly” (PNNL)
- KNIVES (Japan)
- Aggregators
  - Site Controls,
  - Constellation,...
- California
  - ORB
  - Smart AC
  - PCT
- “50.2 Hz problem”
  with 10 GW PV inverters
  in Germany 2011?


The Grid Friendly™ controller uses data from the power grid to balance energy supply and demand.



PNNL: Pacific Northwest National Laboratory
AC: Air Conditioning
PCT: Programmable Communicating Thermostat
PV: Photovoltaics

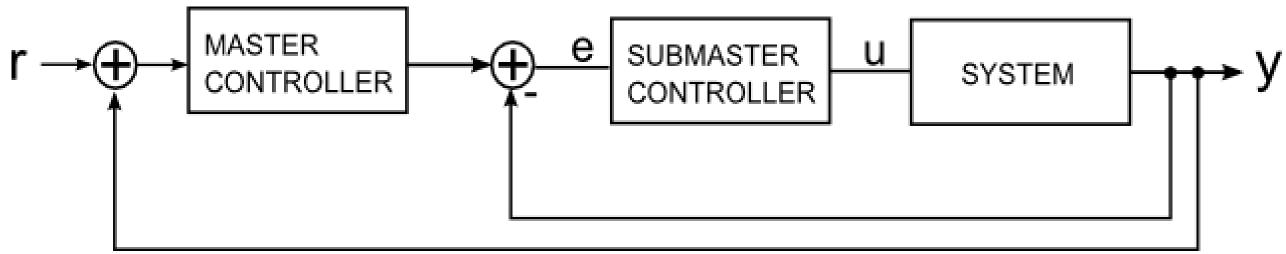
Modern energy (load) management

- Limitations of classical demand side management
  - Complex commissioning
  - No planning (pre-cooling, etc.)
  - No load- or process model → brutal shedding
  - No plug-and-participate, security, scalability, etc.

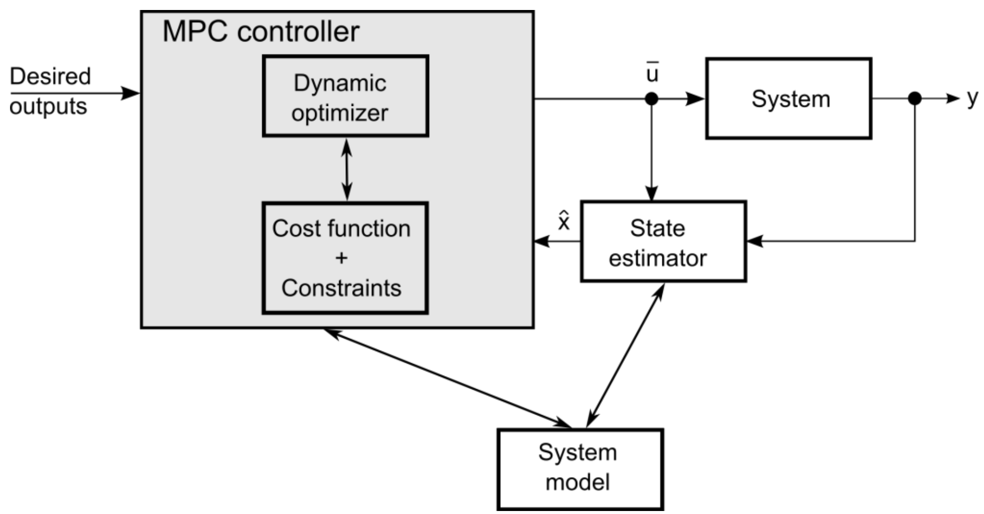
- Missing
  - Dynamic priorities (depend on situation,...) → Algorithm
  - Process model (how full are “virtual storages”?) → Model
  - Devices register and interoperate autonomously with system → Self Organization

Model Predictive Controls (MPC)

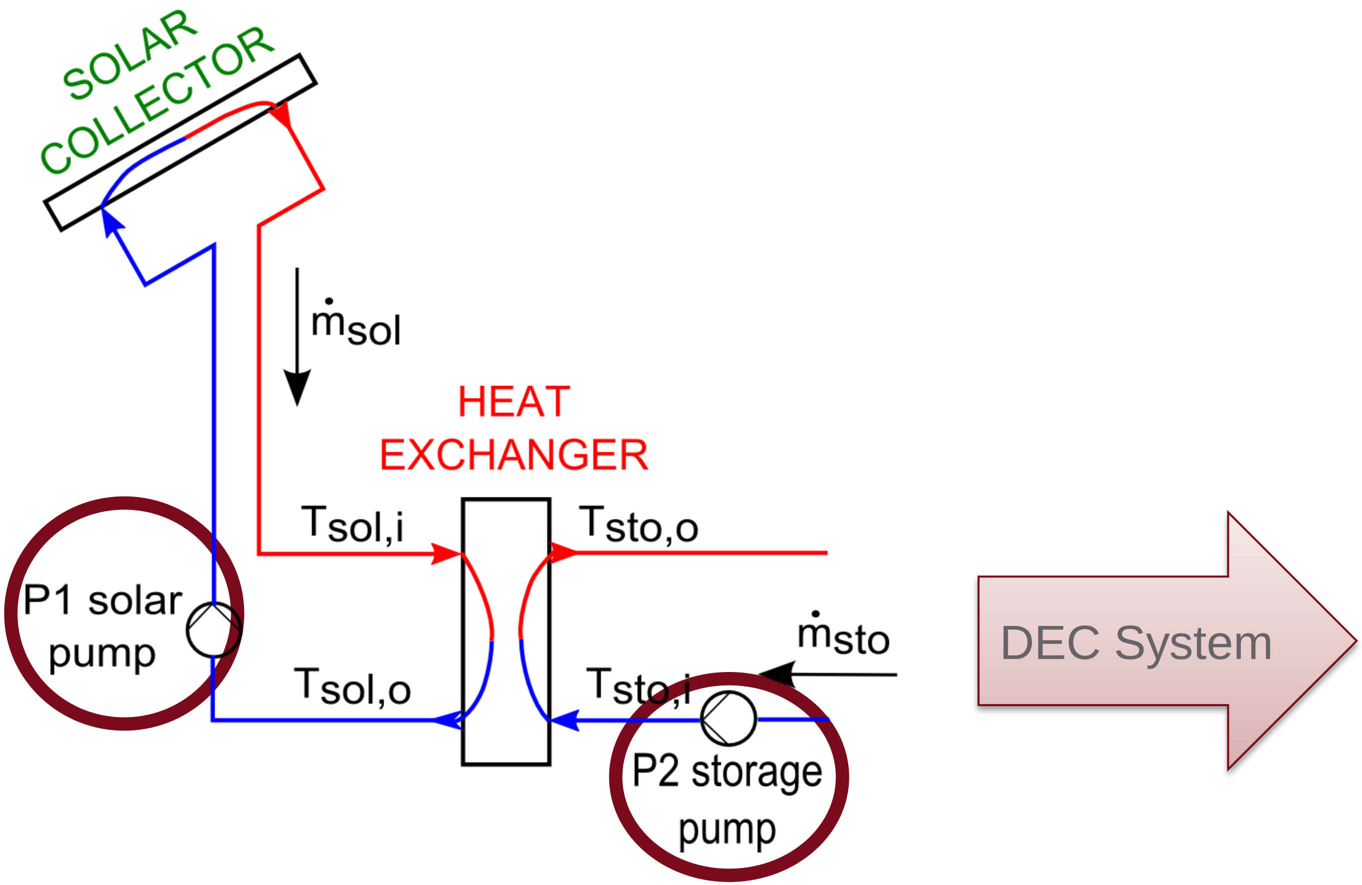
- Classic Controls (PID etc.)



- Predictive Controls
  - Has forecast
  - Has model
  - Has time…



Example Model Predictive Controls



MPC - Details

$$\min_{\hat{\mathbf{u}}} \hat{J}(\hat{\mathbf{x}}, \hat{\mathbf{u}}) := \sum_{k=0}^{N_p-1} \frac{T_s}{2} \left(\mathcal{F}(\mathbf{x}_k, \mathbf{u}_k, t_k) + \mathcal{F}(\mathbf{x}_{k+1}, \mathbf{u}_{k+1}, t_{k+1}) \right) + \mathcal{G}(\mathbf{x}_{N_p})$$

subject to

$$\frac{\mathbf{x}_{k+1} - \mathbf{x}_k}{t_{k+1} - t_k} = \frac{1}{2} \left(\mathbf{f}(\mathbf{x}_k, \mathbf{u}_k, t_k) + \mathbf{f}(\mathbf{x}_{k+1}, \mathbf{u}_{k+1}, t_{k+1}) \right)$$

$$\mathbf{g}(\mathbf{x}_{N_p}) = 0$$

$$\mathbf{h}(\mathbf{x}_k, \mathbf{u}_k, t_k) \leq 0$$

and

$$\mathbf{x}(\mathbf{t}_0) = \mathbf{x}_0$$

with

$$k = 0, 1, 2, \cdots, N_p - 1$$

$$\mathbf{x}(k+1) = \mathbf{\Phi}_k \mathbf{x}(k) + \mathbf{\Gamma}_k \mathbf{u}(k) + \mathbf{\Lambda}_k \mathbf{d}(k)$$
$$\mathbf{y}(k) = \mathbf{C}_k \mathbf{x}(k) + \mathbf{D}_k \mathbf{u}(k)$$

$$\begin{bmatrix} \frac{\mathrm{d}}{\mathrm{d}t} T_{sol,o} \\ \frac{\mathrm{d}}{\mathrm{d}t} T_{sto,o} \\ \frac{\mathrm{d}}{\mathrm{d}t} T_{sol,i} \end{bmatrix} = \begin{bmatrix} \frac{\dot{m}_{sol}}{M_h} (T_{sol,i} - T_{sol,o}) \\ -\frac{A_h U}{2 M_h c_h} (T_{sol,i} + T_{sol,o} - T_{sto,i} - T_{sol,o}) \\ \frac{\dot{m}_{sto}}{M_c} (T_{sto,i} - T_{sto,o}) \\ +\frac{A_c U}{2 M_c c_c} (T_{sol,i} + T_{sol,o} - T_{sto,i} - T_{sol,o}) \\ \frac{1}{c_{dyn}} (A_c (c_0 \; G_{tot} - c_1 (T_{sol,i} - T_{amb}) \\ -c_2 (T_{sol,i} - T_{amb})^2) \\ +\dot{m}_{sol} c_c (T_{sol,o} - T_{sol,i})) \end{bmatrix}$$

$$\Delta T_{i,j}(t) = \frac{1}{2} \left(T_{sol,i-1}(t) + T_{sol,i}(t) \right) - \frac{1}{2} \left(T_{sto,j-1}(t) + T_{sto,j}(t) \right)$$

$$\dot{T}_{sol,i}(t) = \frac{1}{M_{sol} c_{sol}} \left(\dot{m}_{sol}(t) c_{sol} \left(T_{sol,i-1}(t) - T_{sol,i}(t) \right) - A_{sol} U(t) \Delta T_{i,j}(t) \right) + \frac{\kappa_{sol,i}(t)}{M_{sol} c_{sol}} \left(T_{sol,i} - T_{amb} \right)$$

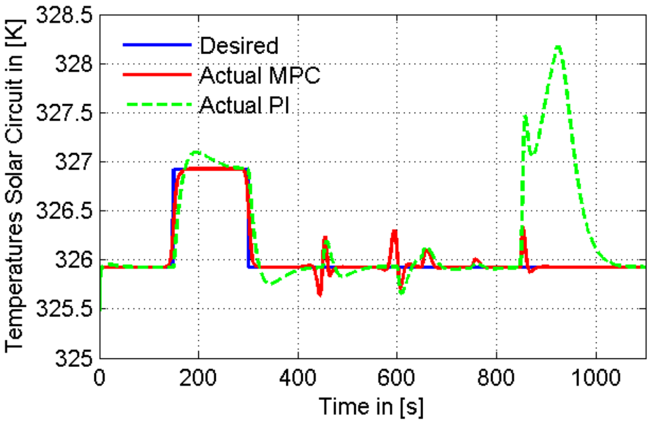
$$\dot{T}_{sto,j}(t) = \frac{1}{M_{sto} c_{sto}} \left(\dot{m}_{sto}(t) c_{sto} \left(T_{sto,i-1}(t) - T_{sto,i}(t) \right) + A_{sto} U(t) \Delta T_{i,j}(t) \right) + \frac{\kappa_{sto,i}(t)}{M_{sto} c_{sto}} \left(T_{sto,i} - T_{amb} \right)$$

$$\min_{\Delta \mathbf{u}} J := \sum_{i=0}^{N_p} \xi_y(i) \left[\mathbf{y}^*(k+i) - \mathbf{y}(k+i) \right]^2 + \sum_{i=0}^{N_c} \xi_u(i) \left[\mathbf{\Delta u}(k+i) \right]^2$$

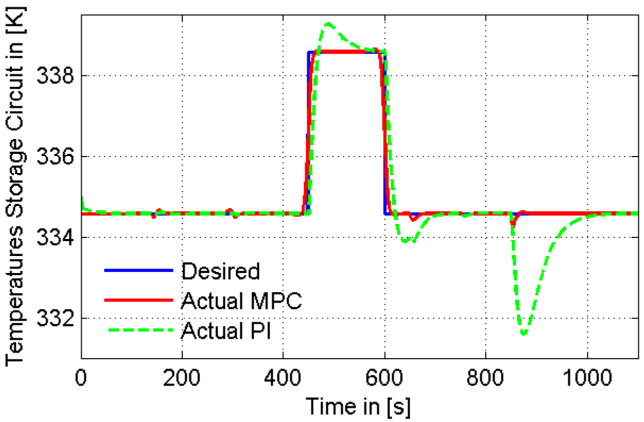
subject to constraints

$$\mathbf{u}_{min} \leq \mathbf{u}(k) \leq \mathbf{u}_{max}$$
$$\mathbf{\Delta u}(k) \leq \mathbf{\Delta u}_{max}$$
$$\mathbf{y}_{min} \leq \mathbf{y}(k) \leq \mathbf{y}_{max}$$

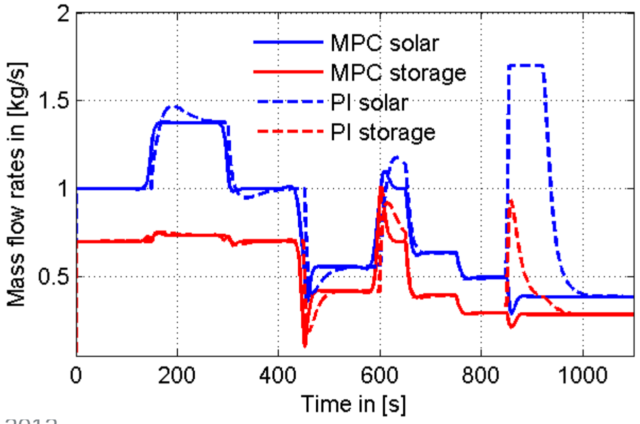
MPC - Results



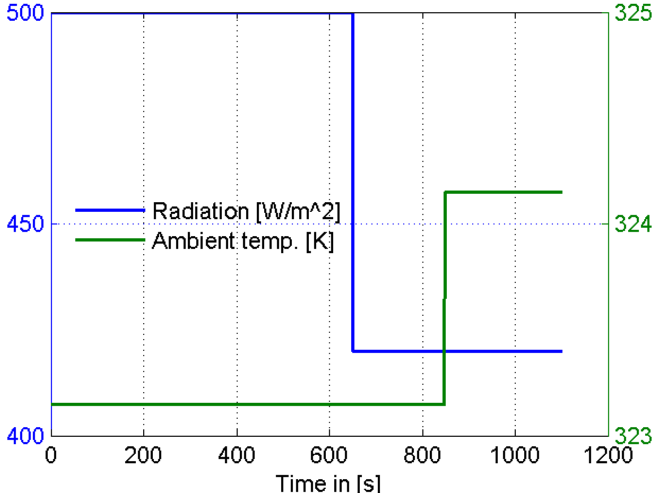
Temperatures Solar Circuit in [K]
328.5
328
327.5
327
326.5
326
325.5
325
0
200
400
600
800
1000
Time in [s]
Desired
Actual MPC
Actual PI



Temperatures Storage Circuit in [K]
338
336
334
332
0
200
400
600
800
1000
Time in [s]
Desired
Actual MPC
Actual PI



Mass flow rates in [kg/s]
2
1.5
1
0.5
0
200
400
600
800
1000
Time in [s]
MPC solar
MPC storage
PI solar
PI storage



500
450
400
325
324
323
0
200
400
600
800
1000
1200
Time in [s]
Radiation [W/m^2]
Ambient temp. [K]

MPC - Details

$$\min_{\hat{\mathbf{u}}} \hat{J}(\hat{\mathbf{x}}, \hat{\mathbf{u}}) := \sum_{k=0}^{N_p-1} \frac{T_s}{2}\left(\mathcal{F}(\mathbf{x}_k, \mathbf{u}_k, t_k) + \mathcal{F}(\mathbf{x}_{k+1}, \mathbf{u}_{k+1}, t_{k+1})\right) + \mathcal{G}(\mathbf{x}_{N_p})$$

subject to

$$\frac{\mathbf{x}_{k+1} - \mathbf{x}_k}{t_{k+1} - t_k} = \frac{1}{2}\left(\mathbf{f}(\mathbf{x}_k, \mathbf{u}_k, t_k) + \mathbf{f}(\mathbf{x}_{k+1}, \mathbf{u}_{k+1}, t_{k+1})\right)$$

$$\mathbf{g}(\mathbf{x}_{N_p}) = 0$$

$$\mathbf{h}(\mathbf{x}_k, \mathbf{u}_k, t_k) \leq 0$$

and

$$\mathbf{x}(t_0) = \mathbf{x}_0$$

with

$$k = 0, 1, 2, \cdots, N_p - 1$$

$$\mathbf{x}(k+1) = \mathbf{\Phi}_k \mathbf{x}(k) + \mathbf{\Gamma}_k \mathbf{u}(k) + \mathbf{\Lambda}_k \mathbf{d}(k)$$
$$\mathbf{y}(k) = \mathbf{C}_k \mathbf{x}(k) + \mathbf{D}_k \mathbf{u}(k)$$

$$\begin{bmatrix} \frac{\mathrm{d}}{\mathrm{d}t} T_{sol,o} \\ \\ \frac{\mathrm{d}}{\mathrm{d}t} T_{sto,o} \\ \\ \frac{\mathrm{d}}{\mathrm{d}t} T_{sol,i} \end{bmatrix} = \begin{bmatrix} \frac{\dot{m}_{sol}}{M_h}(T_{sol,i} - T_{sol,o}) \\ -\frac{A_h U}{2 M_h c_h}(T_{sol,i} + T_{sol,o} - T_{sto,i} - T_{sol,o}) \\ \\ \frac{\dot{m}_{sto}}{M_c}(T_{sto,i} - T_{sto,o}) \\ +\frac{A_c U}{2 M_c c_c}(T_{sol,i} + T_{sol,o} - T_{sto,i} - T_{sol,o}) \\ \\ \frac{1}{c_{dyn}}(A_c(c_0 \, G_{tot} - c_1(T_{sol,i} - T_{amb}) \\ -c_2(T_{sol,i} - T_{amb})^2) \\ +\dot{m}_{sol} c_c (T_{sol,o} - T_{sol,i})) \end{bmatrix}$$

$$\Delta T_{i,j}(t) = \frac{1}{2}\left(T_{sol,i-1}(t) + T_{sol,i}(t)\right) - \frac{1}{2}\left(T_{sto,j-1}(t) + T_{sto,j}(t)\right)$$

$$\dot{T}_{sol,i}(t) = \frac{1}{M_{sol} c_{sol}}\left(\dot{m}_{sol}(t)\, c_{sol}\left(T_{sol,i-1}(t) - T_{sol,i}(t)\right) - A_{sol} U(t)\, \Delta T_{i,j}(t)\right) + \frac{\kappa_{sol,i}(t)}{M_{sol} c_{sol}}\left(T_{sol,i} - T_{amb}\right)$$

$$\dot{T}_{sto,j}(t) = \frac{1}{M_{sto} c_{sto}}\left(\dot{m}_{sto}(t)\, c_{sto}\left(T_{sto,i-1}(t) - T_{sto,i}(t)\right) + A_{sto} U(t)\, \Delta T_{i,j}(t)\right) + \frac{\kappa_{sto,i}(t)}{M_{sto} c_{sto}}\left(T_{sto,i} - T_{amb}\right)$$

$$\min_{\mathbf{\Delta u}} J := \sum_{i=0}^{N_p} \xi_y(i)\left[\mathbf{y}^*(k+i) - \mathbf{y}(k+i)\right]^2 + \sum_{i=0}^{N_c} \xi_u(i)\left[\mathbf{\Delta u}(k+i)\right]^2$$

subject to constraints

$$\mathbf{u}_{min} \leq \mathbf{u}(k) \leq \mathbf{u}_{max}$$
$$\mathbf{\Delta u}(k) \leq \mathbf{\Delta u}_{max}$$
$$\mathbf{y}_{min} \leq \mathbf{y}(k) \leq \mathbf{y}_{max}$$

Modeling future energy **systems**

- Heat exchanger white/grey-box model
- Energy system: black box

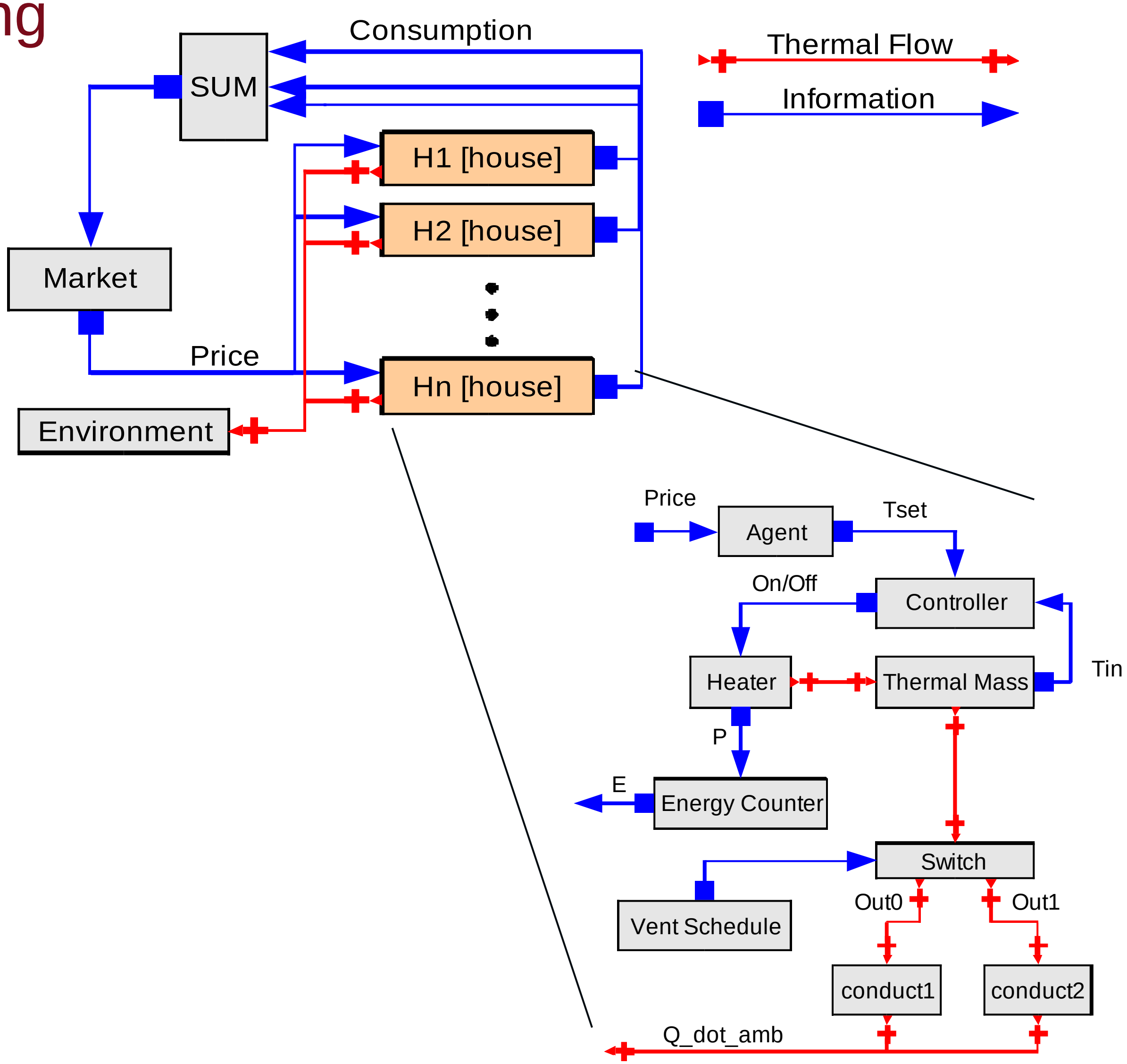
- Four fundamental types of elements
  - **Continuous**: energy technology, infrastructure, physics
  - **Discrete**: ICT, software, controls, communication
  - **Game Theory**: markets, market players, roles, agents
  - **Stochastic**: weather, people, aggregated/not-modeled behavior, statistics

- Multiscale
  - Size from microgrids to interconnected grids
  - Time from harmonics to demographics

Use Case 1: el. heating

- Thermal Domain
- Agents/Market
- Stochastic Events

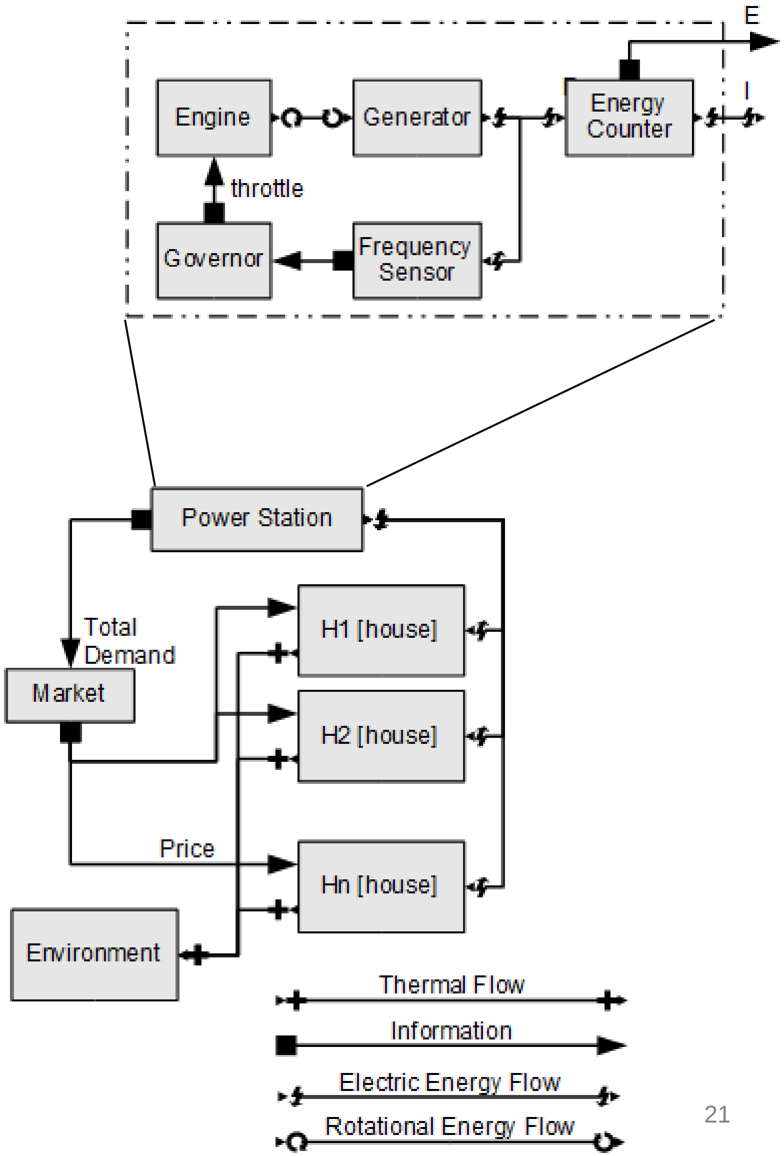
- Describe via bond graph
- Analyze interplay of continuous domain and asynchronous events
- Scalability of platforms
- Physical parts isolated



Use Case 2: el. power station

- Physical parts not isolated
- Plus: Electrical domain
  - Ideal grid
  - Non-ideal power station
- Plus: Mechanical domain

- Further use cases
  - 3: Thermal grid
  - 4: Non-trivial market
  - 5: Communication network
  - 6: EV-charging



EV: electric vehicle

Results up to now

- First fundamental question: Physical domain + asynchronous events i.e. continuous and discrete
- Two types of modeling paradigms / simulation philosophies
  - Agent-oriented
    - Autonomous modules
    - Components determine synchronization points
    - Examples: GridLAB-D, Omnet++
  - Monolithic
    - Equation-based model of physics -> ODE-> code
    - Solver integrates and tries to find zero crossings
    - Examples: Modelica, Simscape

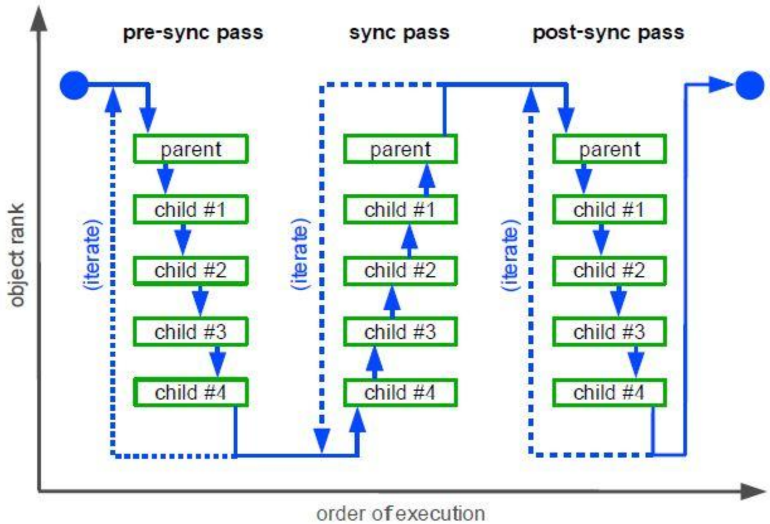
ODE: Ordinary Differential Equations

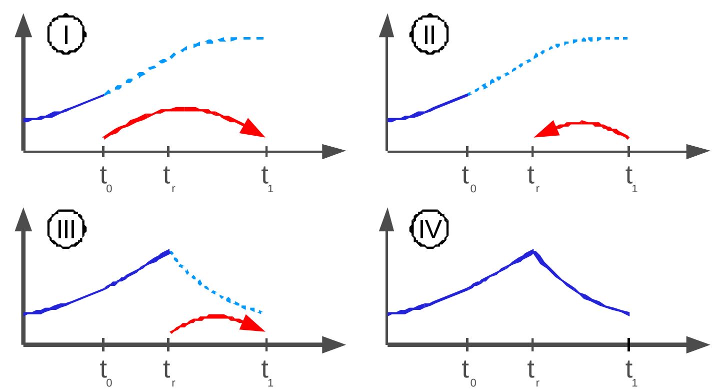
Agent-based Modeling

- E.g.: GridLAB-D (PNNL)

- PRO
  - High Performance
  - Plugin-system
  - Hierarchies
  - Communication utilities

- CON
  - No higher-level simulation (integrators etc.)
  - Written in (legacy) C

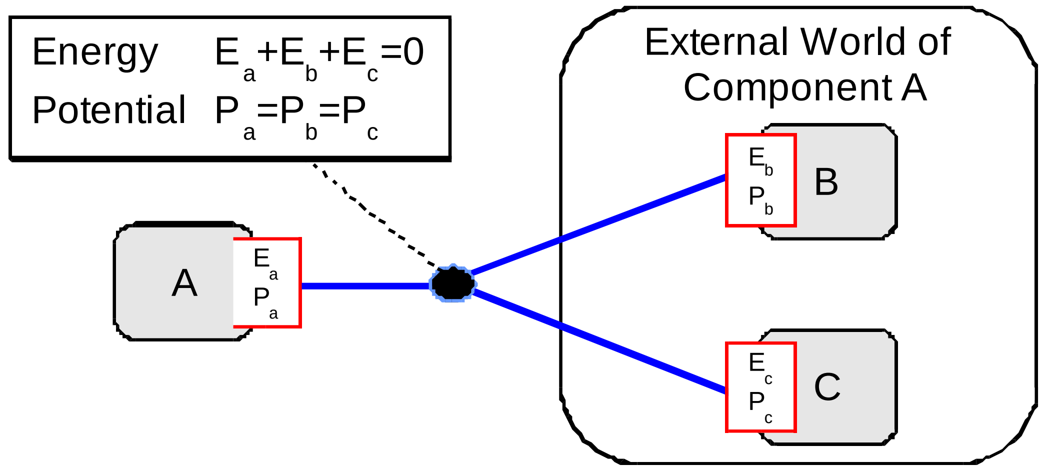


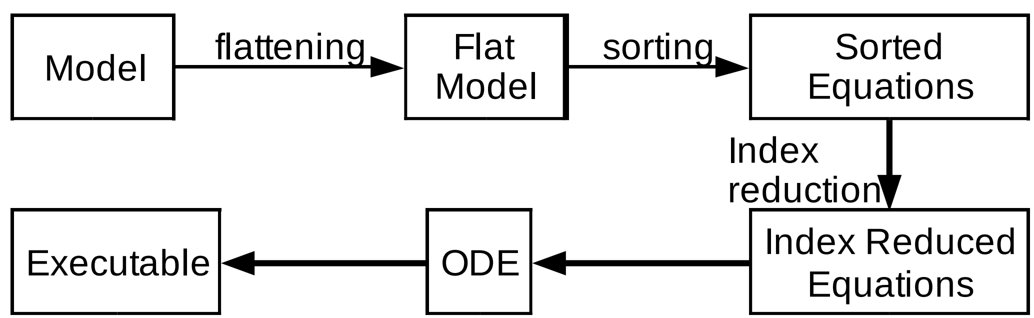


PNNL: Pacific Northwest National Laboratory

Monolithic Modeling

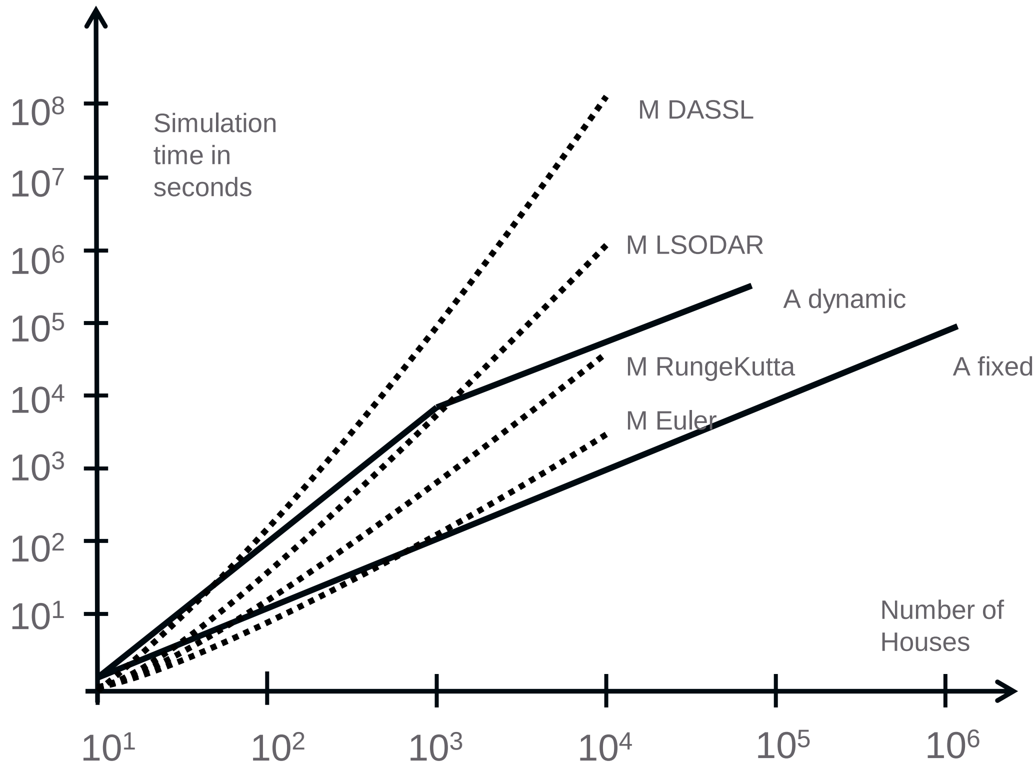
- E.g.: Simscape, Modelica
- PRO
  - Convenient
  - Multi-domain physics
  - Strong syntax
  - Good docu
- CON
  - Low Performance
  - Closed platforms?





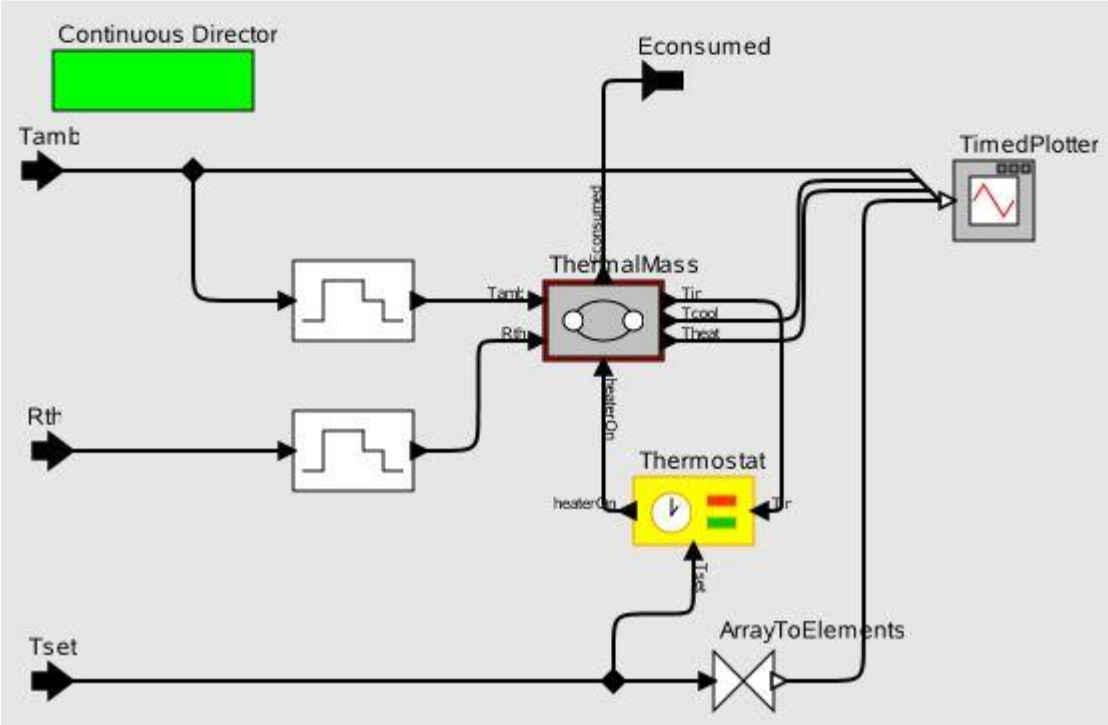
Scalability Test

- M: monolithic
- A: Agent based
- Various solvers tested
- GridLAB-D top scorer
  - UC 1 analytically solved
  - Unfair comparison
- Massive problems with asynchronous events
- Simscape worst
- Tradeoff between comfort and performance
- New candidate: Ptolemy II?



Ptolemy II

- Origin: embedded systems
- Actors/Directors
- Hierarchies
- Heterogeneous Models: continuous and discrete mixed
- Open source, UCB
- Execute sub-models within threads -> multi core!



UCB: University of California, Berkeley

The future: parallel, heterogeneous co-simulation

- Commercial model libraries (PowerFactory, TRNSYS & Co.): 100s of person-years -> use them
- Flexible new tools: no limits -> use them

- Standardized Interfaces a'la FMI (Dymola!), HLA
- Integration via Ptolemy II
- Parallel Computation
  - Clouds/Clusters: Globus, xCAT & Co
- Model decomposition recipes
  - E.g. power line length vs. inter-node simulation latency

xCAT: Extreme Cloud Administration Toolkit
FMI: Funtional Mockup Interface
HLA: High Level Architecture

Conclusion

- Intelligent Load Side?
  - -> Knowledge
    - Process models
    - Communication (prices, schedules,…)
  - -> Decisions
    - MPC Algorithms
    - Communication (negotiations,…)

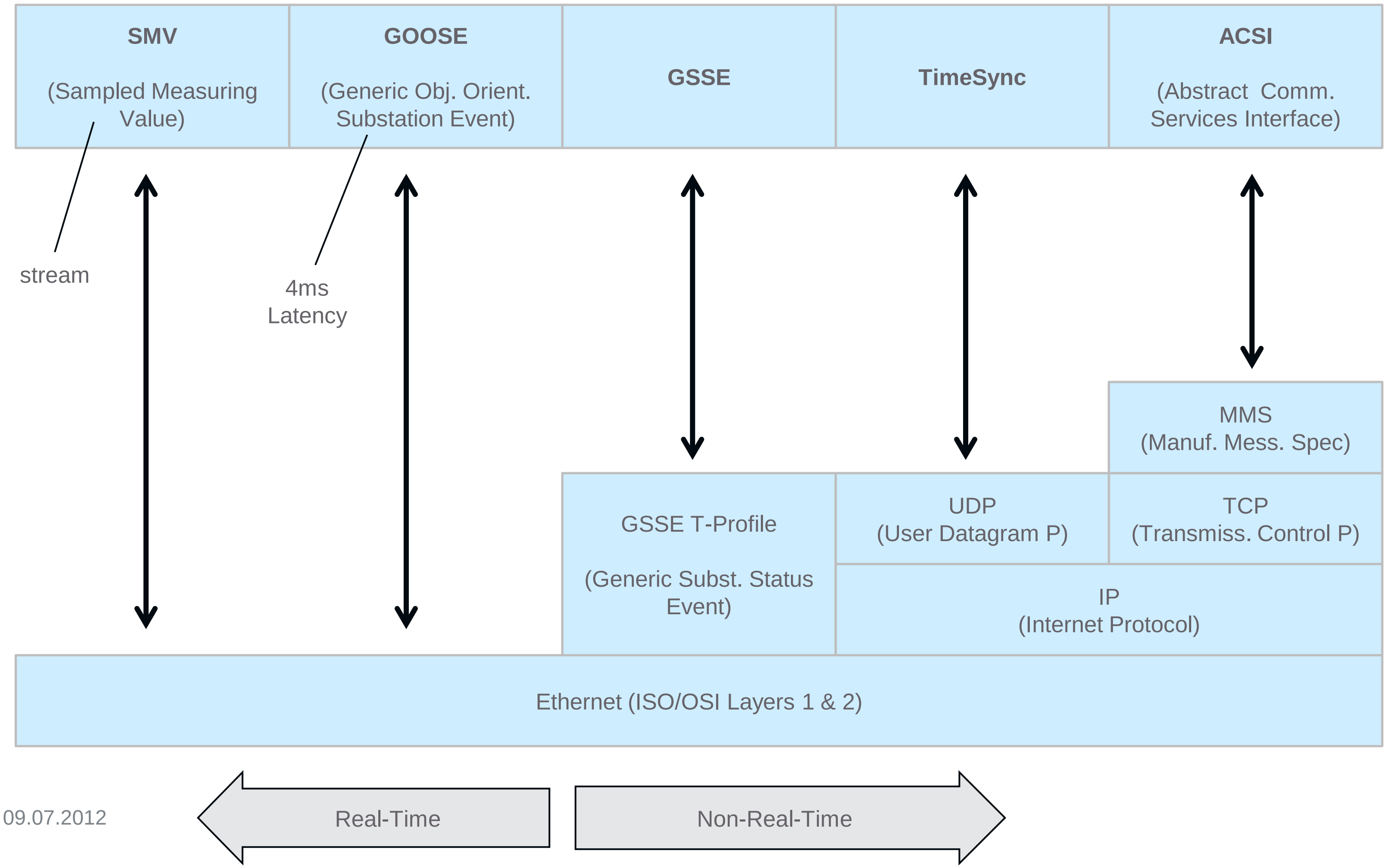
- IT is part of the solution and the problem
- Research needs in modeling systems of systems

MPC: model-predictive controls
IT: information technology

Thank you

Peter Palensky
Principal Scientist
Complex Energy Systems
AIT Austrian Institute of Technology
Energy Department

Example: IEC 61850 Protocol Family



Profiles/Objects for an intelligent load side

- IEC 61850 Standard
  - Transport, data types, profiles
- Zigbee Smart Energy Profile
  - Shedding, metering, time-of-use prices, display, PCT...
- BACnet Load Control Object
  - Shed duration, shed level (%),...
  - Hierarchy of objects
- Others: OpenADR, eBIX, etc.

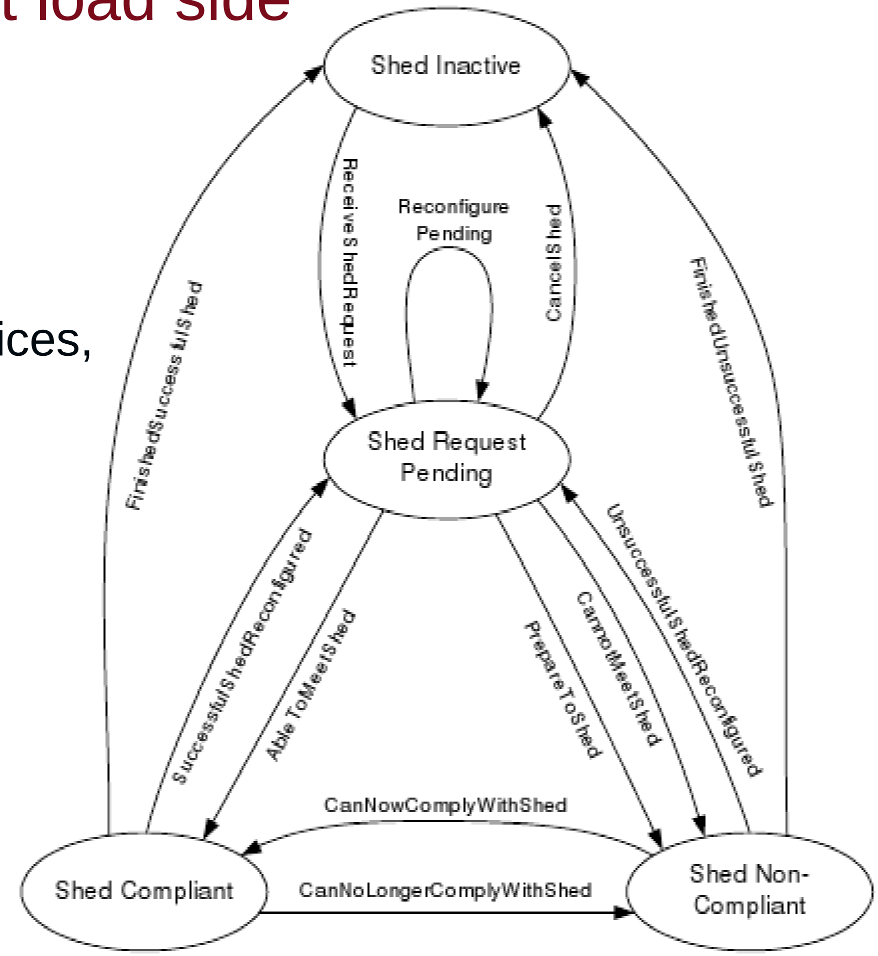
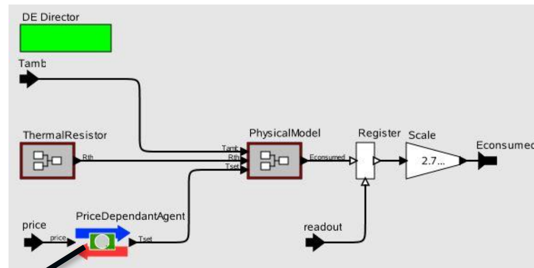
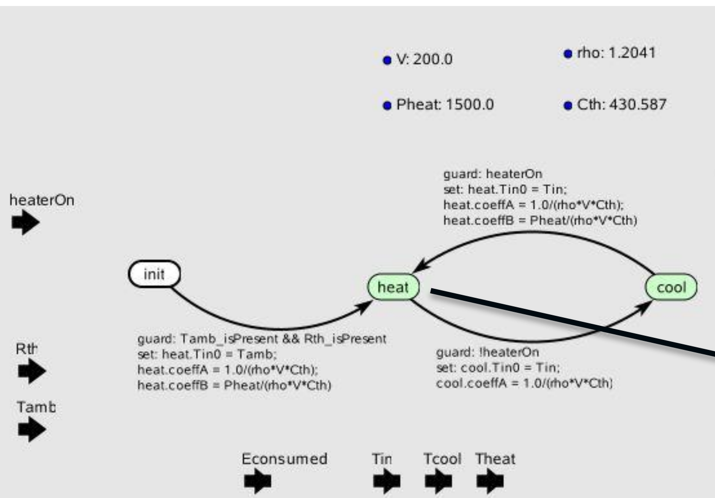


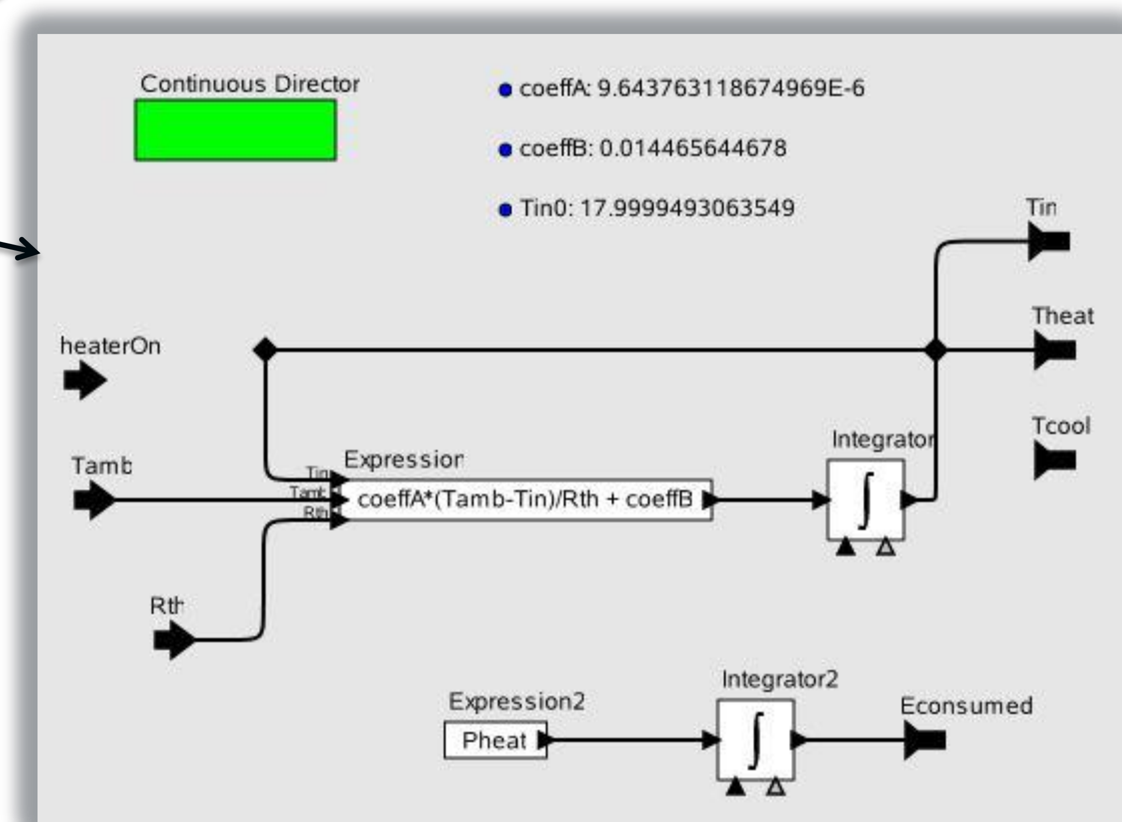
Image: ASHRAE

ADR: Automated Demand Response
PCT: Programmable Communication Thermostat
eBIX: energy Business Information Exchange

Ptolemy II Example: Simple Use Case



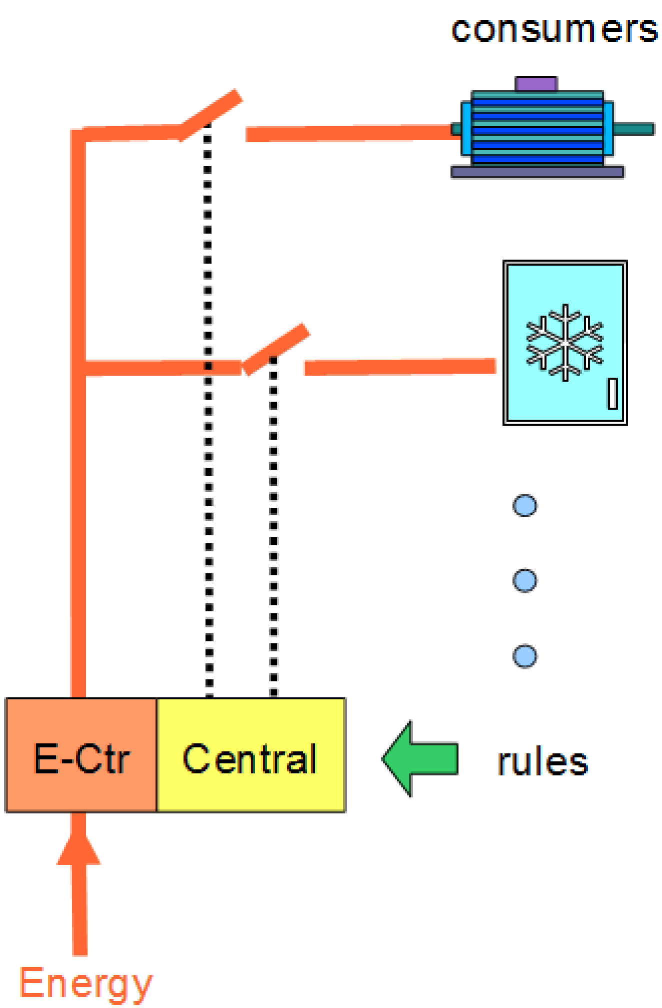




- Example: Software agent for price-dependent operations
- Variable structure dynamics
- Physics via integrator

Classical Maximum Demand Monitor

- Traditional architecture
- Shed limitations
  - Max twice daily,
  - max 30min,
  - not 8am-10am,...
- Desired load profile
  - Pmax, schedule,...
- 1 Energy meter
- Priorities



Simple rule base

- Billing based on energy within measurement period tp
- Energy trajectory within tp
- Static priorities
- P1>P2>P3
- New goal every tp (15min)