Model Predictive Control for Smart Energy Systems

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CITIES Final Conference
November 9, 2020
ZOOM-DTU, Denmark

DTU Compute
Department of Applied Mathematics and Computer Science

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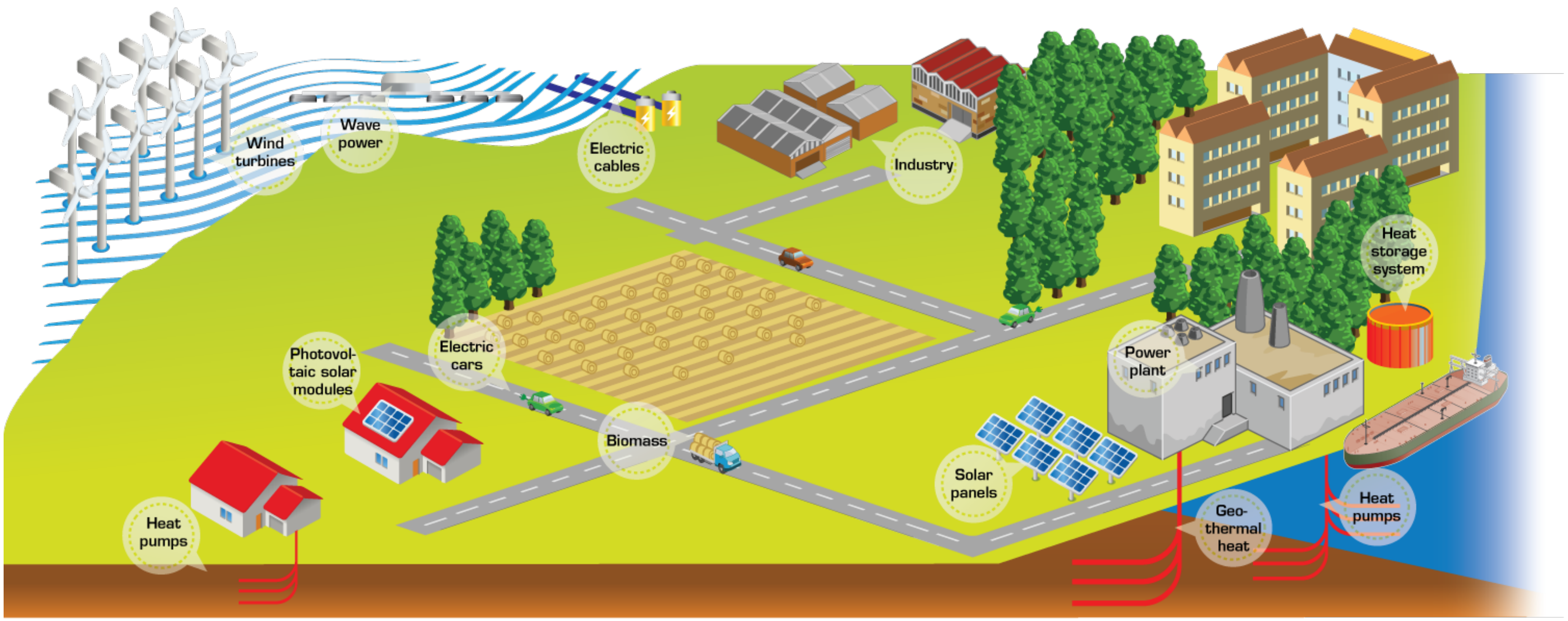
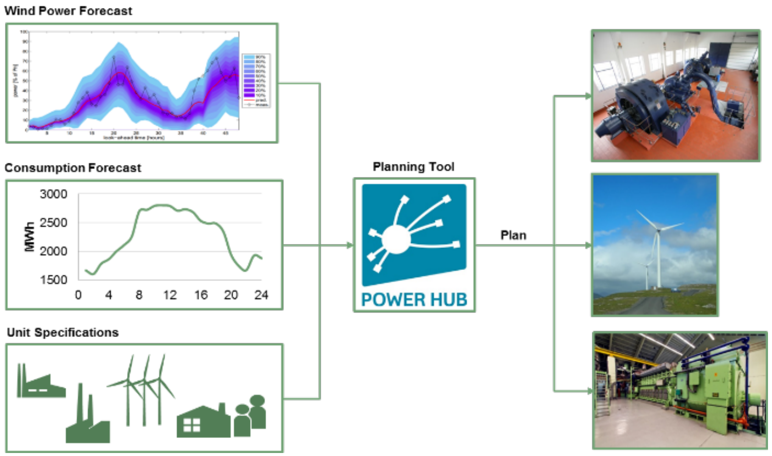
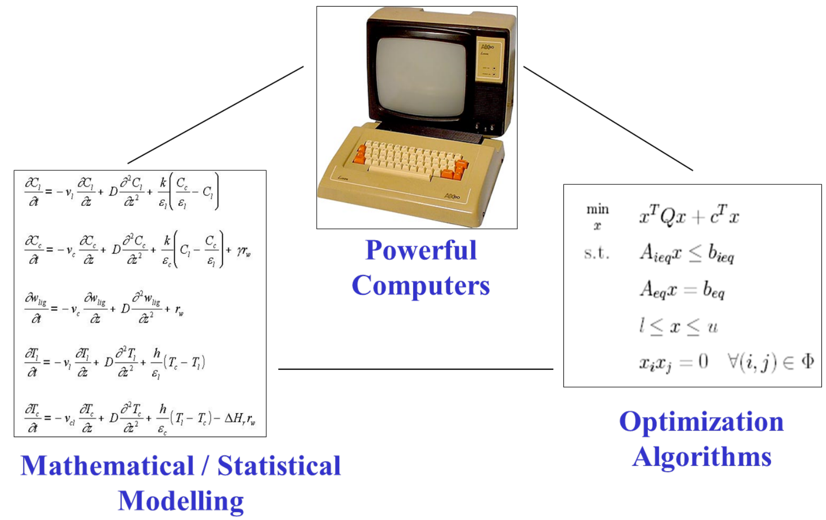
Smart Cities Accelerator

The Vision of Energy-Smart Cities / Municipalities

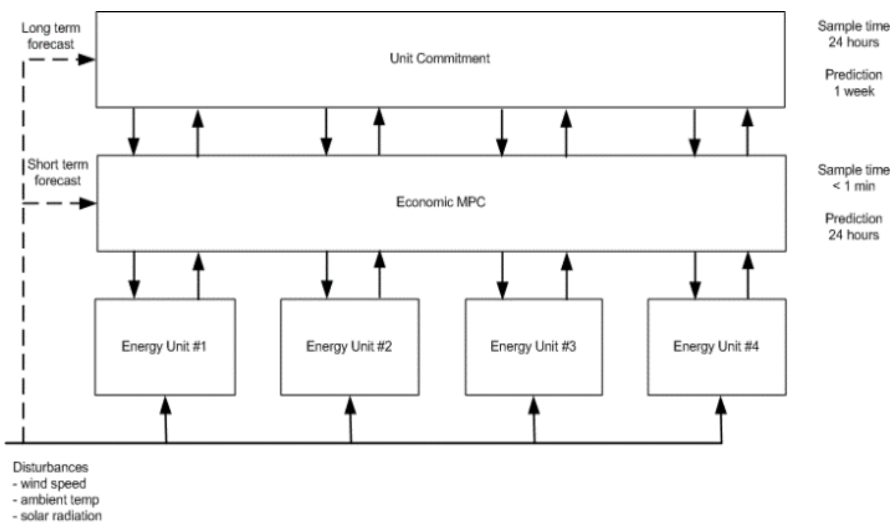


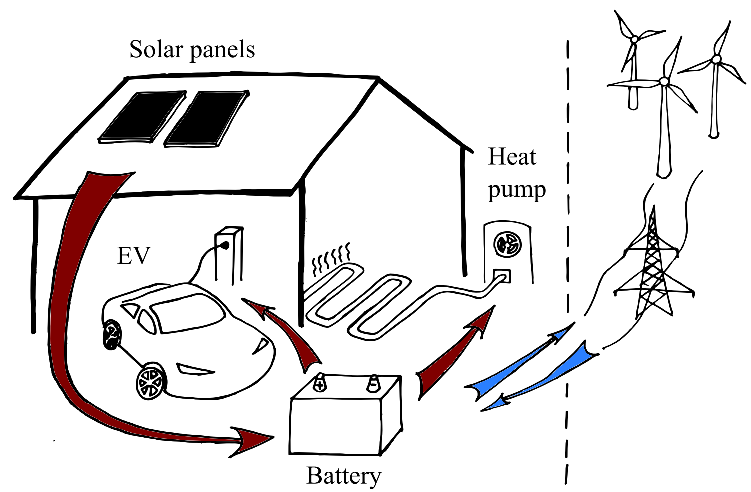
Optimization based control
= Model Predictive Control (MPC)





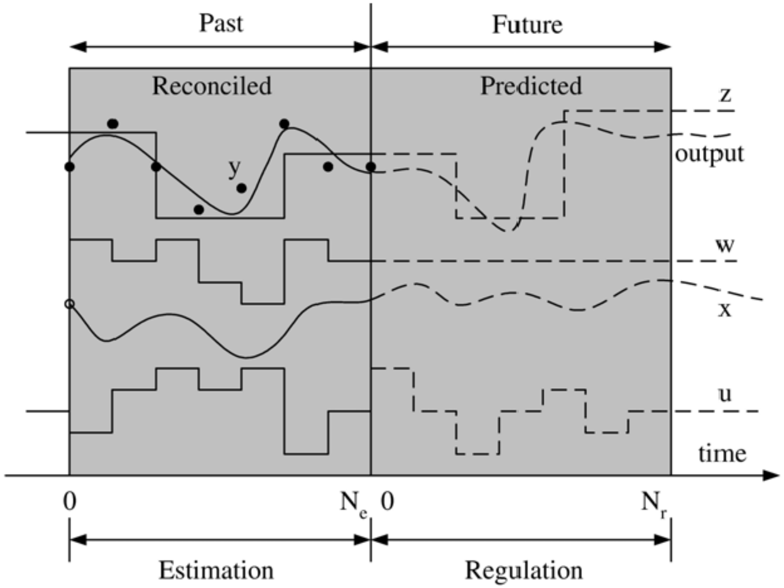
Hierarchical Control Structure

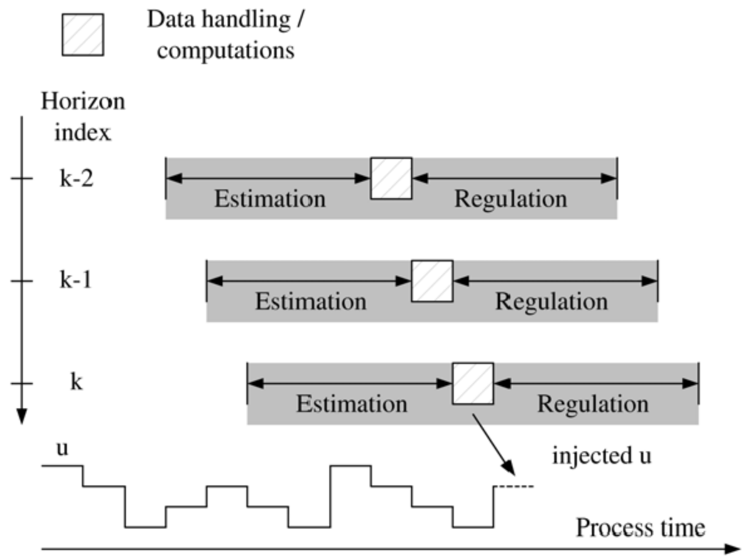




Digitalization, Control and Optimization of Smart Coordinated Energy Systems

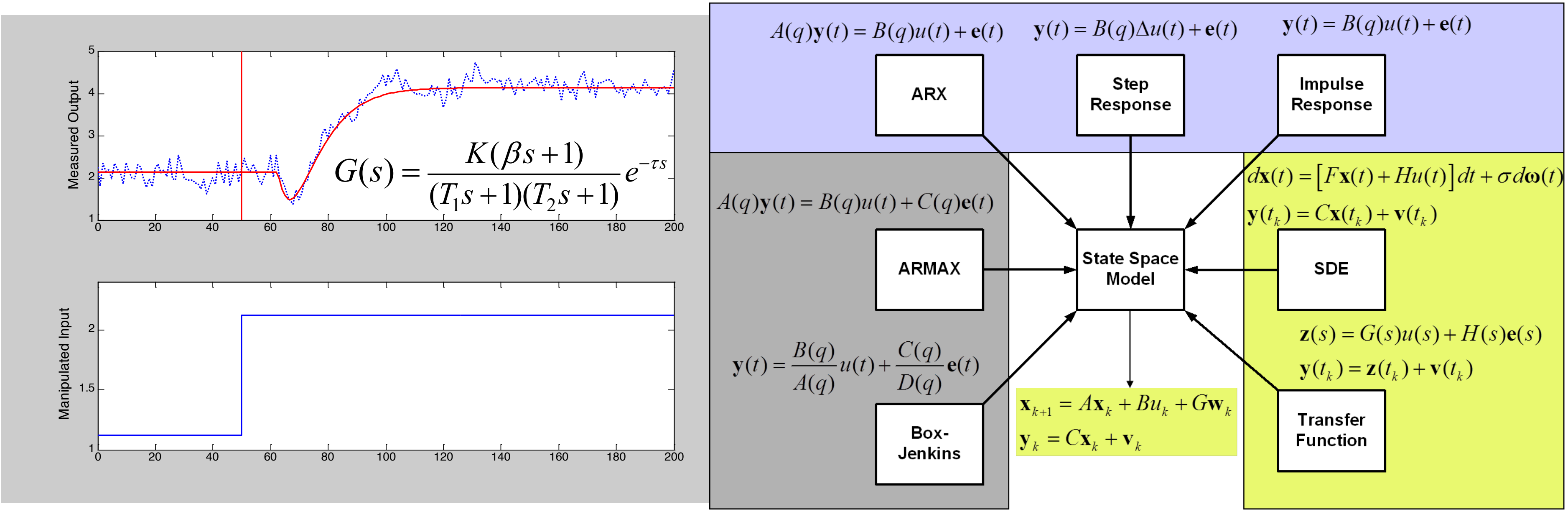
Model Predictive Control





$$
\begin{aligned}
\min_{\{u_k, x_{k+1}\}_{k=0}^{N-1}} \quad & \phi = \phi(\{u_k, x_{k+1}\}_{k=0}^{N-1}; x_0, \theta) \\
s.t. \quad & x_{k+1} = F_k(x_k, u_k, \theta) \qquad k = 0, 1, \ldots, N-1 \\
& u_k \in \mathcal{U}
\end{aligned}
$$

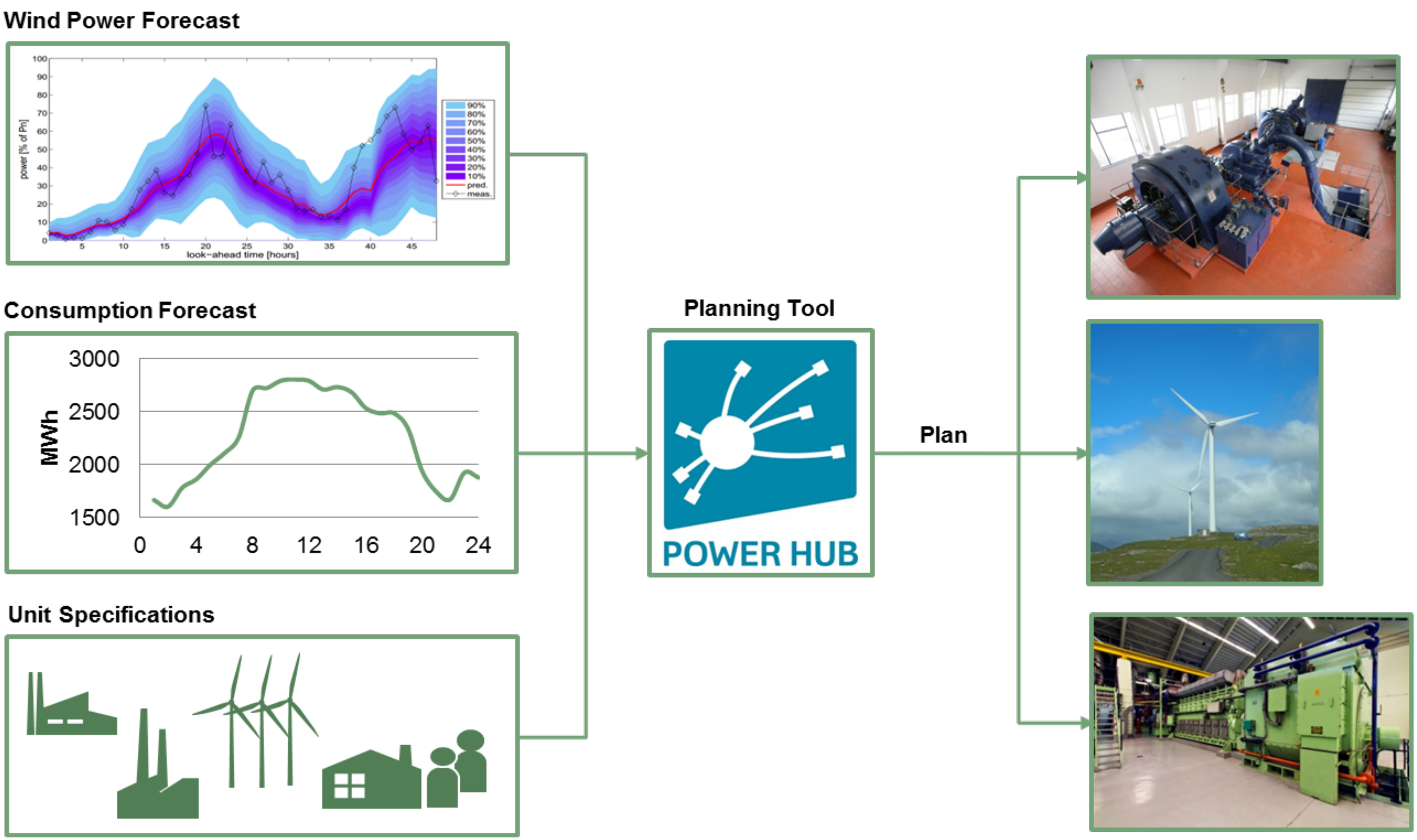
Data based prediction models



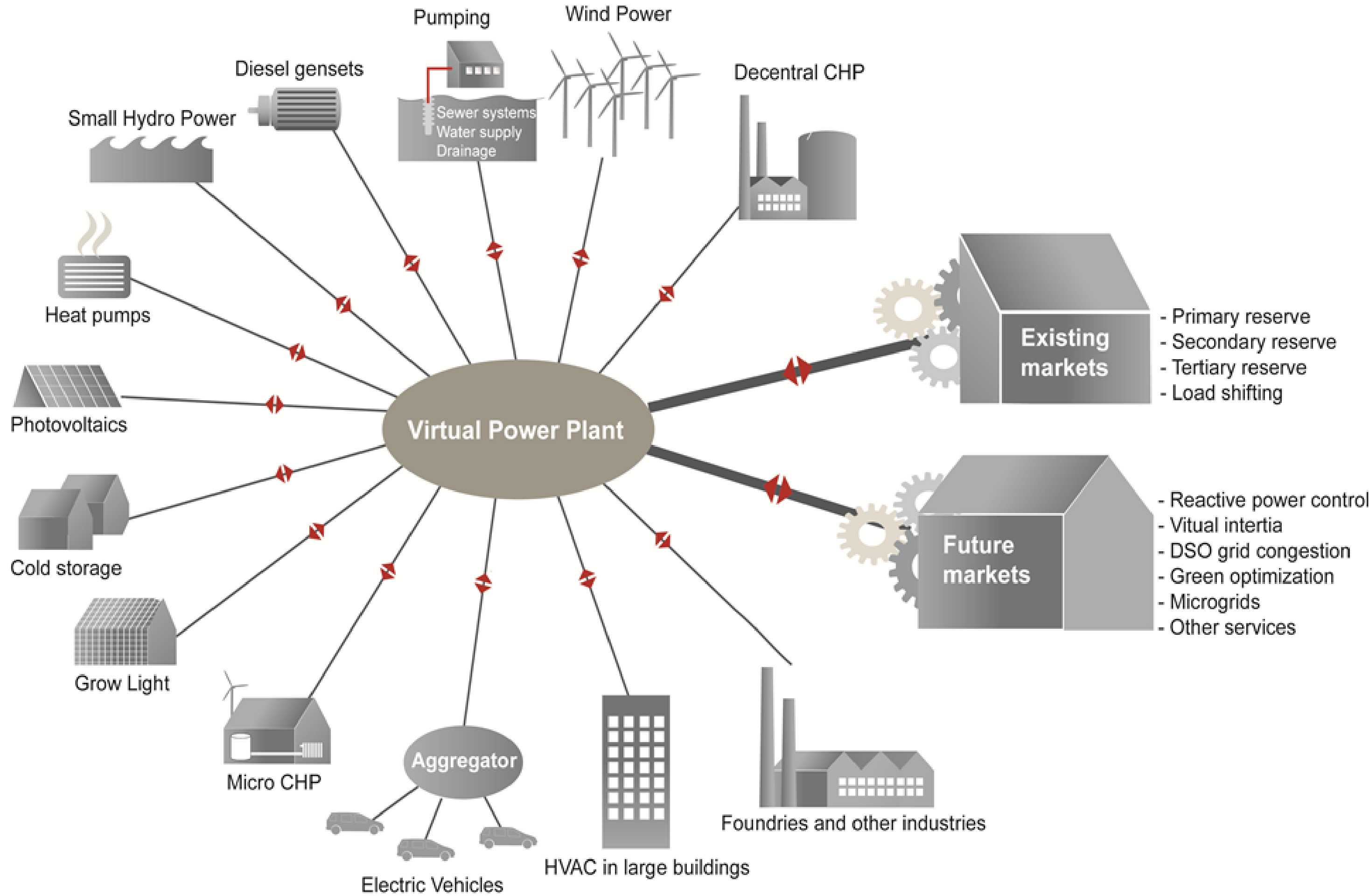
The models for filtering and prediction are

- Adaptive
- Data-based
- Combines a-priori (model) and a-posterior (data) information
- Able to predict the mean values and the uncertainties

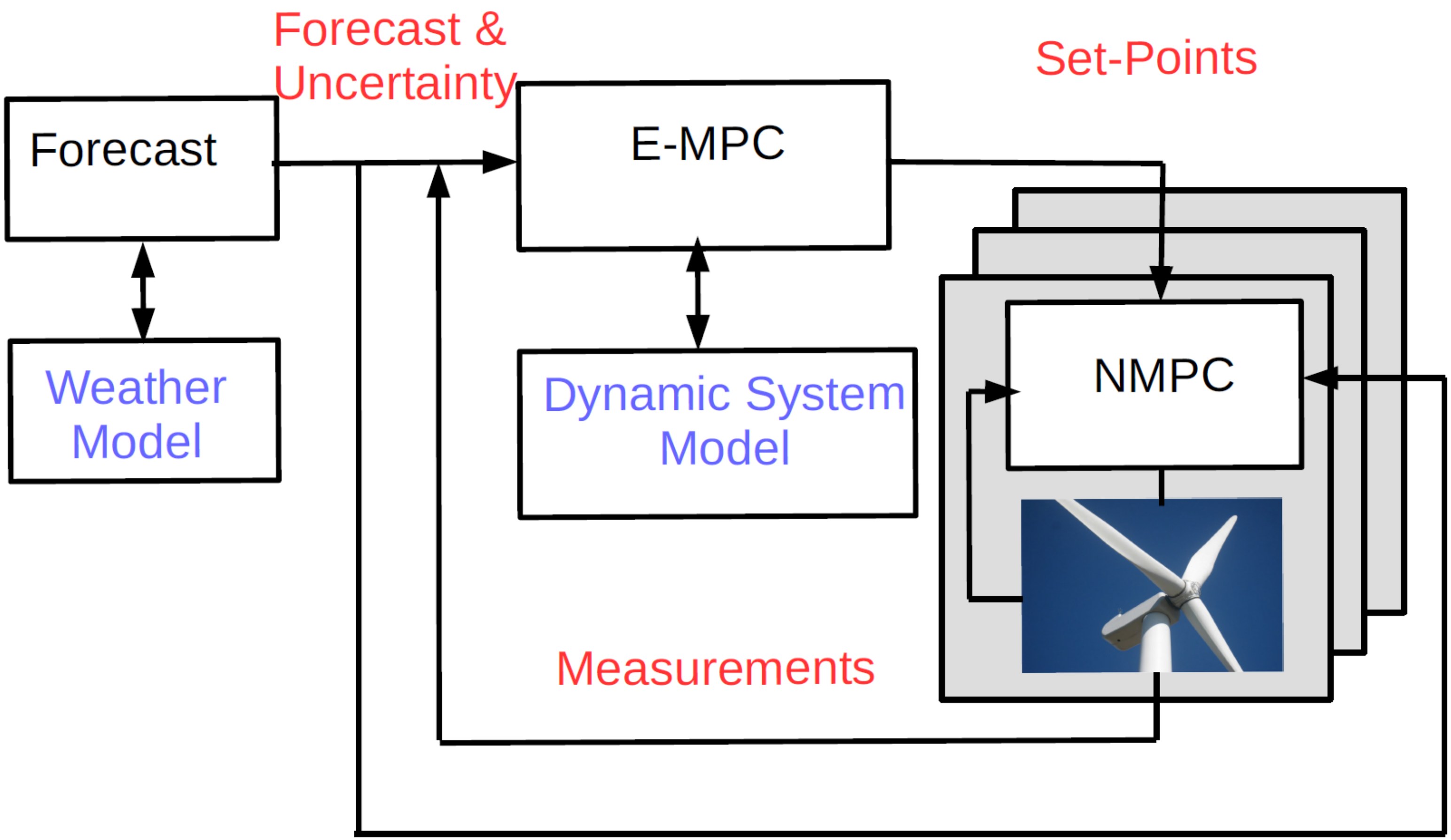
Control of Energy-Smart Systems
= Economic Model Predictive Control



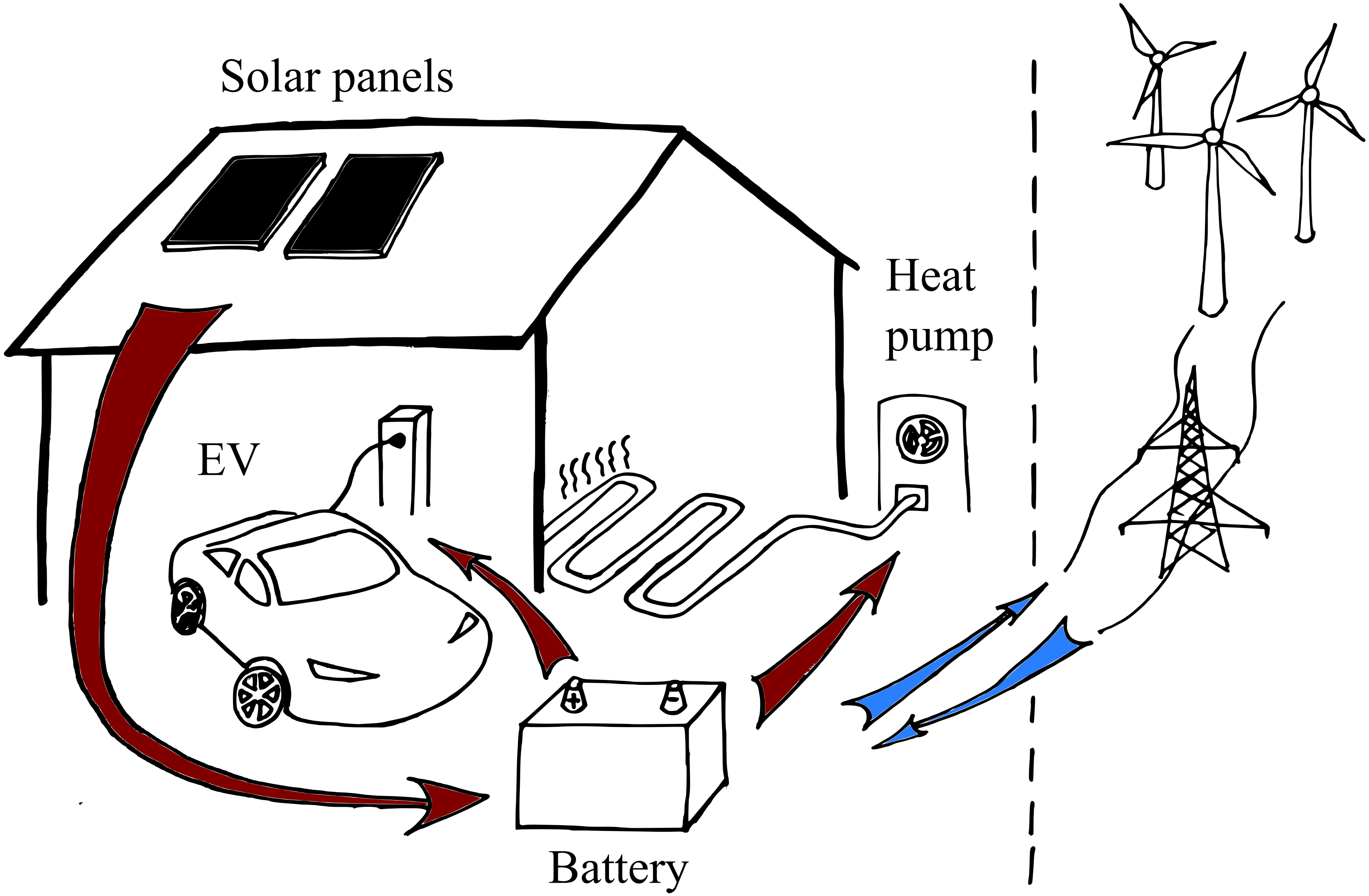
Virtual Power Plant



Forecast Based Hierarchical MPC

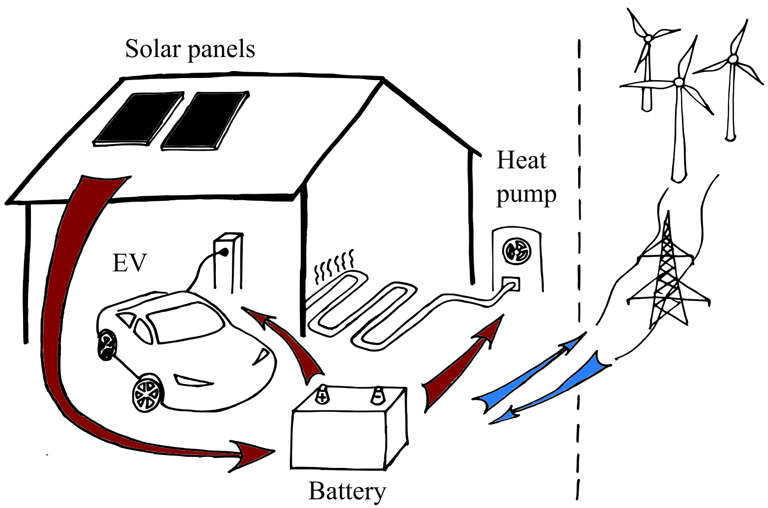


The Vision of Energy-Smart Homes



Elon Musk’s vision of an energy-smart home

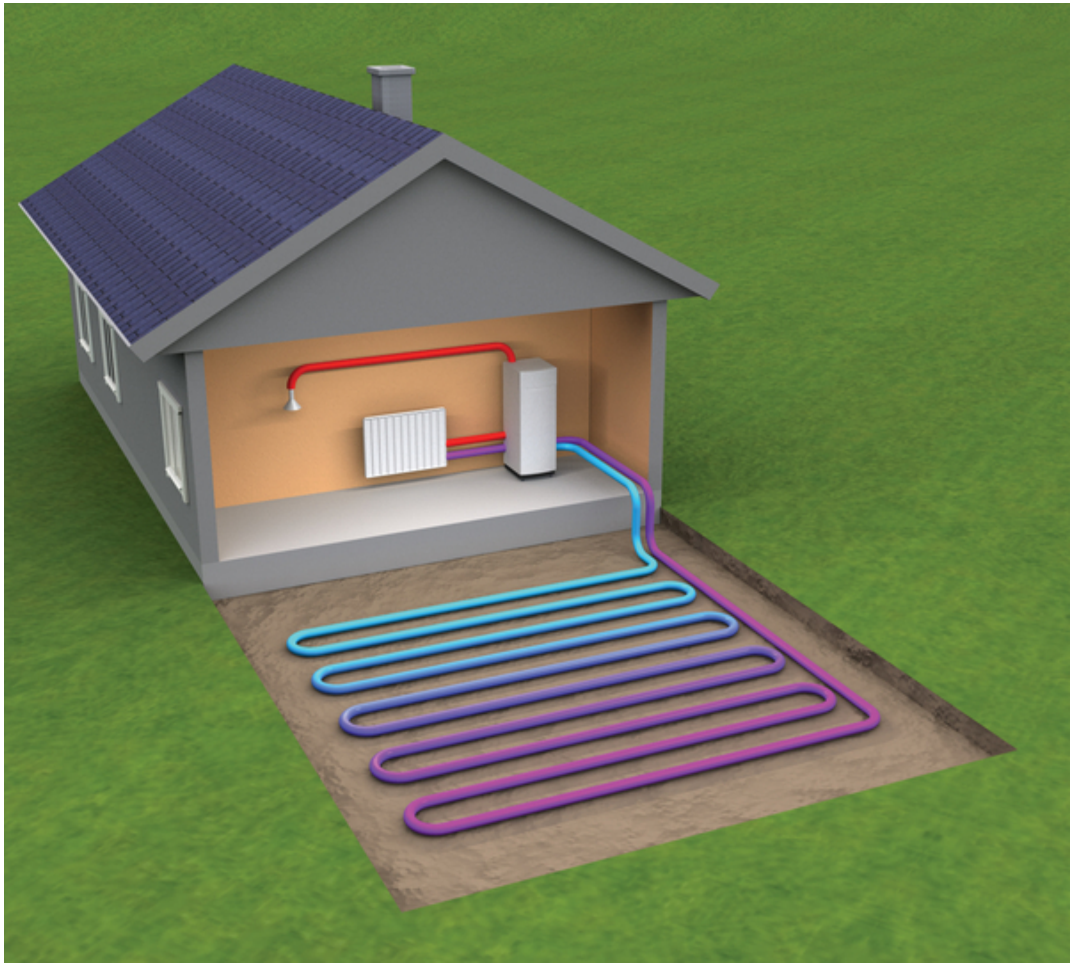
Scientific advances in Economic MPC to enable smart energy homes



Economic MPC for Smart Energy Homes – a number of scientific advances

- Multi-level soft constraints
- Cost-to-go function – value of energy stored at the end of the prediction horizon
- A simple model for simulation, control and optimization of such systems
- Efficient algorithms and computational technologies

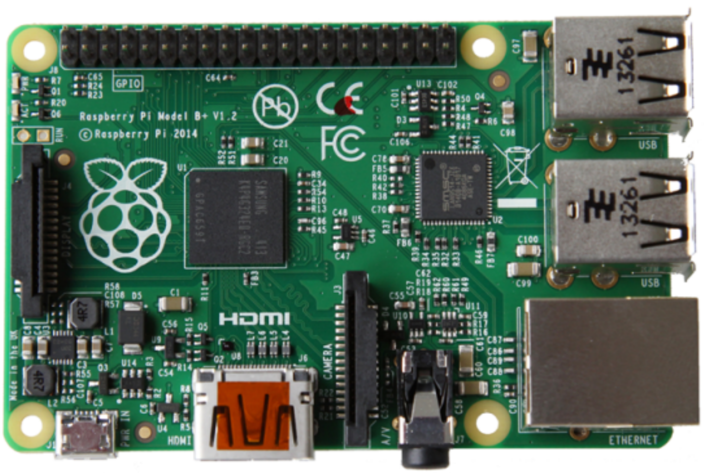
Heat Pumps



Smart Energy Consumption in a Residential Home

Raspberry Pi Embedded Control

Embedded MPC Algorithms for control of individual energy units



$$\min_{\{u_k, x_{k+1}\}_{k=0}^{N-1}} \quad \phi = \sum_{k=0}^{N-1} l_k(x_k, u_k) + l_N(x_N) \qquad \text{(1a)}$$

$$s.t. \quad x_{k+1} = A_k x_k + B_k u_k + b_k \quad k \in \mathcal{N} \qquad \text{(1b)}$$

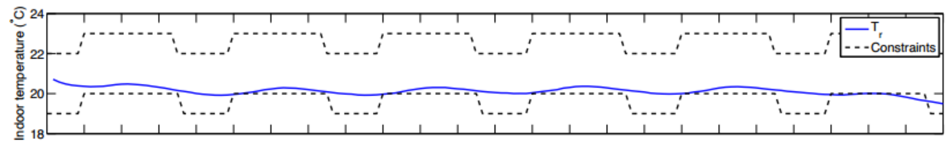
with $\mathcal{N} = \{0, 1, \ldots, N-1\}$ and stage costs defined by

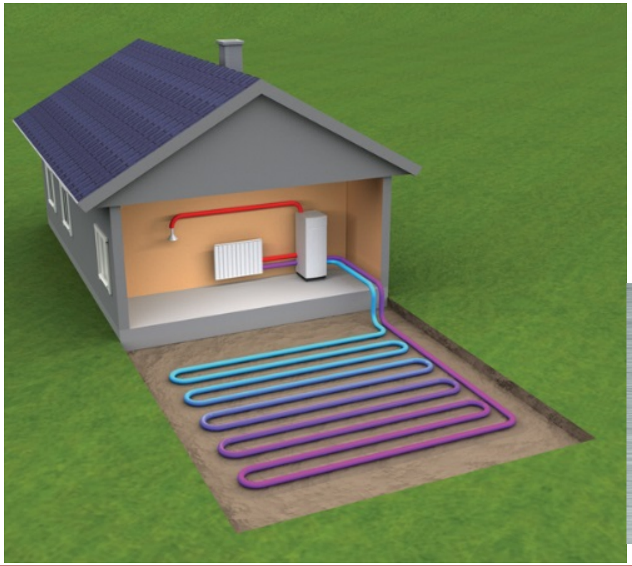
$$l_k(x_k, u_k) = \frac{1}{2} \begin{bmatrix} x_k \\ u_k \end{bmatrix}' \begin{bmatrix} Q_k & M_k' \\ M_k & R_k \end{bmatrix} \begin{bmatrix} x_k \\ u_k \end{bmatrix} + \begin{bmatrix} q_k \\ s_k \end{bmatrix}' \begin{bmatrix} x_k \\ u_k \end{bmatrix} + \rho_k \qquad \text{(2a)}$$

$$l_N(x_N) = \frac{1}{2} x_N' P_N x_N + p_N' x_N + \gamma_N \qquad \text{(2b)}$$

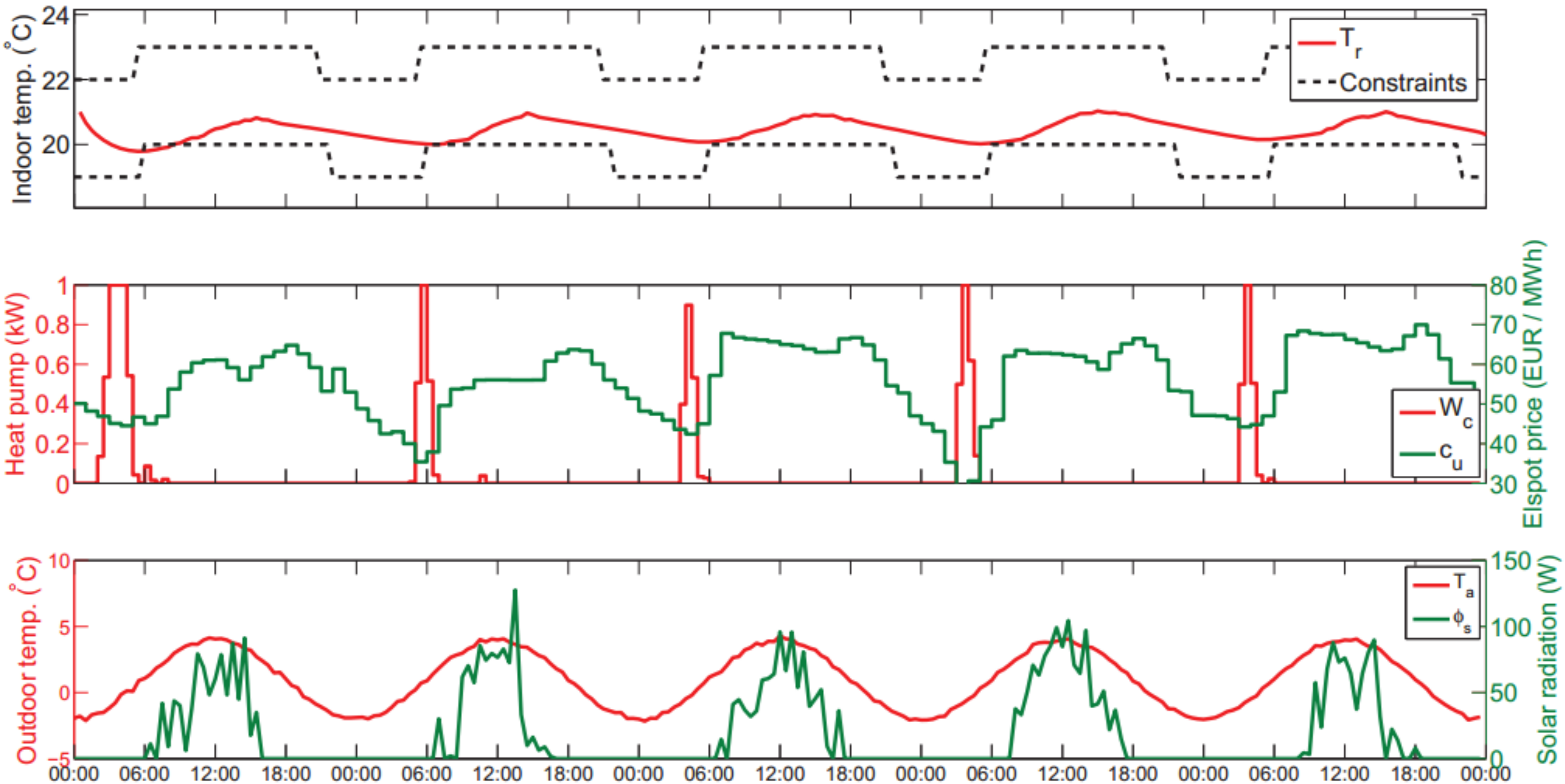
Control from the cloud

The control and forecasting systems are in the cloud.

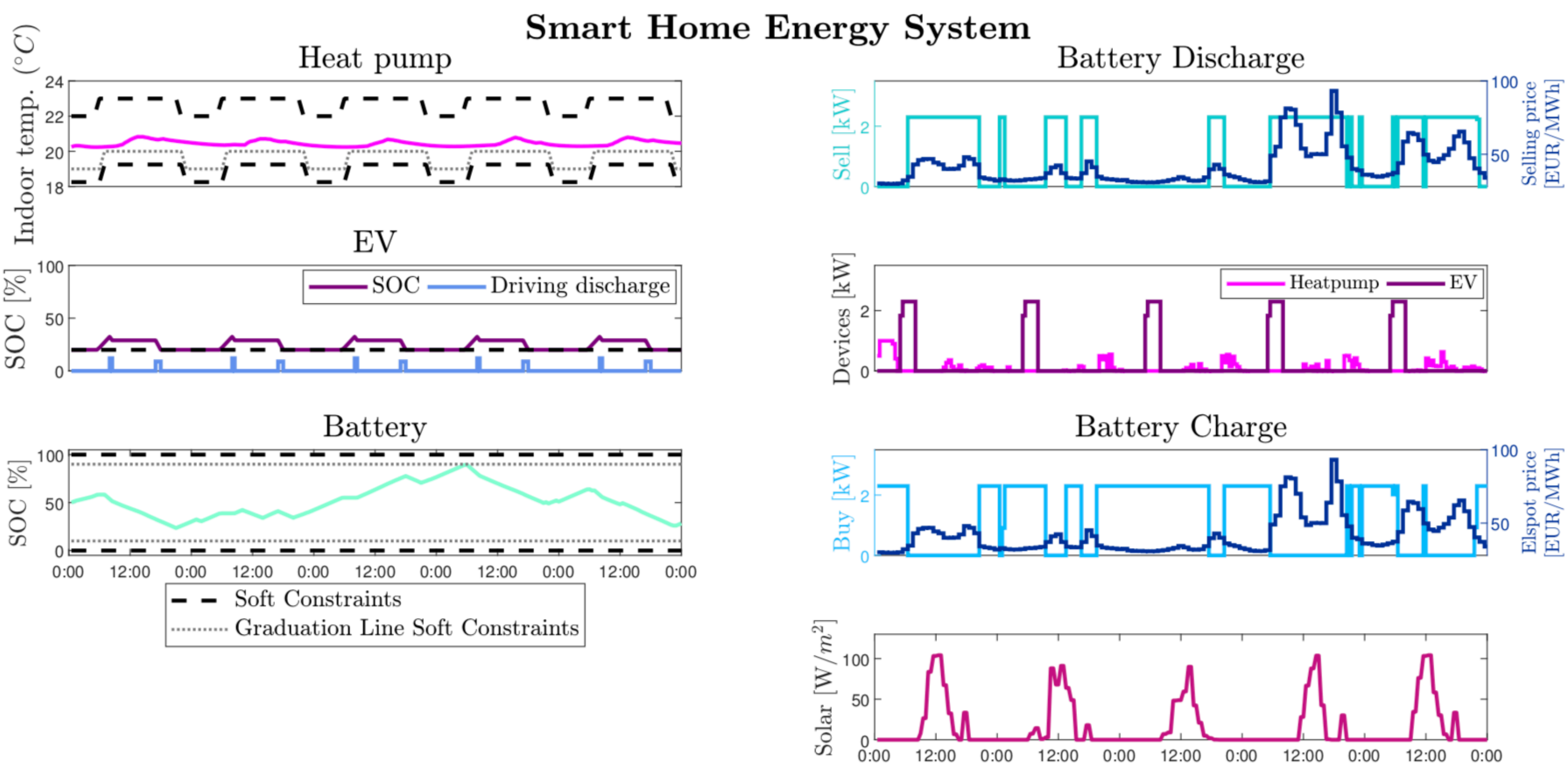




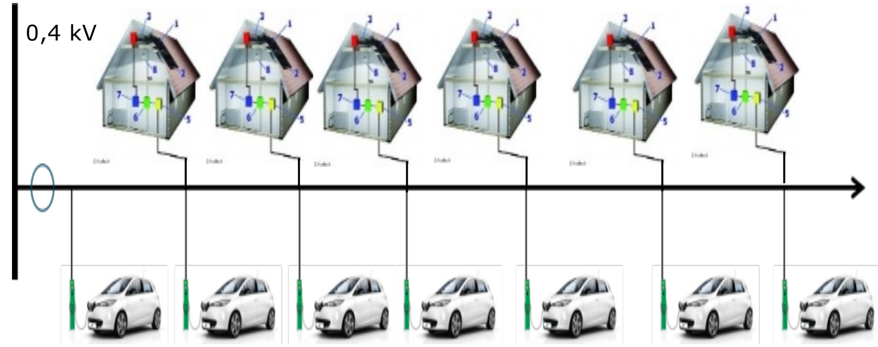
Economic MPC for Building Climate Control

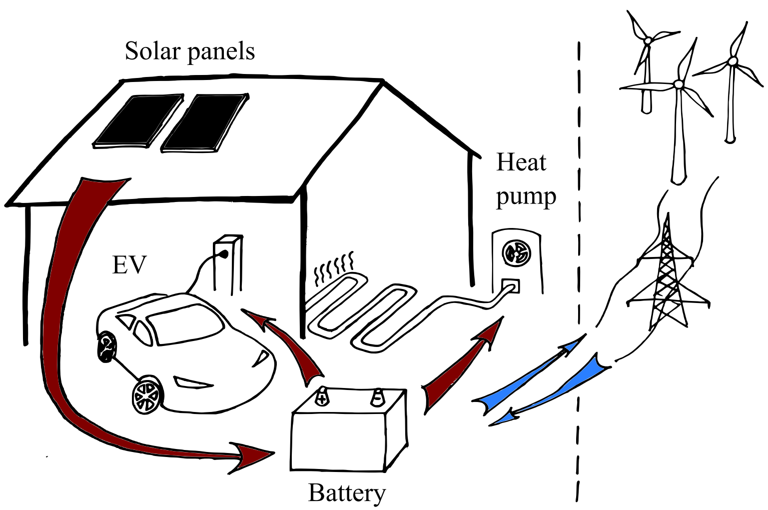


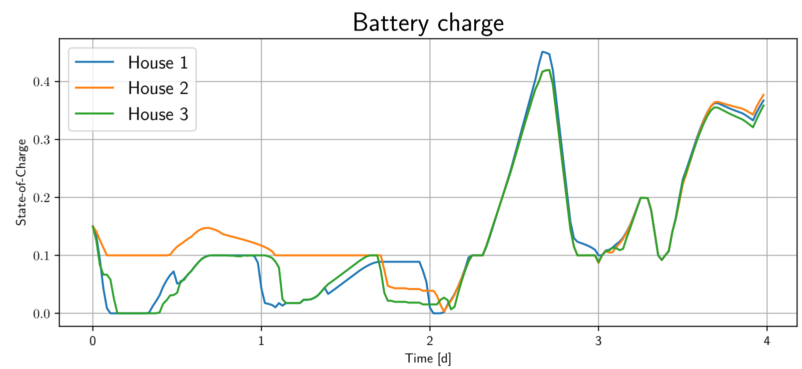
Model Predictive Control for a Smart Energy Home – Simulation Results

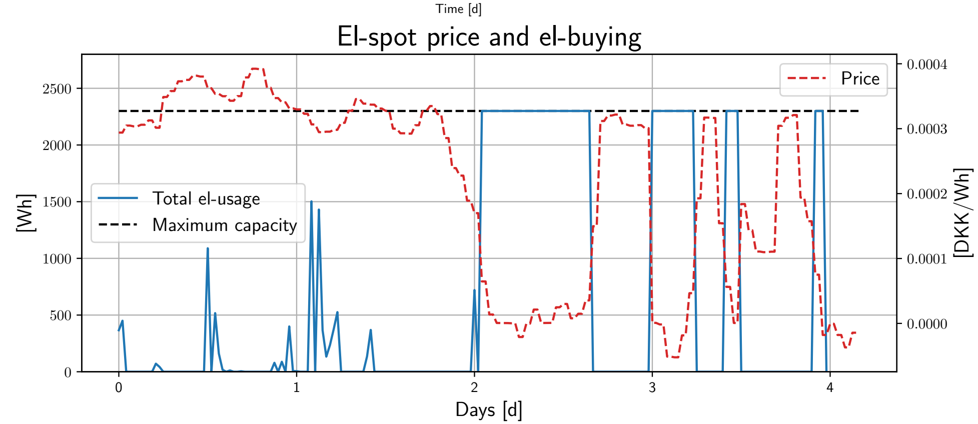


A neighborhood of smart energy homes - Lærkevej

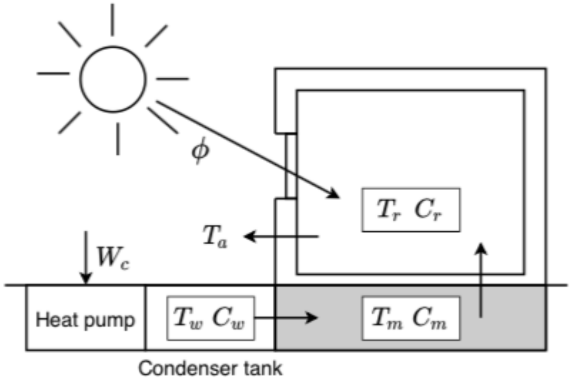






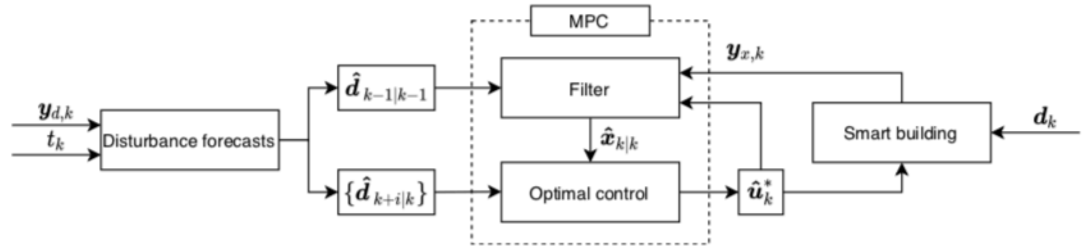


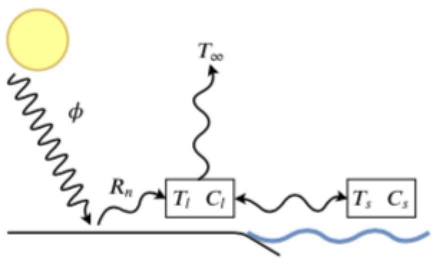
Advanced forecasting and predictive control

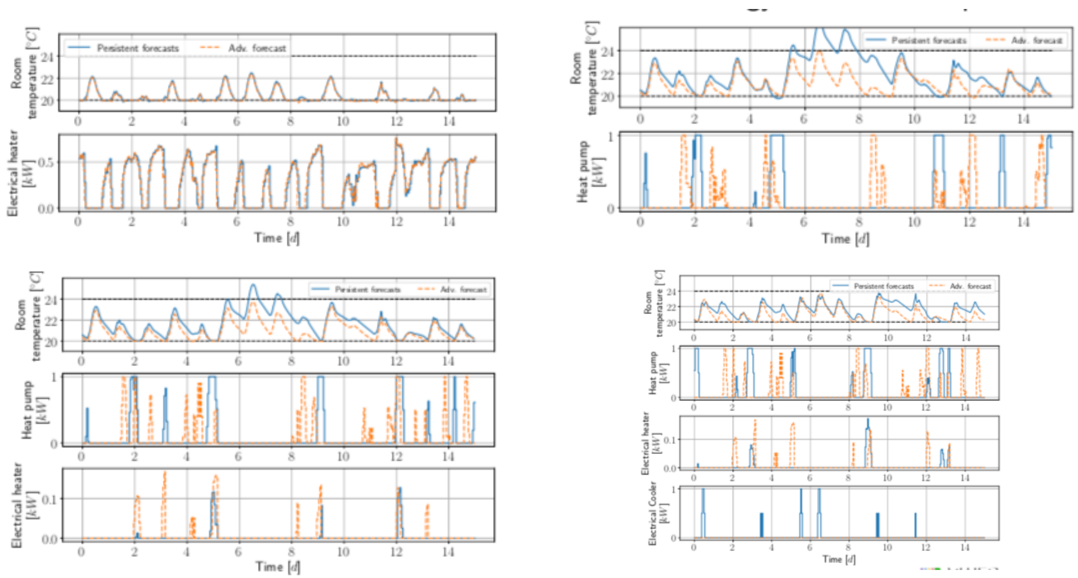


$$\mathrm{d}x(t) = \underbrace{f(x(t), u(t), d(t), t)\mathrm{d}t}_{\text{Drift}} + \underbrace{g(x(t), u(t), d(t), t)\mathrm{d}\omega(t)}_{\text{Diffusion}} ,$$

$$y_k = h(x(t_k)) + v_k , \qquad v_k \sim N(0, R_v) ,$$







$$C_s \mathrm{d}T_s(t) = \left(\frac{1}{R_{sl}}(T_l(t) - T_s(t))\right)\mathrm{d}t + \sigma_s \mathrm{d}\omega_s(t) ,$$

$$C_l \mathrm{d}T_l(t) = \left(\frac{1}{R_{sl}}(T_s(t) - T_l(t)) + \frac{1}{R_{l\infty}}(T_\infty - T_l(t)) + R_n(t)\right)\mathrm{d}t + \sigma_l \mathrm{d}\omega_l(t) ,$$

$$d_{T_a}(t_k) = T_l(t_k) + v_{T_a}(t_k) ,$$

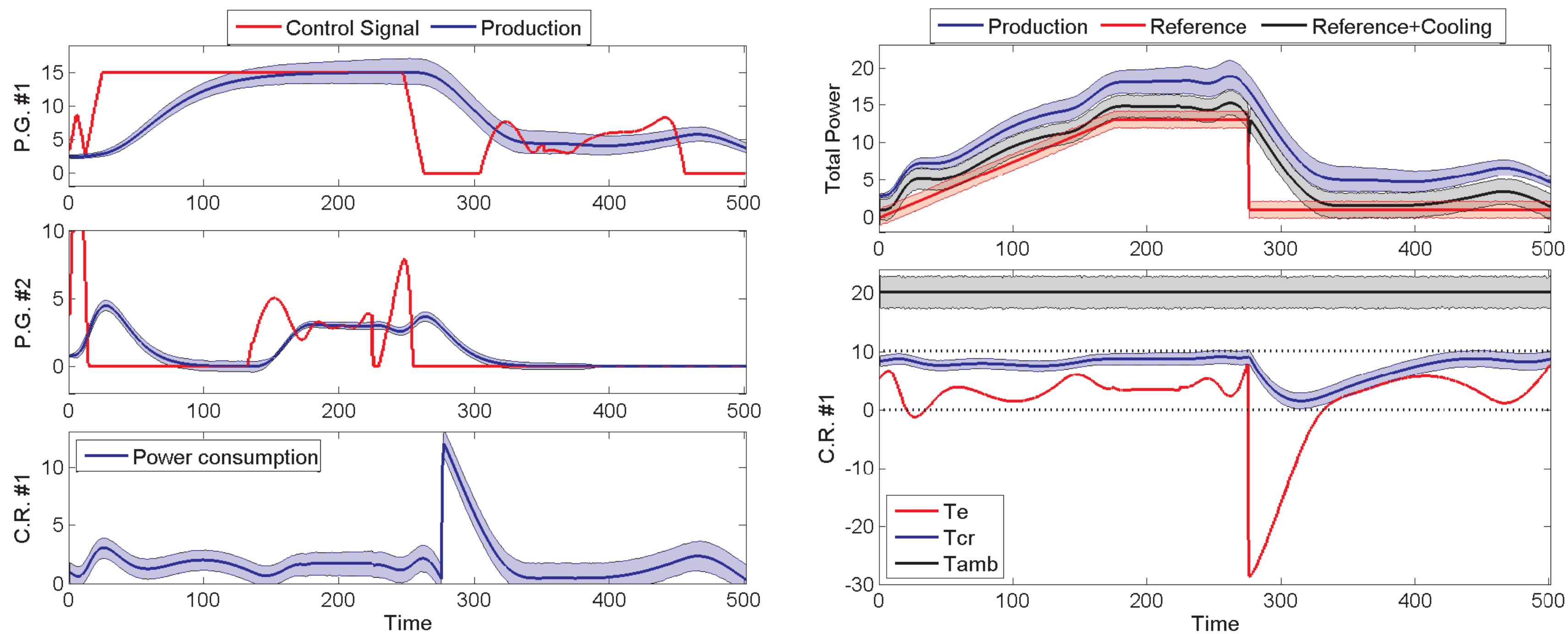
Electricity cost of the simulations

Heating strategy	Persistent	Advanced forecasts	Perfect
Electrical heaters, u_1	303.2	302.2	302.0
Heat pump, u_2	117.3	110.4	107.7
Heat pump plus electrical heaters, $\boldsymbol{u}_3$	113.0	108.2	107.5
Heat pump plus electrical heaters and coolers, $\boldsymbol{u}_4$	117.9	108.3	107.5

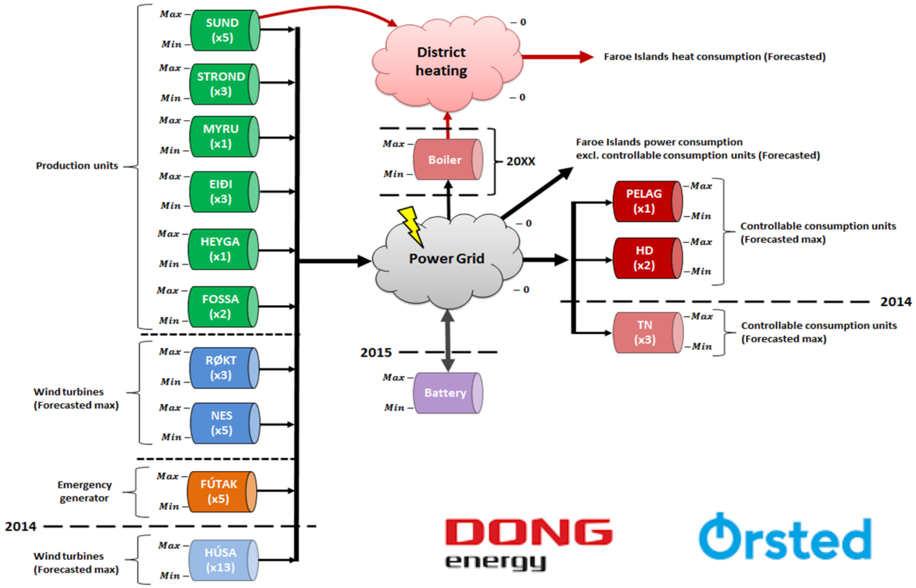
Constraint violation of the control simulations

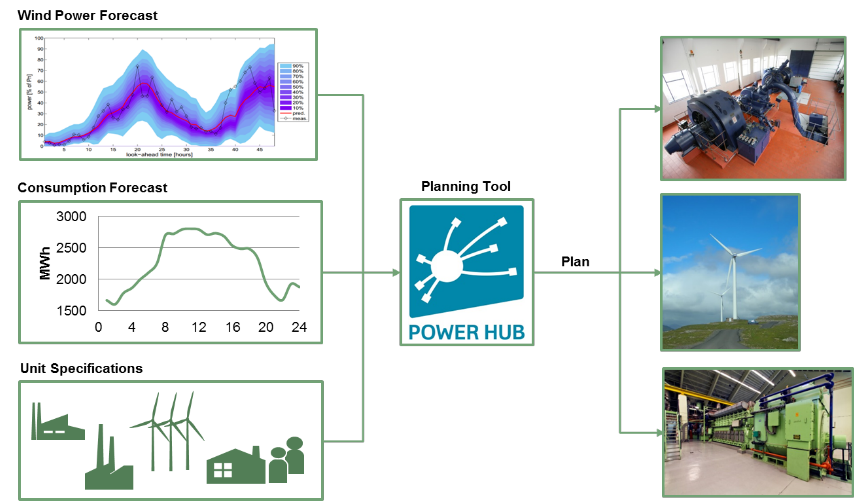
Heating strategy	Persistent	Advanced forecasts	Perfect
Electrical heaters, u_1	48.5	39.6	25.1
Heat pump, u_2	157.9	12.3	1.7
Heat pump plus electrical heaters, $\boldsymbol{u}_3$	48.0	6.7	1.2
Heat pump plus electrical heaters and coolers, $\boldsymbol{u}_4$	4.4	2.4	0

Supermarket Refrigeration – Demand Response

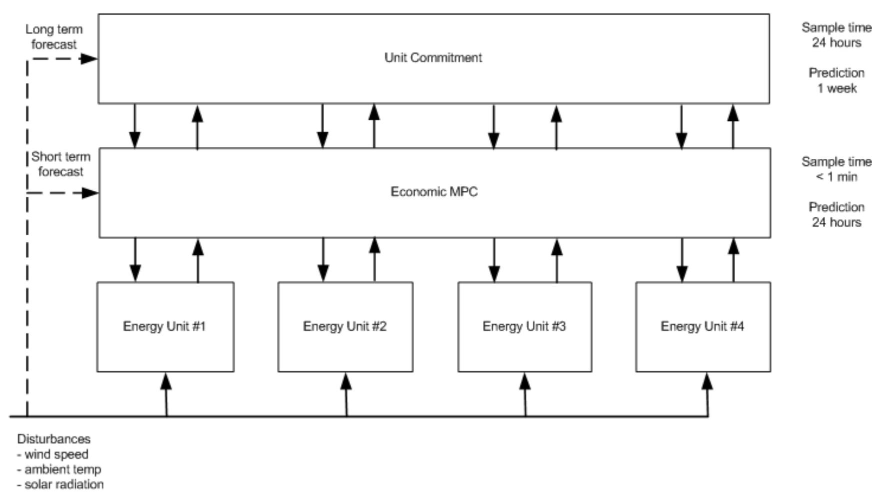


The Faroe Island Power System





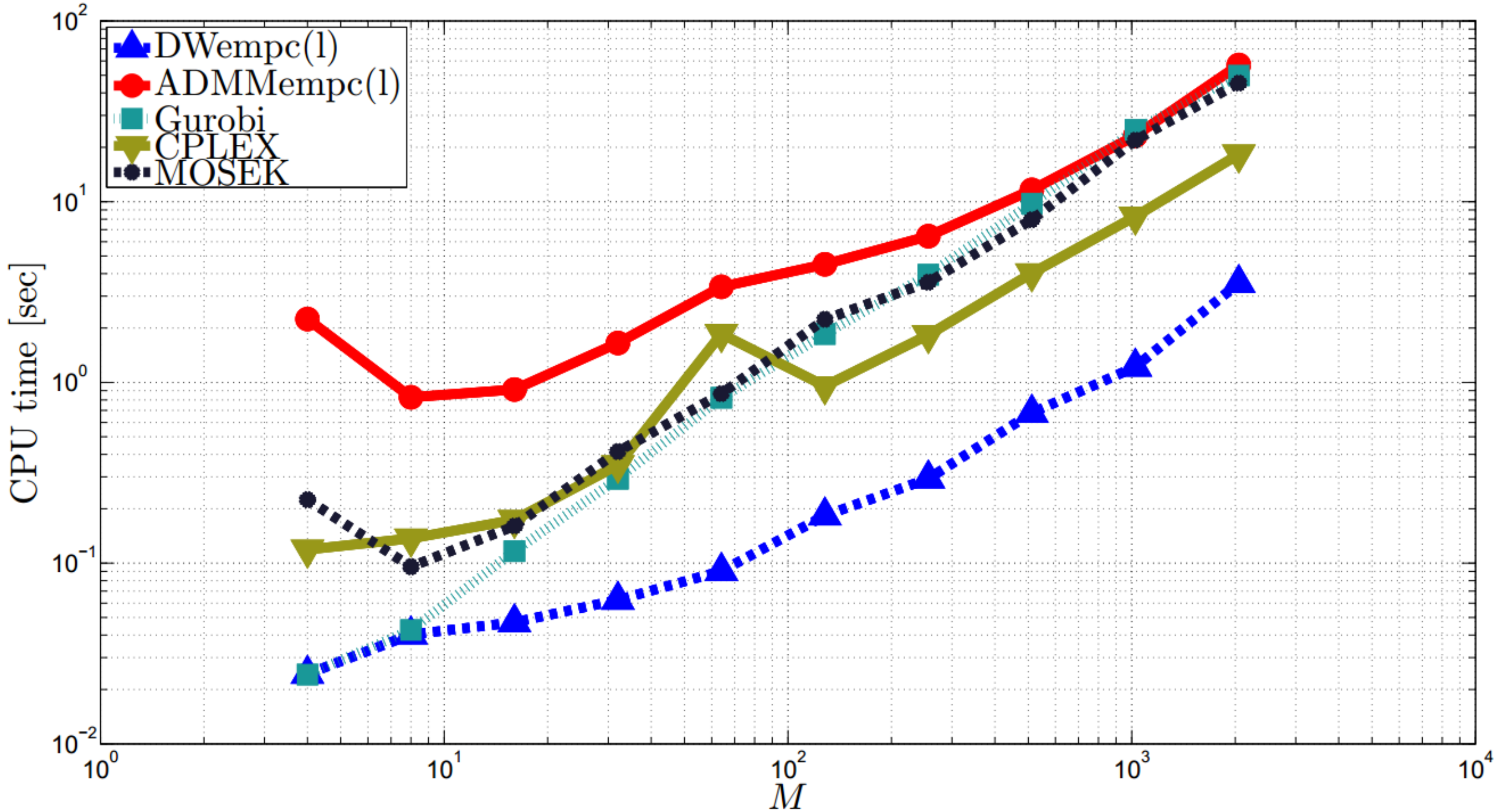
- Controlled the entire Faroe power system for 3 months
- Economic MPC system developed by Orsted (Dong Energy) and DTU Compute as part of an industrial PhD project



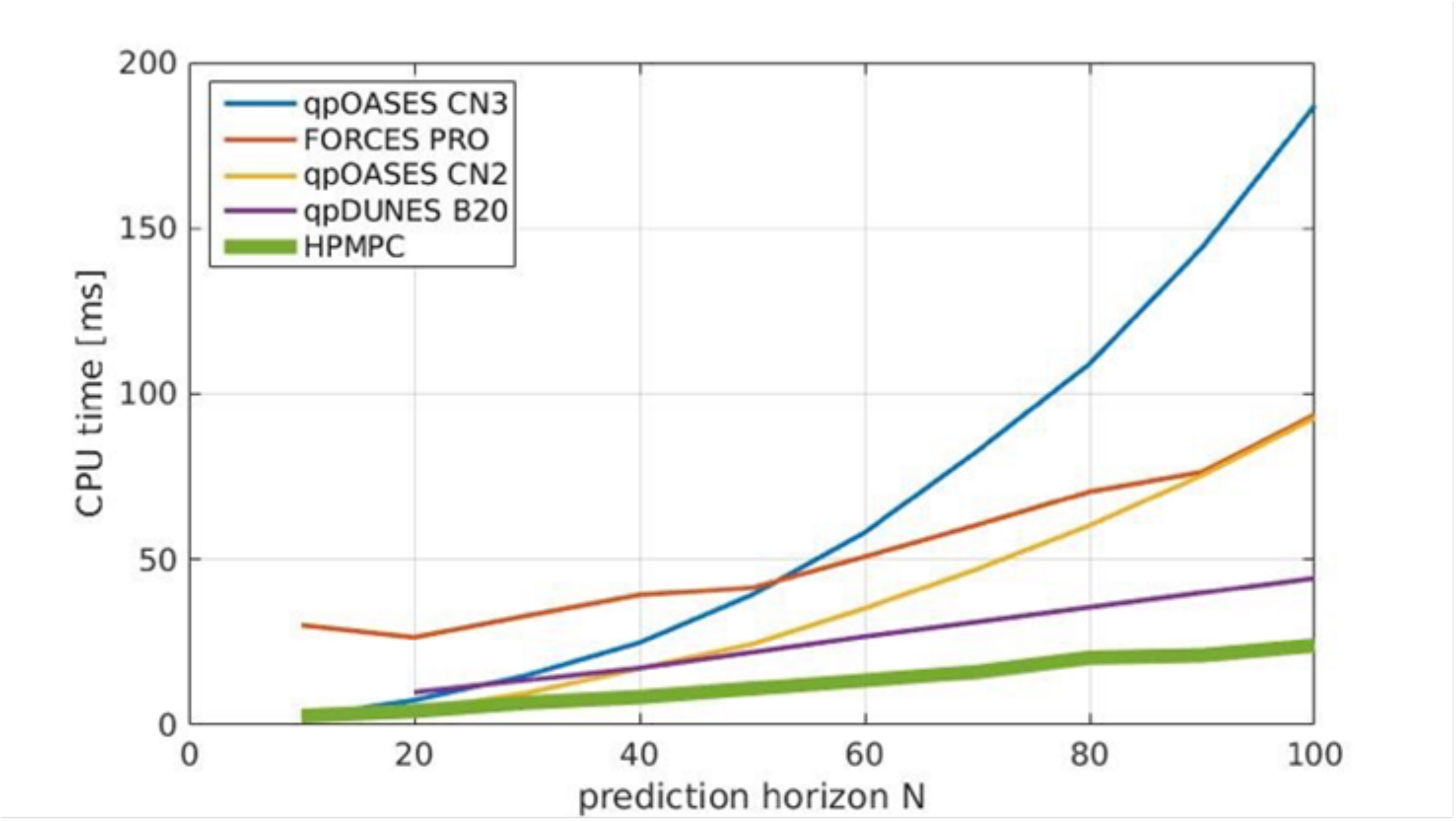
Fast Solver for Direct Control of an Entire City

A Dantzig-Wolfe Decomposition Algorithm for
Linear Economic Model Predictive Control of Dynamically Decoupled Subsystems

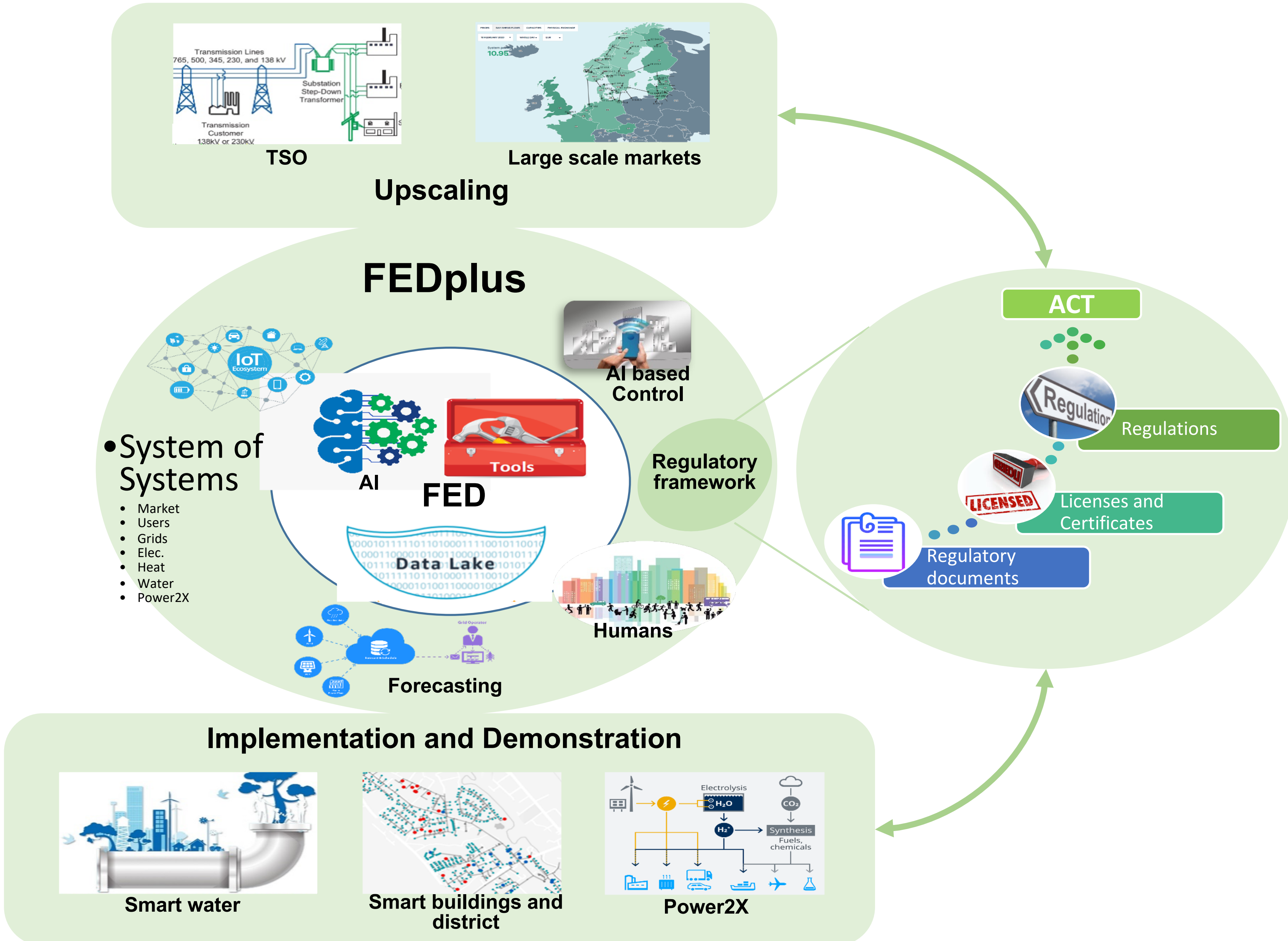
L.E. Sokoler[a,b], L. Standardi[a], K. Edlund[b], N.K. Poulsen[a], H. Madsen[a], J.B. Jørgensen[*,a]



Fast Algorithms for Model Predictive Control - enable new applications

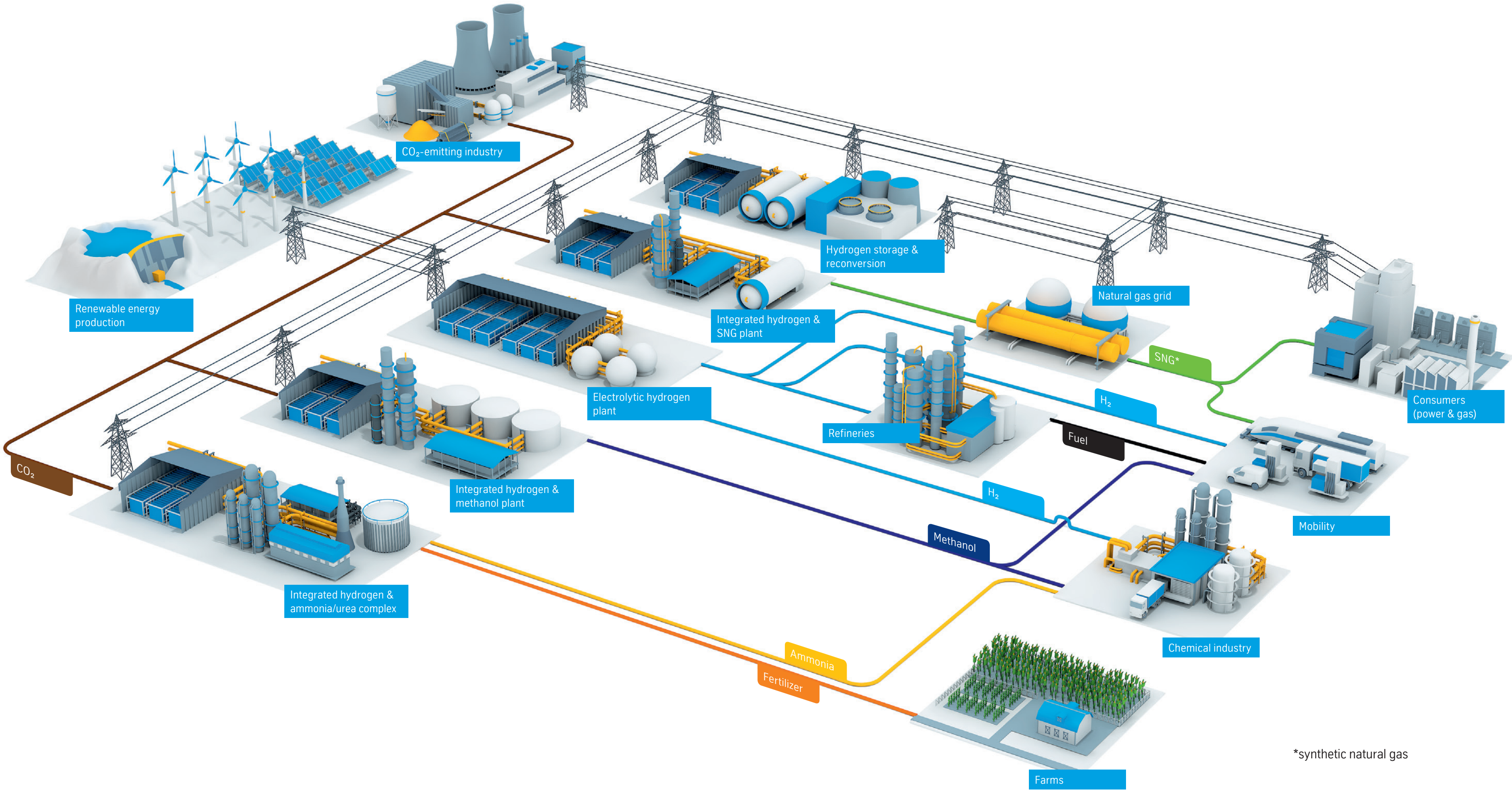


FEDplus



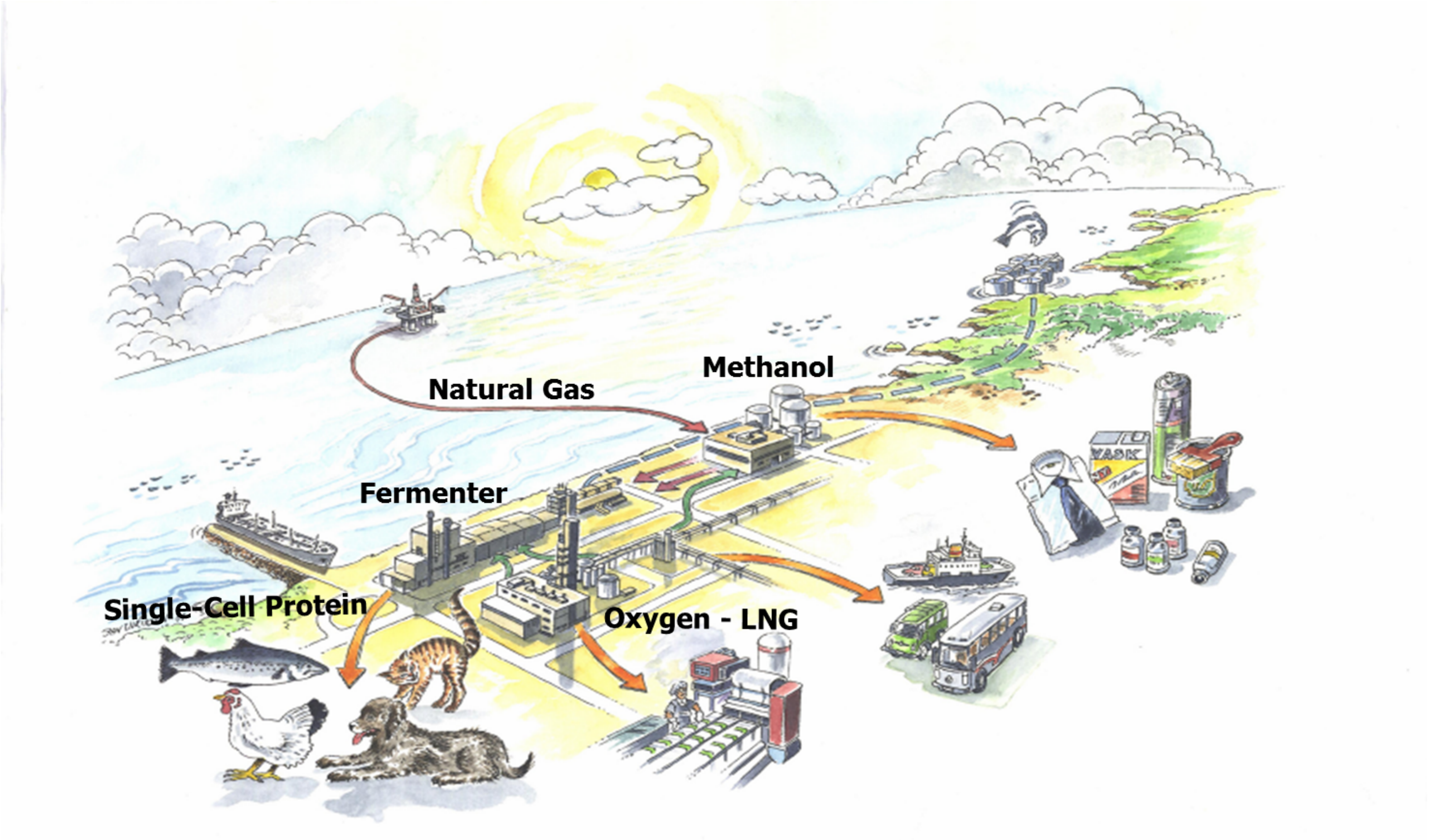
Transmission Lines
765, 500, 345, 230, and 138 kV
Substation
Step-Down
Transformer
Transmission
Customer
138kV or 230kV
TSO
Large scale markets
Upscaling
FEDplus
IoT
Ecosystem
AI based
Control
•System of
Systems
Market
Users
Grids
Elec.
Heat
Water
Power2X
AI
Tools
FED
Data Lake
Regulatory
framework
Humans
Forecasting
ACT
Regulation
Regulations
LICENSED
Licenses and
Certificates
Regulatory
documents
Implementation and Demonstration
Smart water
Smart buildings and
district
Electrolysis
H₂O
CO₂
H₂
Synthesis
Fuels,
chemicals
Power2X

Power-2-X

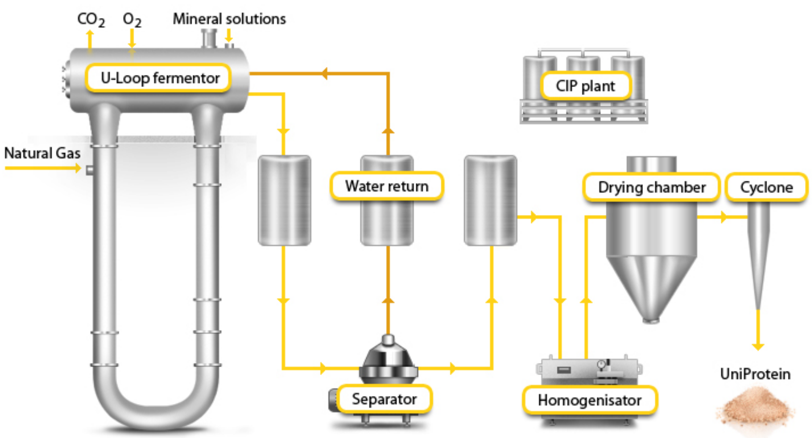


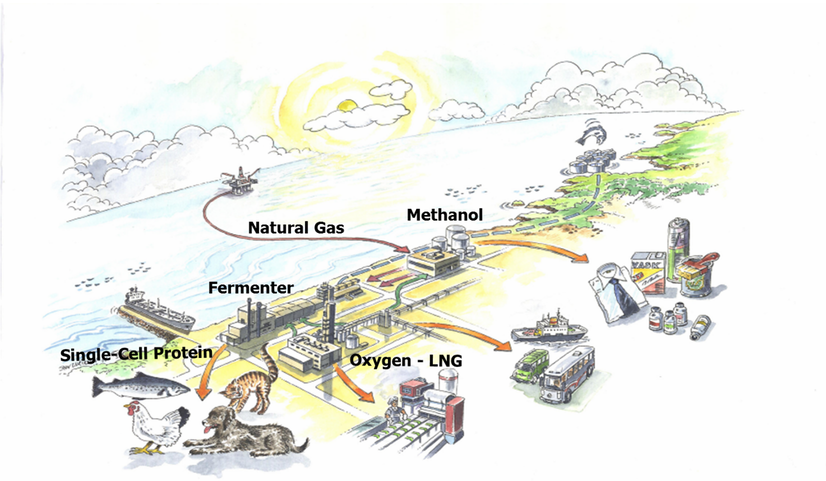
*synthetic natural gas

Proteins from methane
- natural gas, biogas, SNG

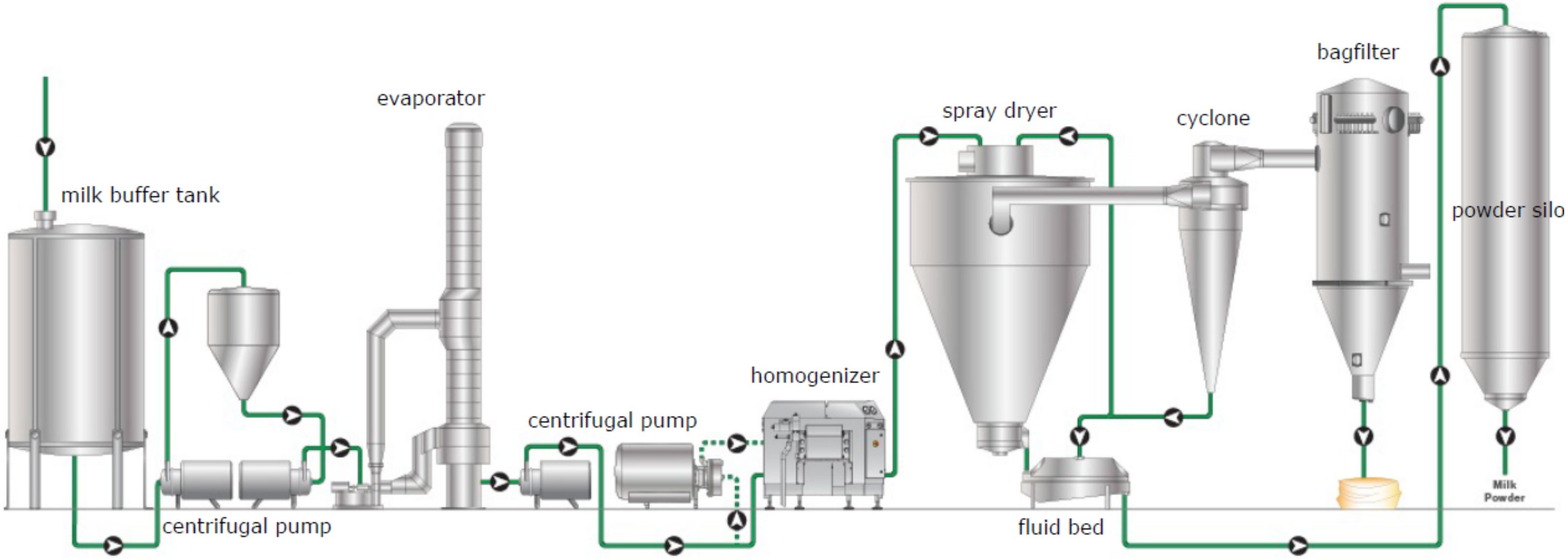


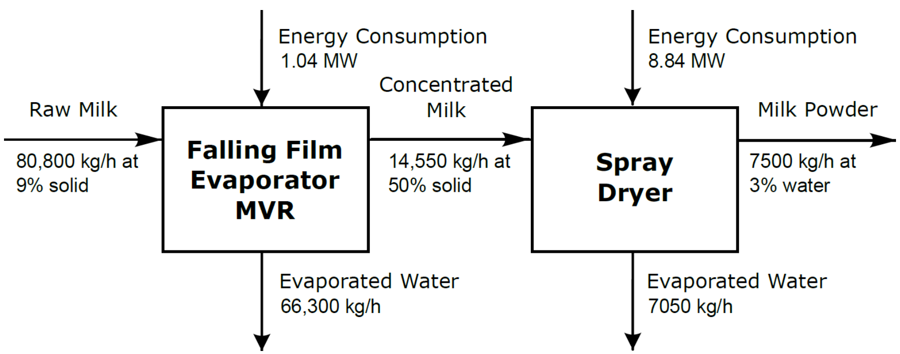
Single-Cell Protein – Unibio A/S

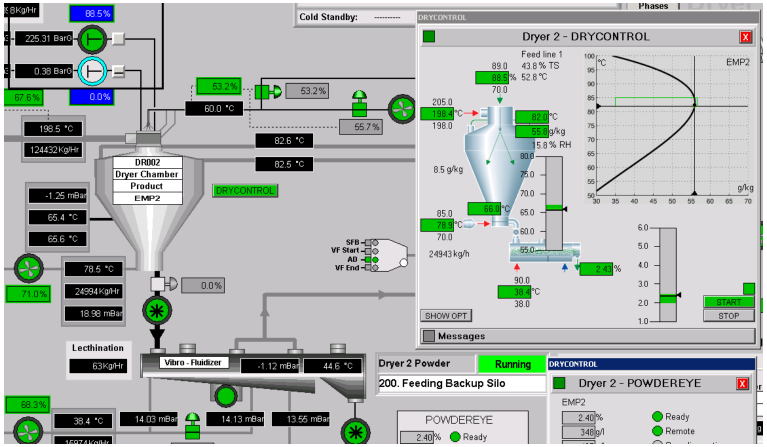




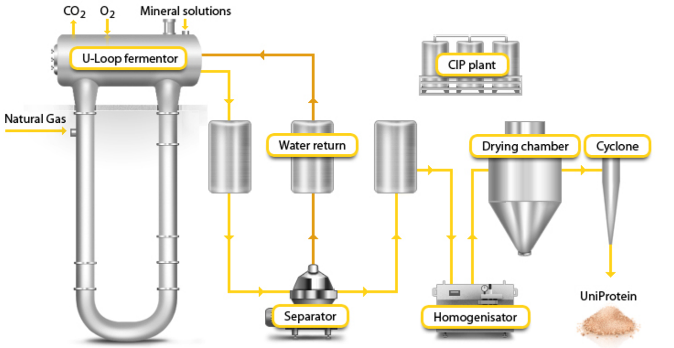
Milk Powder Plant – GEA Process Engineering A/S

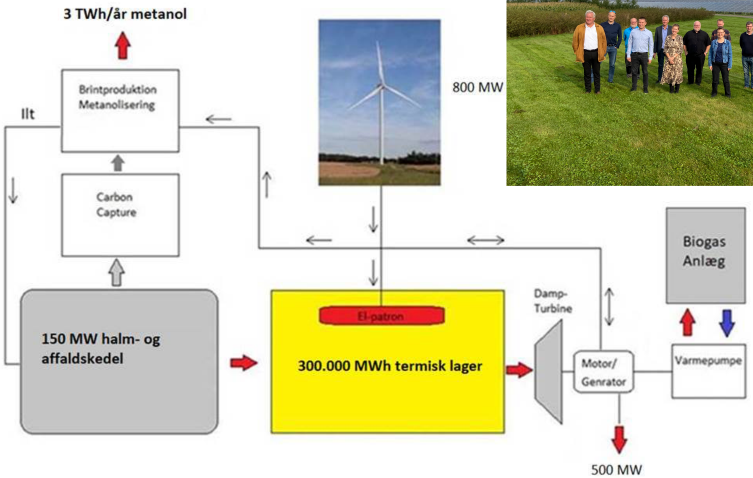


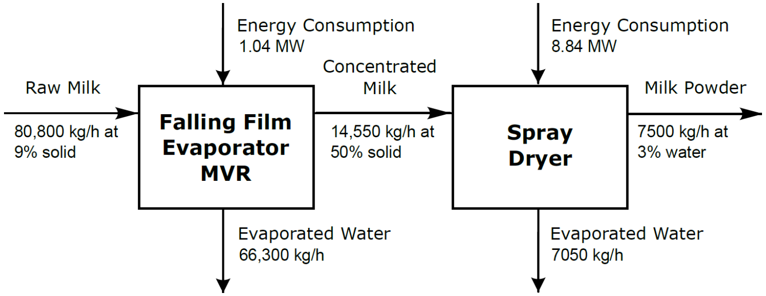




Power-2-X – Local vision Ringkøbing-Skjern







Summary

- **Key MPC technology developments**
  - MPC
    based on stochastic differential equations (SDEs)
  - Algorithmic
    – speed, robustness, embedded, cloud
  - Integrated Forecasting and Control
  - Integrated system identification

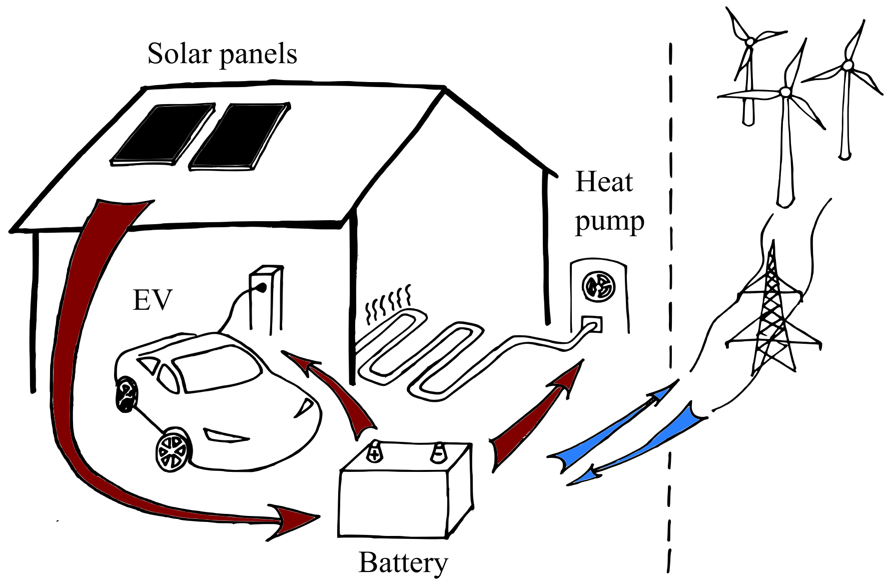
- **Industrial energy related processes**
  - Cement processes (FLS)
  - Food processes (GEA)
  - Single-cell protein production (Unibio)
  - Carbon capture (DTU Chem. Eng)

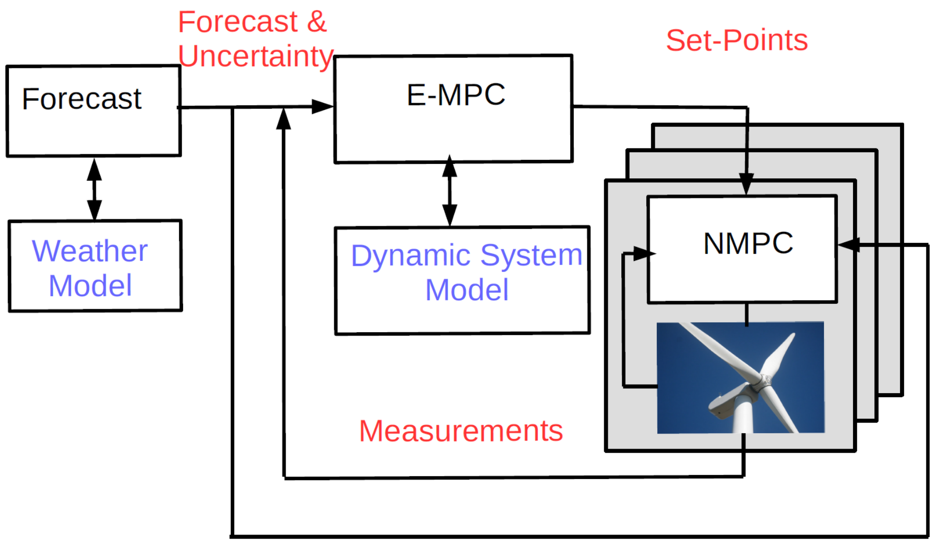
- **Energy Processes**
  - Energy system control (Orsted)
  - Wind turbine control (Vestas)
  - Refrigeration and heating systems (Danfoss)

- **MPC technology is mature and ready**
  to be implemented on large scale for buildings to enable smart cities and smart energy homes.

- **MPC technology is the key enabler**
  for integrated and coordinated systems.

  Implemented in many systems already
  to enable coordinated and efficient operation





Thank You – Q&A

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