Model Predictive Control for Smart Energy Systems

John Bagterp Jørgensen
Technical University of Denmark

Energiråd Ringkøbing-Skjern
September 11, 2020
Ringkøbing, Denmark

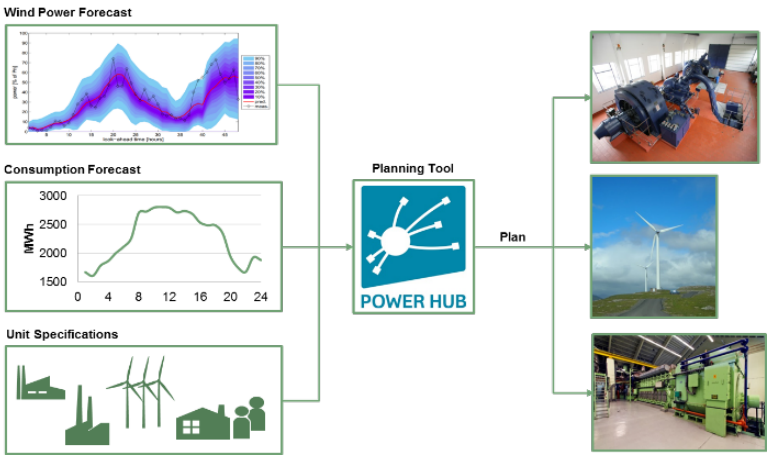
DTU Compute
Department of Applied Mathematics and Computer Science

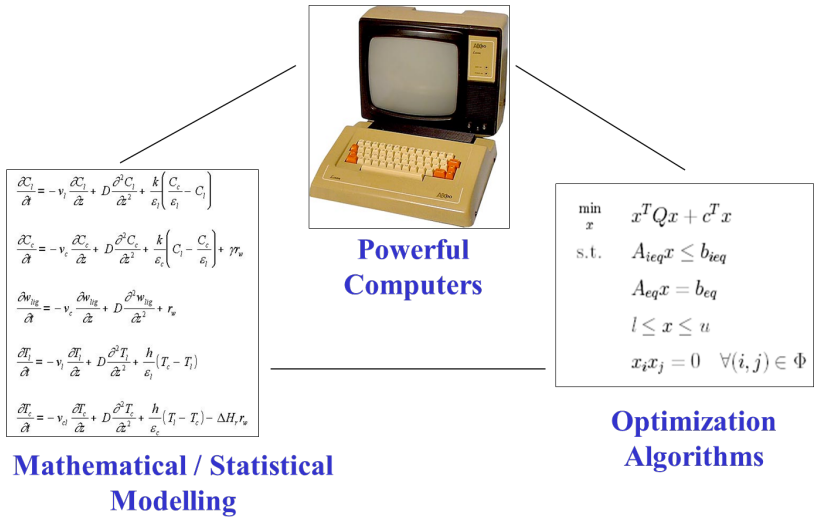
CITIES

Smart Cities Accelerator

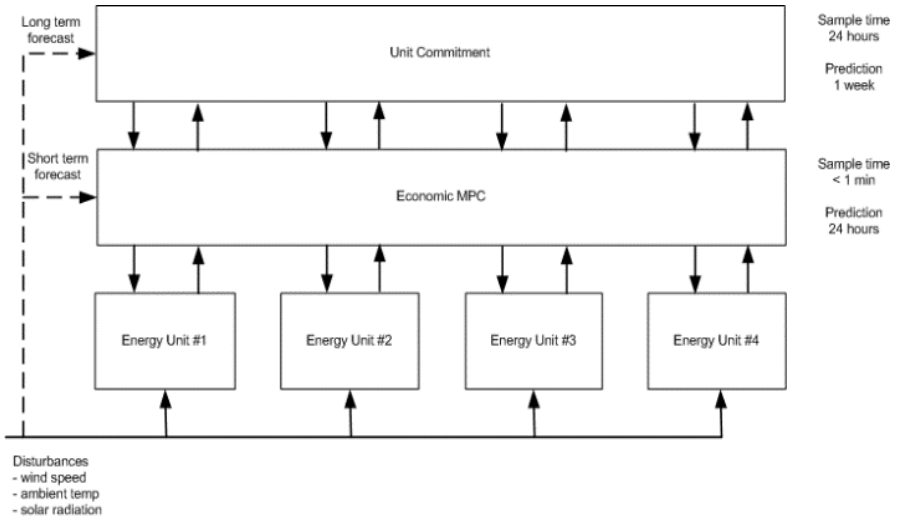
Digitalization, Control and Optimization of Smart Coordinated Energy Systems

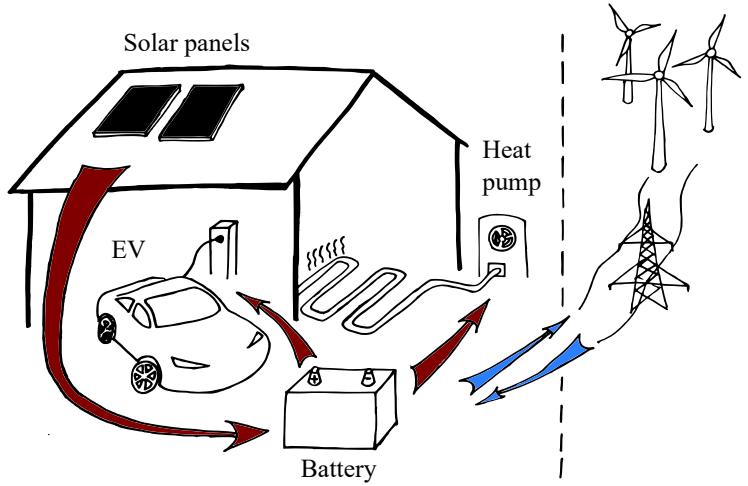
Optimization based control = Model Predictive Control (MPC)



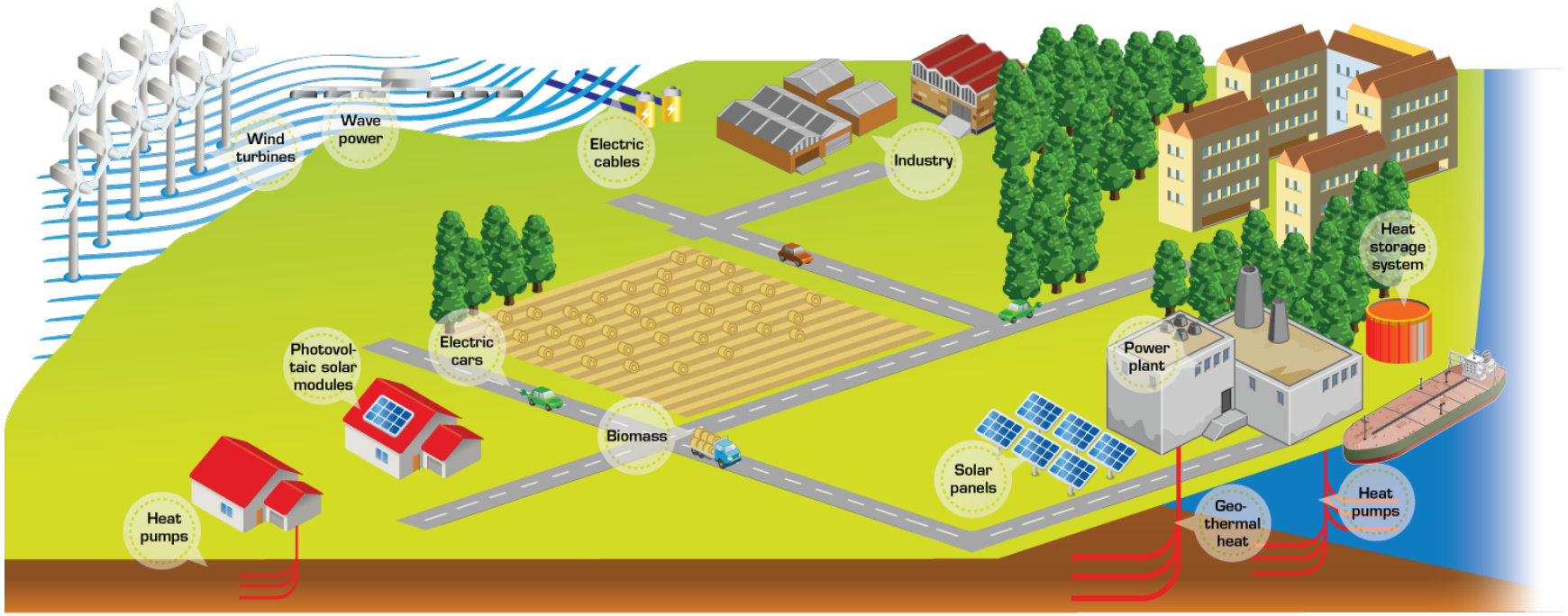


Hierarchical Control Structure

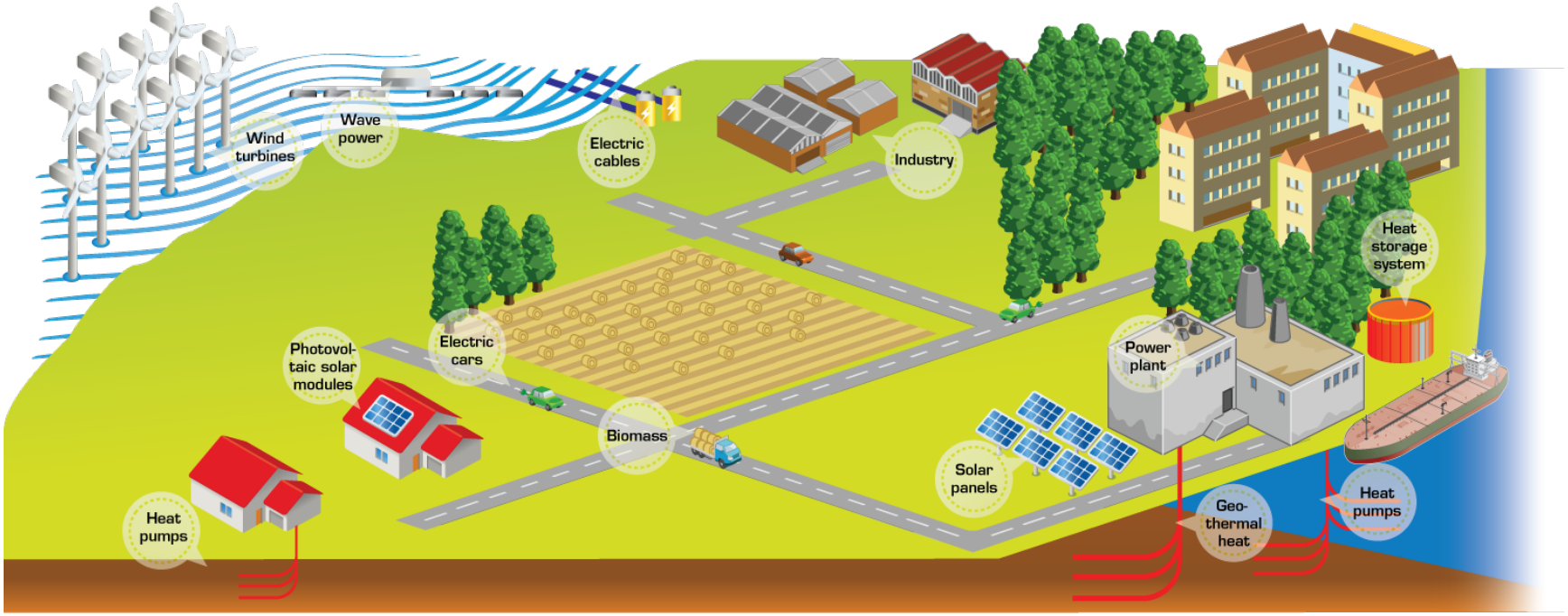




The Vision of Energy-Smart Cities



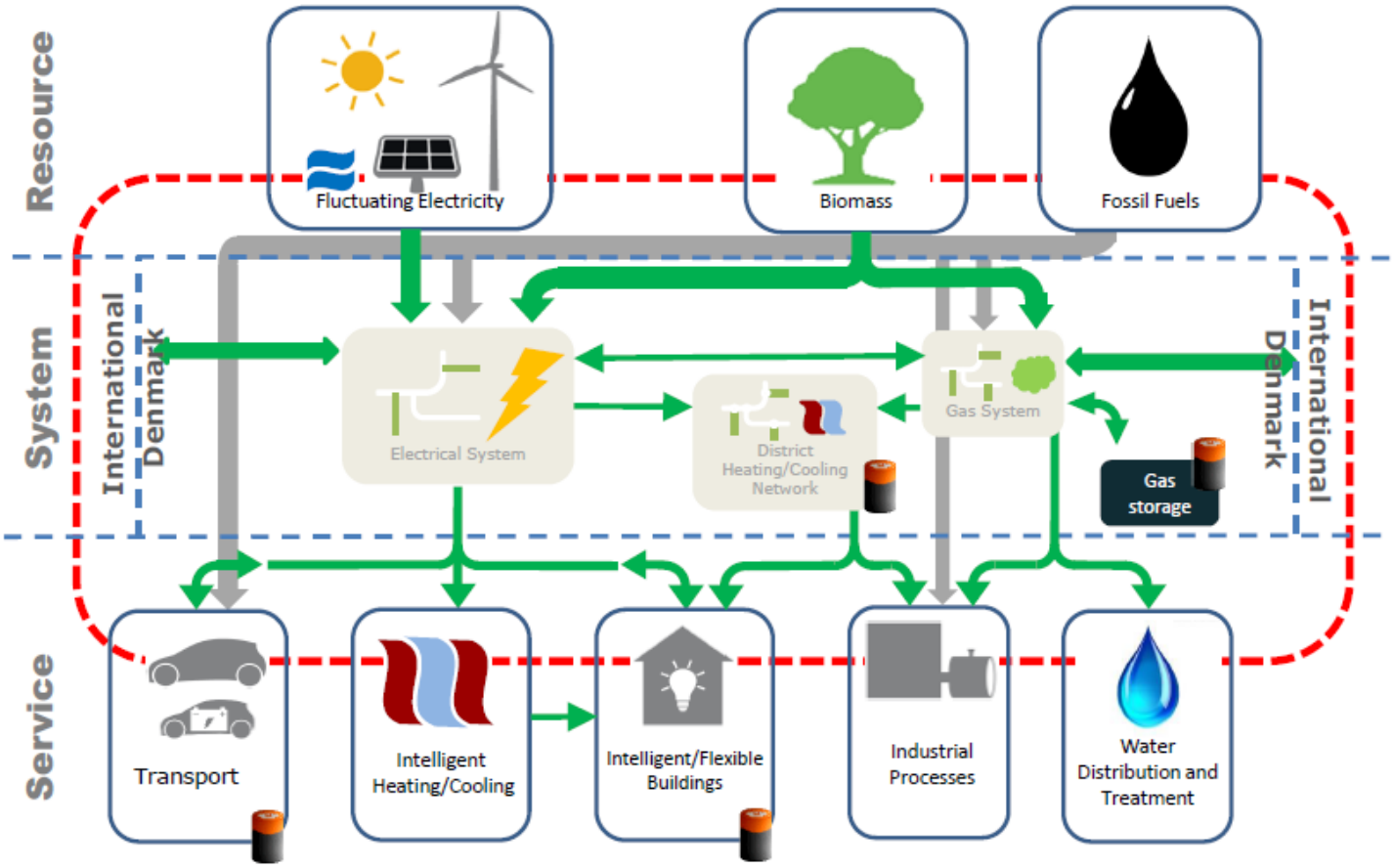
Smart Energy Systems



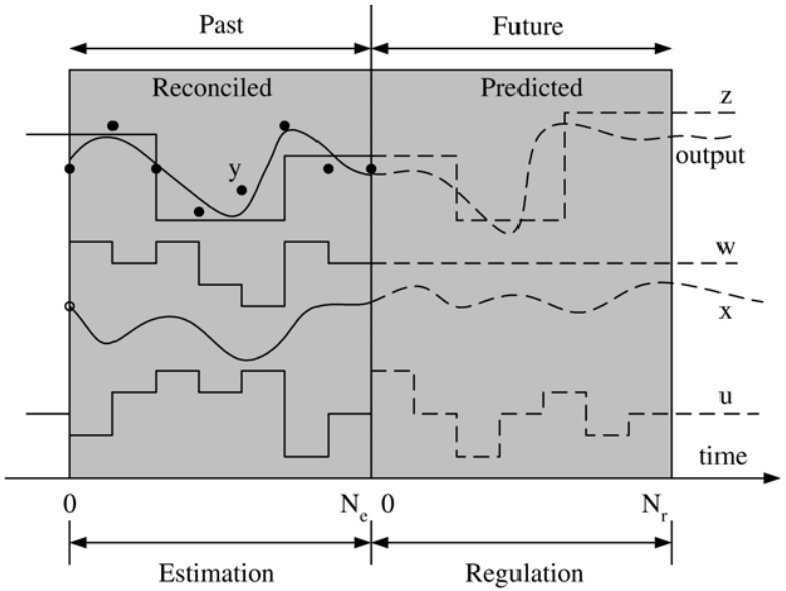
- **Thermal Storage**
  - Heating of floors etc
  - Heating of water accumulation tanks
  - Refrigeration Systems

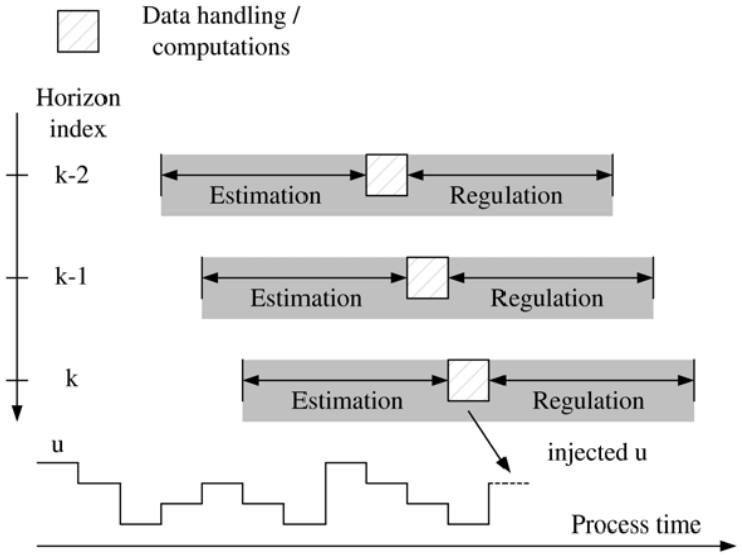
- **Power / Heat Producers**
  - Wind Turbines
  - Photovoltaic Solar Modules
  - Solar Panels
  - CHP Plants
  - Fuel Cells

Connected and Integrated Energy Systems - Model Predictive Control is the enabler



Model Predictive Control



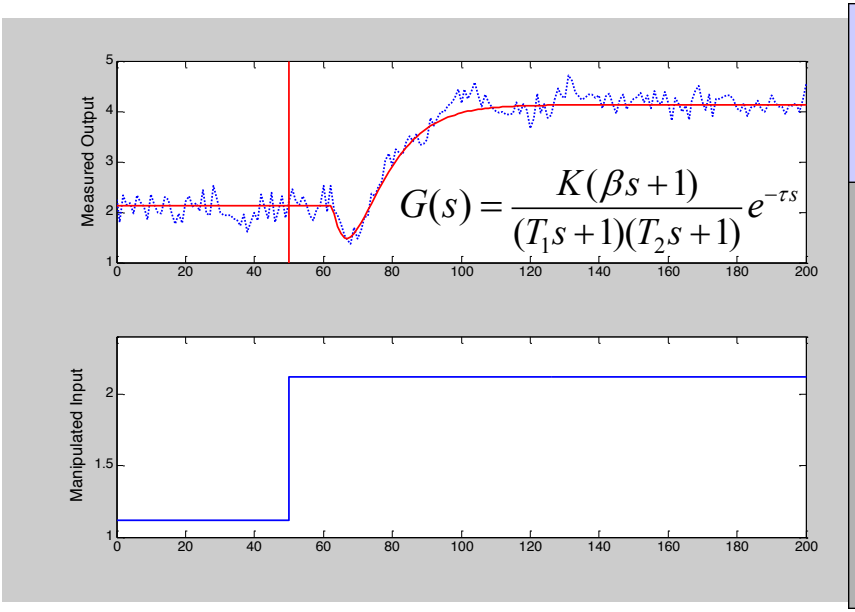


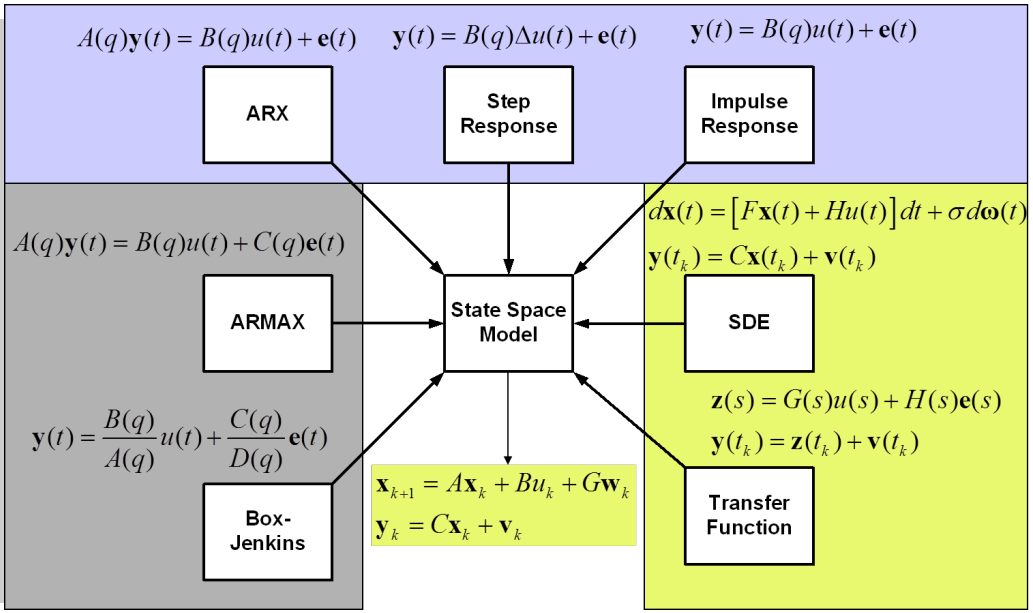
$$\min_{\{u_k, x_{k+1}\}_{k=0}^{N-1}} \quad \phi = \phi(\{u_k, x_{k+1}\}_{k=0}^{N-1}; x_0, \theta)$$

$$s.t. \quad x_{k+1} = F_k(x_k, u_k, \theta) \qquad k = 0, 1, \ldots, N-1$$

$$u_k \in \mathcal{U}$$

Data based prediction models



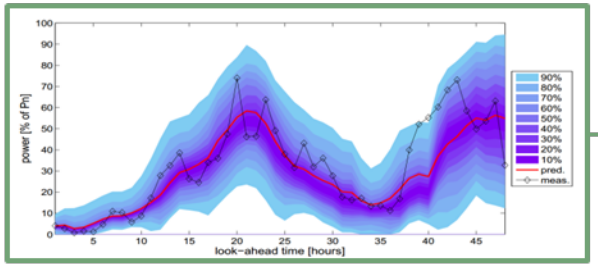


The models for filtering and prediction are

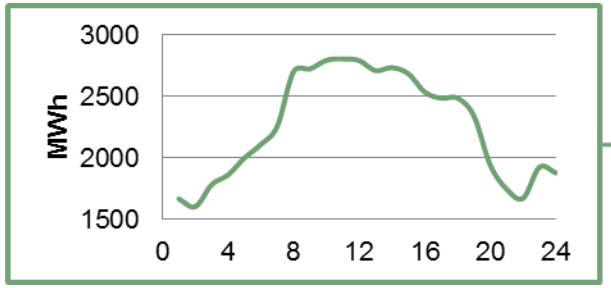
- Adaptive
- Data-based
- Combines a-priori (model) and a-posterior (data) information
- Able to predict the mean values and the uncertainties

Control of Energy-Smart Systems
= Economic Model Predictive Control

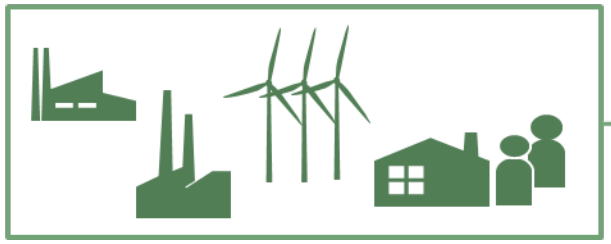
Wind Power Forecast



Consumption Forecast



Unit Specifications

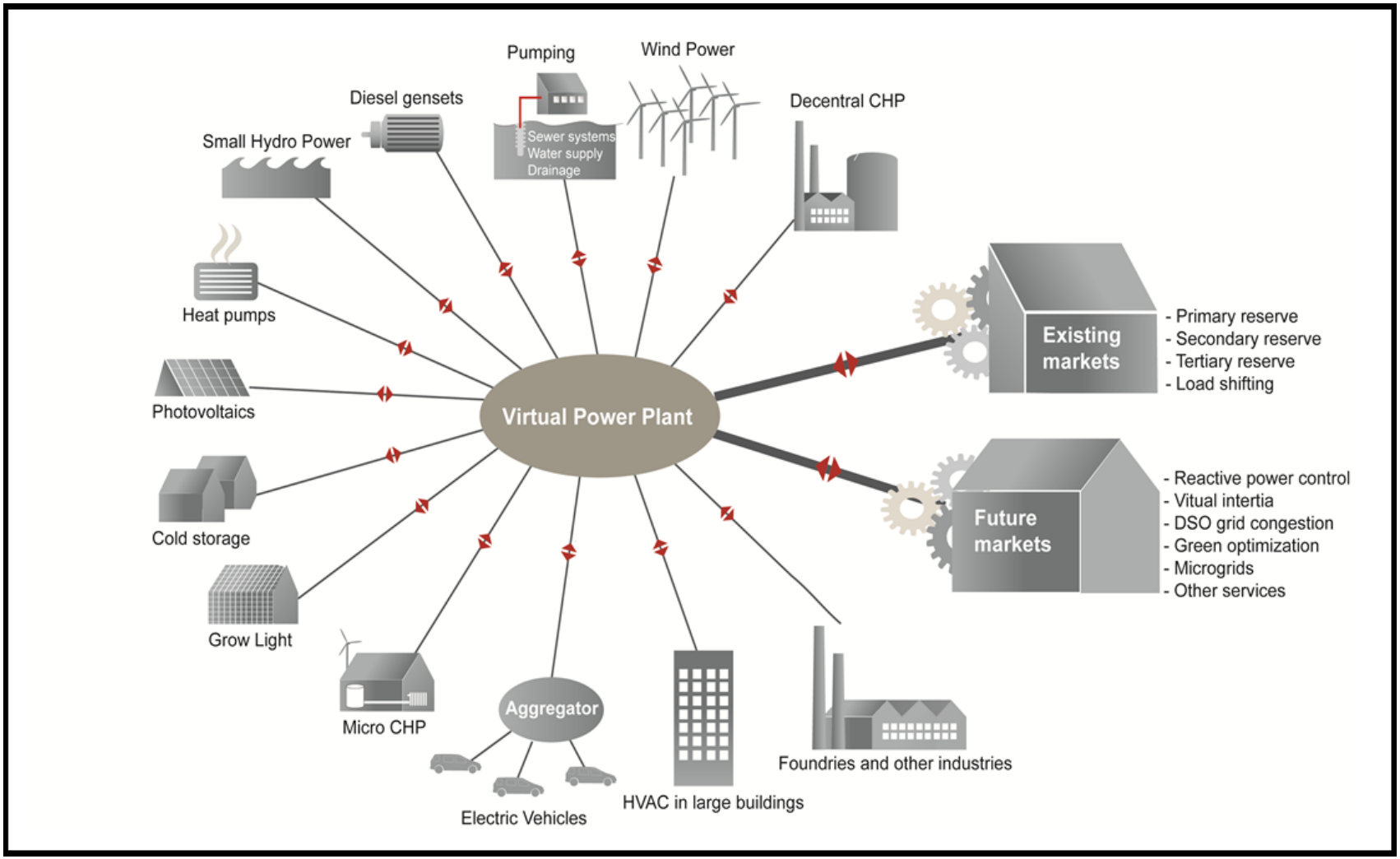


Planning Tool

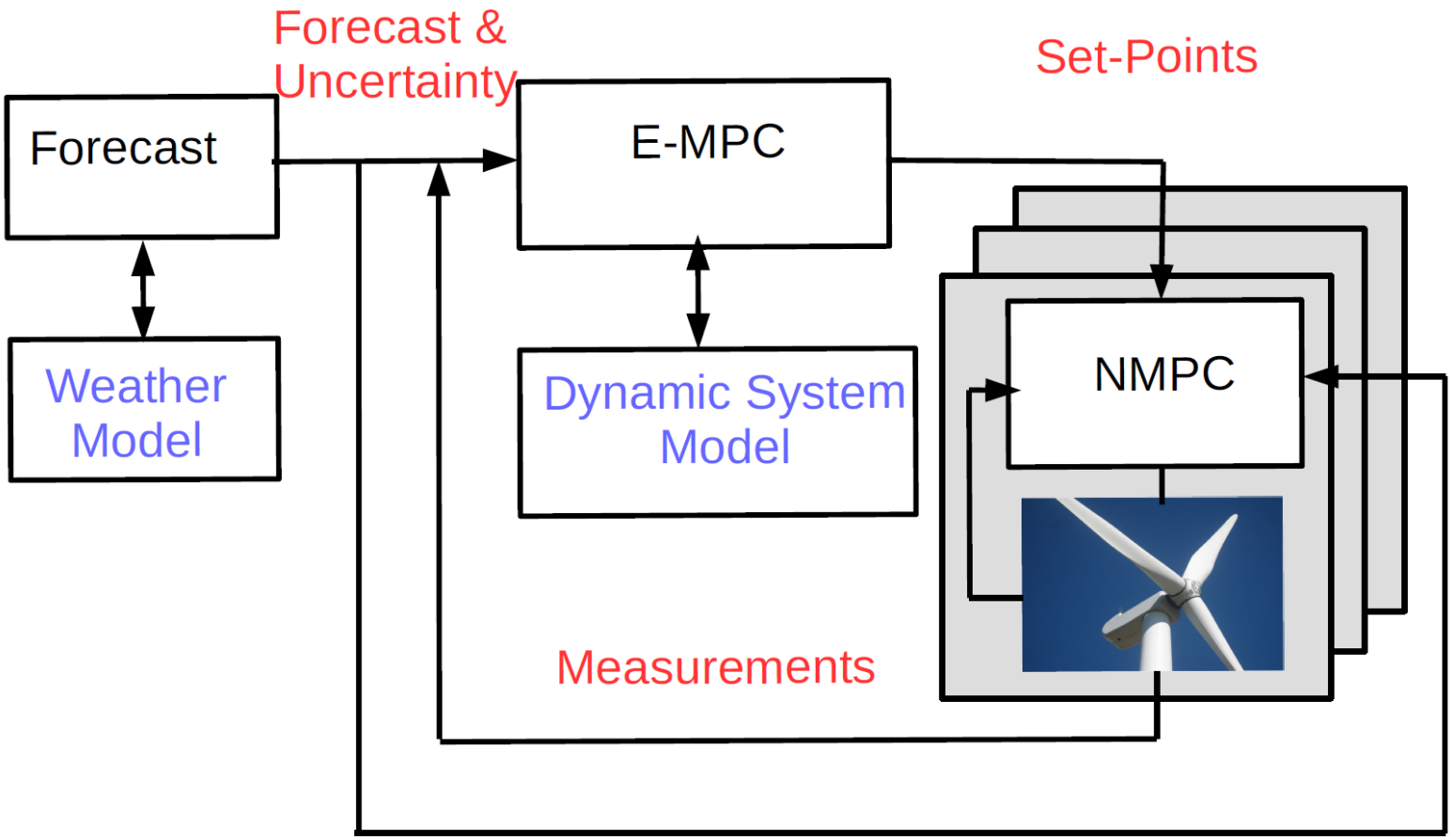
POWER HUB

Plan

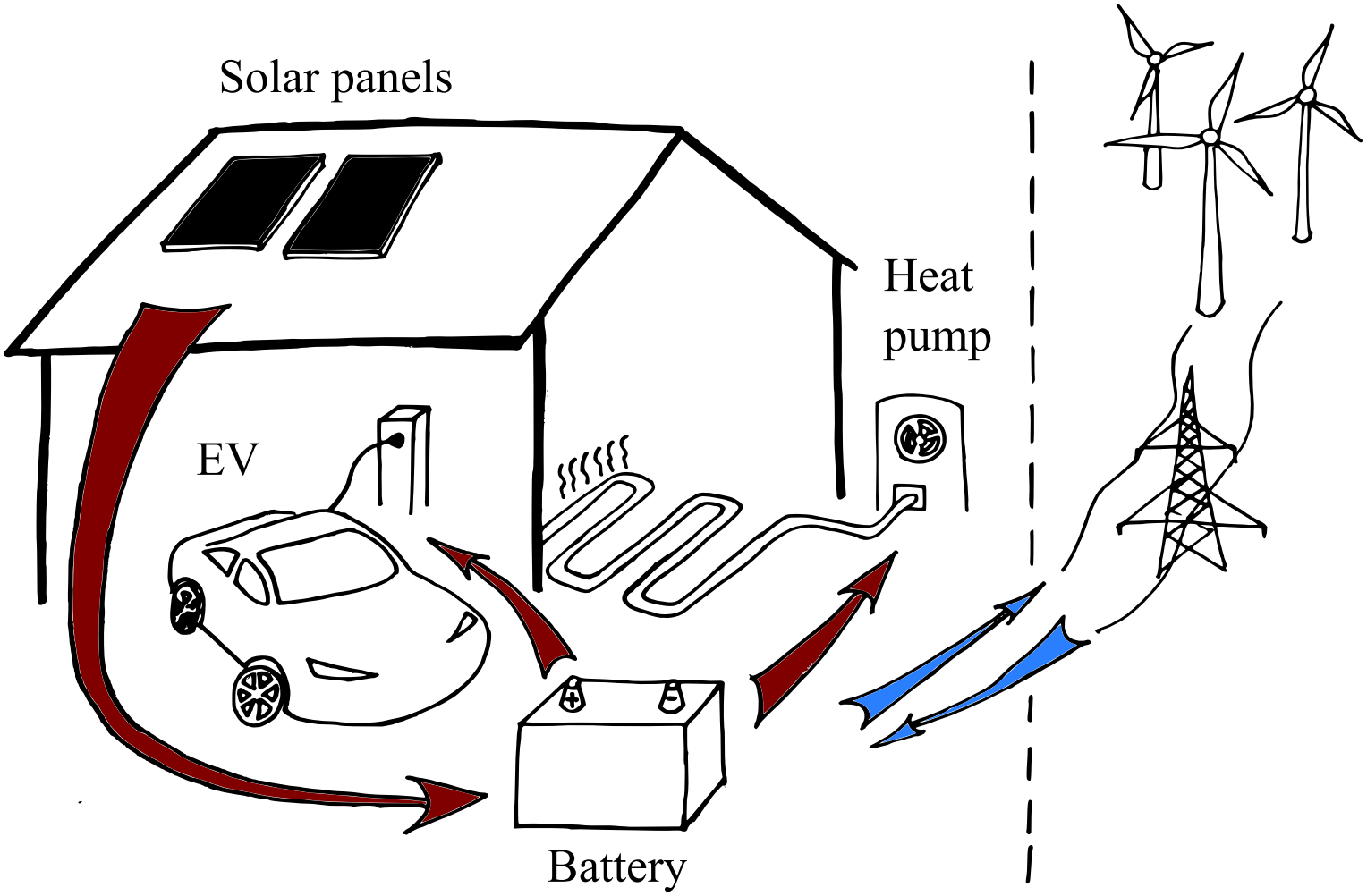
Virtual Power Plant



Forecast Based Hierarchical MPC



The Vision of Energy-Smart Homes

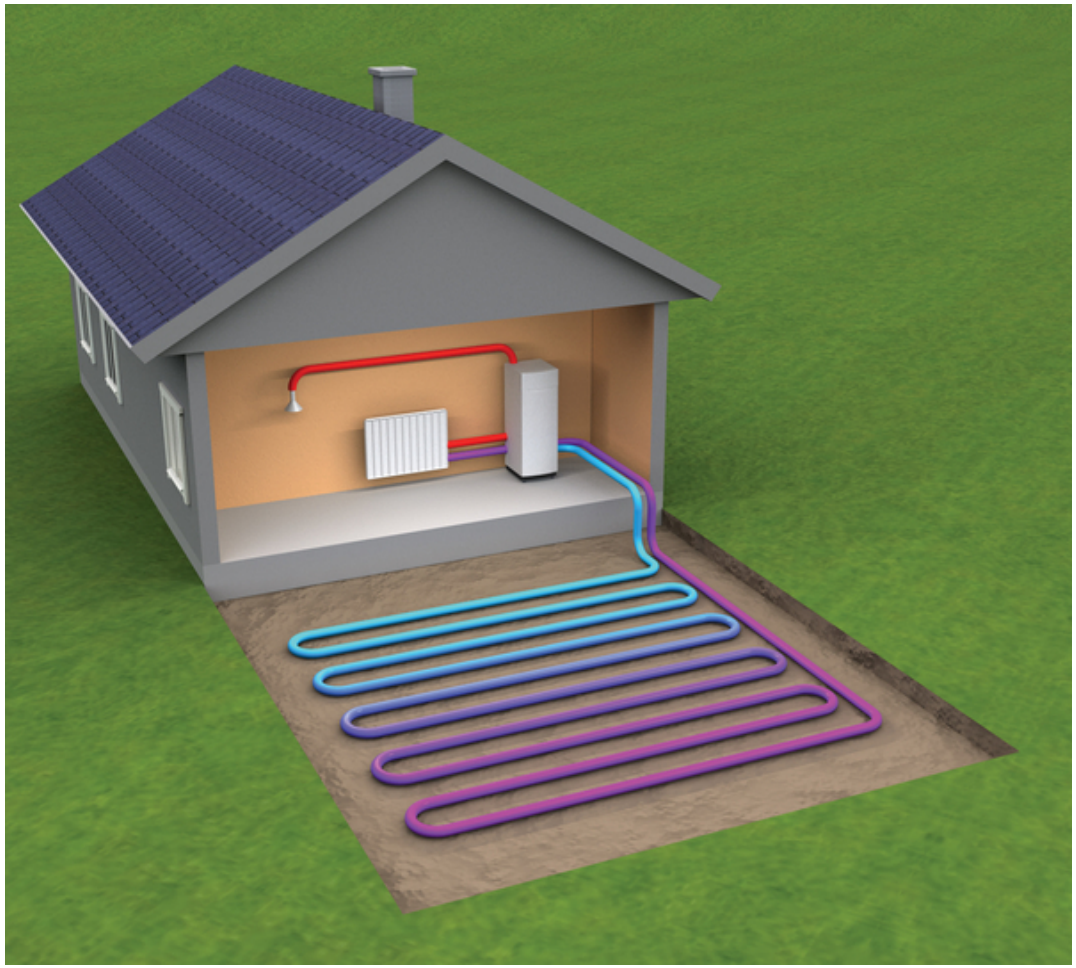


Elon Musk’s vision of an energy-smart home

Electric Vehicles

Solar roof tiles

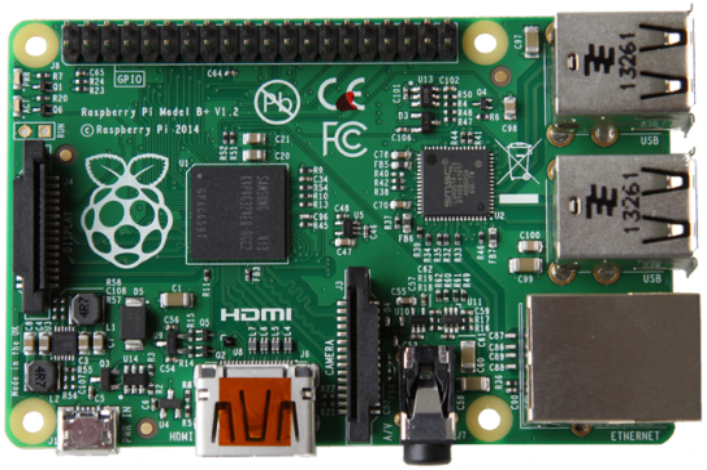
Heat Pumps



Smart Energy Consumption in a Residential Home

Raspberry Pi Embedded Control

Embedded MPC Algorithms for control of individual energy units



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

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

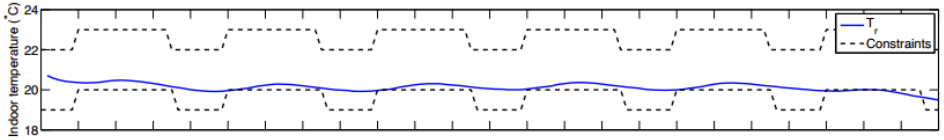
with $\mathcal{N} = \{0, 1, \ldots, N-1\}$ and stage costs defined by

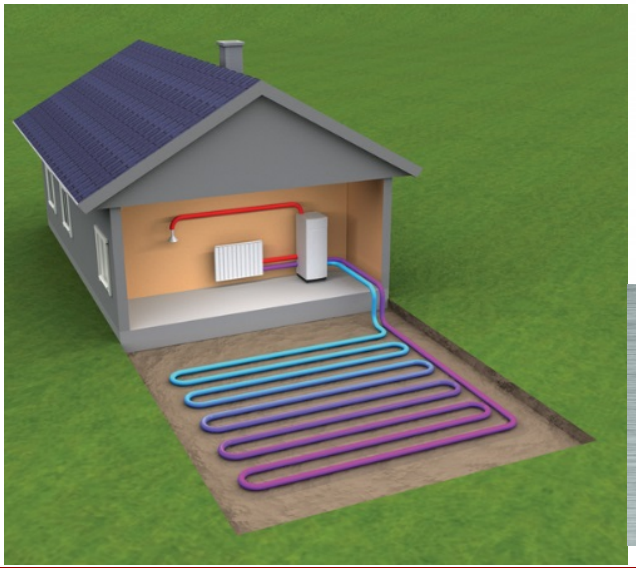
$$l_k(x_k, u_k) = \frac{1}{2} \begin{bmatrix} x_k \\ u_k \end{bmatrix}' \begin{bmatrix} Q_k & M_k' \\ M_k & R_k \end{bmatrix} \begin{bmatrix} x_k \\ u_k \end{bmatrix} + \begin{bmatrix} q_k \\ s_k \end{bmatrix}' \begin{bmatrix} x_k \\ u_k \end{bmatrix} + \rho_k \tag{2a}$$

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

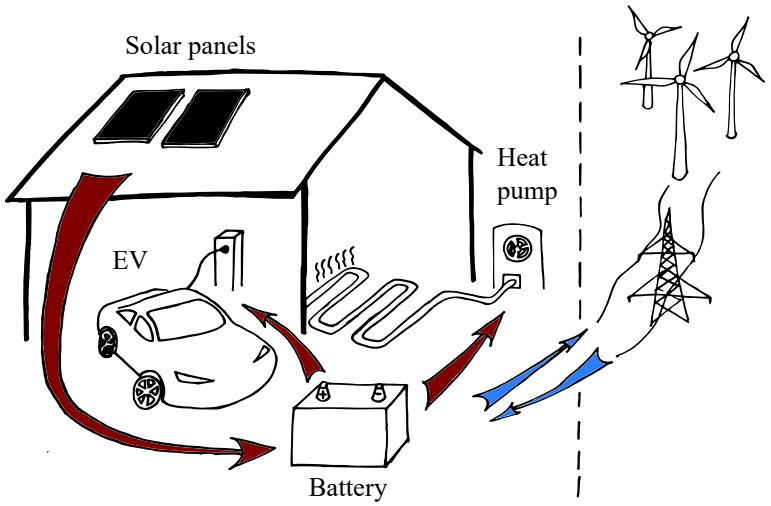
Control from the cloud

The control and forecasting systems are in the cloud.





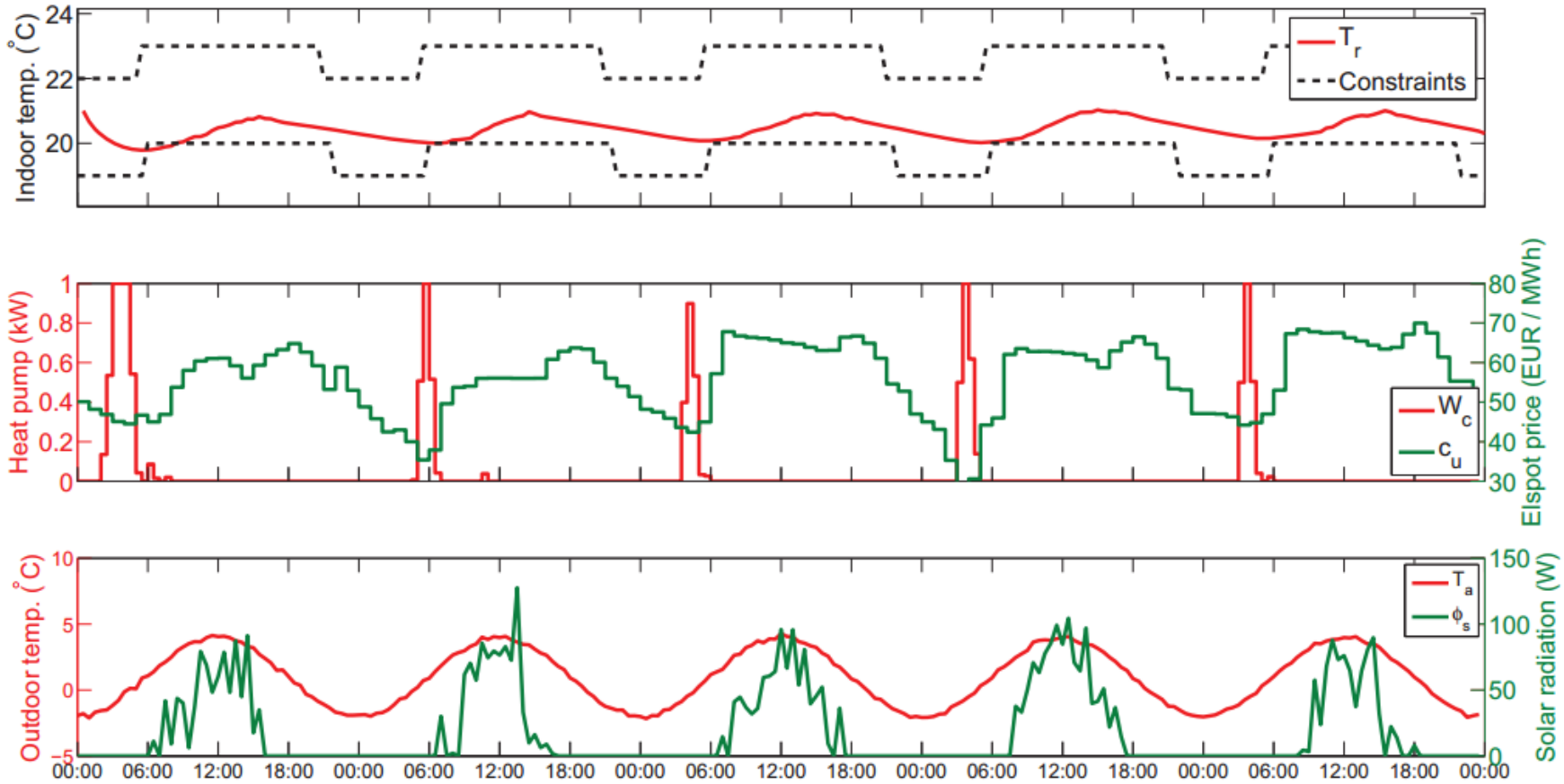
Scientific advances in Economic MPC to enable smart energy homes



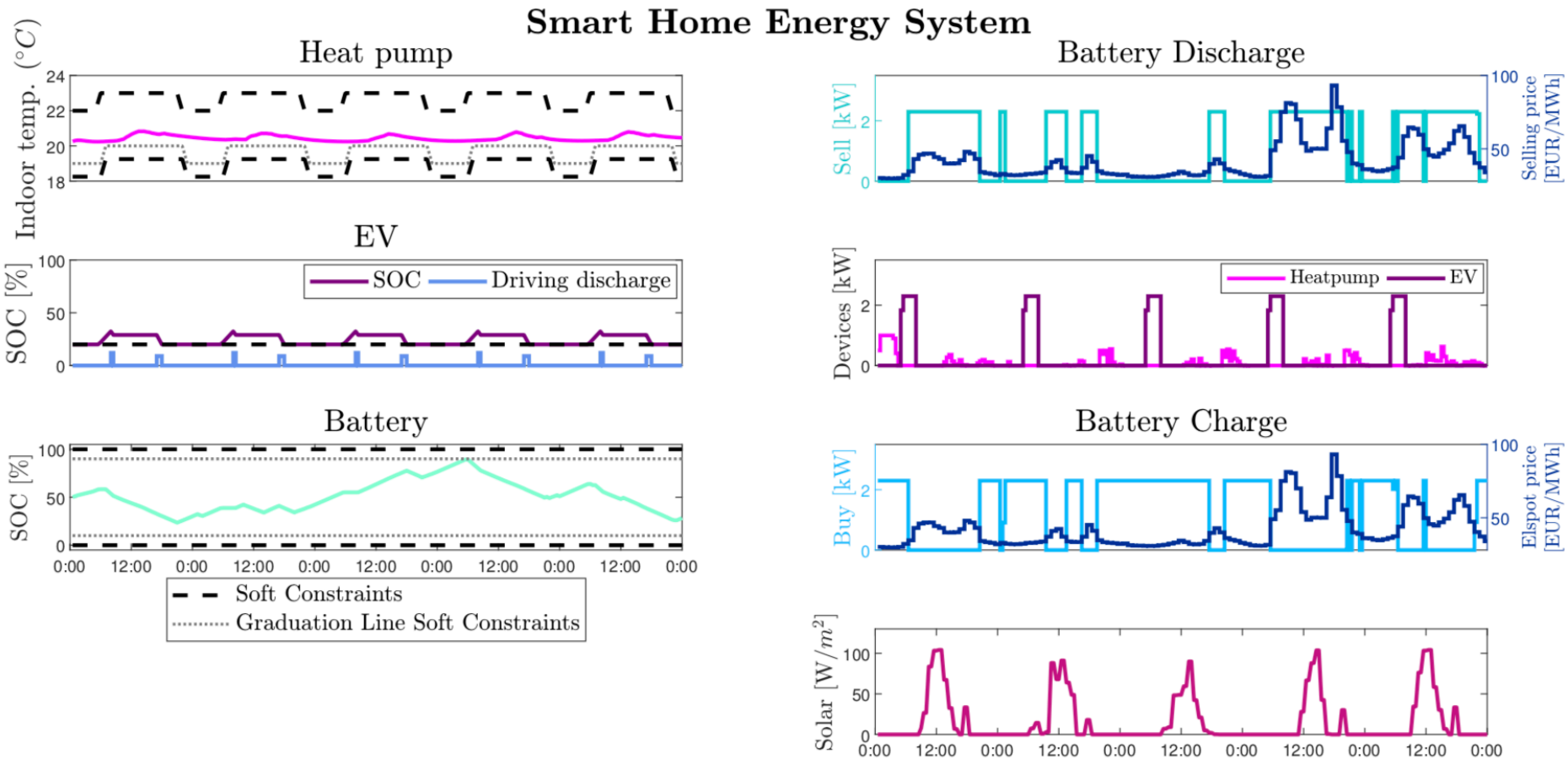
Economic MPC for Smart Energy Homes – a number of scientific advances

- 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

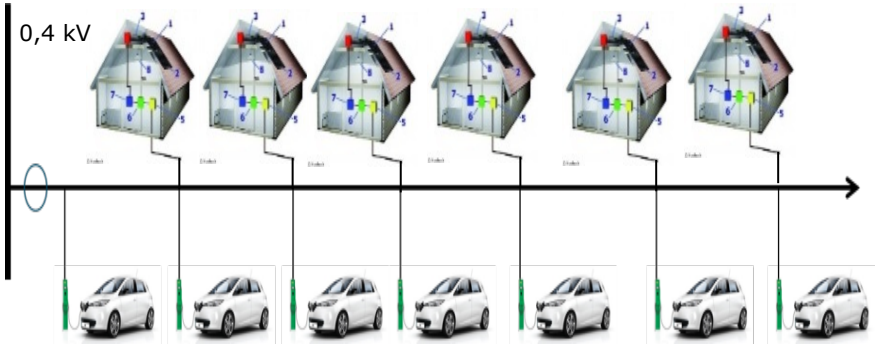
Economic MPC for Building Climate Control

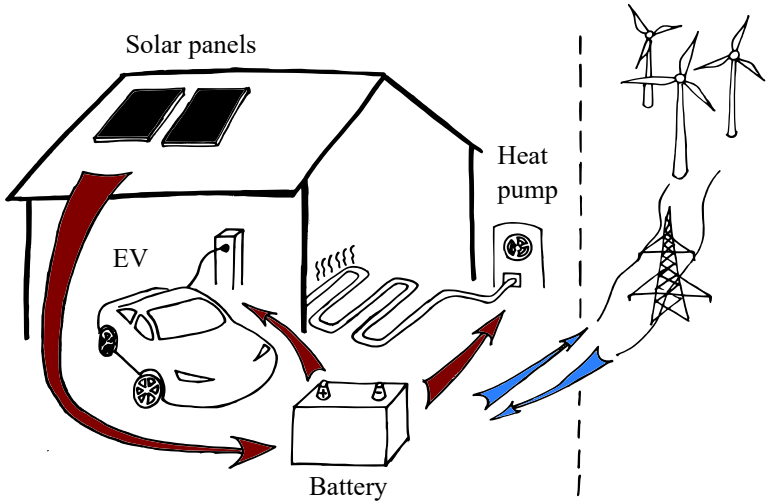


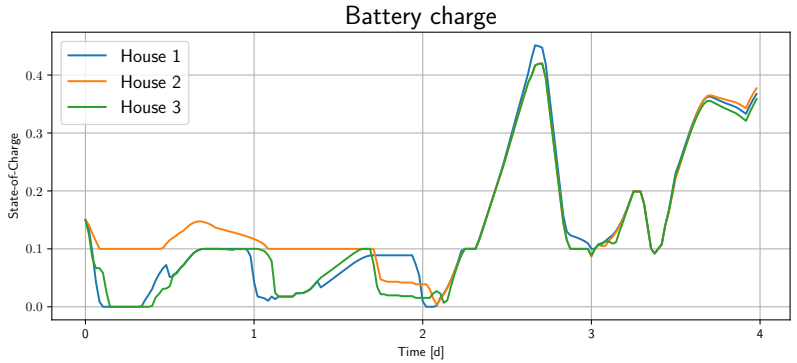
Model Predictive Control for a Smart Energy Home – Simulation Results

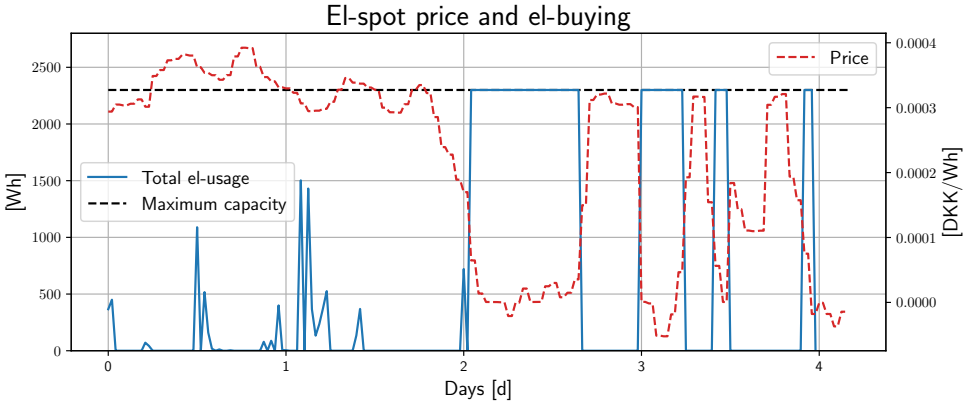


A neighborhood of smart energy homes - Lærkevej

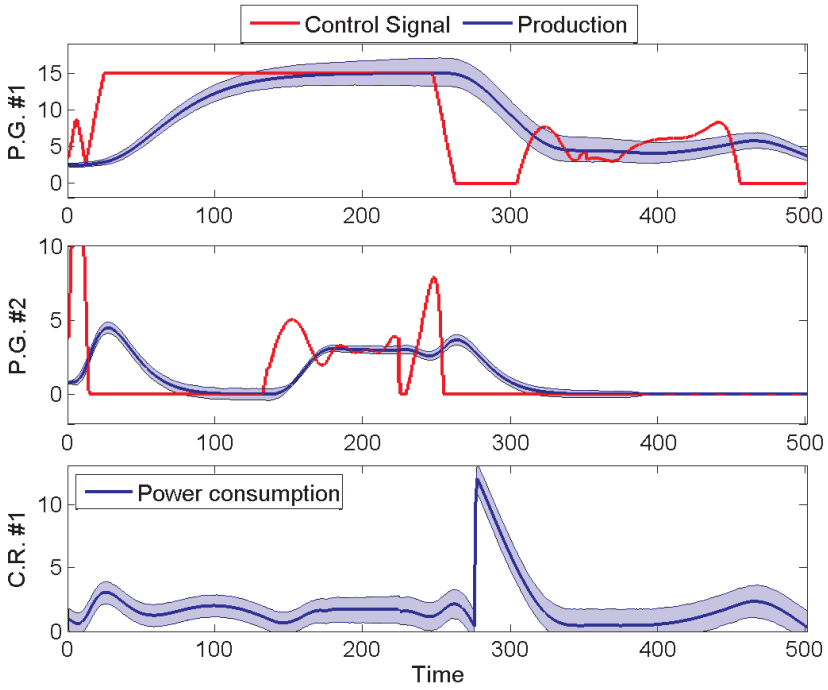


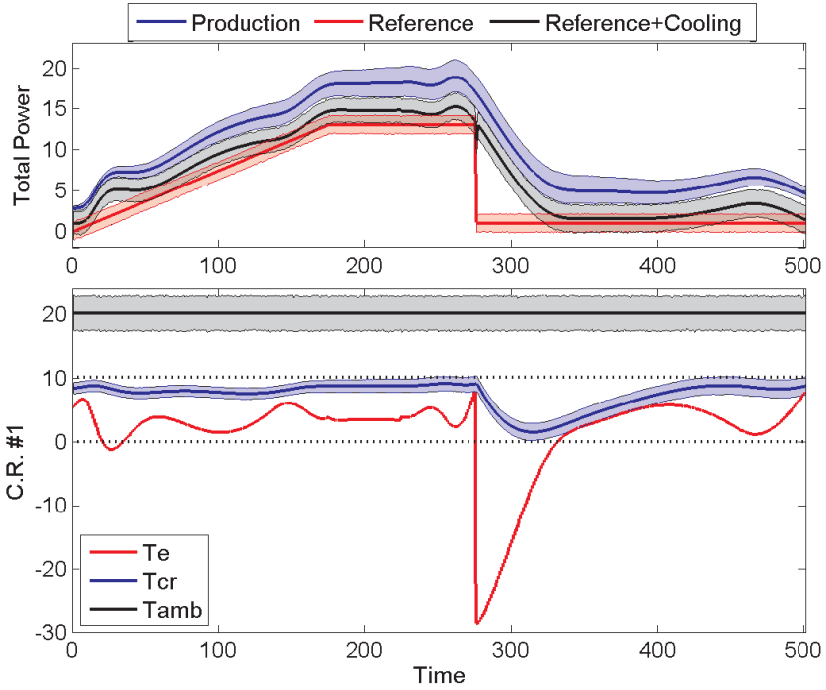


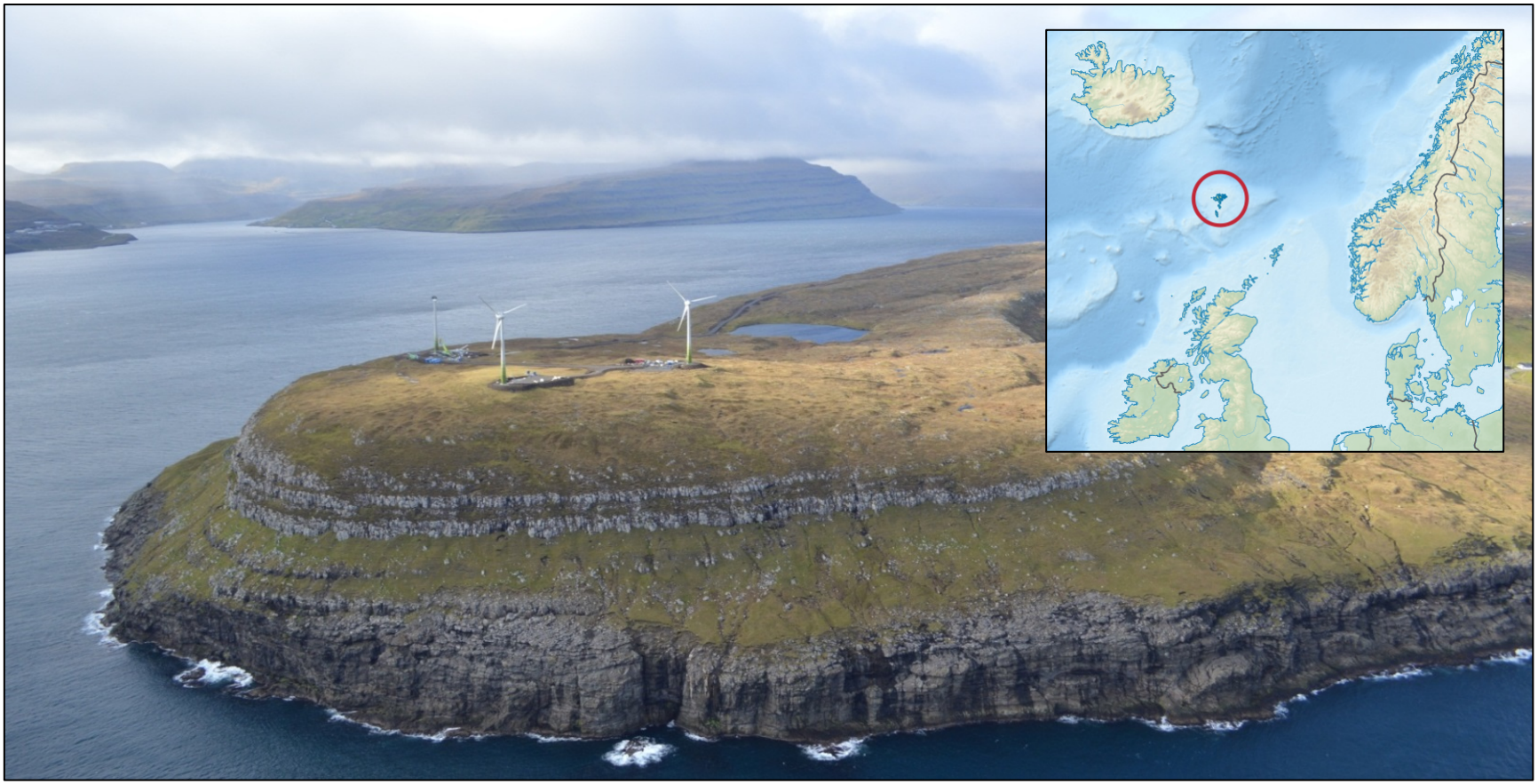




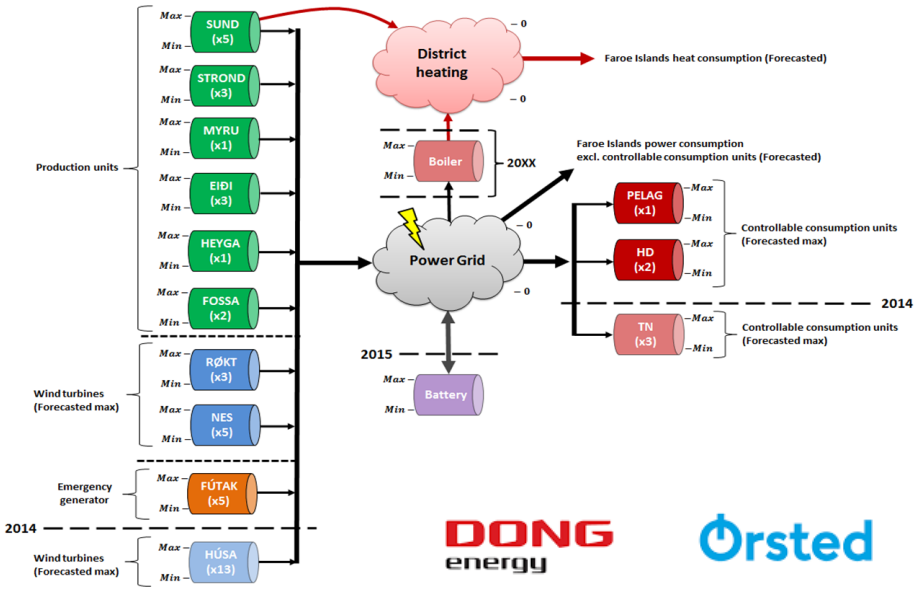
Supermarket Refrigeration – Demand Response

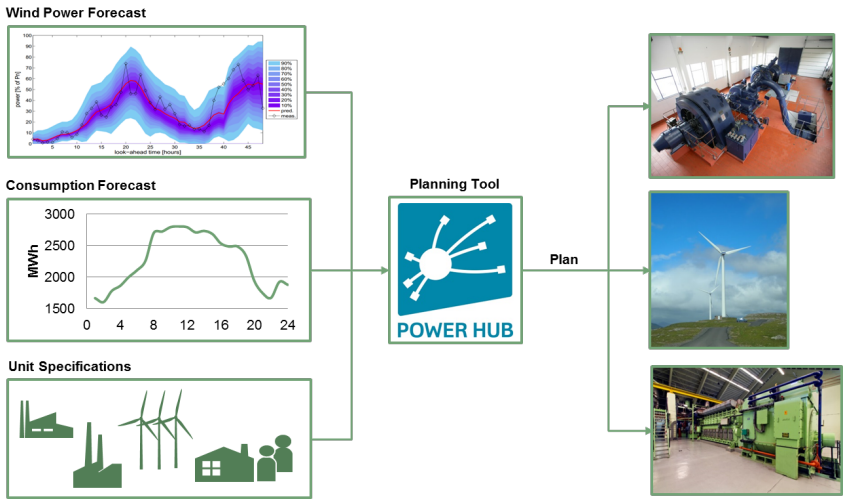




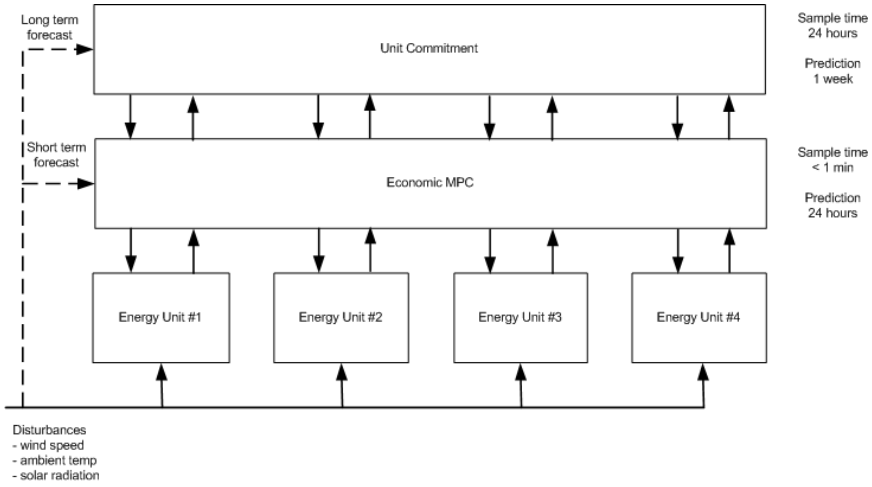


The Faroe Island Power System





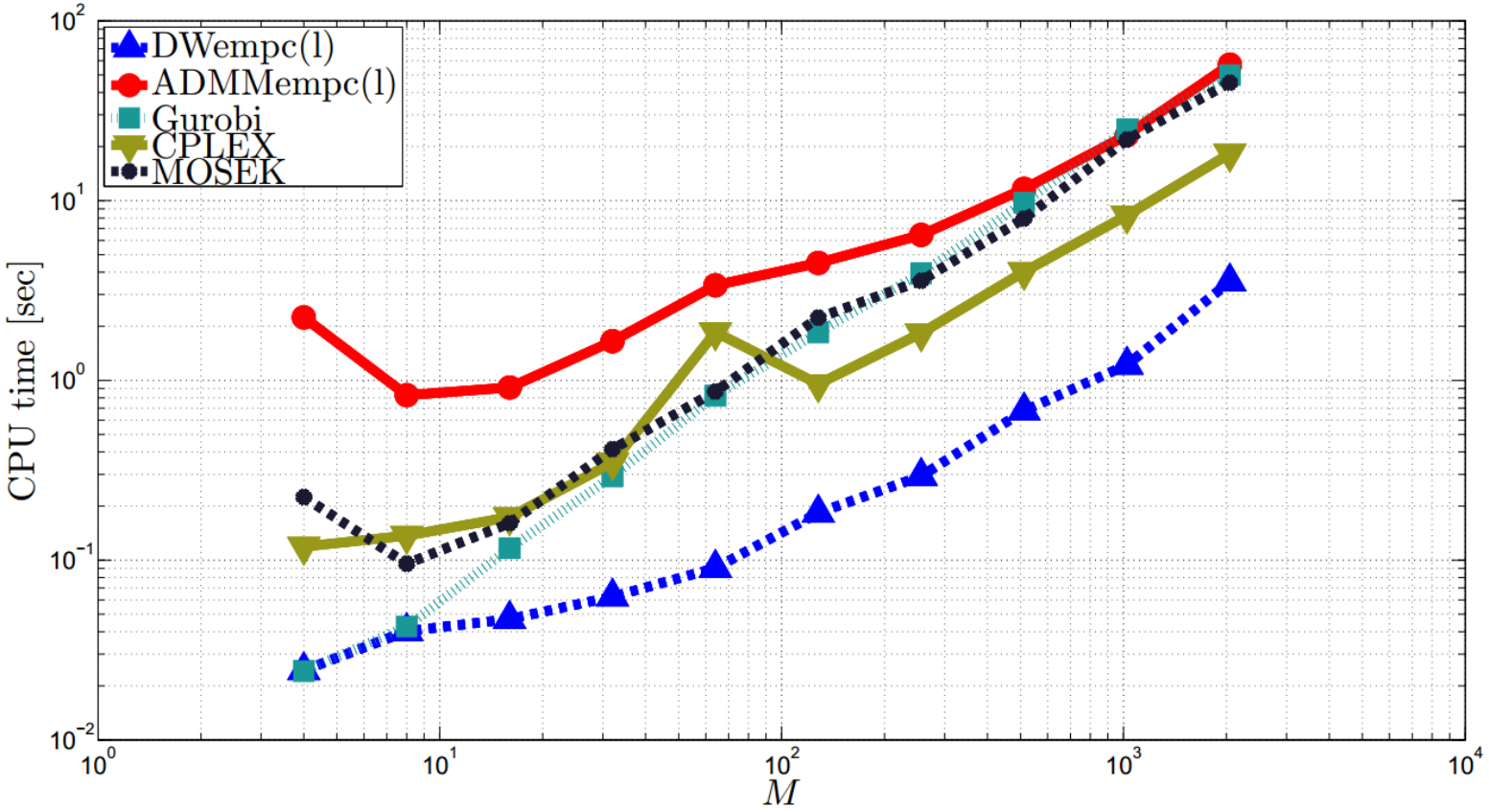
- Controlled the entire Faroe power system for 3 months
- Economic MPC system developed by Orsted (Dong Energy) and DTU Compute as part of an industrial PhD project



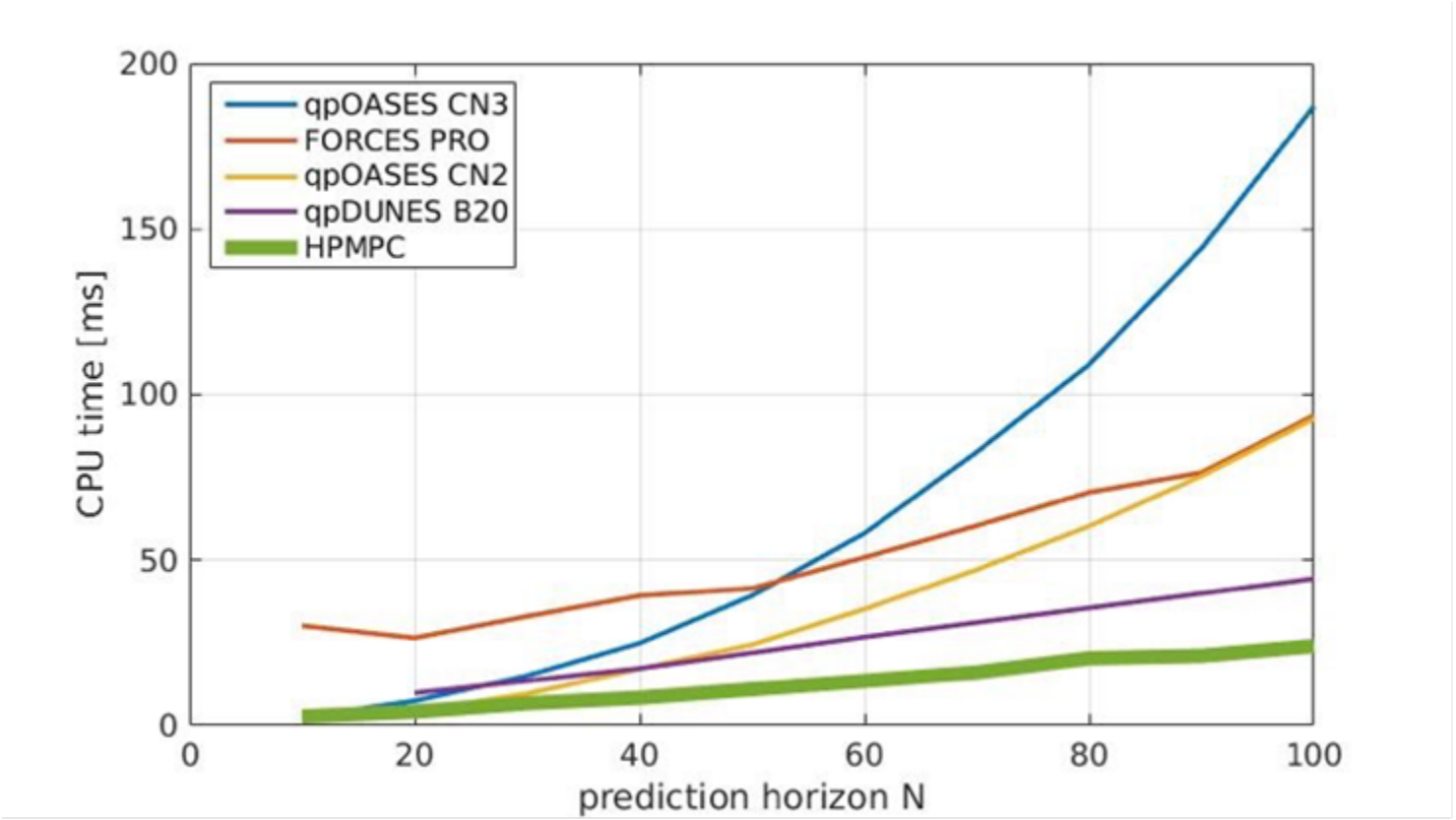
Fast Solver for Direct Control of an Entire City

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

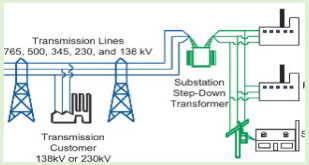
L.E. Sokoler[a,b], L. Standardi[a], K. Edlund[b], N.K. Poulsen[a], H. Madsen[a], J.B. Jørgensen[*,a]



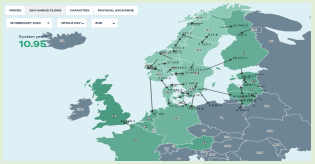
Fast Algorithms for Model Predictive Control - enable new applications



FEDplus



TSO



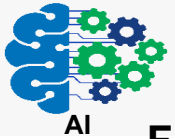
Large scale markets

Upscaling

FEDplus

AI based Control

- System of Systems
  - Market
  - Users
  - Grids
  - Elec.
  - Heat
  - Water
  - Power2X

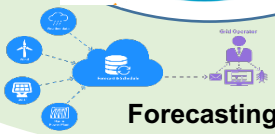


AI

FED

Regulatory framework

Humans



Forecasting

ACT

Regulations

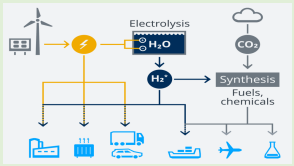
Licenses and Certificates

Regulatory documents

Implementation and Demonstration

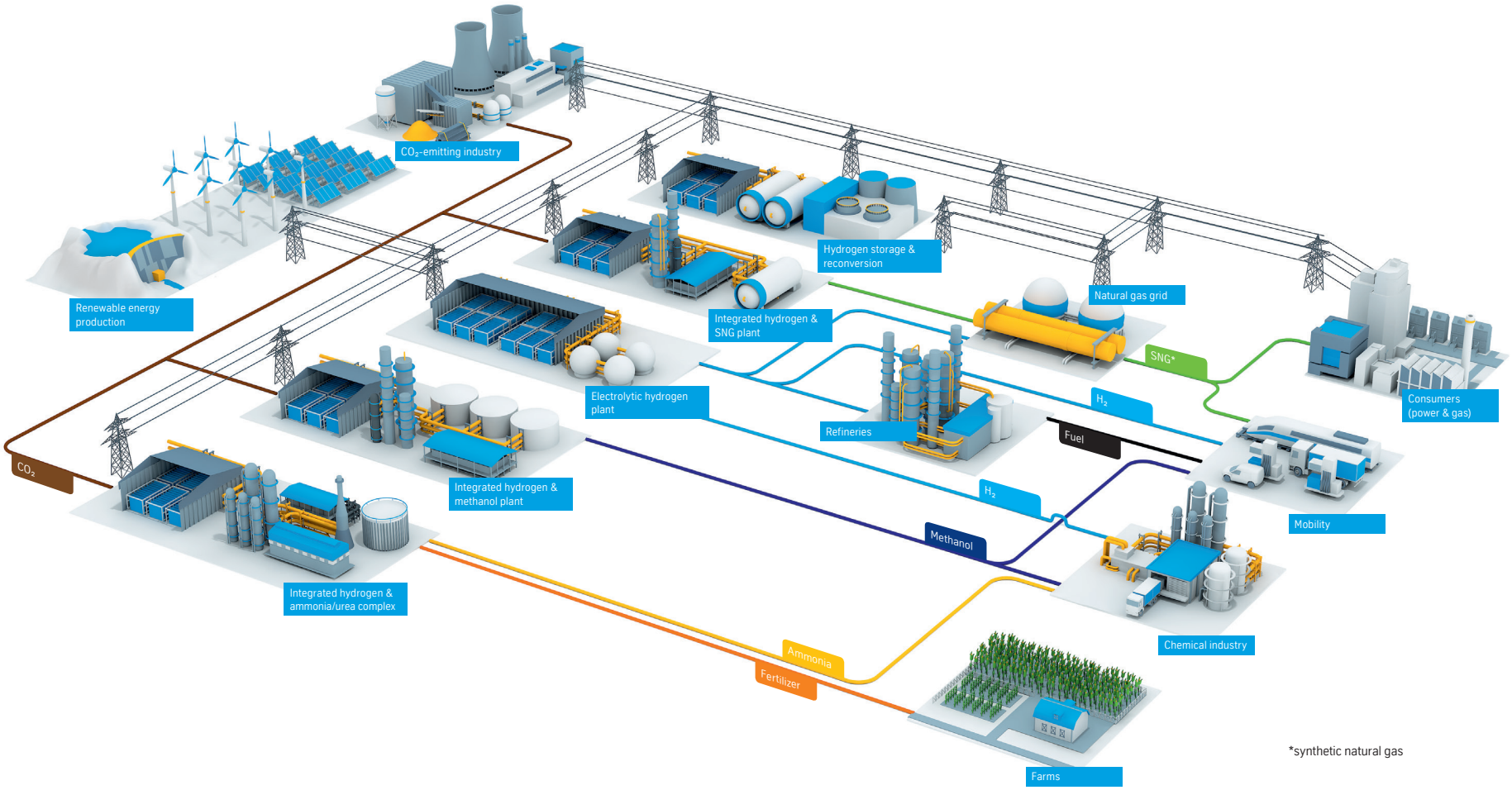
Smart water

Smart buildings and district

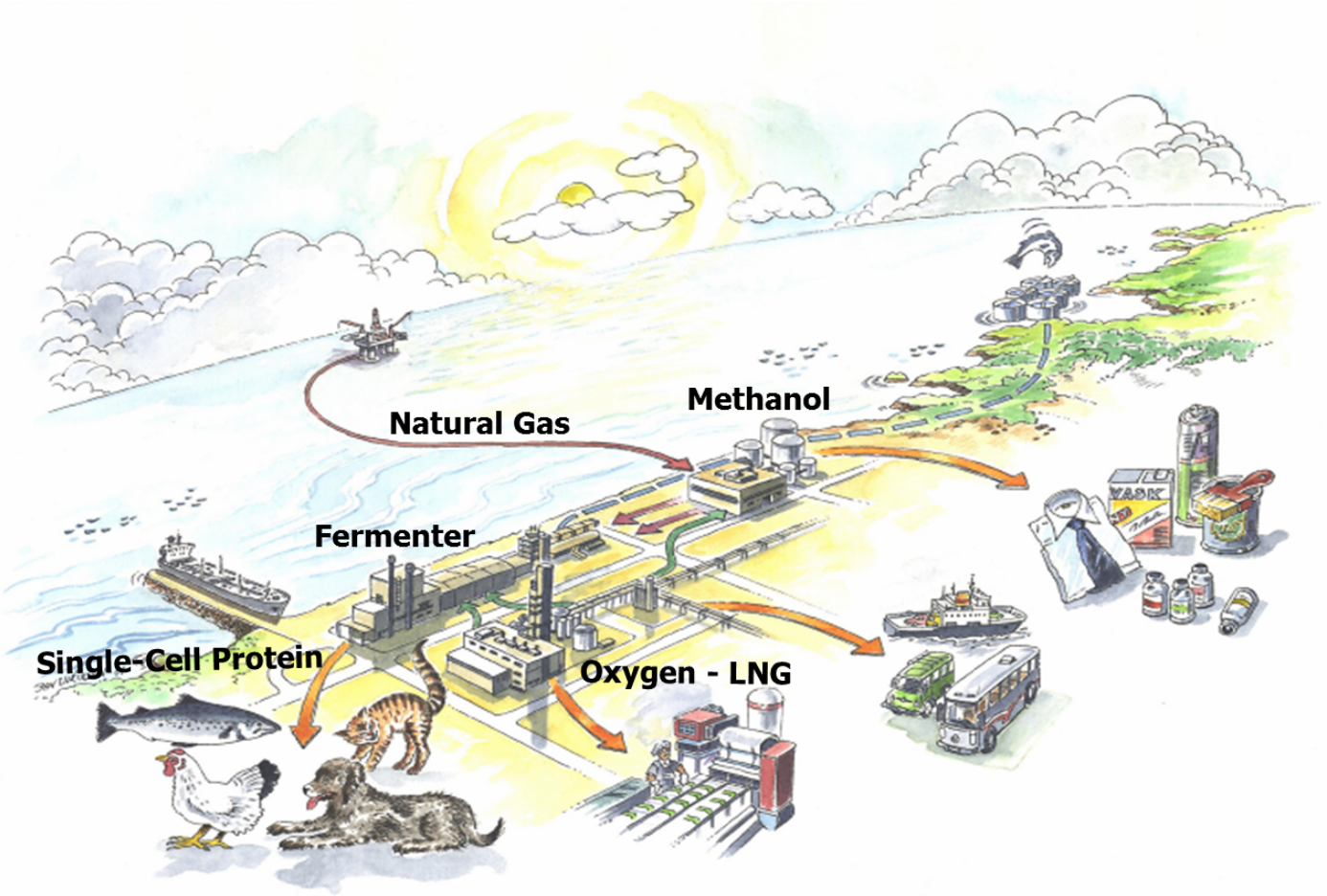


Power2X

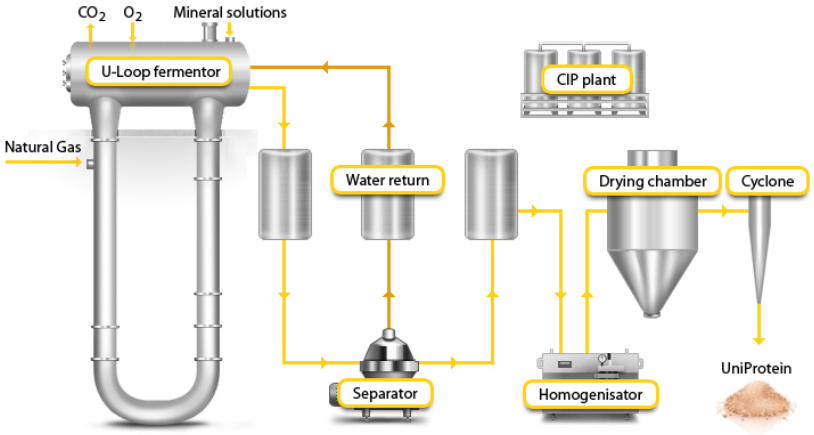
Power-2-X

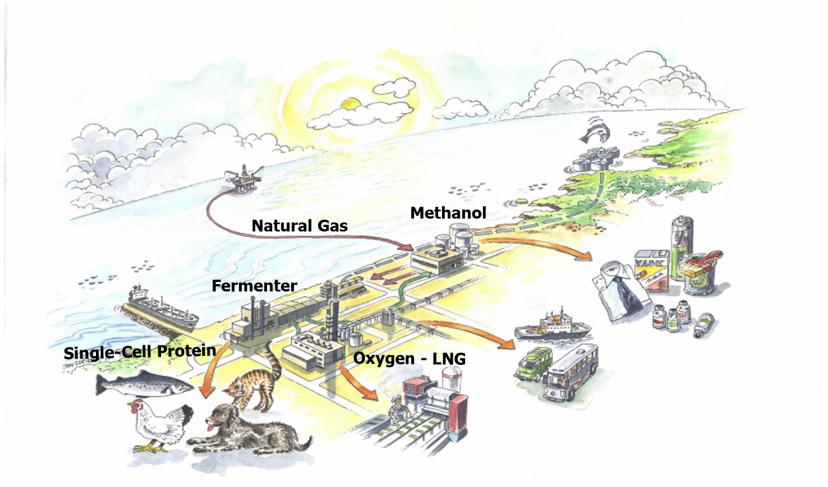

CO_2-emitting industry
Renewable energy production
Hydrogen storage & reconversion
Natural gas grid
Integrated hydrogen & SNG plant
Electrolytic hydrogen plant
SNG*
Consumers (power & gas)
H_2
Refineries
Fuel
CO_2
Integrated hydrogen & methanol plant
H_2
Mobility
Methanol
Integrated hydrogen & ammonia/urea complex
Chemical industry
Ammonia
Fertilizer
Farms
*synthetic natural gas

Proteins from methane
- natural gas, biogas, SNG

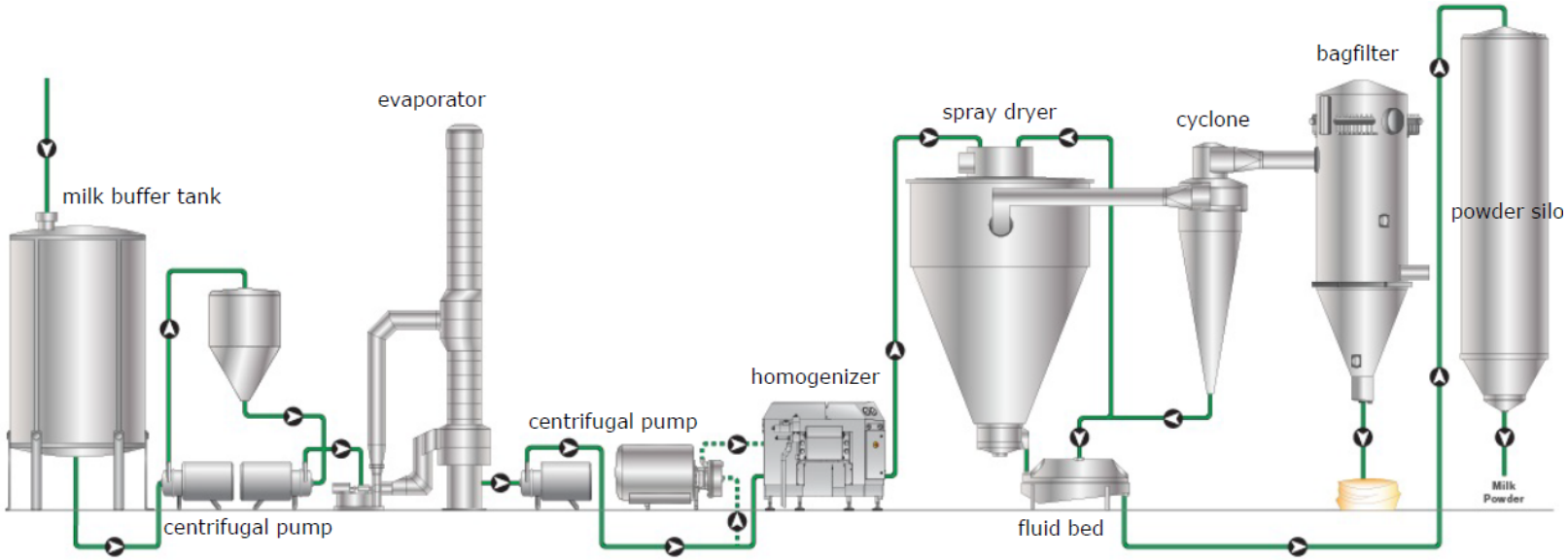


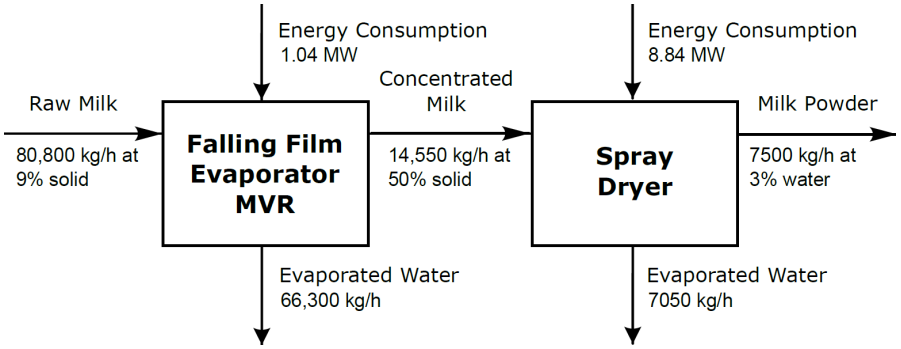
Single-Cell Protein

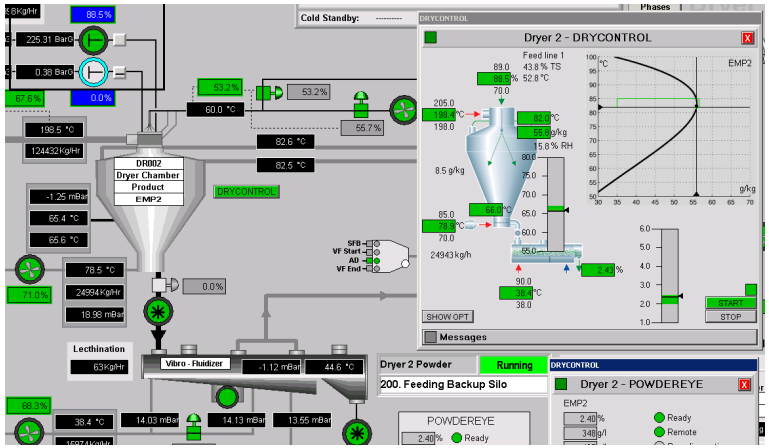




Milk Powder Plant – GEA Process Engineering

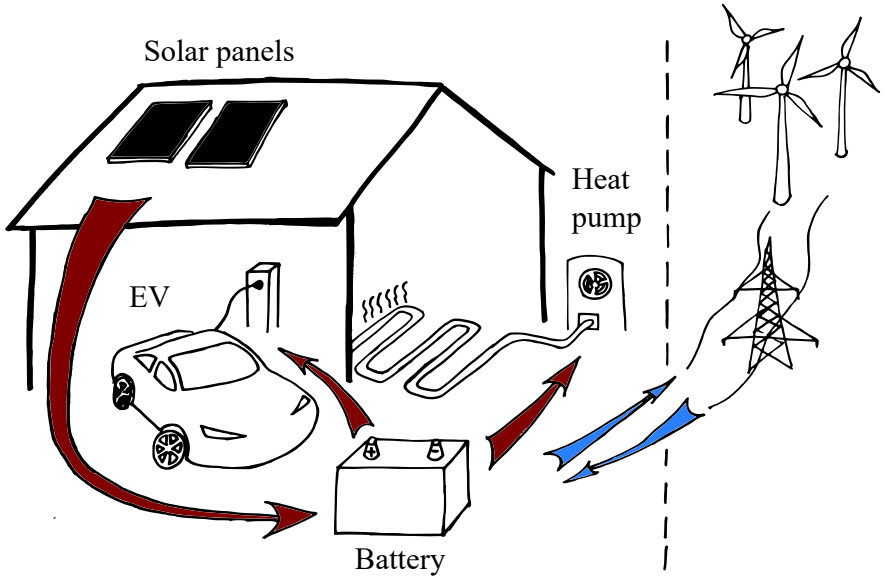


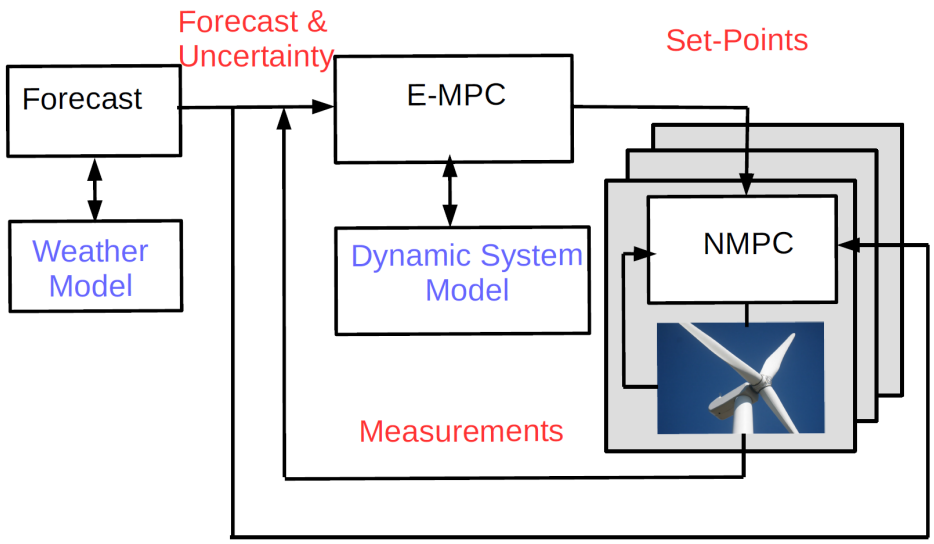




Summary

- MPC technology implemented in many systems to enable coordinated and efficient operation
- Industrial energy related processes
  - Cement Processes (FLSmidth)
  - Food processes (GEA Process Engineering)
- Energy Processes
  - Energy system control (Orsted)
  - Wind turbine control (Vestas)
- 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





Thank You – Q&A

John Bagterp Jørgensen

Technical University of Denmark

E-mail: jbjo@dtu.dk

DTU Compute
Department of Applied Mathematics and Computer Science