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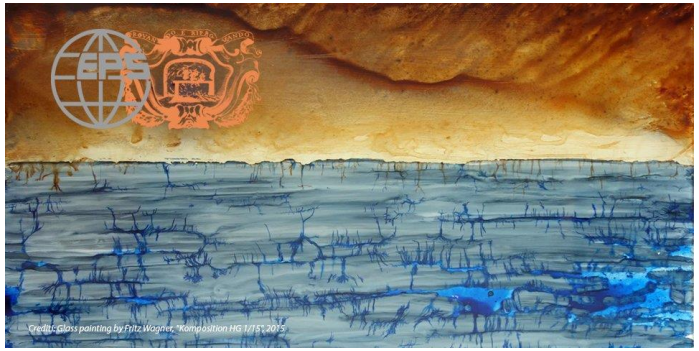
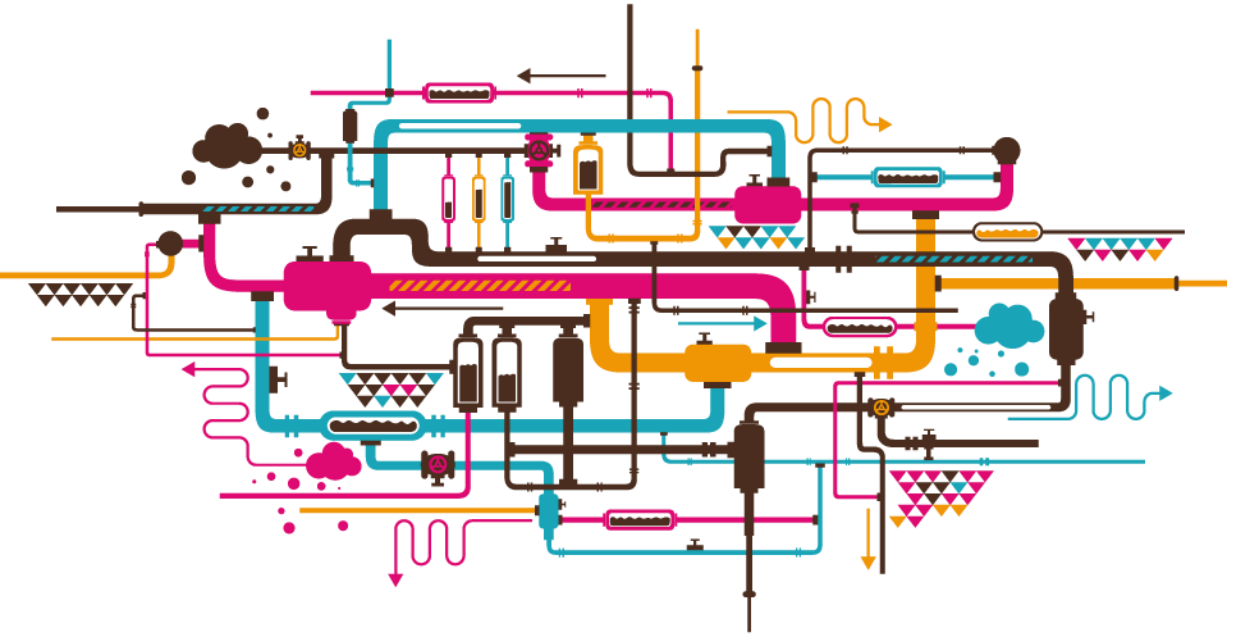


Joint EPS-SIF International School on Energy 2023

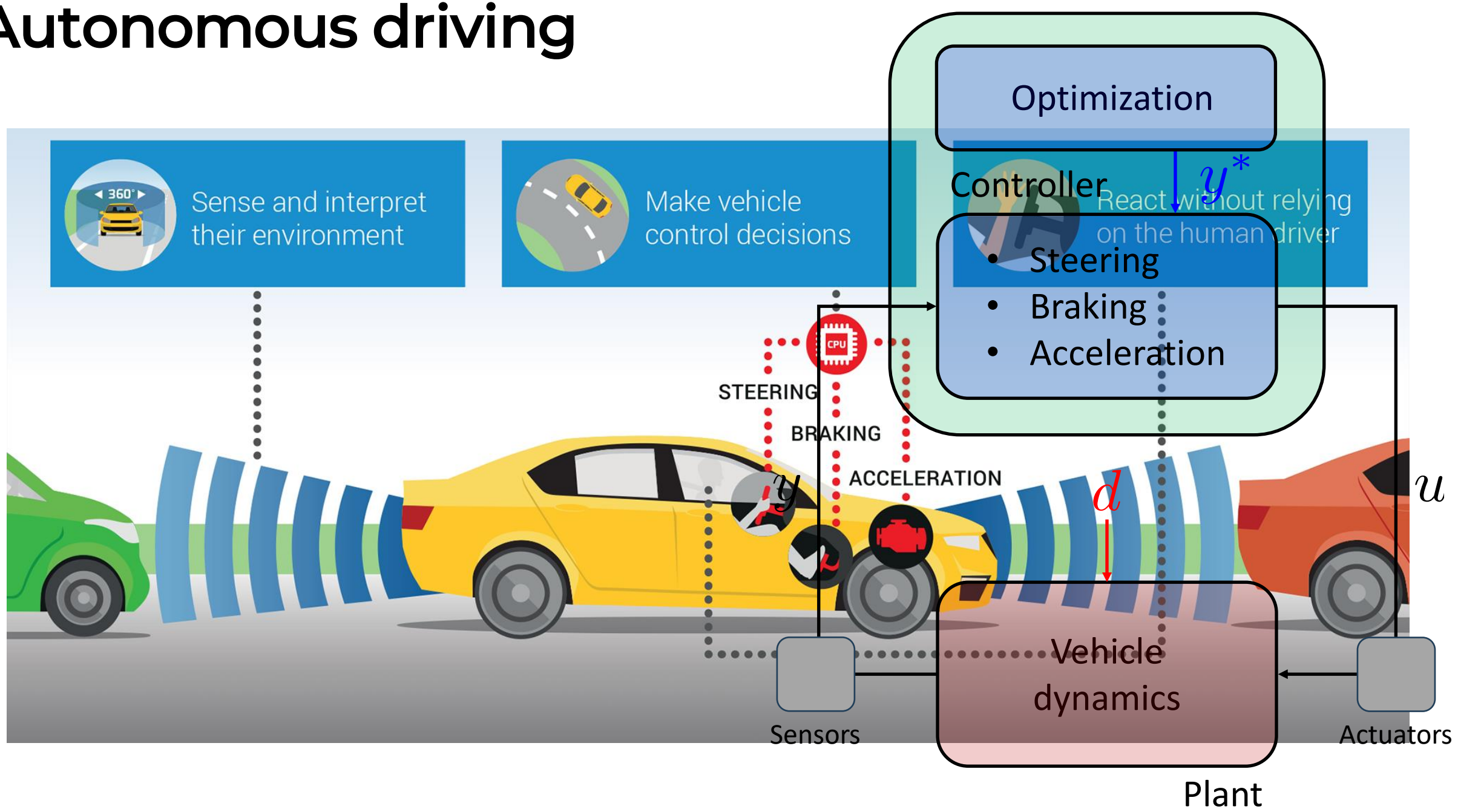


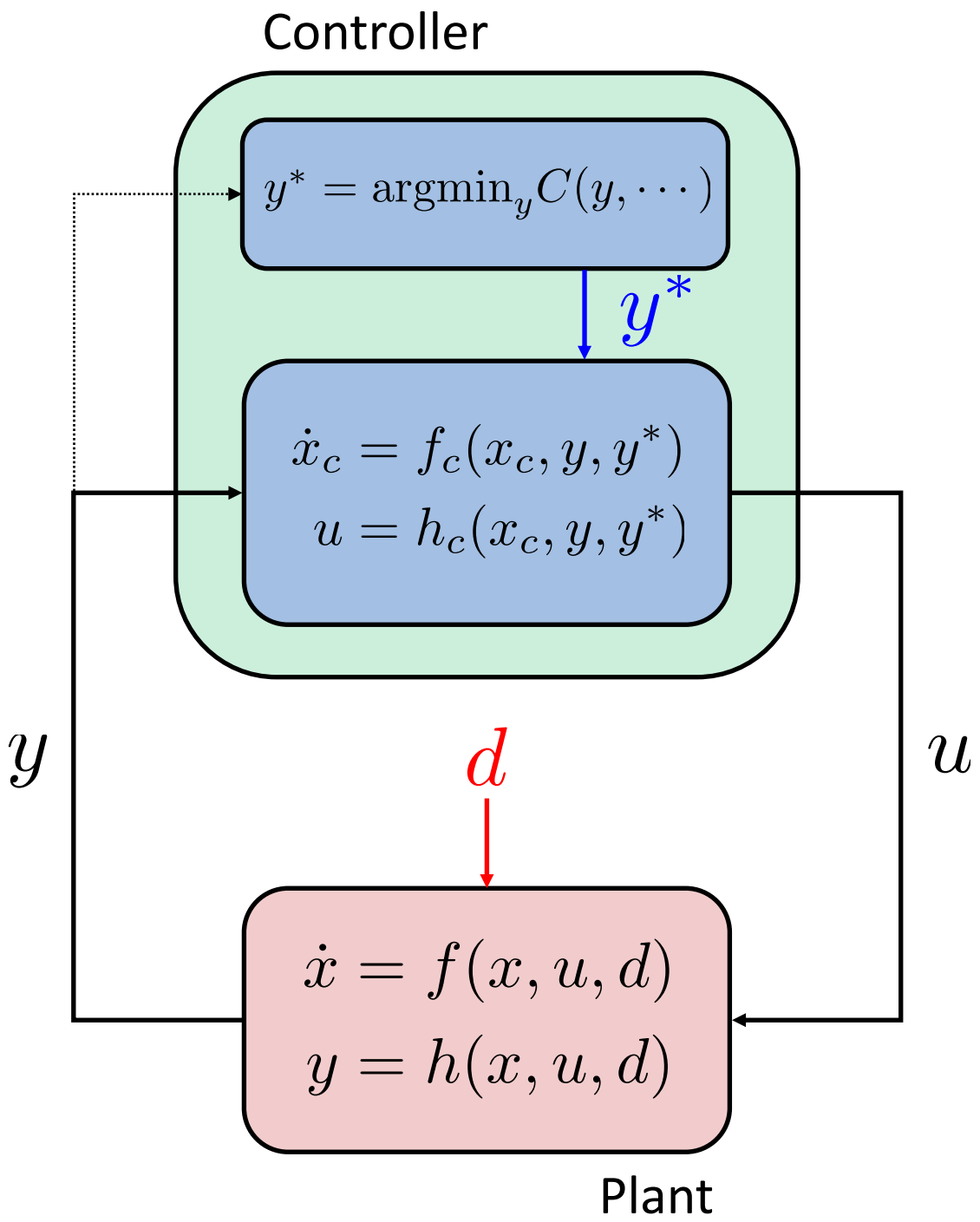
Modelling & Control of

Energy Networks

What is control?

Autonomous driving



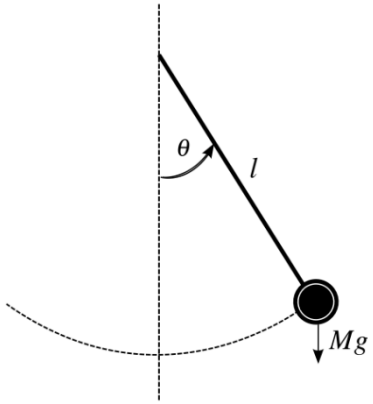


$$\dot{x} = Ax + Bu$$
$$u = Kx$$
$$x(t) = e^{At}x(0)$$

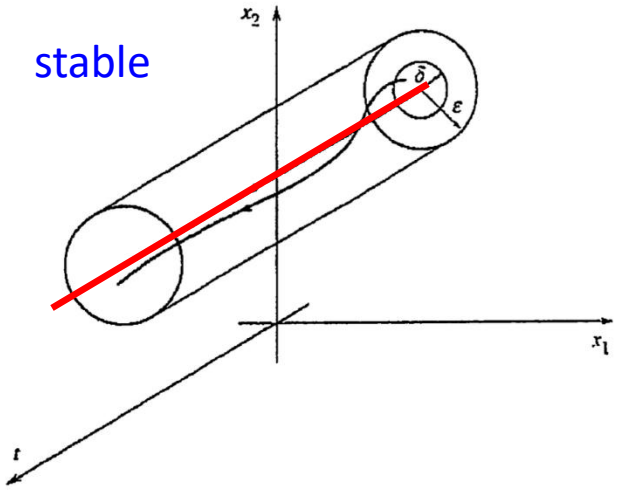
$$\dot{x} = (A + BK)x$$
$$x(t) = e^{(A+BK)t}x(0)$$

Stability concepts

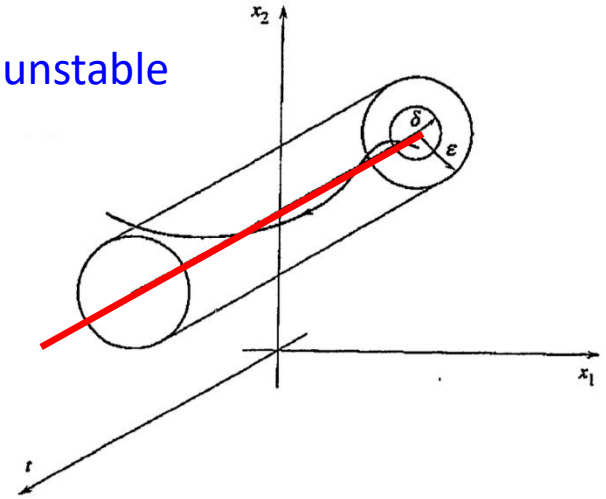
Think about a pendulum



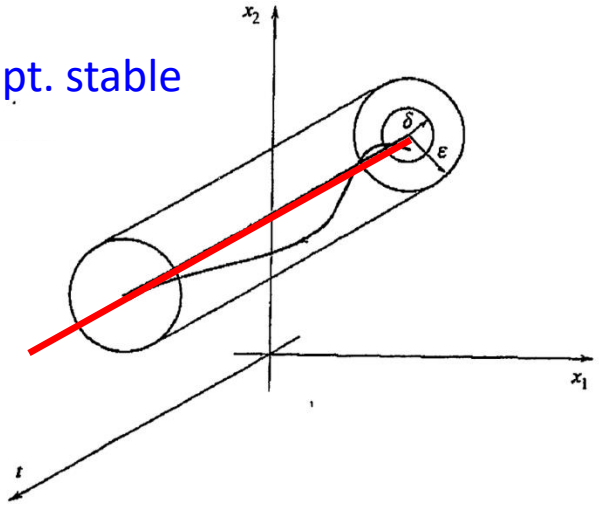
stable



unstable



asympt. stable



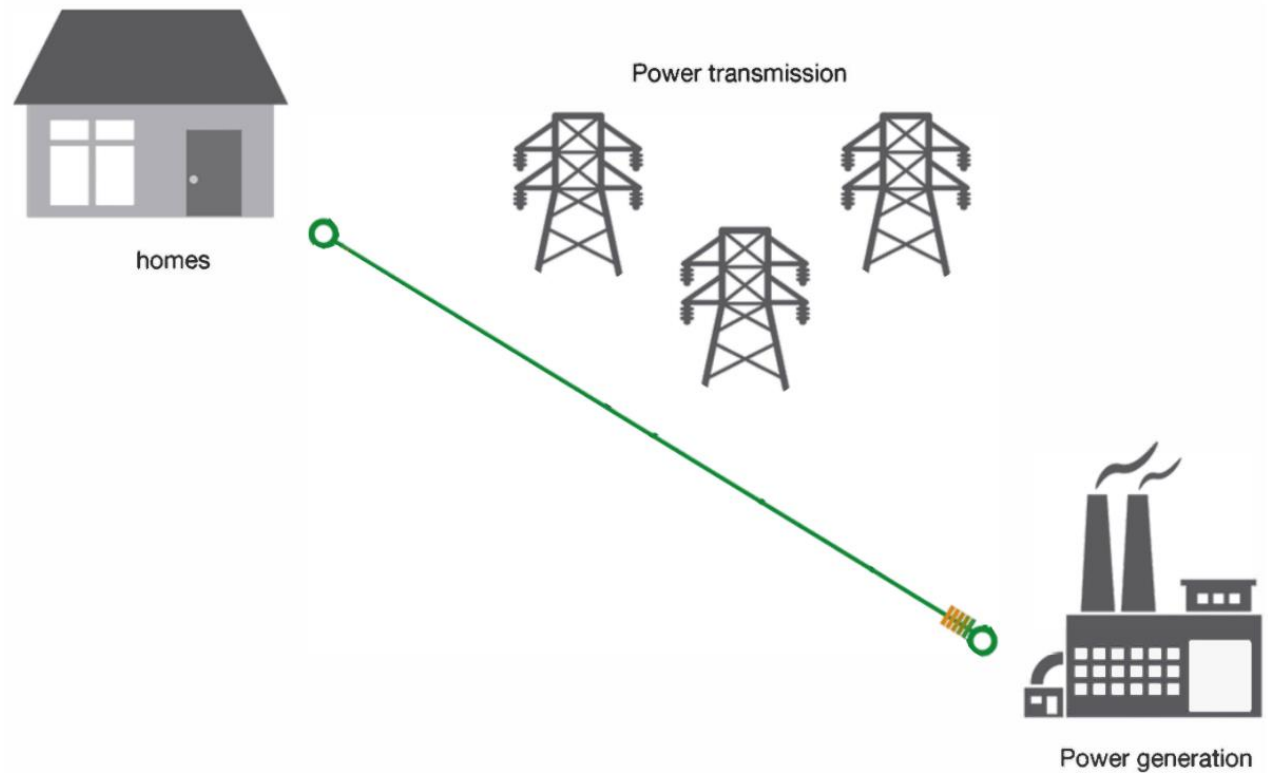
Goals

- Model and its properties
- Design control systems that provide "theoretical" guarantees!
- Stability analysis is related to energy-based considerations

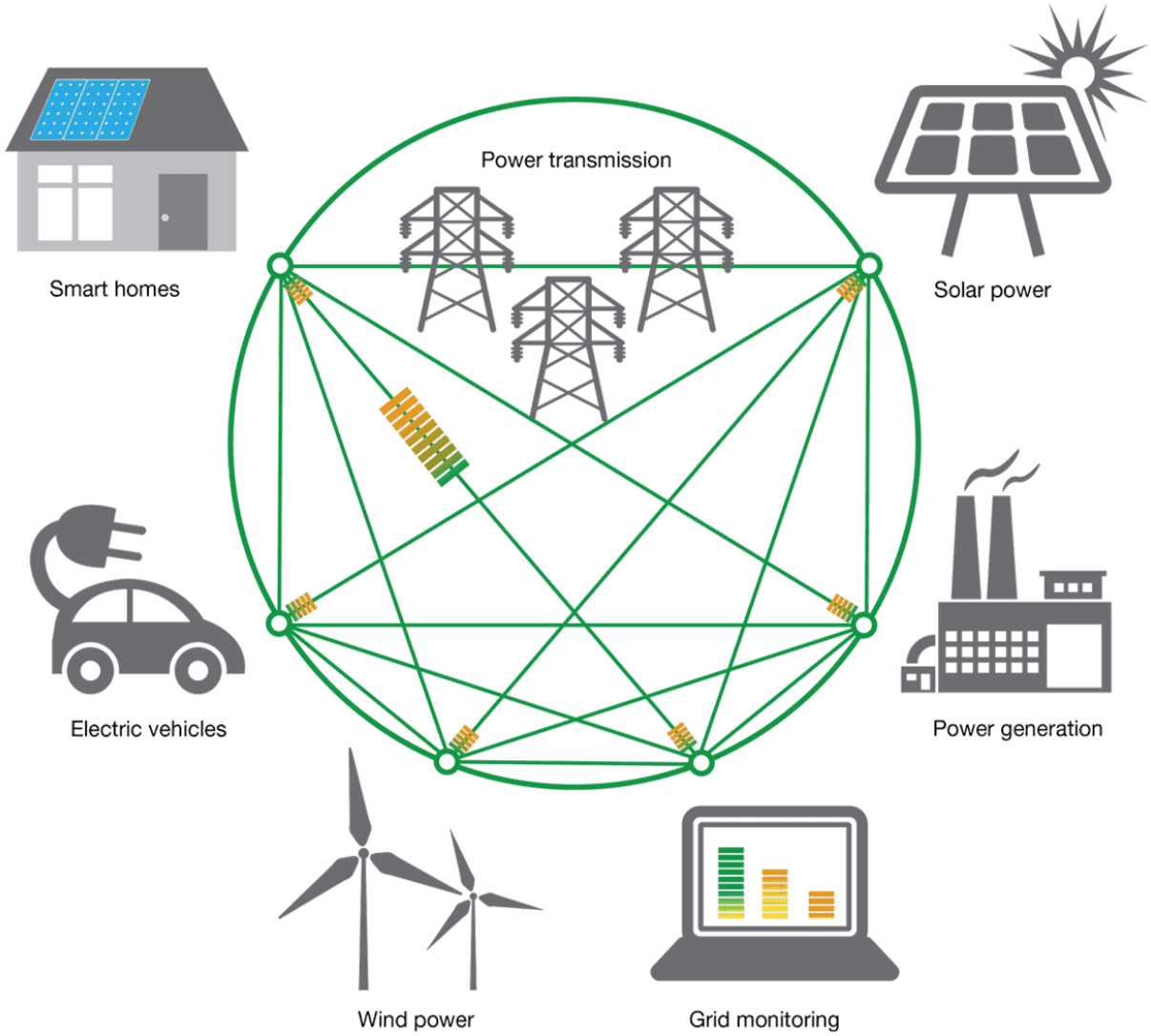
Problem: reality is different from models

George Box (1978): "All models are **wrong** but some are **useful**"

Traditional electricity network



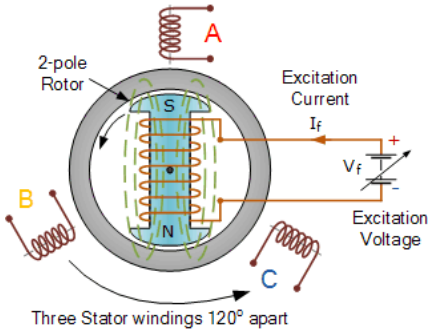
Nowadays electricity network



Problem

Traditional control systems are **NOT adequate** to deal with the increasing share of renewables!

Traditional power systems

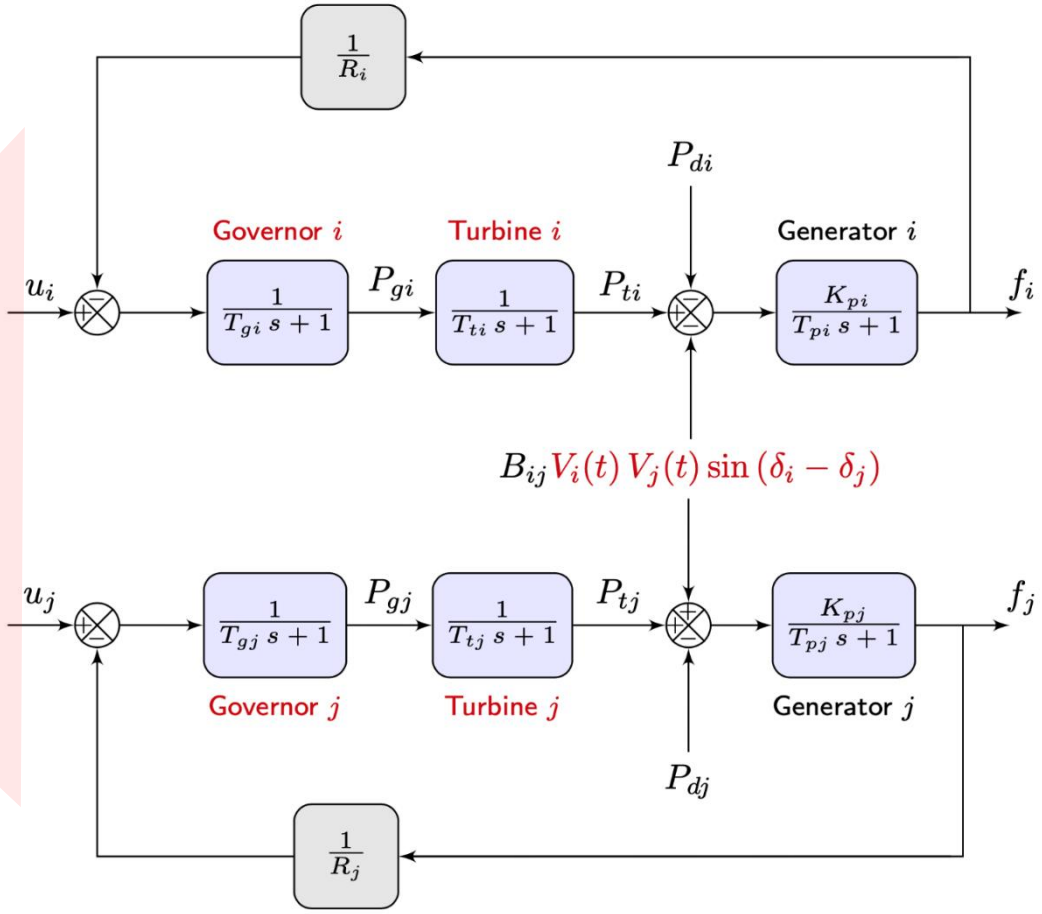


- Very robust and resilient
- Very complex dynamics

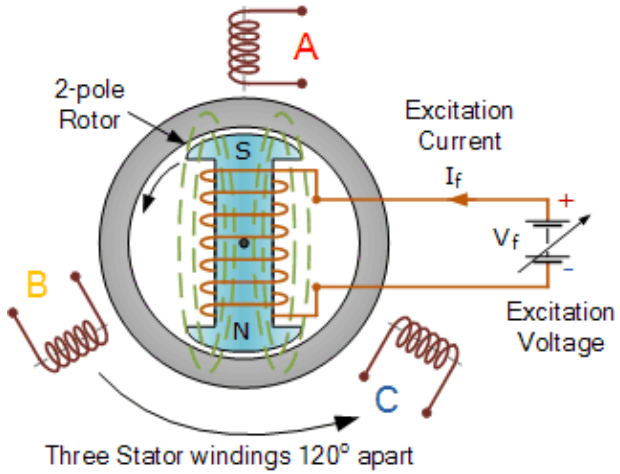
$$\dot{x} = f(x, u, d)$$
$$y = h(x, u, d)$$

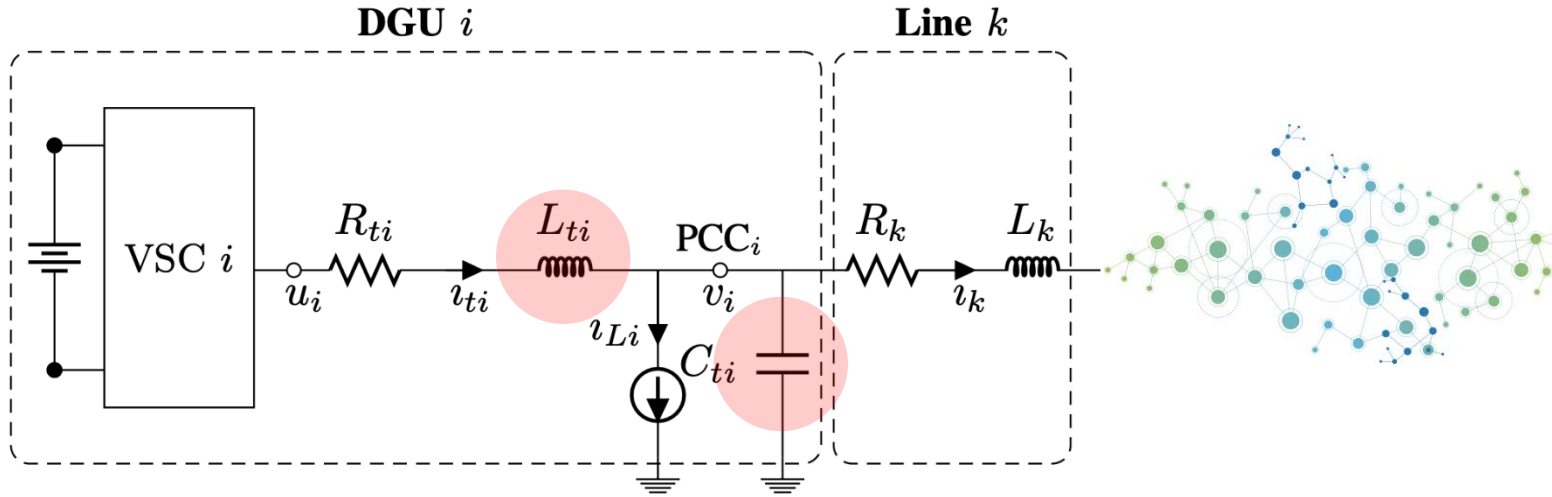
Plant

- Magic?



Will this magic still hold? NO





Power-Electronics-Dominated Systems

Objectives

- Frequency regulation

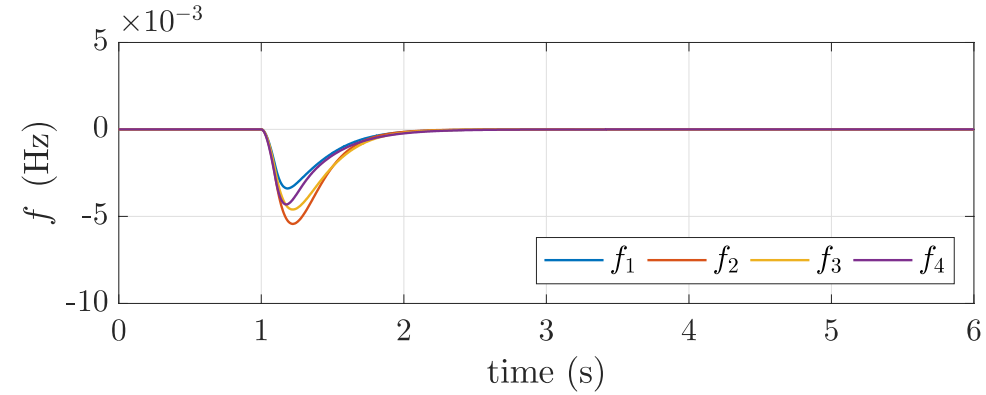
$$\lim_{t\to\infty} f(t) = \mathbf{0}.$$

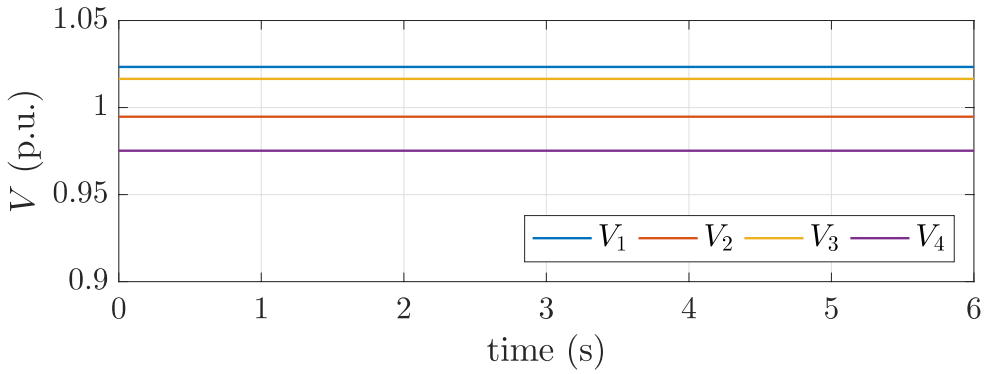
- Economic dispatch

$$\min \sum_{i\in\mathcal{V}} C_i(P_{ti})$$
$$\text{s.t.} \quad \mathbb{1}_n^T(\overline{u} - \overline{P}_d) = 0.$$

Numerical validation

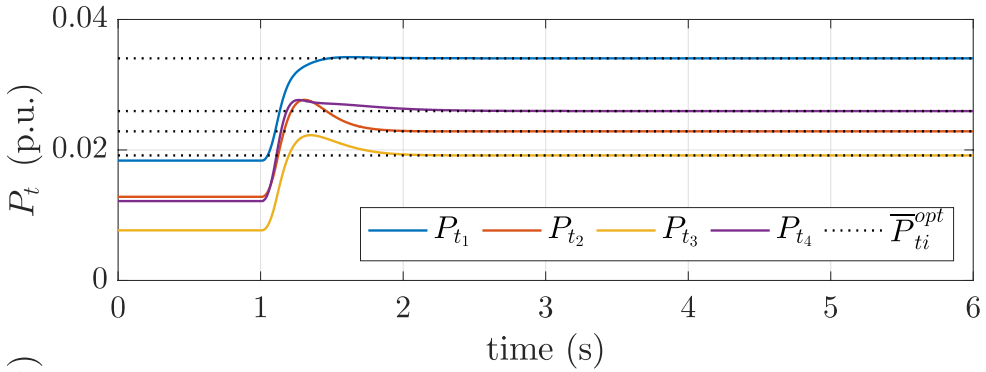
Frequency deviations converge to zero

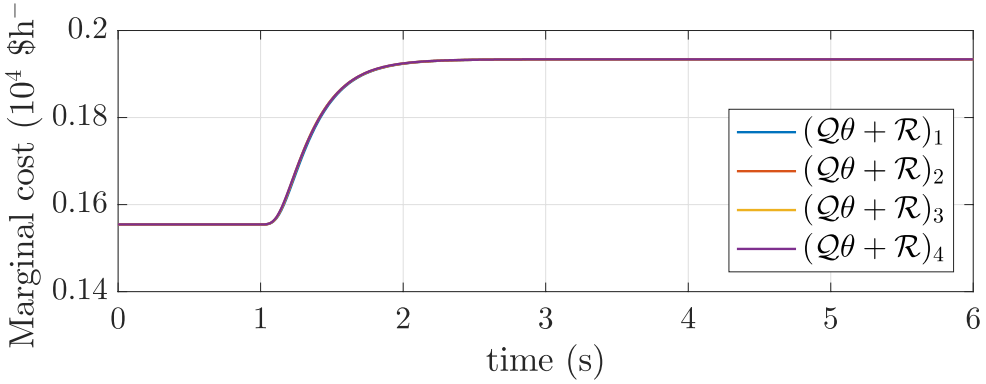




Voltages are stable

Generated powers converge to optimal values





Consensus on the marginal cost is achieved

The war of the currents

Tesla

Westinghouse

Examples

DC-DC converters

There are mainly two types of DC/DC converters:

- **Buck** converters
  step-down the input voltage

- **Boost** converters
  step-up the input voltage

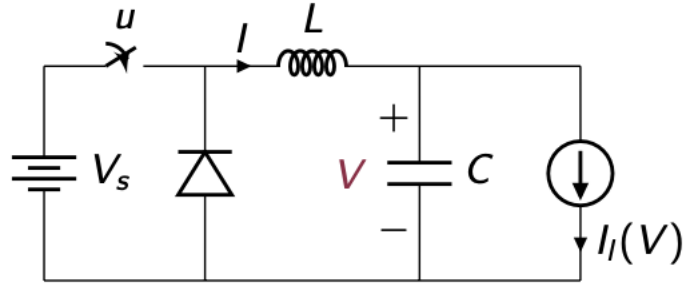


Figure: Buck converter.

$$\begin{aligned} -L\dot{I} &= V - uV_s, \\ C\dot{V} &= I - I_l(V). \end{aligned}$$

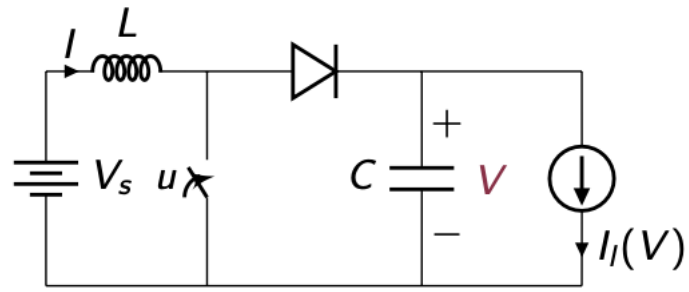


Figure: Boost converter.

$$\begin{aligned} -L\dot{I} &= (1-u)V - V_s, \\ C\dot{V} &= (1-u)I - I_l(V). \end{aligned}$$

Objectives

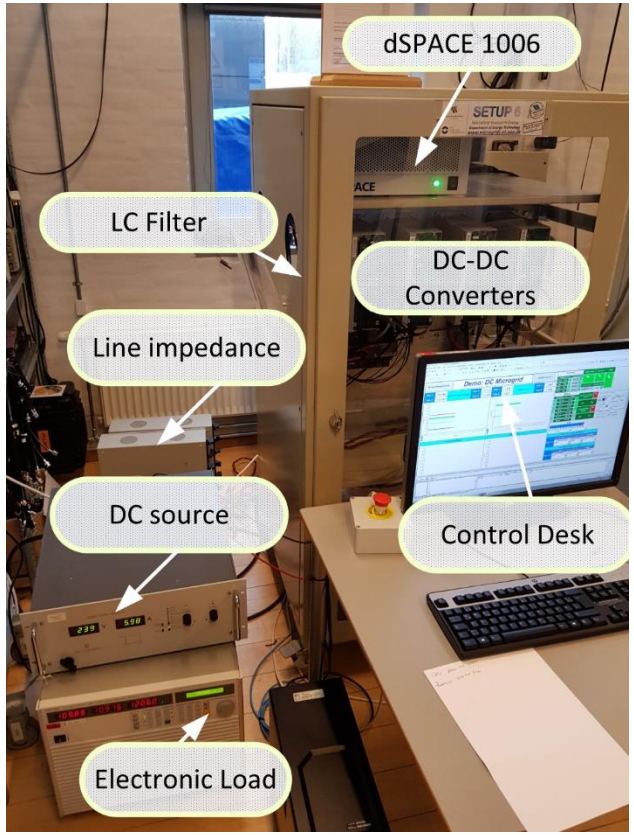
- Voltage regulation

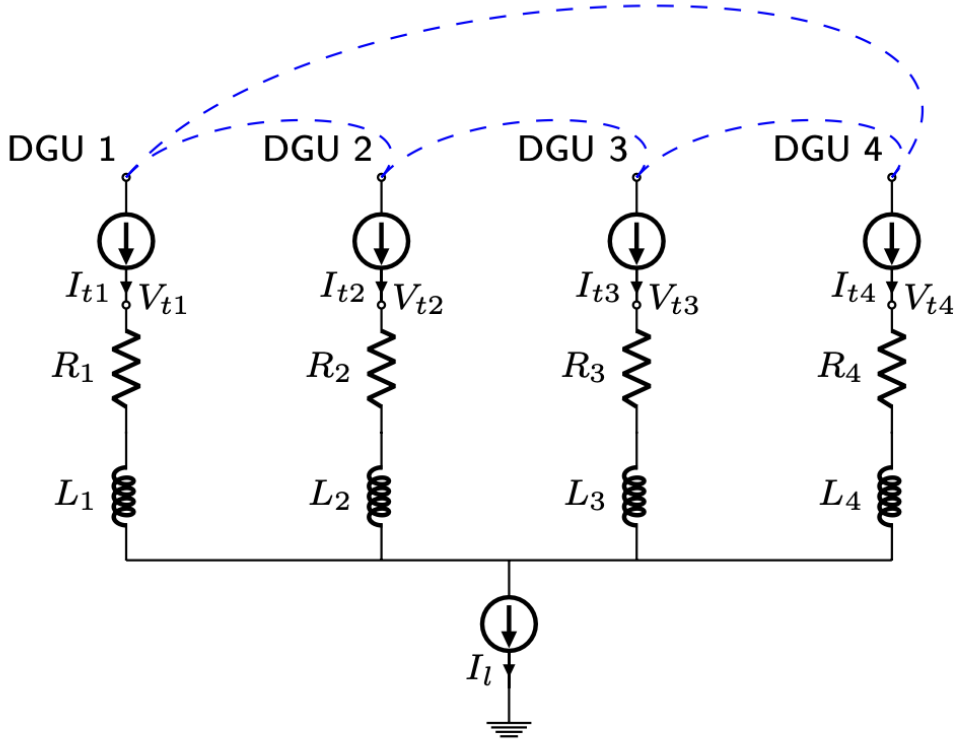
$$\lim_{t\to\infty} V(t) = \overline{V} = V^*.$$

- Current sharing (cooperation)

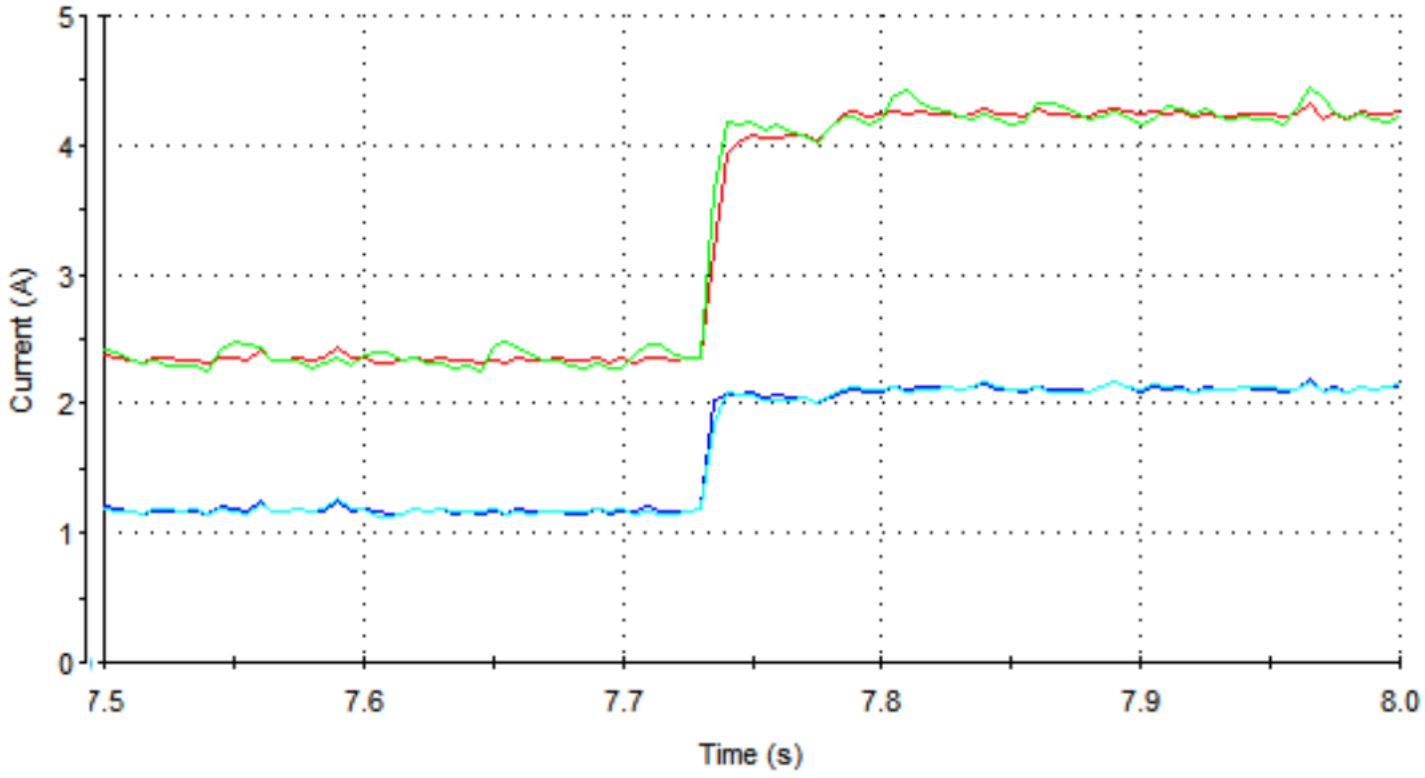
$$I_i = I_j$$

Experiments (Aalborg): current sharing

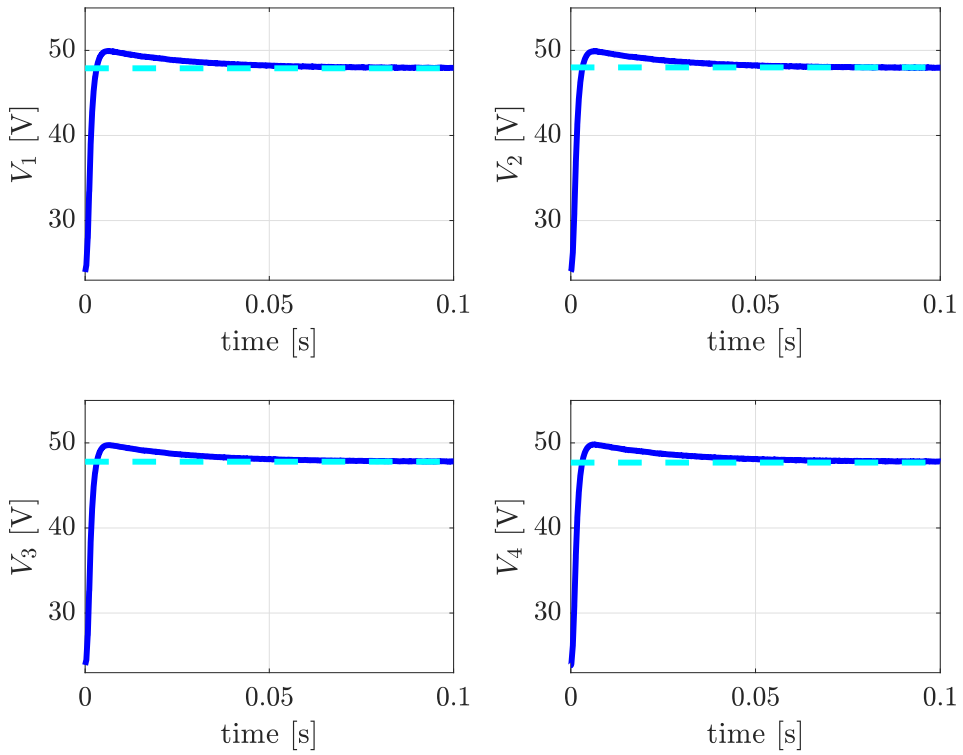


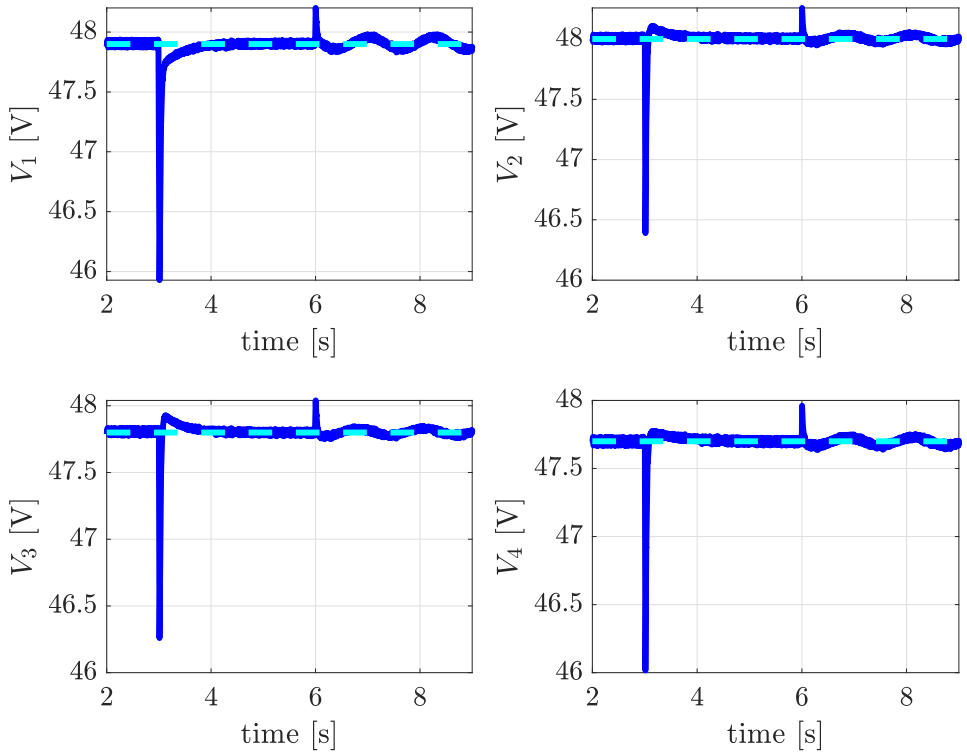


Experiments (Aalborg): current sharing



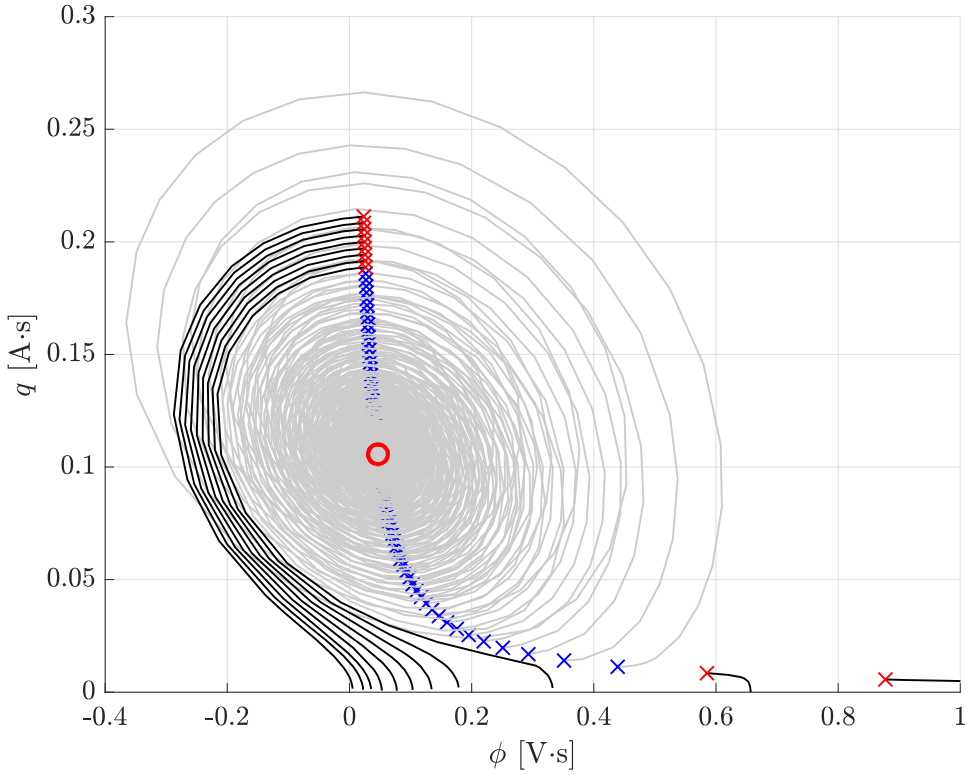
Numerical validation: voltage stability



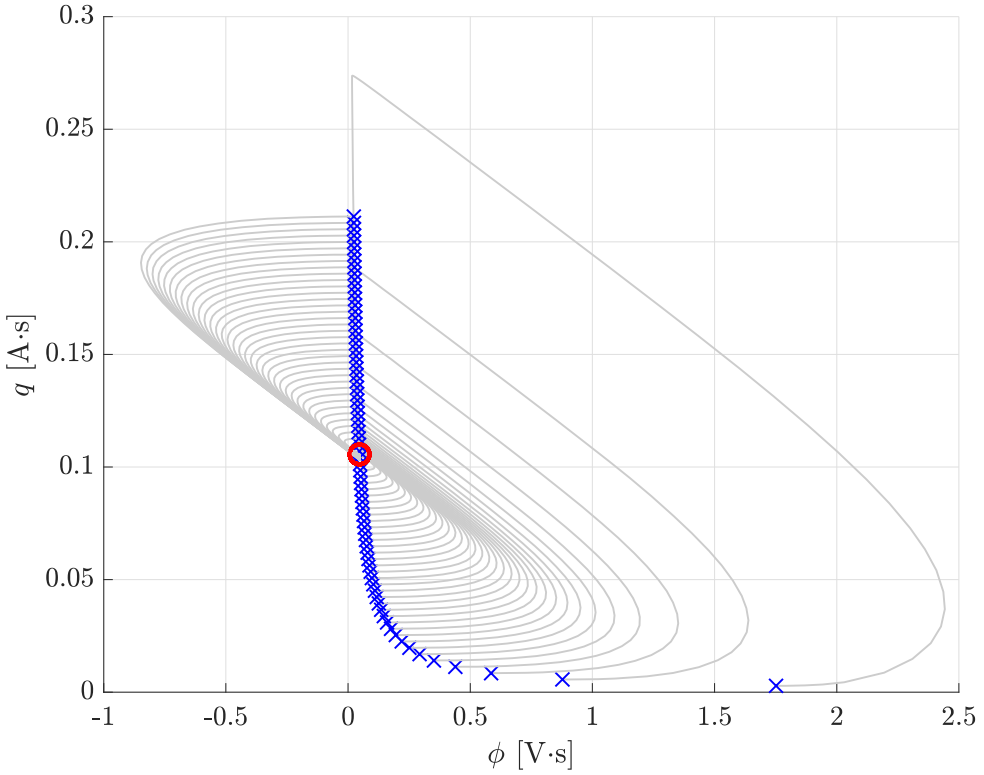


Numerical validation: ZIP loads

ZIP loads: local stability

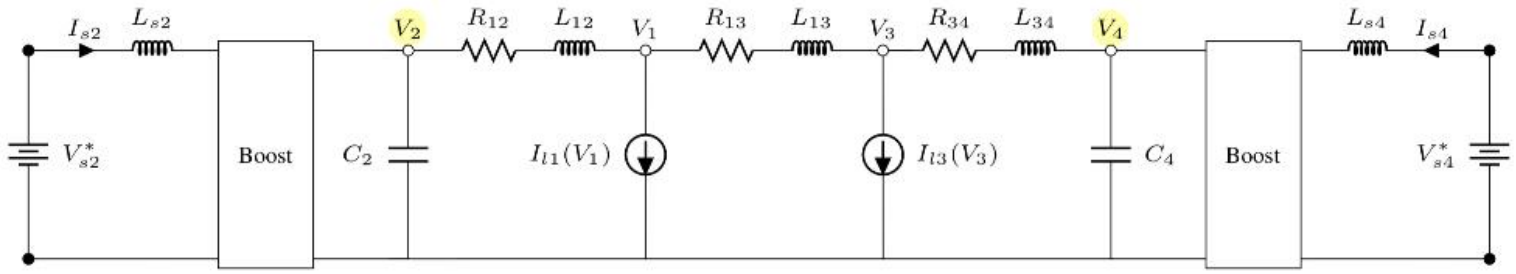


Our controller enlarges the Region of Attraction



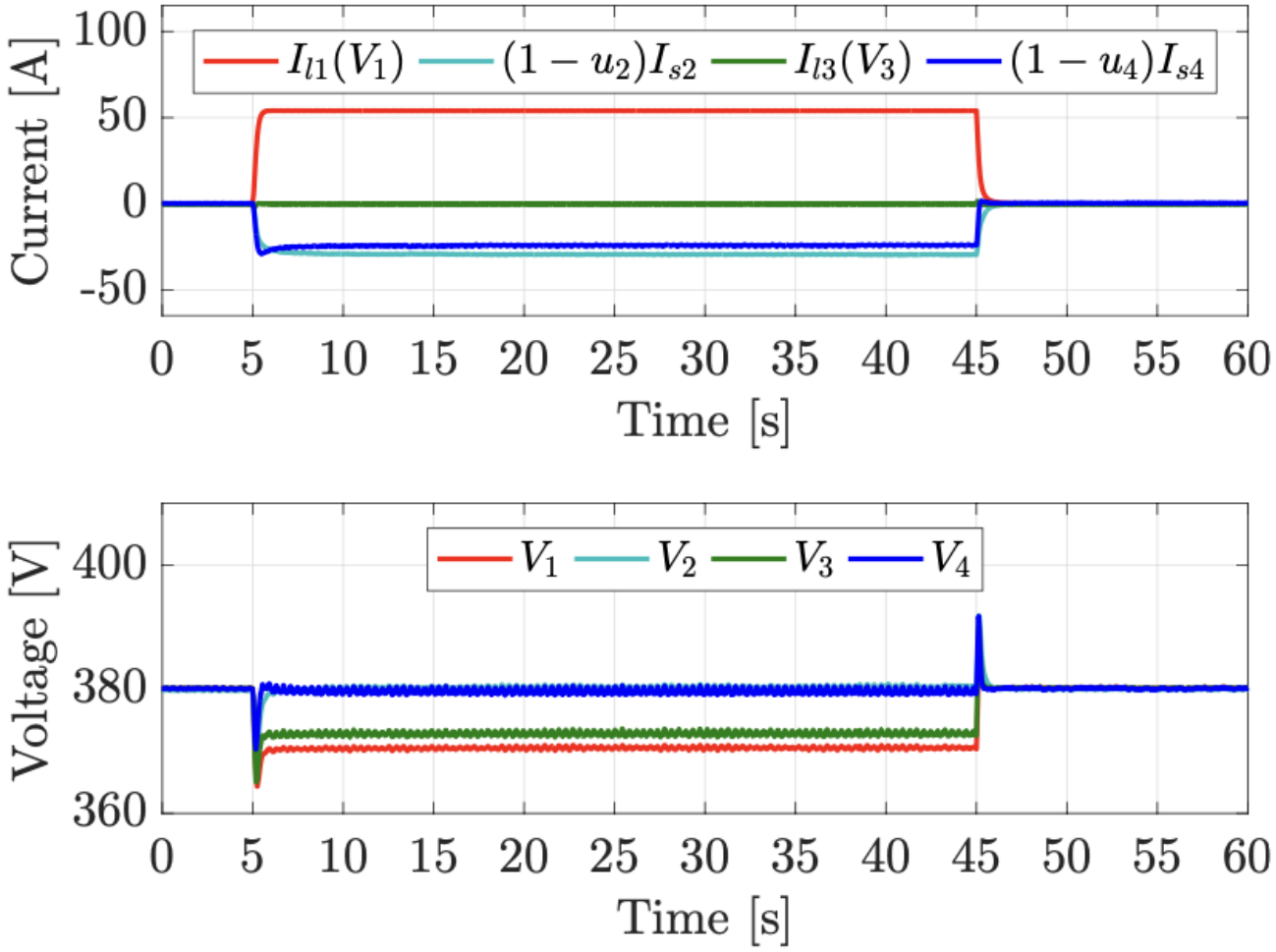
Experiments (Milano): voltage stability

Only V_2 and V_4 are controlled



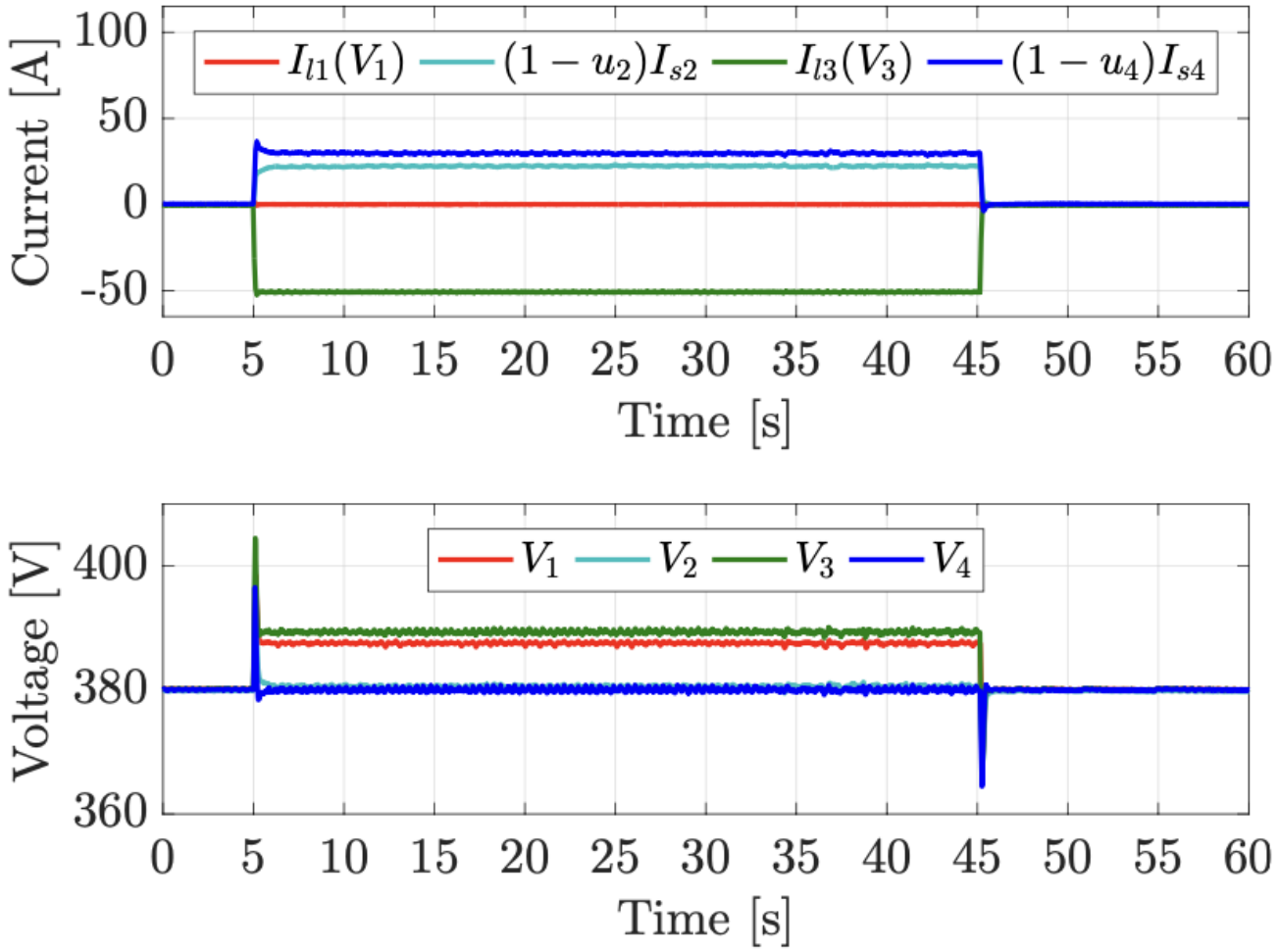
Experiments (Milano): voltage stability

Load variation of 20 kW from $t = 5$ s to $t = 45$ s



Experiments (Milano): voltage stability

PV variation of 20 kW from $t = 5$ s to $t = 45$ s



Ongoing research topics

Energy domain

Heating networks

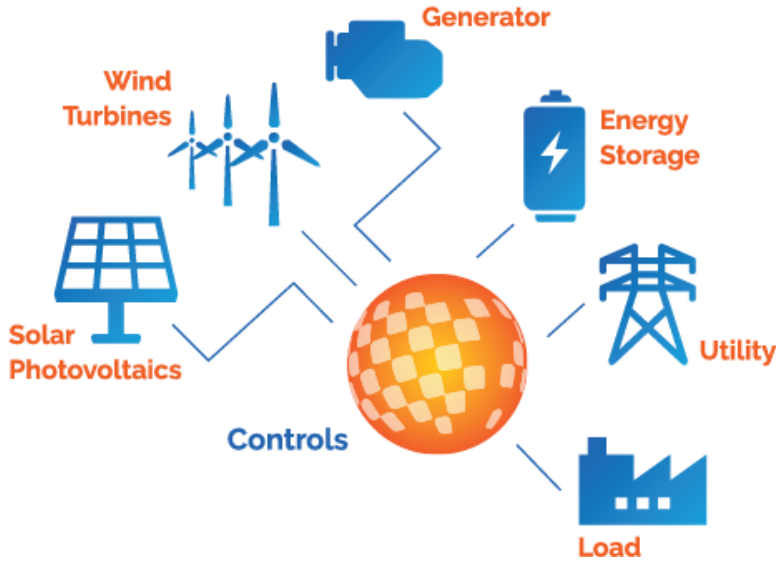
Power networks

EVs

Traffic networks

Energy domain

Heating networks



Power networks

EVs

Traffic networks

Challenges:

- Nonlinearities & uncertainties
- Privacy & cyber security
- Storage systems
- Energy management
- Controllability

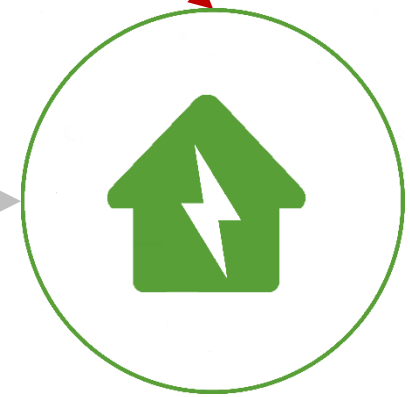
Energy domain

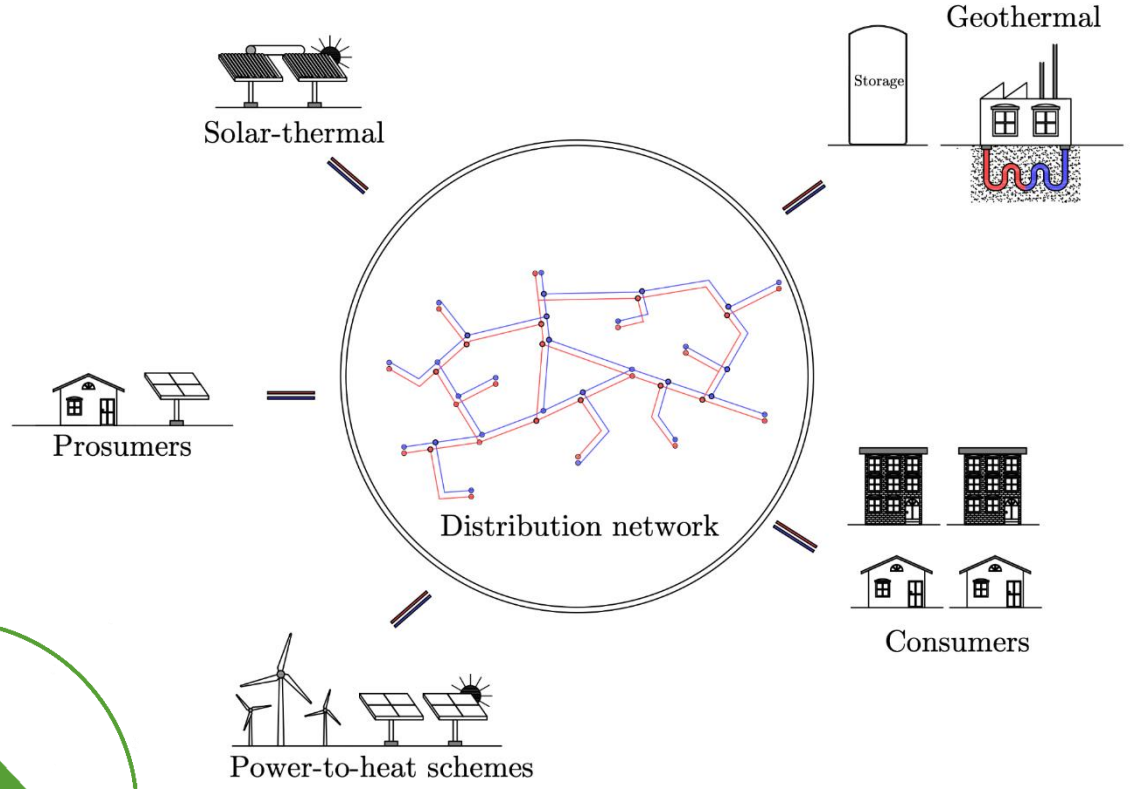
Heating networks

Power networks

EVs

Traffic networks



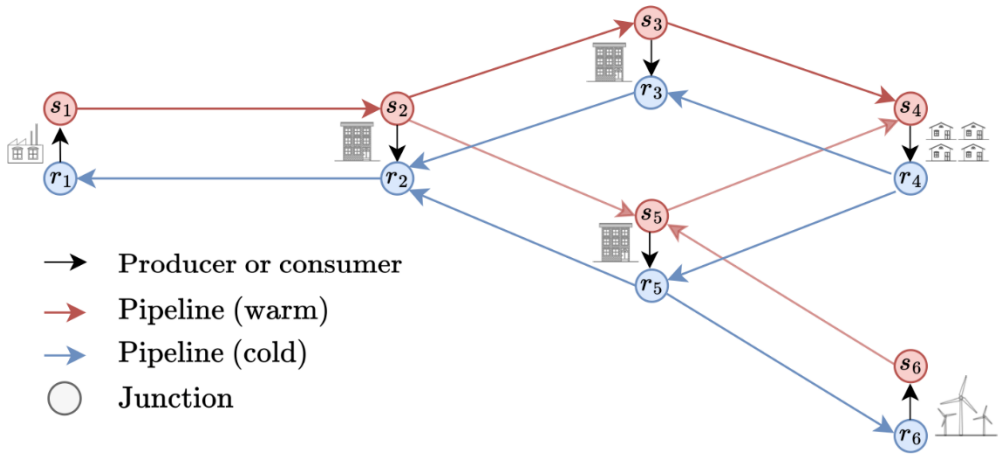


Challenges:

- Lack of results
- Multiple producers/tanks
- Time delays
- Energy management system

Heating networks

Existence and **Uniqueness** of **hydraulic** equilibrium in district heating systems with meshed topology and multiple heat sources/consumers

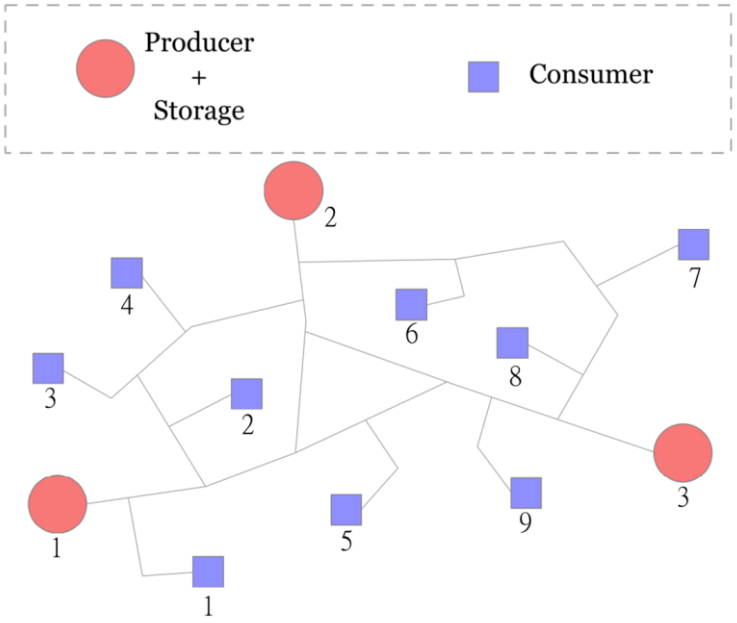


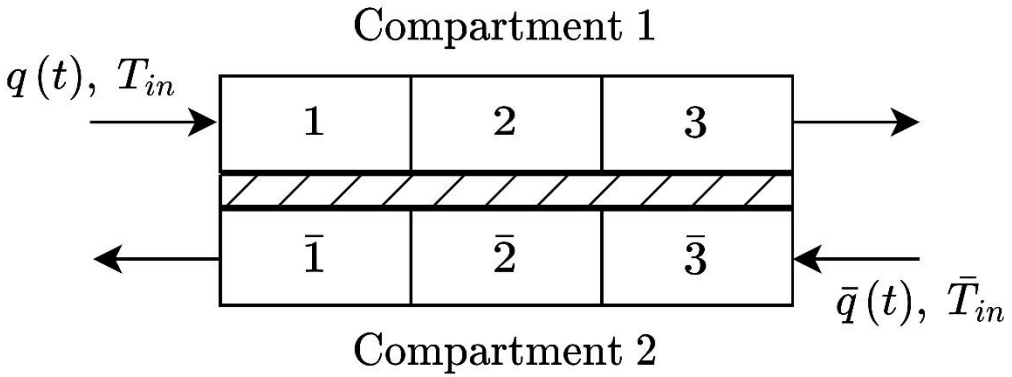
- necessary and sufficient graph-theoretic conditions on the **actuator placement**
- essential step to determine suitable and feasible **setpoints**

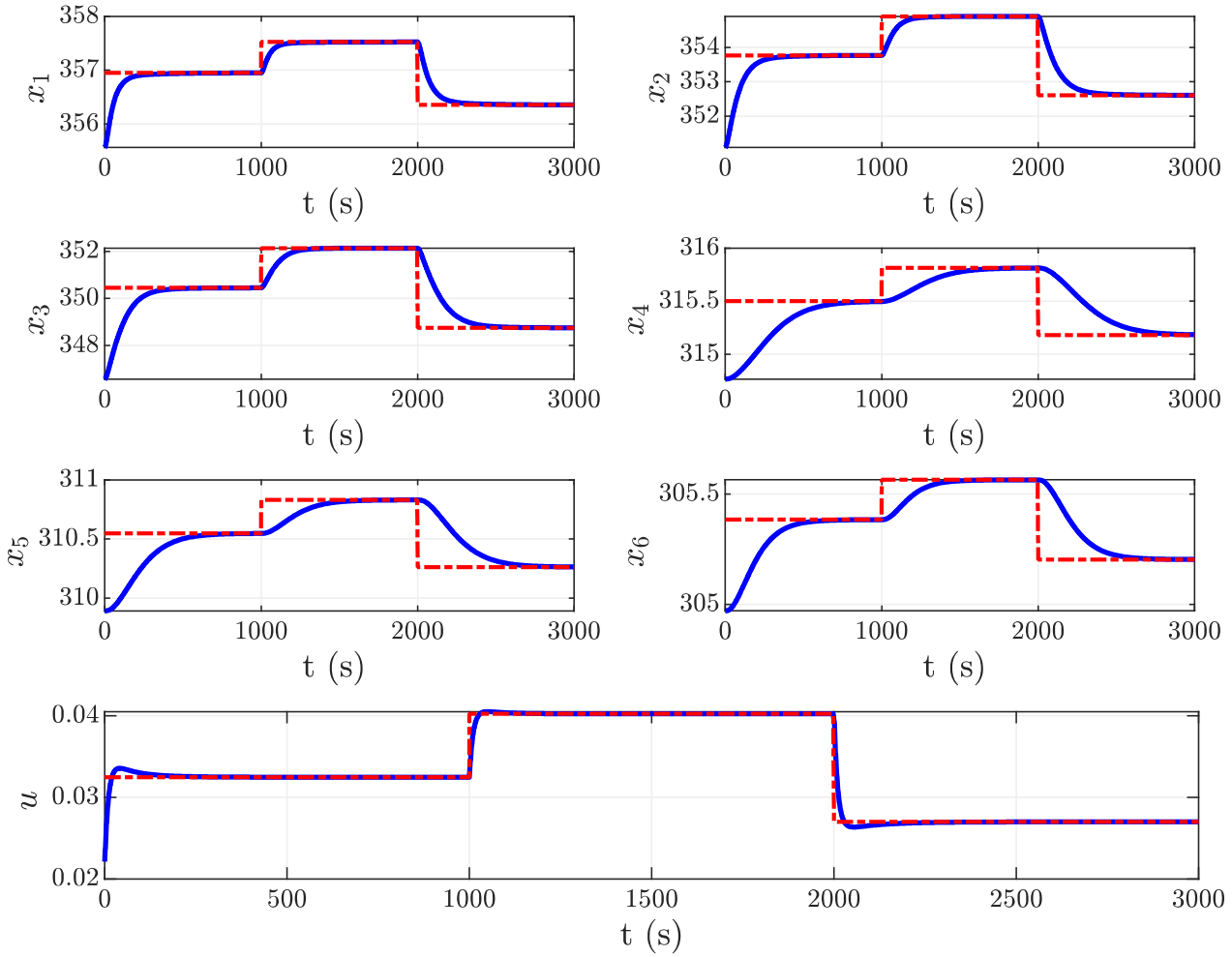
Ongoing results for the **thermal** equilibrium

Heating networks

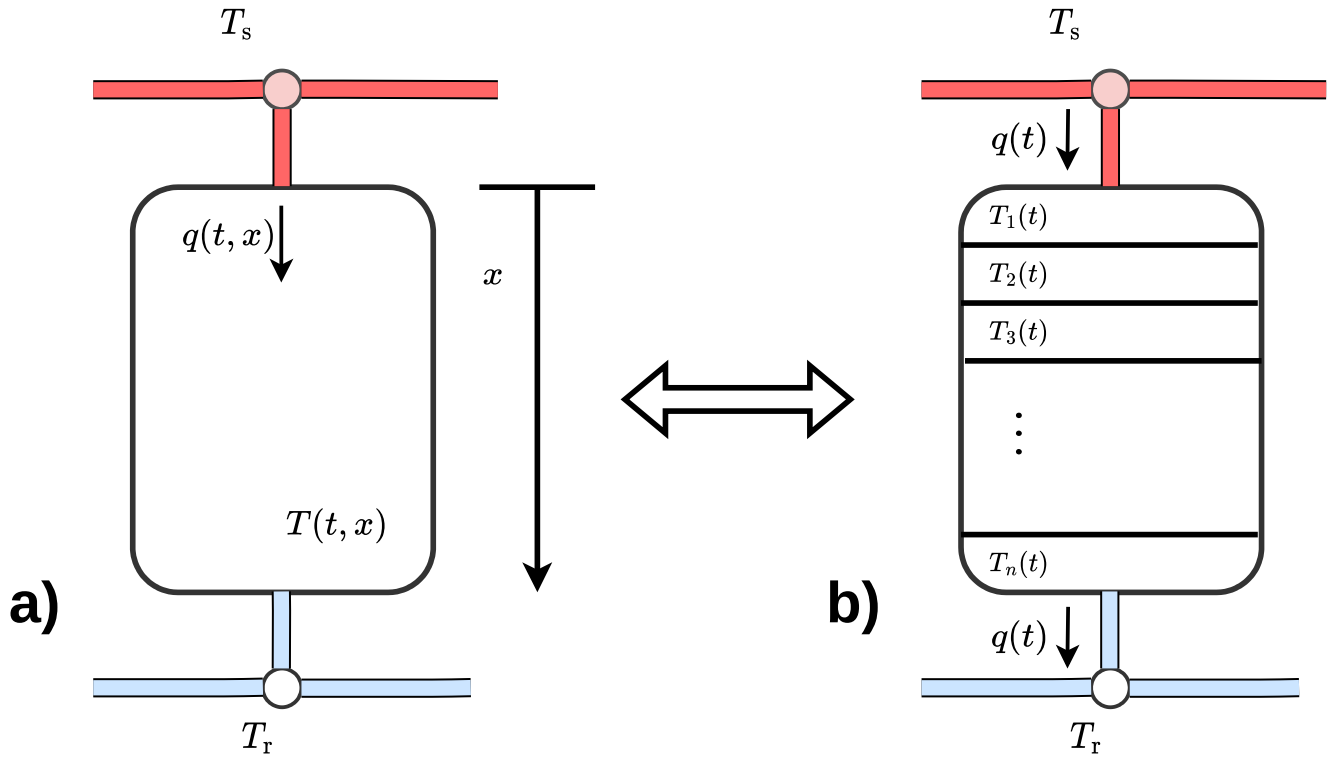
Ectropy…



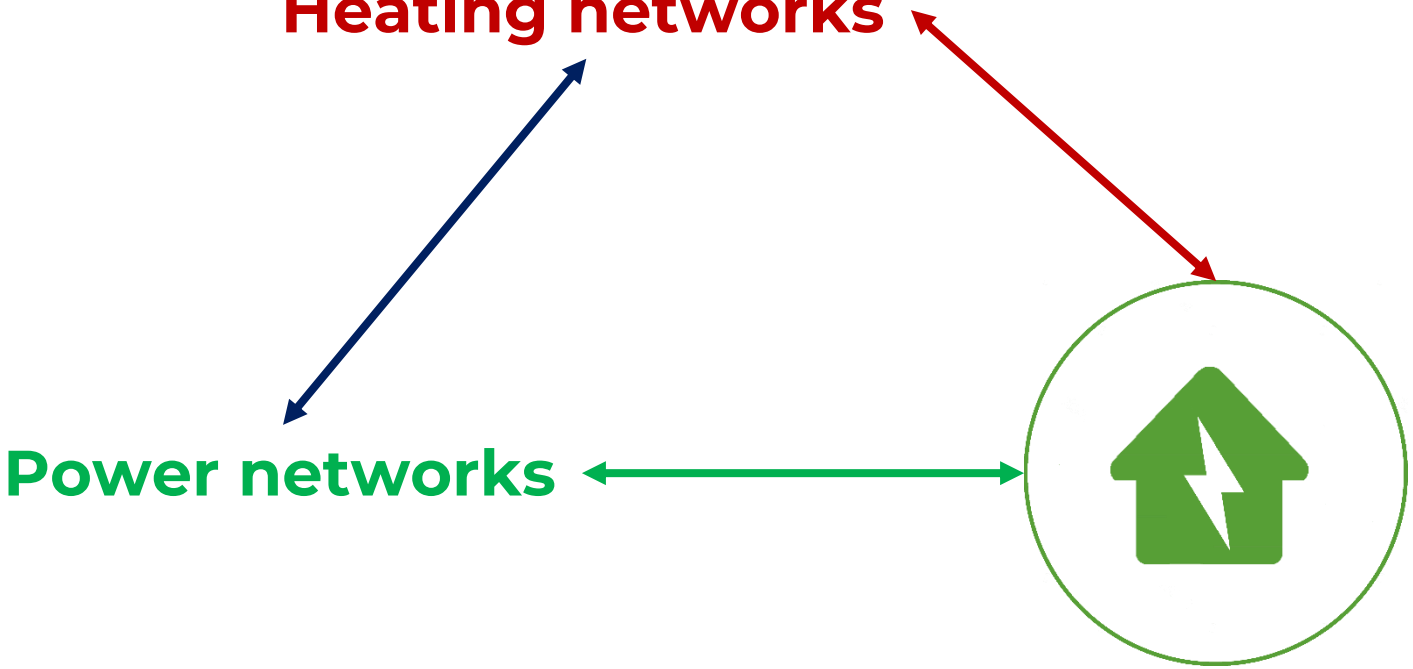


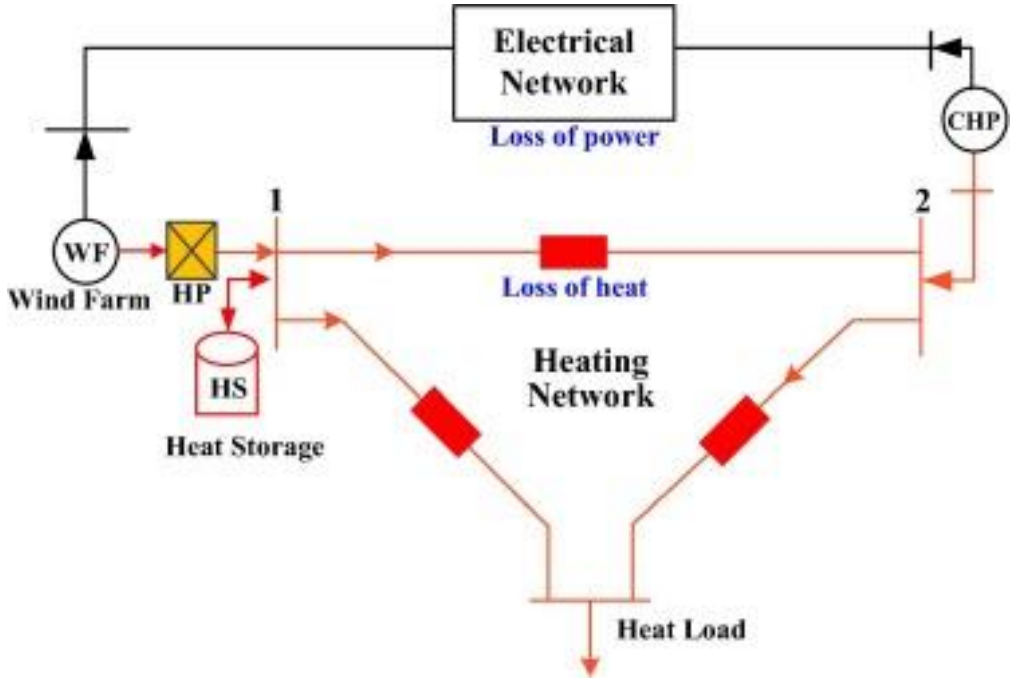


Storage tank: estimation & control



Energy domain

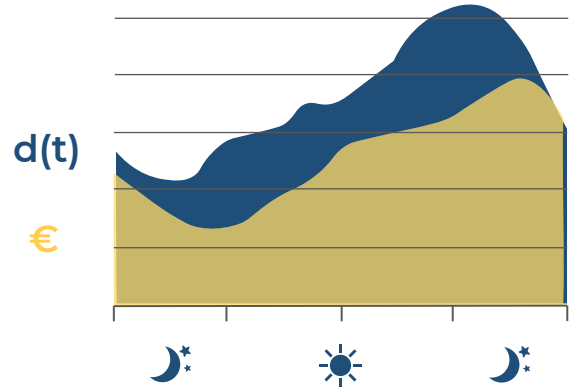




Challenges:

- Integration

Energy domain



- Valley filling
- Price proportional to demand

Heating networks

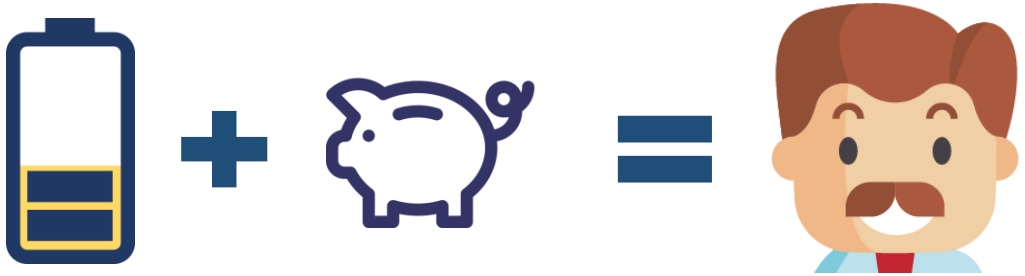
Power networks

EVs

Traffic networks

G2V

V2G

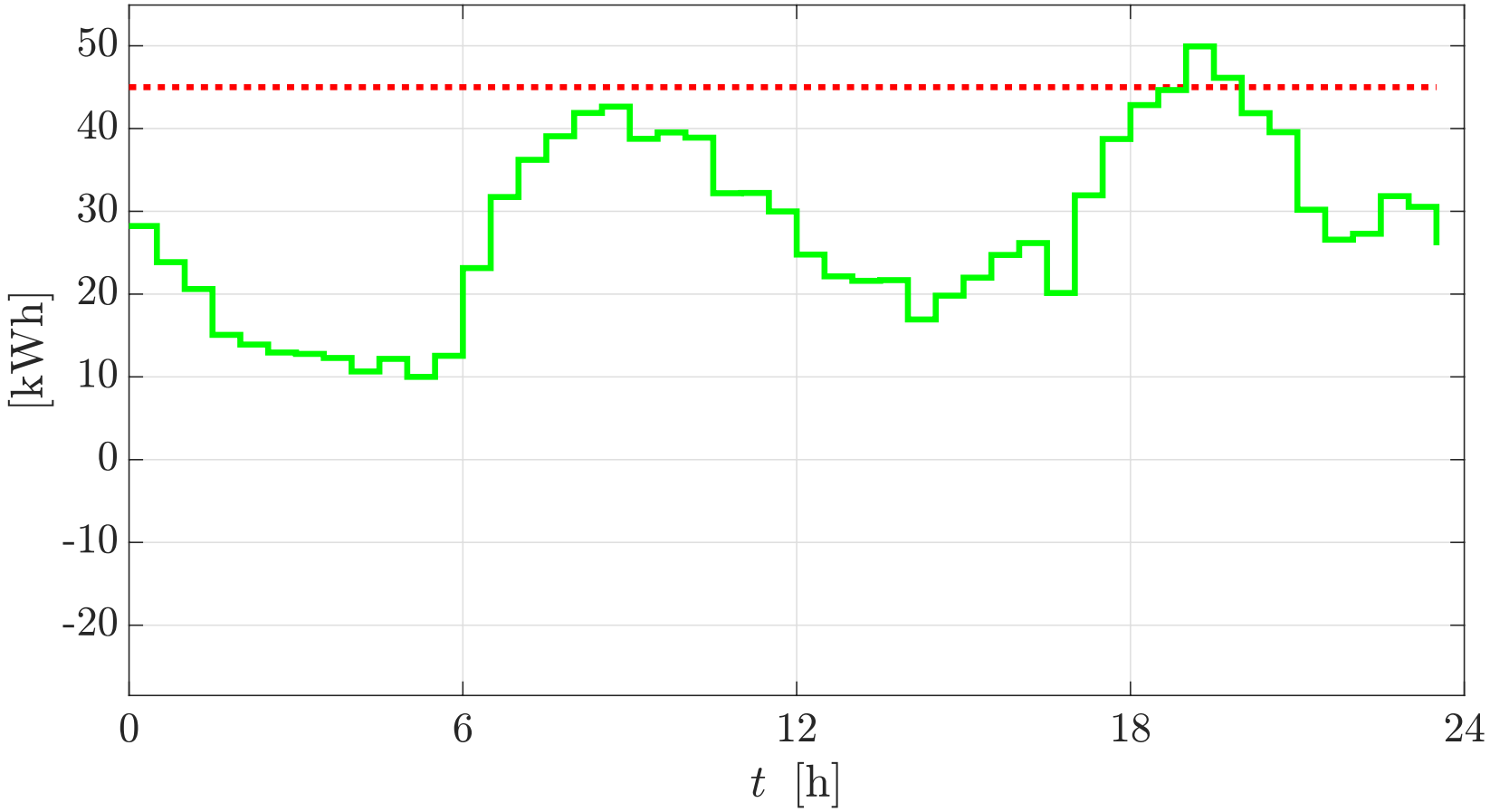


Game theory

Simulations

Grid capacity

Non EV demand

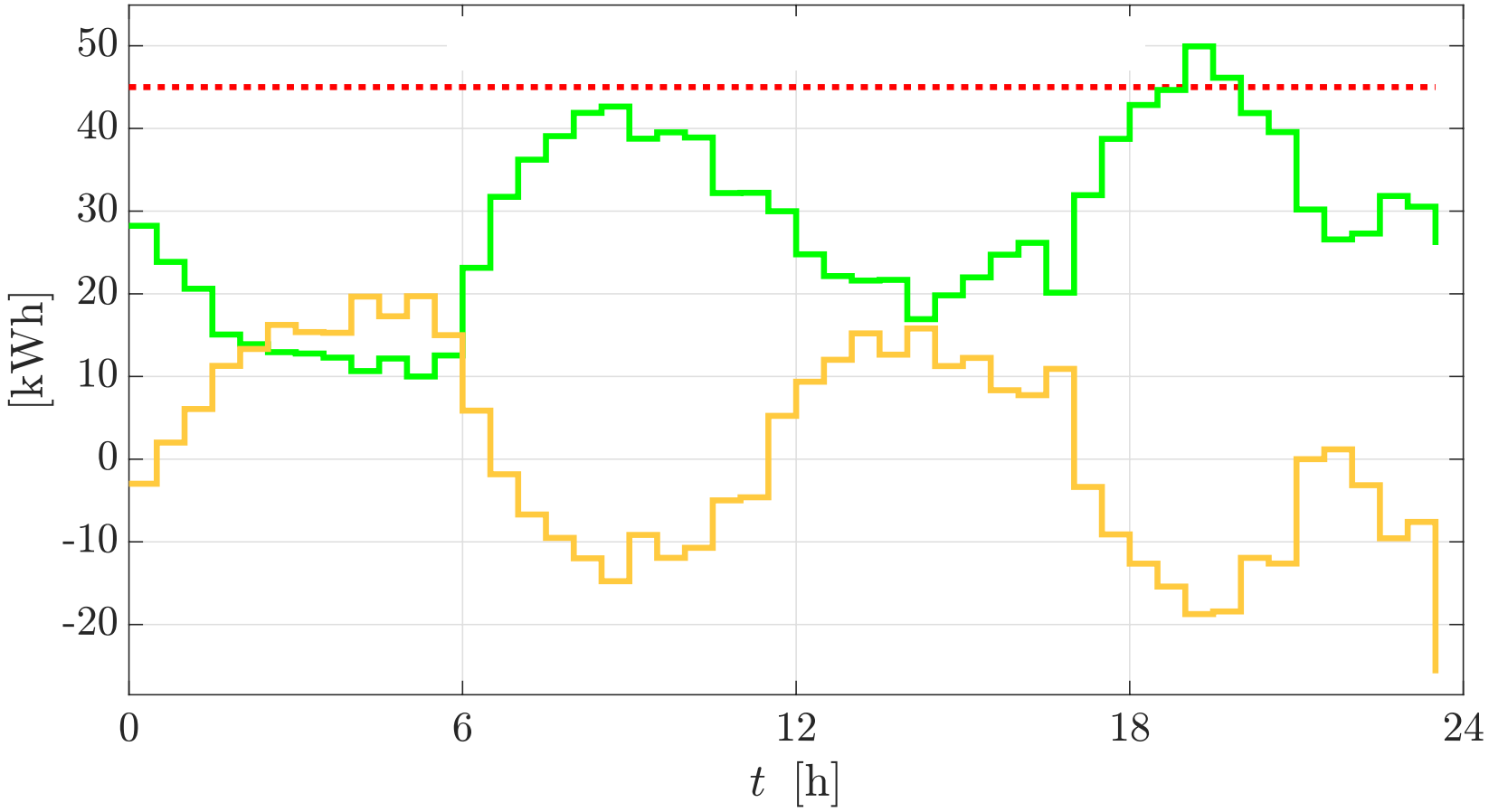


Simulations

Grid capacity

EV demand

Non EV demand

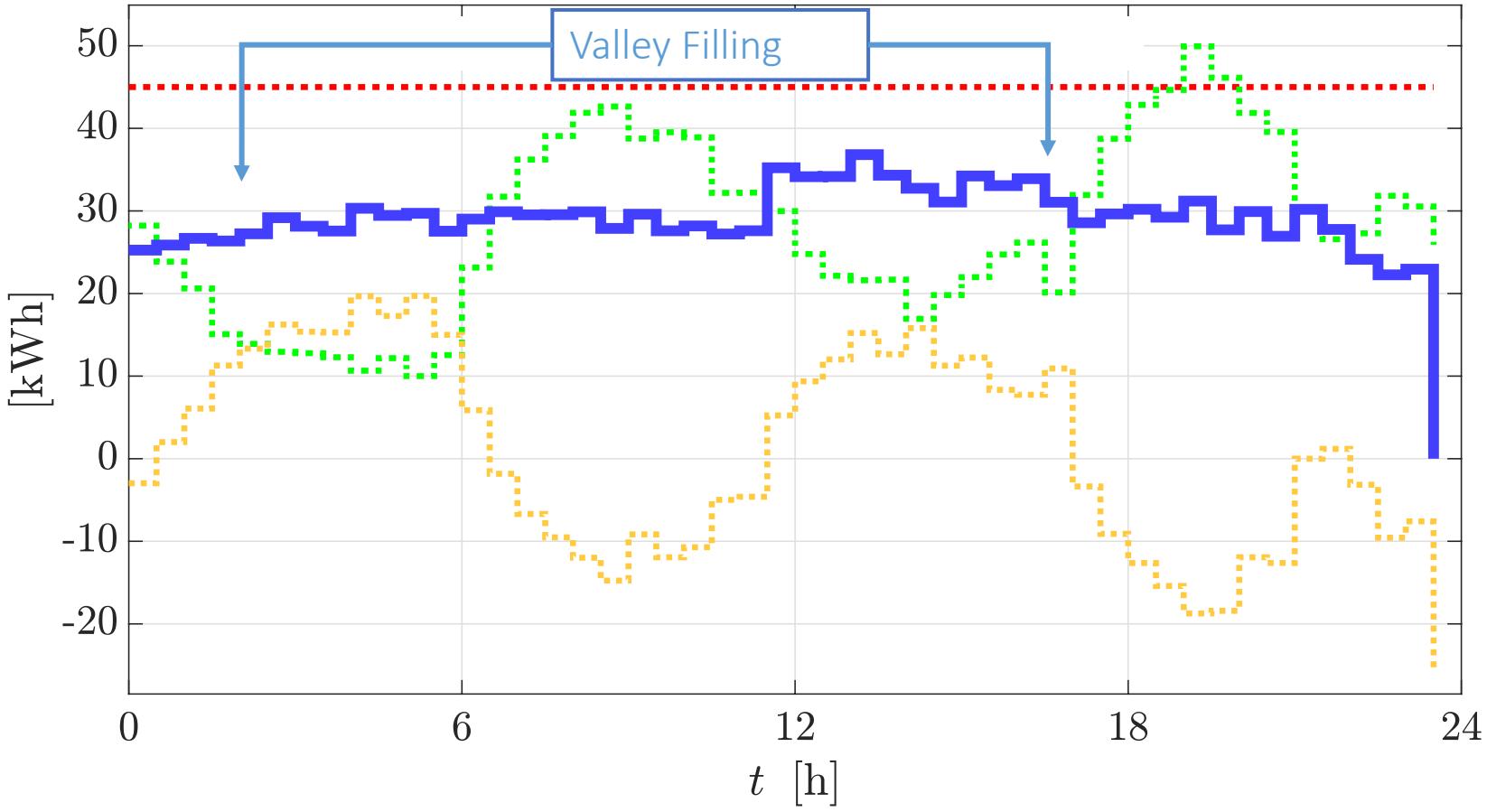


Simulations

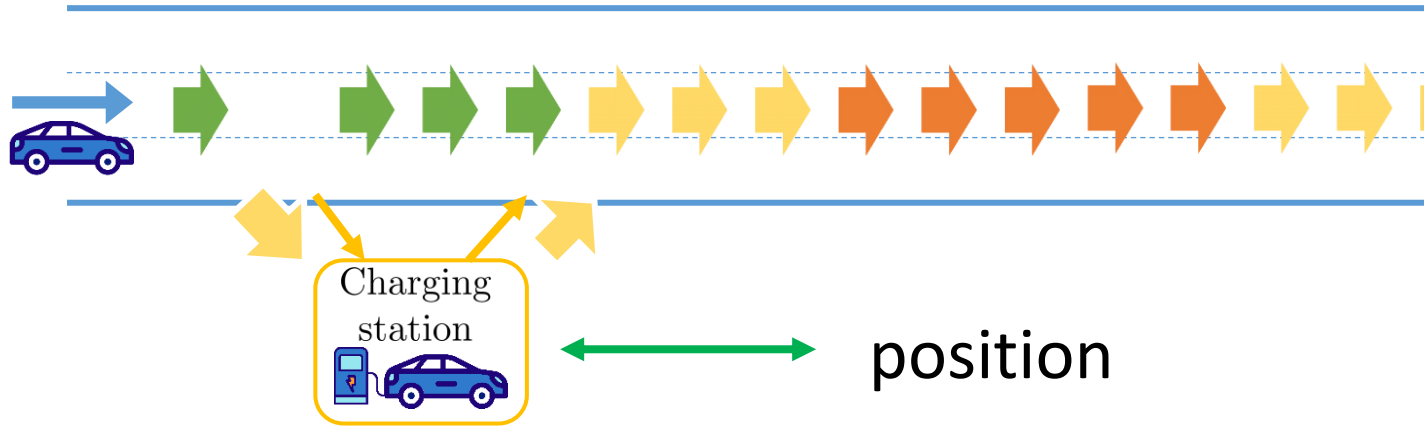
Grid capacity

EV demand

Non EV demand



Energy domain

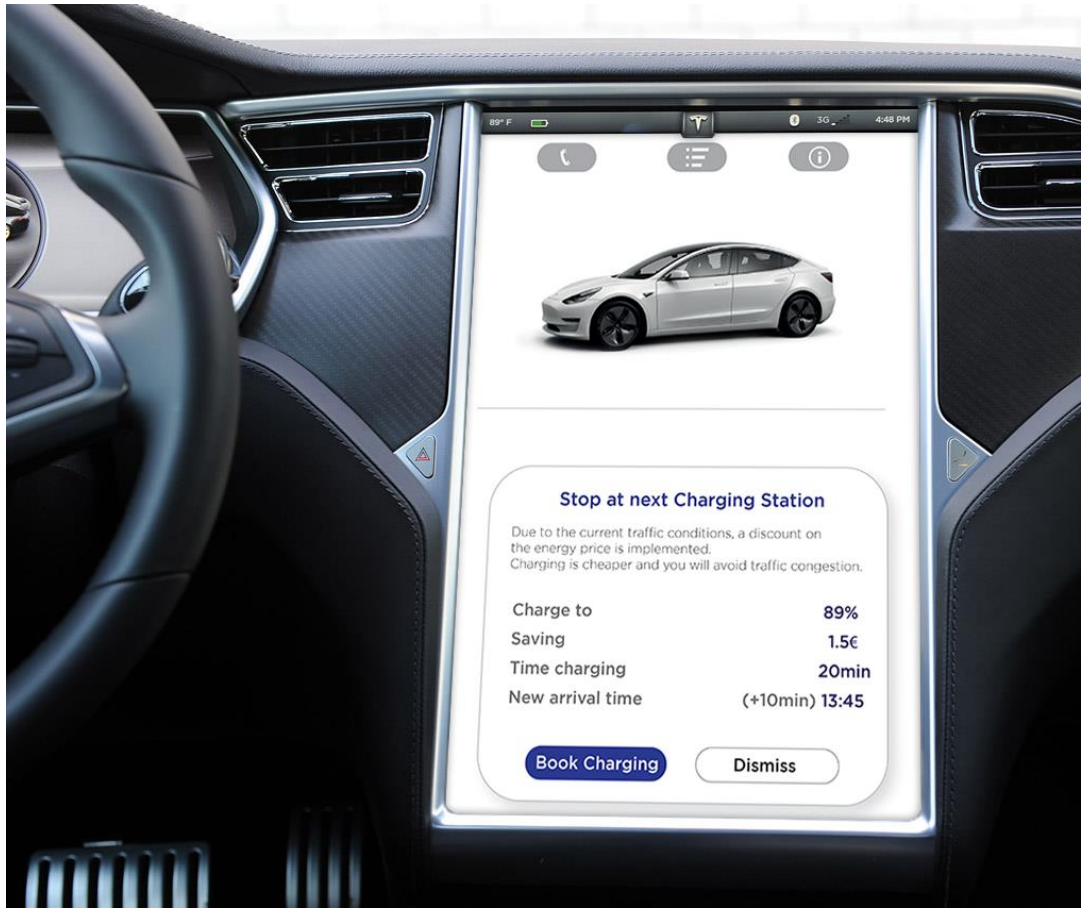


Heating networks

Power networks

EVs

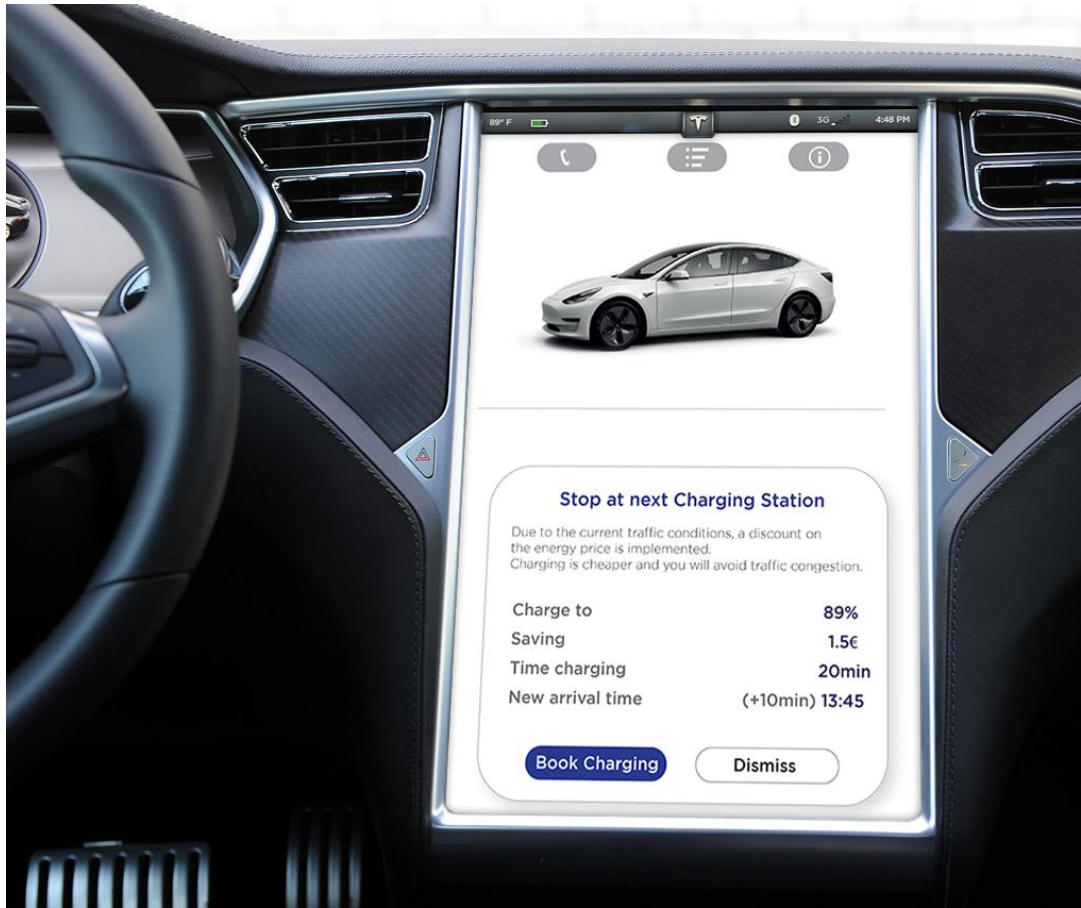
Traffic networks



Is it feasible?

- Stopping time around 30-40 min

- Cost for congestion in EU **€267 billion per year**



Energy domain

Heating networks

Power networks

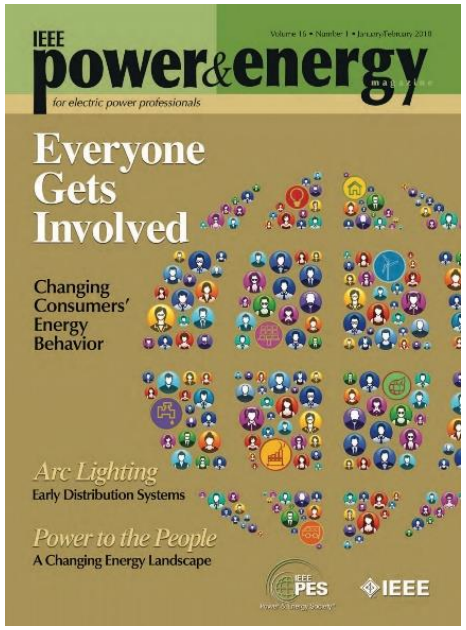
EVs

Traffic networks

Smart cities

Opinion Dynamics

Jan-Feb 2018



REVIEW ARTICLE
https://doi.org/10.1038/s41560-019-0399-x
nature energy

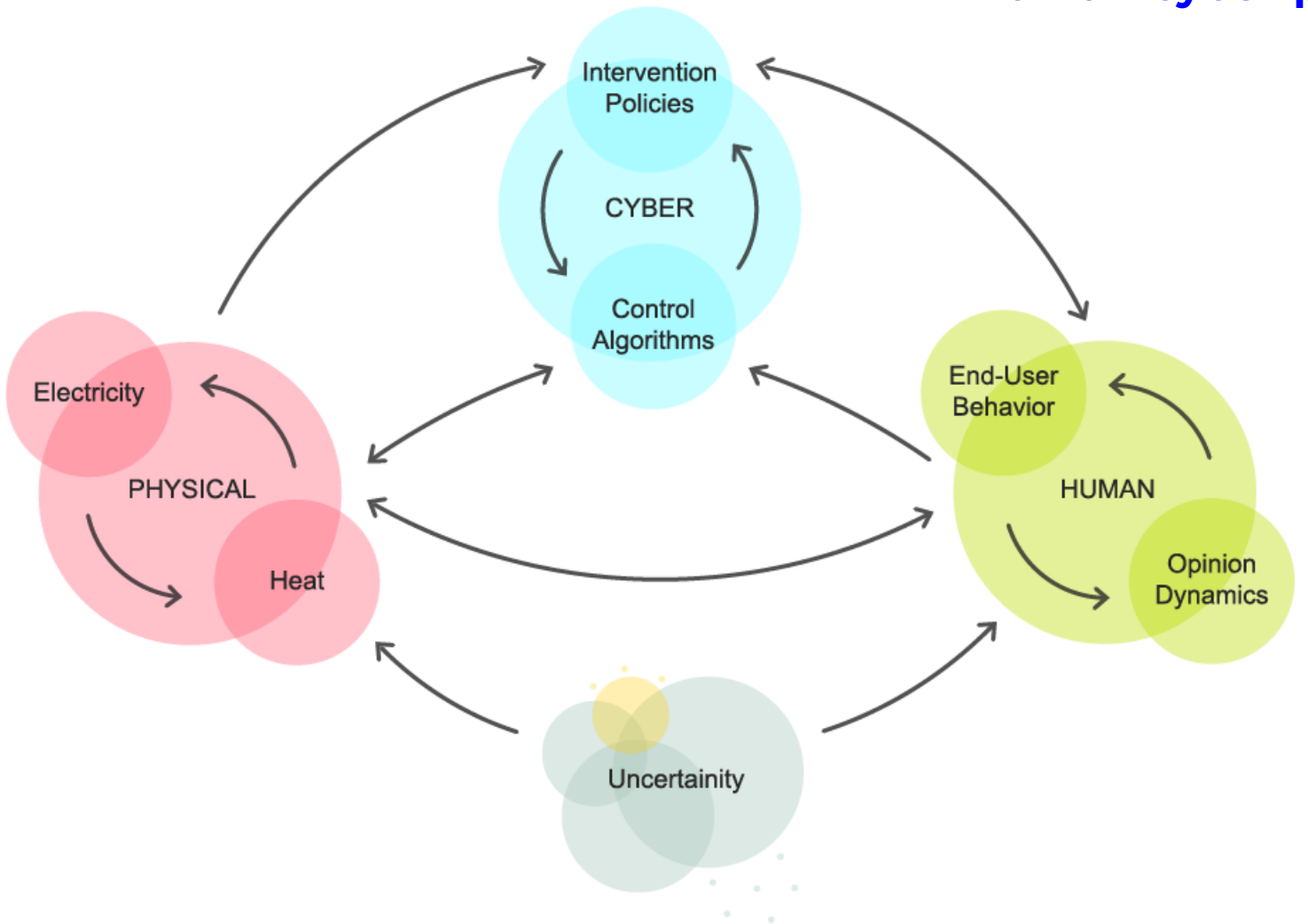
Public perceptions of and responses to new energy technologies

Hilary S. Boudet

May 2019

Energy communities

A human-cyber-physical framework



Thanks!

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