Model Predictive Control for Renewable Energy Systems
– Introduction –

Dr. Lilli Frison and Jochem De Schutter

University of Freiburg and Fraunhofer ISE

April 19, 2023

universität freiburg

Outline of talk

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Team

Dr. Lilli Frison

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Research interests

- optimal control under uncertainty
- model predictive control of building and solar energy systems and heating networks

Jochem De Schutter

jochem.de.schutter@imtek.de

Research interests

- optimal control for airborne wind energy
- efficient economic model predictive control

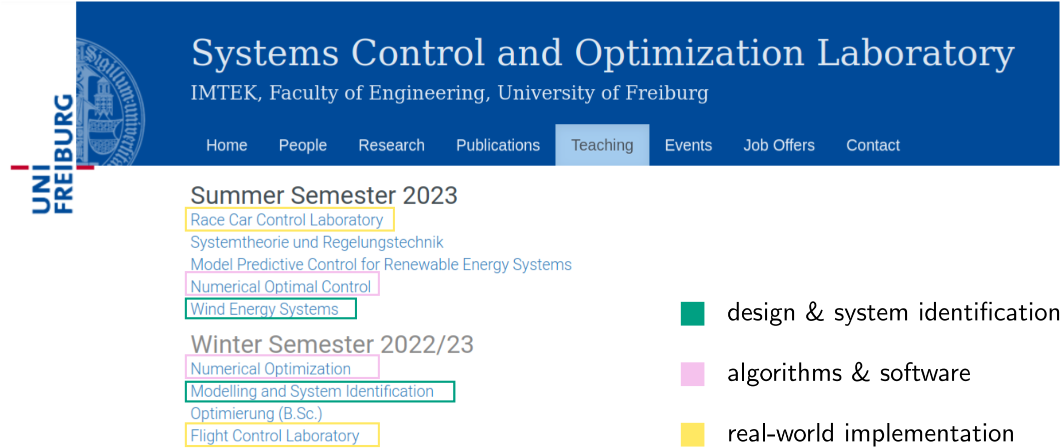
Systems Control and Optimization Laboratory (SYSCOP)

Prof. Dr. Moritz Diehl
Head of group

- *"embedded optimization of nonlinear systems"*
- research activities include:
  - dynamic system modeling
  - optimal control formulations & algorithms
  - open-source software
  - robotics, mechatronics and renewable energy

www.syscop.de

SYSCOP teaching



- design & system identification
- algorithms & software
- real-world implementation

Fraunhofer Institute for Solar Energy Systems (ISE): Business areas

Institute Directors:
Prof. Dr. Hans-Martin Henning
Prof. Dr. Andreas Bett

Employees: ca. 1400
Budget 2021: €116.7 million
Founded: 1981

Photovoltaics
- Silicon Photovoltaics
- III-V and Concentrator Photovoltaics
- Perovskite and Organic Photovoltaics
- Photovoltaic Modules and Power Plants

Energy Efficient Buildings

Solar Thermal Power Plants and Industrial Processes

Hydrogen Technologies and Electrical Energy Storage

Power Electronics, Grids und Intelligent Systems

Fraunhofer ISE: Research Focus

Organization - Lecture

Lecture:

- Wednesdays, 10:15 - 11:00, 11:10 - 11:55h (10 min break)

Learning material:

- Blackboard notes and slides
- Script (digital, updated weekly)
- Video recordings?
- `https://www.syscop.de/teaching`
- Software demonstrations (Python, Jupyter Norebooks)
- Open-source software: `rockit`, `CasADi`, `SCIP`

Date	Topic	Voluntary exercises
19.04.23	Introduction	
26.04.23	Dynamic systems	
03.05.23	Modelling of renewable energy systems: Wind energy systems	Exercise 1 (Dynamic systems)
10.05.23	Modelling of renewable energy systems: Buildings, solar energy, heating networks	
17.05.23	Background on optimization	Exercise 2 (Optimization)
24.05.23	Linear model predictive control (part 1)	
31.05.23	*** Pentecost break ***	
07.06.23	Linear model predictive control (part 2)	Exercise 3 (LMPC)
14.06.23	Midterm quiz & Nonlinear model predictive control (part 1)	
21.06.23	Nonlinear model predictive control (part 2)	Exercise 4 (NMPC)
28.06.23	Special model predictive control formulations	
05.07.23	MPC of building and solar energy systems	Exercise 5 (MPC software)
12.07.23	MPC of wind energy systems	
19.07.23	Summary session	

Organization - Exam

Exercise:

- Bi-weekly, voluntary exercise sheet (with solutions)
- Goal: deepen understanding, get a feel for implementation

Midterm quiz:

- online via ILIAS
- mandatory - infinitely many trials
- one full week to pass the quiz

Final exam:

- format - written, closed-book
- duration - 2 hours
- course load - 3 ECTS
- date - to be determined

Discussion

What are renewable energy systems? What types of renewable energy systems are you interested in?

What are renewable energy systems? What types of renewable energy systems are you interested in?

Our definition: *Renewable energy systems use renewable energy sources (wind, sun, water) to generate electricity and heat.*

Aim of this course

- **Overall goal of the lecture:**

  Theory and application of linear and nonlinear model predictive control (MPC) for renewable energy systems (RES)

- **Learning goals:**
  - develop control-oriented models for RES
  - formulate & transcribe MPC optimization problems
  - apply MPC to challenging RES control problems

Courtesy by DENA, German Energy Agency

Lecture plan

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Topics covered and not covered in this lecture

Maths topics:

- Dynamic system modelling and simulation
- Optimization
- **Linear and nonlinear MPC** - Formulations, methods and (to some extent) theory
- Mixed-integer MPC

Applications:

- Wind energy: wind turbines, airborne wind energy (to some extent)
- Building energy systems: heat pumps, PVT/PV/ST systems, heat storages
- Heating networks

Topics NOT covered in this lecture:

- Time series forecasting (e.g. of energy demand)
- E-Mobility, electricity grids

Recommended Literature (for deeper understanding)

- Rawlings, Mayne, Diehl - Model Predictive Control: Theory and Design
- Borelli, Bemporad, Morari - Predictive Control for Linear and Hybrid Systems
- Maciejowski - Predictive Control: with Constraints

(free PDFs online)

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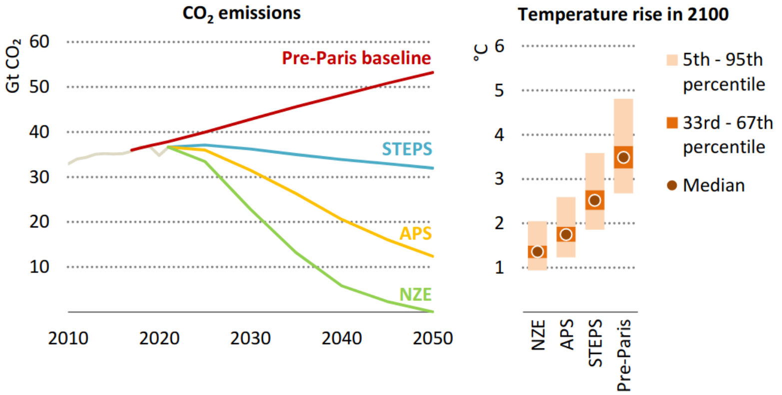
CO_2-emissions and climate change

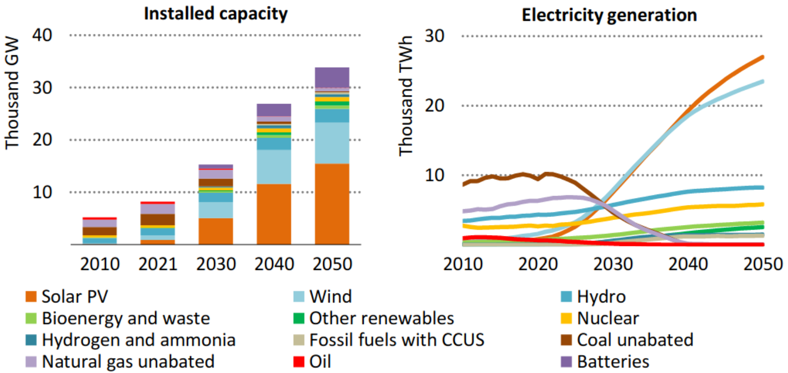
Figure 1.19 ▷ **Energy-related and process CO_2 emissions, 2010-2050 and temperature rise in 2100 by scenario**



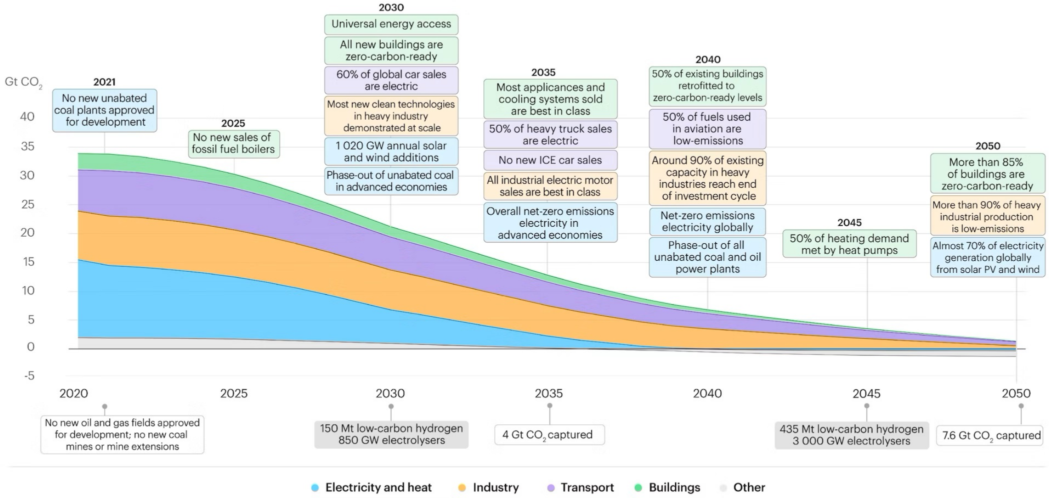
IEA. CC BY 4.0.

Electricity sector outlook

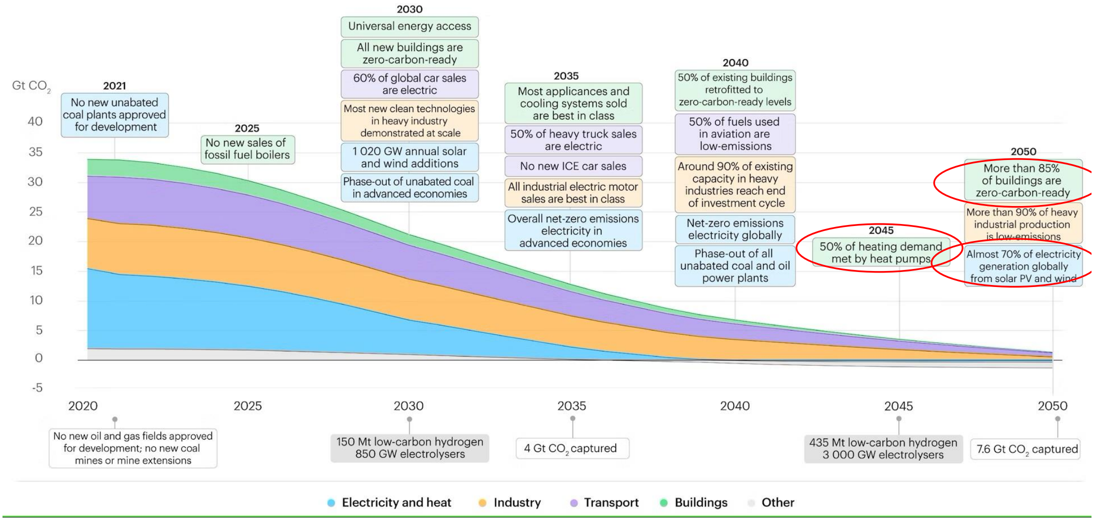
Figure 3.10 ▷ Total installed capacity and electricity generation by source in the NZE Scenario, 2010-2050



Key milestones in the pathway to net zero



Key milestones in the pathway to net zero



Electricity generation in Germany in 2022

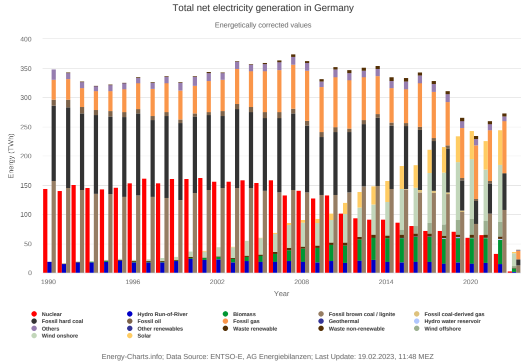


Figure: Annual total net electricity generation in Germany from 1990 to 2023 (partly) grouped by type of energy source (nuclear, renewable, fossil).

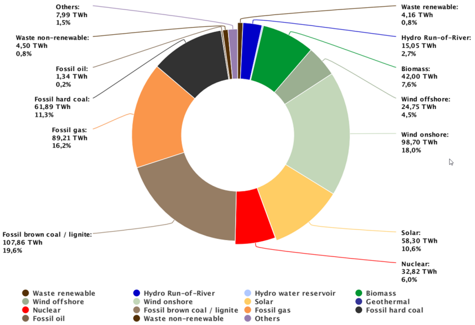


Figure: Total net electricity generation in Germany in 2022. Source: energy-charts.info

Control challenges in a renewable-based energy system

Transition from a fossil fuel based to a renewable-based energy system poses new challenges:

- high energy yield but fluctuating $\rightarrow$ **control challenge**
- grid stability, supply reliability $\rightarrow$ **control challenge**
- energy storage $\rightarrow$ **control challenge**
- energy efficiency (e.g. buildings, heating networks, technologies) $\rightarrow$ **control challenge**

Renewable-based energy system are highly diverse and complex systems:

- nonlinear (wind energy, hydraulics)
- mixed-integer (heating networks, min-up/down times)
- fast and slow dynamics (heating network with seasonal storage, PV plants with converters)

$\rightarrow$ **Increasingly complex systems** (multi-energy networks, 4/5G district heating, integrated PVT-HP systems) and **technologies** (heat pumps, PV/PVT, seasonal storages, (airborne) wind energy) require **advanced control techniques**.

Classical feedback and feedforward control

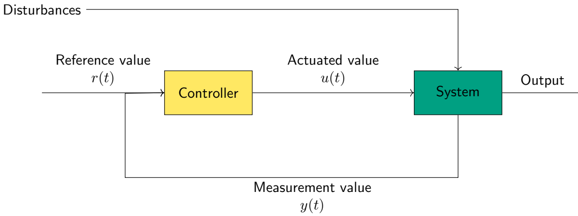
Feedback control

- Measure output of the process ("sensors")
  → compare with set point
  → error is given to controller
  → controller generates manipulated variable ("actuator") to control the process
- Ex.: PID controller

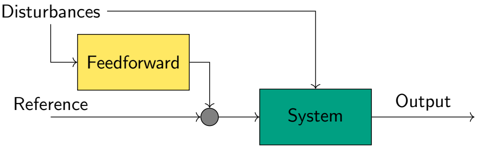
Feedforward control

- Need a disturbance model
- Disturbances are measured and accounted for before they have time to affect the system.
- Ex.: Heating curve controller

Feedback control

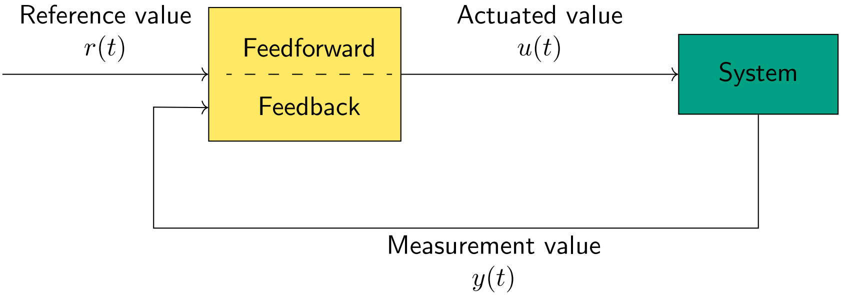


Feedforward control



Introducing Model Predictive Control

- Most relevant higher control concept in industry applications
- Controller explicitly contains a model of the system

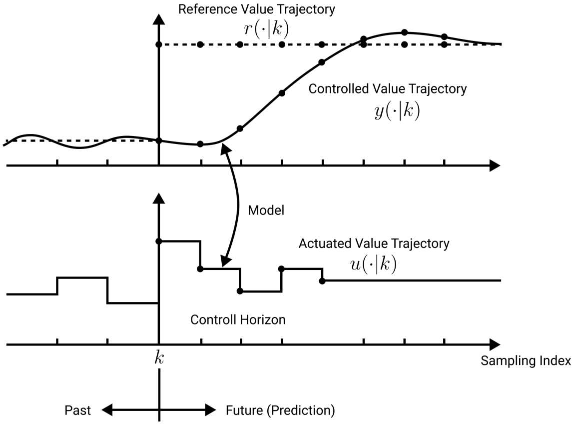


What is Model Predictive Control?

Model predictive control

- Model-based
- Predictive
- Control: optimization-based feedback control

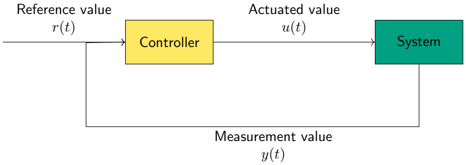
Main principle: repeat at each time step the procedure of **looking into the future** using the **process model** followed by solution of an **optimization problem**

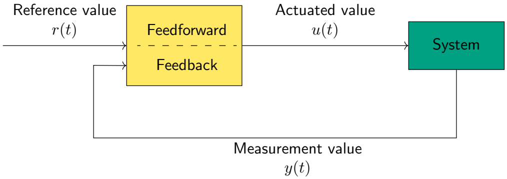


receding horizon control

Summary: classical vs. model-based control

Classical control	MPC
+ Can be implemented without much system knowledge	+ Flexible: nonlinear, constrained, time delay, MIMO, non-minimum phase
+ No model needed	+ Tuning more intuitive
+ Low computational demands	+ High control quality
– No constraints possible	– Model of the process needed
– Extension to MIMO systems difficult	– High computational effort
$\rightarrow$ Suited for small, simple, linear systems/ specific task, e.g., low-level control	$\rightarrow$ Suited for high performance, complex systems





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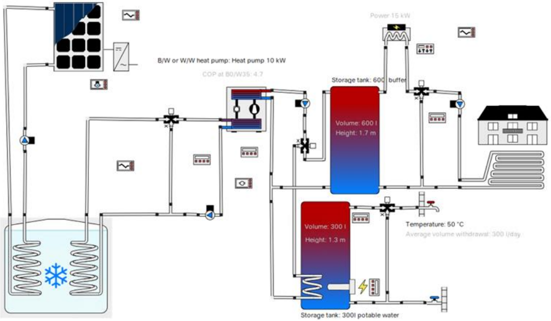
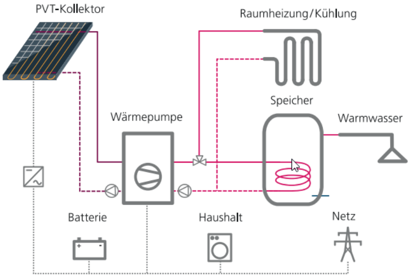
MPC for a HP-PVT building heating system

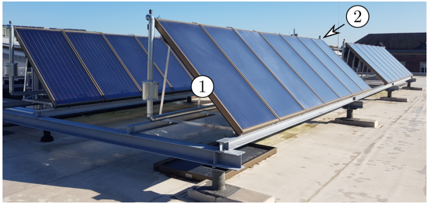


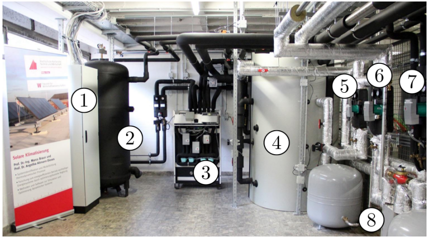


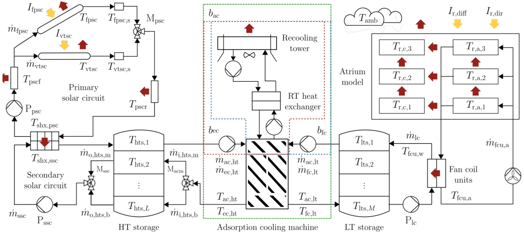
- PVT and Ice Storage are source for HP
- Ice Storage stores heat (over weeks) and extracts heat from ground (acts as heat source)

https://www.ise.fraunhofer.de/de/forschungsprojekte/HPPVT40.html

Nonlinear Mixed-Integer Control of a Solar Adsorptive Cooling Machine



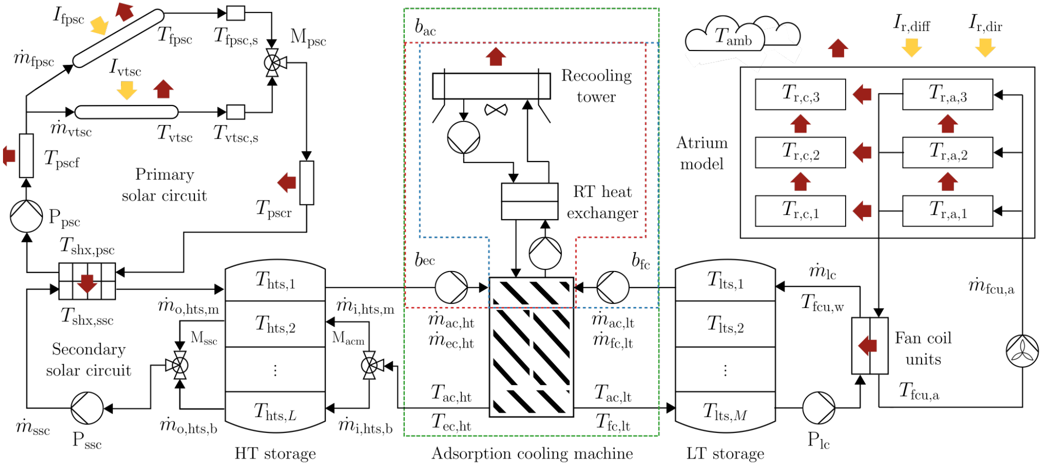




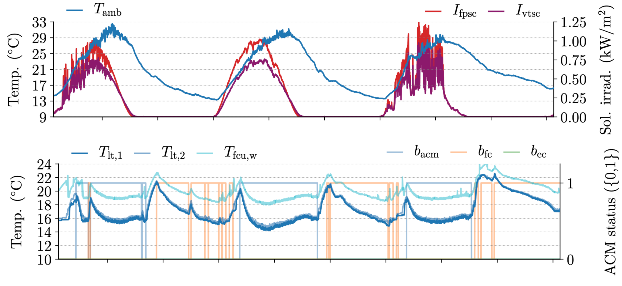
- After discretisation of PDE components, obtain nonlinear ODE with 39 states, 6 continuous and 2 binary inputs.
- Predict 24 hours
- Aim: minimize electricity consumption

Bürger et al., Experimental operation of a solar-driven climate system with thermal energy storages using mixed-integer nonlinear model predictive control, Optimal Control Applications and Methods, 2021, 1-17

Solar Adsorptive Cooling Machine: Model Overview

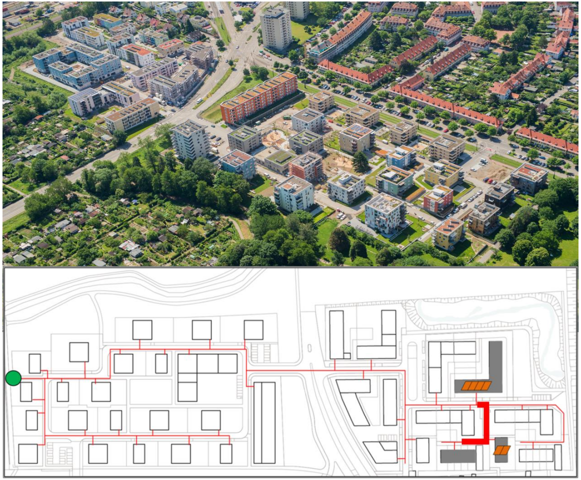


Experimental MPC Results from Sept 14-17, 2019



Every 2 minutes, a new optimization problem is solved, using a real-time algorithm based on CasADi, IPOPT [Wächter and Biegler 2006], and Pycombina [Bürger et al, 2019], an implementation of the combinatorial integral approximation (CIA) method [Sager 2009].

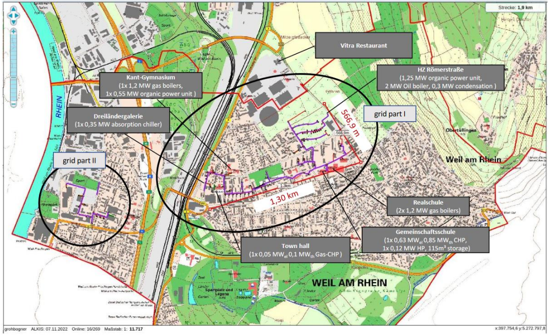
Prosumer-based solar district heating networks



- Prosumer-based solar district heating networks: buildings generate and store heat
- MPC for optimal operation of heat supply and cooperative heat transfer between the different prosumer buildings
- Aim: maximize network self-coverage from solar heat
- Application in »Freiburg-Gutleutmatten« (~40 buildings with STC)
- Results (simulation study June 2020): centrally produced heat is reduced by 75%

https://www.ise.fraunhofer.de/de/forschungsprojekte/enwisol.html

MPC for existing district heating networks with decentrally produced heat

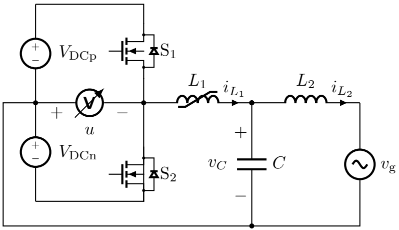


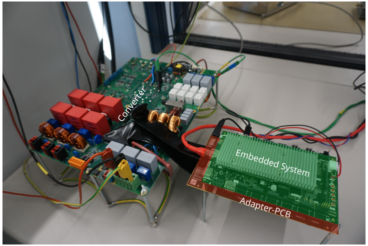
- MPC for the control of heating networks with decentralized energy sources/storage facilities
- Power and heat optimized operation

- **Demonstration sites Weil am Rhein & Rheinfelden**
  - 3-10 producers:
    - CHP, biomass, heat pump
    - gas and oil boiler for peak loads
    - waste heat source
  - storage tanks
  - Current control: Rule based prioritization between production units

Verbundvorhaben: EnEff:Wärme: WOpS - Wärmefluss-Optimierung zur Sektorenkopplung in Fernwärmenetzen mitttels MPC unter Berücksichtigung eines strommarktorientierten Betriebes

NMPC for Power Electronics





- Convert DC from PV panels into AC for feeding into the grid
- Bipolar DC/AC converter
  - 11 kW
  - 48 kHz switching frequency
- NMPC implemented on ARM/FPGA-based embedded platform
- Optimizes switching times of $\mathrm{S}_1/\mathrm{S}_2$
- Can deal with nonlinearities
  - Inductor saturation
  - Blanking times
- Executes in $\sim 17\mu s$

Stickan, Frison, Burger, Diehl: "A nonlinear Real-Time Pulse-Pattern MPC Scheme for Power-Electronics Circuits Operating in the Microseconds Range," 2022 American Control Conference (ACC)

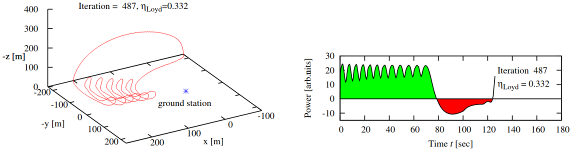
eco4wind: MPC for wind turbine control

Nonlinear MPC with about 40 states based on ACADO code generation with QP solver HPIPM running on industrial hardware at IAV

Optimal control of airborne wind energy: Skysails Power

`www.skysails.com`

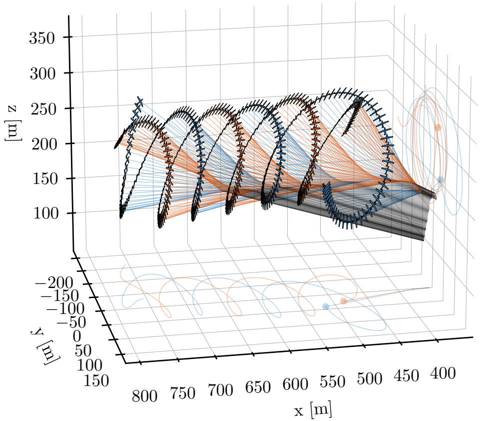
- SKS PN-14: 200kW prototype
- pilot project with permit to feed electricity into grid on the island of Mauritius (Jan. 2023)
- power optimization with periodic optimal control using CasADi + IPOPT [Wächter and Biegler 2006]
- simulations on smaller prototype show increase in power output with factor of 2 compared to naive experimental flight pattern



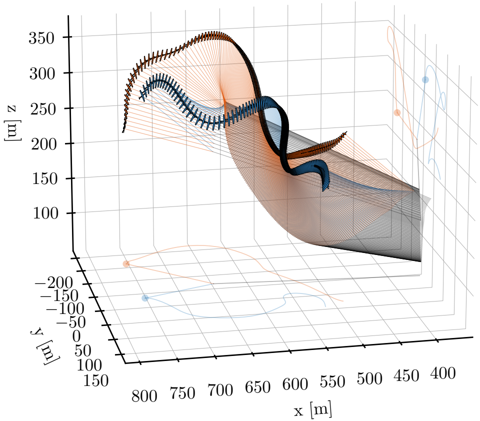
Erhard et al., A quaternion-based model for optimal control of an airborne wind energy system, Journal of Applied Mathematics and Mechanics, 97 (1), 2017

Optimal control of airborne wind energy: Multi-wing systems

Power production phase



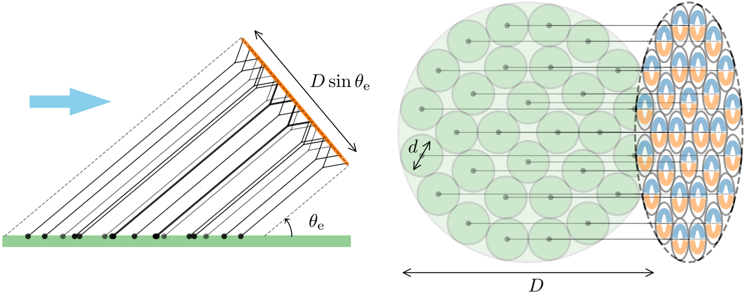
Power consumption phase



De Schutter et al., AWEbox: An Optimal Control Framework for Single- and Multi-Aircraft Airborne Wind Energy Systems, Energies 2023, 16(4), 1900

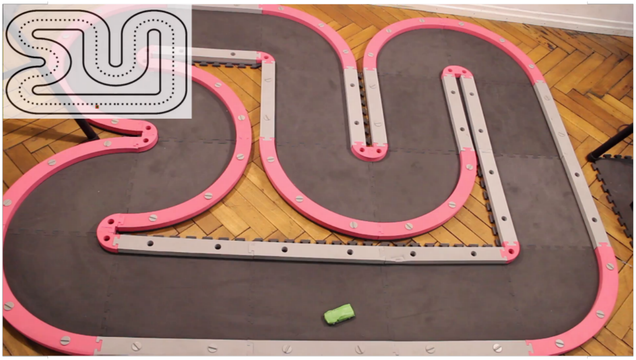
Optimal control of airborne wind energy: Vertical wind farms

- "Vertical" wind farms have potential power density of 43 MW/km^2, a factor 17 larger than conventional wind (2.4 MW/km^2, for cubically averaged wind speed of 7 m/s)
- Detailed optimal-control based studies result in more modest 6.5 MW/km^2.
- Requires advanced control and coordination of many flying systems



De Schutter et al, Vertical Airborne Wind Energy Farms with High Power Density per Ground Area based on Multi-Aircraft Systems, European Control Conference, 2023

MPC in other applications: Freiburg Race Cars



- time-optimal MPC formulation
- acados coupled into ROS
- optimization every 10ms

Kloeser et al., NMPC for Racing Using a Singularity-Free Path-Parametric Model with Obstacle Avoidance, Proceedings of the IFAC World Congress 2020