Robust control of smart energy systems using fuel cell cars

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Car as power plant

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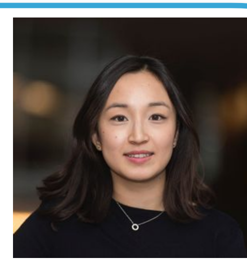
Research on car as power plant

PhD 1:
Technological feasibility

PhD 2:
Control system

PhD 3:
Social & economical aspects



Postdoc:
Integration, business model

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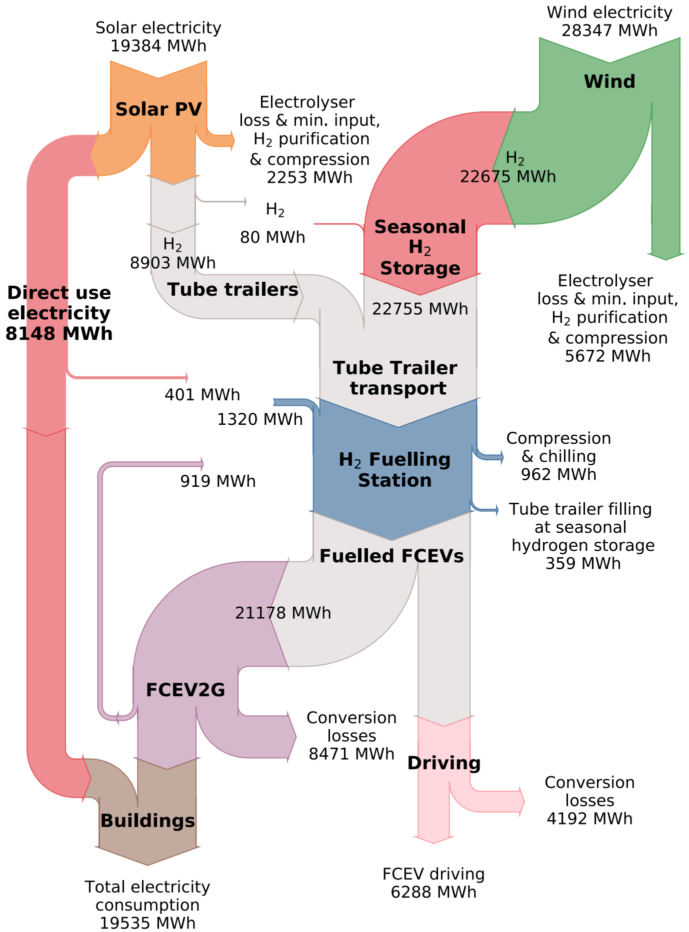
Annual energy balance for a 2050 fully renewable, heating, and road transport system for the city of Hamburg



- V. Oldenbroek, L. A. Verhoef, and A. J. M. van Wijk. Fuel cell electric vehicle as a power plant: Fully renewable integrated transport and energy system design and analysis for smart city areas. *International Journal of Hydrogen Energy*, 42:8166–8196, 2017.

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Outline

- Car as power plant
- Modeling
- Optimization problem
  - Grid-connected mode
  - Islanded mode
- Distributed control architecture
- Conclusions

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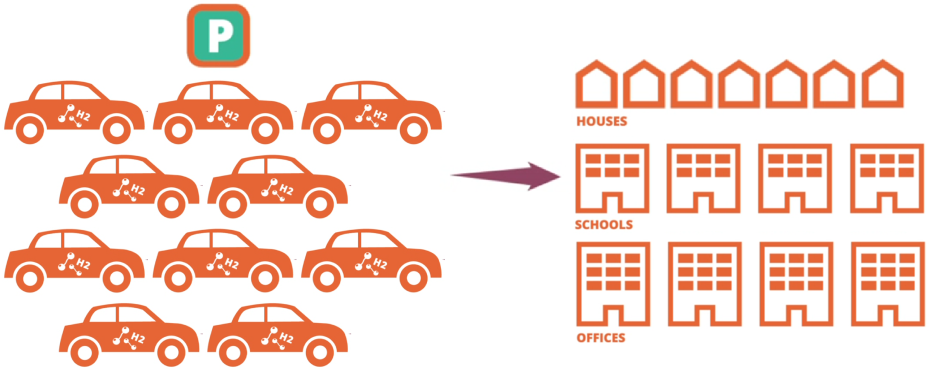
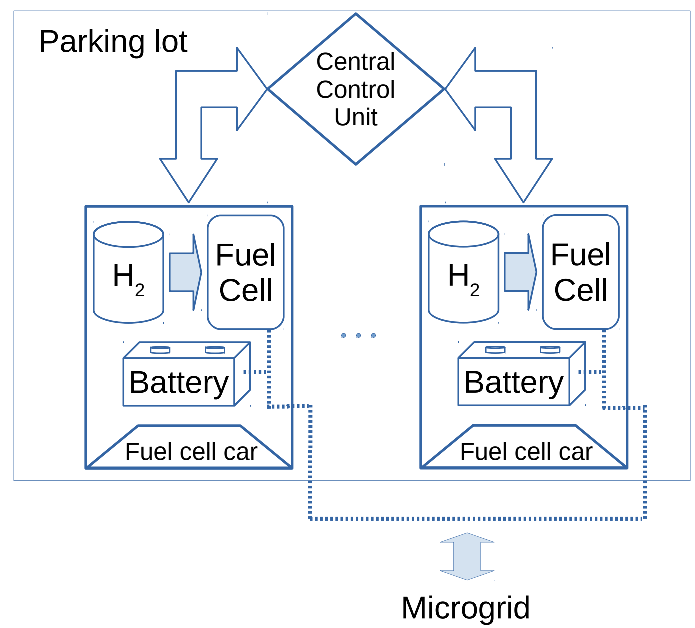
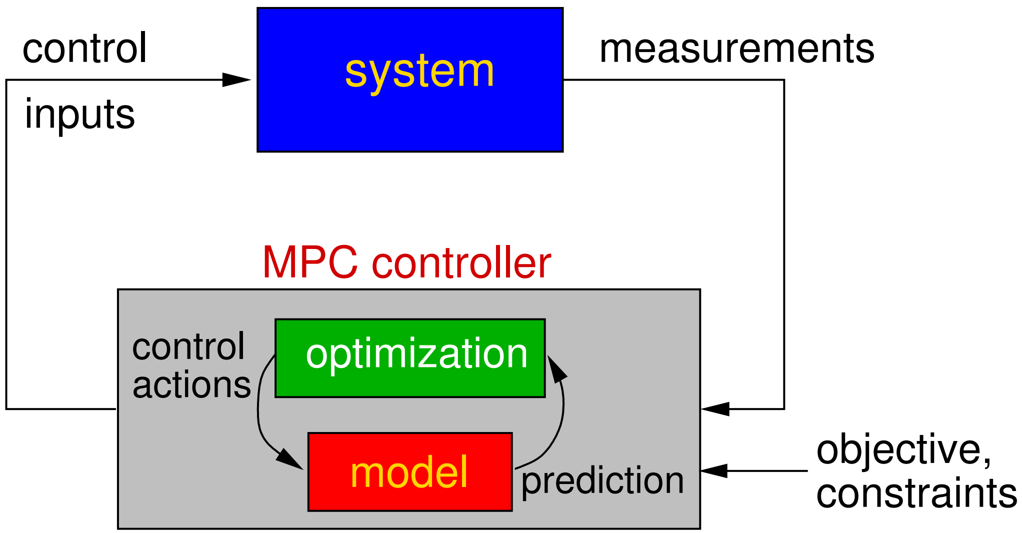
Car as power plant





Model predictive control



- Research topics:
  - Model of system
  - Optimization problem with respect to uncertainty

Model of fuel cell

- System state: fuel level $x_{\mathrm{f},i}$
- Control inputs
  - Net power generation $u_{\mathrm{f},i}$
  - ON/OFF mode $s_{\mathrm{f},i}$

$$x_{\mathrm{f},i}(k+1) = \begin{cases} x_{\mathrm{f},i}(k) & \text{if } s_{\mathrm{f},i}(k) = 0 \\ x_{\mathrm{f},i}(k) - (\alpha_{\mathrm{f},i} u_{\mathrm{f},i}(k) + \beta_{\mathrm{f},i}) T_{\mathrm{s}} & \text{if } s_{\mathrm{f},i}(k) = 1 \end{cases}$$

- Constraints

$$\text{if } s_{\mathrm{f},i}(k) = 0 \text{ then } u_{\mathrm{f},i}(k) = 0$$

$$0 \leq u_{\mathrm{f},i}(k) \leq \bar{u}_{\mathrm{f},i}$$

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Model of battery

- System state: stored energy $x_{\mathrm{b},i}$
- Control inputs
  - Charging/discharging power $u_{\mathrm{b},i}$
  - Charge/discharge mode $s_{\mathrm{b},i}$

$$x_{\mathrm{b},i}(k+1) = \begin{cases} x_{\mathrm{b},i}(k) + \frac{T_\mathrm{s}}{\eta_{\mathrm{d},i}} u_{\mathrm{b},i}(k) & \text{if } s_{\mathrm{b},i}(k) = 0 \\ x_{\mathrm{b},i}(k) + T_\mathrm{s}\eta_{\mathrm{c},i} u_{\mathrm{b},i}(k) & \text{if } s_{\mathrm{b},i}(k) = 1 \end{cases}$$

- Constraints

$$u_{\mathrm{b},i}(k) \geq 0 \Leftrightarrow s_{\mathrm{b},i}(k) = 1$$

$$\underline{u}_{\mathrm{b},i} \leq u_{\mathrm{b},i}(k) \leq \bar{u}_{\mathrm{b},i}$$

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Model of overall system

- Mixed logical dynamical model

$$\begin{cases} x(k+1) = Ax(k) + B_1 u(k) + B_2 \delta(k) + B_3 z(k) \\ E_1 u(k) + E_4 x(k) + E_5(k) \geq E_2 \delta(k) + E_3 z(k) \end{cases}$$

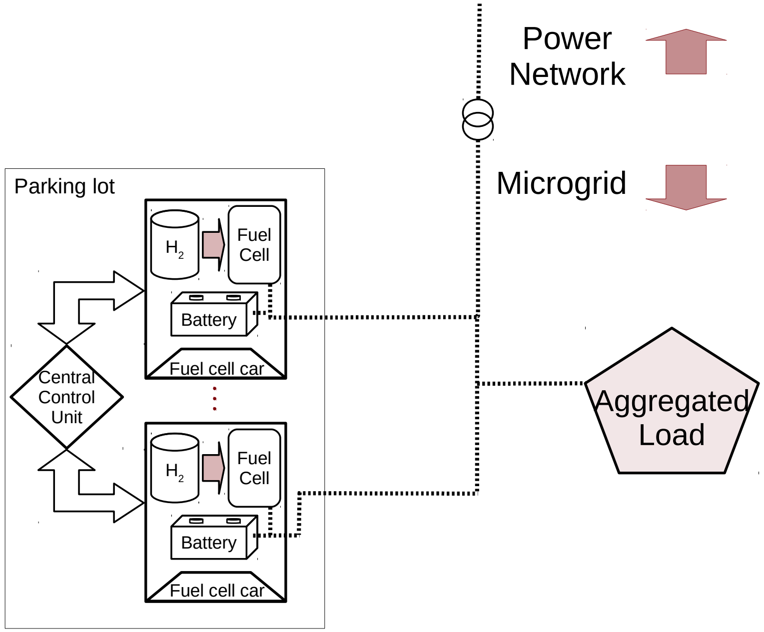
$$x(k) = \left[x_1^T(k), ..., x_{N_{\mathrm{veh}}}^T(k)\right]^T$$

$$u(k) = \left[u_1^T(k), ..., u_{N_{\mathrm{veh}}}^T(k)\right]^T$$

Mixed binary-real

Central controller design for grid connected mode

- Bounded power exchange with power network
- Uncontrollable loads
- Maximum power generation for all renewable energy sources
- Fuel cells generate electricity
- Batteries generate/ store electricity



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Problem formulation

- Control actions
  - Power generation of fuel cell cars
  - Charging/discharging batteries of cars

How to control fuel cell and battery of cars such that power balance of microgrid is maintained while operational cost of system is minimized?

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Developed robust control methods

- Min-max
- Chance constrained
- Standard scenario-based
- Lenient scenario-based

Optimization problem is in form of
Mixed Integer Linear Programming (MILP)

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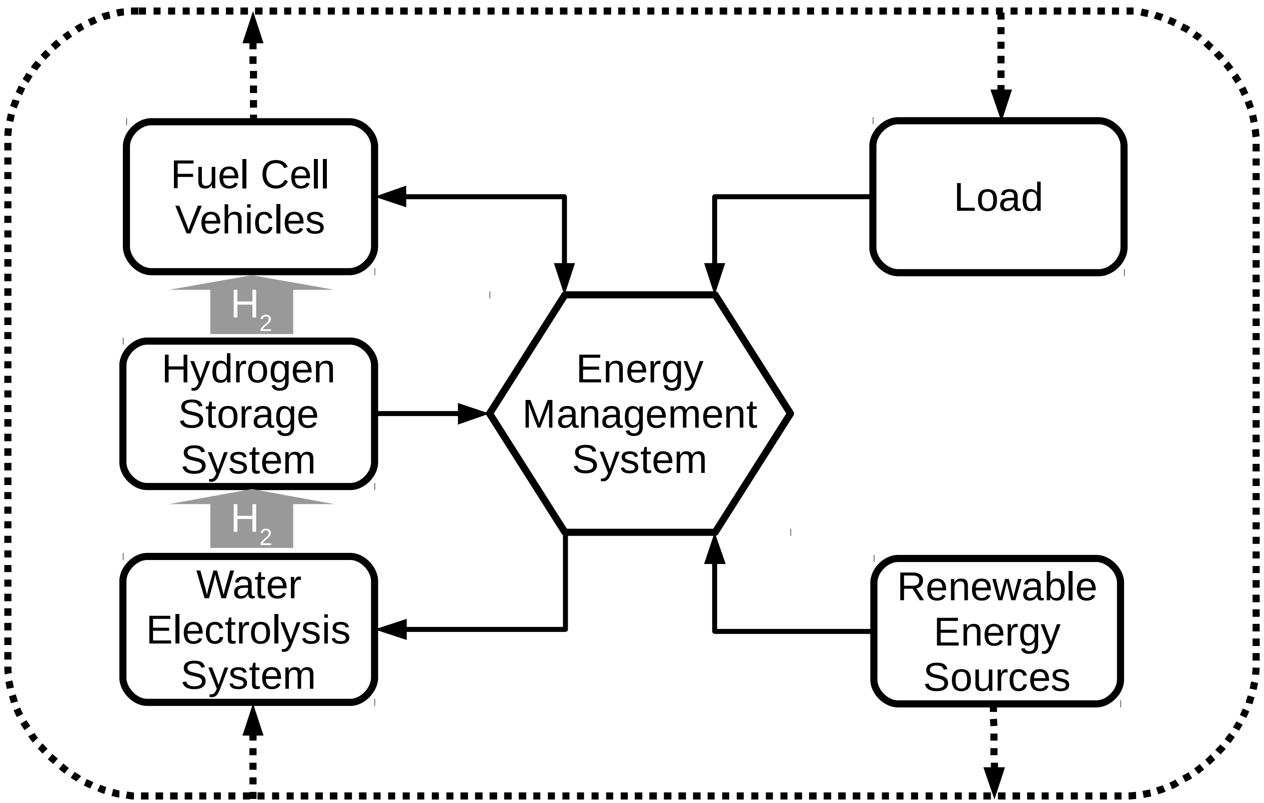
Problem formulation (islanded mode)



Islanded-mode microgrid

- Uncontrollable loads
- Maximum power generation of all renewable energy sources
- Fuel cell cars generate electricity
- Water electrolysis system produces hydrogen
- Fuel cell cars are also used for transportation

Problem formulation

- Control actions
  - Power generation of fuel cells
  - Refilling process of cars
  - Hydrogen production of electrolyzer

How to control fuel cell cars and electrolyzer such that power balance is maintained and total operational cost is minimized?

our goal

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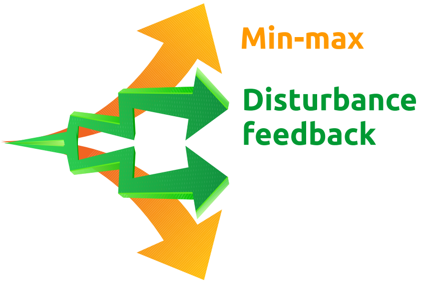
Disturbance feedback min-max method

- Control law:

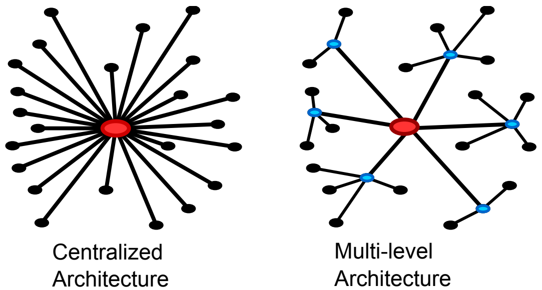
$$u_{\mathrm{f},i}(k+j) = v_{\mathrm{f},i}(k+j) + K_{\mathrm{f}}(k+j)\omega_{\mathrm{f},i}(k+j-1)$$

- Reduction of conservatism
  - Prevents expansion of possible state trajectories



- Optimization problem is in form of MILP

Distributed control architecture



- Separating MPC optimization problem into:
  - Master problem ⇨ coordinator
  - Slave problem ⇨ individual cars
- Result
  - Faster to solve
  - No sharing of driving patterns

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Primal problem

$$\min_{x_i \in \mathbb{X}_i, \forall i \in \mathcal{I}} \sum_{i \in \mathcal{I}} J_i(x_i)$$

$$\text{subject to } g(x) = \sum_{i \in \mathcal{I}} g_i(x_i) = 0$$

- $\mathcal{I}$ set of fuel cell cars
- x_i decision variable related to fuel cell car i
- $J_i(x_i)$ operational cost of fuel cell car *i*
- $g(x)$ power balance constraint

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Dual problem

$$\max_{\lambda \in \mathbb{R}} \min_{x_i \in \mathbb{X}_i, \forall i \in \mathcal{I}} \sum_{i \in \mathcal{I}} J_i(x) + \lambda \sum_{i \in \mathcal{I}} g_i(x_i)$$

- Separable!

Master problem

Given x_i update λ as

$$\lambda_{\text{new}} = \begin{cases} \lambda_{\text{old}} + \alpha & \text{if } g(x) < 0 \\ \lambda_{\text{old}} - \alpha & \text{if } g(x) > 0 \end{cases}$$

Slave problem

Given λ, solve:

$$\min_{x_i \in \mathbb{X}_i} J_i(x_i) + \lambda g_i(x_i)$$

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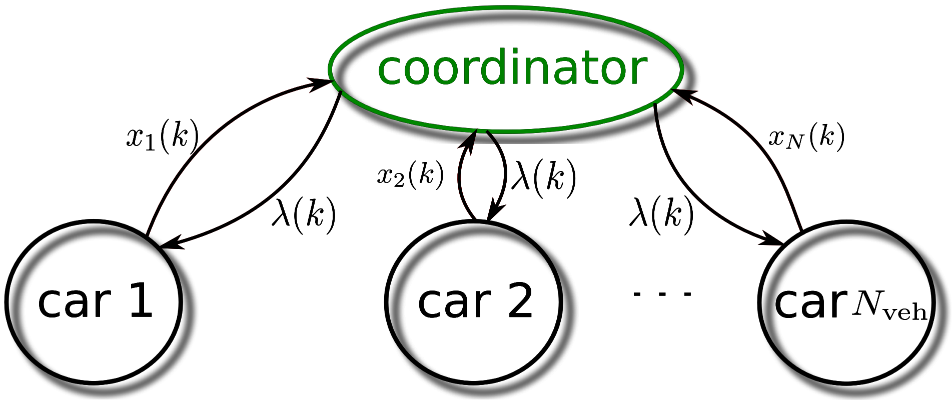
Dual decomposition



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Summary

- Mixed logical dynamical models
- Different control strategies in islanded and grid-connected modes
- Reduction of conservatism with disturbance feedback method
- Distributed control methods to
  - increase the privacy of car owners
  - reaching solution faster

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