Modellprädiktive Energiemanagementstrategien für Brennstoffzellen-Systeme

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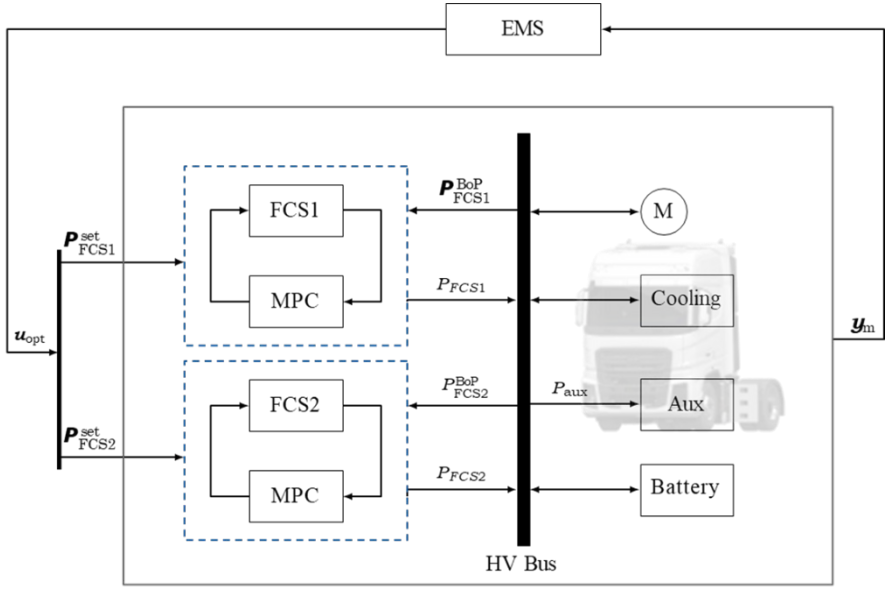
Institut für Regelungstechnik, RWTH Aachen University

Duisburg, den 15.10.2025



HeavyDuty Congress

irt Institut für Regelungstechnik

RWTH AACHEN UNIVERSITY

Das Institut für Regelungstechnik

Campus Melaten in Aachen Nord

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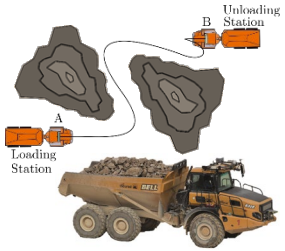
Das Institut für Regelungstechnik

Methoden

Modellprädiktive Regelung | Maschinelles Lernen | Sensor Fusion

Anwendungsgebiete

Mobilität und Navigation



Energiesysteme

Biomedizintechnik

Industrie- & Produktionssysteme

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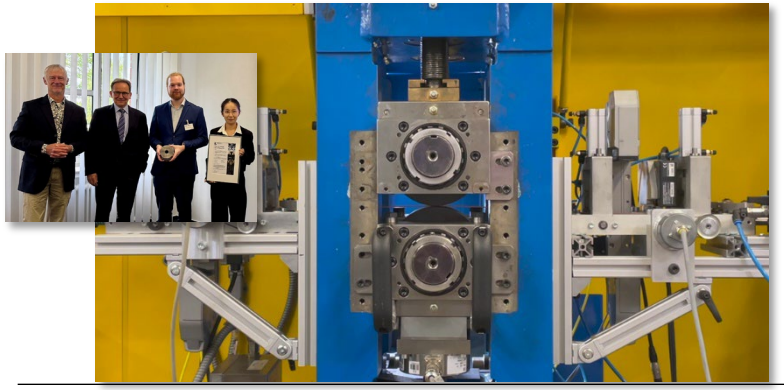
Das Institut für Regelungstechnik – Highlights 2024

Modellprädiktive Regelung von Windenergieanlagen

Andreas Klein

Maximilian Basler

Kaltwalzen



Christopher Schulte

Sebastian Stemmler

Automatisierte Schifffahrt

Rinat Prezdnyakov

Haoming Zhang

Tim Reuscher

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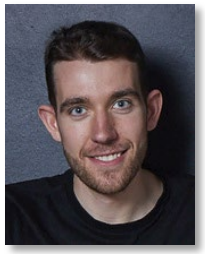
Gruppe Wasserstofftechnologien

Abteilungsleiter

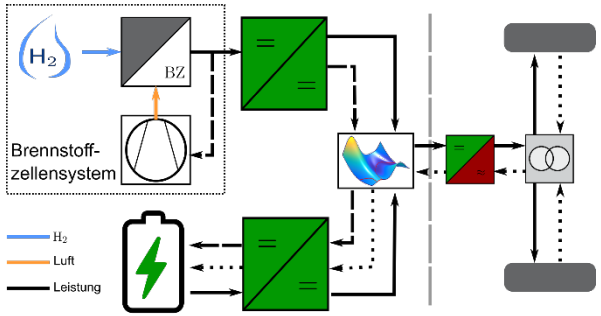
Gruppenleiter

Team

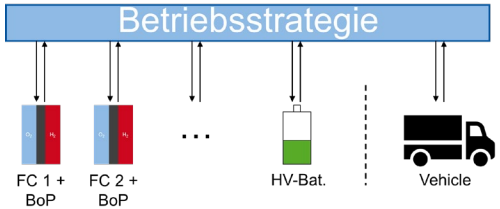


Brennstoffzellensysteme

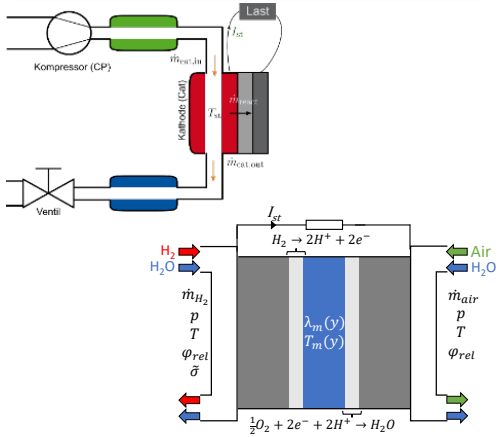
Hybride Energiespeicher



Multi-Systeme



Luftpfad & Stack



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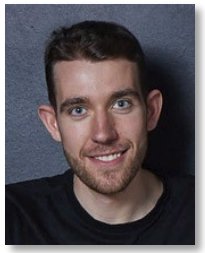

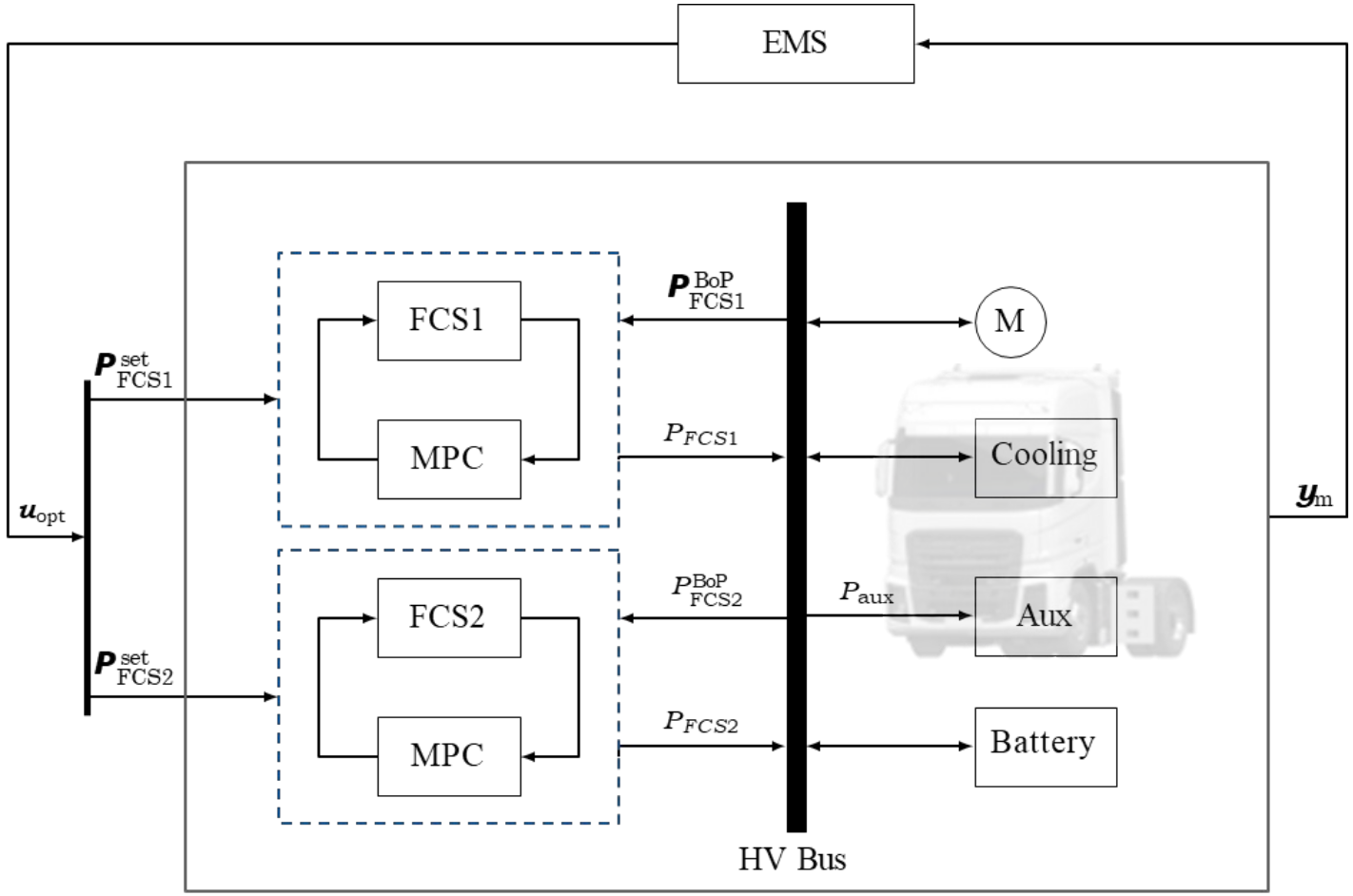

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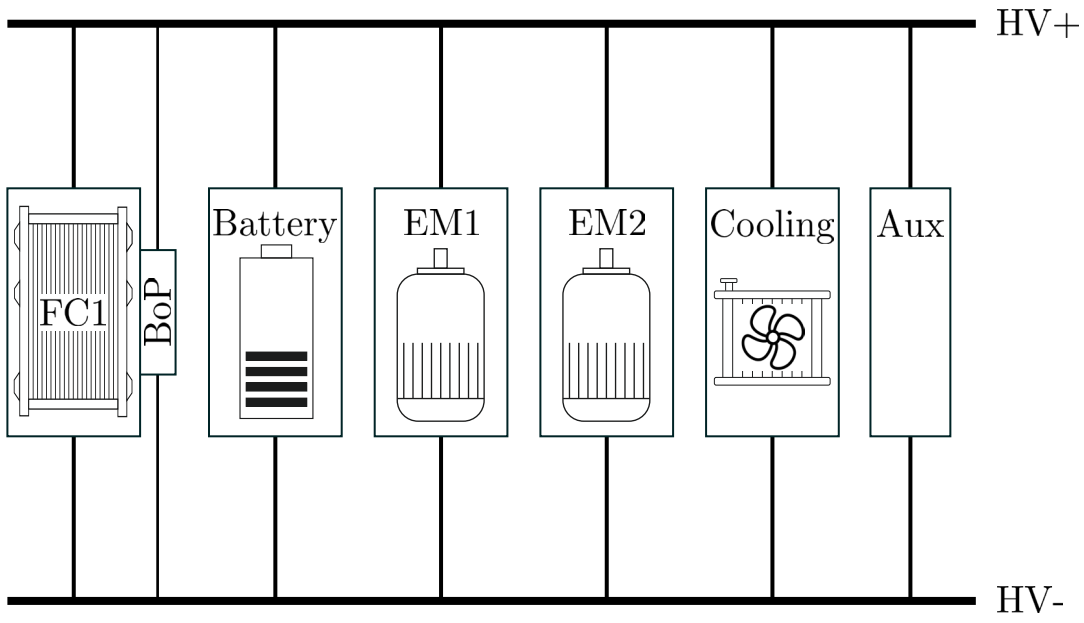
Systemarchitekturen



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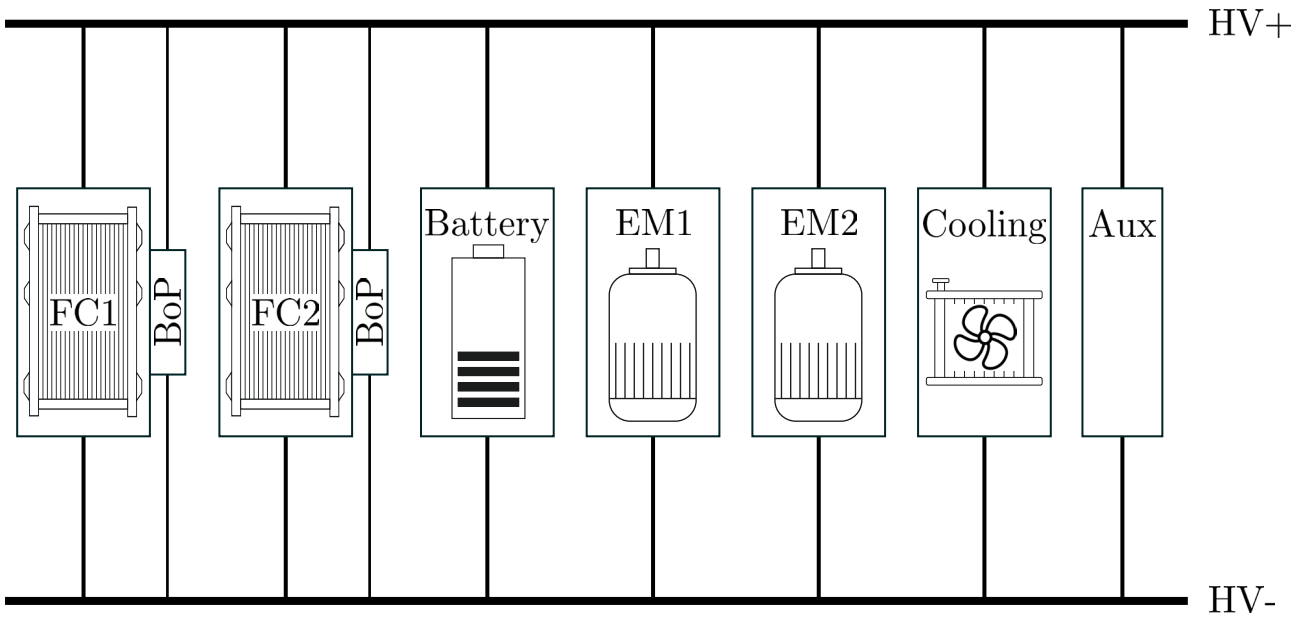
Systemarchitekturen



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Anforderungen an EMS

Lebenszykluskosten

$$\min \quad C = C_{\mathrm{m_{H_2}}} m_{\mathrm{H_2}} + \sum_n C_{\mathrm{fcs}} P_{\mathrm{fcs}}^{\mathrm{max}} r_{\mathrm{fcs,n}} + C_{\mathrm{bat}} E_{\mathrm{nom}} r_{\mathrm{bat}}$$

Leistungsaufteilung BZS & Batterie

$$P_{\mathrm{dem}} = P_{\mathrm{del}}$$

Maximale Systemeffizienz

$$\min \quad m_{\mathrm{H_2}}$$

Erhöhte Lebensdauer

$$\min \quad r_{\mathrm{bat}} + \sum_n r_{\mathrm{fcs,n}}$$

SOC-Erhaltung

$$\min \quad |SoC - SoC_{\mathrm{ref}}|$$

Einhalten aller Systemgrenzen

$$P_{\mathrm{fcs}}^{\mathrm{min}} \leq P_{\mathrm{fcs,n}} \leq P_{\mathrm{fcs}}^{\mathrm{max}} \qquad \Delta P_{\mathrm{fcs}}^{\mathrm{min}} \leq \Delta P_{\mathrm{fcs}} \leq \Delta P_{\mathrm{fcs}}^{\mathrm{max}}$$

$$SoC_{\mathrm{min}} \leq SoC \leq SoC_{\mathrm{max}} \qquad I_{\mathrm{bat}}^{\mathrm{min}} \leq I_{\mathrm{bat}} \leq I_{\mathrm{bat}}^{\mathrm{max}}$$

Praktische Anwendung

Modular für verschiedene Topologien/Größen

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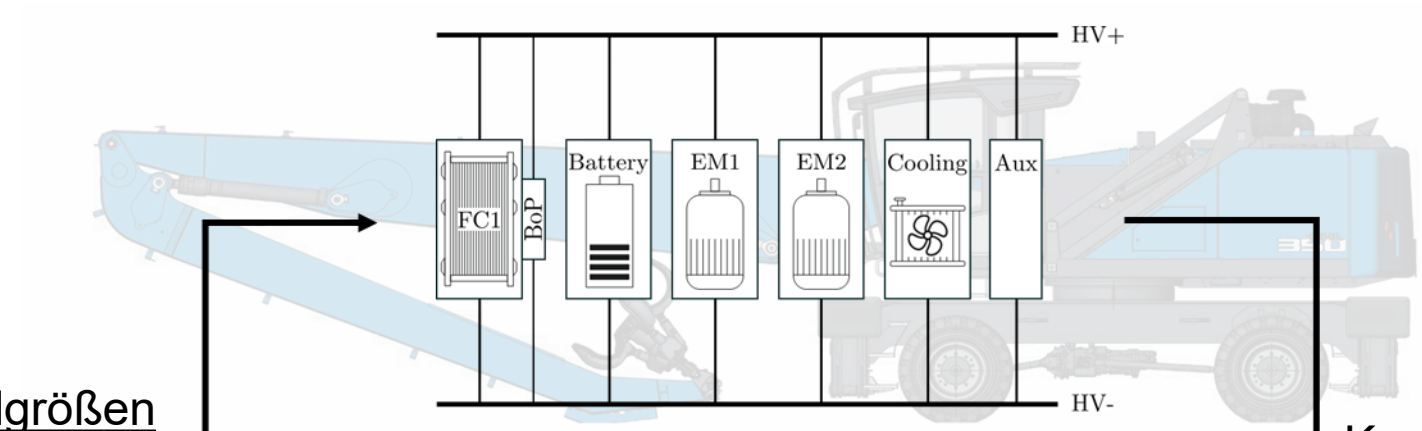
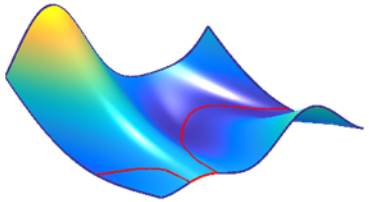
Modellprädikitve EMS



Stellgrößen

Leistungen BZ

Modellprädiktive EMS



Messgrößen

Komponentenleistungen
H2-Massenstrom
Mittlere Zellspannung
Kühlmitteltemperatur
SoC

HyFCD

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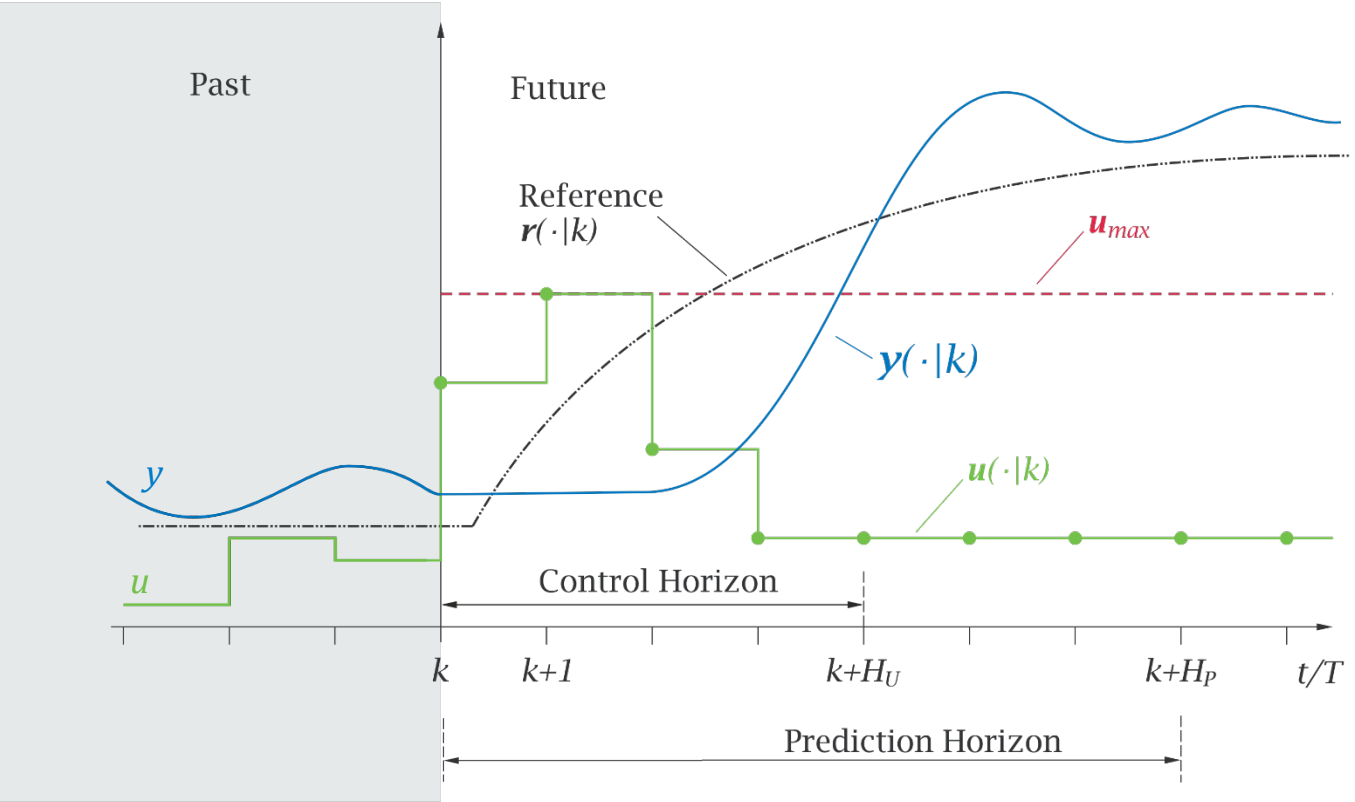
Modellprädikitve EMS

$$
\begin{aligned}
\underset{\boldsymbol{P}_{\mathrm{fcs}}}{\text{minimize}} \quad & \sum_{k=0}^{H_{\mathrm{P}}} \|SoC_{\mathrm{ref}} - SoC_k\|_{q_{\mathrm{SoC}}}^2 + \|m_{\mathrm{H}_2,k}\|_{q_\eta}^2 + \\
& \|\Delta \boldsymbol{P}_{\mathrm{fcs},k}\|_{\mathbf{S}}^2 + \|r_{\mathrm{bat},k}\|_{q_{\mathrm{bat}}}^2 \; \|\boldsymbol{r}_{\mathrm{fcs},k}\|_{\boldsymbol{q}_{\mathrm{fcs}}}^2 \\
\text{subject to} \quad & \boldsymbol{x}_{k+1} = \boldsymbol{F}\left(\boldsymbol{x}_k, \boldsymbol{u}_k, \boldsymbol{d}_k\right), \quad \boldsymbol{x}_0 = \hat{\boldsymbol{x}}, \\
& \boldsymbol{y}_k = \boldsymbol{g}\left(\boldsymbol{x}_k, \boldsymbol{u}_k, \boldsymbol{d}_k\right), \\
& \boldsymbol{P}_{\mathrm{fcs}}^{\min} \leq \boldsymbol{P}_{\mathrm{fcs},k} \leq \boldsymbol{P}_{\mathrm{fcs}}^{\max}, \\
& \Delta \boldsymbol{P}_{\mathrm{fcs}}^{\min} \leq \Delta \boldsymbol{P}_{\mathrm{fcs},k} \leq \Delta \boldsymbol{P}_{\mathrm{fcs}}^{\max}, \\
& SoC_{\min} \leq SoC_k \leq SoC_{\max}, \\
& I_{\mathrm{bat}}^{\min} \leq I_{\mathrm{bat},k} \leq I_{\mathrm{bat}}^{\max}
\end{aligned}
$$



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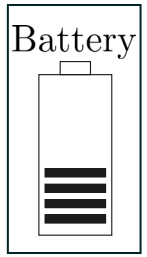
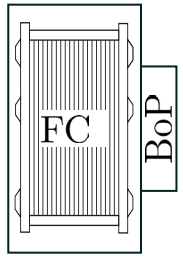
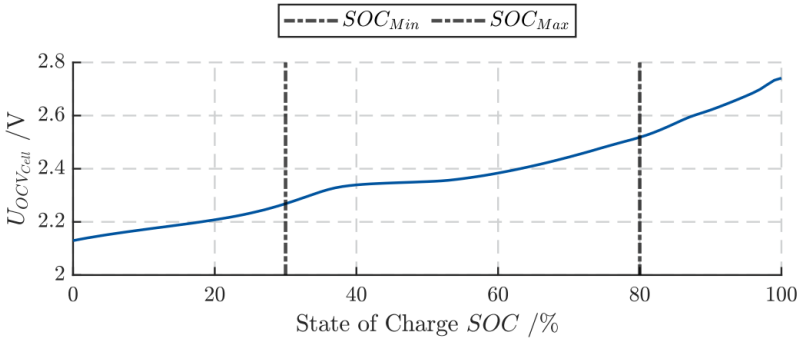
Modellierung: Dynamisches Verhalten

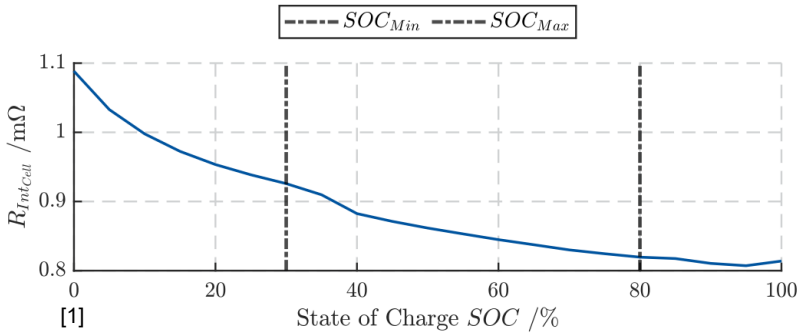




Leerlaufspannung



Innenwiderstand

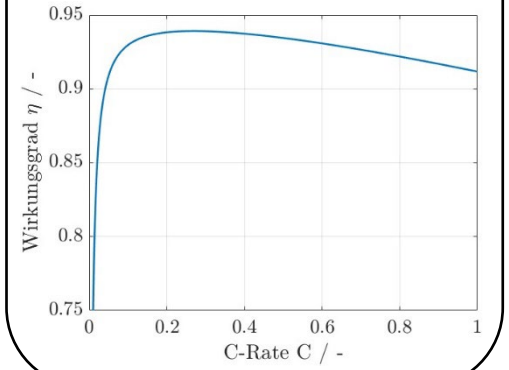


[1]

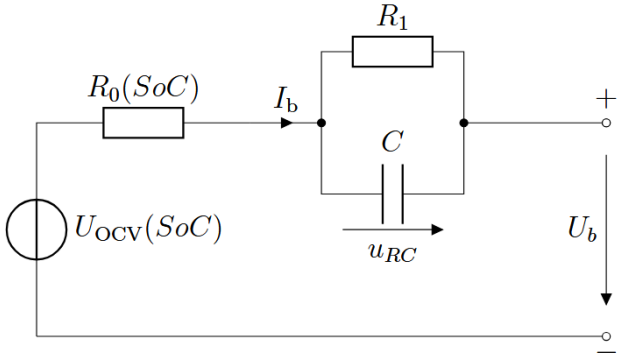
Zyklische Degradation

$$D_{\text{bat}} = \frac{\int |I_{\text{bat}}|\,\mathrm{d}t}{0.8 \cdot Q_{\text{nom}} \cdot EFC_{\text{EoL}}}$$

Wirkungsgrad DC-DC



Dynamisches Verhalten



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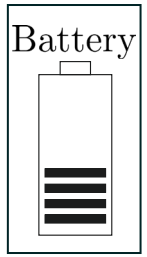
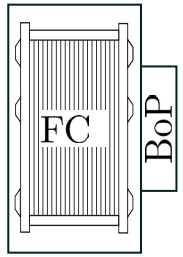
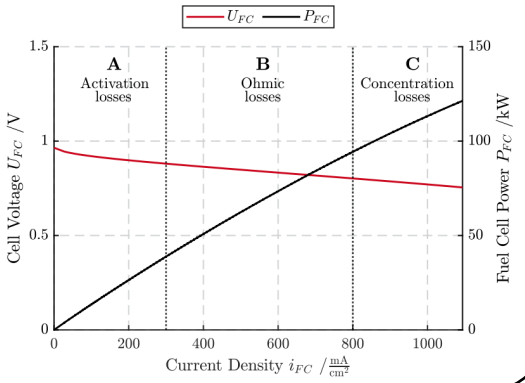
Modellierung: Dynamisches Verhalten

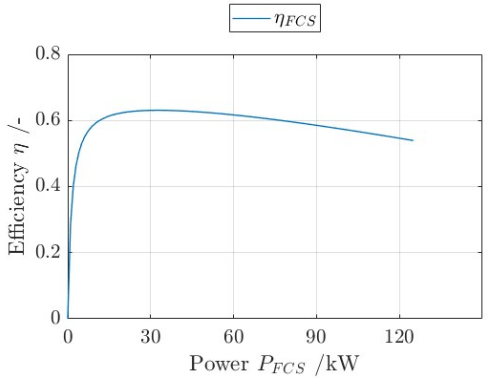




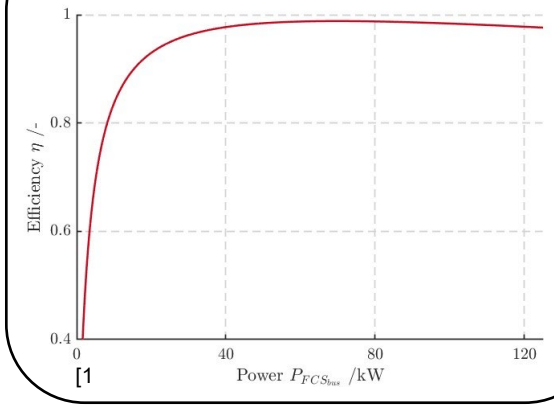
Polarisationskurve



Wirkungsgrad BZS



Wirkungsgrad DC-DC



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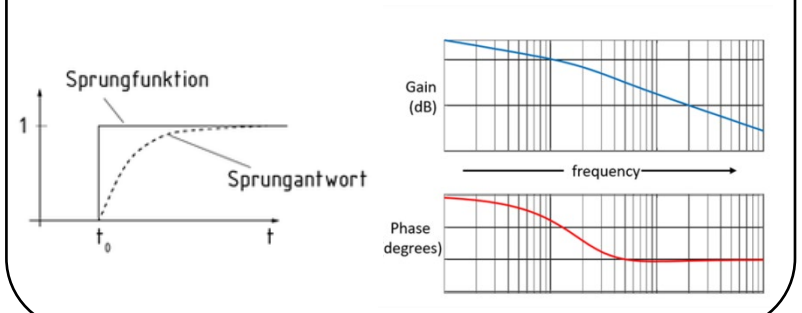
Dynamisches Verhalten



Aktuell: Degradation (implizite Berücksichtigung)

Operation	
On/Off	$xx.x\,\frac{\mu V}{cycle}$
High Power	$xx.x\,\frac{\mu V}{h}$
Low Power	$xx.x\,\frac{\mu V}{h}$

Operation	
Mid Power	$xx.x\,\frac{\mu V}{h}$
Transient Load	$xx.x\,\frac{\mu V}{kW}$

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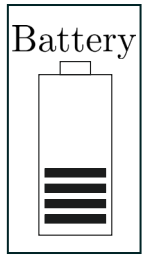
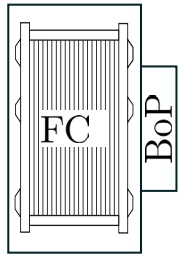
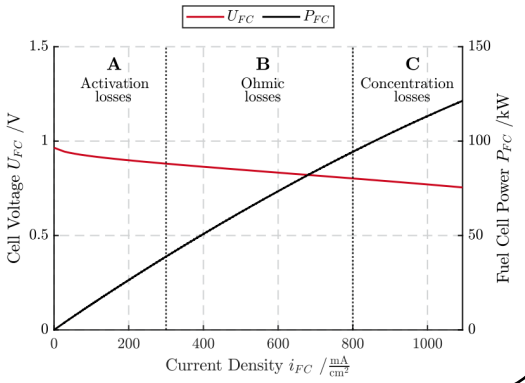
Modellierung: Dynamisches Verhalten

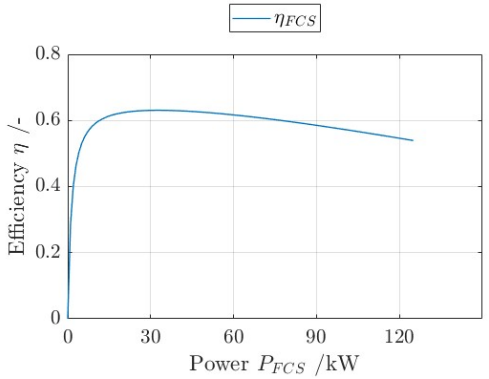




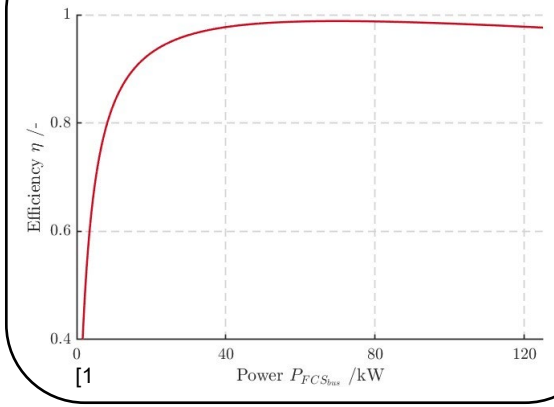
Polarisationskurve



Wirkungsgrad BZS



Wirkungsgrad DC-DC



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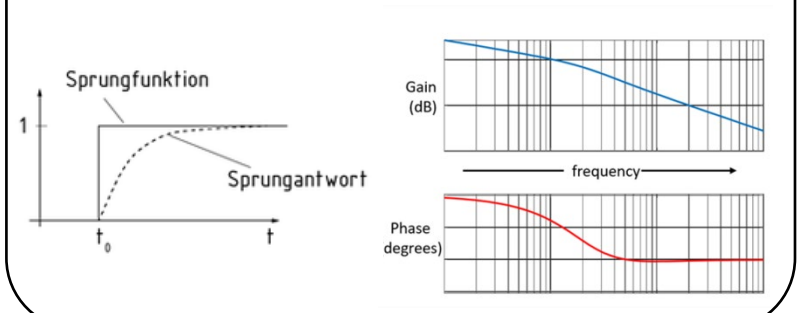
Dynamisches Verhalten



Degradationsmodell

Explizite Berücksichtigung von SoH und Degradation

ZBT

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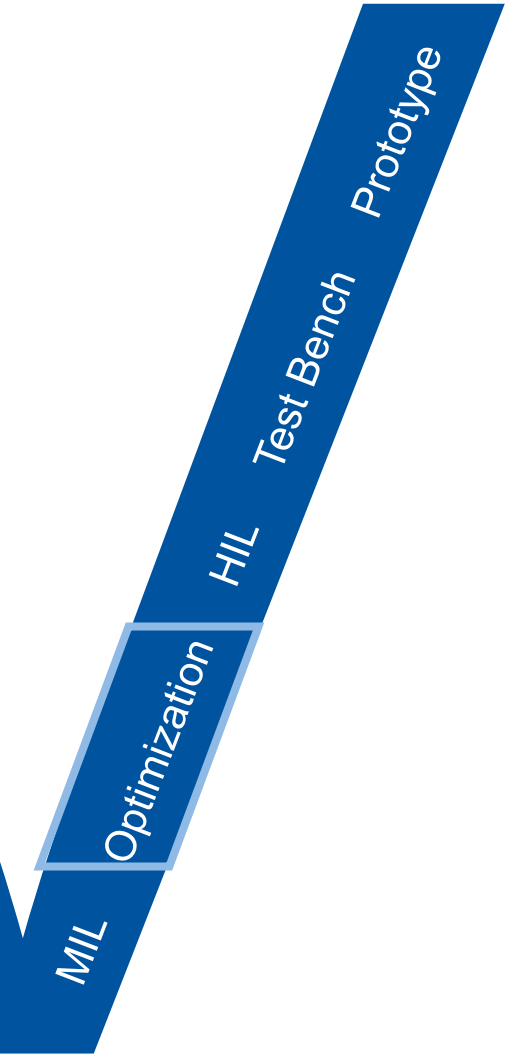
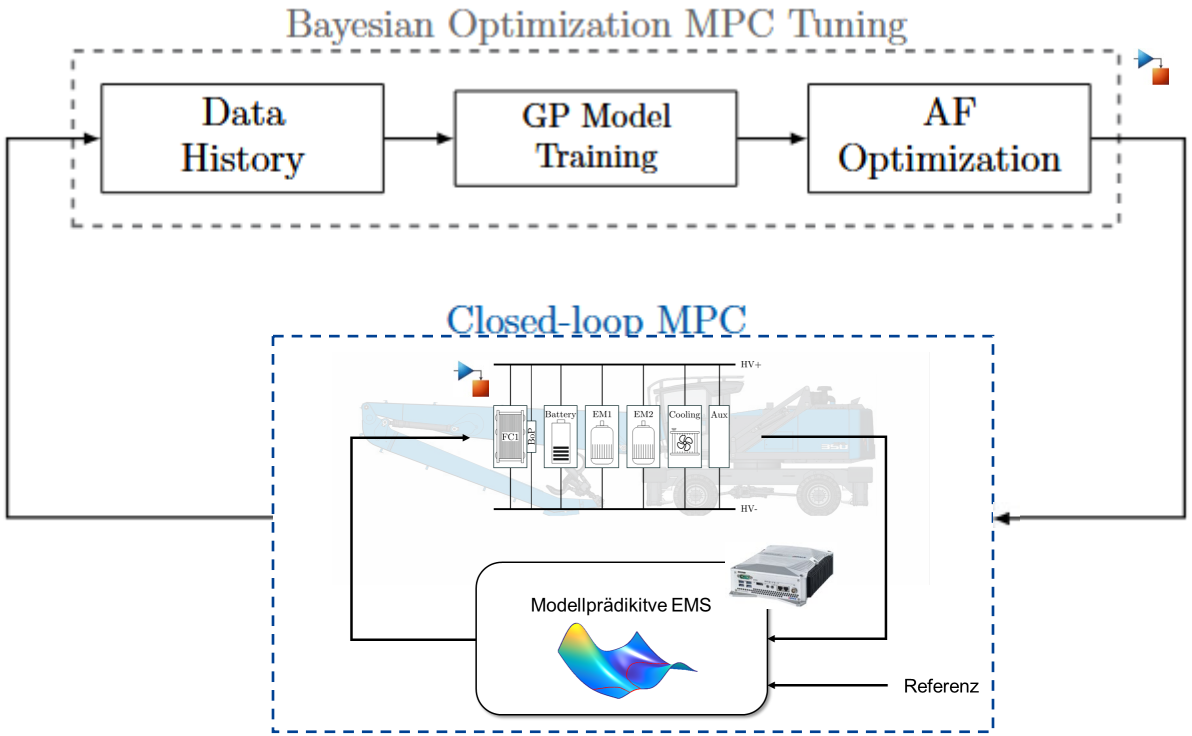
Umsetzung



$$\min \quad C = C_{\mathrm{m_{H_2}}} m_{\mathrm{H_2}} + \sum_n C_{\mathrm{fcs}} P_{\mathrm{fcs}}^{\max} r_{\mathrm{fcs,n}} + C_{\mathrm{bat}} E_{\mathrm{nom}} r_{\mathrm{bat}}$$



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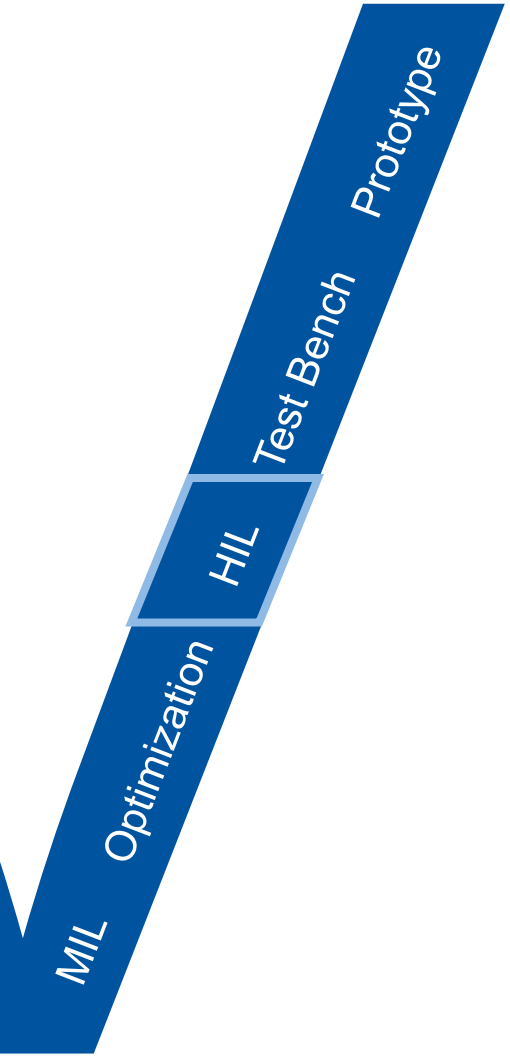

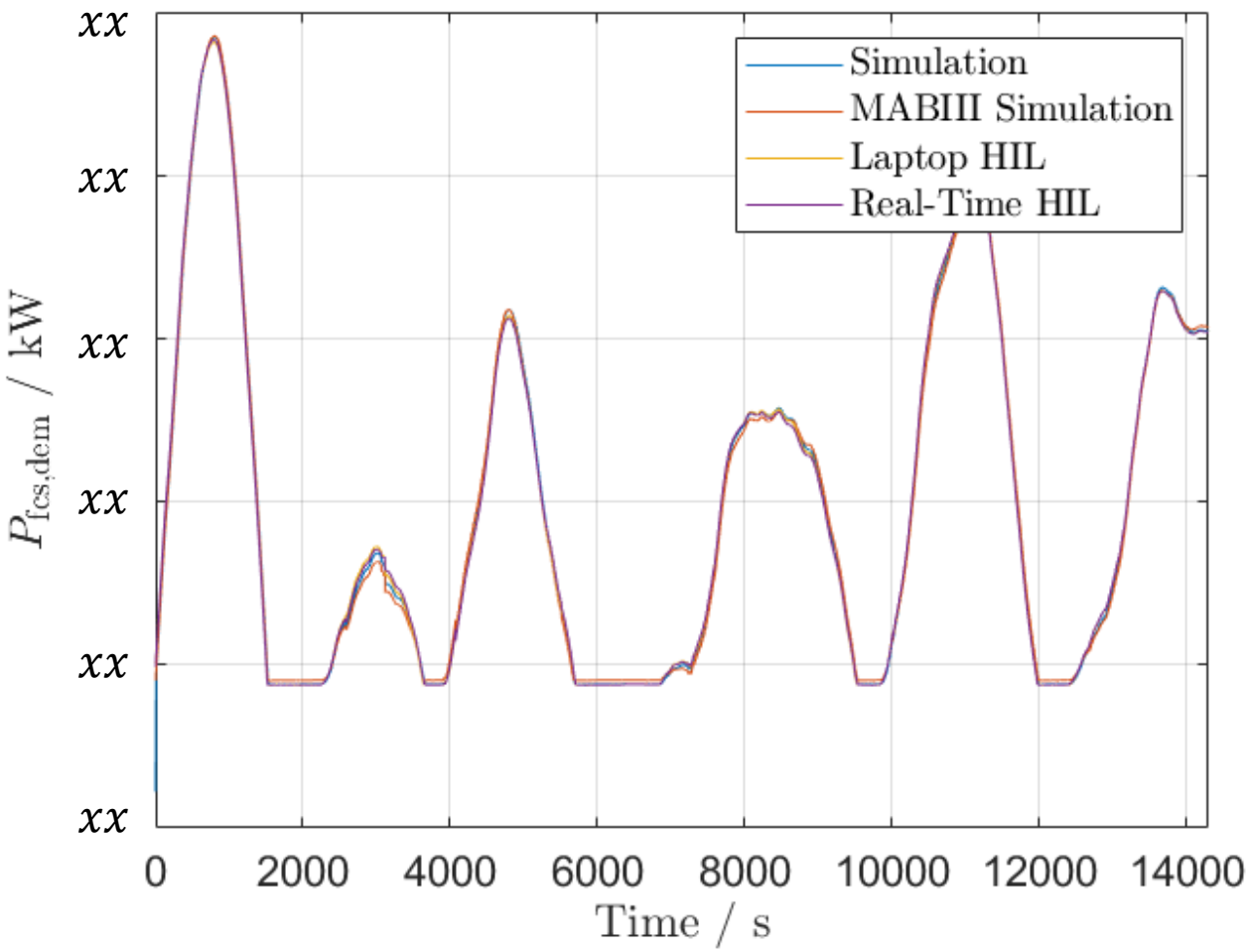

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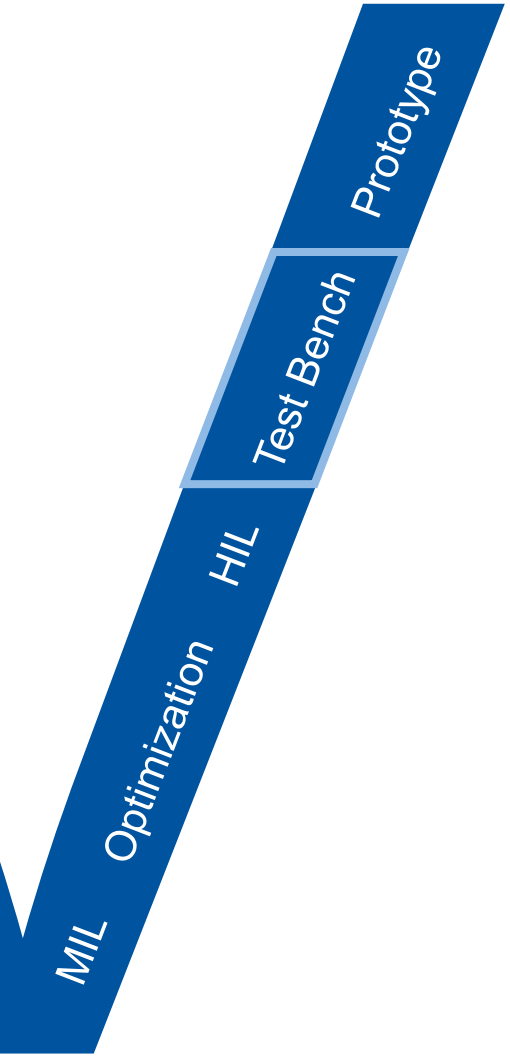

Lehrstuhl und Institut für Maschinenelemente und Systementwicklung, RWTH Aachen University

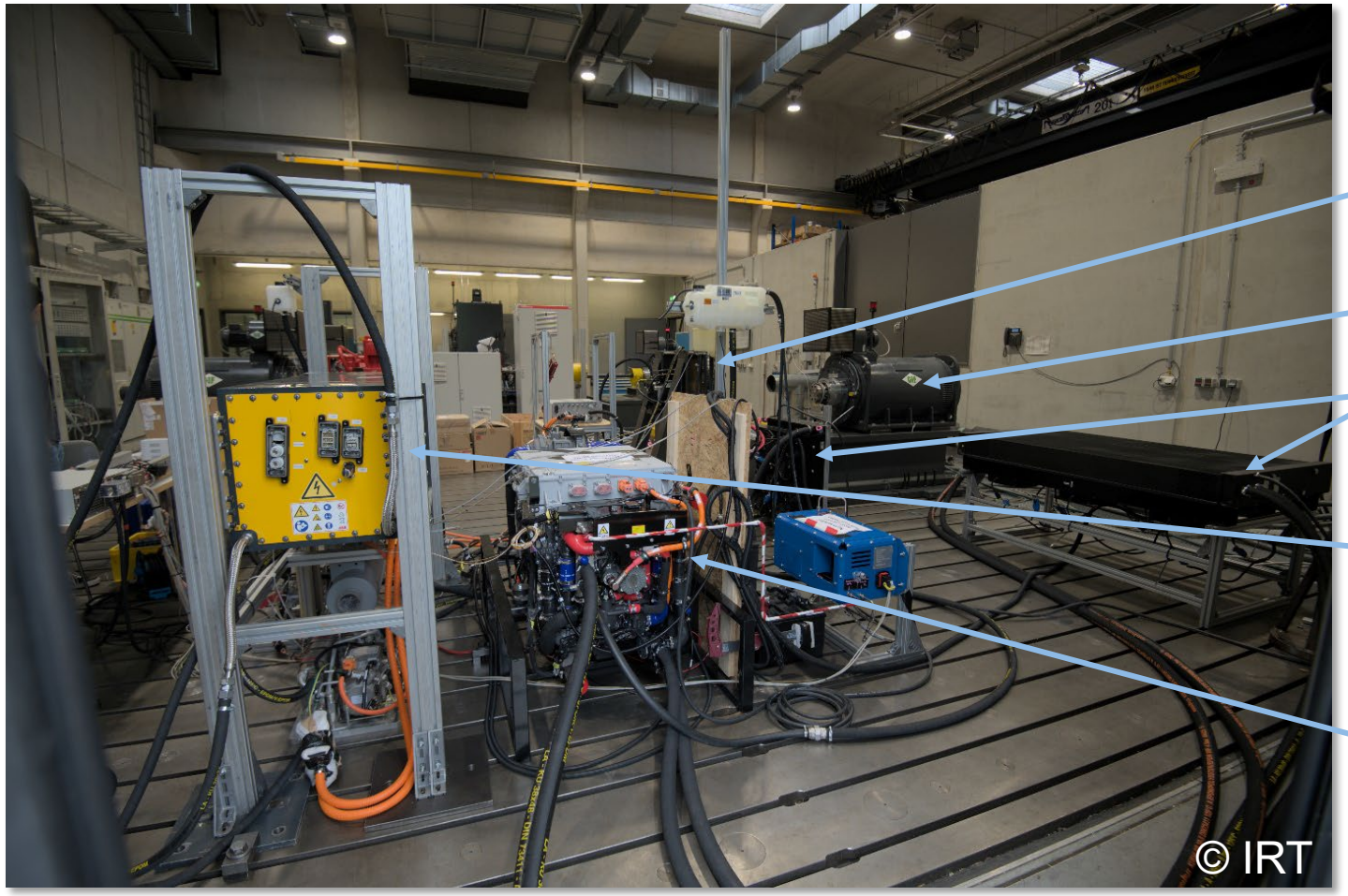

ABB AMXE160S
- PMSM
- 196 kW peak Power

Dyno

Intercoolers

ABB Boardline Max 700
- LTO Battery
- 24.3 kWh
- 400 A peak current
- 240 kW Power

Refire Prisma 18
- Fuel Cell System
- 180 kW Power

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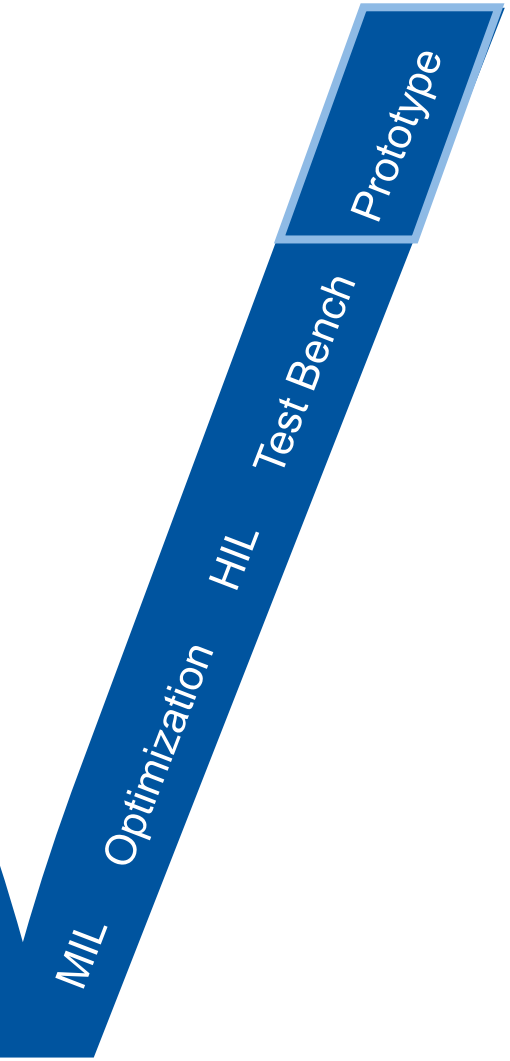
Umsetzung



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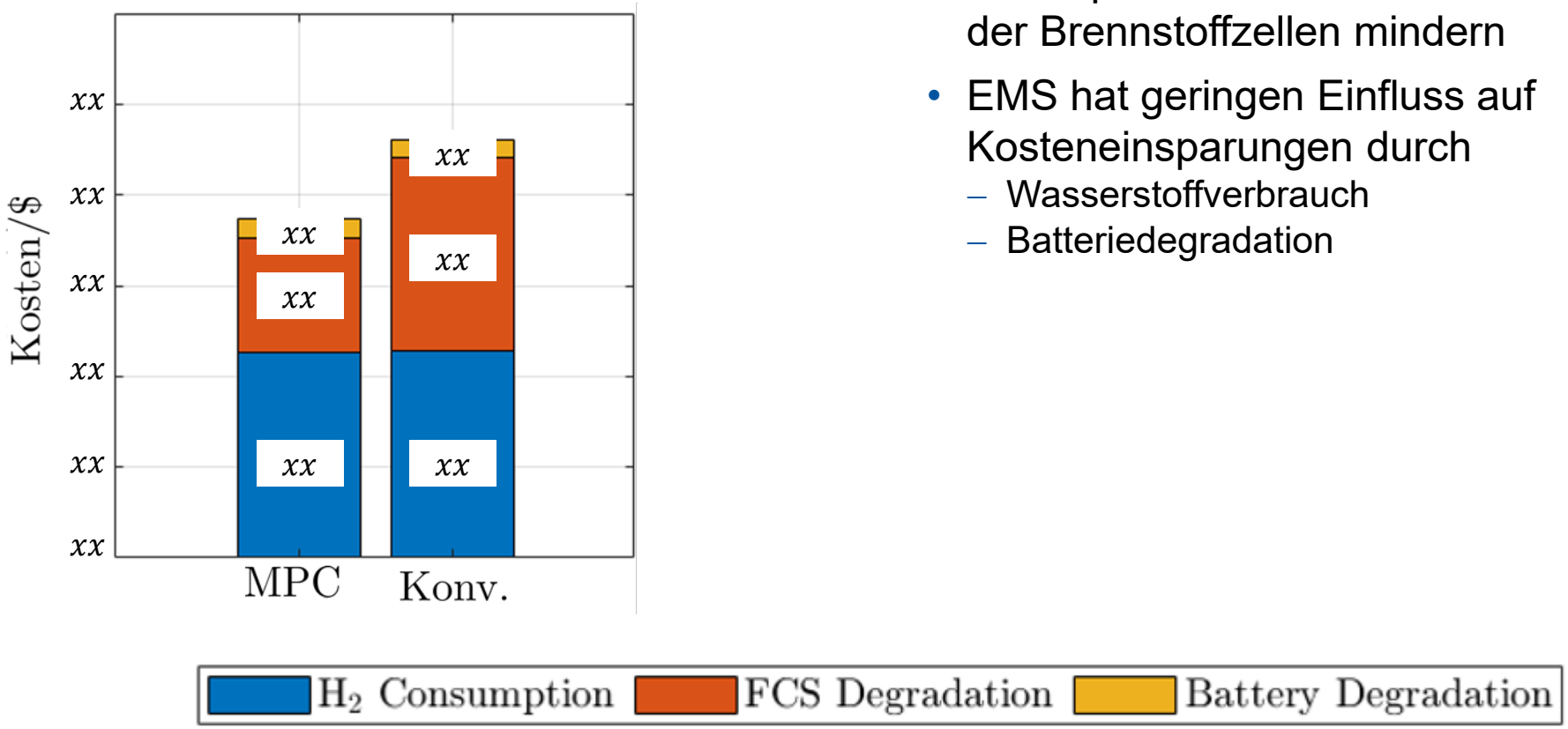
Vorläufige HIL-Ergebnisse

Kosten über Arbeitszyklus



- Modellprädiktiver Ansatz kann Degradationskosten der Brennstoffzellen mindern
- EMS hat geringen Einfluss auf Kosteneinsparungen durch
  - Wasserstoffverbrauch
  - Batteriedegradation

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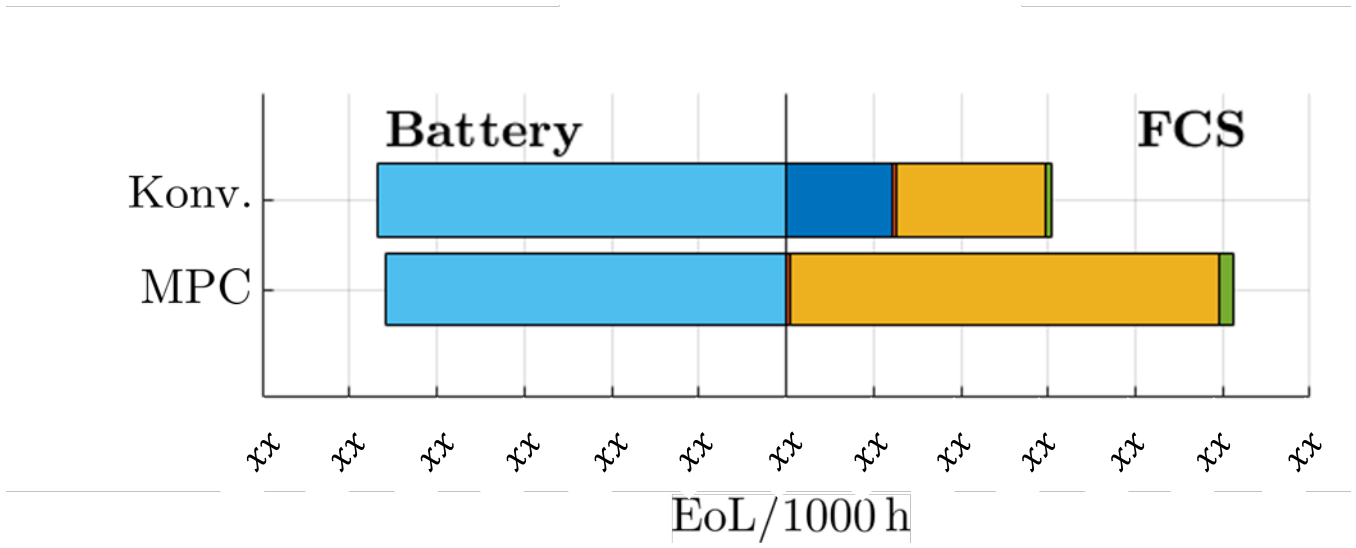
Vorläufige HIL-Ergebnisse

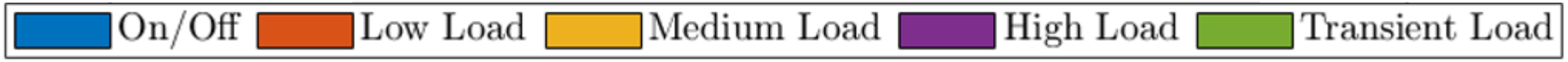
Lebensdauer



- Großer Unterschied in Komponentenalterung kann ausgeglichen werden
- Synergetische Degradation

- Haupteinfluss auf Degradation der Brennstoffzelle
  - Transienter Betrieb
  - On/Off

➢ Trade-off zwischen transientem Betrieb des Brennstoffzellen-Systems und Batterienutzung/-dimensionierung



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Vielen Dank
für Ihre Aufmerksamkeit