

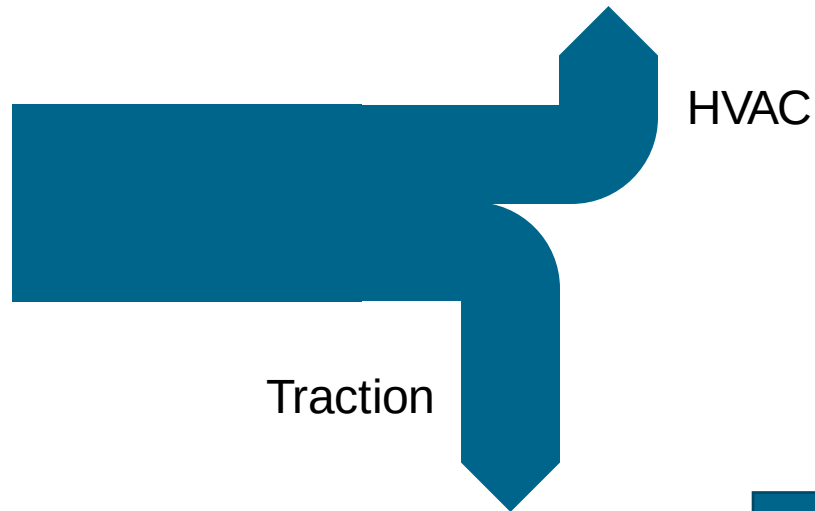
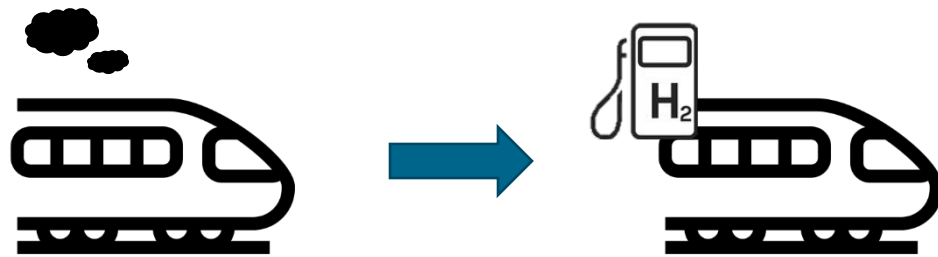
INNOVATIVE METAL HYDRIDE REFRIGERATION SYSTEM

Calculating Energy Savings by Functional Mock Up Based Co-Simulation

ECS Simulation Conference 2023 – Kuli, 10/05/2023

Markus Kordel, DLR – Institute of Vehicle Concepts





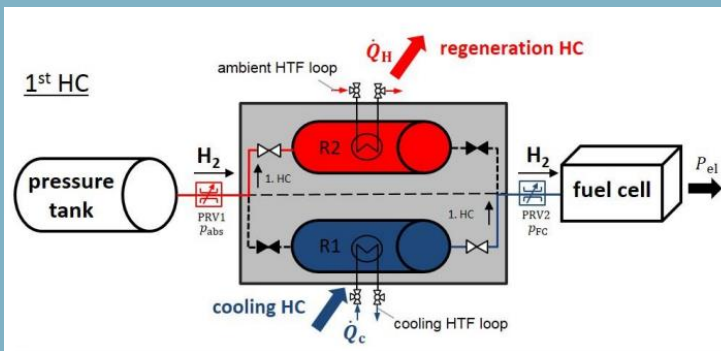
- **2,824 diesel powered** multiple units (DMU) are registrated in Germany ⁽¹⁾
- By 2030 10 – 40 % of diesel powered multiple units (DMU) are intended to be replaced by fuel cell electric multiple units ⁽¹⁾
- Up to 50 % of on board energy demand is dedicated to the HVAC system
 - Reducing HVAC demand increases autonomous range
 - Technology is necessary

1) Garrison, F. et al. (2019)

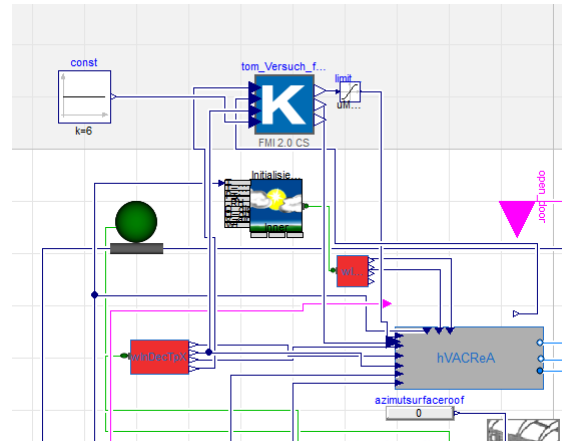
Agenda + Objective

➔ How to assess a waste energy usage method with coupled models?

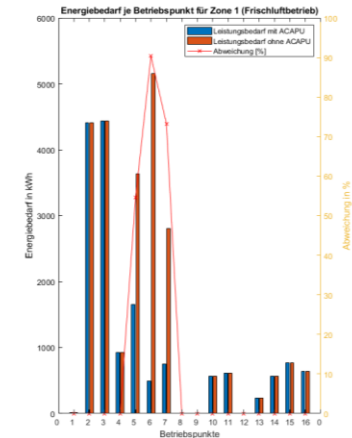
Propose Solution
Metal Hydride System



Evaluate Solution
Kuli + Modelica (FMU)



Present and discuss results



Propose Solution

Metal Hydride System

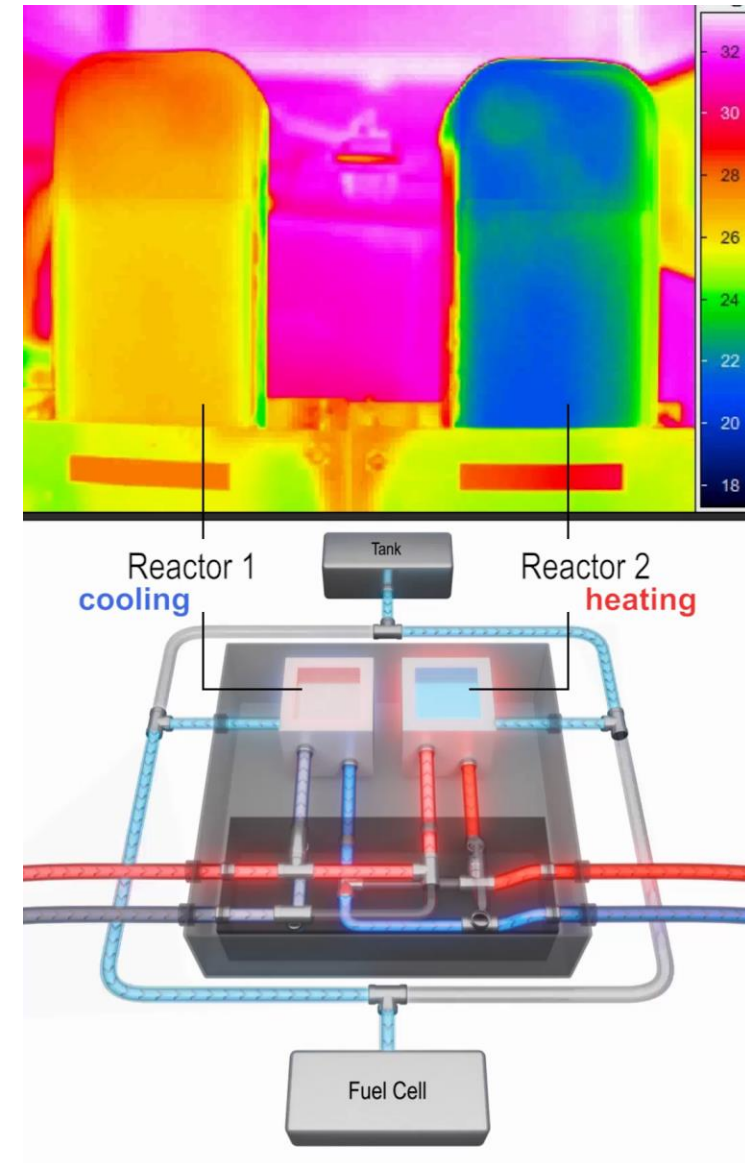
Functional Principle:

- No hydrogen consumption (Potential energy at hydrogen refueling station)
- Absorption and desorption of H₂ provides hot and cold flows
- Quasi continuous power with 2 reactors

Reactors und Specs of Proof of Concepts:

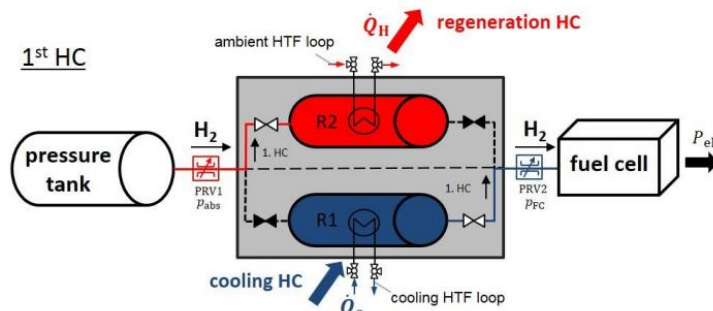
- Material: C2-Hydralloy (TiMn₂ based alloy)
- Reactors total Mass (without valves): 12,2 kg
- Total volume reactors: 5,4 l
- Absorption pressure: 35 bar
- Desorption pressure: 4 bar
- Cooling power: 662 W at 20°C cooling temperature and 30°C ambient temperature at 5 kW fuel cell power

➡ System needs to be scaled up for train application

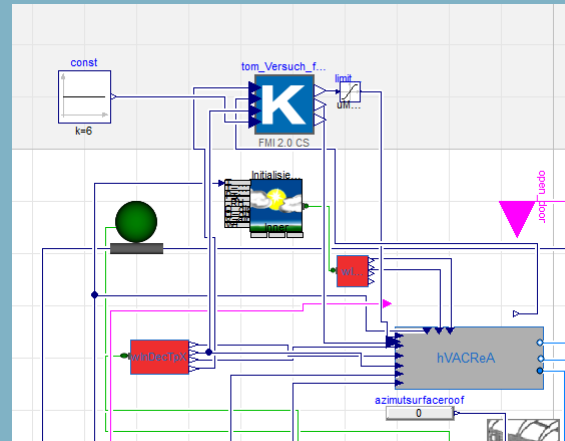


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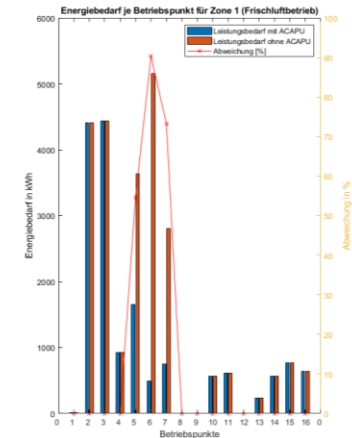
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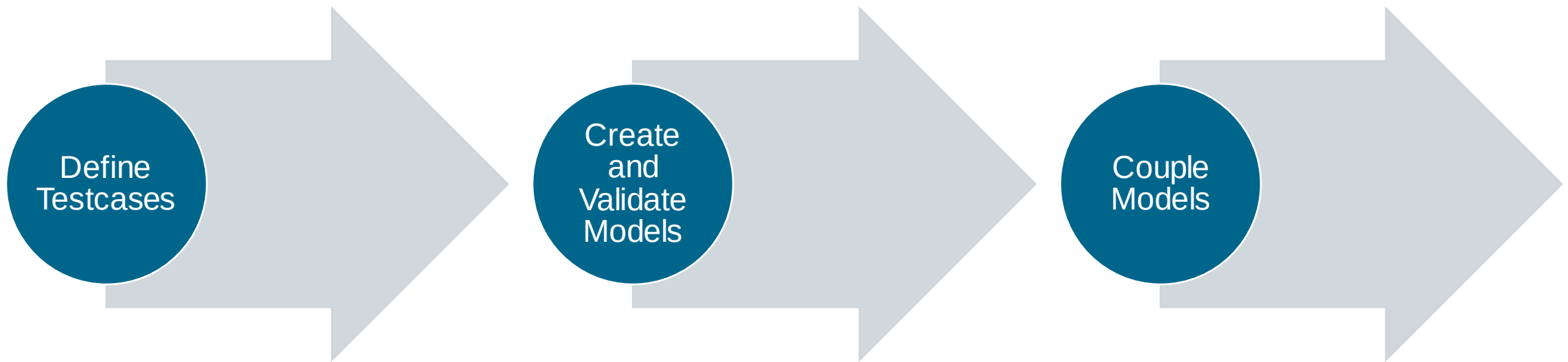


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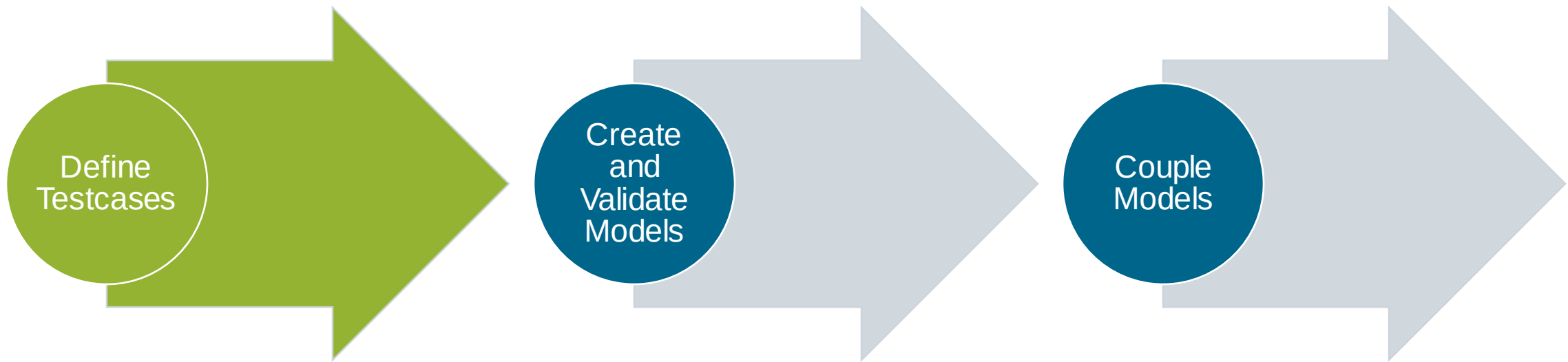
Evaluate solution

Methodology



Evaluate solution

Methodology



Define Testcases

Calculate Annual Energy Consumption

- EN 14750-1:2006 Part 1 and 2
 - ➔ Define ambient conditions and control quality



Temperature

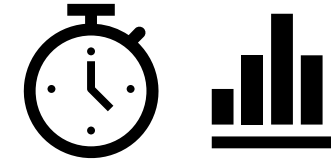


Humidity



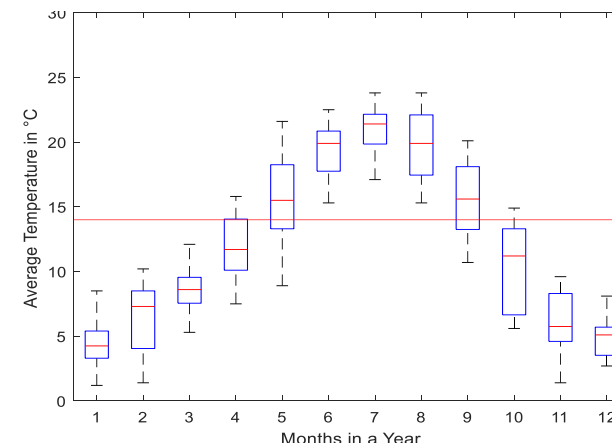
Solar Radiation

- EN 50591:2019
 - ➔ Defines annual energy consumption based on 27 weighted static test cases for 2 climate zones



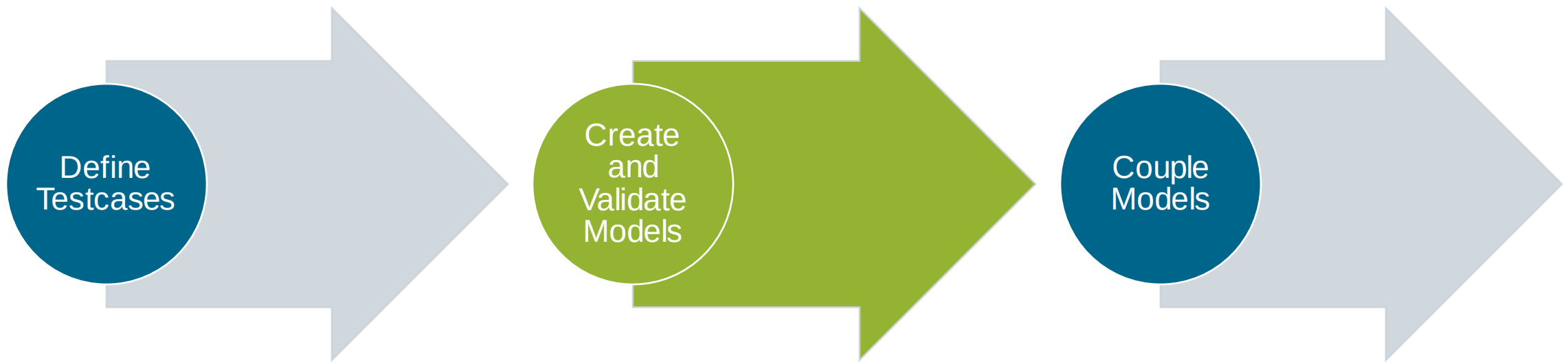
Annual Energy Consumption

- Meteorological weather data
 - ➔ 25 years of weather data were included to approximate real energy consumption at train operation location



Evaluate solution

Methodology



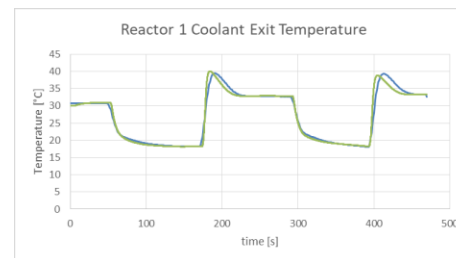
Create and Validate Models

Starting Position

Kuli Model: Metal Hydride Model
For Range Extender Passenger Car

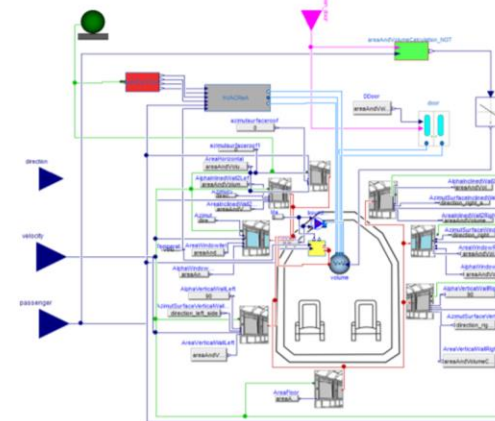


- 3.2 kWh battery pack
- 7 kW fuel cell system
- 5 kg reactor mass
- Model validated with test bench data

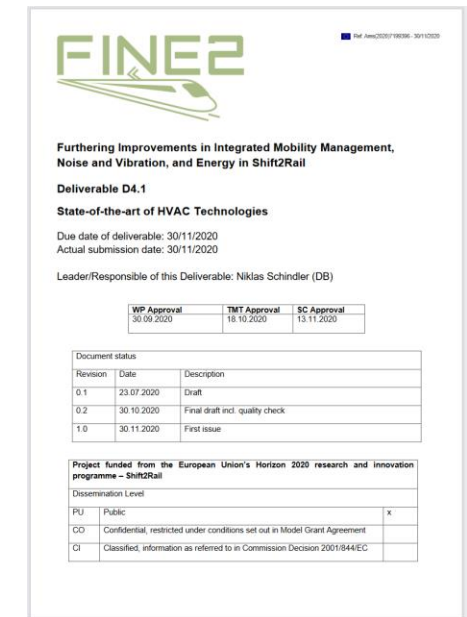


3)

Modelica Model: Thermal Car Body Model for Railway
Passanger Car



- Thermal model of one typical passenger car
- Model includes conventional HVAC system
- Model was validated in climate chamber



2)

2) Schindler, N.(2020)

3) Pöhl, J. et al. (2021)

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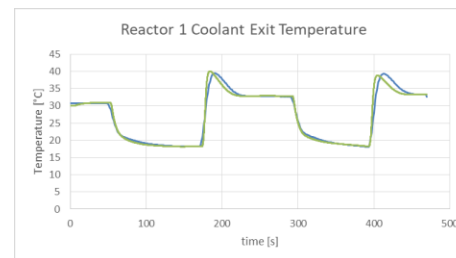
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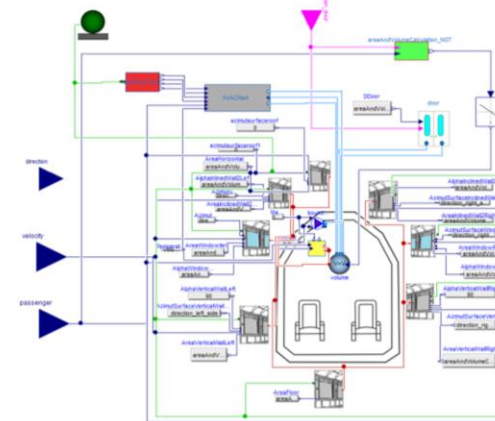


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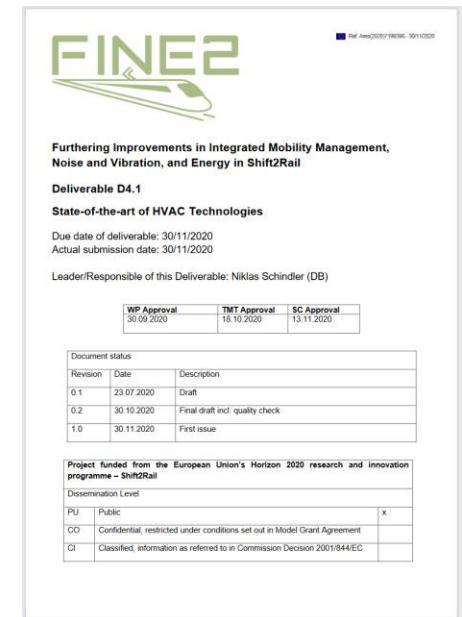


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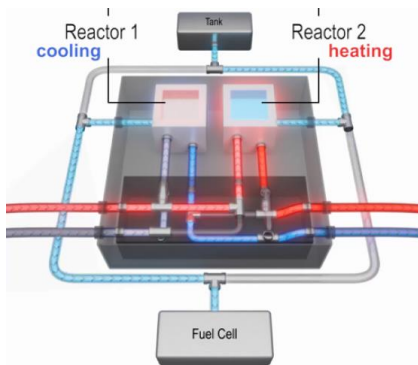
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3) Pöhl, J. et al. (2021)

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Integration in HVAC of FCEMU

Upscaling: Reactor model for passenger cars



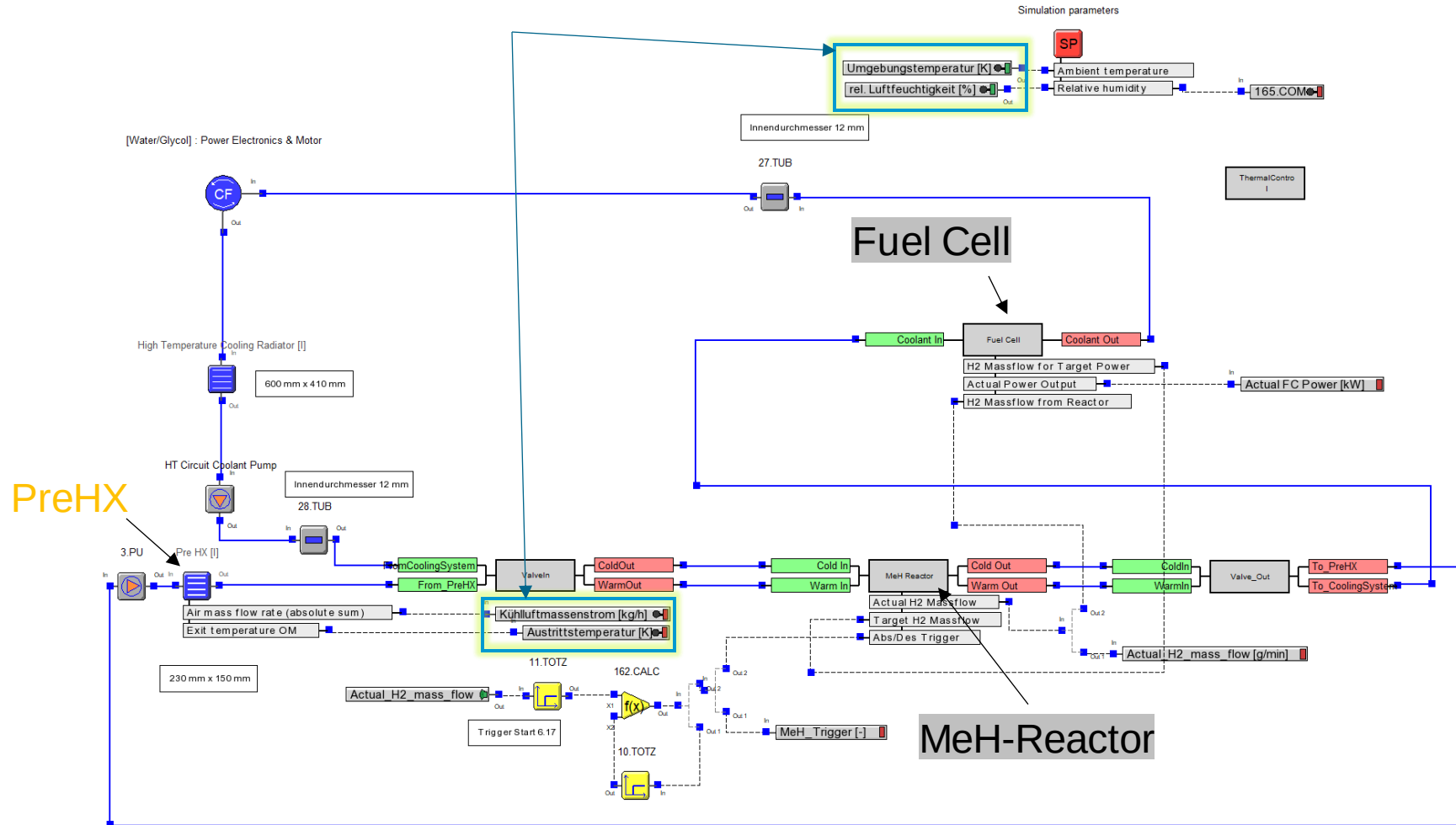
	Reactor Car	Reactor Train
Hydrogen Mass flow	4.5 g/min	178.2 g/min
Metal hydride mass	3 kg	120 kg
Scaling metal hydride mass	1:40	
Metal mass (steel)	9.6 kg	233.6 kg
Scaling metal mass	1:25	
heat transfer fluid mass	0.8 kg	31.2 kg
Sum Mass	13.4 kg	384.8 kg



Metal hydride mass scales linear with expected hydrogen mass flow
Metal mass to metal hydride ration is improved due to novel reactor concept

Interfaces to FMU Model

Com-Objects as interface for FMU



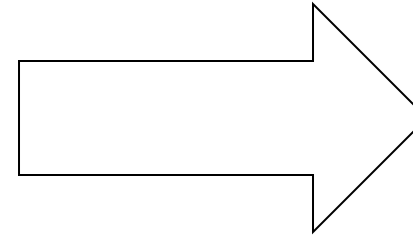
3) Pöhl, J. et al. (2021)

Interfaces to FMU Model

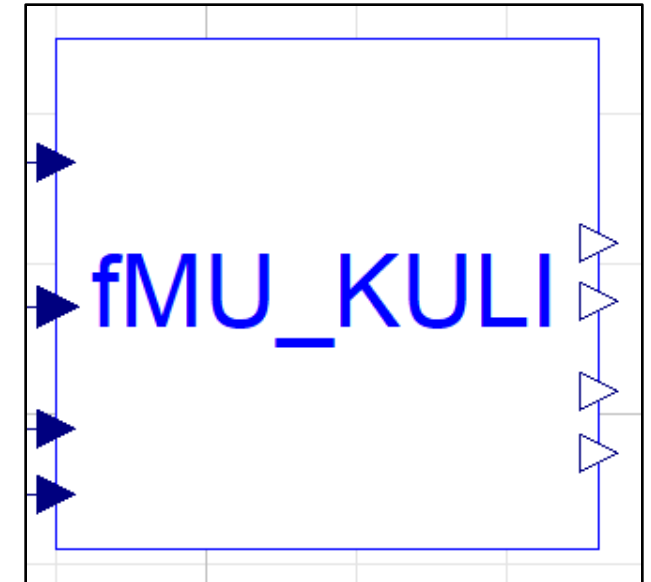
Outputs and inputs are defined via COM Objects

Inputs	Outputs
• Ambient Temperature • Airflow • Humidity	• Output Temperature • Airflow • Humidity

Export via FMU
Generator



In DYMOLA wird die
FMU als Co-
Simulation importiert



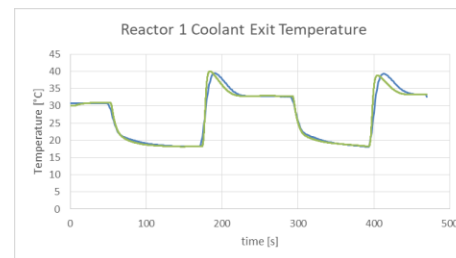
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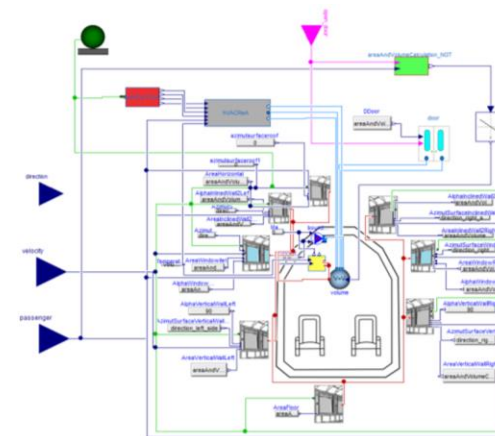


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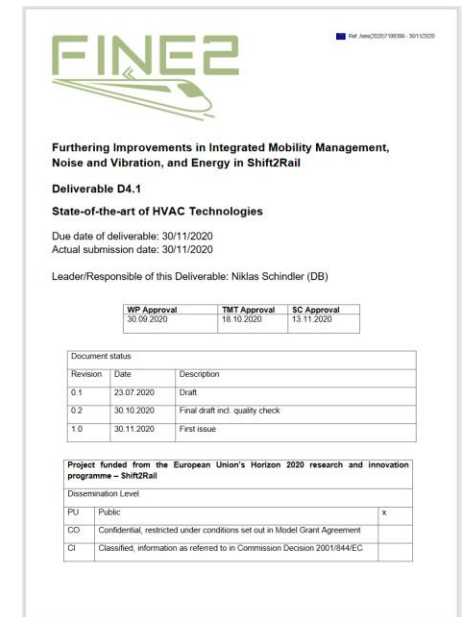


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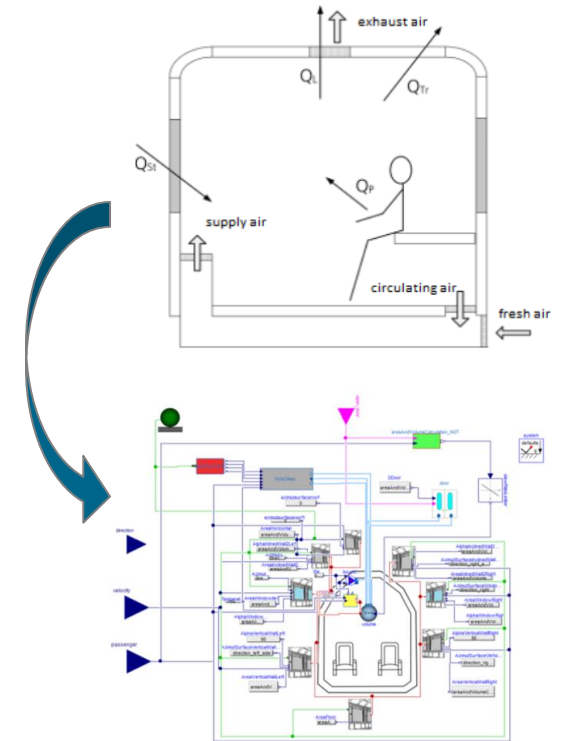
2) Schindler, N.(2020)

3) Pöhl, J. et al. (2021)

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Thermal Car Body Model

- Hybridization tool to design component size and to calculate traction energy demand and hydrogen mass flow ⁴⁾
- Thermal Car Body Model (TCBM) determines **energy demand for HVAC**
- 13 HVAC operating points, defined in DIN EN 50591, were validated in a climate chamber
- Validation results were published in FINE2 Framework ²⁾



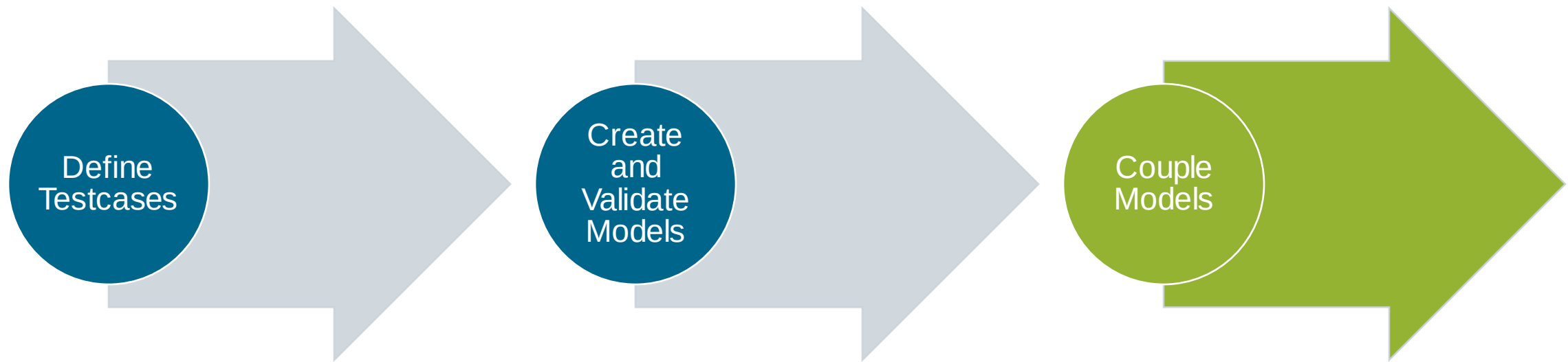
 2 validated simulation models need to be coupled to achieve a train system

2) Schindler, N.(2020)

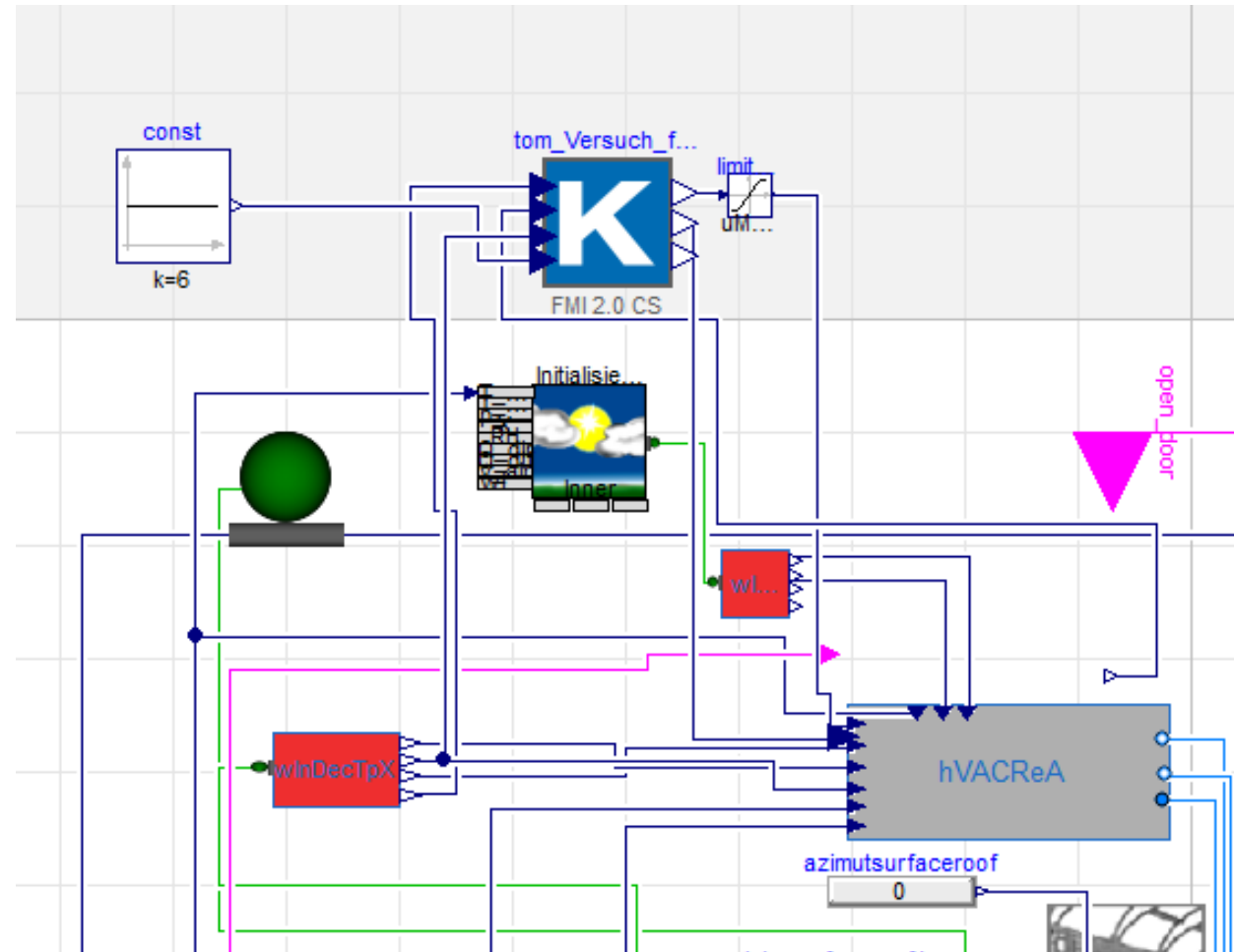
4) Kühlkamp, F.(2022)

Evaluate solution

Methodology

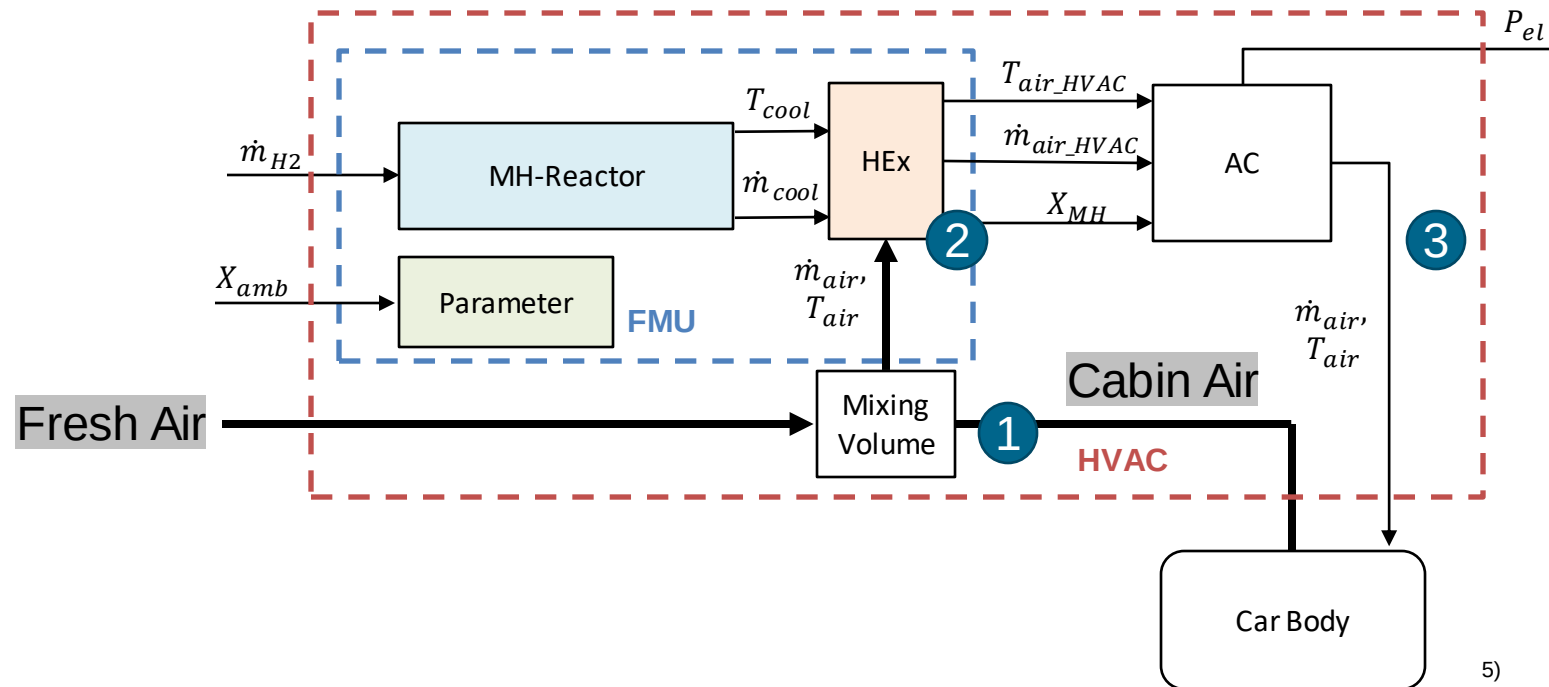


Coupled model



Coupled model

Mixed Air

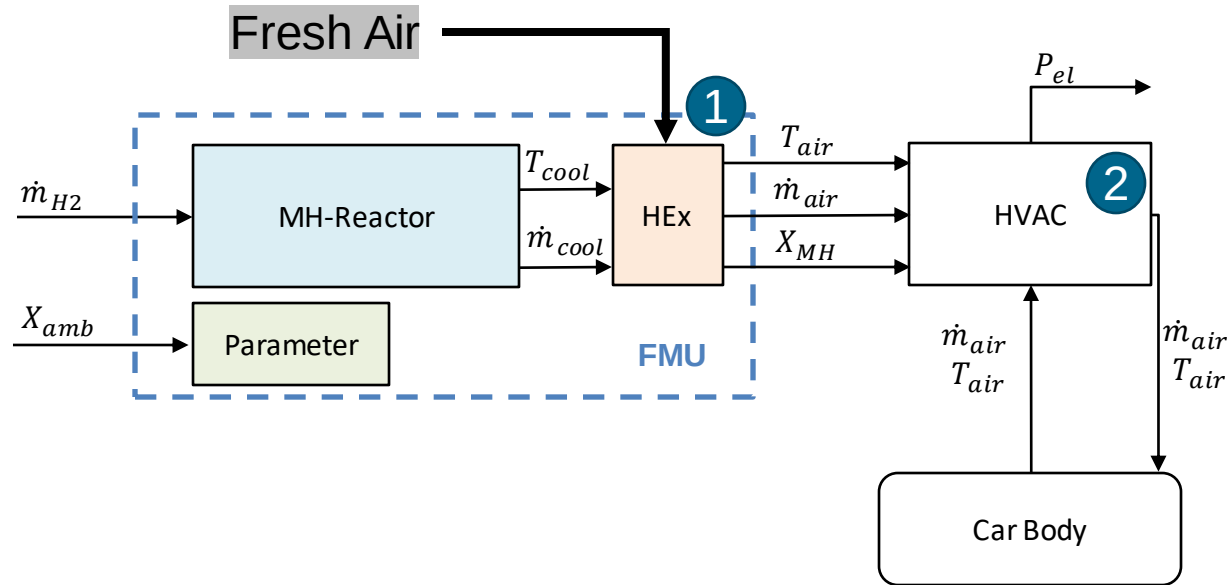


1. Fresh air is mixed with cabin air according to comfort standards
2. MH heat exchanger precools air
3. Target temperature is achieved by standard vapor compression air conditioning system

5) Dehn, F.(2022)

Coupled model

Fresh Air



5)

1. Only fresh air is precooled by metal hydride system
2. HVAC System mixes precooled air with cabin air and cooles mixed air down to target temperature



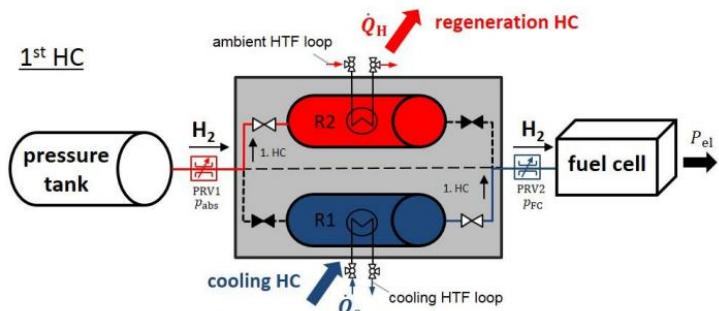
+ Temperature difference between hot and cold reactor is smaller → Efficiency is higher
 - MH System only operates, when fresh air is needed → Passenger

5) Dehn, F.(2022)

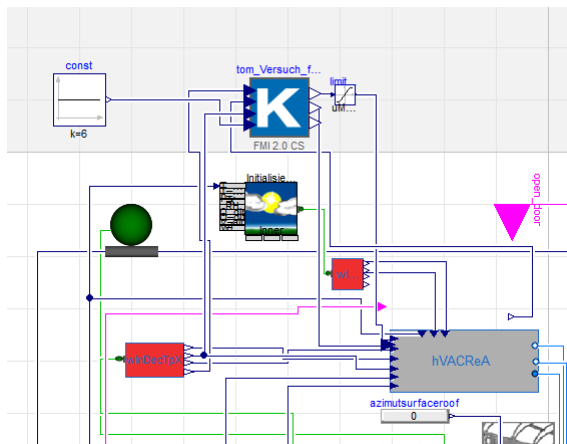
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Agenda + Objective

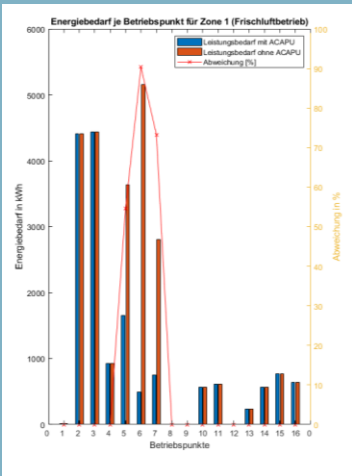
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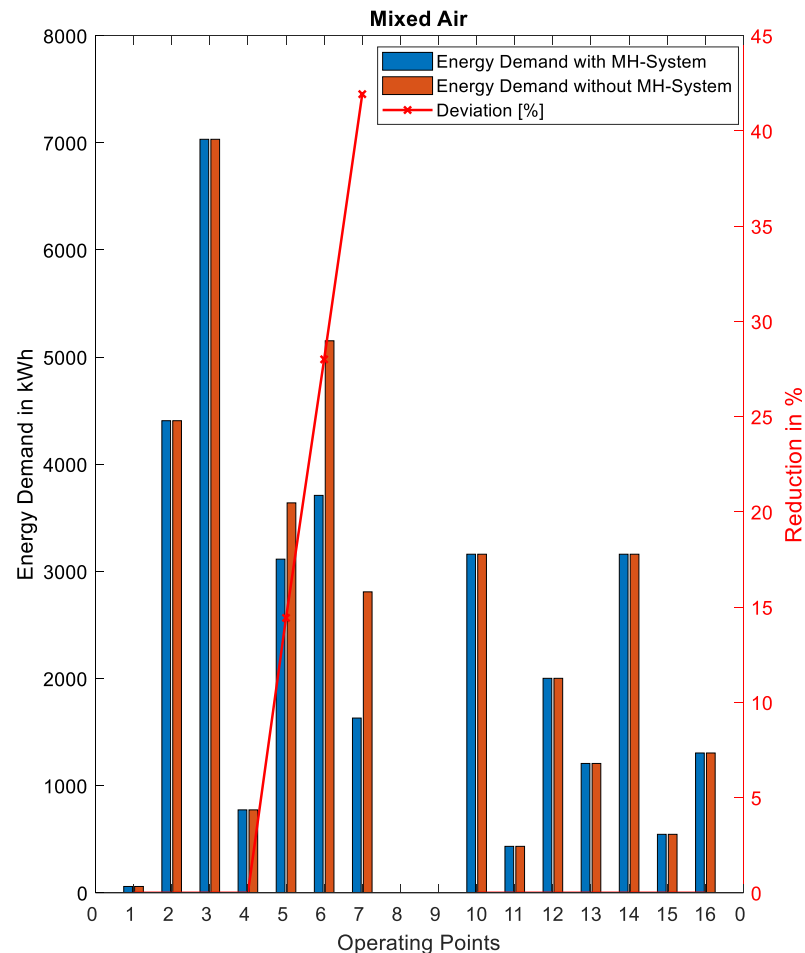
Evaluate Solution
Kuli + Modelica (FMU)



Present and discuss results



First Results



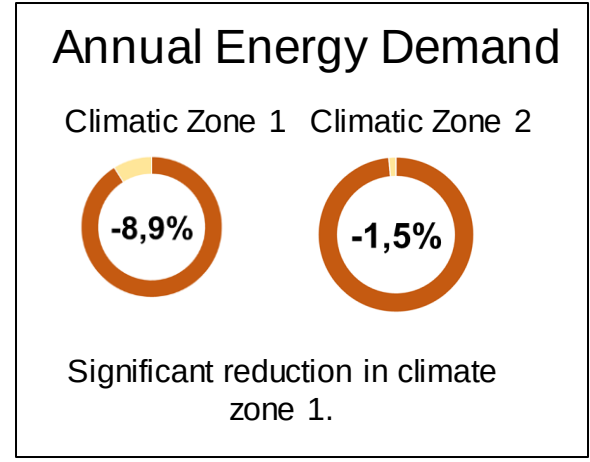
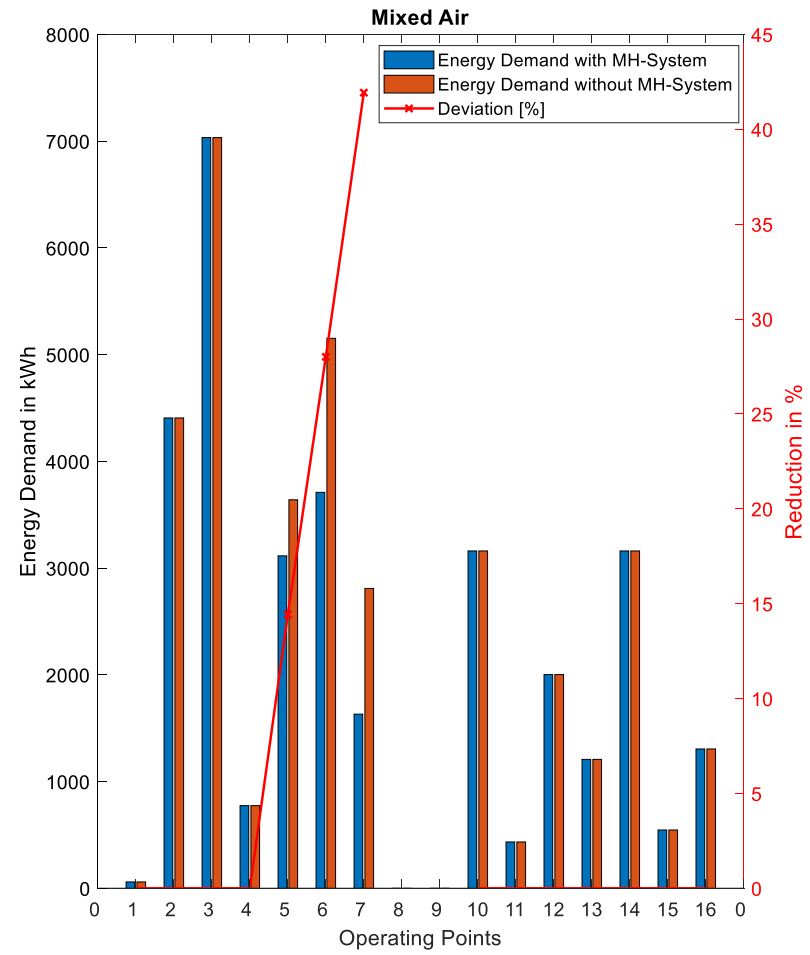
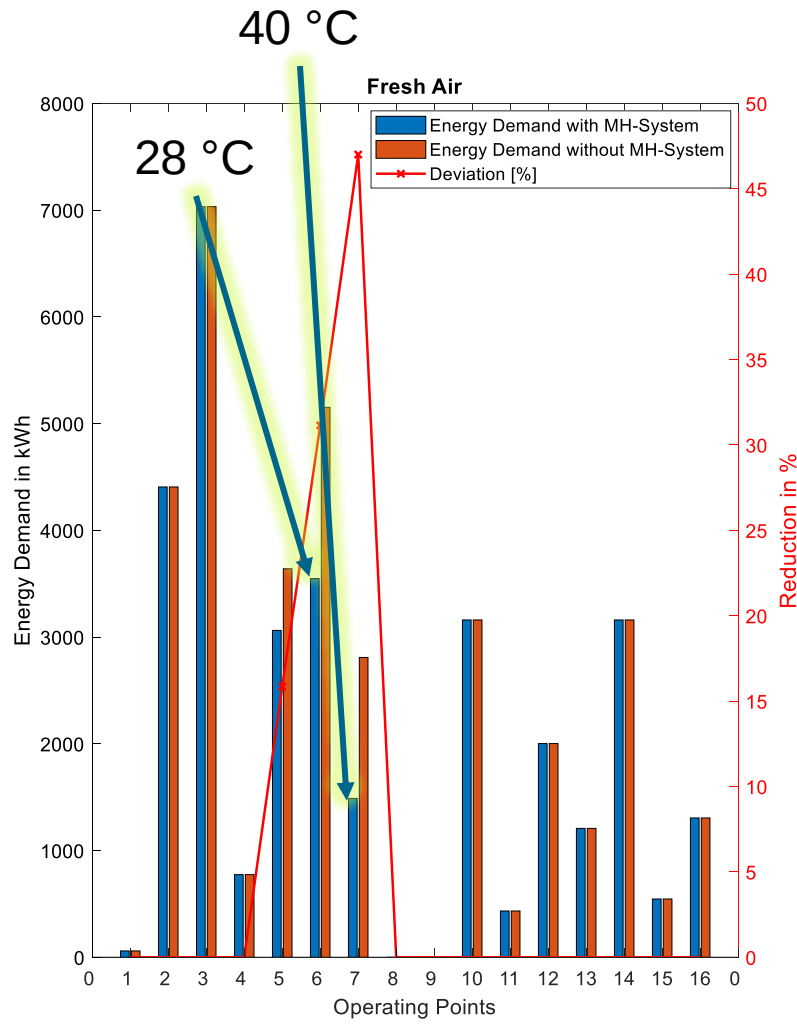
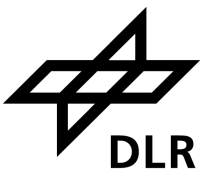
- 16 weighted testcases for each climatic zone
- 1 – 7 train is in operation
- 8 – 16 train is outside normal operation
- Parameter set: e.g. T_{amb} , solar radiation, number of passenger, humidity
- Energy demand for each test case is cumulated

Energy demand
without HVAC

Climatic zone 1:
35,687 kWh

Climatic zone 2:
54,097 kWh

First Results



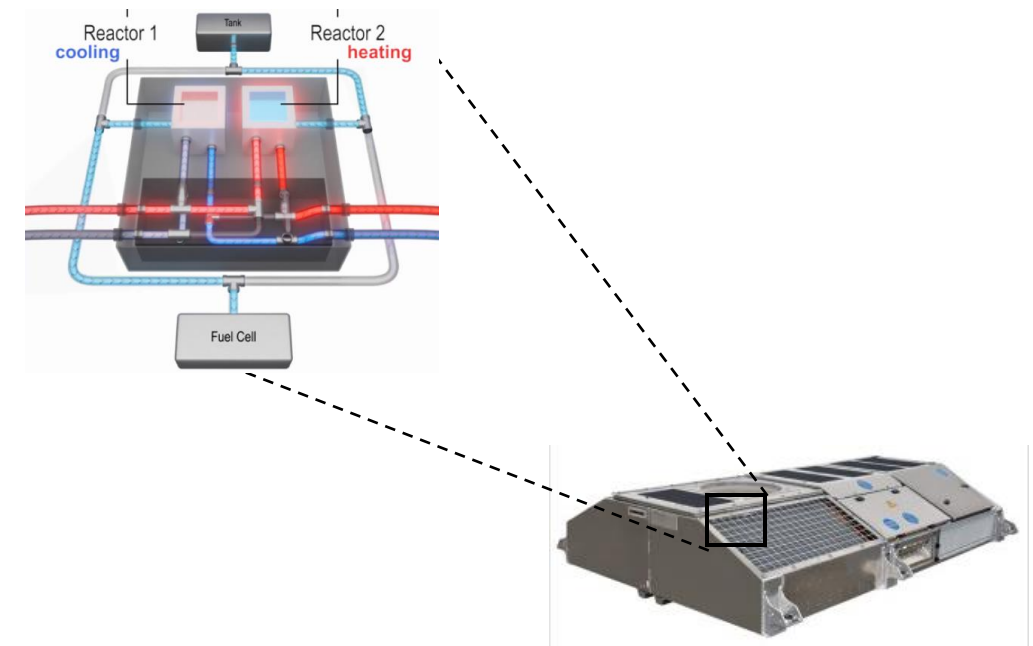
5)

5) Dehn, F.(2022)

Summary

Model Coupling

- 2 Validated Models were coupled
- FMU was used to implement Kuli model into a Dymola (Modelica) model
- The integration strategy mixed air and fresh air was simulated
- Annual energy demand was calculated according to DIN EN 50591



Summary

Preliminary results

- No significant energy reduction potential difference between integration options
- Energy reduction potential differs between climatic zones

Next steps

- FC system pressure reduction allows significant increase of efficiency
- Optimized materials need to be investigated
- Further evaluation of results need to be performed

Annual Energy Demand

Climatic Zone 1 Climatic Zone 2



Significant reduction in climate zone 1.

Pressure Adjustments

**-59% Reduction of
Energy demand**

- 1) Fuel Cells and Hydrogen 2 Joint Undertaking, Shift2Rail Joint Undertaking, Garrison, F., Andrae, P., Erofeeva, S., et al., *Study on the use of fuel cells and hydrogen in the railway environment*, Publications Office, 2019, <https://data.europa.eu/doi/10.2881/495604>
- 2) Schindler, N.; Fine2; Deliverable D4.1; State-of-the-art of HVAC Technologies (2020)
- 3) Pöhl, J., Kordel, M., Heckert, F., Wimmer, A. und Bürger, I. (2021) Benefit studies of an innovative metal hydride air-conditioning system for FCEVs by using thermal management simulation. 2021 ECS SIMULATION CONFERENCE, 18. - 20. Mai. 2021, Online.
- 4) Kühlkamp, F., Schenker, M., Pagenkopf, J., Dittus, H., Herwartz, S., Fernández Del Rey, A., Varela, M. (2022) The FCH2RAIL Project: A Demonstration of a Modular Fuel Cell Hybrid Power Pack. TRA - Transport Research Arena, 14. - 17. Nov. 2022, Lissabon.
- 5) Dehn, F. (2022) Kältebereitstellung mit Metallhydriden in einem Brennstoffzellen-Hybridzug - Simulative Energieeffizienzbetrachtung durch ein thermisches Wagenkastenmodell. Masterarbeit, Technische Universität Berlin.