MAN Energy Solutions
Future in the making

BATTERY CONFERENCE
March 28-30, 2022

Simulating the Temperature Spread within a Commercial Li-Ion Battery Module

A performant and non-destructive Characterization and Modeling Process

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EU-Project NAUTILUS

Nautical Integrated Hybrid Energy System for Long-haul Cruise Ships

Motivation

- Shipping represents 13% of EU's transport GHG emissions
- Reducing emissions necessary to comply with EU regulations and customer requirements

Goal

- Concept for 5-60 MW SOFC + battery hybrid energy system
- Design and operation of 80 kW functional demonstrator
- Techno-economic, life cycle and future fuel analysis

Consortium

- Cruise companies, manufacturers and academics
- MAN ES as system provider for future energy systems

This project received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 861647.

Motivation

Thermal gradients within large-scale battery systems

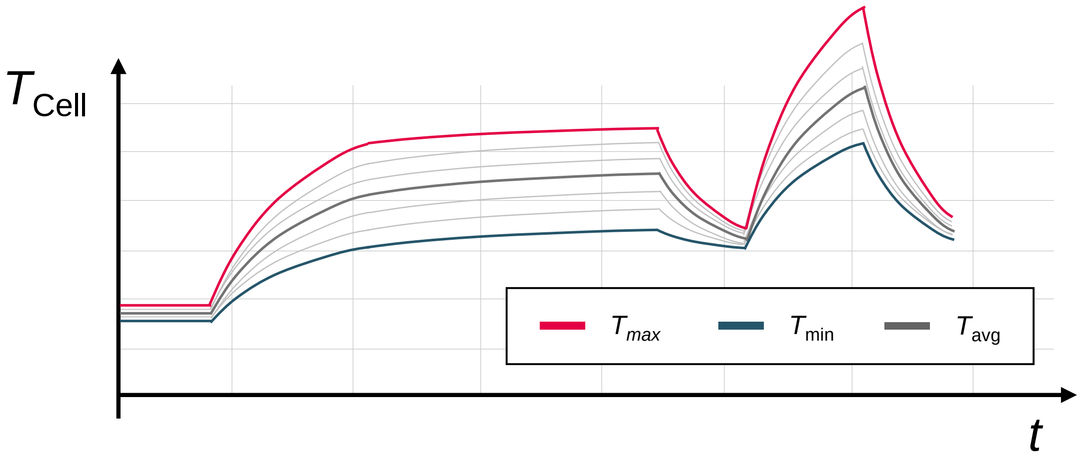
Simulation of **thermal gradients within a system** of interest due to influence on aging, safety, electrical behavior,…

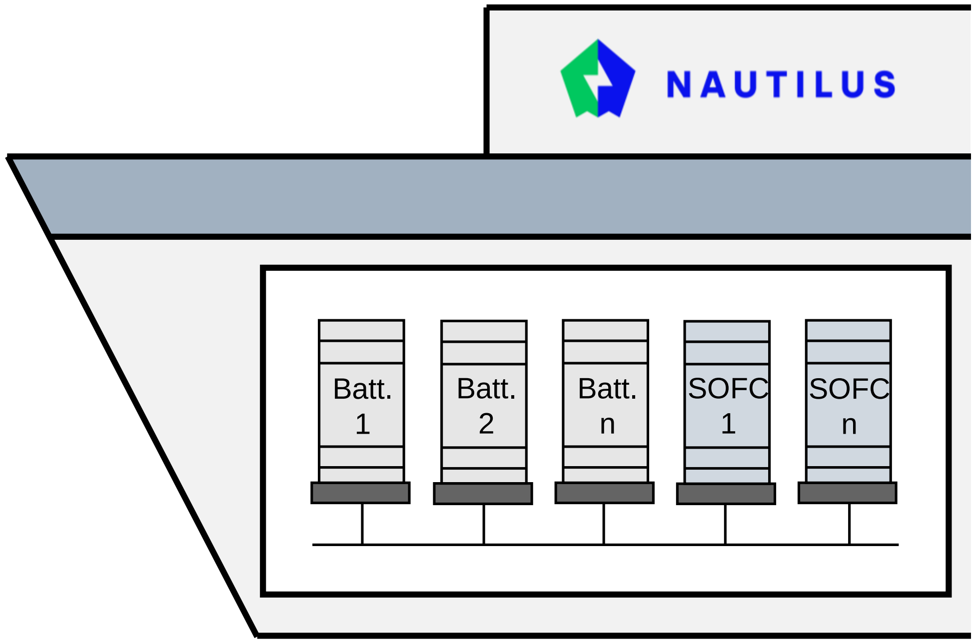
Usual approach: FEM/CFD or thermal equivalent circuit models → calculation of cell-specific temperature

Difficulty: Large-scale systems with > 1000 electro-thermally coupled cells → massive effort in model computation

Novel approach: Structural model simplification

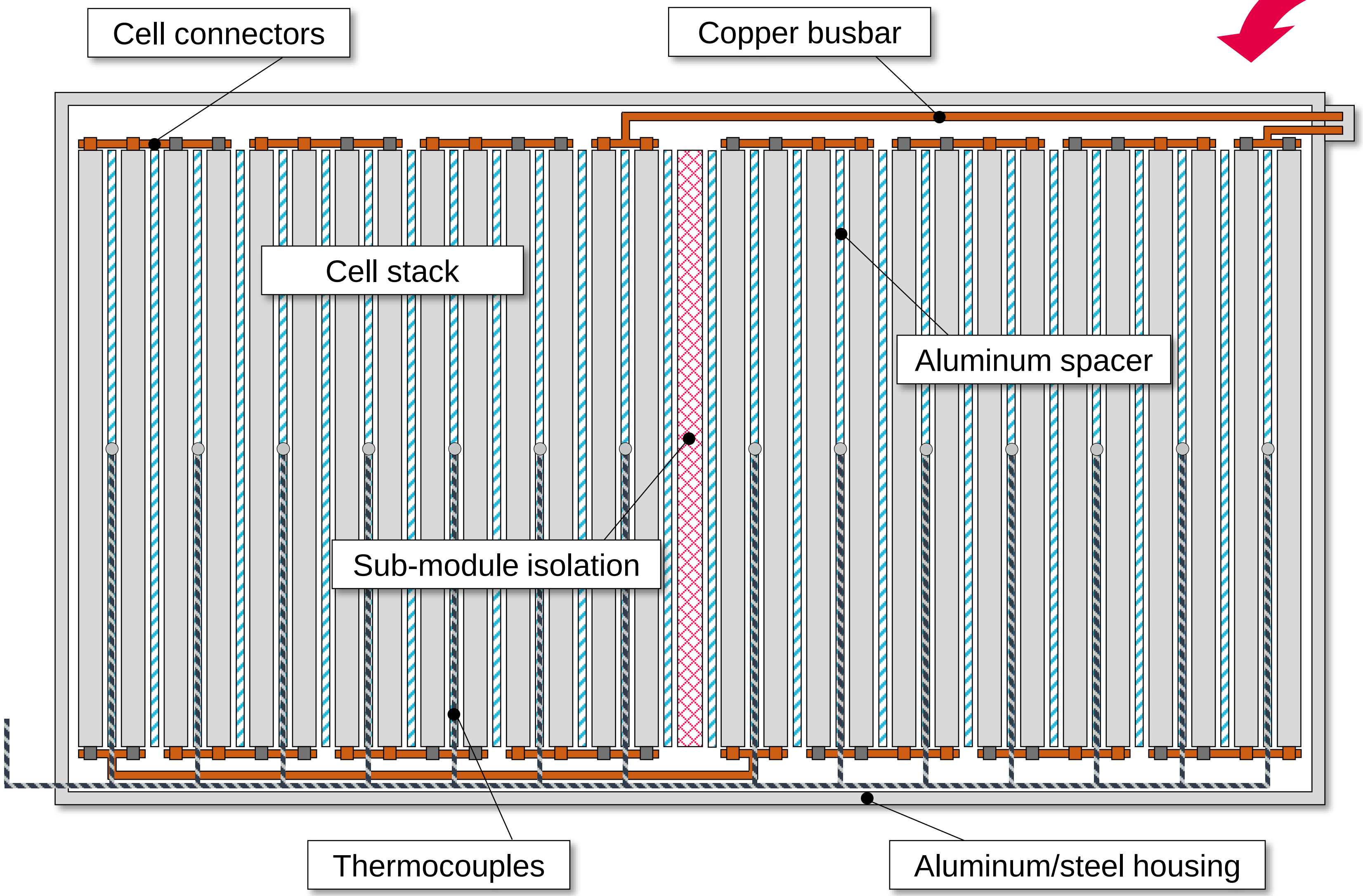
- Simplifying full-scale thermal equivalent circuit model
- Average + min/max temperature instead of cell-specific temperature
- Reduction of computational effort by orders of magnitude → Enabling real-time parallel computation for large-scale systems

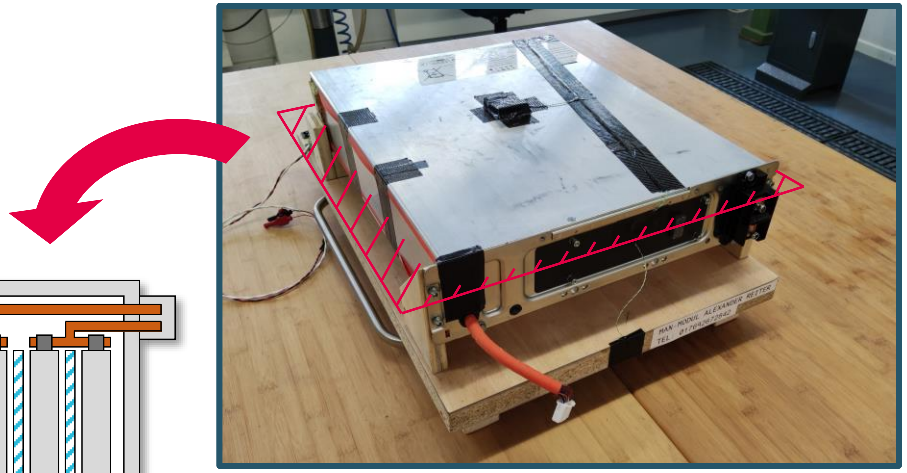




Agenda

System under Investigation

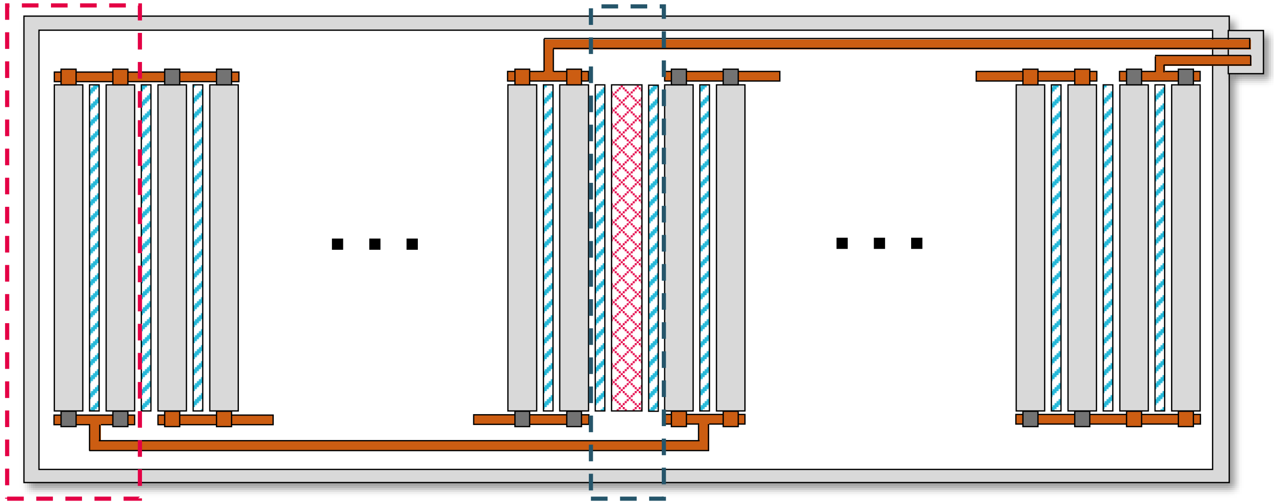




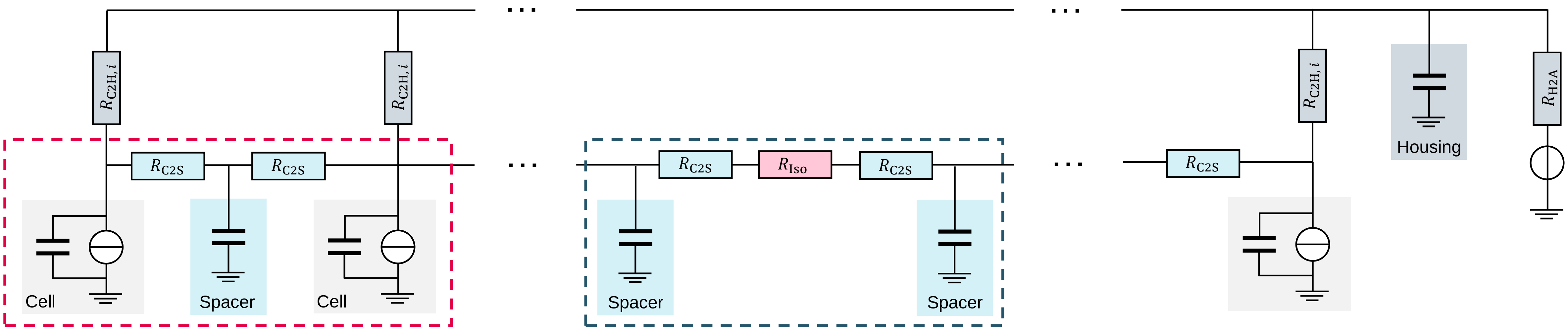
Commerical Li-ion battery module for stationary applications

- 14s2p-configuration
- NMC pouch cells
- 128 Ah nominal capacity

Characterization and Modeling



Parameter	Determination Method	Value
$\dot{Q}_{gen,\,irr}$	Electrical losses (ECM)	$f(R, I)$
$\dot{Q}_{gen,\,rev}$	Dynamic pseudo-calorimetry [1]	$f\left(T, I, \frac{dOCV}{dT}\right)$
$C_{th,\,Cell}$	Cooling curve	1549.0 J/K
$C_{th,\,Spacer}$	Analytical	64.8 J/K
$C_{th,\,Housing}$	Analytical	5857.9 J/K
$R_{th,\,H2A}$	Steady state	0.0971 K/W
$R_{th,\,C2H,\,i}$	Steady state	$f(A_{contact})$
$R_{th,\,Iso}$	Analytical	11.09 K/W
$R_{th,\,C2S}$	Steady state – external heating	2.628 K/W

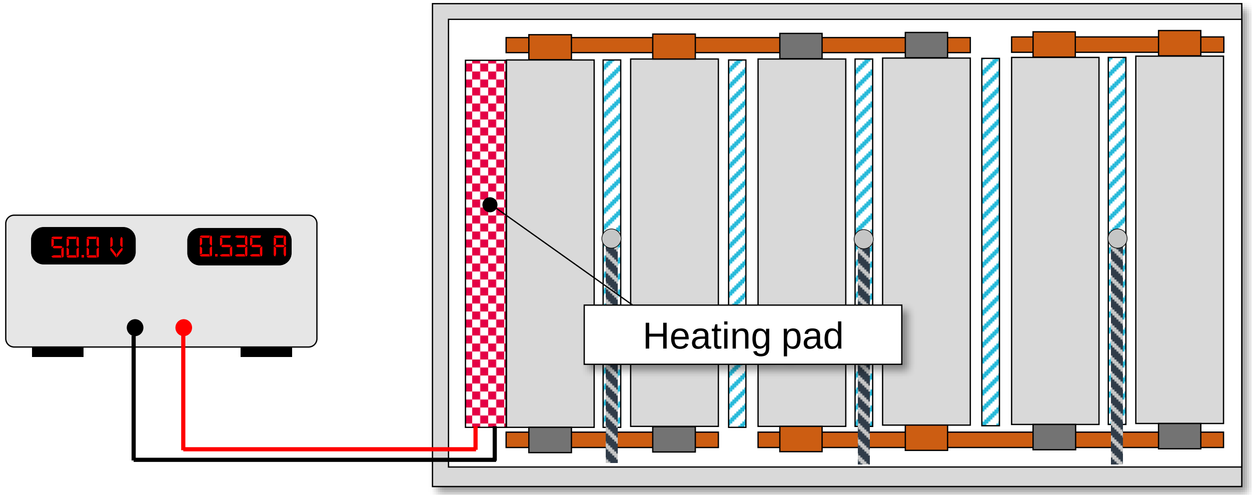


[1] A. Damay et. al. “A method for the fast estimation of a battery entropy-variation high-resolution curve – Application on a commercial $LiFePO_4$/graphite cell”, *Journal of Power Sources*, 2016

Cell-to-Spacer Resistance via External Heating

External heating experiment

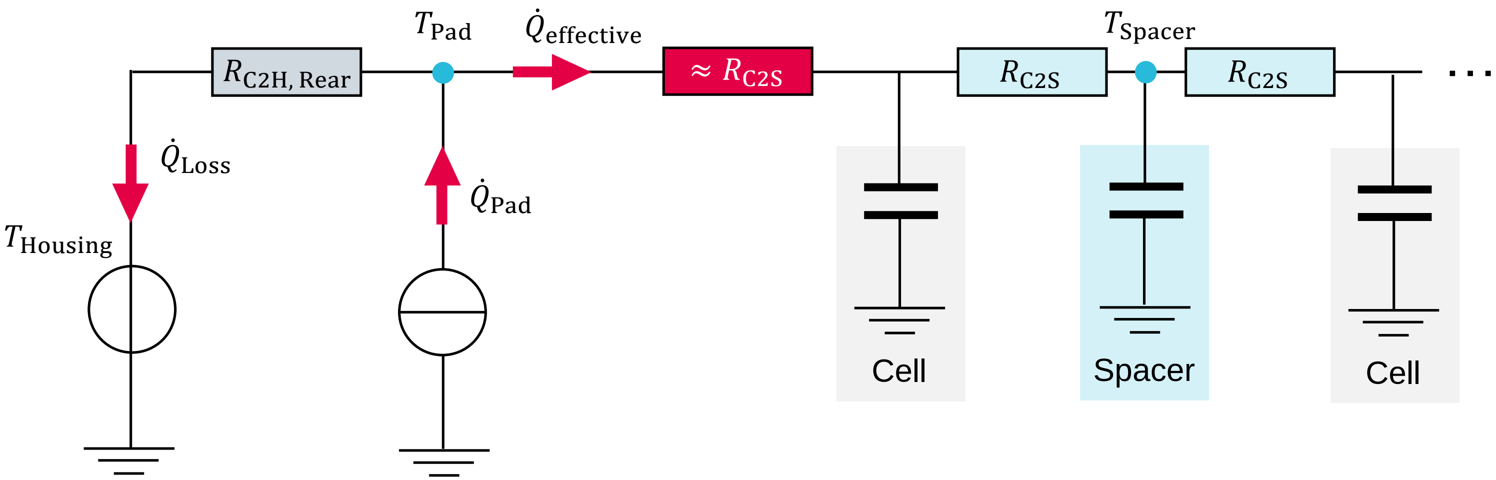
- External heating via heating pad
- No isolation required
- Effective heat flow by considering heat losses to housing
- Steady state → calculating thermal resistances from ΔT



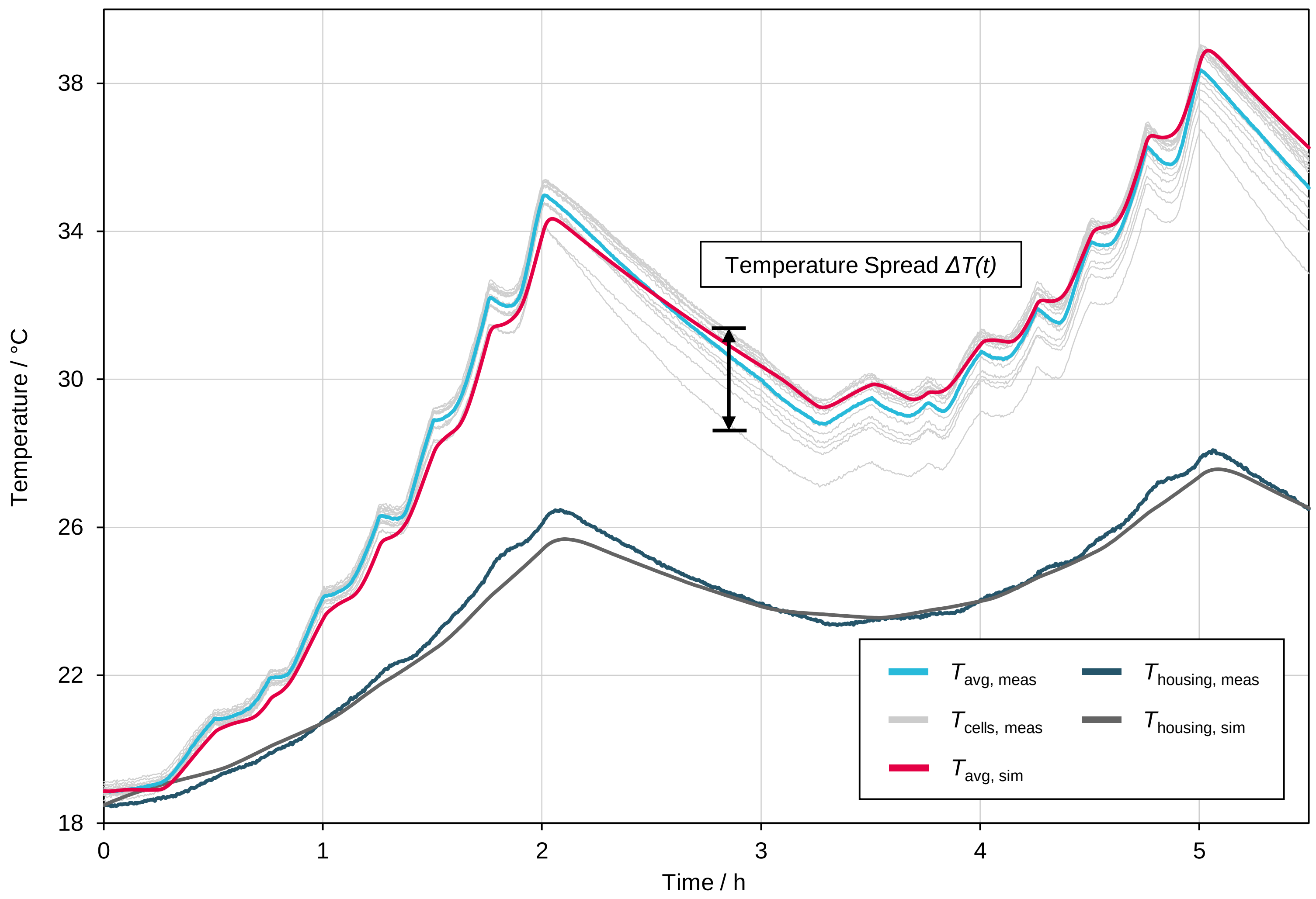
(I) $\dot{Q}_{\text{effective}} = \dot{Q}_{\text{Pad}} - \dot{Q}_{\text{Loss}}$

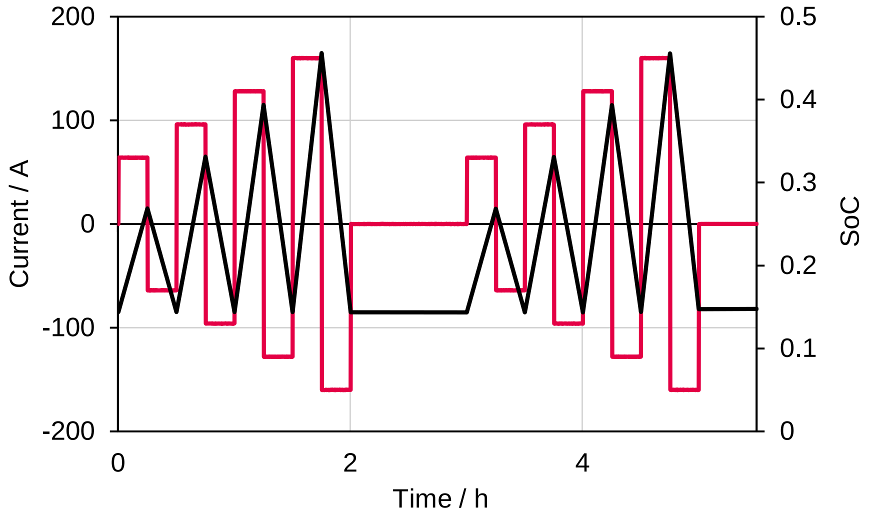
(II) $\dot{Q}_{\text{Loss}} = \dfrac{(T_{\text{Housing}} - T_{\text{Pad}})}{R_{\text{C2H, Rear}}}$

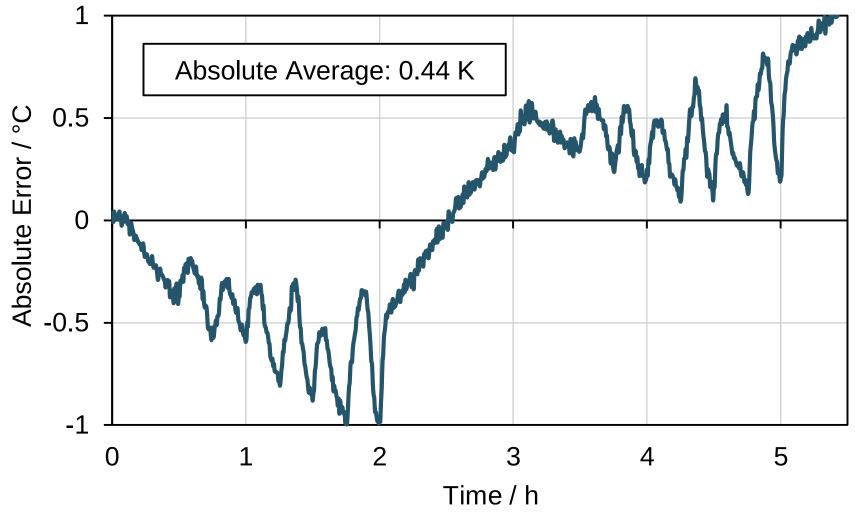
(III) $R_{\text{C2S}} = \dfrac{(T_{\text{Spacer}} - T_{\text{Pad}})}{2 \cdot \dot{Q}_{\text{effective}}}$



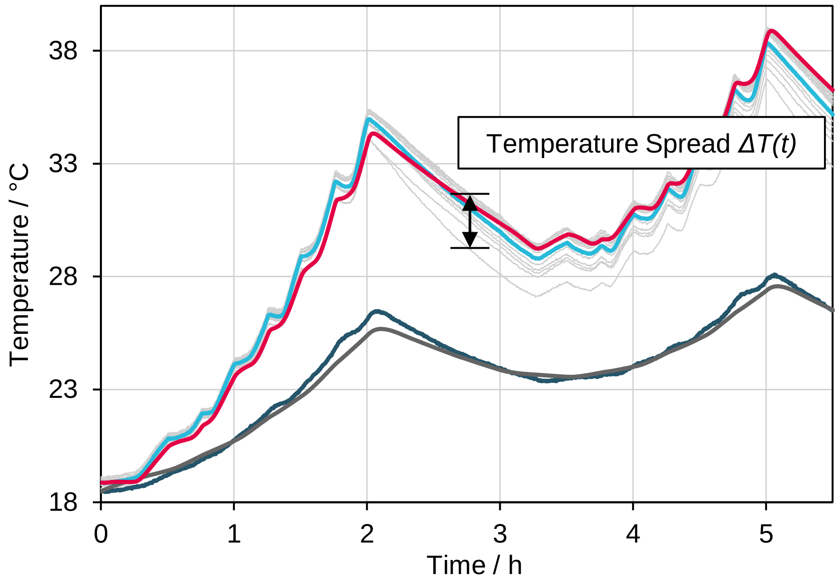
Full-Scale Model Validation (Average Temperature)

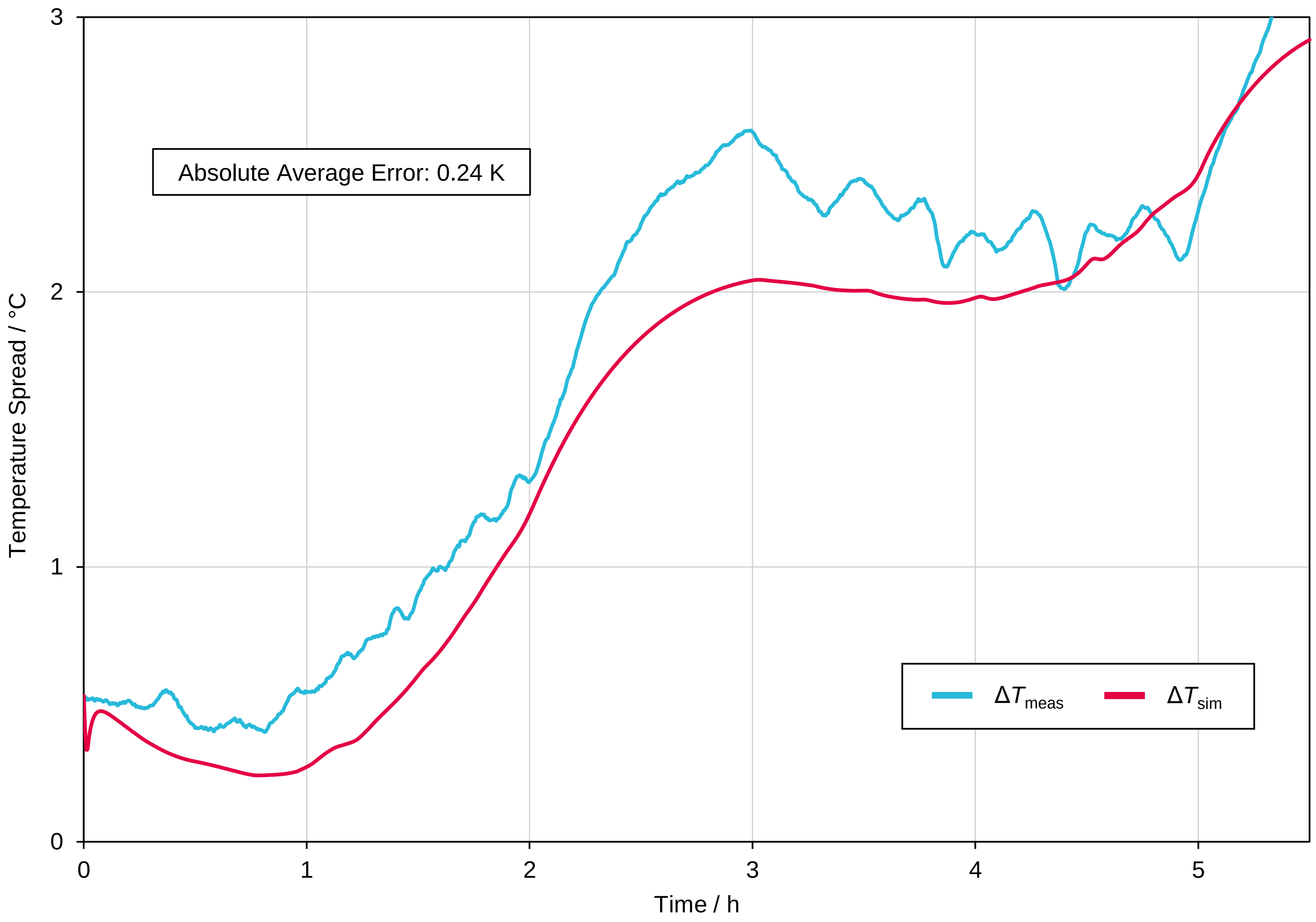






Model Validation (Temperature Spread)





Validation Results

- Average temperature and spread can be effectively simulated
- **Simulation time on desktop pc: 122.3 seconds per hour profile time**

Model Simplification

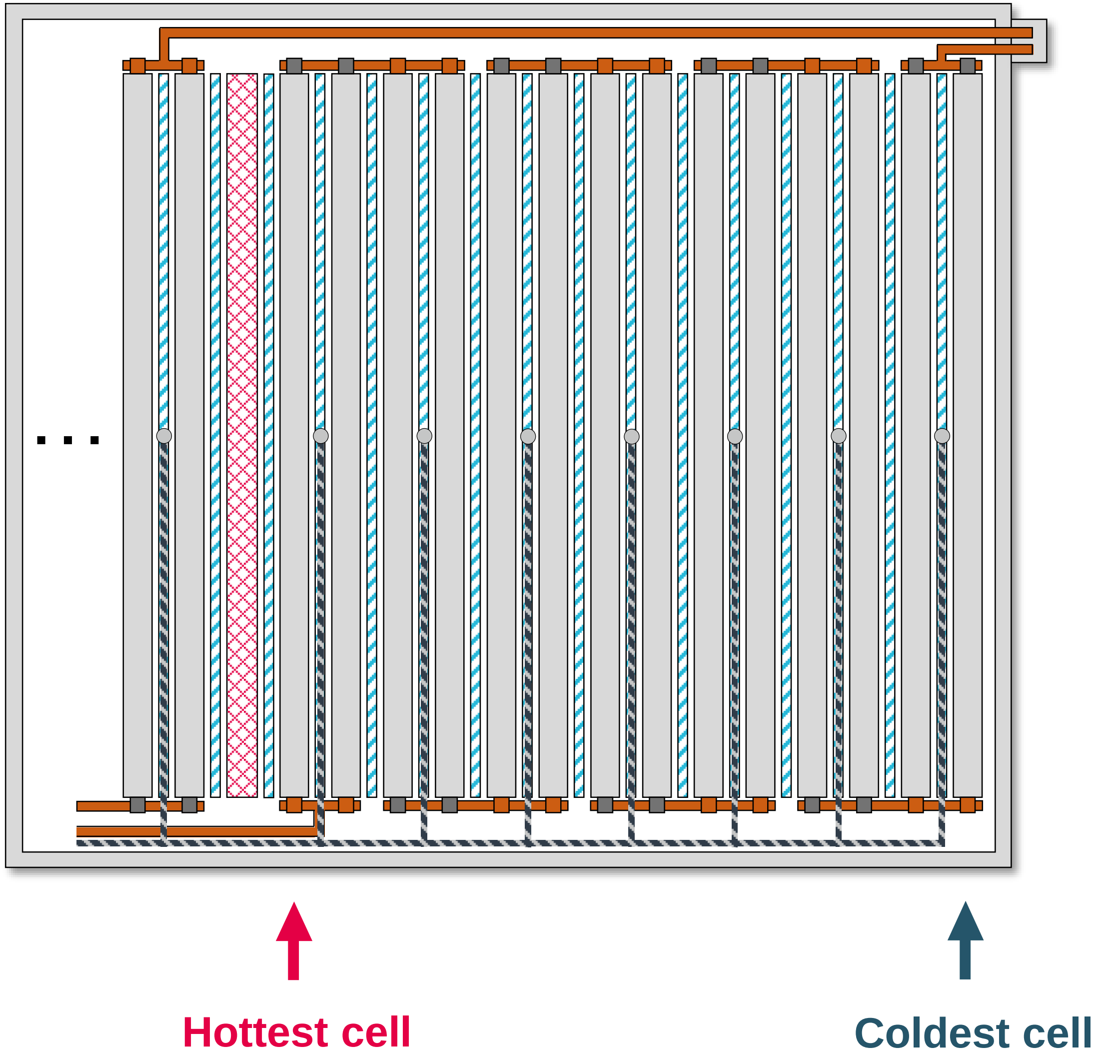
Motivation

Problem: Computational effort of full-scale model → Real-time parallel simulation of large-scale systems not feasible

Approach: Simulating only extrema and average values → significant increase in performance expected

- **Calculation of average temperature**
  - Estimating module as uniform heat capacity
  - Intuitive process: Averaging all parameters
- **Calculation of temperature extrema**
  - Goal: Emulating ambient conditions for hottest and coldest cell without simulating intermediate cells
  - Problem: Cells as active components → can not be simplified as thermal resistance

  → **Novel simplification approach necessary**

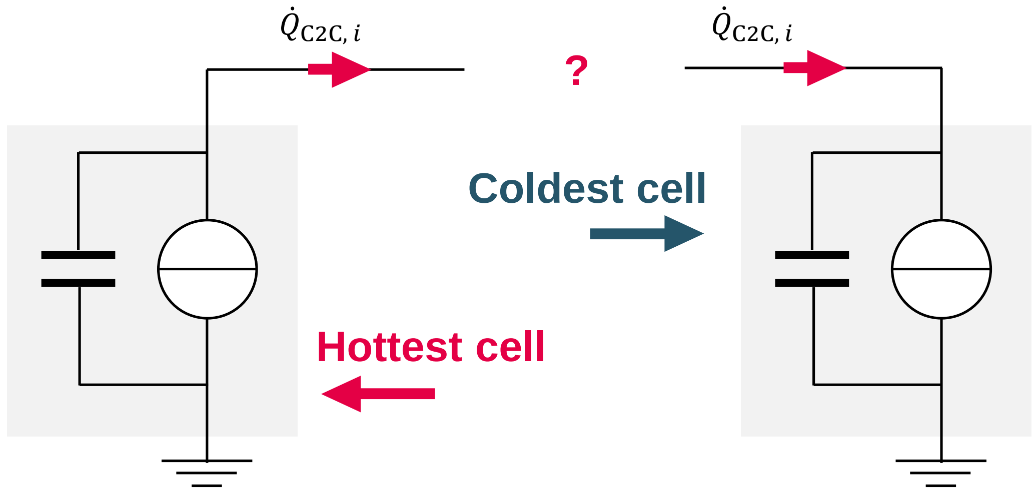


Model Simplification

Cell-to-cell heat transfer

Approach: Simplifying intermediate cells by differential equation

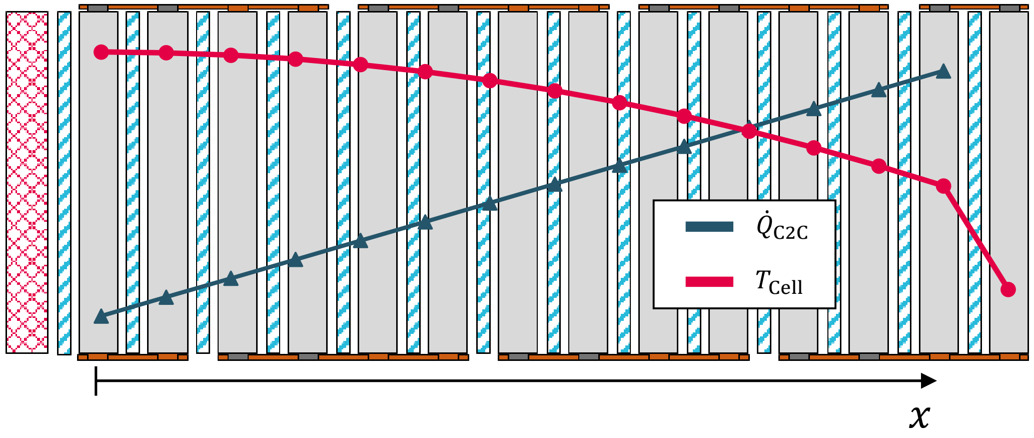
- Assumptions
  - Thermal symmetry with isolation pad as adiabatic wall
  - Half-stack as continuous 1D heat capacity in x-direction
  - Equal material parameters and heat generation over x
  - Constant dissipation to housing over x (except for last cell)
    → discontinuity has to be considered



$$\text{(I)} \quad 0 = \dot{Q}'_{gen} + \frac{d\dot{Q}_{C2C}}{dx} + \dot{Q}'_{C2H}$$

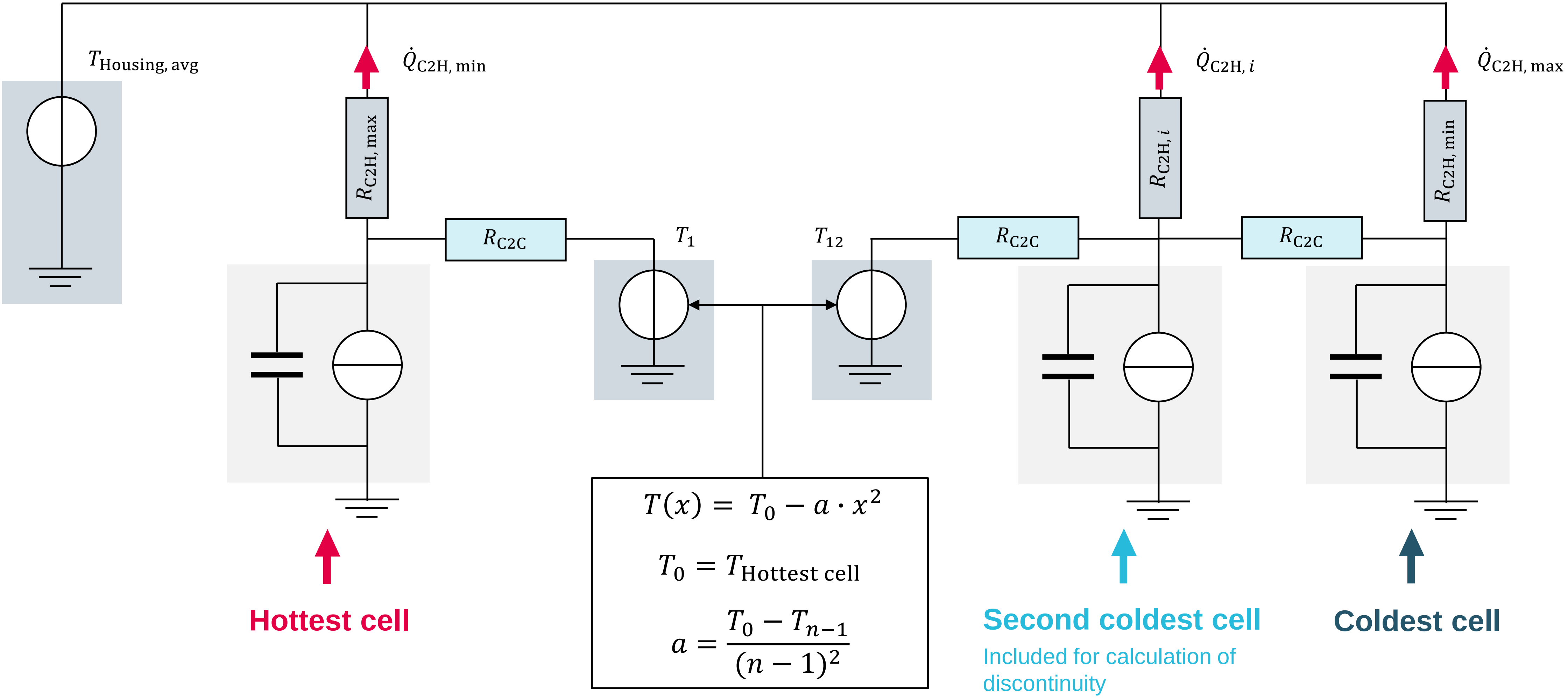
$$\text{(II)} \quad \frac{dT}{dx} = \dot{Q}'_{C2C} \cdot R'_{C2C}$$

$$\text{(I) in (II)} \quad T(x) = T_0 - \frac{1}{2}(\dot{Q}'_{gen} + \dot{Q}'_{C2H}) \cdot R'_{C2C} \cdot x^2$$



Model Simplification

Simplified equivalent circuit



$$T(x) = T_0 - a \cdot x^2$$

$$T_0 = T_{\text{Hottest cell}}$$

$$a = \frac{T_0 - T_{n-1}}{(n-1)^2}$$

Model Simplification

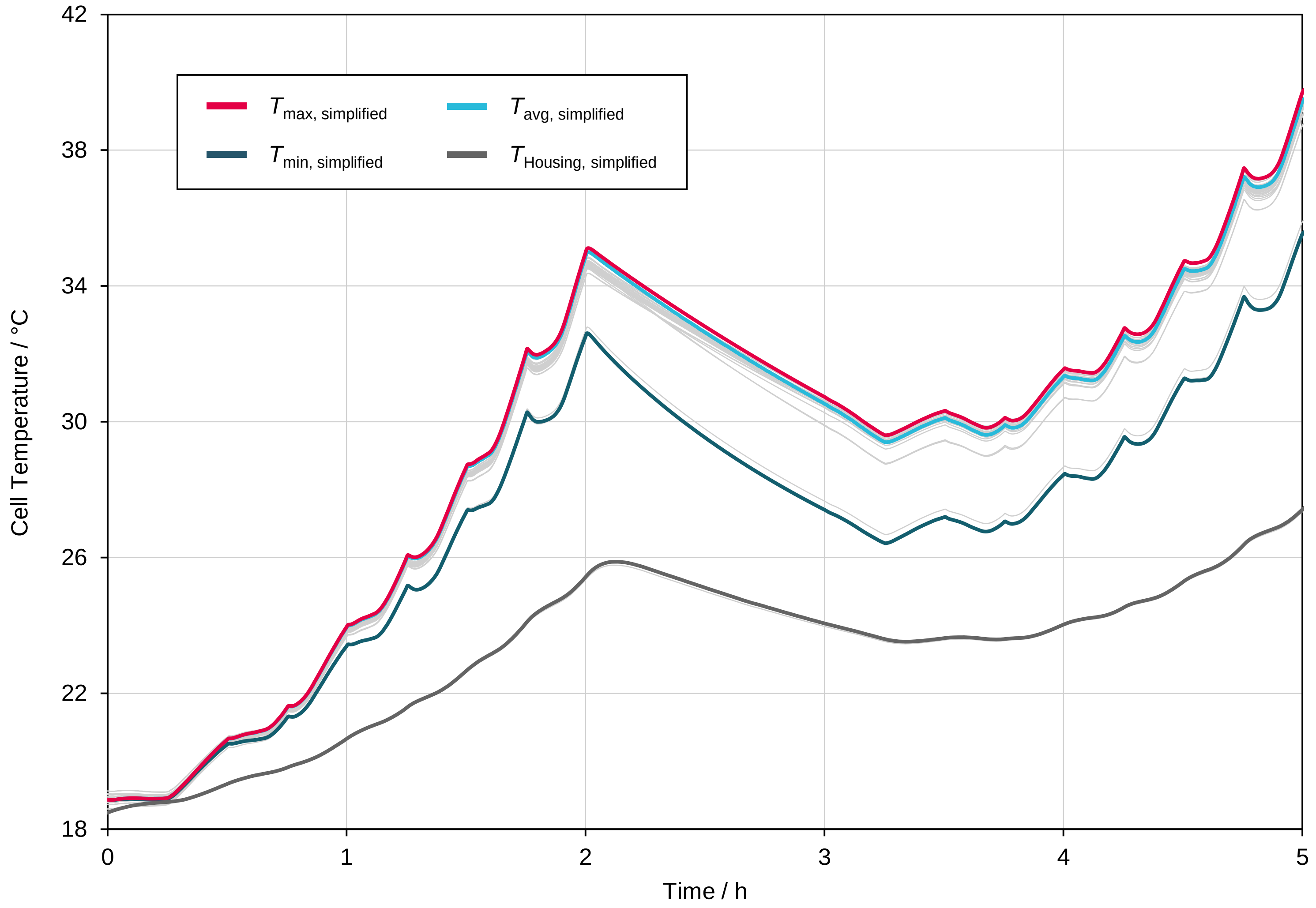
Comparison to full-scale model

Validation Results

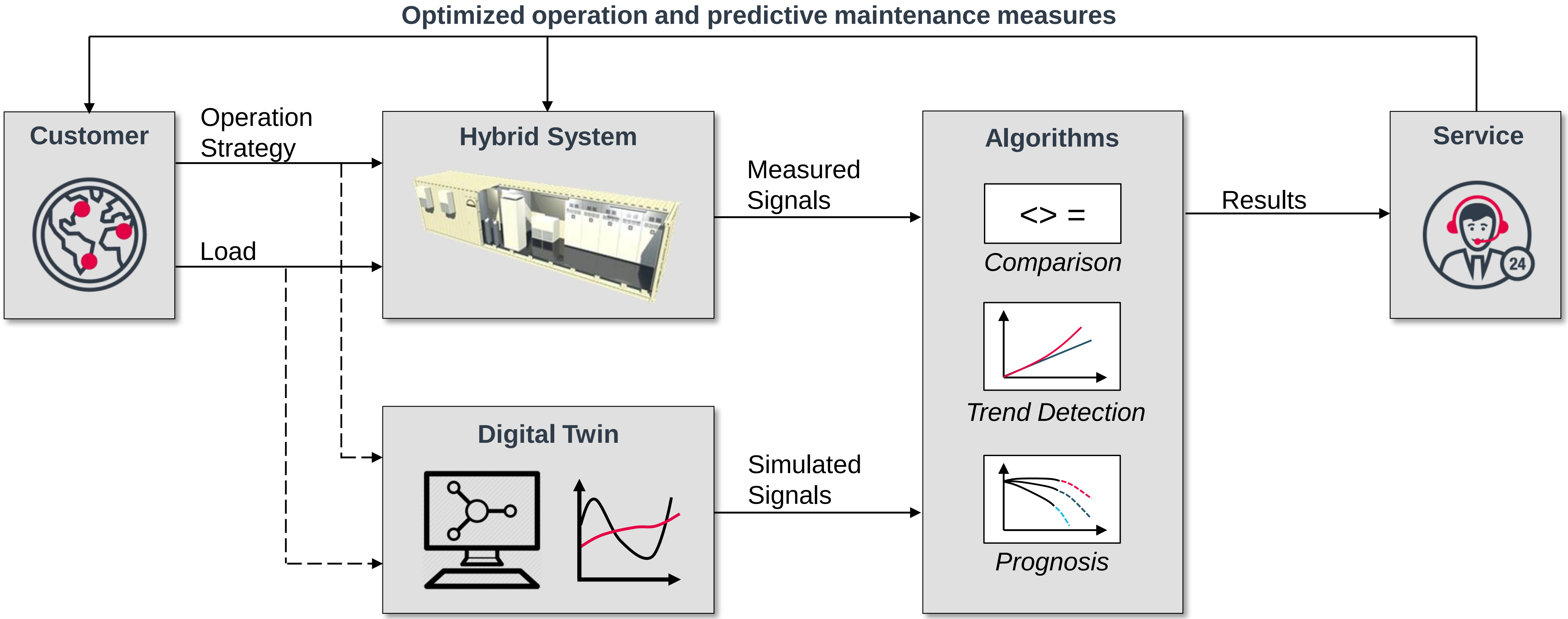
- Model simplification replicates extrema and average with high precision
  - Average temperature error: 0.26 K
  - Max. temperature error: 0.07 K
  - Min. temperature error: 0.04 K
- Assumptions proven valid for relevant temperature range
- **Massively reduced simulation time:**

  1.8 s/h (simplification)

  122.3 s/h (full-scale)



Application



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Thank you for your attention!

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About NAUTILUS

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