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Thermal Management Systems Symposium

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October 14-15, 2025 | Ypsilanti, Michigan

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Thermal Management Systems Symposium
October 14-15, 2025
Ypsilanti, Michigan

Energy Management, Operator Comfort and Simulation in Off-Highway Applications

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Agenda

01 Modern Off-Highway Vehicle Thermal Management and Changing Responsibilities

02 Transient Load Cycles and Energy Management

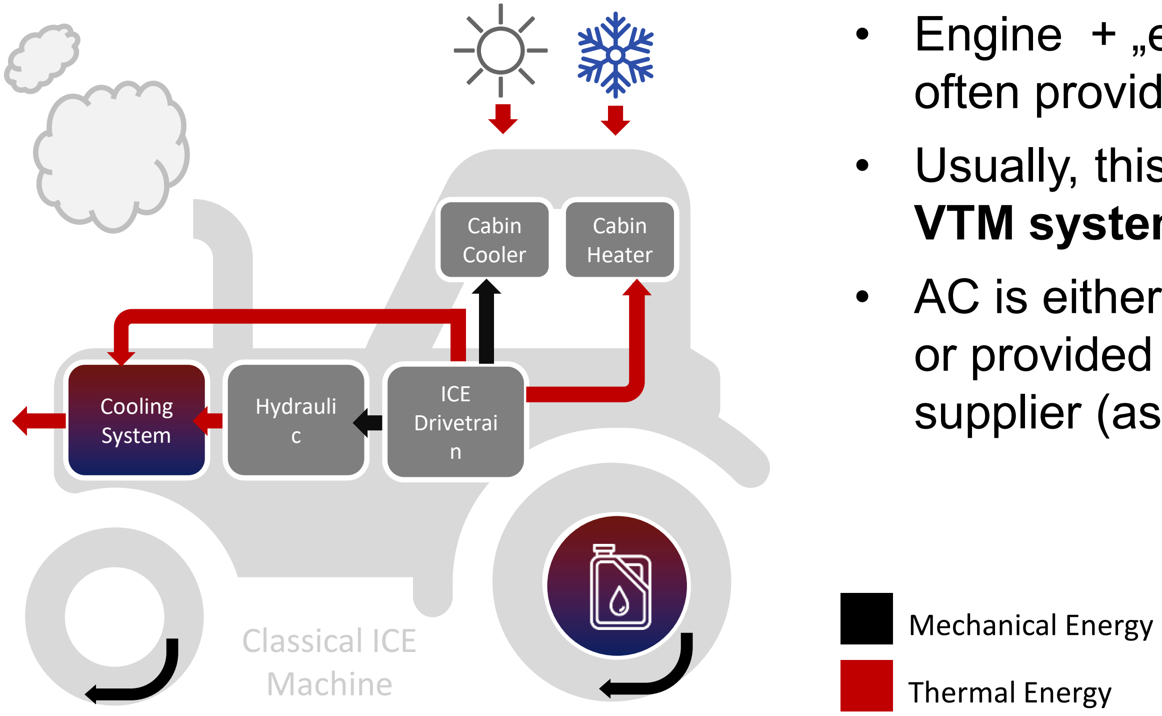
03 Operator Comfort and Energy Efficient HVAC-Systems

04 Implications for Development Processes and Simulation Environments

01

Modern Off-Highway VTM and Changing Responsibilities

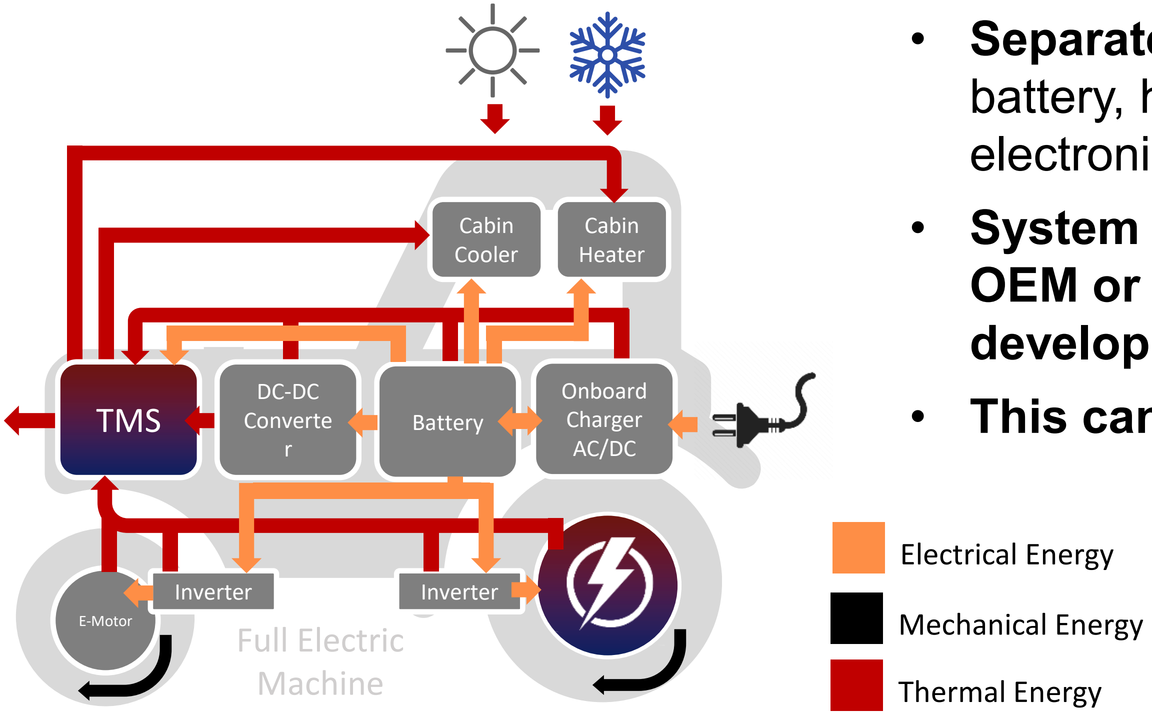
Off-Highway VTM – The Past



- Engine + „engine auxiliaries“ often provided by **one supplier**
- Usually, this defines the **complete VTM system** and its requirements
- AC is either part of this, too… or provided by a separate HVAC supplier (as an independent unit)

(Image by Josef Graubmann, Ymer Technology)

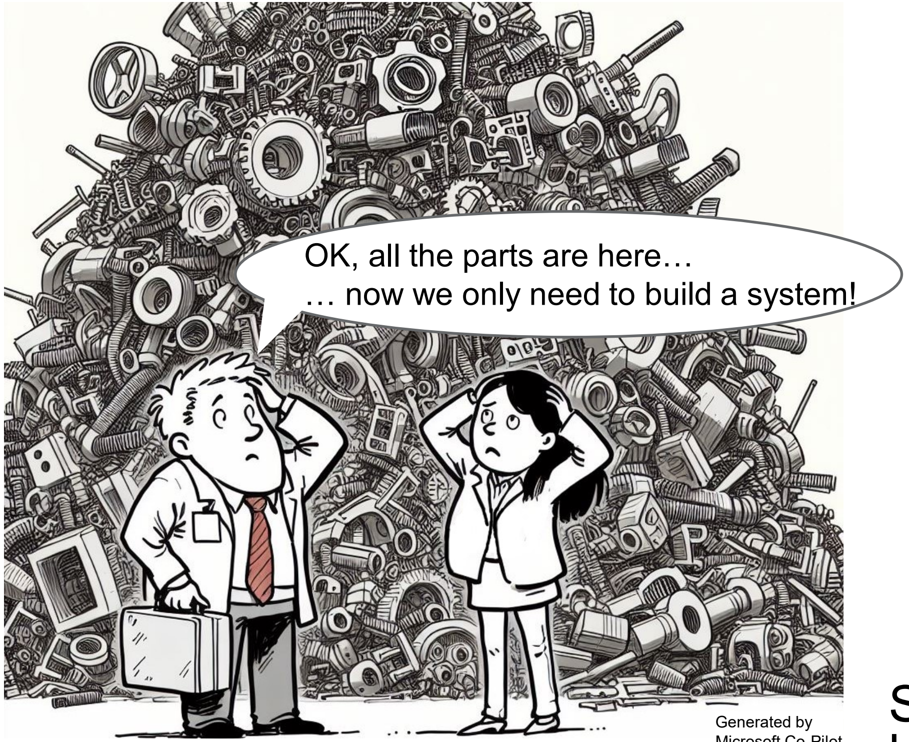
Off-Highway VTM – The Present



- **Separate suppliers** for motors, battery, heat exchangers, power-electronics, pumps, fans…
- **System integration falls to the OEM or to dedicated system development partners**
- **This can be a huge challenge…**

(Image by Josef Graubmann, Ymer Technology)

Thermal System Engineering Responsibilities



Generated by
Microsoft Co-Pilot

Typical tasks include…

System **requirements** engineering

Validation of system requirements

Comparison of different system-architectures regarding

- **Performance**
- **Efficiency**
- Costs (BOM + manufacturing + operation)
- Functional safety

Development, definition and validation of **system controls**

Simulation is essential in the **blue** highlighted parts…

Transient Load Cycles and Energy Management

Understanding Transient System Behavior..

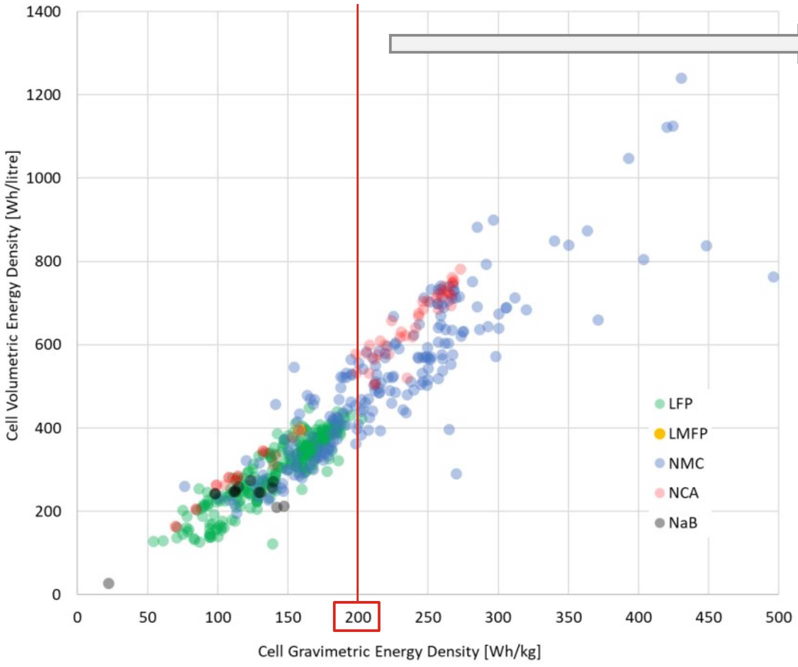
… and why this has important implications on system requirements

- **Traditional off-highway thermal engineers** are used to design systems to withstand **sustained combustion engine peak loads**
- For ICEs this is a reasonable requirement
- **Electric motors**, on the other hand, can only provide significantly **smaller loads continuously than during short-time peaks**.
- Designing the cooling system for **"continuous peak loads" that never occur** (because the motor physically is not capable) would lead to
  - Massive **over-sizing** of all VTM components
  - Increased system **costs**
  - High **vehicle integration efforts** of the VTM system

⇨ **How much cooling capacity do we really need?**

Thermal Capacities in Electric Vehicles

Battery Packs



1kWh approx. 5kg (cell level!)

200kWh approx. 1000kg

Thermal Capacity:

- Cells ~ 1000J/kg/K
- Steel ~ 500 J/kg/K
- Aluminum ~ 920 J/kg/K
- Coolant ~ 3400 J/kg/K

ø 1000 J/kg/K

1000 kJ/K

At 2kW waste heat it takes 8min 20s to warm up such a pack by 1K

Thermal Capacities in Electric Vehicles

Battery Packs

At **2kW** waste heat it takes **>8min** to warm up a typical Off-Hwy battery pack by **1K**

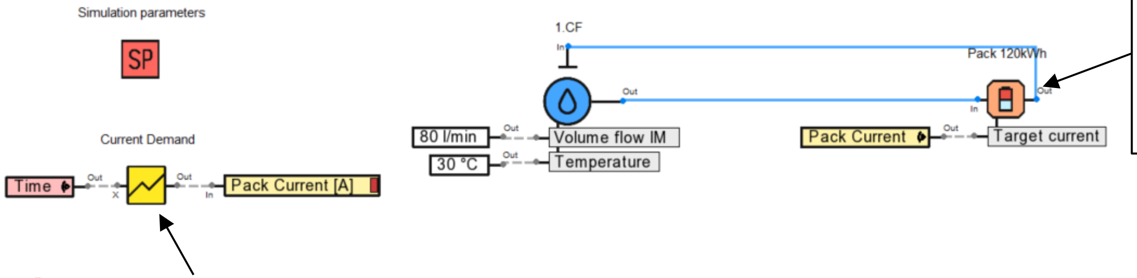
→

Why do we need thermal conditioning of battery packs at all?

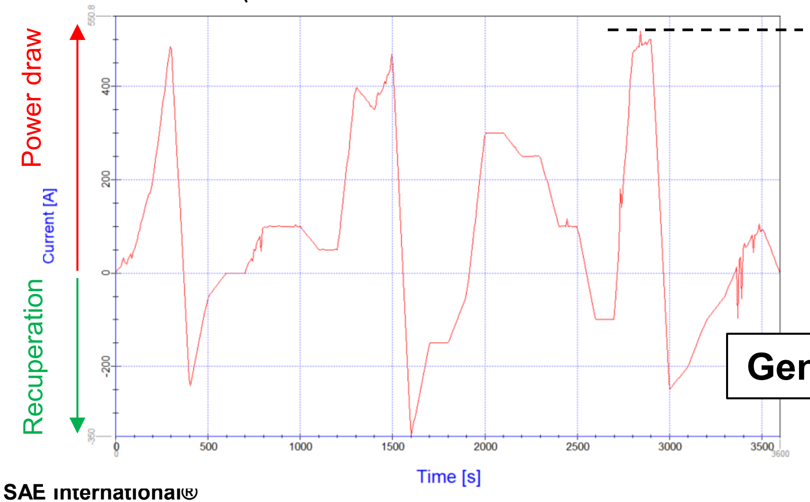
- What to do when the **battery is hot-soaked** (parking outside in summer)
- Even worse: What to do when the **battery is very cold** (parking outside in winter)

- **Battery thermal capacity helps to buffer** load peaks and thus reduces effective peak cooling requirements
- **Battery thermal capacity is a problem**, when **active battery conditioning** is required

A Very Simple Example



Battery Pack:
Capacity: 120kWh / 150Ah
Voltage: 800V
Mass: 600kg

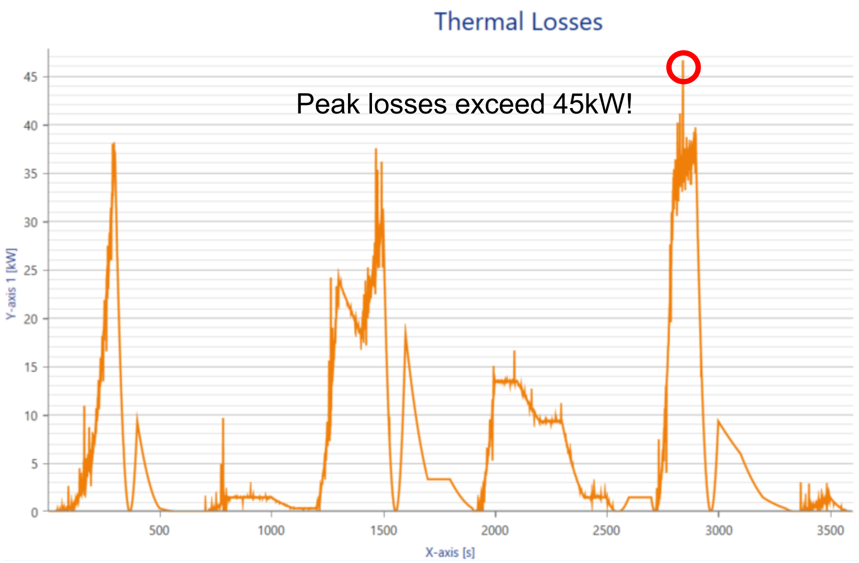


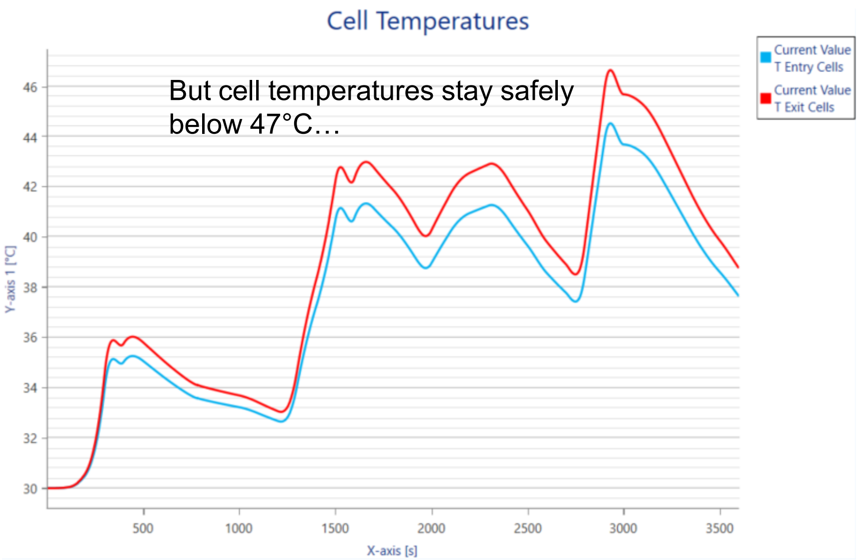
Peak C-Rate ~3.5

Let´s run a simulation in **KULI thermal management software**…

Generic 1h Operation Cycle

Simulation Results…

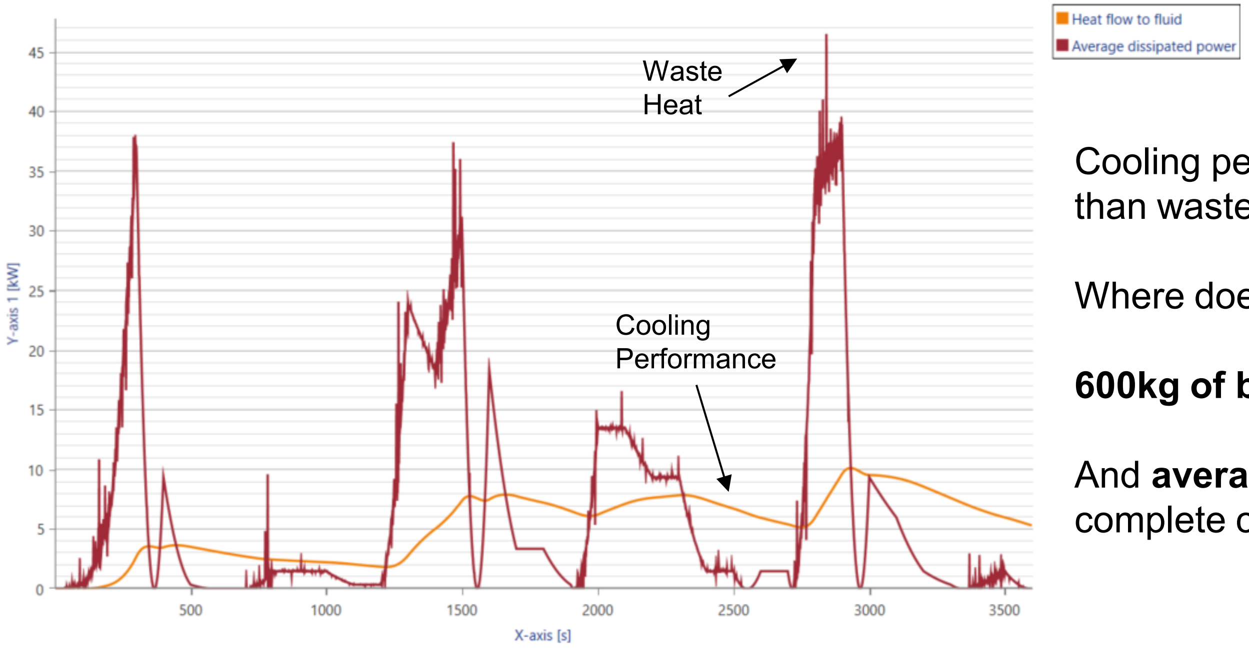




We have very high loads, but safe cell temperatures…

… what about the **cooling system performance**?

Simulated Cooling System Performance



Cooling performance is **significantly** lower than waste heat peaks!

Where does the rest go?

600kg of battery mass are a huge buffer.

And **average thermal losses** for the complete cycle are only **~6.7kW**

The **cooling system** usually **does not need to fulfill peak loads continuously**… for **pack design** the peaks may be decisive, though!

Thermal Capacities in Electric Vehicles
Motors and Power Electronics

- **E-Motors:**
  - Gravimetric power density up to 9kW/kg (Tesla)
  - Reference value for ICE: 1.7-3.7kW/kg
  - Typical weight e.g. 40kg (avg cp ~ 600J/kg/K)
  - **Thermal capacity 24kJ/K**
  - (compare to battery 300kJ/K, factor 12)

- **Power electronics:**
  - Typical weight e.g. 10kg (avg cp ~ 600J/kg/K)
  - **Thermal capacity 6kJ/K**
  - (compare to motor 24kJ/K, factor 4)

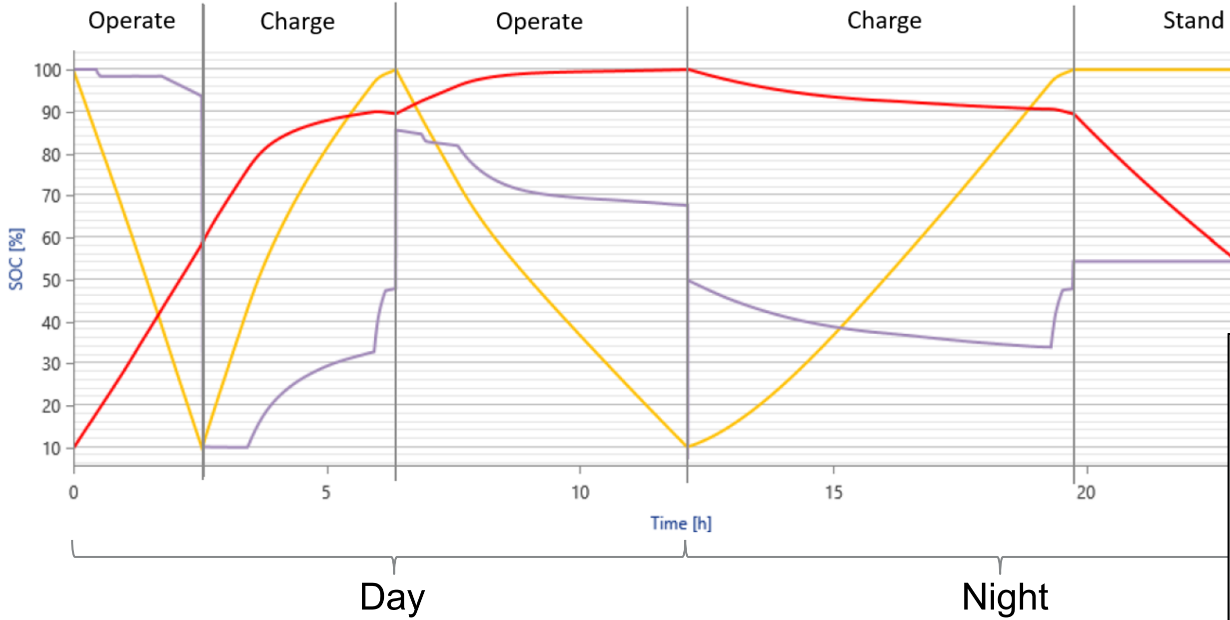
⇨ **Motors and power-electronics usually react much faster to load peaks than battery packs!**

⇨ **Local "thermal bottlenecks" can make this even more critical!**

03

Operator Comfort and Energy Efficient HVAC

A Typical 24-Hour Work-Profile of an Electric Excavator



Symbolic image generated with Microsoft Co-Pilot

Task: Maximize operation time during day

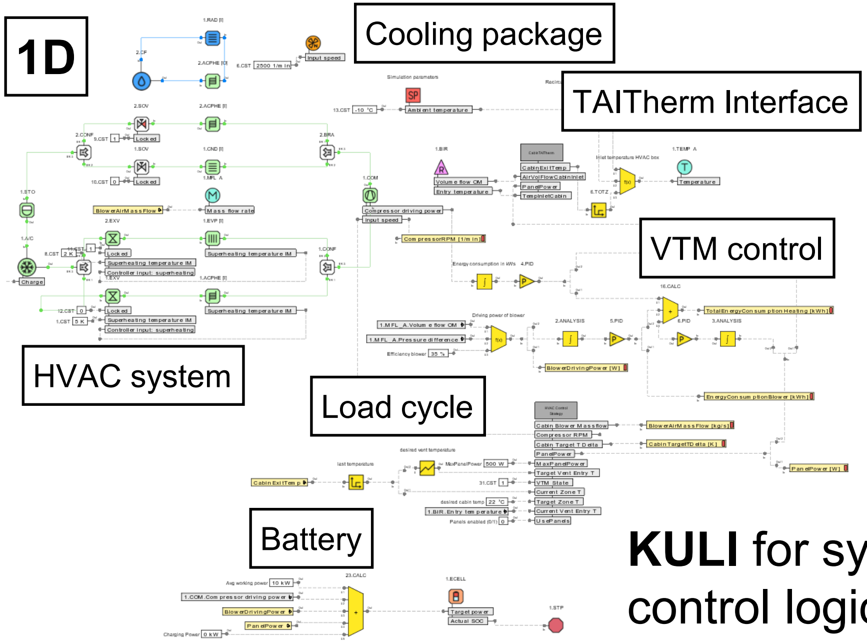
Influence of the Cabin
Impact on energy consumption

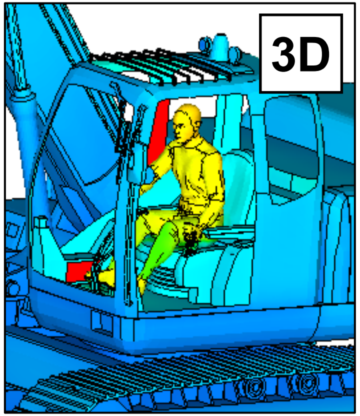
- **Operator comfort** is becoming increasingly important for construction vehicles
- Often poor insulation of the operator compartment and large windows (required!)
  → High loads for the HVAC system
- Total energy consumption vs. „unplugged“ energy consumption
  - Energy consumption and losses during charging are important, too!
- Alternative heating/cooling concepts
  - Is it necessary to install a heat-pump? (more costly parts and higher system complexity)
  - Can heating panels in the cabin help?

- Once again, we need to understand the whole system, to optimize energy efficiency!

How to Assess Energy Consumption

Suitable tools for a detailed investigation





(TAITherm model is integrated into KULI as an FMU)

KULI for system simulation, control logic and energy management

TAITherm for detailed analysis of cabin and comfort

Comparison of 3 Variants

Heating scenario with ambient temperature -10°C

- **Variant 1 (red)**
  - Heat pump
  - High target cabin temperature (22°C)
  - No radiant panels
- **Variant 2 (blue)**
  - Heat pump
  - High target cabin temperature (22°C)
  - Radiant panels (600 W)
- **Variant 3 (orange)**
  - Heat pump
  - Lower target cabin temperature (18°C)
  - Radiant panels (600 W)

Heat pump with standard air temperature targets

Heat Pump + panels with standard air T targets

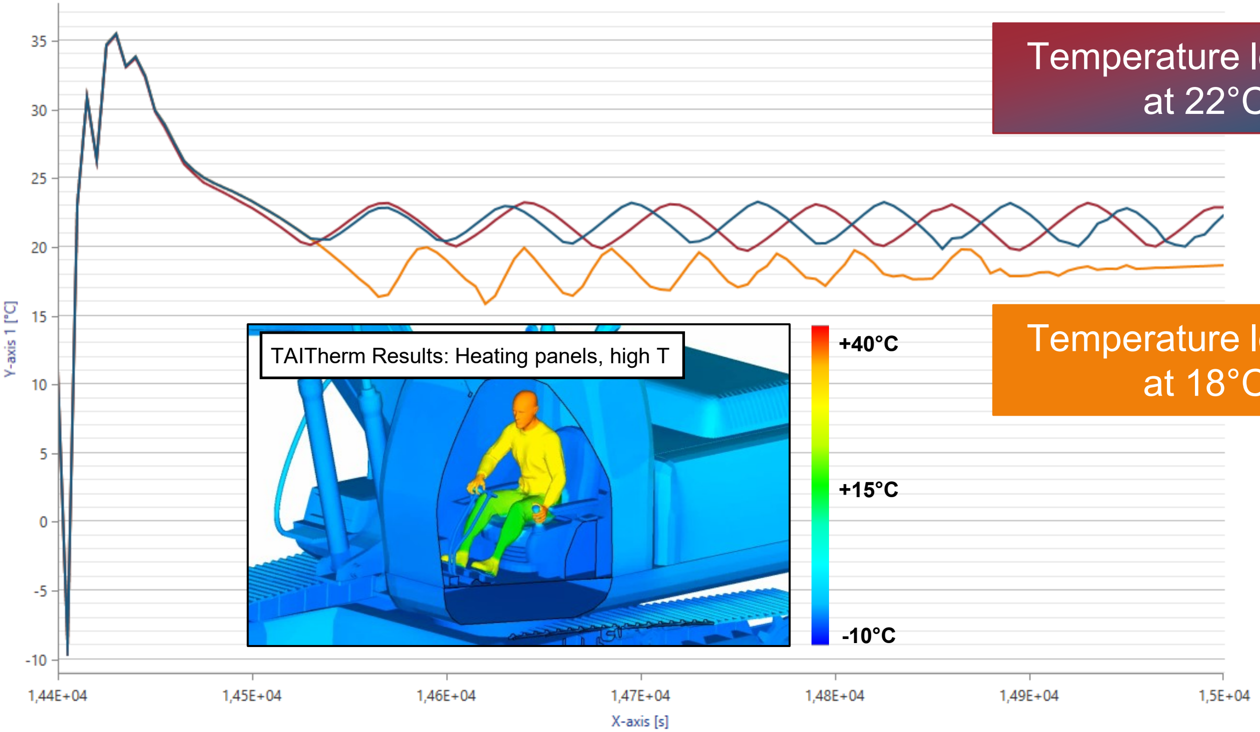
Heat Pump + panels with **reduced** air T targets

Temperatures inside the Cabin

High temp., no panels

High temp., panels

Low temp., panels



Temperature levelling at 22°C

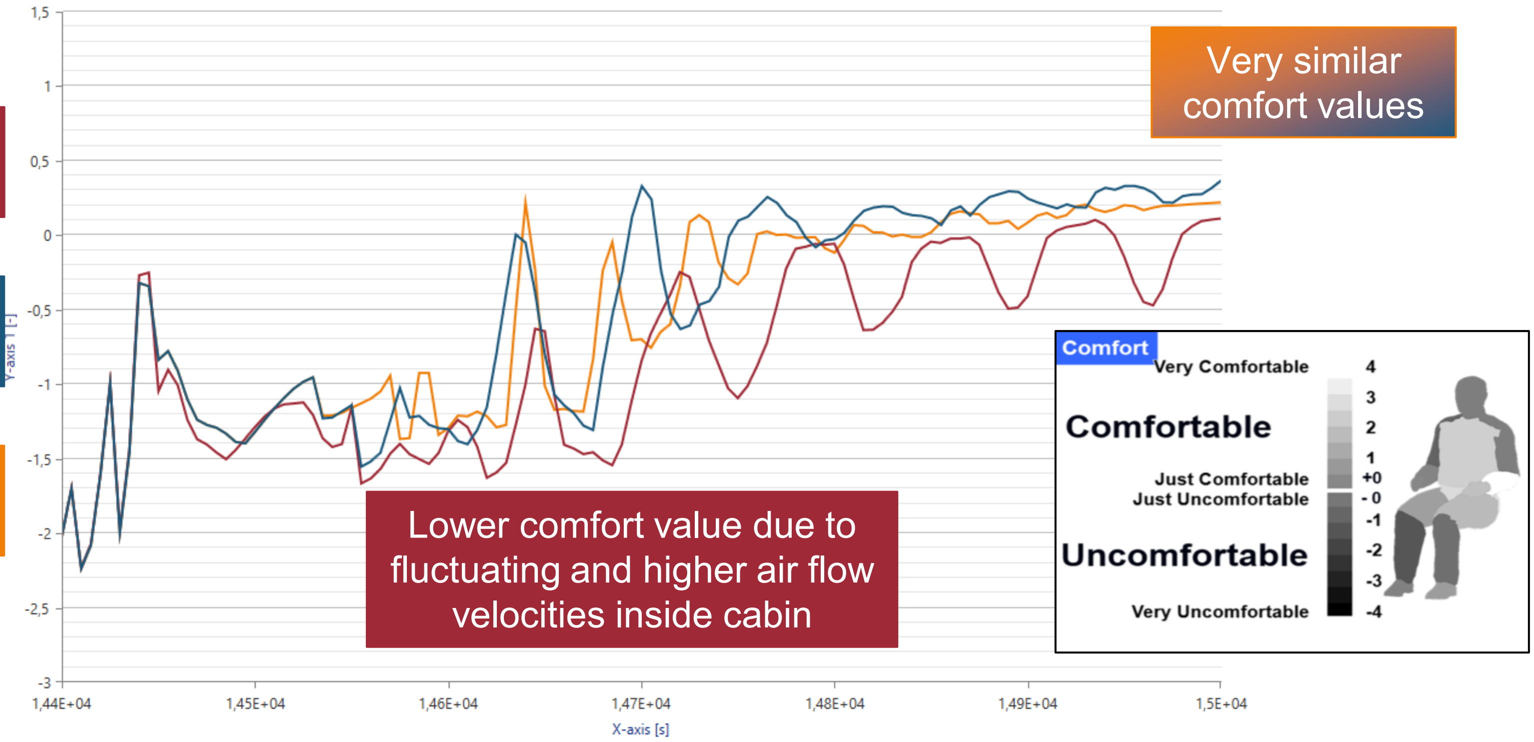
Temperature levelling at 18°C

Berkeley Comfort Value

High temp., no panels

High temp., panels

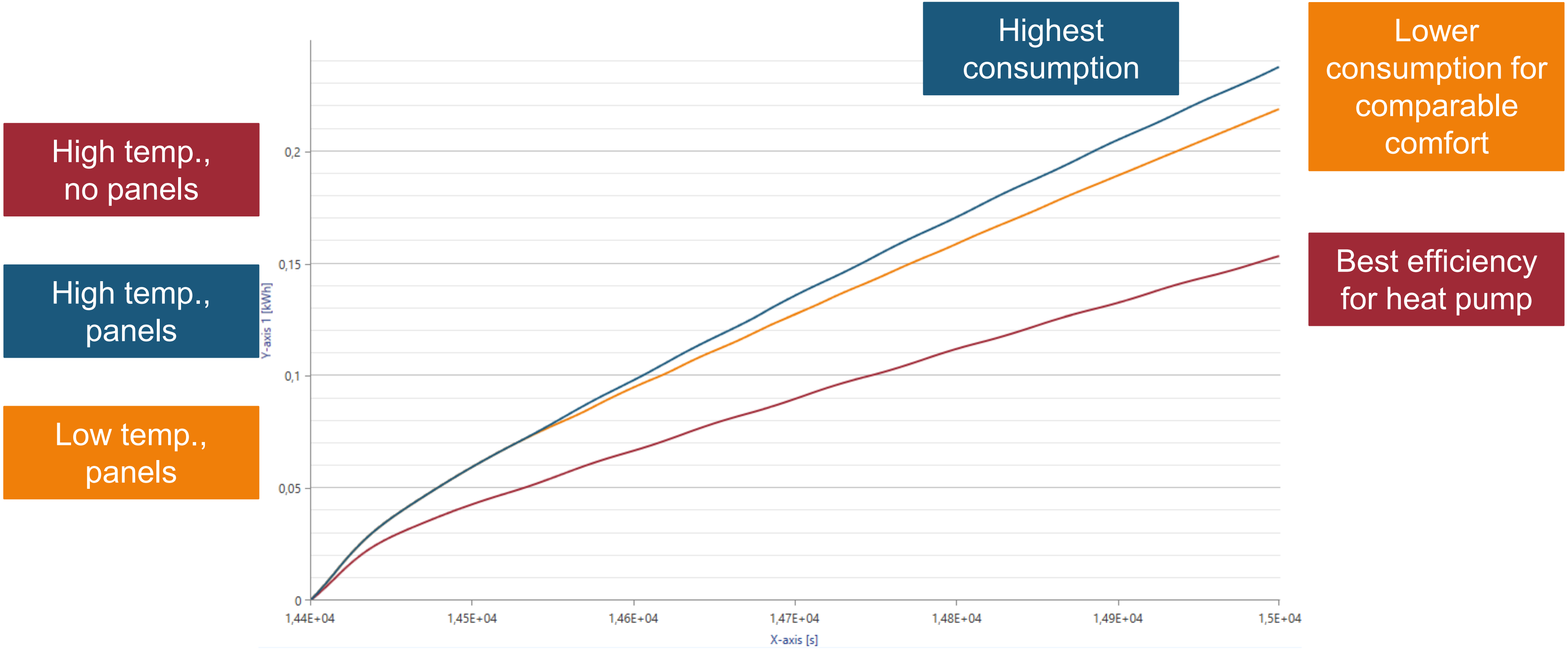
Low temp., panels



Very similar comfort values

Lower comfort value due to fluctuating and higher air flow velocities inside cabin

Energy Consumption for Heating
Compressor + panels + blower



Electric Power for Maintaining Comfort

	Heater	Panels	Total	
Heat pump, high cabin temp., no panels	720 W		720 W	Best efficiency!
Heat pump, high cabin temp., panels	580 W	600 W	1180 W	Best comfort!
Heat pump, low cabin temp., panels	465 W	600 W	1065 W	
Electric heater, high cabin temp., no panels	1950 W		1950 W	Lowest cost!
Electric heater, low cabin temp., panels	1100 W	600 W	1700 W	Best compromise?

- Smaller air volume and „single seat“ layout reduce panel benefits compared to passenger car applications
- But: Lower system integration efforts for PTC heaters (compared to heat pump)
- Additional panel benefits, in „open window“ scenarios or with operators frequently getting in and out of the cabin…

⇨ **Architecture decisions require “big picture“ view and system understanding!**

Implications for Development Processes and Simulation Environments

Summary

- **Outsourcing of "Thermal Management"** to typical component / module suppliers becomes **increasingly complicated** for electric off-highway machinery

- **Dedicated system engineers** taking **overall responsibility** for "Energy Management" are needed for efficient system design
  - **Requirements engineering!**
  - **Balanced costs** vs. **benefits**
  - Optimized electric **operation time** ("range")
  - Achievement of <u>all</u> **vehicle targets** (performance, battery lifetime, operator comfort…)

- Related tasks typically combine **different engineering-domains and –tools**

- All of this means significantly **increased complexity** compared to classic ICE applications.

Simulation is essential to master these challenges!


Forward.
For all.