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Impact of thermal-electric networks on the usability of EVs based on a study with a C-segment car

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Abstract

One of the major concerns of contemporary Fully Electric Vehicles (FEV) is the high dependency of the maximum range on ambient temperature conditions. In some cases the range of an EV can drop by more than 50%. One of the main reasons for this behaviour is the energy demand required by the thermal conditioning of the passenger compartment. Within this paper a comprehensive approach will be presented to reuse the waste heat energy of the powertrain components combined with a thermal storage for conditioning the car's cabin.
To evaluate the influence of the ambient temperature on the vehicle range, an electro-thermal simulation of a C-segment car, including the HVAC (Heating, Ventilation and Air Conditioning) and the cooling system was performed. The following components/systems were considered: battery, thermal energy storage, thermal insulation as well as heat pump and thermal preconditioning due to an inductive charger.
It will be shown that, despite a low amount of waste heat from the high voltage components, the combination of the heat pump with the thermal energy storage (using advanced control strategies) leads to a remarkable range improvement.
This research is based on the integration of new electro-thermal system components including novel control algorithms into the thermal system layout. In this article modern control approaches for heat-pump subsystem as well as overall control strategies for complete electro-thermal networks will be discussed. Model-based development has been proven to be an efficient way of control algorithms and software design, including advanced control techniques like MPC and virtual sensors.
To validate the simulation results the system will be integrated in a demonstrator car (Mercedes Benz B-Class).

This research was carried out in the project H2020 653514 OSEM-EV, Optimized and Systematic Energy Management in Electric Vehicles, which belongs to the GV-2-2014 call.

Keywords: EV range extension, waste heat energy, phase change material, comprehensive vehicle simulation, heat pump system, heat pump controller, wireless charger

1. Introduction

Today's electric vehicles still suffer drastically from range deviation induced by the environmental conditions they may face. More than 50% range drop has been reported because of colder climatic conditions: this is unacceptable for the customers and is one of reasons for a slow market penetration. This issue has become mission critical for a faster market penetration of EVs. To solve the reasons for the range drop, a handshake of several usually very much separated disciplines in the car development becomes mandatory. Maybe obvious sounding solutions like boosting the battery capacity do not work out since the EV's are already perceived as high cost vehicles and increasing the battery capacity would equally boost the price tag.

The presented approaches have a high degree of novelty, most of the work is being introduced for the first time in such systems. However, some work was already done during the eDAS project, which was a first trail with respect to some thermal concepts, serving as input for our project. Compared to eDAS, the OSEM-EV system addresses to highly improved thermal electric architecture concepts (e.g., thermal storage of both cold and heat, a new heat pump system with state of the art control algorithms using innovative controlled valves).

For the numeric impact evaluation of the new system layouts on the vehicle range a comprehensive simulation model approach was used in the project. Detailed sub system simulation models were developed which strongly focus on the quantitative precision as a basis for the model-based design of the respective components. The models are the basis for further energy optimization and are required for the development of the electro-thermal network control functions. The simulation platform Model.CONNECT™ enabled the opportunity to choose the best suitable simulation software for each sub system and combine them in the comprehensive vehicle model. Finally, the simulation model was used for the numeric assessment of the electric energy benefits for different system layouts.

AVL has provided the sub-system simulation models for the vehicle powertrain, the cooling system, the heat pump system, and the vehicle cabin. With the simulation platform Model.CONNECT™ all sub-systems were connected according their interactions and the electro-thermal energy flow. More refined sub simulation models, like the PMOR battery model developed by Fraunhofer IISB, can easily be integrated into the comprehensive model. This increases the accuracy of the comprehensive vehicle model by the combination with the advanced control strategy developed by the CEITEC BUT.

2. Thermal energy storage subsystem (Hutchinson)

The Simcenter Amesim simulation platform which provides physical domain libraries for fluids and thermodynamics was used to setup the thermal energy storage subsystem model.

The thermal energy storage subsystem is composed of (see Figure 1):

- encapsulated Phase Change Materials (PCMs) used to store and release thermal energy during the process of melting & freezing.
- PCM formulation based on Graphite used in a triple wall to enlarge and ensure the heat capacity of the thermal energy storage subsystem,
- super thermally insulating materials (Vacuum Insulating Panels – VIPs) based on organic aerogel technology and used in a double wall to insulate the thermal energy storage,
- a thermal energy storage inner and outer casing, to ensure a safe and efficient usage.

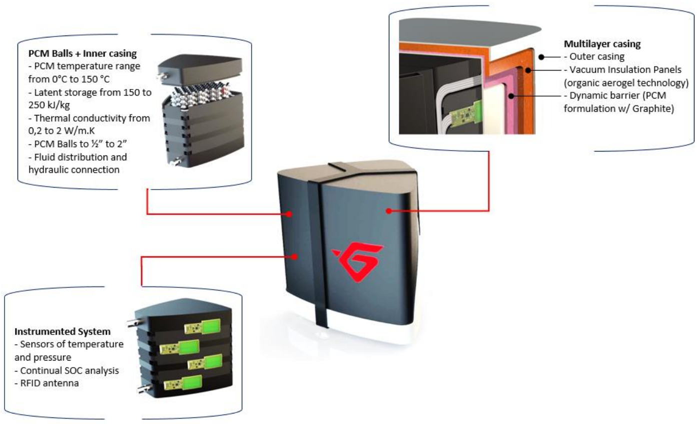


Figure 1: Example of thermal energy storage subsystem with PCMs and VIPs materials implementation

2.1. Thermal energy storage model definition

The thermal energy storage subsystem model definition has been based on a holistic approach with a careful partitioning of the subsystem and a clear definition of interfaces between the different components.

In spite of modelling all of the thermal energy storage with more than 300 PCM Balls, a first approach of discretization with 3 layers has been used.

It contains:
- 3 PCMs elements defined with reference parameters to model the PCM Balls,
- Conductive heat transfers through the Aluminum shells of the PCM Balls,
- Conductive heat transfers through the Dynamic barrier and thermal insulation layers,
- Convective heat transfers with circulating fluid,
- a complementary material element defined to simulate the storage insulation layer,
- a complementary PCM material element defined to simulate the dynamic barrier,
- the pressure drop along the system,
- an outlet volume defined to measure the outlet temperature.

The thermal energy storage subsystem model on Simcenter Amesim simulation platform covers the storage device and the coolant element including the general data of the subsystem such as nominal dimensions and masses, thermal properties, pressure drop, etc.

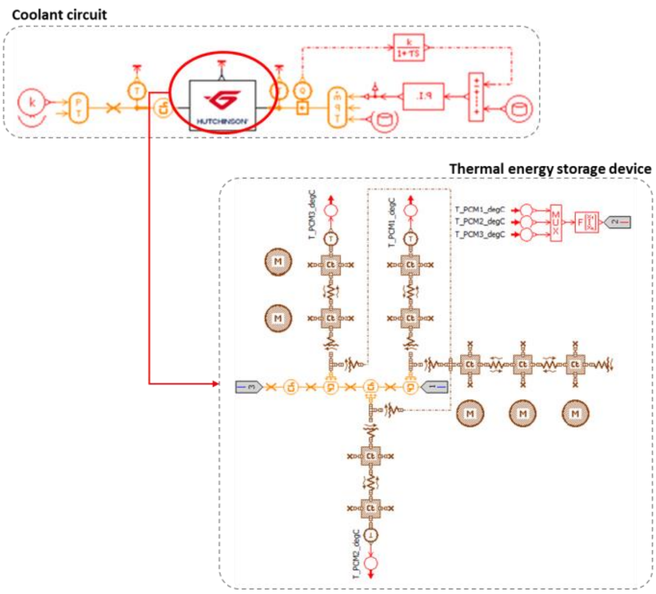


Figure 2: Thermal energy storage model on Simcenter Amesim

2.2. Thermal energy storage model development

The thermal energy storage subsystem model has been validated with experimental measurements: charge and discharge tests at 3, 5 and 9 L/min.

The inlet water flow rate and temperature has been imposed and set to reference experimental measures and the model validation conditions were the water outlet temperature comparison and the energy released/stored into the thermal energy subsystem.

The heat storage equations to suit real-time computations are:

$$E_{PCM}[kJ] = m_{PCM}[kg] * \begin{bmatrix} Cp_{sol}\left[\frac{kJ}{kg.K}\right] * \left(\mathrm{T} < \left(\mathrm{T_{melt}} - \frac{dT_{melt}}{2}\right)\right) \\ + \\ \frac{\mathrm{H_{melt}}\left[\frac{kJ}{kg}\right]}{\mathrm{dT_{melt}}[K]} * \left(\mathrm{abs}(\mathrm{T} - \mathrm{T_{melt}}) \leq \frac{\mathrm{dT_{melt}}}{2}\right) \\ + \\ \mathrm{Cp_{liq}}\left[\frac{kJ}{kg.K}\right] * \left(\mathrm{T} > \left(\mathrm{T_{melt}} + \frac{dT_{melt}}{2}\right)\right) \end{bmatrix} . \mathrm{dT}[K]$$

$$E_{solid}[kJ] = \left[m_{alu}[kg] * Cp_{alu}\left[\frac{kJ}{kg.K}\right] + m_{case}[kg] * Cp_{case}\left[\frac{kJ}{kg.K}\right]\right] * dT[K]$$

$$E_{water}[kJ] = m_{water}[kg] * Cp_{water}\left[\frac{kJ}{kg.K}\right] * dT[K]$$

With: m is the mass, T_{melt} is temperature of PCM melting point, T is temperature of coolant, Cp stands for heat capacity, H is PCM latent heat and dT is temperature difference.

By applying these measures, simulations based on the comprehensive thermal energy storage subsystem model were performed:

Validation results:
Charge test at 9 l/min

Validation results:
Discharge test at 9 l/min

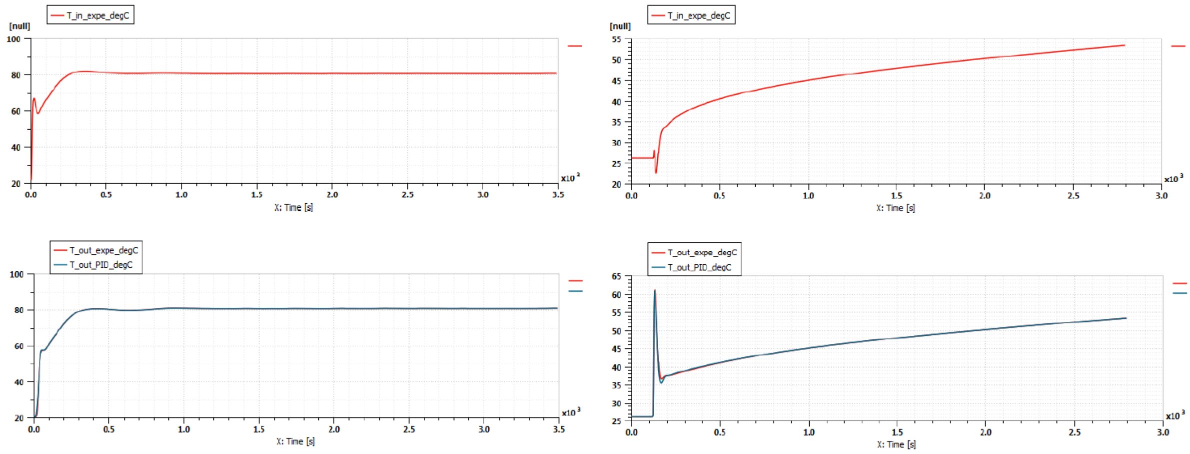


Figure 3: Simulation results with LMS Imagine.Lab Amesim: T_{in_PCM} and T_{out_PCM} = f (time) for a charge and discharge run at 9 L/min

Further parameterized studies based simulation models were used, on the one hand to optimize parameters of the subsystem such as the discretization, on the other hand to provide a sub-model for the overall vehicle thermal management.

As shown in Figure 3, the thermal energy storage subsystem as a component model provides results in agreement with the experimental results. A next step will be the implementation of this component into the overall vehicle thermal management model.

3. Vehicle electro-thermal network control (CEITEC BUT)

The Fully Electric Vehicles (FEV) have quite a large number of heat sources and -sinks, especially if it should be possible to reuse the waste heat energy and enable energy storage as well. As heat sources and sinks ambient air, cabin air, waste heat from electric motor and power electronics, batteries and the heat storage can be considered. That causes a quite large number of possible configurations based on demand for cooling or heating. For the best vehicle performance it is important to select the optimal configuration for the current conditions.

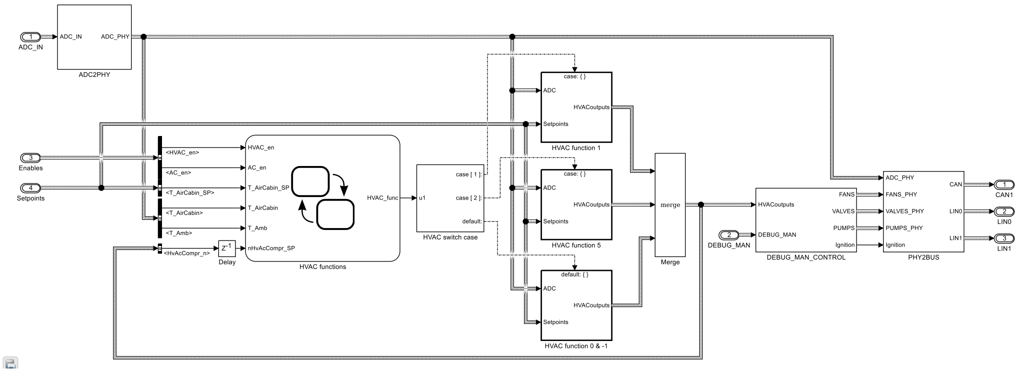


Figure 4: Thermal decision controller with thermal functions

A Thermal Decision Controller (TDC) was designed and implemented, which solves the problem above. The TDC selects the appropriate configuration of heat sources and sinks (by actuating valves, flaps etc.) and furthermore, chooses a suitable control algorithm for the continuously controlled devices (like fans, compressor, pumps etc.).
The TDC is based on Matlab Simulink Stateflow. C-code is then generated from the Simulink model and subsequently triggered in AURIX Tricore microcontroller. The model utilizes buses, which are beneficially translated as structs and then used by Matlab code, CAN and LIN software drivers and ADC. In Figure 4 a part of the TDC (example of three thermal functions for Heating, Ventilation and Air Conditioning) is shown.
Additionally we are also working on advanced control techniques like MPC (Model Predictive Control), virtual sensors and others. An example of a virtual sensor for heat storage is explained in the next section.

3.1. Heat storage (PCM) virtual sensor

The heat storage is based on a phase change material (PCM), thus it is not possible to use a temperature sensor for receiving the remaining available heat capacity [1]. A virtual sensor, which is based on the following equations, can be implemented for the estimation of the current storage status.

$$S(k)=\begin{cases} 0 & T_{hs}<T_m \\ S(k-1)+\dfrac{t_s\dot{m}(k-1)c\left[T_{in}(k-1)-T_{out}(k-1)\right]}{L} & T_{hs}=T_m \\ 100 & T_{hs}>T_m \end{cases} \quad [\%]$$

With: S is heat storage status, T_{hs} is temperature of heat storage, T_m is temperature of PCM melting point, k stands for current discrete time, $\dot{m}$ is coolant mass flow rate, c is coolant specific heat, T_{in} and T_{out} are the temperatures of heat storage coolant inlet and outlet respectively, t_s is sampling time and L is latent heat of overall heat storage.

3.2. Heat pump test bench

A heat pump test bench was built up to enable the evaluation of the control algorithms. It consists of a variable speed scroll compressor, an evaporator, a condenser, a chiller, expansion and shut-off valves, an evaporator blower, a condenser fan and control and measurement devices.
Figure 5 shows the first measurements from the test bench. At a time of 120 s the compressor was started and its revolutions (n_{cmpr}) were controlled to keep the evaporator outlet temperature (T_{evap}) at the defined set point (T_{evapSP} = 12 °C). The condenser fan speed was controlled based on the high side pressure (p_{high}) to keep the condensing temperature at the defined level. Currently, we are working on new experiment set up with implemented advanced

control techniques.

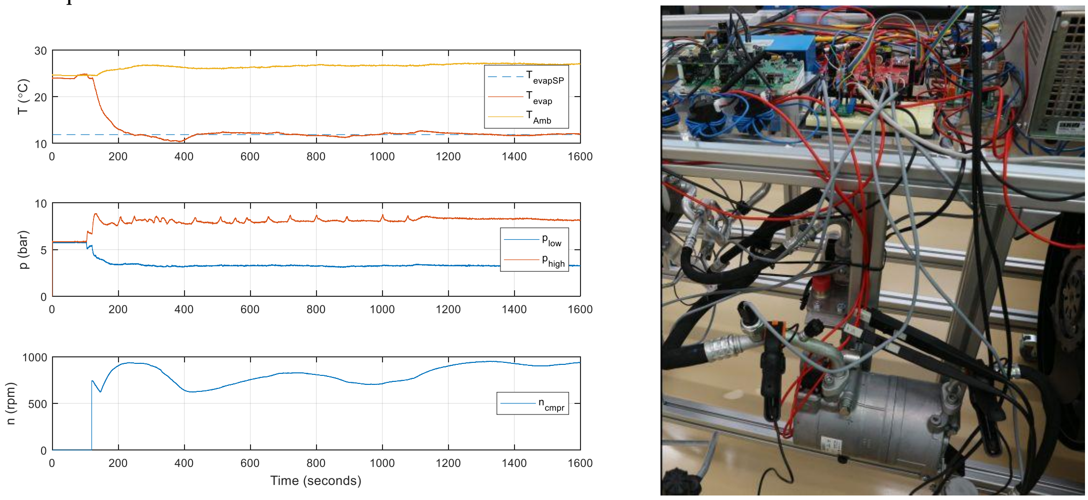


Figure 5 Heat pump test bench: (left) first measurements; (right) test bench photo

4. Battery model (Fraunhofer IISB)

Lithium Ion batteries have temperature dependent properties, such as the useable capacity, the internal electrical resistance or the rate of ageing. These parameters are directly affecting the range, power output and service life of an electric vehicle. In order to control this impact, the thermal management on battery system level aims to achieve spatial and temporal temperature homogenization. This includes for example the reduction of temperature differences for synchronized ageing rates of the cells and the avoidance of temperatures at the upper or lower specified limits and thus, prevent accelerated ageing.

Regarding the designed battery system, a low thermal resistant coupling between battery cells and cooling plate is realized in order to reduce the maximum temperature rise and gradients within the system. Due to a direct attachment of the modules on a central cold plate, which is only separated by a gap filler and a HV insulation layer, a low thermal contact resistance is ensured. The cooling channels of the cold plate are optimized in terms of spatial temperature homogenization in order to avoid local hot spots. In Figure 6 the uniform temperature distribution at the optimized cold plate is shown for an assumed use case of continuous discharging with the maximum specified current rate in a CFD simulation.

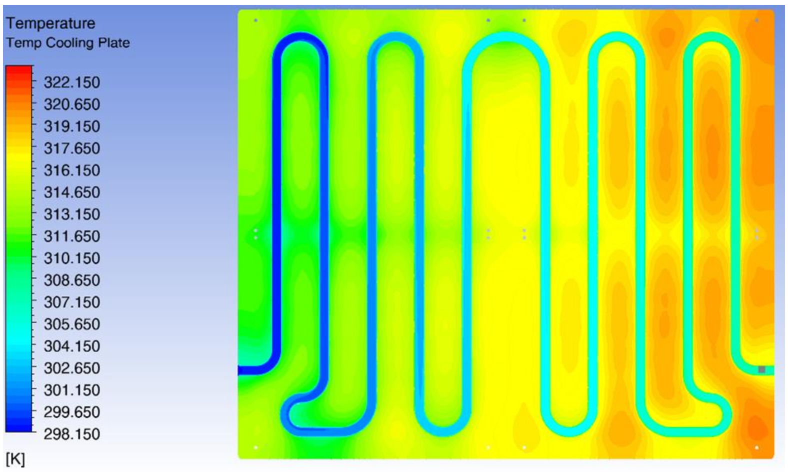


Figure 6: Temperature distribution of optimized cold plate

Internal temperature differences are also reduced by the thermal separation of the battery cells with mica sheets to limit heat flux between the single cells. Also thermal runaway propagation to neighboring cells in case of incidents is reduced by these high temperature resistant sheets. In order to control the external heat flux to the environment, a high thermally insulated housing using Vacuum Insulation Panels (VIP) covers the battery system, which minimizes the impact of fluctuations in ambient conditions.

By applying these measures, the battery provides a thermally controllable subsystem, with a beneficial role in the vehicle level thermal management. Further parameterized FEM based simulation models are used, on the one hand to optimize parameters of the system such as an adequate VIP thickness, on the other hand to provide a sub-model for the superordinate vehicle thermal management. Model Order Reduction MOR techniques allow a significant reduction of the calculation times, accelerating this optimization process.

5. 10 kW Wireless Charger Subsystem (TU Dresden)

The Wireless Charger Subsystem (WCS) is a 10 kW inductive power transfer system developed for the purpose of charging and thermal preconditioning of the EV. The WCS forms the 3 phase 400 VAC, 16 Arms grid input to an 85 kHz alternating current (acc. to IEC 61980) driving a primary coil in the ground pad module (GPM). The generated magnetic field induces an alternating current within the secondary coil in the car pad module (CPM). After rectification and filtering, the current charges the EV's battery system (ref. Figure 7) and can be freely distributed within the electric-thermal network of the car.

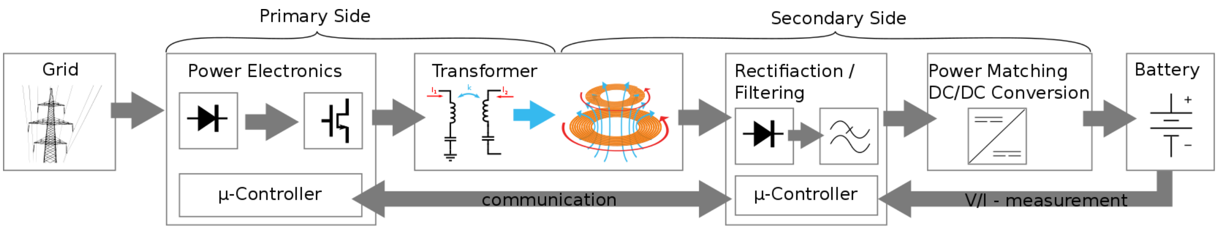


Figure 7: Schematic overview of the 10 kW wireless charger subsystem

The power is transferred over a distance of up to 20 cm with an efficiency of 85-95%. The CPM is cooled passively to save weight and installing space.

Use Cases

The primary, main use case for the WCS is the charging of the EV's battery. This takes place in public areas like car parks or supermarket parking bays as well as in the private garage at home. Once the car is parked and primary and secondary coils are aligned, the charging process starts automatically. A further use case is the thermal preconditioning of the battery system or the drivers cabin.

Charging: State of the art WCS provide a nominal charging power of up to 3.6 kW which is the maximum output of standard mains. However, battery sizes in EV's are increasing to meet the customers range demands. Thus, batteries with more than 40 kWh capacity cannot be recharged fully within one night (i.e. 10 hours). A 10 kW WCS however is able to recharge a Tesla Model S overnight, which is considered to have the largest capacity on the market.

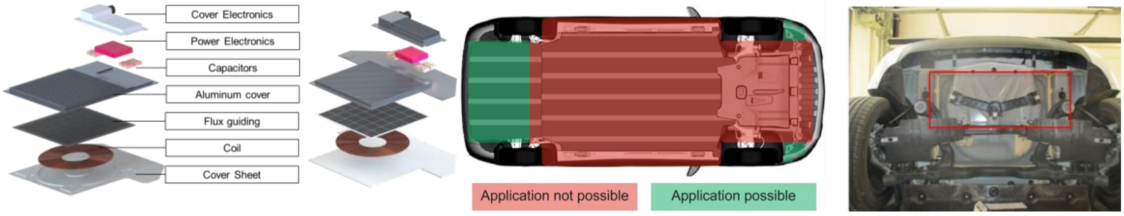
Table 1 Comparison of the charging time for different battery capacities

Vehicle	**Battery Capacity in kWh**	**Charging time in hours**		
		@ 3.6 kW	**@ 7.2 kW**	**@ 10 kW**
Chevrolet Bolt	60	16.7	8.3	6.0
Daimler B-Class	28	7.8	3.9	2.8
Nissan Leaf	30	8.3	4.2	3.0
Tesla Model S	100	27.8	13.9	10.0

Preconditioning: Air and battery conditioning can have a huge impact on the range of an EV, especially in hot or cold weather conditions. Thus, a thermal preconditioning of the EV before start can increase the range by saving battery capacity for traction. To heat the compartment from 0°C to +23°C within 10 minutes an electrical energy of 1.5 kWh was consumed, which leads to an electrical power demand of 9 kW [2].

Car Integration

The WCS shall be installed into a Mercedes-Benz B-Class. Therefore an investigation on the usable design space was performed. Based on field measurements with a generic coil it was proven that the front of the car is not well suited for a WCS. This is mainly because the motor, inverter and gearing are very closely located to the covering lid of the underbody. Thus an extensive shielding would be required in order to mitigate the possibility of interference with those components. Furthermore, the battery is not usable as well since the covering lid is fully metallic, which may cause extensive heating in case of misalignment between the GPM and the CPM. In contrast to the highly dense front and middle part of the underbody the back of the car is significantly more spacious. The CPM relies on a glass fiber reinforced plastic (GFRP) baseplate which is either ribbed or structured, a litz wire coil, a ferrite layer and an aluminum cover shield with cooling fins. The design foresees a second aluminum housing which protects the necessary resonant tank capacities as well as the power electronics.



a) b)

Figure 8: a) Explosion view of the CPMs final design variants b) Integration possibilities of the WCS into the B-Class demonstrator

6. Comprehensive vehicle simulation model (AVL List)

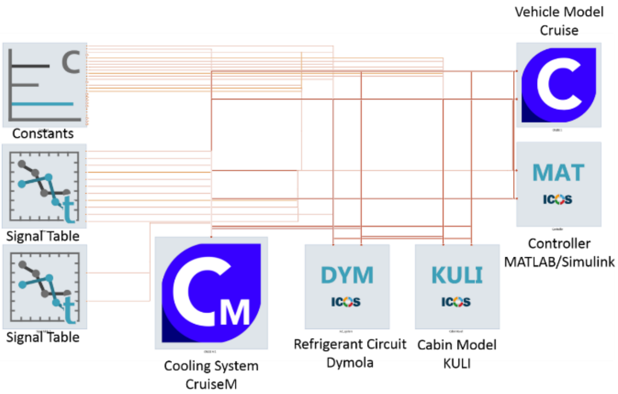


Figure 9: Comprehensive vehicle simulation model in AVL Model.CONNECT^{TM}

Figure 9 shows the comprehensive vehicle system simulation model created in AVL Model.CONNECT^{TM}. This is a platform to set up and execute system simulation models which are composed of subsystem and component models from multiple model authoring environments. Models can be integrated either based on standardized interfaces (Functional Mockup Interface, FMI) or based on specific interfaces connecting a wide range of well-known simulation tools. It supports the user in organizing variants of the system model, which describe different configurations of the system investigated as well as different testing scenarios and testing environments.

Each subsystem model of the vehicle (vehicle model, cooling system model, cabin model, model of the thermal control strategy and the refrigerant circuit model) was set up in a different software and connected based on energy flow and signal interactions. All subsystem models were connected in Model.CONNECT™ using the direct interface. This feature enables a huge modularity on co-simulation level. Each sub-model can easily be exchanged by others with different complexity levels but the same interface. The system development for different vehicle variants (e.g. vehicle families with the same powertrain) can easily be investigated via exchange of the different vehicle models for each variant.

6.1. Powertrain model

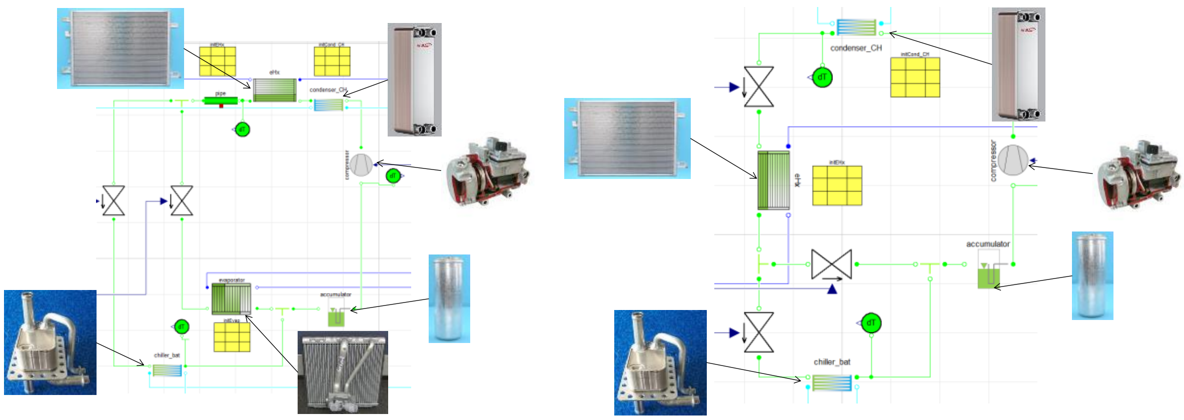
The powertrain model was based on a Mercedes Benz B class electric vehicle. It was set up in AVL Cruise, a 1D simulation tool for power trains and vehicle longitudinal dynamics. The model covers the vehicle and powertrain elements including the general data of the vehicle such as nominal dimensions and masses, battery, E-motor, tire properties, aerodynamic resistance, etc.

6.2. Cooling system and HVAC model

CruiseM, a simulation tool by AVL for engine, after treatment, drivetrain, cooling and control systems, was used to set up the cooling system simulation model. It contains the cooling circuits for battery, E-motor, cabin, the cooling air path of the front-end cooling package and the thermal network which is representing the thermal inertia of the components (e.g. battery, PCM and E-motor).

The HVAC (Heating Ventilating Air Conditioning) system consists of the vehicle cabin and the air path. ECS KULI simulation software has been introduced with an improved, more detailed zonal cabin model considering moist air and solar radiation.

The refrigerant circuit was set up in Dymola and consists of two separate models. One model was implemented to cover the cooling mode at warm and hot operating conditions and the other one for cold ambient conditions. Generally, it would be possible to but the entire functionality in one model, but this approach would lead to unnecessarily enhanced simulation time, because the refrigerant circuit model is the main contributor in terms of computing time within the entire vehicle simulation in Model.CONNECT™.



Cooling Heating

Figure 10: Dymola models of the refrigerant circuits for cooling mode and heating mode [3]

7. Simulation results summary and outlook

Simulations based on the comprehensive vehicle model were performed to investigate the influence of the different operating modes of the heat pump system on the driving range. The WLTC cycle (Worldwide Harmonized Light-Duty Vehicles Test Cycle) was chosen to show the benefits of the developed thermal-electric system layouts on the all-electric range. Two scenarios – the vehicle cabin heat up and the cool down of the cabin were simulated to enable a numeric assessment of the different operating modes.

The holistic vehicle model is able to predict the energy consumption of the EV considering the driving cycle and the ambient conditions. The simulation model initial control functions allow to show the base functionality of the system. The following trend in terms of energy consumption can be determined:

- Using the PCM as a heat source enables to reduce the compressor power and to shorten the duration for the cool down phase of the cabin (at 35°C ambient temperature) leading to a reduction of the entire energy consumption for one WLTC cycle by of 7%.
- Implementing a conventional PTC heater for the cabin heating at -10°C ambient temperature increases the energy consumption by 104% compared to the baseline simulation at 20°C with a deactivated HVAC system.
- With the usage of a heat pump as a heat source at an ambient temperature of -10°C the energy consumption is limited by an increase of 43% but the cabin target temperature is reached only at the end of the WLTC (after 25 minutes).
- Using a PCM with 25°C as heat source temperature for the warm-up leads to a minor reduction of the energy consumption but it allows reaching the cabin target temperature within 5 minutes.

Table 2 Comparison of cooling case with baseline

Use Case	Energy consumption difference
Baseline @ 20°C ambient	0%
Cooling with ambient as heat sink @ 35°C ambient	+31 %
Cooling with ambient and 15°C PCM @ 35°C ambient	+23%
Cooling with ambient and 25°C PCM @ 35°C ambient	+24%

Table 3 Comparison of heating case with baseline at -10°C ambient

Use Case	Energy consumption difference
Baseline without cabin heating	0%
Heating with PTC	+104%
Heating with ambient as heat source	+43%
Heating with 15°C PCM and ambient as heat source	+43%
Heating with 25°C PCM and ambient as heat source	+40%

The initial holistic vehicle simulation results lead to following conclusions:

- The heat pump system is a feasible solution to significantly reduce the energy demand of the HVAC system at low ambient temperature
- A PCM heat storage up to 0.75 kWh allows getting sufficient heating power with the heat pump system also for cold ambient conditions
- A PCM heat storage up to 0.9 kWh allows the storage of the entire condenser heat for cabin cool-down.
- It is recommended to integrate a 1 kWh PCM storage with a phase changing temperature of 15-25 °C.

The simulation showed that the electric energy consumption for the heating and cooling modes could be significantly reduced with the new system layout, providing comparable climatic comfort to the passengers. The results showed the potential of using waste heat and a heat/cold storage to increase the vehicle range.

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