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Big batteries: Solution for the Future?

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Summary

The greenhouse effect requires an ongoing decrease of CO_2 emissions and e-mobility offers a significant potential to achieve this target. To achieve range parity with conventional ICE powertrains, the trend goes towards bigger batteries with capacities up to and beyond 100 kWh. Though this solves the range issue, with the current battery energy density and CO_2 production footprint, it negatively influences the driving performance and the lifecycle CO_2 footprint of BEVs as well as the cost. MAHLE shows in the work alternative solutions from efficiency gains of the electric traction drives, quick charging, efficient cabin climatization and reduced energy demand of a bespoke urban 4-wheeler concept.

Keywords: LCA (Life Cycle Assessment), thermal management, air conditioning, fast charge, BEV (battery electric vehicle), efficient electric powertrain

1 Climate Targets

At the UN Convention on Climate Change 2015 (COP21) in Paris, 197 countries agreed to pursue a common set of climate policy targets. Over three-fourths of the 197 Parties have already ratified the Climate Agreement. For the first time, the Paris Agreement brings all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects.

“The Paris Agreement’s central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius“, [1].

Fig. 1 shows the temperature development from the beginning of industrialization and the outlook until the year 2100. To stay below 2°C global warming, a significant CO_2 reduction is now necessary within the next years – not the next decades – and battery electric vehicles (BEV) can contribute significantly to this reduction.

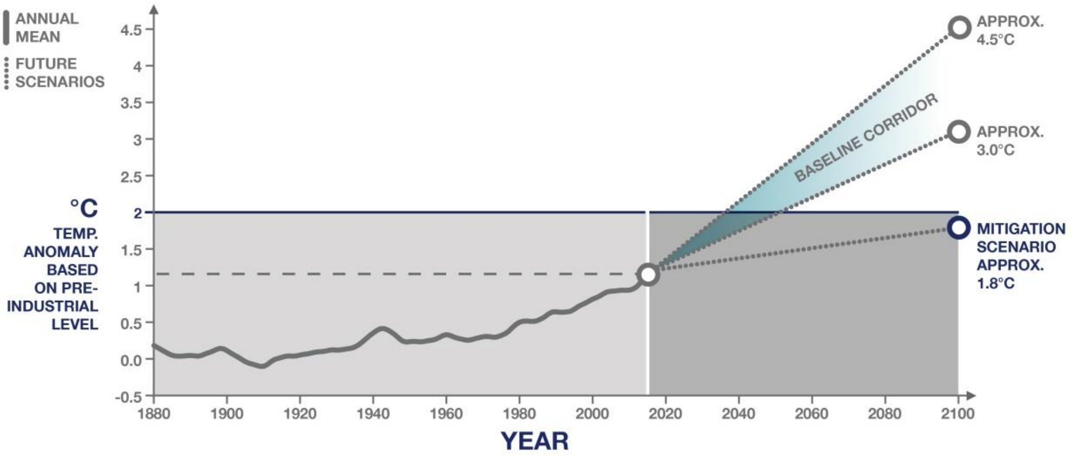


Figure 1: Annual mean temperature vs. year [2, 3, 4]

2 Influence of battery size on driving range and performance

One of the key obstacles for the market success of BEVs is the useful driving range under real world operating conditions. Though this can be addressed by increasing the battery size, this ‘simple’ solution not only raises the cost but also increases the vehicle energy demand. In addition, it leads to a deviation from the linear relation between battery capacity and driving range in particular for larger batteries, see Fig. 2. The energy demand simulated for a compact class vehicle varies from less than 13 kWh/100 km for the NEDC cycle with ‘NEDC road loads’ to values in excess of 20 kWh/100 km for the ‘aggressive’ RTS95 with ‘real world’ road loads. This leads to nominal battery capacities of approximately 60 kWh to 80 kWh (assuming that the usable battery capacity is 90% of the nominal capacity) for a 300 km – 400 km driving range. With a typical energy density of 120 Wh/kg for a state of the art battery, this increases the vehicle weight by approximately 300 kg when doubling the battery size from 36 kWh to 72 kWh.

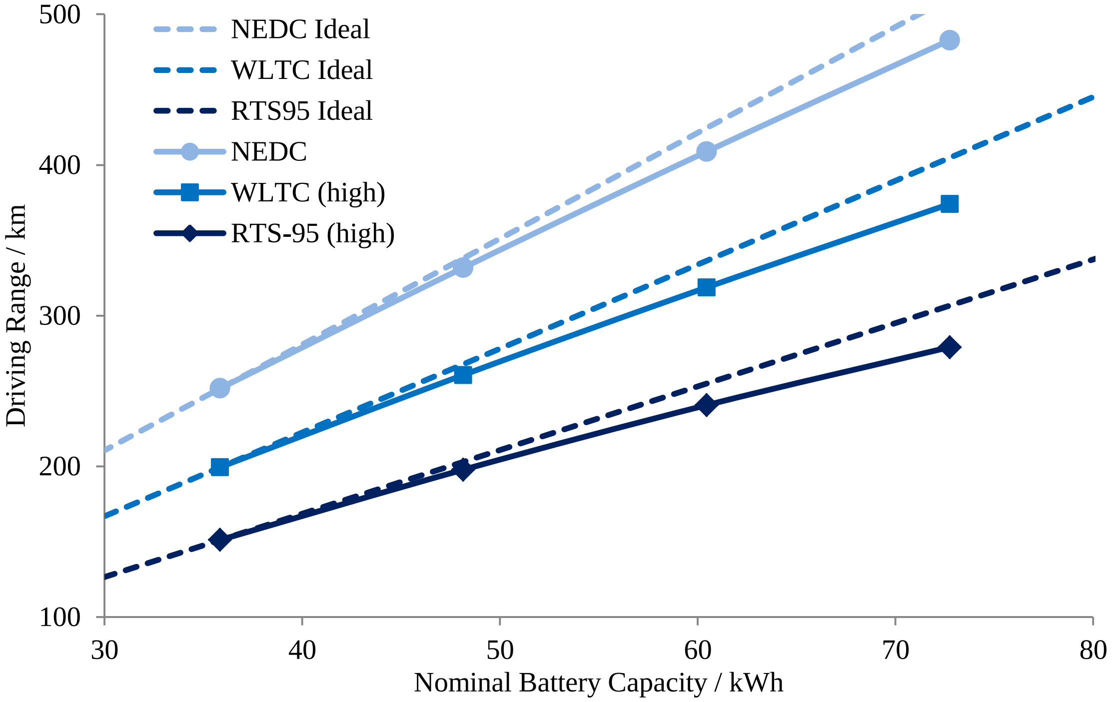


Figure 2: Driving range vs. battery size for a compact class vehicle and different drive cycles

With the recuperation possibility of a BEV, the vehicle mass seems to be less important, however, the rolling resistance and the total amount of energy that needs to be recuperated increases significantly and the recuperation itself has an efficiency of less than 100%. This causes a deviation from linearity in the range of 6% to 10% depending on the drive cycle energy demand when doubling the battery capacity, see also table 1.

Table 1: Energy demand for a compact class vehicle

kWh/100 km	Baseline	+300 kg	Δ / %
NEDC	12.7	13.4	+5.8
WLTP (low/high)	14.5 / 16	15.5 /17.3	+7.3 / +8.2
RTS 95 (low/high)	18.7 / 21.1	20.7 / 23.2	10.4 / 9.9

The acceleration performance is also negatively affected by the weight increase, see Fig. 3. After 3 s, the lighter vehicle runs 6 km/h faster and after 5 s it is more than one vehicle length ahead compared with the heavier vehicle. For an equivalent driving performance, the heavier vehicle requires approximately 15% higher peak torque and peak output.

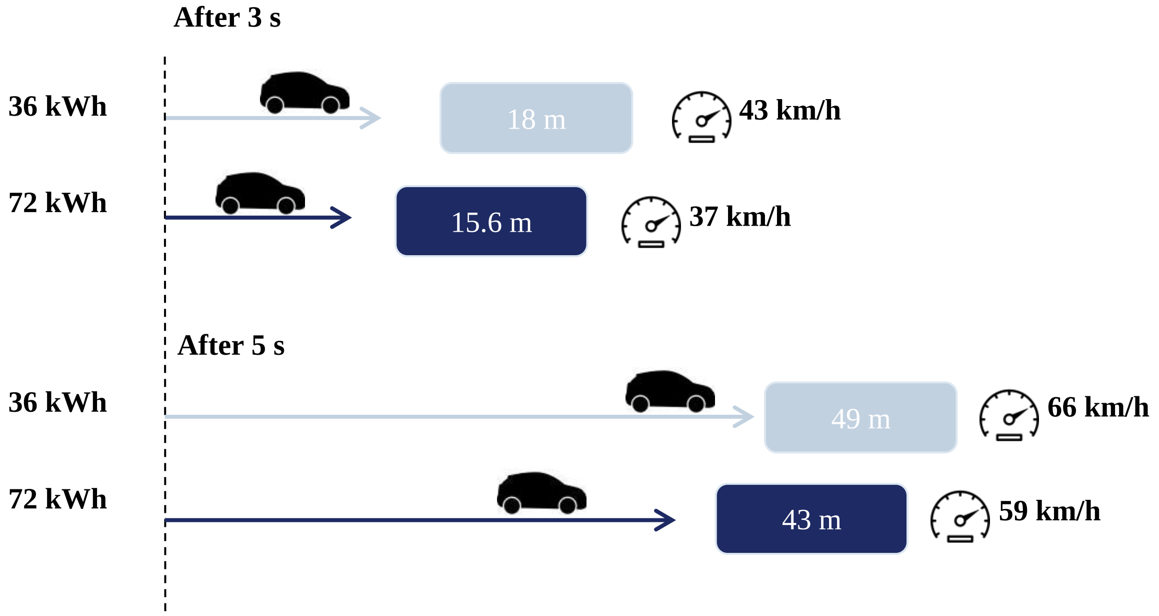


Figure 3: Influence of battery weight on acceleration performance of a BEV

The main benefits of BEVs are local zero emissions and the significantly reduced CO_2 emissions during operation compared to a vehicle with an internal combustion engine (ICE). However, in a life cycle assessment (LCA), the total CO_2 (equivalent) emissions including the vehicle and battery production are taken into account. Fig. 4 shows the equivalent CO_2 emissions for a conventional vehicle and two BEVs. The production of a compact class vehicle with a conventional powertrain typically produces 4 - 6 tCO_{2eq} [5]. The literature values for the equivalent CO_2 emissions from battery production vary from 100 gCO_{2eq}/Wh up to 250 gCO_{2eq}/Wh [6, 7, 8, 9]. For this analysis, an average value of 150 gCO_{2eq}/Wh is taken into account. This battery production CO_2 footprint roughly doubles the total CO_2 footprint of the BEV with a 36 kWh battery and triples it with the 72 kWh battery compared to a vehicle with a conventional ICE powertrain.

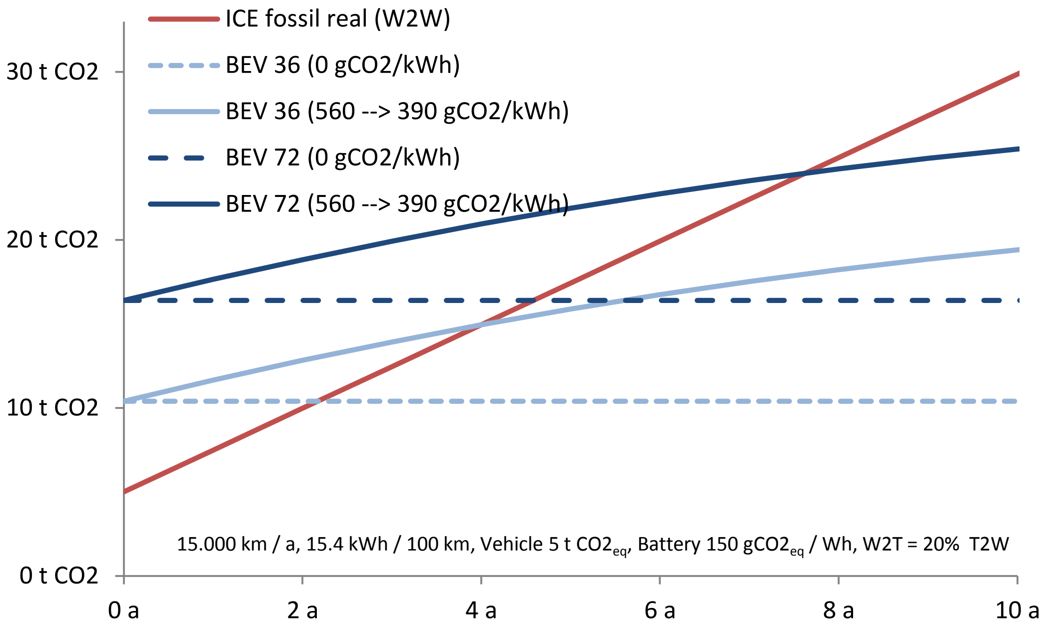


Figure 4: Lifecycle CO2 emissions for different powertrain concepts of a compact class vehicle

With a 'small' battery and green electricity (i.e. 0 gCO_2/kWh), this production footprint can be compensated within 2 years compared to an ICE powered vehicle. On the other extreme, a large battery and an average electricity mix of Germany (taking the increase of renewable energy share within the next years into account), leads to 8 years and 120.000 km before break even. Summarized, the simple solution to achieve range parity of BEVs with ICEs by increasing the battery size negatively influences the vehicle cost, driving performance and lifecycle CO_2 emissions. In the following chapter, alternative solutions for increasing real world driving range are discussed.

3 MAHLE solutions

Until the breakthrough of battery technology, there are challenges to overcome and efficiency to gain. MAHLE contributes to improve market success, e.g. by developing innovative solutions to enable quick charging, increase efficiency of propulsion and comfort to use energy on board best possible.

3.1 Efficient propulsion

The cooling design of the electric drivetrain is a fundamental technology to improve the efficiency of propulsion. Enhancing the cooling effect has a reducing influence on various different loss mechanisms. Due to the higher conductance of copper or aluminum for lower material temperatures, the ohmic losses of the stator and the rotor of electric machines can be reduced. The improved cooling effect can also be used to increase the power density of the electric drivetrain by weight and volume. The combined approach with the consequent use of light materials instead of metal - wherever possible - results into a significant weight reduction of the electric drivetrain and increases the real driving cycle range and performance. Nevertheless, it's necessary to employ a system approach. The enhanced cooling effect can be used to decrease the flow rate of the cooling fluid, which subsequently reduces the power consumption of the cooling auxiliaries. The utilization of an improved cooling performance for efficient propulsion of the electric drivetrain is therefore an optimization task. In practice, requirements and boundary conditions of the customer are driving the solution.

A possible solution to achieve an enhanced cooling effect is shown in Fig. 5. The stator package of an electric motor is covered by a water jacket with an optimized pin fin design. Compared to a standard water jacket solution, the pin fin approach achieves a 70% increase of the water jacket surface. Furthermore the pin fins have a special design to create turbulent areas, which significantly increases the heat transfer to the cooling fluid. Compared to a standard water jacket, the pin fin solution achieves a 30% - 50% higher cooling performance for operation with equal pressure drop. The additional production and assembly costs can be minimized through a modular design approach with identical and interlocking segments.

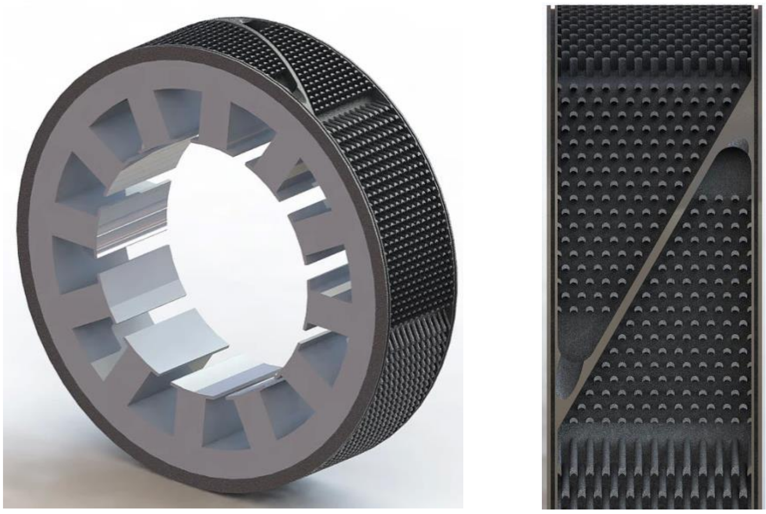


Figure 5: Pin fin water jacket in side view (left) and top view (right)

Another heat source of an electric drivetrain is the traction inverter. An enhanced cooling design solution for a traction inverter has to consider the hot spots, caused by the structural shape of power semiconductors. The left part of Fig. 6 presents the housing of a traction inverter with grooves below the area for attaching the semiconductor baseplate. The grooves form the counterpart of a cooling channel. Pin fins with a design to create turbulent areas are placed close to the hot spots (Fig. 6 right) and improve selectively the heat transfer. The transition channels of the cooling liquid from the high side to the low side semiconductors have a U-shape to minimize the pressure drop. The measured pressure drop at the test bench is 32 mbar at 5 l/min during a temperature difference between inlet and outlet of Δ7 K. The thermal conductance of the heat sink at this operating point is 360 W/K. The design features the optimization to achieve an outstanding performance at high flow rates. The integration of the cooling channels into the inverter housing also ensures cost-effective production for this solution.

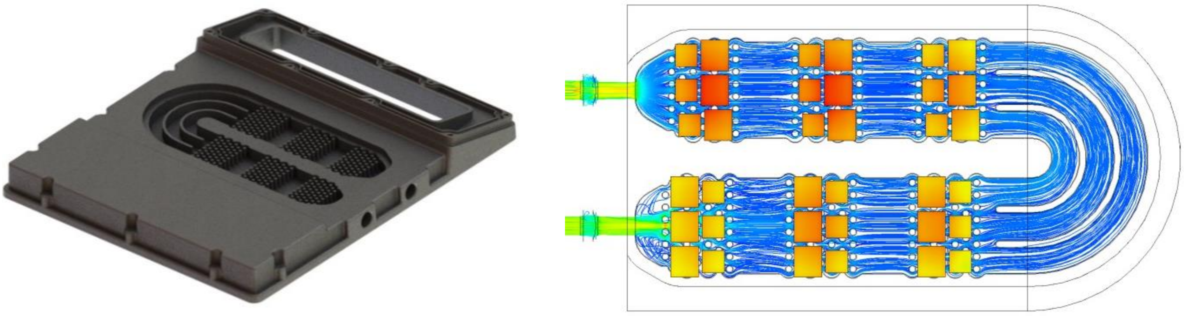


Figure 6: Traction inverter housing with cooling channel (left) and related thermal simulation (right)

3.2 Quick charging

Quick charging – sometimes also referred to as ultra-fast charging if the charging power exceeds 350kW@800V – is a considerable strain for each single cell, for bus bars and for electric connectors but also for the cooling systems that has to reject the waste heat to the environment. The stress for a cell is mainly caused by the charge rate (ratio of maximum charging amperage and cell capacity, correlating with the charging time), maximum cell temperature as well as internal temperature gradients. All three parameters interdepend and correlate with the cell cooling solution applied. The strain for bus bars and electric connectors is mainly caused by the amperage resulting in Joule heat and in waste heat by electrical contact resistance. The overall charging power has a direct impact on the amount of overall waste heat that has to be rejected to environment by the cooling system.

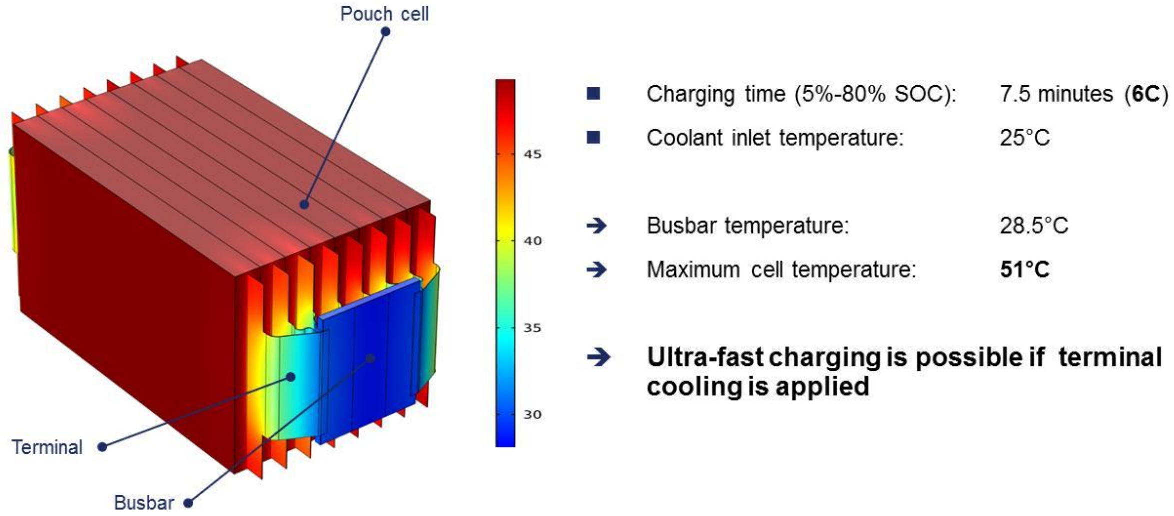
Following dependencies and implications on thermal management occur:

a) The higher the charge rates the shorter the charging time.

From customer point of view high charge rates are a basic must-have for broad acceptance of electro mobility. Short charging times in combination with sufficient infrastructure for charging stations increase the acceptance of smaller batteries. That is a considerable leverage for costs. Thus, thermal management as enabler for quick charging is the key for cost reduction.

b) The higher the charge rates the higher the waste heat of the cell. The higher the waste heat of the cell the higher the maximum cell temperature and the higher the temperature gradient inside the cell.

Cell cooling is the crucial issue for quick charging. It has to be applied as close to the cell as possible. The amount of thermal interfaces between the heat sources within the jelly roll and the heat sink in the cooling fluid has to be reduced to a minimum. Most of the existing cooling solutions on the market are not suitable for quick charging and cannot be toughened up due to physical restrictions. New solutions have to be developed. A very promising approach is conductor cooling since a good electrical conduction path is also a good thermal conduction path. Fig. 7 shows simulation results for a pouch cell module under quick charging conditions.



- Charging time (5%-80% SOC): 7.5 minutes (**6C**)
- Coolant inlet temperature: 25°C

➔ Busbar temperature: 28.5°C

➔ Maximum cell temperature: **51°C**

➔ **Ultra-fast charging is possible if terminal cooling is applied**

Figure 7: Cell cooling, quick charging

c) If the charge rate is given: the bigger the battery the higher the current. The higher the current the higher is the thermomechanical stress for bus bars and electrical connectors.

Thermal management for quick charging is not only crucial for cells but also for all electromechanical components within the battery. If bus bars, module connectors and battery connector are cooled properly the efficiency is increased due to reduction of Joule heat and electrical contact resistance.

Furthermore, there is the potential to downsize cable cross-sections and thus, weight and costs. E.g. a cooled connector enables reduced cable cross-sections by up to 50%.

d) If the charge rate is given: the bigger the battery the higher the overall charging power. The higher the overall charging power the higher is the amount of waste heat to be rejected by the cooling systems.

Not only the cell cooling within the battery is very challenging but also the final heat rejection to the environment. A big amount of waste heat flows into the cooling circuit during quick charging. For 350 kW charging power and a realistic overall efficiency of less than 95% more than 17.5 kW waste heat has to be absorbed by the coolant, transported to the front end of the vehicle and finally rejected to environment via the radiator. Challenging is the quite low cooling fluid temperature level of less than 40°C as well as the missing air stream at the low temperature radiator since the vehicle is parking. That means for high ambient temperatures that the complete waste has to be rejected by the refrigerant circuit (air conditioning system). A common air conditioning system is able to provide approximately 8 kW cooling power to cool down the cabin at idling conditions. For quick charging more than twice as much cooling power is required. Following measures are necessary to toughen the refrigerant system up: increase the displacement of the compressor accordingly or apply a second compressor in parallel, increase the size of the chiller, increase the size of the (indirect) condenser and increase the power of the cooling fan in the front end. Fig. 8 shows a coolant system with relevant components to be modified for quick charging. The red arrows indicate thereby …

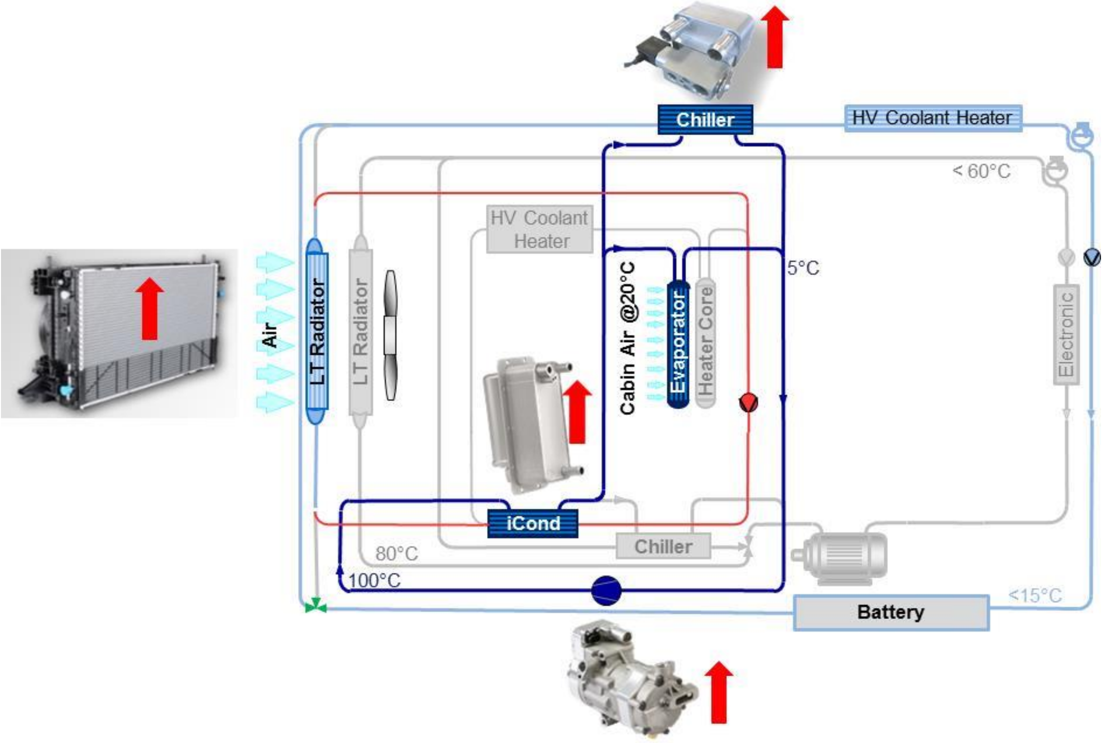


Figure 8: Cooling system for quick charging

3.3 Efficient Cabin Comfort

Cabin heating at low ambient temperatures and cabin cooling at high ambient temperatures have a huge impact on electric driving range. The acceptance of electrical vehicles suffers accordingly. Fig. 9 shows the impact of cabin heating on driving range for a compact vehicle with a small-sized battery (20 kWh) and a medium-sized vehicle with a large-sized battery (80 kWh) at ambient temperature of 0°C. The compact vehicle is mostly driven in cities with a mean driving power of 3.0 kW and the heating performance for the cabin is 2.0 kW. The medium-sized vehicle requires 2.5 kW heating performance for the cabin. This vehicle type is also driven outside of cities and thus, the mean driving power is 9 kW. The cabin heating performance depends only on cabin size which differs just slightly between compact vehicle and medium-sized vehicle. The cabin heating reduces the electric driving range by 40% in case of the compact vehicle: instead of e.g. 150 km range only 90 km range can be achieved. This considerable impact is caused by the fact that the driving power and the heating power are more or less equal. For the medium-sized vehicle the impact of cabin heating is smaller since the mean driving power is considerable higher than the heating performance. Nevertheless, a range reduction of approximately 20% is still significant.

The range reduction can be halved in both cases by using a heat pump basing on a refrigerant circuit, se Fig. 9. A heat pump pumps ambient heat and waste heat coming from the cooling circuit of the electric power train from a low temperature level to a higher temperature level which is suitable for heating the cabin.

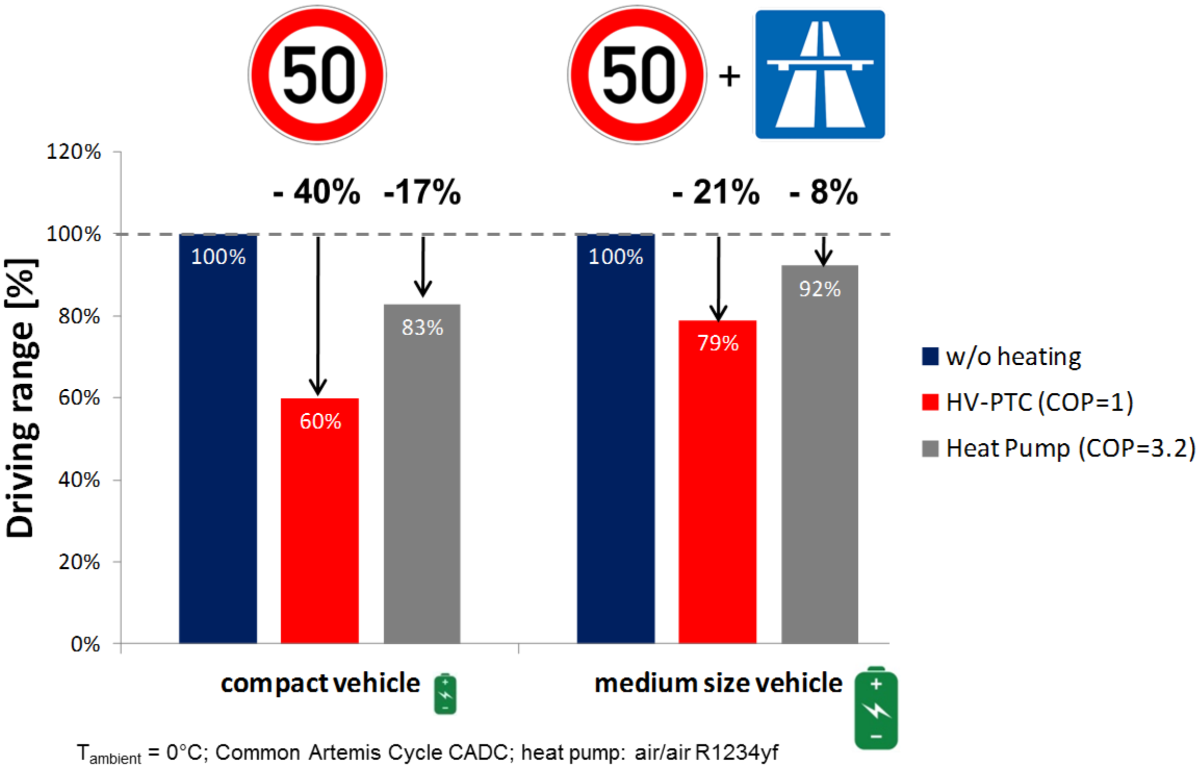


Figure 9: Impact of cabin heating on electric driving range

An attractive alternative for a refrigerant-based heat pump is a thermoelectric heat pump, see Fig. 10. Using the so called peltier effect, a thermoelectric heat exchanger pumps waste heat from the cooling circuit of the electric power train into the heating circuit of the HVAC-unit. In contrast to a refrigerant-based heat pump, that requires a system setup for heat pumping, a thermoelectric heat pump can be realized in a single component. Thus, the complexity and the package needs are significant smaller. However, the efficiency is lower. Instead of approximately 50% reduction of impact of cabin heating only 33% reduction are achievable. Compared to a PTC-heater that only converts electric energy into heat without heat pump functionality, a thermoelectric heat pump is an attractive compromise between costs (better than refrigerant-based heat pump) and efficiency (better than PTC-heater).

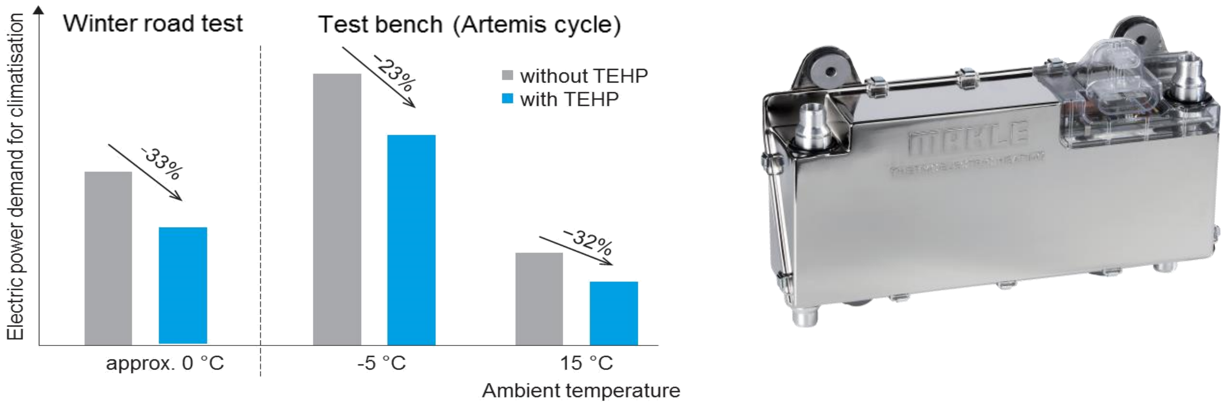


Figure 10: Thermoelectric heat pump

3.4 Urban Mobility

For urban mobility maximum efficiency, intuitive operation and agility are keys for future vehicle concepts. Derived from these overall requirements, MAHLE developed a dedicated urban mobility concept vehicle using its combined powertrain and cabin system expertise.

MeeT – MAHLE efficient electric Transport

With the background of an application for urban areas, the technical focus of the demonstrator, see Fig. 11, is to meet the challenge of highest energy efficiency. The interplay of various energy-saving technologies in the areas of powertrain and thermal management increases the efficiency and consequently also increases the electrical range of the vehicle especially at low outside temperatures.

The low vehicle mass and the limited top speed of around 100 km/h are optimized for urban use and thus lower the required peak traction power. Comprehensive “real world” urban drive cycle test data from 10 drivers driving multiple times and under various traffic and environmental conditions a Stuttgart city cycle showed that a maximum demand of around 20 kW of electrical traction power is enough in urban areas. In order to be able to drive even with higher speed up to 100 km/h on longer distances (e.g. drive to the Stuttgart Messe or airport), MAHLE has opted for a twin drive system with 2 x 20 kW power output. This highly efficient e-drive still allows for applying a cost efficient 48 volt board net.

Highly efficient MAHLE 48-volt e-drive

The MAHLE IPM (IPM = interior permanent magnet synchronous motor) is a highly efficient combination of a synchronous motor with permanent magnets and integrated 48-volt power electronics. The motor offers maximum efficiency and dynamics in a wide speed range and in particular the “real world” driving conditions derived from the test data. In the MeeT demonstrator the drive unit consists of two motors with 20 kW mechanical continuous power, 80 Nm of torque and a peak efficiency of > 96%. The drive unit connects to the rear wheels via a central gearbox. This solution offers several further advantages:

- The design is modular and can easily be retrofitted depending on the application, for example as a drive unit / electric axle for hybrid vehicles
- Functional safety is increased by redundancy in the electric drive train
- Agility and maneuverability can be improved by torque vectoring
- Due to the high rotational speed of the motors, no manual gearbox is required, the system efficiency increases due to the absence of switching losses.

Overall, the dedicated urban mobility concept offers significant potential to improve efficiency as well as vehicle range whilst keeping battery size, weight and cost as small as possible.

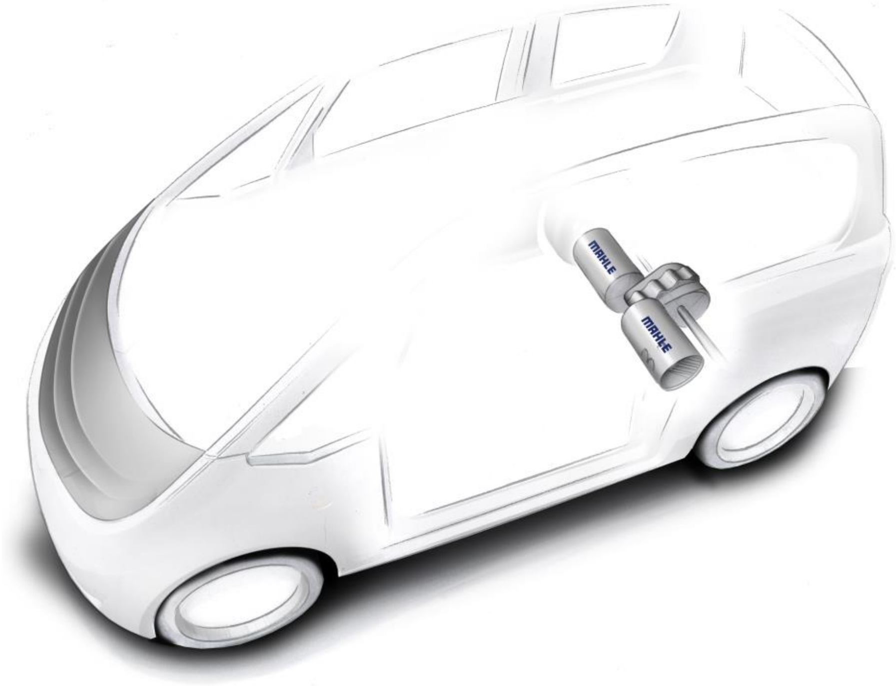


Figure 11: MAHLE efficient electric Transport (MeeT) concept vehicle with 48 V e-drive

4 Conclusion and Outlook

Instead of simply increasing battery capacity MAHLE present alternative solutions to increase range and thus acceptance of BEVs.

The energy demand for a compact class vehicle under real world driving conditions varies from less than 13 kWh/100 km for NEDC cycle with ‘NEDC road loads’ to values in excess of 20 kWh/100 km for the ‘aggressive’ RTS95 with ‘real world’ road loads leading to nominal battery capacities of 60 kWh to 80 kWh for a 300 km to 400 km range. Though big batteries solve the range issue, with the current energy density and CO_2 production footprint they negatively influence both the driving performance and lifecycle CO_2 footprint of BEVs. Alternatively, the enhancement of the cooling performance of the electric drivetrain leads to a more efficient propulsion. The efficiency gain is achieved by the reduction of the ohmic losses, the weight of the electric drivetrain and the power consumption of the auxiliaries. From a customer point of view quick charging is a basic ‘must have’ for broad acceptance of electro mobility. It significantly reduces range anxiety and increases the acceptance of smaller batteries, which is a considerable leverage for cost. Thermal management plays a crucial role for quick charging both on cell cooling level and on system cooling level. MAHLE is working on technologies for higher than 4C charge rate. While for conventional vehicles efficient cabin comfort is a nice to have, it is a ‘must have’ for electrified vehicles. Heating in winter and cooling in summer have a significant impact on the electric range. New thermal management solutions like heat pumps can help to overcome these challenges.

Furthermore, a dedicated urban mobility concept offers significant potential to improve efficiency as well as vehicle range whilst keeping battery size, weight and cost as small as possible.

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