Long distance e-mobility in the trade-off between battery capacity & charging power – Battery immersion cooling as enabler technology?

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Abstract

The electric vehicle market 2015 until 2020 was driven by vehicle purchases of innovators, local subsidies and restrictions as well as efforts of institutions to replace their current vehicle fleets. For a further market ramp up of e-mobility, wider customer groups must be convinced by fulfilling their dedicated mobility needs. This also includes the suitability for long distance drives and their related needs of vehicle price, energy consumption and charging time. Based on a customer analysis, this paper analyses different vehicle configurations for a long distance travel of 800 kilometers. In the trade-off between cost and technical features it can be shown that vehicles with a high charging power > 200 kW combined with smaller and cheaper batteries will be dominant use cases. To enable these high charging power solutions, technical configurations must be adjusted which could result in a bord net voltage of 800 V combined with a high power battery pack with the need of an improved battery thermal management. Immersion cooling could be a very promising solution to offer best in class thermal management without a significant price increase and improved total system cost.

1. Introduction

The last decade in the automotive industry from 2010 until 2020 was the beginning of a massive transformation. This transformation can be divided in the so called ACES megatrends, which summarize the future technology fields of autonomous driving, connectivity, electrification, and shared mobility.

Based on the Paris Climate Agreement of 2015, 196 participating nations are struggling to decrease their CO₂ emissions to achieve the common goal of limiting the global warming to preferably 1.5 degrees Celsius. Also, the automotive industry must contribute and need to drastically decrease the CO₂ emissions of their vehicle production fleets. Hybridization and electrification are the main enabler to achieve this goal which resulted in enormous development efforts and increasing production volumes of electrified vehicles in the last years.
Based on the reference year 2015 with 2.2 million global produced full hybrid (FHEV), plugin hybrid (PHEV) and battery electric vehicles (BEV), the production nearly tripled until 2020 [1]. Sales of electrified vehicles in the last years were mainly driven by early innovators, purchasing programs of governmental institutions and massive financial subsidies. For a further continuation of electrification and the massive, forecasted ramp up to 26.9 million hybrid and battery electric vehicles for the year 2025, upcoming vehicle projects need to address the mass market and related customer needs [1]. In addition to their advantages on short routes, BEV long distance capabilities need to be improved to further convince current owner of combustion engine vehicles.

2. Conceptional vehicle design for long distance

The suitability of BEVs for long distances can be mainly improved with the three technical levers battery capacity, charging speed and vehicle efficiency. Vehicle efficiency is the result of various resistances. It can be mainly influenced by improved aerodynamics, consequent focus on lightweight design which includes a lower battery weight and the electric drive efficiency improvement by implementing innovative e-motor concepts, efficient silicon carbide inverters and higher board net voltages.

Fig. 1: BEV volume-weighted average battery capacity and peak DC charging power classes [2]

Figure 1 shows how BEV battery capacities and peak direct current (DC) charging power is constantly increasing. With the consideration of the average battery cell density, the progress in battery technology can be derived as main factor for the capacity increase. In addition, the falling battery production prices per kWh enabled OEMs to increase the battery capacities on a constant price level. However, the increase of cell density reduced not the vehicle weight. Instead, constant or slightly heavier batteries can be seen. Latest announcements of Nio for the new sedan ET7 include a solid-state battery with 150 kWh battery capacity which is one of...
the highest announced battery capacities so far [3]. In the BNEF summit in February 2020 Bloomberg showed selected energy densities of battery cells from 2006 to 2020 [4]. With a linear regression of the data, the average battery cell densities in Wh / kg could be estimated. It could be shown, that the installed battery cell weight was raised by 7.9% but in parallel the battery capacity was increased more than four times higher. The same technical trend could be seen on pack level. Based on a teardown analysis of 31 different BEVs from 2010 to 2020, the battery pack energy density increased from 80 Wh / kg above 150 Wh / kg in 2020 [5].

In addition, OEMs are improving the DC charging power. Current benchmark is the Porsche Taycan with a maximum charging power of 270 kW and a gross battery capacity of 93.4 kWh. This leads to a c-rate, as measure how a battery is charged in relation to its maximum gross capacity, of 2.9 [6]. For this new generation of high power charging (HPC) capable vehicles, infrastructure provider are currently installing several 350 kW charging points to realize reduced charging times with higher charging power. Leading European provider are for example Ioniity and the Dutch company Fastned. These initiatives on vehicle and infrastructure side are seeking to reduce the recharging time down to a fuel station tank stop of a conventional vehicle with combustion engine.

Target of this paper is to evaluate the influence of battery capacity and charging power by simulating six different long distance use cases. In addition, the Audi e-tron and VW ID.4 are analyzed as reference vehicles. Optimized combinations, which fulfill customer needs and cost expectations best, should be identified. In addition, the technical feasibility of the examined combinations will be checked. Pre-condition is the stepwise increase of fast charging infrastructure, which is a base for this evaluation. Nevertheless, the charging network performance as a critical point for customers is considered in the evaluation.

Determination of optimal combinations from customer perspective will follow the listed steps:

I. Identification and prioritization of customer criteria in the defined use case set up
II. Parameter setting for use case analysis
III. Determination of rational optimal combinations
IV. Determination of optimal combinations with prioritized customer criteria
V. Sensitivity analysis of selected parameters
VI. Implications for the battery system and technical feasibility

The use case analysis will focus on long distance e-mobility for BEVs in the middle-class segment. The defined set up targets on the private car usage, including holiday trips. The
commercial usage with company cars will have significant deviating requirements and are not in the scope of this analysis. Publications like the dissertation of Matthias Pfriem with an analysis of BEV real usage in commercial fleets to define a dedicated vehicle design can be used to understand these differing requirements [7].

3. Identification and prioritization of customer criteria

For the long-distance use case analysis potential customer criteria were selected via customer interviews, brainstorming and a meta-analysis of e-mobility studies about customer requirements. This longlist with potential customer criteria can be seen in the next figure 2.

![Fig. 2: Selection of customer criteria to determine combinations of battery capacity and charging speed](image)

To identify the relevant criteria for the use case analysis, it was determined if the selected criteria depends on the two decision variables battery capacity and charging power. If not, a more detailed examination can be dispensed with and the criteria is defined as constant for all use cases. The criteria of reliability and technological maturity as well as battery lifetime, availability of models and safety concerns are assumed to be constant and therefore independent. Effects on this through variation of the capacity and charging power are nevertheless conceivable. For example, a larger battery can be seen as greater safety risk in an accident. An innovative fast charging system with 350 kW must also be assumed to have a different technological maturity and reliability than a comparable established system. Under the premise that all systems have been developed and tested in accordance with applicable automotive standards, the differences are assumed to be negligible, and the correspondingly defined criteria are therefore simplified as independent.
After the identification of relevant criteria, their quantifiability must be checked. The vehicle cost with different battery and related charging systems are calculated with a vehicle base price and the Battery Performance and Cost (BatPaC) model software of the Argonne National Laboratory [8]. The batteries are calculated in three different sizes of 60, 90 and 120 kWh. Selected input parameters for all sizes are prismatic NMC 622 cells, an active battery thermal management and a calculated annual production capacity of 100,000 battery packs. The range as customer criteria results from the energy consumption and the battery capacity of the analyzed vehicle. The charging time is calculated with the charging power in kW, a state of charge (SOC) window from 10% as minimum and 80% as maximum, charging losses of 10% and a modelled charging curve in kW over SOC. The charging curve is needed to consider a derating from the peak DC charging power over time and state of charge. This derating effect and real charging curves were analyzed in the P3 automotive charging index in April 2021 and clarified the gap between the peak DC charging power and the average DC charging power over SOC [9].

The energy consumption in the first use case with a 60 kWh battery and 120 kW charging power is calculated with 17 kWh / 100 km derived as average WLTP consumption of 50 different BEVs on the market. The variation in battery capacity and consequently in battery weight is considered by a deterioration in energy consumption of 4% per 100 kg additional weight [10] [11]. The charging network performance is estimated by using the network density as well as the network capacity of the corresponding charging points along a selected reference route. The possible unavailability of charging points or possibly waiting times due to occupied charging points is also included.

The vehicle weight and related driving dynamics, the vehicle space and package as well as the material and CO₂ production footprint can be calculated for the six different use cases with various methods. But the calculation of effects on the real usage is sometimes very complex. For example, changes in the available interior space are influenced by the battery installation space and vehicle design. Modularized battery concepts in which the number of battery modules can be varied in one standard housing will not affect the available interior space. A quantitative assessment is therefore difficult here, too. Due to their complex calculation, for the customer these criteria are more a qualitative criterion and difficult to determine in a conjoint analysis.

For the prioritization of the defined customer criteria two different ways were considered. First the meta-analysis of various e-mobility studies as secondary data and in a second step an own customer survey.
For the meta-analysis, various publications about the acceptance of e-mobility from the last years were selected and summarized. Since all studies include a different set of customer criteria, only the relevant criteria vehicle price, range, charging time, energy consumption and charging network performance are selected and analyzed. This results in the mean values of 25% for vehicle price, 29% for range, 9% for charging time, 16% for energy consumption and 20% for charging network performance. In general, it should be assumed that the collected publications are analyzing E-mobility acceptance in general and not specifically aimed at the suitability of electric vehicles for long-distance journeys. It can be assumed that costumer requirements for vehicles on long distance journeys will be different compared to urban purposes. For example, a higher relevance of the charging speed can be assumed. Therefore, in this paper a dedicated conjoint analysis is done to verify the customer needs for long-distance e-mobility.

In the choice-based conjoint analysis, product alternatives described as stimuli are evaluated by the test persons. This is done with trade-off decisions by combining the characteristics of the selected attributes, which are summarized in figure 3.

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>350 km</td>
</tr>
<tr>
<td>Vehicle price</td>
<td>40,000 €</td>
</tr>
<tr>
<td>Charged range after 10 minutes</td>
<td>100 km</td>
</tr>
<tr>
<td>Distance of charging points along highway</td>
<td>90 km</td>
</tr>
<tr>
<td>Energy costs</td>
<td>4,5 € / 100 km</td>
</tr>
</tbody>
</table>

Fig. 3: Selection of attributes

For the first attribute range, three different characteristics values of 350 km / 500 km / 750 km are assigned. Based on the WLTP consumption of selected electric vehicles, average and weighted average values can be determined by considering the production volumes in 2020. The three values of 350 km, 500 km and 750 km are intended to meet future vehicle ranges.

For the minimum value, we used the current average WLTP range of electric vehicles as a reference. For 2025, we assume that this can be assumed to be the minimum future requirement. The maximum value was chosen so that it would not become a dominant characteristic for the respondent.

The average price of a mid-range BEV without a battery system can be estimated by comparing combustion and electric vehicles with similar features and sizes. Based on a
pairwise comparison of BEVs and corresponding combustion engine vehicles on the market, e.g. BMW i3s 120 Ah versus BMW 218d Active Tourer average prices for both vehicle types can be calculated. Charging times are queried using the chargeable range per 10 minutes of charging time, which is easier to understand for end customers. The two values of 100 km and 300 km are the result of calculations in which charging powers of 120 kW and 350 kW inclusive charging losses and dedicated charging curves are assumed. The energy consumption is not in kWh / 100 km, but instead given as energy costs in € / 100 km. In this way, a simpler comparison of the respondents with empirical knowledge from the use of combustion vehicles can be guaranteed. A kWh price of 0,30 € and the specific consumption values of average electric vehicles are used for the calculation. 4,50 € per 100 km corresponds to an efficient mid-range vehicle, on the other hand 6,90 € approximate the consumption values of the Audi e-tron [12][13]. Charging distances along the motorway are determined by taking a representative view of the reference route Munich-Hamburg. For this purpose, the average and maximum distances of all charging stations within a radius of 5 km along the route, each with 150 kW or with 350 kW charging points, were recorded.

The online tool 1000minds is used to conduct the survey consisting of a choice based conjoint analysis with trade-off decisions and additional questions [14]. The main argument for this provider was the possibility to use the PAPRIKA (as acronym for potentially all pairwise rankings of all possible alternatives) methodology and thus to minimize the number of pairwise comparisons for respondents. It was shown that the benefit determination by the trade-off comparison of only two characteristics and the successive elimination of dominated stimuli using the PAPRIKA method is possible with an average of 13 comparisons. Figure 4 shows an exemplary comparison for two vehicle configurations.

Fig. 4: Exemplary pairwise comparison of the used conjoint analysis

The additional questions in the survey are attached for better segmentation of the user groups. In addition to the age of the participants, it is also asked whether they already own a BEV and
if buying one as next vehicle would be considered. Further on, the available number of vehicles in the household for use is asked, how good the charging infrastructure along the highways is assessed, what additional price would still be acceptable when buying a BEV, what minimum range a BEV would need and how long break times are perceived as appropriate for long-distance journeys.

The survey was distributed globally in the MAHLE Intranet and some external channels to achieve a high number of participants. In the 16 days period in August 2021, 922 participants completed the survey, thereof 473 in Germany, 164 in China, 131 in Europe without Germany and 81 North America. Figure 5 contains the survey results of the conjoint analysis for the German participants. The two most important customer criteria are the vehicle price and the range with 25.6% and 24.7%, followed by the charging speed with 19.9%. The energy cost follow with 17.7% and the charging network performance is ranked on the fifth rank with 12.0%.

![Fig. 5: Conjoint analysis results for the prioritization of customer criteria (n=473)](image)

### 4. Parameter setting for use case analysis

The use case analysis is based on the 791 km long reference route from Munich to Hamburg to analyze optimal combinations of battery capacity and charging speed in battery electric vehicles. An average travel speed of a constant 120 kilometers per hour was also defined as the standard value. With the six use cases, consisting of a battery size of 60 / 90 and 120 kWh combined with a 120 kW and 350 kW charging system, an attempt is made to be able to compare several conceivable vehicle configurations in the future. The Volkswagen ID.4 and the Audi e-tron are also included in the evaluation to simplify the interpretation and comparability of the results. For each charging process, six minutes are considered for starting and stopping the charging process. For the Audi e-tron, the actual charging curve calculated by the ADAC is used and for the VW ID.4, due to the lack of corresponding measurement data, the one from the ID.3 is used [15][9]. For vehicles with 120 kW charging power, an approximately average charging curve for current vehicles is assumed, and for those with 350 kW charging power, an optimized one that is similar to that of the e-tron.
The BatPac model is used to determine the volumetric and gravimetric energy density as well as the OEM's costs per kWh at the battery pack level [8]. For the HPC cases, the model assumes higher copper requirements for the interconnection of cells and modules as well as different cell properties to meet the higher charging currents. Additional component costs are calculated with an estimated OEM surcharge margin of 50%.

5. Determination of rational optimal combinations

An Excel-based simulation tool was set up for the analysis and optimization of the long-distance-relevant parameters. This enables a comparison of six vehicle configurations with regards to total travel, idle and charging time as well as energy consumption along a selectable distance of 10 to 1,500 km. The aim here is to minimize travel time through the shortest possible downtime and a minimum of charging. For example, it is considered that the charging time of the last stop in each case should only last so long that the previously defined minimum SOC remains in the battery at the destination.
Input variables are the battery capacity, the energy consumption, the maximum charging power, the battery cost per kWh, the OEM surcharge, the gravimetric and volumetric energy density of the battery. In addition, the standard values are overwritable for the parameters charging losses, times for starting and ending the charging processes, SOC at the start of the journey, minimum SOC below which charging should take place, maximum SOC up to which charging with maximum charging power is possible, as well as charging curve progressions. Figure 7 shows a screenshot of the “Dashboard & Overview” worksheet with the central input and result fields of the use cases.

To determine the rationally optimal configuration, the driving time, stop time and vehicle cost are analyzed. By focusing on the total travel time, Figure 8 shows the clear superiority of all cases with 350 kW charging power compared to the other with 120 kW. Within the use cases with the same charging power, the slight advantage of larger battery capacities is evident. The 120 kWh / 350 kW case achieved the shortest overall travel time of 6 hours and 52 minutes. Despite a very different battery capacity and charging power of the Audi e-tron and VW ID.4 this results in an almost identical time of around 7 hours 30 minutes. This is due to the relatively poor vehicle efficiency of the Audi e-tron, which requires an additional charging stop despite
the larger capacity and better charging performance. Overall, there is a difference of 52 minutes between the shortest and longest travel times, which corresponds to approx. 13%.

When battery costs are also considered, the combination of a small battery capacity with a powerful charging system is beneficial from rational perspective. Figure 8 shows on the right for example, that the 60 kWh / 350 kW case is superior to the 90 kWh / 120 kW case in terms of additional cost on the x-axis and total travel time on the y-axis.

![Figure 8: Comparison of battery cost and total travel time](image)

6. Determination of optimal combinations with prioritized customer criteria

The consideration of irrational customer requirements could lead to different optimal use cases. To analyze this, the utility fulfillment from the customer’s point of view is determined with the weighted customer requirements of the already explained conjoint analysis in the third section above. For this purpose, a metric and a scale range are initially defined for each criterion. The respective best and worst characteristics of the conjoint analysis were used as scale boundaries.

The calculated average BEV price without energy storage is offset against the specific end customer prices of the respective battery per use case including current subsidies and compared with the average costs of a combustion vehicle. A 100% requirement fulfillment is given with price parity and 0% with a vehicle price of 60.000 €.

The scale for the charging time will be six minutes as minimum and 45 minutes as maximum. A parity with refueling stops for combustion vehicles, which according to a study last about six minutes, is interpreted as complete fulfillment of the requirements. Recommended break times of 15 minutes for every two hours of travel time of the German Green Cross leads to downtimes of 45 minutes for the route between Munich and Hamburg [16]. This recommendation was also asked in the long distance e-mobility survey in August 2021. The majority of 58% consider it
to be sufficient or even too short. Longer downtimes are therefore included with 0% degree of fulfillment.

To determine the charging network performance, three different sub-criteria are considered. The network capacity, the network density as average distance of charging stations and the waiting time in case of occupied charging stations. For the network capacity and density the charging infrastructure will be compared with the ICE fueling infrastructure and a parity will be ranked as best case. On the reference route between Munich and Hamburg 26 charging stations with 150 kW or less and 26 stations up to 350 kW are available, which lead to an average distance of 30.8 and 72.7 km. Assuming that the charging network in Germany will grow as required, a comparison with the filling station network is possible. This is assumed to be optimal along the reference route with the counted 92 gas stations and an average distance of 8.4 km. If very optimistic 12 fuel pumps per filling station and thus a very good network capacity is assumed, this results in a network capacity of 11,040 vehicles per hour along the entire route with 6 minutes of refueling time per vehicle. By comparing the registered combustion, hybrid and pure electric vehicles as well as the ratio of their average ranges a minimum needed capacities per use case can be calculated. The charging network along the reference route must therefore currently be assessed as very good.

However, since the perceived charging network performance is more relevant for a purchase decision in addition to the actual capacity, an assessment of the highway charging infrastructure was also included as additional question in the survey and was ranked from a majority as insufficient and improvable and show the need for further investments in charging infrastructure. The actual number of charging points was therefore decreased by the factor of 4 to simulate the perceived charging network. Defect or blocked charging stations are also considered in the charging network performance. For this, the number of tolerable vehicles within the recommended break times is considered.

**Requirement fulfillment**

The scales and metrics for the selected customer criteria combined with the weighting factors, result in the following use case fulfillment of the requirements.
The 350 kW charging use cases number two, four and six can achieve significant higher fulfillment degrees compared to the 120 kW cases. In addition, use case two with a degree of 47% dominates use case three with 45%, also use case four dominates use case five. Overall, it can be seen that the increase of charging power should be prioritized in comparison with a higher battery capacity. The advantages of the longer range are more than offset by the negative effects of higher vehicle prices, weights and a worse material and CO₂ production footprint.

The three cases with the increased charging power each achieve five to nine percentage points (p) better fulfillment of requirements, despite poorer energy densities and costs than comparable vehicles with 120 kW charging power. Overall, the increase in capacity does not represent significant benefits from the customer's point of view. The reference vehicle VW ID.4 achieves a comparably good rating, which is also parameterized in a correspondingly similar manner. The very negative rating of the Audi e-tron is surprising, which is mainly due to the poor vehicle efficiency and the heavy battery. However, the different vehicle segments must be considered when interpreting them.

7. Sensitivity analysis of selected parameters

Starting from use case 3, which represents the base vehicle, the effects of all input variables as well as further values, assumed to be relevant, are investigated via a sensitivity analysis. These are the battery capacity, the energy consumption, the nominal charging power and the effective charging power, which is influenced by the shape of the charging curves, the idle times for starting and stopping the charging process, the charging losses, gravimetric and volumetric energy density, the costs per kWh as well as the margins of the OEMs. These are varied by +10% and -10%, respectively, and their effects on travel time and on overall
fulfillment are evaluated. Furthermore, all customer requirement weightings are also varied individually. The boundaries of the applied scales are also analyzed with respect to their influence on the overall fulfillment levels as well as their effects on different use cases. Figure 10 visualizes the key findings.

Fig. 10: Results of the sensitivity analysis

The results show the strong influence of vehicle efficiency on the total travel time. Nominal charging power and the shape of the charging curve also have a significant impact. By increasing the battery capacity, small positive effects can also be achieved. As expected, idle times are included directly in the travel time calculation. Small effects can be seen when the gravimetric energy density varies. No significant influence on travel time can be identified for any of the other variables considered.

When focusing on the degree of fulfillment, the variation of energy consumption shows strong effects in the expected direction. An increase in battery capacity leads to an improvement of 3.4 percentage points. Gravimetric energy density, which impacts vehicle weight and energy consumption, also shows slight effects. Increases or reductions of costs per kWh affect the degree of fulfillment in the expected direction and extent. Changes of the nominal charging power or the charging curve also result in slight changes. The influence of all other variables on the degree of fulfillment, including the weighting factors, is negligible or non-existent.

8. Implications for the battery system and technical feasibility

Summarized, the use case analysis in this paper provided the evidence, that on the chosen reference trip distance of 800 km between Munich and Hamburg, the HPC 350 kW use cases
are superior compared to the 120 kW charging cases. The results show, on one hand, that higher battery capacities can decrease the total travel time and improve the customer requirement fulfillment. On the other hand, the charging speed is essential to improve the total travel time from rational perspective, but also to improve the customer requirement fulfillment. For example, the analysis could prove that the second use case with 60 kWh / 350 kW is dominant from rational perspective but also in the customer requirement fulfillment compared to the third 90 kWh / 120 kW use case. In addition, a strong influence of vehicle efficiency could be shown in the sensitivity analysis.

To achieve a cost parity of BEVs to vehicles with combustion engine in the mid of this decade, a high focus on the battery cost is needed. Improvements in battery cell and pack technology are an enabler for higher battery capacities. But in parallel the increase of charging speed is crucial for the long distance use case and lower vehicle costs. This relationship is understood, and many OEMs launch new electric vehicle platforms with 800V board net voltage to be ready for high power charging. For example, the latest announcement of Stellantis to launch an 800V electric drive module, which will be installed in their new STLA Medium, STLA Large and STLA Frame vehicle platforms [17]. The importance of high power charging was also emphasized by Markus Schäfer, Member of the Board of Management of Daimler AG. Group Research and Mercedes-Benz Cars Chief Operating Officer. For 2030 the aim of Daimler is to recharge 80% of the battery in six minutes, which is comparable to the conventional refueling stop of a combustion engine vehicle [18]. Michael Steiner, Member of the Executive Board of Porsche AG Research and Development stated that from sustainable aspects, a fight for the longest range should not be the goal. Most daily distances are on short routes and for long distance very fast charging and a sufficient charging infrastructure is more important [19].

To enable improved battery lifetime and high power charging, which led in combination with smaller battery capacities to high c-rates, new battery thermal management concepts moving into focus. Coming from state-of-the-art technologies like refrigerant or coolant cooled battery cooling plates, new technologies such as immersion cooling, which refers to the application of a dielectric fluid in direct contact with all cells and electrical connectors, are coming into focus. Immersion cooling is considered as the enabler of high performant, very effective and uniform thermal management. Further benefits are a longer battery lifetime and enhanced safety aspects. MAHLE developed tailored solutions for all three common cell formats (pouch, prismatic and cylindrical) as part of a modular base kit. In the next figure 11, a cooling concept comparison for a prismatic hardcase cell is shown. In the comparison of a bottom cooling,
double sided cooling and immersion cooling concept, the significant improvement of the cooling performance can be seen.

For the management of the dielectric fluid, a liquid management module will be needed. This module mainly consists of a heat exchanger, chiller, fluid filter and electric pump and guarantees an optimized internal flow for low pressure loss. With the reduction of fluid connectors and hoses and a high modularity, competitive system costs can be achieved. The implementation of immersion cooling on electric vehicles requires a full system approach, starting from the battery system and the fluid management which needs to be embedded in the vehicle thermal management, compare figure 12. Dedicated equipment for the filling of the circuit in series production and for service complements the full system approach for future hybrid and battery electric vehicles.

![Fig. 11: Comparison of cooling concepts HPC350 charging – Prismatic Hardcase Cell [MAHLE]](image1)

![Fig. 12: Battery Immersion cooling as full system approach [MAHLE]](image2)
References


