Holistic Battery Pack Design

Dr.-Ing. Claude **Bouvy**
Forschungsgesellschaft Kraftfahrwesen mbH Aachen, Germany

Dipl.-Ing. Sven **Ginsberg**, Dipl.-Ing. Peter **Jeck**, Dipl.-Ing. Bastian **Hartmann**,
Dipl.-Ing. Sidney **Baltzer**, Prof. Dr.-Ing. Lutz **Eckstein**
Institut für Kraftfahrzeuge, RWTH Aachen University, Germany

Summary

A new methodical approach to develop battery packs for mobile applications is presented. Due to the numerous interactions and resulting conflicts a sequential development process is not advisable for battery packs. That is why a holistic, integrated development process, based on dynamic simulations is pursued. The benefits of such a holistic approach are exemplarily shown in two applications: the development of a new alternative battery design concept and on the functional level the use of the battery as a thermal storage.

1 Introduction

It is well known, that the traction battery is one of the key components for future electrified vehicle concepts. Due to the small energy densities of today's battery technologies compared to fuels, the vehicle's mass and thus, the overall power demand at the wheels is influenced. A second effect of the small energy densities is the resulting volume and consequently the packaging and the integration in the vehicle. Furthermore, today's traction batteries are rather sensible components. On the one hand the crash safety has to be guaranteed by either housing the battery in a rigid and in general heavy structure or by a design allowing controllable shock absorption. On the other hand the operational cell temperatures have to be guaranteed at every time. A lower temperature level, e.g. 0°C, is critical for charging and limits the recuperation potential of the vehicle's kinetic energy. Exceeding an upper temperature limit, e.g. 40°C, influences the lifetime and hence the total costs of the battery pack.

These examples show that not only the coupling on the electric level, but the thermal, fluidic and mechanical integration of the battery into the vehicle is essential. Furthermore, the logical level has to be taken into consideration. On this level a given design will set boundary conditions for realisable functionalities and the linked management systems (e.g. battery management system, thermal management system and overall energy manager).

Due to these numerous interactions and resulting conflicts a sequential development process, i.e. first electric energy, then heating/cooling and last the physical design, of battery packs is not advisable. That is why a holistic, integrated development process, based on dynamic simulations is pursued at the Forschungsgesellschaft Kraftfahrwesen mbH Aachen (fka) and the Institute for Automotive Engineering of RWTH Aachen University (ika). This approach leads to the development cycle shown in Fig. 1, which allows an a priori analysis of the physical behaviour of the battery pack itself and the linked components. Thus, the parallel development of the software algorithms and operational strategies for functional implementation is possible. This approach results in saving time in the development process and consequently reducing the costs. Furthermore, the holistic approach (i.e. taking into consideration all energetic flows, control logics and the physical design) leads to battery packs that are best adapted to the overall system and the target functionalities, thus improving efficiency, range and costs. The results from laboratory tests are finally used to validate and to improve the various models.

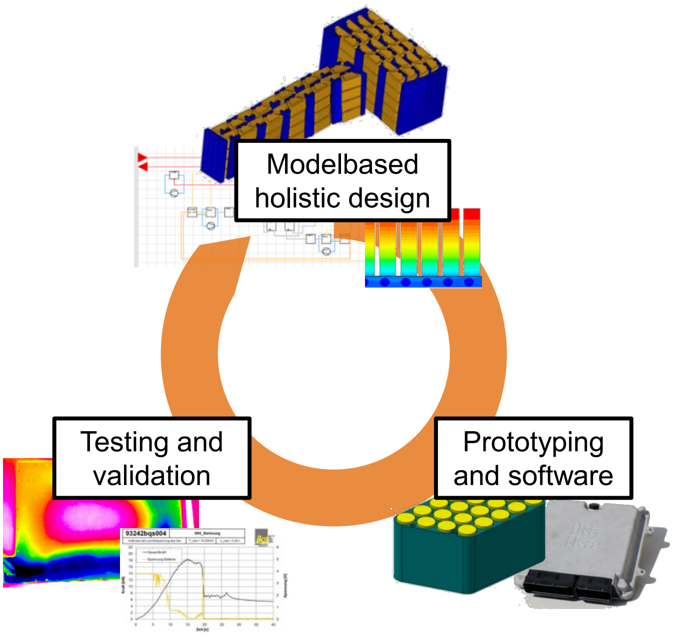

Fig. 1: Battery development cycle

2 Methodical approach

In this section the fundamental conflicts of the battery design process are identified and the influence parameters are deduced. Furthermore, it will be discussed how the chosen methodology solves the design conflicts and supports the engineers in the development process.

2.1 Physical interactions and influence parameters

The development of battery packs may be interpreted in the area of conflict between three criteria: overall efficiency, safety and functionality (cf. Fig. 2). The main function of a battery is to store electric energy. Depending on how well the conflicts between these criteria can be solved, the overall costs of the battery pack and all related components will result.

As shown in Fig. 2 the design criteria define three main conflict areas: a mechanical, a thermal and a system design conflict. The aim of the introduced methodology is to support the design engineer in finding an overall optimum for defined operational conditions.

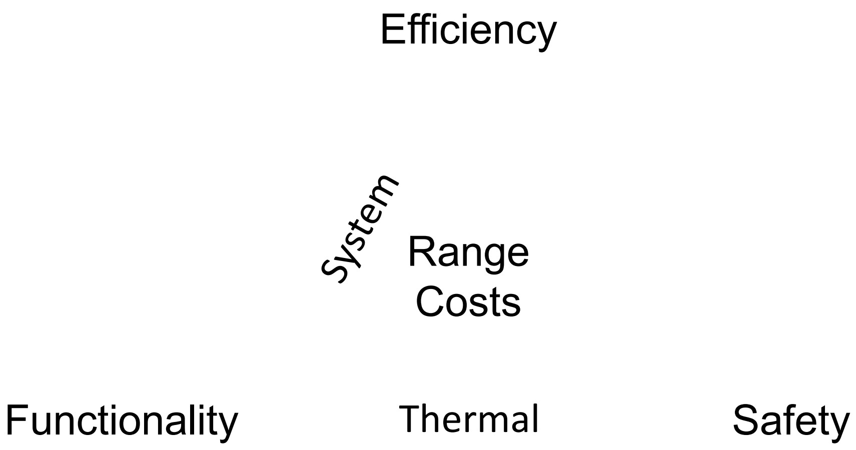

Fig. 2: Conflicts in the design process of battery packs

2.1.1 Mechanical conflict

The conflict between safety (i.e. crash-safety) and efficiency is a mechanical one. On the one hand the traction battery may be encased in a rigid protection structure. Such a frame structure, which may be integrated in the vehicle's architecture, will protect the traction battery during a crash. Such a solution was realised at the ika for an electric city bus within the research project Smart Wheels (cf. e.g. [1] and [2]). However, such housing structures will increase the weight of the vehicle and thus, increase the power demand at the wheels. As a consequence the battery's capacity and thus, the costs are increased and the overall efficiency will drop.

On the other hand more innovative designs are possible. Eckstein et al. (cf. e.g. [3]) developed a new battery pack concept within the research project “e performance” (cf e.g. [4]) in close cooperation with the Institute for Power Electronics and Electrical Drives (ISEA) of RWTH Aachen University. The idea behind this concept is to avoid rigid and rather heavy battery housings by making the entire battery system deformable, when a certain impact force is applied. This approach saves weight and provides more deformation space for energy absorption. Due to a special shape of the so-called macrocells, the energy is deployed in several directions and gets absorbed by deformation elements (cf. also section 3.1), whereas the macrocell itself is rigid due to foam filling. Due to the weight reduction of this integrated design, the power demand at the wheels is reduced compared to a heavy housing. However, due to a clearly increased complexity of this conceptual design, the manufacturing costs may at first increase, until such an approach is used in order to build up a large variety of battery packs always using the same macrocells.

A global statement, which approach is the best, cannot be given yet, as it depends on different specifications. A lightweight approach is most likely better fitted to battery electric vehicles (BEV), as the battery's capacity is larger and thus the weight saving potential is bigger. In contrast the housing approach may be interesting for vehicle architectures with a small traction battery, e.g. mild hybrids. Thus, a detailed, ab initio analysis, within the defined vehicle specifications and operational conditions, to determine the optimal design at least costs is necessary.

2.1.2 Thermal conflict

Besides the battery's mass, the thermal behaviour (e.g. thermal capacity and heat exchange) and consequently, the cooling and heating concept are of essence. It mainly defines the conflict between functionality and safety. In general there are three possibilities to cool down and heat up a traction battery: by air, by liquid or by a phase change material (PCM, e.g. refrigerant).

On the thermal side, safety may be interpreted as battery lifetime safety (i.e. directly costs) and crash safety. As stated above the thermal limits of today's traction batteries are critical and thus, the cooling/heating architecture has a direct impact. A cooling heating by evaporation/condensation of a refrigerant (e.g. in Mercedes Benz S400 hybrid, cf. [5]) makes a quasi isothermal heat transfer possible, and thus thermal stress is minimised. However, such systems are complex in development (especially to guarantee a homogenous phase change) and consequently, are comparatively expensive. The advantage on the functionality level is the possibility of a direct coupling to a heat pump system for cabin heating in winter scenarios. Of course such systems will positively influence the overall efficiency (cf. e.g. [6]). However, after a crash such a refrigerant system complicates the cooling of a damaged battery to avoid the thermal runaway. Furthermore, the behaviour of direct contact of the new refrigerant HFO-1234yf with a damaged battery cell was not yet investigated and may lead to critical safety problems.

A liquid cooling/heating approach has the advantage on the functional side that the compressor may be bypassed by rejecting heat to ambient via the front-end heat exchanger. Also, a direct electric heating via a high voltage PTC is made possible this way. A liquid cooling/heating system will result in a temperature gradient along the cooling system and thus, will increase the thermal stress in the battery pack, compared to the quasi-isothermal refrigerant approach. Furthermore, it has to be guaranteed that in crash scenarios no liquid gets in contact with the cells, to avoid short circuits, which could lead to or worsen thermal runaways.

An air cooling system will reduce the possible functionalities, as e.g. waste heat recovery is hardly possible. Also, the controllability of the battery's cells temperature decreases and thus, the thermal damaging risk is increased. However, such systems are cost effective and reduce the overall weight and thus again have an influence on the overall efficiency (cf. e.g. [7]).

2.1.3 System design conflict

The system level defines the conflictual area between functionality and efficiency. Of course, this level is directly influenced by the cooling/heating design. System designs allowing a high functionality, e.g. heat recovery from the different cooling circuits, clearly increase the complexity and in general the number of components and thus, the costs. Furthermore, the energy demand for secondary consumers, e.g. pumps and valves, will increase during operation and will decrease the overall efficiency. However, the increased functionality will in general reduce the overall amount of waste heat and thus improve the overall efficiency. It is clear, that no generalised statement can be given and that a detailed analysis is essential. Again, an optimal solution will be dependent on the vehicle and component specification and on the operational scenarios.

On this level the operational efficiency of the battery pack's cells (depending on cell type and management algorithms) is coupled to peripheral equipment, e.g. front end heat exchanger or circulation pump. In order to avoid an oversizing of the coupled systems a detailed layout under realistic user scenarios is again advisable to reduce costs and weight.

2.2 Holistic and model based design approach

The design conflicts discussed above make a detailed ab initio analysis and layout recommendable. The methodology at fka and ika unites four computer based tools for this purpose (cf. Fig. 3). The integration into an overall system and the influence on efficiency and functionality is analysed with an 1 D energetic simulation platform. The cooling/heating concept and the resulting parameters (e.g. heat transfer coefficients) of a geometrical design are determined by means of computational fluid dynamics (CFD). The resulting parameters are used to fit the 1 D energetic models. For the structural analysis and thus, the crash behaviour finite element method (FEM) tools are used. Again, the resulting parameters (e.g. mass) are transferred to the 1 D energetic simulation platform. All construction data base on computer-aided design (CAD) tools. As CFD and FEM simulations are state of the art a detailed description is not given in this paper. The 1 D energetic approach will be introduced shortly. A more detailed description can be found for example in [8].

The 1 D energetic simulations are based on a holistic model library taking into consideration all energetic (mechanical, electrical, thermal and chemical) and logical (sensors, actors and control units) flows including dynamic boundary conditions (e.g. driving cycles, ambient conditions) of automotive concerns. It follows a layer based level approach comprising four levels. At the lowest level (base level) generalized elements are implemented which can easily be adapted due to the object oriented modelling property of inheritance or instantiation. The second level, the components level, combines a variable number of base elements to generate models to a chosen level of design. At the system level (third level) the interactions of energy and signal flow between all components are implemented.

The top level, i.e. the vehicle level, combines all vehicle sub models such as the power train, the respective cooling circuits, the power supply and the passenger cabin. Beside the global boundary conditions, such as the driving cycle, the route profile, ambient conditions or initial conditions a control block which consists of the driver and the ECU manages all concerns of control.

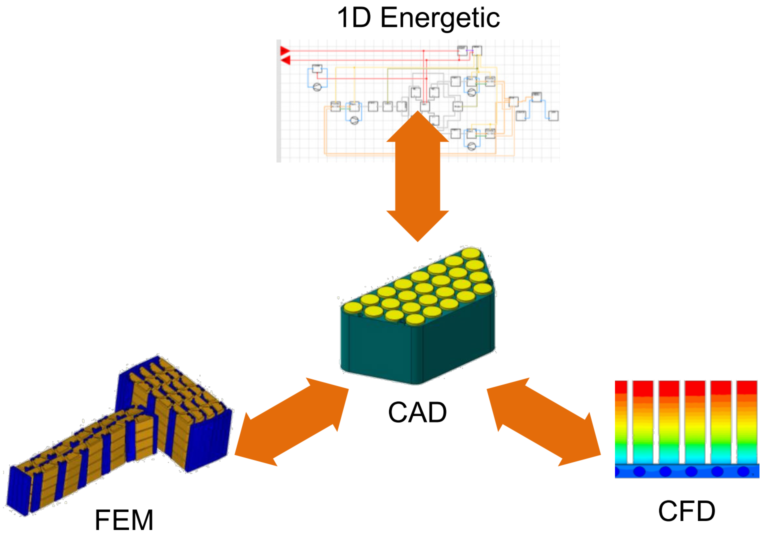

Fig. 3: Computer tools for a holistic battery pack design

This approach allows, beside the determination of the influence of relevant structural design parameters (e.g. heat transfer from CFD, mass from FEM), a first layout of the operational layout, i.e. the management algorithms (cf. Fig. 1) under quasi realistic conditions. Thus a first software development is possible in parallel to the prototyping.

3 Exemplary application of the methodology

3.1 Alternative battery pack design

Within the research project “e performance” a new battery pack approach was developed at the ika (cf. e.g. [4]). The development of this innovative concept was based on the methodology presented in this paper. A more detailed description is found in Eckstein et al. (cf. [3]).

The basic idea behind the presented battery principle, with regard to the mechanical design, is the use of the battery pack as a deformable member which can absorb deformation energy in a crash. It exploits the fact that with the used 18650 cells, geometrically very small battery cells were selected for the project. If a certain quantity of these cells is combined as a mechanical unit, its design can be selected relatively freely. The concept of macrocells is therefore the smallest and rigid unit in the deformable battery pack. It should be noted that the concept was worked out for 18650 cells due to project constraints, but an implementation is possible with other cell types. It is only important that a trapezoidal unit is created, cf. Fig. 4.

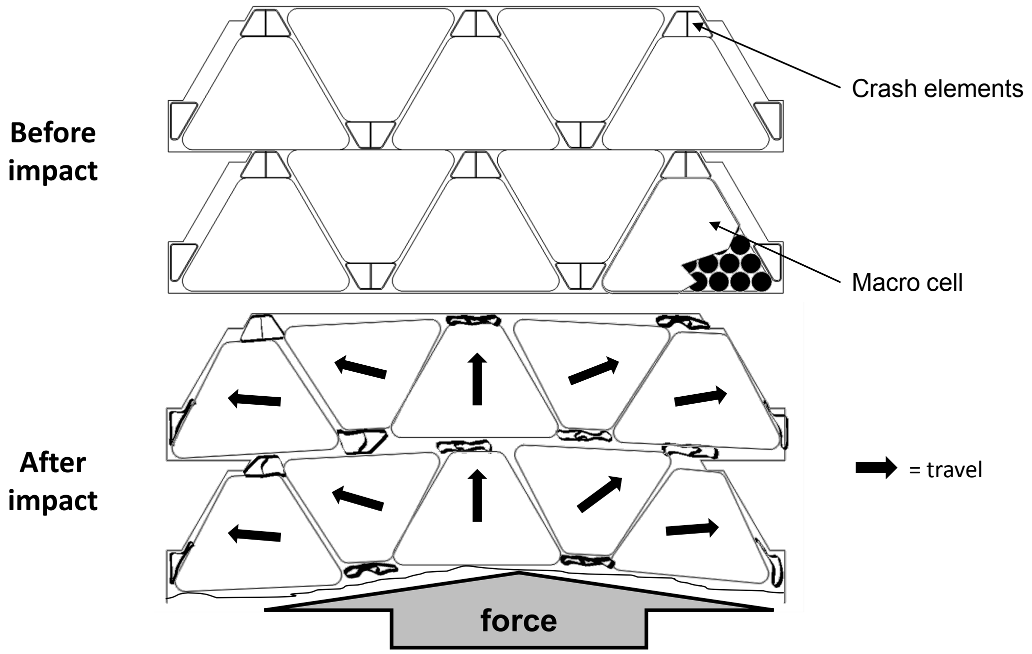

Fig. 4: Principle of the crash deformable battery pack design (cf. [3])

This trapezoidal shape ensures the transmission and distribution of occurring deformation forces by shifting the non-deformable macrocells into different directions. The energy is absorbed in deformation elements between the macrocells. These elements are made of aluminium profiles with a given wall thickness for this application example. For larger production numbers they can be made for example from extrusion profiles. The profiles could also perform other functions and serve as channels for example as ducts for the cooling fluid or for degassing and ventilation of the cells. Advantages of such an approach, in addition to the primary weight savings by the elimination of a rigid housing, are savings to the body structure, as adjacent load paths must be designed less massive. By the deflection of the forces in other directions in areas with relatively small deformation zones (e.g. vehicle tunnel in the side impact), sufficient energy may be absorbed and the acceleration of the occupant is reduced.

Besides the mechanical crash tests of the battery pack under realistic scenarios, the development of the cooling ducts were supported by CFD simulations. This methodology enables an ab initio evaluation of heat transfer coefficients, temperature gradients on the cooling plate and pressure losses for defined conditions. These results and electric performance tests were used to fit the parameterised 1 D models and consequently, to test the different development generations of battery packs in the vehicle’s environment under realistic boundary conditions (e.g. drive cycle and ambient conditions).

Besides the “e performance”-demonstrator, the new pack design is used in the concept SpeedE, a cooperation between the ika and the Transportation Design Department of Hochschule Pforzheim. The integration of the battery pack is shown in Fig. 5.

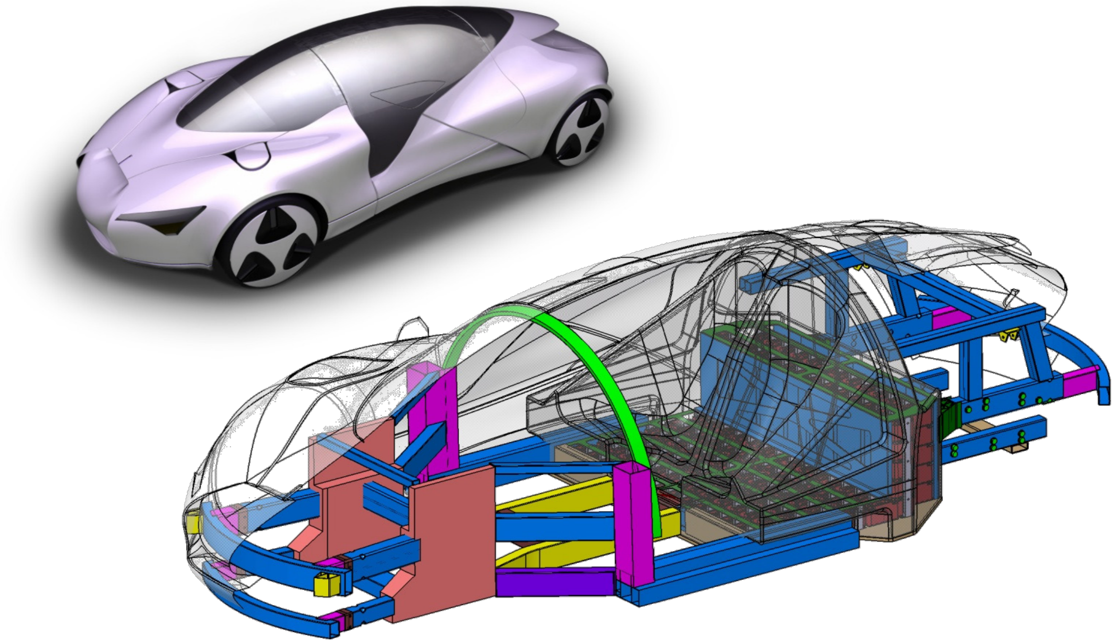

Fig. 5: Battery pack integration in the concept SpeedE (cf. [9])

3.2 Functional design: the battery as thermal storage

Due to the discontinuous availability and the low temperature level of waste heat in electric vehicles, thermal storage systems are an interesting technology for efficient future car architectures. Besides additional units, as for example sensible, latent or adsorption heat storages, the use of the traction battery for this purpose may be interesting, as additional weight, volume and costs may be avoided. This is a new functionality of the battery and implies a fluidic cooling/heating system. In this example the efficiency improvement potential and the influence on the system design and control algorithms are discussed. A more detailed analysis is found in Bouvy et al. (cf. [10]).

In this exemplary application of the methodology two different architectures are considered. Both layouts have a 44 kW range extender unit, a 80 kW ASM electric engine and a lithium-ion-battery with a nominal capacity of 8.6 kWh.

3.2.1 SOC controlled range extender without heat pump

The first architecture represents the state of the art of a BEV with a range extender unit (cf. Fig. 6). The internal combustion engine is SOC controlled: it starts when the battery charge state falls below 20% and is turned off at a SOC value of 30%. The available waste heat from the range extender's cooling circuit (taking into consideration thermal masses and the thermostatic valve) is used for cabin heating. The remaining demand is covered by a high voltage air heater in the HVAC, with a maximal heating power of 5 kW.

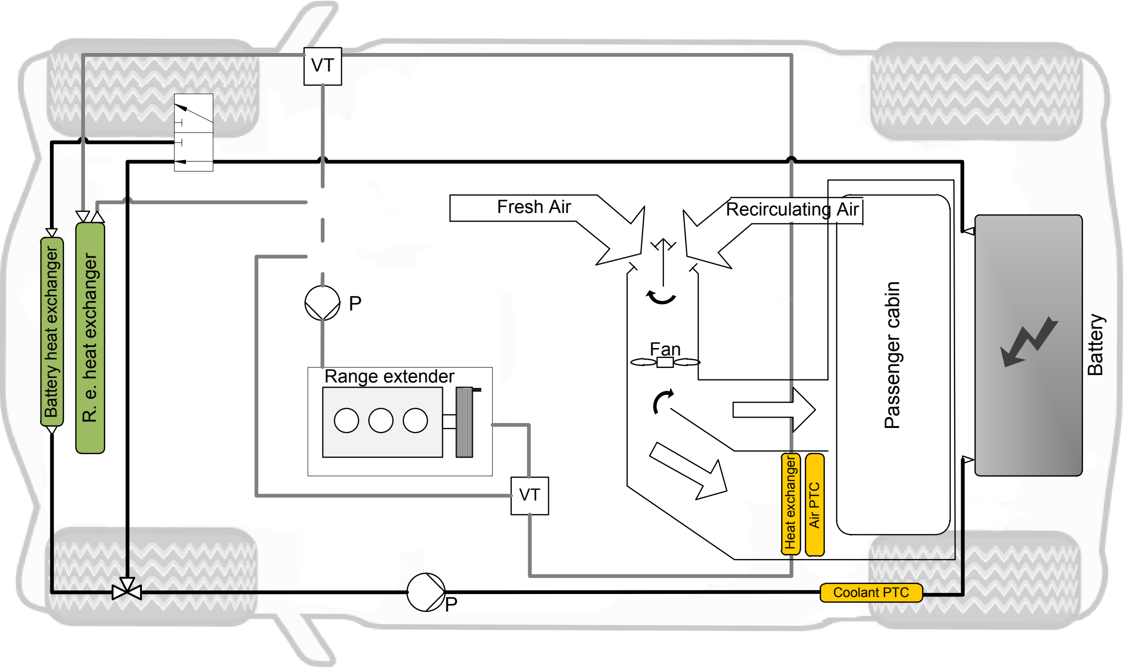

Fig. 6: Reference architecture

3.2.2 Thermally controlled range extender with heat pump

For the second architecture, c.f. Fig. 7, a heat pump system is considered, using the battery circuit as heat source. Additionally, the internal cooling circuit of the combustion engine is connected to the battery circuit by a liquid/liquid heat exchanger. This allows a thermal charging of the battery with waste heat of the range extender unit. For this architecture a different control approach is pursued. The internal combustion engine is thermally controlled, with the goal to keep the cell temperatures within an optimal range between 20°C and 30°C. While operating the range extender excessive heat is used both for heating the passenger cabin and for charging the battery thermally. If the internal combustion engine is switched off, the electric heat pump covers the heating demand of the cabin using the rather high and constant temperature level in the battery´s cooling circuit as heat source. This operation guarantees high COPs of the heat pump system, but on the other hand an excessive cool down of the battery needs to be prevented by the control unit. In both cases the thermal peak loads are covered by an electric high voltage heater (5 kW).

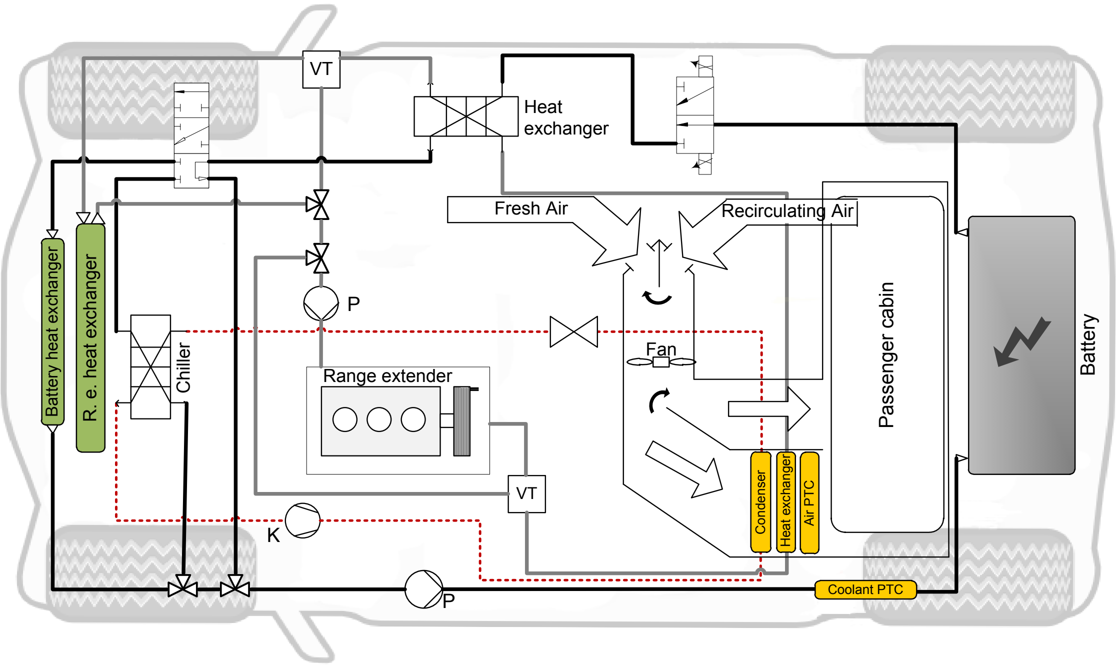

Fig. 7: Enhanced architecture

3.2.3 Boundary conditions and operational strategies

All simulations are performed for a Central European winter scenario with an ambient temperature of 0°C and solar radiation values according to Strupp et al. (c.f. [11]). At *t*=0 s all masses are in thermal equilibrium (starting temperature 0°C). Before the simulated ride (five consecutive NEDCs) the traction battery of the vehicle is thermally conditioned, to allow regenerative braking immediately at the beginning of the drive cycle. For all variants the preheating of the battery is performed with an externally supplied electric high voltage heater (P_{max} = 5 kW). It is assumed, that this thermal conditioning takes place in a garage and consequently, no heating up of the vehicle due to solar radiation occurs.

For the analysis three different variants are defined. The first variant considers a BEV with a SOC controlled range extender (architecture 1) and the battery is thermally conditioned until a minimal cell temperature of 5°C is reached. For this variant the battery is electrically charged at the beginning (SOC = 90%) and the internal combustion engine will be operated in the “Charge Sustaining – Mode”. For this purpose an operation point at the lowest specific fuel consumption of the internal combustion engine, i.e. with a constant mechanical output power of 19 kW is chosen to charge the battery and deactivate the range extender as soon as possible (state of the art operation of a range extender).

The second and the third variants are both based on vehicle architecture 2, using the thermal masses of the traction battery as a heat storage system. They only differ from each other in the starting conditions.

Similar to variant 1, the traction battery is preconditioned to a minimal cell temperature of 5 °C for variant 2. Thus, for this approach, the internal combustion engine will start at the beginning of the driving cycle. Consequently, the starting SOC has to be reduced for this variant to 75 % to enable electrical charging from the beginning.

In the third variant the traction battery is preheated to a higher temperature of 30°C before the first drive cycle. Due to the higher temperature, the stored thermal energy may immediately be used for cabin heating by means of the heat pump system. As for this approach the range extender will not be operated in the beginning of the first NEDC, a SOC of 90% was chosen in analogy to variant one.

For the two variants based on architecture 2, the operation point of the range extender is reduced to 10 kW, in order to better fit the power to heat ratio to the demand (c.f. [6]). It is to note, that the internal combustion engine is not longer operated in the point of lowest specific fuel consumption, but the benefit of cogeneration is maximised.

3.2.4 Results

Fig. 8 shows the time dependent SOCs for the three scenarios. Due to the use of the battery as a thermal storage a higher SOC is reached at the end of the driving cycle thus, allowing a higher flexibility to the customer.

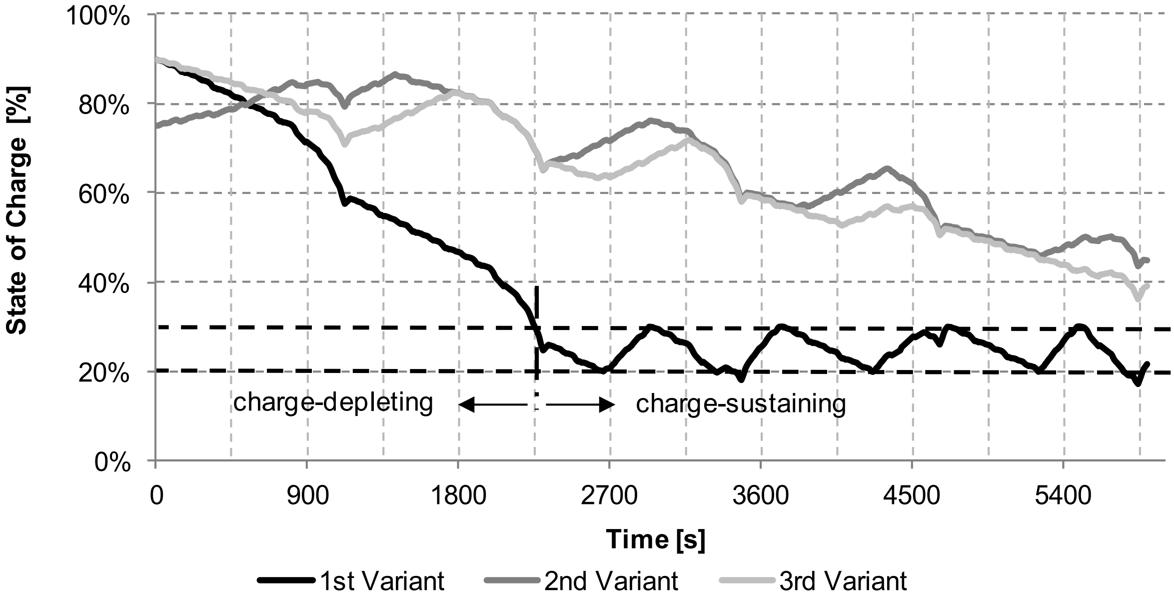

Fig. 8: Time dependent SOC for the three scenarios

The primary energy demand for the three scenarios is shown in Fig. 9.

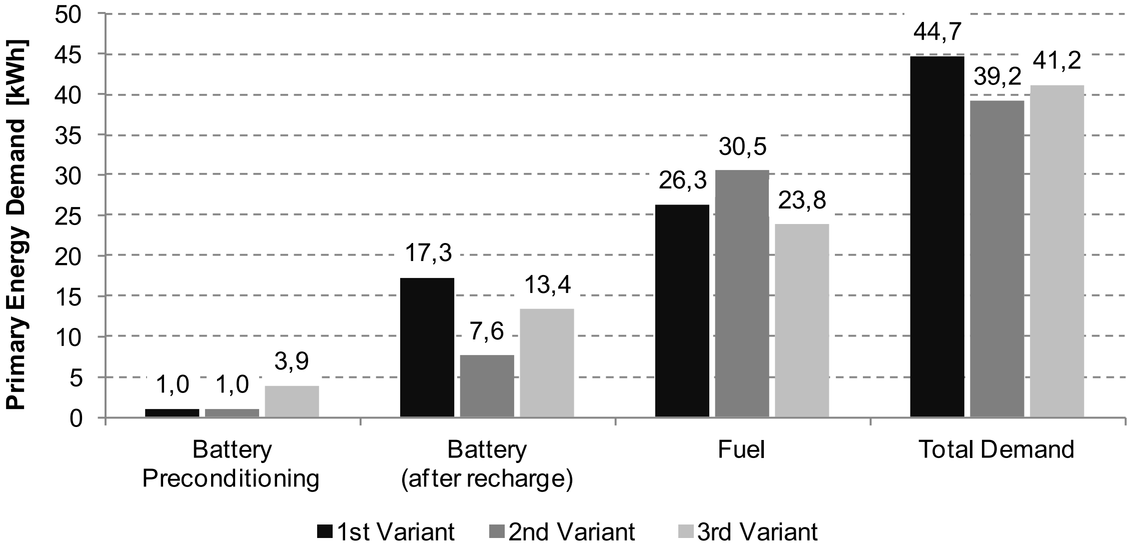

Fig. 9: Primary energy demand

Fig. 9 shows, that the overall efficiency of BEV with a range extender can be considerably improved by operating the internal combustion engine according to the thermal demand and using its waste heat on the one hand directly for cabin heating and on the other hand indirectly via a thermal storage. The traction battery, with its high thermal mass, is advisable as heat storage system, to avoid costs, volume and weight. A further advantage of such an approach is that the traction battery will mostly be operated in an optimal temperature range and thus, best charge/discharge efficiencies and lifetimes are reached if the range is wisely chosen. However, the influence of this control strategy on the battery's lifetime has to be investigated on an experimental level.

Due to the battery's temperature restrictions, the temperature level of the stored heat is rather low. Therefore, a heat pump system is optimal for cabin heating. As such an operation mode will cool down the battery rather quickly the range extender should be thermally driven to guarantee a battery temperature within a defined range.

For the considered winter scenario a reduction of primary energy of more than 11.5 % was calculated, which clearly shows the potential benefit of a cogeneration approach in combination with a heat pump and a thermal storage systems.

4 Conclusions

The two exemplary applications of the new, holisitc methodology for battery pack design show that a test of early concepts in a vehicle environment under realistic user scenarios is possible. Due to this approach a first evaluation of a given design is possible, illustrating advantages and disadvantages. Furthermore, this approach avoids an excessive over-dimensioning of connected system components and thus helps in finding efficient vehicle designs.

5 Acknowledgments

The authors would like to thank the German Federal Ministry of Economics and Technology (BMWi) for the funding of the research project Smart Wheels. The works within the project e performance were kindly financed by the German Federal Ministry of Education and Research (BMBF).

6 References

[1] BIERMANN, J.-W.; ECKSTEIN, L.; GEULEN, G.; HOMANN, J.; SAUER, D.-U.; LUNZ, B.; ROTHGANG, S.; MARTIN, C.; LARESGOITI, I.
Electric City Bus “Smart Wheels” – A Concept for Electric Mobility in Public Transportation.
26th Electric Vehicles Symposium
Los Angeles, 2012

[2] GEULEN, G.; ECKSTEIN, L.; ROTHGANG, S.; SAUER, D.-U.
Elektro-Minibus für den ÖPNV-Einsatz mit Schnellladefunktion
ATZ elektronik, 04/12
Wiesbaden, 2012

[3] ECKSTEIN, L.; GINSBERG, S.; HARTMANN, B.; FUNCKE, M.; JECK, P.
Development, design and build-up of a crash-deformable battery pack for electric vehicles.
8. VDI-Tagung „Fahrzeugsicherheit - Fokus Elektromobilität“
Berlin, 2011

[4] ALLMANN, C.; GINSBERG, S.; SCHÜSSLER, M.; HARTMANN, B.
Research project “e performance” – Design approach for a holistic BEV.
26th Electric Vehicles Symposium
Los Angeles, 2012

[5] LAMM, A.; WARTHMANN, W.; SOCZKA-GUTH, T.; KAUFMANN, R.; SPIER, B.; FRIEBE, P.; STUIS, H.; MOHRDIEK, C.
Lithium-Ionen-Batterie Erster Serieneinsatz im S 400 Hybrid.
ATZ 07-08/09
Wiesbaden, 2009

[6] BOUVY, C.; JECK, P.; LICHIUS, T.
On the influence of cabin heating on the overall efficiency of car concepts.
20th Aachen Colloquium Automobile and Engine Technology
Aachen, 2011

[7] ECKSTEIN, L.; GÖBBELS, R.; WOHLECKER, R.
Benchmarking of the Electric Vehicle Mitsubishi i-MiEV.
ATZ 12/11
Wiesbaden, 2011

[8] BOUVY, C.; BALTZER, S.; JECK, P.; LICHIUS, T.; GISSING, J.; ECKSTEIN, L.
Holistic vehicle simulation using Modelica – An application on thermal management and operation strategy for electrified vehicles.
9th International Modelica Conference 2012
Munich, 2012

[9] URBAN, P.; FAßBENDER, S.; FUNCKE, M.; GINSBERG, S.; HÖREN, B.; ECKSTEIN, L.
SpeedE - neue Ansätze bei der Karosseriegestaltung eines Elektro-Sportwagens.
Strategien des Karosseriebaus 2012
Bad Nauheim, 2012

[10] BOUVY, C.; JECK, P.; LICHIUS, T.; BALTZER, S.; GISSING, J.; ECKSTEIN, L.
The battery as thermal storage in range extender vehicles: Influence on the architecture and the operating strategy.
Hybrid and Electric Drivetrains 2012
Aachen, 2012

[11] STRUPP, N.C.; LEMKE, N.
Klimatische Daten und Pkw-Nutzung: Klimadaten und Nutzungsverhalten zu Auslegung, Versuch und Simulation an Kraftfahrzeug-Kälte-/Heizanlagen in Europa, USA, China und Indien
Frankfurt am Main, 2009