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Framework and Classification of Battery System Architectures

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Abstract: In this paper, battery system architectures are methodologically derived in order to find the key type differences. In a first step, the system levels are identified and distinguished. In order to be able to completely cover the solution space of battery system architectures, a distinction is also made between mono- and multifunctional materials. Based on the system levels, a framework for possible architectures is derived. Four system architecture generations with a total of eight different types are identified and analyzed in the dimensions "Nomenclature", "Approach", "Omitted Components" and "Industry Examples". In this way, upcoming system architectures, such as cell-to-pack and cell-to-chassis, can be clearly differentiated. Finally, fundamental product characteristics for the four system generations are derived and compared.

Keywords: battery electric vehicle; battery system architecture; Cell-to-Pack; CTP; Cell-to-Chassis; CTC; Cell-to-X; CTX; structural battery

1. Introduction

In the years from 2010 to 2020, electromobility was for a long time only a marginal phenomenon in the international automotive industry. This is changing, and battery electric vehicles are finding their way into the portfolios of major car companies. In order to complete the mobility transformation, the acceptance of electric vehicles must be further improved. The two biggest obstacles for electric cars cited in surveys are high purchase costs [1] and a short range [2,3] (p. 44). Both arguments can be traced back to the battery, which is why development priorities are being set here in order to achieve full EV market penetration in the future. In this context, the energy and power densities of battery cells have risen continuously in recent years [4] (pp. 4–5) linked to decreasing costs at the cell level [5]. However, it is not only the price and energy density of the cells that is decisive for a high-performance battery system, but rather the characteristics of the entire battery system.

Figure 1 shows the typical modular product structure of the battery system in the automotive sector. The voltage of individual cells is limited by the basic chemical elements. Therefore, single battery cells are interconnected in series and/or parallel to form a battery module. This encapsulates the intercontacted cells and a battery management unit (BMU)-Slave with the corresponding voltage measurement and temperature sensors. A connection or the cooling system itself, e.g., in the form of a cooling plate, can also be part of the battery module. For voltages up to 60 V (DC), no special high voltage safety measures apply during module assembly. Above 60 V (DC), the regulations of the DGUV have to be observed [6] (p. 9). For this reason, the voltage of 60 V (DC) was usually not exceeded in the past within the individual modules. To achieve the required battery pack voltage, several battery modules are connected in series to a battery string [7] (pp. 31–32). To increase capacity, serial strings of battery modules can be connected in parallel to form a larger battery pack [8] (p. 300). The battery pack contains the BMU-master interfaces for the external systems and has a high IP protection class. In the passenger car sector, the battery pack is usually equivalent to the battery system that is integrated into the vehicle chassis. In the commercial vehicle sector, several battery packs are typically connected in series and/or parallel to form the commercial vehicle battery system. In the passenger car sector,

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battery systems currently have voltages of up to 924 V [9] and usable energy contents of up to 210 kWh [10]. For example, the Tesla Model S has a 100 kWh storage unit weighing over 500 kg [11]. The size of the battery pack is significantly limited by the available installation space inside the vehicle.

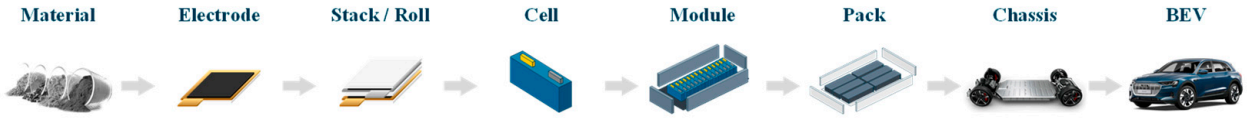


Figure 1. Simplified BEV product structure based on a conventional battery system architecture.

The energy density of available battery packs is on average around 50% of the volumetric energy density at the cell level [4]. There is thus potential to increase energy density at the overall system level through efficient battery cell integration. Disruptive system architectures, e.g., *Cell-to-Pack* (CTP) or *Cell-to-Chassis* (CTC), are promising approaches to exploit the existing potential. The usual composition of the system layers—battery active materials, battery electrodes, battery electrode stack, battery cell, battery module, battery pack/system, (vehicle) chassis, full battery electric vehicle—is abandoned by skipping individual system levels, i.e., the cells are directly integrated into the pack housing/vehicle chassis or may in the future even replace chassis/vehicle parts. These direct integrations save weight and volume and increase the energy density at the overall system level while ideally maintaining the same energy density at the cell level. To achieve the aforementioned developments, a number of technical challenges have to be solved both on product and on process levels.

The current state of research investigates different aspects of various battery system architectures. A central aspect is the investigation of energy density improvements through architectural innovations based on both real observed developments [4] and calculated energy densities of different theoretical implementations [12]. The analysis of the current state-of-the-art based on the various patents of different OEMs has also been carried out in the literature [13,14]. Domain-based architectures are derived by Kampker et al. [15]. In science, however, a holistic framework is missing, which allows for a methodical differentiation of the system architectures, and which is why the aim of this paper is to close this gap.

This analysis of the technical and economic conditions of *Electrode Stack-to-X* (ETX) and *Cell-to-X* (CTX) solutions intends to motivate the development and production of these systems. So far, the different system architectures cannot clearly be distinguished from each other. This work is intended to remedy the situation and provide a classification of the different system architectures based on the number of skipped system levels. To this end, the existing system levels in the literature are first described in part two, and additionally a differentiation is made between mono- and multifunctional materials. Based on this, the regulatory framework is methodically derived in chapter three and existing vehicle architectures are classified accordingly based on their characteristics. The resulting fundamental implications are discussed in Section 4.

2. Materials and Methods

In this publication, the delimitation of (battery) system architectures is methodologically based on the number and combination of main system levels.

2.1. System Levels

Up to now, a precise differentiation and overview between the individual (battery) system architectures has not been made on a scientific basis. In the following, the different system architecture approaches are classified into generations (G) based on the number of their main system layers/levels. Hence, the electrochemical system levels predefined in the literature are listed in the following to provide a basis for further classification:

- "**Active materials** is used as a collective term for materials that react chemically to produce, store or release electric energy inside the battery cell" [16] (p. 64). It is therefore defined as the lower limit of the system levels to be considered in this paper.
- "**Electrode**, electrically connected to one terminal of a cell, in electric contact with the electrolyte of that cell and on which the electrode reaction occurs" [17].
- **Electrode stack (stack)/jelly roll (roll)** is an assembly of stacked/rolled battery electrode sheets (anodes and cathodes) with the separator in between [18]. The electrode stack/jelly roll is considered the minimum viable functional system level in combination with the electrolyte.
- "**(Battery) cell** means a single encased electrochemical unit containing one positive and one negative electrode which exhibits a voltage differential across its two terminals" [19].
- "**Battery module** means a set of battery cells that are connected together or encapsulated within an outer casing to protect the cells against external impact, and which is meant to be used either stand-alone or in combination with other modules" [16] (p. 64).
- **Battery pack** is an "Energy storage device that includes cells or cell assemblies connected with cell electronics, high voltage circuit and over current shut-off device including electrical interconnections, interfaces for external systems (e.g., cooling, high voltage, auxiliary low voltage and communication)" [20].
- **Battery system** is an "Energy storage device that includes cells or cell assemblies or battery pack(s) as well as electrical circuits and electronics (e.g., BCU, contactors)" [20].
- **Chassis/body in white** (BiW) is the outer shell of the battery electric vehicle (BEV) [21] (p. 3).
- "A **Battery Electric Vehicle** or **BEV** is a vehicle that uses a battery as the sole means of energy storage for the propulsion of the vehicle" [22]. The BEV is therefore the highest possible layer considered in this paper, in which the product is considered as a whole.

The lower system levels can be observed by reviewing the main production steps in LIB cell manufacturing. The process starts out with a slurry mixing of the active materials, before producing the battery electrodes. The electrode stack/jelly roll is intentionally listed, as the levels distinguished here are assembly-based. After the electrode stack or jelly roll is assembled, the battery cell is the next conceivable system level [18].

Current mass production LIBs are limited to single-digit voltages as well as up to two or three-digit ampere hours, which is why cells are electrically contacted in series and parallel to reach higher voltages and capacities. The cells are mechanically aggregated via a module housing to form larger assembly groups (modules). On the module level, there are basic electric/electronic components, e.g., sensors and the BMU slave. The modules are integrated into a pack housing and equipped at the string ends with the additional electrics and electronics such as the BMU Master, fuses and contactors [23]. One of the main electric differences between a module and a pack is therefore the ability to actively electrically separate from its environment. Modules are generally hardwired to the adjacent modules via busbars, whereas packs are required to be able to disconnect electrically from the pack external DC link, e.g., in case of a fault. The housing difference between a module and a pack lies in the ingress protection (IP) class as well as in the main mechanical tasks. Module enclosures have no or only a low IP rating, as usually at least one side is open to allow for a short thermal path between cells and the thermal system/cooling plate. The module housing for pouch and cylindrical cells often comprises pressure plates and tension rods to fix the cell inside the pack. Pack housings have the highest IP ratings, as their main task is to protect the cells from external forces and environmental influences [24].

Since in battery-powered electric cars there is predominantly only one installation space available for the traction battery, in this paper the battery pack and battery system in passenger cars are considered equivalent. Nevertheless, larger commercial vehicles can provide several installation spaces for battery packs. Several battery packs are connected in series and/or in parallel to form one decentralized (mechanically distributed) battery

system. Thus, a battery system comprises at least one or also several (intrinsically safe) battery packs. For example, the Volvo heavy duty electric truck has 90 kWh battery packs, of which up to six can be connected in parallel to form a 540 kWh battery system [25]. The number of possible system layers is debatable, but is here defined as eight for battery electric cars and nine for larger commercial BEVs, as their battery systems are typically multi-pack architectures [25–27]. Based on the defined system levels, the conventional battery electric vehicle structure can be detailed for cars as shown in Figure 2. An alternative approach is to use a domain-based product structure [15].

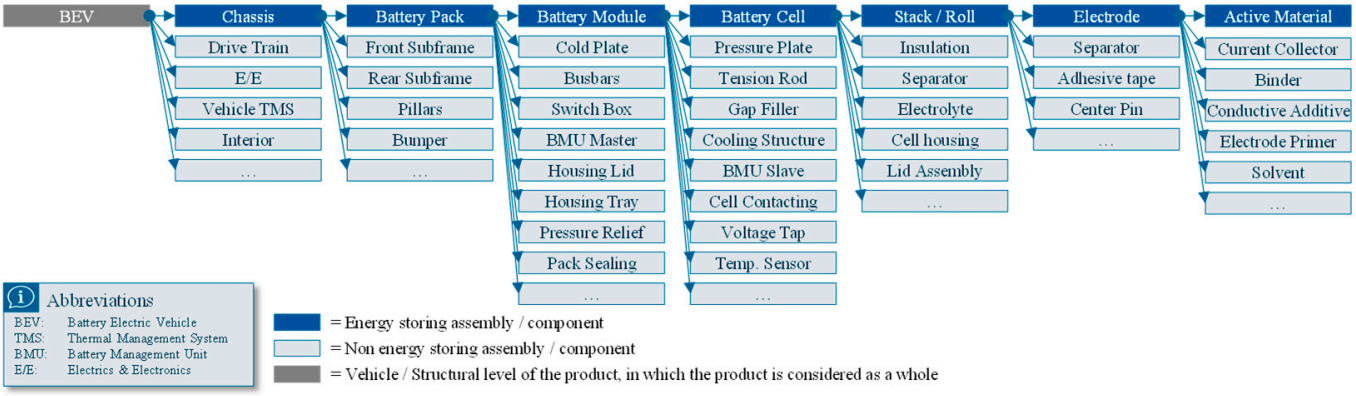


Figure 2. Detailed BEV product structure based on a conventional battery system architecture.

2.2. Mono- vs. Multifunctional Materials

In order to fully capture the possible variations of system architectures, this paper distinguishes two different ways to approach structural system architectures.

2.2.1. Monofunctional Materials with Decoupled Functions

The first category is based on a separation of functions, wherein one material stores electrochemical energy, and the other is used for carrying mechanical loads [28]. Examples are cells with a liquid electrolyte and other mechanically soft internal cell components, which have the ability to carry significant mechanical forces only from the cell's outer shell onwards, i.e., of the shelf lithium–ion battery cells. These conventional battery cell active materials are dedicated to one main function—the electrochemical storage of energy, which is why they are referred to as monofunctional. The basic mechanical functionality of these cells is mainly achieved by passive cell materials, e.g., the current collectors and the cell housing/can. In case of pouch and prismatic cells, additional necessary mechanical functions for an extended cycle lifetime, i.e., the compression of these cells—is achieved on a higher system level through clamping on the module, pack or chassis level. If lithium–ion battery cells are embedded into composite structures to achieve a structural battery system, they are known under the name "embedded batteries" [29]. In this case, the cell housings contribute to the overall mechanical functionality of the system as there is a direct mechanical force path from one side of the pack housing/chassis through the cell housings toward another place of the pack housing/chassis. Another example is the integration of commercially available lithium–ion batteries in composite structures [30,31].

2.2.2. Multifunctional Materials with Coupled Functions

This second approach refers to battery cells whose materials and components themselves can already withstand mechanical forces. Materials that can carry mechanical loads while storing electrical energy are referred to as "structural power composites" with the sub class "structural battery composites" (SBCs) [32]. The constituents of these multifunctional structural materials synergistically and holistically perform two very different tasks, e.g., carrying mechanical loads whilst storing electrochemical energy [33]. Carbon fibers (CFs) are state-of-the-art negative electrodes in SBCs. Due to their excellent strength and stiff-

ness properties, the CFs are the primary load-carrying material. CFs also act as a host for lithium–ions and conduct electrons. A bicontinuous polymer electrolyte system, referred to as a structural battery electrolyte (SBE), consists of a porous methacrylate polymer (for mechanical load transfer) impregnated with a liquid electrolyte mixture containing lithium salt (for ionic conductivity). An aluminum film-supported positive electrode similarly provides combined mechanical and electrical functionality [32]. It has to be pointed out that these are just a few examples of possible SBC materials and architectural designs [34].

2.2.3. Comparison of Mono- and Multifunctional Materials

Figure 3 illustrates the key difference between both approaches. Monofunctional battery materials have excellent capabilities in the area of the electrochemical energy storage but lack the ability to carry mechanical forces on the lowest system levels. Structural integrity is only achieved from the level of the cell housing and improves through the higher levels of the integration. However, the mechanical load should not exceed certain limits; otherwise, faults/short circuits may occur inside the cell [35,36]. On the other hand, cells based on multifunctional materials aim to fulfil these two core functions—electrochemical energy storage capability and mechanical load-bearing capability—simultaneously and directly on the lowest system levels. The result is an excellent fulfilment of the mechanical functionalities but current prototypes of multifunctional cells based on SBC do not yet reach the energy densities of conventional/monofunctional LIB cells [32]. The qualitative rating of the function fulfilment in the following figure is based on the current state of research, which states that decoupled structural batteries generally outperform coupled versions [28]. The capability to store electrochemical energy is measured in Wh/kg or Wh/L, and the practical specific energy density decreases from the lower to the upper system levels [37]. The overall mechanical properties improve from the low system levels to the high ones. As several functions can be combined into a single entity, the number of system levels potentially required can be significantly reduced compared to the previews identified eight layers for battery electric cars and nine for battery electric trucks. This core idea is picked up through the following paper.

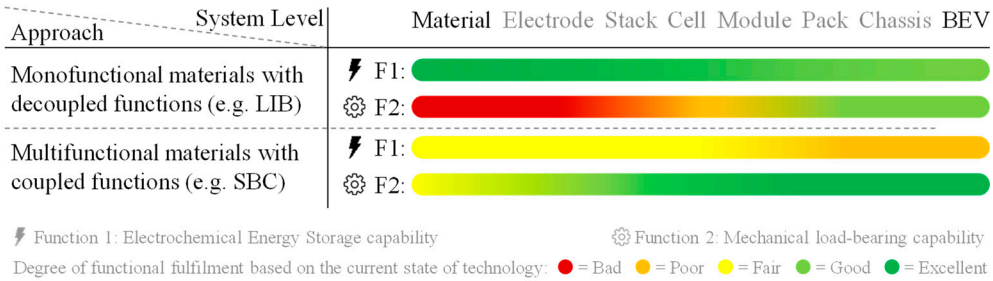


Figure 3. Elementary differences between monofunctional and multifunctional materials.

3. Results

The previously defined and detailed "*Conventional System Architecture*" (see Figures 1 and 2) represents the starting point for the subsequent classification of the arising system architectures. The numeral zero "*Generation 0*" corresponds to the maximum number of eight system layers. From there, the quantity of system layers is reduced up to five main system layers at "*Generation III*". The possible different expressions within individual generations are numbered consecutively with Arabic numerals. The nicknames are assigned to systems from *Generation I*, *II* and *III* by naming the neighbors of the skipped system levels. Figure 4 provides an overview of the derived system architecture generations. The two highest as well as the three lowest system levels of an electric car are considered necessary in this paper, as no evidence could be found in the literature that a BEV could be built up without the chassis on the higher level and an assembly of stacked or rolled anodes and cathodes on the lower levels. The three middle levels (cell, module, pack/system) are considered potentially integrable into the other system levels. In addition, a distinction

is made between two approaches. The system architectures which are bordered solid are based on the *Cell-to-X* approach, where the "X" is a placeholder for a higher system level. In practice, these CTX system architectures are currently based on conventional (LIB) cells consisting of non-load-bearing active materials. The electrode stack-to-X architectures are bordered with a dotted line and represent the alternative approach to achieve structural battery systems by utilizing multifunctional materials with coupled functions (e.g., SBC).

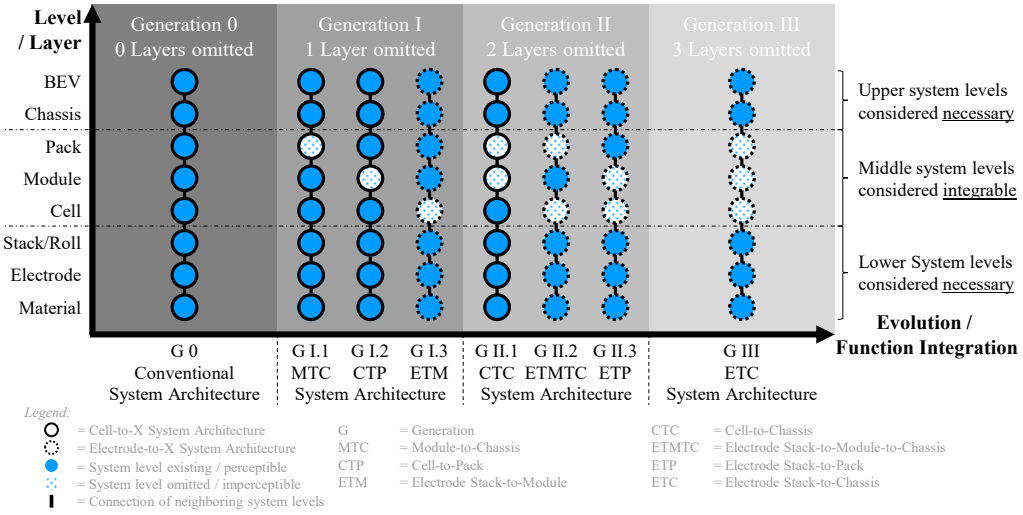


Figure 4. Differentiation of architecture generations based on the number of omitted system layers.

In the following, the characteristics of the individual generations are classified.

3.1. *Generation 0*—*0 Layers Omitted*

"*Generation 0*" (*G 0*) are "*Conventional System Architectures*" that use all previous identified system levels and are therefore based on eight layers—active material, electrode, electrode stack/roll, cell, module, pack/system, chassis/body (in white) and the overall vehicle/BEV (cf. Figures 1 and 2). Within this solution space, a distinction is made to acknowledge the improvements of the last two decades. As no system level is skipped, the *G 0* expressions are assigned based on the two different design approaches.

3.1.1. *Generation 0*—Conversion Design

- Nomenclature: The first generation of LIB mass market BEVs was based on the conversion of existing internal combustion engine (ICE) vehicle platforms, leading to the nickname "*Conversion Design*" [38] (p. 54).
- Approach: To save both investments in development and production cost, the already developed ICE chassis/vehicle platform as well as the existing production lines were used to build the first BEVs. This leads to significantly lower costs and risks for the manufacturer, but to disadvantages in the technical implementation, as innovations and package advantages can only be achieved within limits.
- Omitted Components: Compared to vehicles with combustion engines, the ICE is replaced by an electric drive train.
- Industry Examples: The arguably first highway legal serial production of an all-electric car to use lithium–ion battery cells was the Tesla Roadster 2008 [39], which was partly based on a Lotus Elise platform, even though they did not share the same production line [40]. Another well-known example is the e-Golf, which VW assembled on the same production line in Wolfsburg as the Golf combustion models [41]. In the early 2020s, there are still many models available with both combustion engines and pure battery electric vehicles (BEVs). These include, among others BMW 4, 7, X1 and X3 [42]; Citroën C4 [43]; DS 3 Crossback [44]; Fiat 500 [45]; Hyundai Kona [46]; Mini [47];

Opel Corsa, Mokka and Zafira [48]; Peugeot 208, 2008 and Traveller [49]; Renault Master [50]; Toyota Proace and Verso [51]; Volvo XC40 [52], VW e-up [53].

3.1.2. *Generation 0*—Purpose Design

- Nomenclature: Instead of converting existing ICE vehicles, the next generation system architecture is a dedicated "*Purpose Design*" BEV platform, often executed as a skateboard platform [54].
- Approach: The *Purpose Design* platforms aim to exploit the advantages of electric drive trains. Battery systems no longer have to be squeezed into existing installation spaces, but the platform design is optimized for a purely electric powertrain—a dedicated EV platform.
- Omitted Components: New degrees of freedom result from the elimination of the vehicle tunnel, which enables a considerably simplified vehicle underbody and thus also simplified operating equipment in the area of chassis construction [38] (p. 55). By eliminating the combustion engine, the wheelbase can be extended to gain more space between the axles and accommodate a larger battery in the underbody of the vehicle. [55] In comparison with different BEV conversion designs, it can be argued that the multi-pack variants are omitted. Instead of electrically connecting two mechanically separated battery packs to form one battery system, as in the conversion design of the 2015 FORD Focus EV [56], for *Purpose Design* platforms there is predominantly only one installation space for the battery system. This reduces the number of pack housings from two to one and also lowers the number of necessary thermal and electrical interfaces (connectors).
- Industry Examples: *Generation 0* in the purpose design manifestation can be considered as state-of-the-art in 2023, as the BEVs in mass production are predominantly based on purpose design architectures with all system levels. Examples include Geely SEA platform [57], Hyundai E-GMP [58], Rivian Skateboard [59], Tesla [60], Volkswagen Group MEB platform [61] and Xpeng SEPA [62], among others.

3.2. Generation I—1 Layer Omitted

"*Generation I*" is based on the partly omission of one system level, which leads to seven instead of eight main system layers. Since the battery materials, electrodes and electrode stacks display lower boundary conditions and the chassis (BiW)/BEV the upper ones for the application of electrochemical energy storages inside a battery electric vehicle, there are three possible *Generation I* manifestations.

3.2.1. *Generation I.1*—Module-to-Chassis

- Nomenclature: The "*Generation I.1*" expression is based on the partly omission of the pack/system level. Based on the nomenclature defined in the introduction of this chapter, *Generation I.1* can be described with the nickname "*Module-to-Chassis*".
- Approach: Cells are assembled into modules and these are then integrated into the vehicle chassis (parts). Previously separate pack and chassis components can be brought closer together/combined, such as the battery pack lid with the chassis base. It is possible to integrate former pack functionalities/components into the underlying assembly group—the battery module. The pack level is partially omitted, as probably not all pack components can be merged with components of other levels. Examples for components that cannot be easily transferred to other system levels can be found in the pack domains of the thermal system and high-voltage. The pack component groups of the temperature control system (cooling and heating elements) and the battery junction box (contactors, fuses, currents sensors, BMU master, etc.) can be partially moved from the pack level to the neighboring module or chassis level on paper, but only lead to an increase in energy density if they are intelligently functionally integrated.
- Omitted Components: The battery pack housing and the vehicle chassis merge into one component/assembly.

- Industry Examples: Until the beginning of 2023, there are no announcements for *Module-to-Chassis* system architectures.

3.2.2. *Generation I.2*—Cell-to-Pack

- Nomenclature: "*Generation I.2*" partly skips the module level. Cells are directly integrated into the pack housing, which is then married to the chassis—a "*Cell-to-Pack*" system architecture. In the existing literature, this approach is also known under the description "module-less" [63] or "module-free" [64] battery pack technology.
- Approach: "*Cell-to-Pack*" describes a new type of structure of battery systems, which is characterized by the direct integration of the battery cells into the battery pack [13]. This allows for the reduction in the passive/non-energy storing components of the battery module. Inside this *Generation I.2*, different types of execution can be observed. Some manufacturers only eliminate the module housings, but preserve cell sub-assemblies, while other manufacturers rely on one complete cell block (cf. industry examples).
- Omitted Components: Incremental improvements can be observed by omitting the module housing [12]. The functions of the module housing, e.g., the mechanical clamping of pouch and prismatic cells, are no longer carried out by module pressure plates and module tie rods, but instead are achieved on the high pack level [65]. The previously required fastening of the individual modules as well as the space needed around these modules in order to be able to integrate them into the pack housing can be significantly reduced; thus, the cells can be packed in a denser manner and a higher overall system energy density is achieved. The saved parts also lead to a cost reduction.
- Industry Examples: Multiple cell manufactures as well as leading vehicle original equipment manufacturers (OEMs) have filed patents for *Cell-to-Pack* system architectures, announced plans for a product market launch or already have a product in production. These companies are, among others, BYD (Patent 2019 [65]—Announcement 2020 [66]); CATL (2019 [67], 2022 "CTP 3.0 battery "Qilin" [68]); LG Chem (2020 [69]); Mercedes-Benz Group (2020 [70]); Nio (2020 [71]); Stellantis (2021 [72]); SVOLT (2021 [73] & 2022 [74]); Tesla (2020 [75]) and Volkswagen Group (2021 [76]).

3.2.3. *Generation I.3*—Electrode Stack-to-Module

- Nomenclature: "Generation I.3" skips the classic battery cell and is called "Electrode Stack-to-Module" system architecture based on the neighboring system levels of the skipped battery cell level.
- Approach: Instead of building individual cells, a battery module is built up directly out of electrode stacks. Lithium–ion battery cells based on LNMC/LNCA cathodes exhibit a typical nominal voltage of around 3.6 to 3.7 V or 3.2 Volts if the cathode is based on LFP. A key performance indicator of the *Electrode Stack-to-Module* approach therefore is a larger voltage difference between the two module terminals, in the region of current battery modules, i.e., 7.2–59.2 V (nominal). Starter batteries in ICE vehicles are predominantly lead–acid batteries and can be described as an approximation to the *Electrode-to-Module* approach, as the individual cells do not have their own fully enclosed housing, but the 12 V lead acid battery consists of multiple serially connected electrode sets, which are separated by insulation walls [77] (pp. 247–264). A similar approach is conceivable for an advanced battery chemistry in which the inner jelly rolls/electrode stacks of a battery are not (only) connected in parallel, but (also) in series. Liquid electrolytes of current LIBs decompose under voltage differences higher than 4.2 V [78], which is why until now no industry implementation of LIB-based ETM system architectures can be found. However, next gen solid-state electrolytes can resist higher voltage differences and therefore enable bipolar stacking/a serial connection of the individual monocells [79,80].

- Omitted Components: The passive battery cell/module housing material is significantly reduced, which leads to a better ratio of cell housing mass to active material mass. If bipolar electrodes are used, the external wiring (tabs and wires) of the individual electrode stack can be omitted, as all electrodes are connected in series and only the two tabs at the end of the stack need to be connected [81].
- Industry Examples: By early 2023, there are different announcements for electrode stack-to-module system architectures based mainly on solid-state electrolytes, but no systems in series production, e.g. the company ProLogium announced an EV battery pack based on solid-state technology and describe their approach as "Cell is Modul (CIM)" [82]. Additionally, the first research results provide an impression of what an implemented approach may look like [81,83,84].

3.3. *Generation II*—2 Layers Omitted

"*Generation II*" is based on the partly omission of two system layers, which leads to six instead of eight main system layers.

3.3.1. *Generation II.1*—Cell-to-Chassis

- Nomenclature: "*Generation II.1*" is known as "*Cell-to-Chassis*" (CTC). By (partly) avoiding the module and the pack level, the battery cells are directly integrated into the chassis. Therefore, this approach is also known under the nicknames "*Cell-to-Body*" (CTB) referring to the body in white, "*Cell-to-Vehicle*" (CTV), "*Cell-to-Car*"(CTC) [85] or "*Cell-to-Frame*" (CTF) [86]. Since the battery cell and chassis levels are considered necessary for conventional LIB cells, *Generation II.1* represents the methodological limit of what can be achieved with conventional battery cells by omitting the system levels in the vehicle.
- Approach: The functions previously taken over by the module and pack have to be redistributed to the remaining system levels. The degree of function integration increases parallel to the decrease in the number of system levels. The module and pack housing functionalities have either to be taken over by the chassis or by the cell. The cells are mechanically connected to the chassis and contribute significantly to their stiffness, which is why the system is also called a "*Structural Battery Pack*" [87]. The difference to the previously described *Cell-to-Pack* approach lies in the interface between the pack and the chassis, whereas with a CTP the battery system can still be detached from the chassis and the vehicle interior without leaving a hole in the bottom of the vehicle chassis. With CTC technology, the interior components (e.g., the seats) are directly connected to the battery system lid, which leads to challenges during the disassembly [88]. Current announcements by manufacturers are limited to the integration of cells into the vehicle floor. The integration of cells into the cavities of adjacent body components, such as the A-, B-, C-pillars or the doors, has not been announced. The reasons can be found, among other things, in the safety of LIBs in the event of a crash. As the key technology battery cell increasingly merges with the entire vehicle, this leads to changes in the development process. Due to the significantly higher system energy density of the CTX approaches, a development focus lies in the field of battery system safety, and more specifically in the topics of cell selection, gas flow and thermal propagation prevention. Due to the increased mechanical integration of the cells, repairs become more challenging [89], which must lead to higher quality requirements to prevent field failures due to a lack of repair capability.
- Industry Examples: In recent years, there has been an increase in announcements and implementations in the field of CTC technology. These include, among others, BMW [86]; BYD [90]; CATL [91]; Leapmotor [92,93] and Tesla [88]. As the volumetric system energy density of *Generation II* is significantly improved over *Generation 0*, it paves the way for alternative battery chemistries that have lower volumetric energy density at the cell level and are therefore not yet considered a viable option for long-

range BEVs, but excel in other areas such as safety, cost, sustainability and cycle life, e.g., sodium–ion batteries (SIB) and lithium iron phosphate (LFP) batteries.

3.3.2. *Generation II.2*—Electrode Stack-to-Module-to-Chassis

- Nomenclature: "*Generation II.2*" is an "*Electrode Stack-to-Module-to-Chassis*" system architecture.
- Approach: This *G II.2* pursues the idea of skipping the cell level and then integrating these battery modules into the vehicle chassis. Therefore, this approach is a combination of the previously introduced Generations *G I.1*, Module-to-Chassis, and *G I.3*; *Electrode Stack-to-Module*.
- Omitted Components: Battery cell housings and merging of pack housing and chassis.
- Industry Examples: Until 2023, there are no announcements for *Electrode Stack-to-Module-to-Chassis* system architectures. This generation can only be expected after the previous generations *G I.1*—MTC and *G I.3*—ETM have been successfully implemented.

3.3.3. *Generation II.3*—Electrode Stack-to-Pack

- Nomenclature: "*Generation II.3*" is an "*Electrode Stack-to-Pack*" system architecture.
- Approach: The *G I.3—Electrode-to-Module* system architecture idea is taken and developed on step further by aiming to build up system level characteristics coming from an electrode stack level.
- Omitted Components: The cell housings as well as the module housings are (partly) omitted.
- Industry Examples: Until 2023, there are no announcements for electrode stack-to-pack system architectures. Nevertheless, there are patents that could be interpreted in this direction [94].

3.4. Generation III—3 Layers Omitted

"*Generation III*" is based on the partial omission of three system layers, which leads to five instead of eight main system layers.

Generation III—Electrode Stack-to-Chassis

- Nomenclature: "*Generation III*" is an "*Electrode Stack-to-Chassis*" system architecture.
- Approach: *G III* is enabled by realizing the electrochemical energy storage function as a chassis component or the other way around. The extreme approach combines the previously separate levels of the battery cell and the chassis components. One way of approaching this highly function-integrated *Generation* would be to use SBC electrode stacks surrounded only by the matrix material of the carbon-fiber-reinforced polymer (CFRP). This drastically reduces the number of housings/intermediate system layers—the active material housing is concurrently the chassis component. Decentralized segments of body structure/panels can be electrically connected to form the entire battery system.
- Omitted Components: Components of the classic battery system with predominantly mechanical functionality, such as cell, module and pack housings, will be (partly) omitted. The electrical interface between the battery system and the vehicle (BMU, contactors, etc.) will be probably retained in part.
- Industry Examples: Until 2023, there are no announcements for electrode stack-to-chassis system architectures. Nevertheless, different research teams are working on structural integrated LIBs [95] as well as structural battery composites [32], which could lead to viable products in the future. As the ETC cost would be high at the beginning, an application in the aviation or even aerospace industry is initially more likely than in the car industry [96].

4. Discussion

The methodically derived system architectures show the theoretically conceivable solution space based on the current state of technology. As the numerous examples from the industry show, *Cell-to-X* system architectures are currently of particular practical relevance. However, *Electrode Stack-to-X* system architectures are becoming more relevant, as *Cell-to-Chassis* reaches the limit of what is theoretically and technically possible with the CTX approach. Based on the findings above, characteristics can be derived for the different Generations.

While *Generation 0* uses a differential design approach, a trend toward function integration and thus integral design can be observed from *G I* systems onwards. This trend means that not only monofunctional materials with decoupled functions are used, but multifunctional materials with coupled functions are increasingly used in the higher generations. *Generation 0* battery systems are generally good to repair, as components and assemblies (e.g., battery modules) can be exchanged due to their modular design. Higher generation systems offer advantages in terms of energy density as the number of parts and interfaces is reduced, but this also leads to inferior repairability. From *Generation I* onwards, primarily passive components (e.g., module housing, packing lid/chassis base) are omitted, which increases the share of active materials. Since differential design is fundamentally good for low volumes and integral design is fundamentally good for high volumes [97] (p. 85), there is a need for higher production volumes for the higher generation systems. Conversely, this can also be observed in *Generation 0*, as many of the conversion design vehicles listed above were produced in comparatively small numbers. Announcements from the industry confirm that the number of components is decreasing in the direction of the higher generations, while at the same time component complexity and dimensions are increasing due to multifunctionality. For *Generation 0*, the overall mechanical system stability is provided by the higher system levels, while the lower system levels (cells and levels below) are largely decoupled from the mechanical operating forces. From *Generation I* onwards, the operating forces are transferred more strongly to the lower system levels. Figure 5 summarizes these observations.

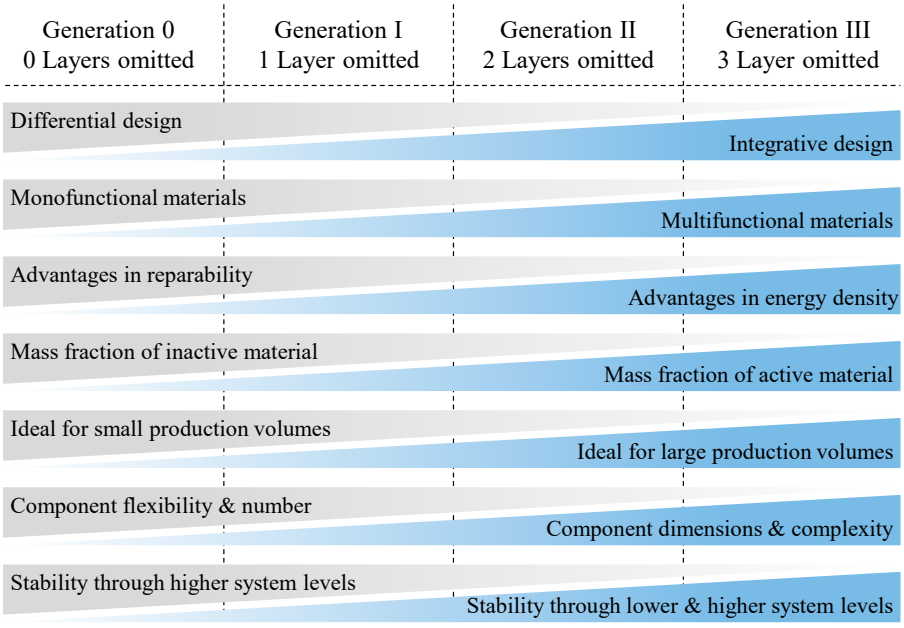


Figure 5. Derived implications for the distinguished battery system architectures.

The authors assume that, due to the increasing numbers of units and lower costs, *Cell-to-Pack* and *Cell-to-Chassis* system architectures in particular will penetrate the market in different variations in the near future. While improvements in system energy densities in the decade from 2010 to 2020 were mainly due to improvements in cell energy densities,

the focus of development in the current decade is also on efficient system integration. Challenges and thus future research needs for the higher generations lie in particular in product and process design with regard to the reparability, dismantlability and recyclability of the highly integrated systems.

In summary, this paper shows which basic system levels exist and which components and component groups can be assigned to them. A comprehensive framework for battery system architectures is provided that allows for a clear assignment of existing batteries to system generations and illustrates the extent to which there is potential for future architecture developments.

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