# Preparatory Study on Ecodesign and Energy Labelling of Batteries under FWC ENER/C3/2015-619-Lot 1

TASK 3 Report

Users – For Ecodesign and Energy Labelling

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Project website: https://ecodesignbatteries.eu/

**Version history:**

**Version 1:** Version made available in December 2018 for the Stakeholders to comment and discuss in the first stakeholder meeting.

**Version 2:** Version made available in April 2019 in preparation of the second stakeholder meeting

- review based on the input from the stakeholder comments (some data input and remarks on the base case selection)

- QFU formula and Application Service Energy formula improved, calculation of losses added

- substitution of base case passenger BEV and light commercial BEV with BEV medium-to large-sized and BEV small-sized

- adapted argumentation for base case selection

- some data assumptions, related to the bases cases were changed

- missing sections were added

**Version 3:** (this version) Version made available in August 2019

- consideration of feedback from the second stakeholder meeting and of written feedback received after the second stakeholder meeting

- argumentation for selection of base cases slightly adapted (LCV represented partially by passenger cars)

- information on potential impact of vehicle to grid services on battery added

- increase of annual cycles of residential ESS due to provision of grid services discussed

- discrepancy of battery and vehicle lifetime addressed

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## List of abbreviations

| Abbreviations | Descriptions |
|---|---|
| AC | Alternating current |
| Ah | Ampere-hour |
| AS | Application service energy |
| BEV | Battery-electric vehicles |
| BMS | Battery management system |
| C | Capacity |
| $C_n$ | Rated capacity |
| DC | Direct current |
| DOD | Depth of Discharge |
| E | Energy |
| EOL | End of life |
| EPA | Environmental Protection Agency |
| $E_{Rated}$ | Rated energy |
| ESS | Energy storage system |
| EV | Electric vehicle |
| FC | Full cycle |
| FESS | Flywheel energy storage systems |
| FTP | Federal Test Procedure |
| GHG | Greenhouse gases |
| GVW | Gross vehicle weight |
| HDT | Heavy-duty truck |
| HDTU | Heavy-duty tractor unit |
| I | Current |
| ICEV | Internal combustion engine vehicles |
| $I_t$ | Reference test current |
| kWh | Kilowatt hour |
| $L_{Cal}$ | Calendar life |
| $L_{Cyc}$ | Cycle life |
| LFP | Lithium iron phosphate |
| LIB | Lithium-ion battery |
| $NaNiCl_2$ | Sodium nickel chloride |
| NaS | Sodium-sulphur |
| nC | C-rate |
| NEDC | New European Driving Cycle |
| NiMH | Nickel-metal hydride batteries |
| NMC | Nickel manganese cobalt |
| Pb | Lead-acid |
| PEF | Product environmental footprint |
| PEM-FC | Proton exchange membrane fuel cell |
| PHEV | Plug-in-hybrid-electric vehicle |
| PV | Photovoltaic |
| $Q_{FU}$ | Quantity of functional units |
| R | Internal resistance |
| RFB | Redox-flow battery |

| | |
|---|---|
| RT | Room temperature |
| SD | Self-discharge |
| SOC | State of charge |
| SOH | State of health |
| $SOH_{cap}$ | Capacity degradation |
| T | Time |
| V | Voltage |
| VKT | Vehicle kilometres travelled |
| $V_L$ | Voltage limits |
| $V_{OC}$ | Open circuit voltage |
| $V_R$ | Rated voltage |
| WLTP | Worldwide Harmonized Light Vehicle Test Procedure |
| $\eta_E$ | Energy efficiency |
| $\eta_V$ | Voltaic efficiency |

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# 3. Task 3: Users

The objective of Task 3 is to present an analysis of the actual utilization of batteries in different applications and under varying boundary conditions as well as an analysis of the impact of applications and boundary conditions on batteries' environmental and resource-related performance. The aims are:

- to provide an analysis of direct environmental impacts of batteries during use phase
- to provide an analysis of indirect environmental impacts of batteries during use phase
- to provide insights on consumer behaviour regarding end-of-life-aspects
- to identify barriers and opportunities of batteries linked to the local infrastructure
- to make recommendations on a refined product scope and on barriers and opportunities for Ecodesign

## 3.1. Subtask 3.1 - System aspects in the use phase affecting direct energy consumption

Subtask 3.1 aims at reporting on the direct impact of batteries on the environment and on resources during the use phase. Direct impact refers to impact, which is directly related to the function of the battery: the storage and provision of energy. Different scoping levels will be covered in the analysis: first, a strict product approach will be pursued which is then broadened to an extended product approach. After that, a technical system approach will follow, leading to an analysis from a functional system perspective.

- **Strict product approach:** In the strict product approach, only the battery system is considered. It includes cells, modules, packs, a battery management system (BMS), a protection circuit module (PCM) and passive cooling and heating elements (plates, fins, ribs, pipes for coolants). The operating conditions are nominal as defined in standards. Since relevant standards (e.g. IEC 62660, ISO 12405, IEC 61427-2, and IEC 62933-2) already differentiate between specific applications, those will also be discussed within this approach and base cases will be defined.
- **Extended product approach:** In the extended product approach, the actual utilisation and energy efficiency of a battery system under real-life conditions will be reviewed. Further, the influence of real-life deviations from the testing standards will be discussed. In that context, the defined base cases will be considered.
- **Technical system approach:** Batteries, as defined in Task 1, are either part of a vehicle or of a stationary (electrical) energy storage system, which comprise additional components such as a power electronics (inverter, converter), chargers, active cooling and heating systems and other application related equipment. However, energy consumption of these components is considered indirect losses and thus, discussed in chapter 3.2.
- **Functional approach:** In the functional approach the basic function of battery systems, the storage and provision of electrical energy, is maintained, yet other ways to fulfil that function and thus other electrical energy storage technologies are reviewed, as well.

### 3.1.1. Strict product approach to battery systems

As mentioned in Task 1, the product in scope is the battery system, referred to as battery. It comprises one or more battery packs, which are made up of battery modules, consisting of several battery cells, a battery management system, a protection circuit module, and passive cooling or heating elements, such as plates, fins or ribs as well as coolant pipes (see Figure 1 within the red borderline). Active cooling and heating equipment, such as fans, heat exchangers for tempering of coolant, heat pumps, heater elements etc., is usually located outside of the battery system, thus cooling and heating energy is considered as indirect loss. Furthermore, power electronics (e.g. inverter, converter), chargers and other application-related equipment (see Figure 1) is located outside of the battery system as well and thus, losses related to those components are also considered as indirect losses or even entirely out of the scope of this study and thus external.

Depending on the application, the number of cells per module, of modules per pack and of packs per battery or even the number of battery systems to be interconnected can vary.

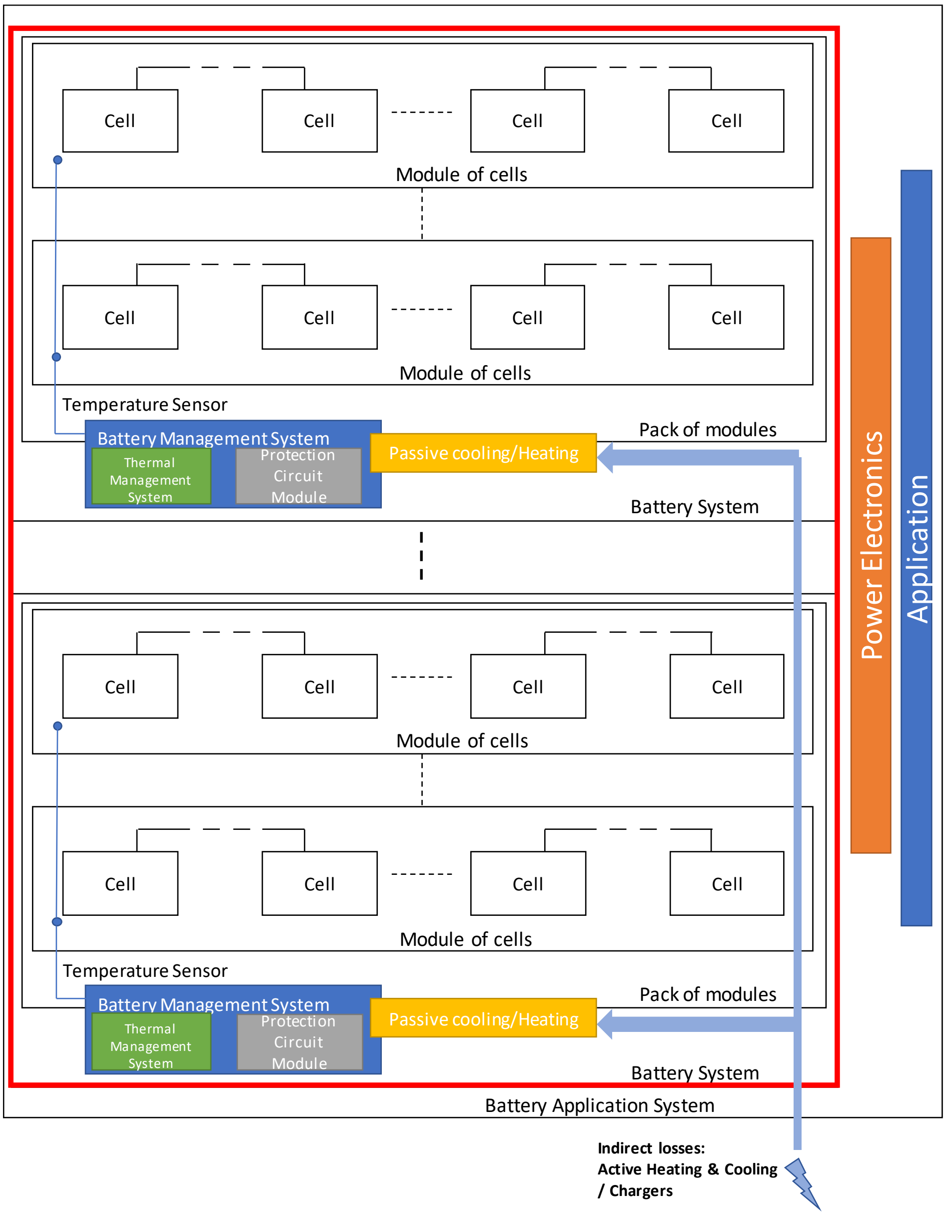


*Figure 1: Representation of the battery system components and their system boundaries.*

The primary function of a battery is to deliver and store electrical current at a desired voltage range and accordingly the storage and provision of electrical energy. Consequently, following the definition in Task 1, the functional unit (FU) of a battery is defined as one kWh of the total energy delivered over the service life of a battery, measured in kWh at battery system level, thus, excluding charger-, power electronics-, active cooling and heating equipment- as well as application-related losses. This is in line with the harmonized Product Environmental Footprint (PEF) for High Specific Energy Rechargeable Batteries for Mobile Applications (Recharge 2018). Accordingly, a battery is no typical energy-consuming product as for example, light bulbs or refrigerators are, but it is an energy-storing and energy-providing product. Thus, energy consumption that can directly be linked to a battery, as understood within that report, is the battery's efficiency in storing and delivering energy. Initially, the functional unit and the battery efficiency will be defined, before standard testing conditions concerning battery efficiency are reviewed and base cases are defined.

As already explained in Task 1, energy consumption during the use phase of a battery beyond its efficiency can include losses from power electronics and losses during charge, discharge and storage. Those will be modelled as 'indirect system' losses, which are part of a subsequent section 3.2. This is a similar approach to the PEF where it is called delta approach (EC 2018). It intends to model energy use impact of one product, in this case the battery, by taking into account the indirect losses caused by another product, in this case the charger. This means that the excess consumption of the charger shall be allocated to the product responsible for the additional consumption, which is the battery. A similar approach is pursued in section 3.2.

#### 3.1.1.1. Key parameters for the calculation of the functional unit

The functional unit is a unit to measure the service that an energy related product provides for a certain application. Key parameters of a battery that are related to the functional unit and the links of those parameters to the Product Environmental Footprint pilot are the following:

- **Rated energy $E_{Rated}$ (kWh)** is the supplier's specification of the total number of kWh that can be withdrawn from a fully charged battery pack or system for a specified set of test conditions such as discharge rate, temperature, discharge cut-off voltage, etc. (similar to ISO 12405-4 "rated capacity"). E.g.: 80 kWh/full cycle
- **Capacity (Ah or kWh)** is the total number of ampere-hours that can be withdrawn from a fully charged battery under specified conditions (ISO 12405). Strictly, the ampere-hours are used in the standards but this parameter can be also be expressed in kilowatt-hours (see Task 1).
- **Depth of Discharge DOD (%)** is the percentage of rated energy discharged from a cell, module, and pack or system battery (similar to IEC 62281) (similar to PEF "Average capacity per cycle"). Some tier 1 battery suppliers use DOD as the state of charge window for cycling: e.g. 80%
- **Full cycle FC (#)** refers to one sequence of fully charging and fully discharging a rechargeable cell, module or pack (or reverse) (UN Manual of Tests and Criteria) according to the specified DOD. It is similar to the PEF "Number of cycles". The cycle life of a battery (see section 3.1.1.2.1) is usually specified in FC. e.g. 1,500
- **Capacity degradation / State of Health $SOH_{cap}$ (%)** refers to the decrease in capacity over the lifetime (service life) as defined by a standard or declared by the manufacturer.

A $SOH_{cap}$ of 80% at the end of a battery's service life (EOL) indicates a capacity degradation of 20%. $SOH_{cap}$ is often indicated by SOH only. e.g. 80% $SOH_{cap}$ at EOL

- The **quantity of functional units of a battery $Q_{FU}$** is the maximum number of kWh a battery can deliver during its lifetime. It can be calculated as follows (the input figures are just exemplary and could represent a battery-electric medium- to large-sized vehicle):

$$\boldsymbol{Q_{FU}} = \underbrace{E_{Rated} * \mathrm{DOD}}_{PEF\ energy\ delivered\ per\ cycle} * \underbrace{\mathrm{FC}}_{PEF\ number\ of\ cycles} = 80\mathrm{kWh} * 80\% * 1{,}500\mathrm{FC}$$
$$= 96{,}000\ \mathrm{FU}\ (\mathrm{kWh\ per\ battery\ lifetime})$$

Consequently, it is assumed, that the DOD defines the energy delivered per cycle and that the absolute value of the energy delivered per cycle stays constant over the battery lifetime. This can be justified by the BMS, that usually limits the usable battery capacity in such a way, that the absolute DOD can be assured over the whole battery lifetime.

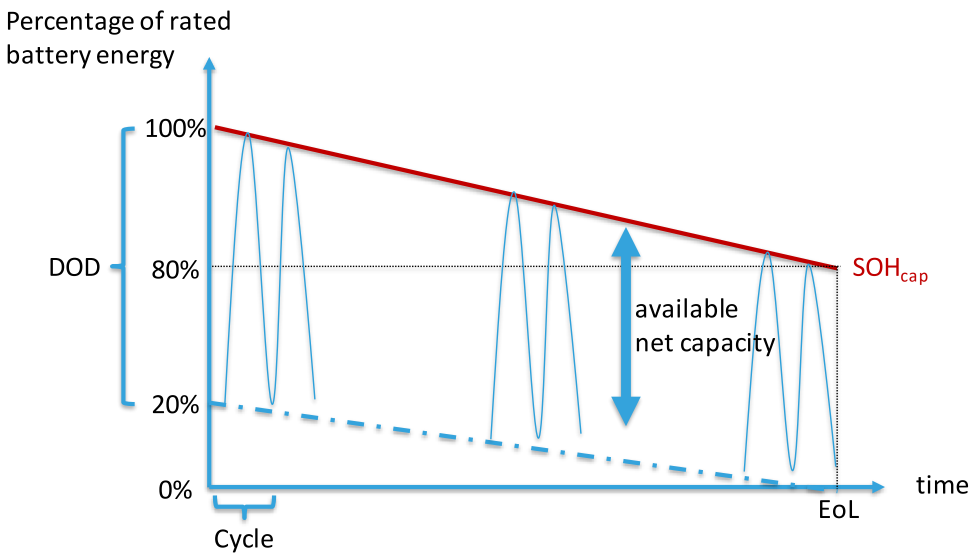


*Figure 2: Visualisation of terms related to $Q_{FU}$ calculation.*

### 3.1.1.2. Standards for battery testing and testing conditions

Having a look at standards linked to the testing of battery cells and battery packs or systems, numerous tests and testing conditions can be found in standards on batteries for electric vehicles (EV) or for electrical energy storage systems (ESS).

General standard testing conditions for batteries can hardly be found. This is because (1) most standards already focus on specific applications of battery cells and battery systems for example in EV, such as battery-electric vehicles (BEV) or plug-in-hybrid-electric vehicles (PHEV) (such as IEC 62660-1, ISO 12405-4) or in on-grid and off-grid ESS (IEC 61427-2 or IEC 62933-2) and (2) for each test usually a big variety of testing conditions is specified. Parameters that define the testing conditions in the IEC and ISO standards are:

- **C-rate *n*C (A),** Current rate equal to n times the one-hour discharge capacity expressed in ampere (e.g. 3C is equal to three times the 1h current discharge rate, expressed in A) (ISO 12405-4).
- **Reference test current $I_t$ (A)**: equals the *rated* capacity: $C_n$ [Ah]/1 [h]. Currents should be expressed as fractions of multiples or fractions of $I_t$. if n = 5, then the discharge

current used to verify the rated capacity shall be 0.2 $I_t$ [A] (IEC 61434). Note: the difference between C-rate and $I_t$-rate is important for battery chemistries for which the capacity is highly dependent on the current rate. For Li-ion batteries, it is of minor importance. See for more information the section “Freedom in reference capacity: C-rate and $I_t$-rate” in White paper (2018).

- **Temperature T / Room temperature RT (°C)** which is a temperature of 25+/-2°C (ISO 12405-4)
- **State of charge SOC (%)** is the available capacity in a battery pack or system expressed as a percentage of rated capacity (ISO 12405-4).

  with

- **Capacity C (Ah)** as the total number of ampere-hours that can be withdrawn from a fully charged battery under specified conditions (ISO 12405-4)
- **Rated capacity $C_n$ (Ah)** which is the supplier's specification of the total number of ampere-hours that can be withdrawn from a fully charged battery pack or system for a specified set of test conditions such as discharge rate, temperature, discharge cut-off voltage, etc. (ISO 12405-4). The subscript n refers to the time base (hours) for which the rated capacity is declared (IEC 61434). In many standards, this is 3 or 5.

#### 3.1.1.2.1. Key parameters for the calculation of direct energy consumption of batteries in applications (application service energy)

In the context of this study, it is not useful to go into the details of all of the above-mentioned standards, tests and test conditions, but to select the most important ones who are related to energy consumption. In order to be able to determine the direct energy consumption of a battery based on the quantity of functional units of a battery system, the following parameters, mainly referring to IEC 62660 and ISO 12405-4, are to be considered. IEC 62660 relates to the cell level, whereas ISO 12405 relates to the battery system level. For this study, according to the definition of the strict product approach, the system level has to be taken into consideration:

- **Energy efficiency $\eta_E$ (energy round trip efficiency) (%)** - each FU provided over the service life of a battery is subject to the battery’s energy efficiency. It can be defined as the ratio of the net DC energy (Wh discharge) delivered by a battery during a discharge test to the total DC energy (Wh charge) required to restore the initial SOC by a standard charge (ISO 12405-4). E.g. 96% (PEF)
  - In most standards, energy efficiency of batteries is measured in steady state conditions. These conditions usually specify temperature (e.g. 0°C, RT, 40°C, 45°C), constant C-rates for charge and discharge (discharge BEV 1/3C, PHEV 1C according to IEC 62660, charge by the method recommended by the manufacturer) as well as SOCs (100%, 70%; for BEV also 80% according to IEC 62660, 65%, 50%, and 35% for PHEV according to 12405-4)
  - For batteries used in PHEV however, in ISO 12405-4 for example, energy efficiency is also measured at a specified current profile pulse sequence, which is closer to the actual utilisation, including C-rates of up to 20C.
  - For batteries used in ESS, in IEC 61427-2 for example, also load profiles for testing energy efficiency are defined (see Figure 3)

- **Self-discharge/charge retention SD (%SOC/month)** - each battery that is not under load loses part of its capacity over time (temporarily). Charge retention is the ability of a cell to retain capacity on open circuit under specified conditions of storage. It is the ratio of the capacity of the cell/battery system after storage to the capacity before storage (IEC 62620). E.g. 2%/month
    - Self-discharge of EV batteries is measured by storing them at 45°C, 50% SOC and for a period of 28 days (IEC 62660-1), or at RT to 40°C and 100% SOC for BEV, 80% SOC PHEV with a fully operational BMS (ISO 12405-4), storing the batteries for 30 days
    - The remaining capacity after the self-discharge period is measured at 1C for PHEV and 1/3C discharge for BEV, leading to the self-discharge.
- **Cycle life $L_{Cyc}$ (FC)** is the total number of full cycles a battery cell, module or pack can perform until it reaches its End-of-Life (EOL) condition related to its capacity fade or power loss (EOL will be further explained in section 3.3). E.g. 1,500 FC
    - Cycle life of EV batteries is determined by using specified load profiles for PHEV and BEV application (see Figure 4) at temperatures between RT and 45°C
    - PHEV cycle life tests cover SOC ranges of 30-80% and C-rates of up to 20C. If the manufacturer's specified maximum current is lower than 20C, then the test profile is adapted in a predefined way.
    - BEV cycle life tests cover SOC ranges of 20-100%
- **Calendar life $L_{Cal}$/storage life (a)** is the time in years, that a battery cell, module or pack can be stored under specified conditions (temperature) until it reaches its EOL condition (see also SOH in section 3.1.1.2.3). It relates to storage life according to IEC 62660-1, which is intended to determine the degradation characteristics of a battery. E.g. 15 years
    - Ambient conditions for the determination of calendar life are 45°C and a measuring period of three times 42 days
    - Initial SOC for (P)HEV is at 50%, the discharge after storage takes place at 1C
    - Initial SOC for BEV is at 100%, the discharge after storage takes place at 1/3C

The actual service life of a battery cell, module, pack or system is defined by the minimum of cycle life and calendar life.

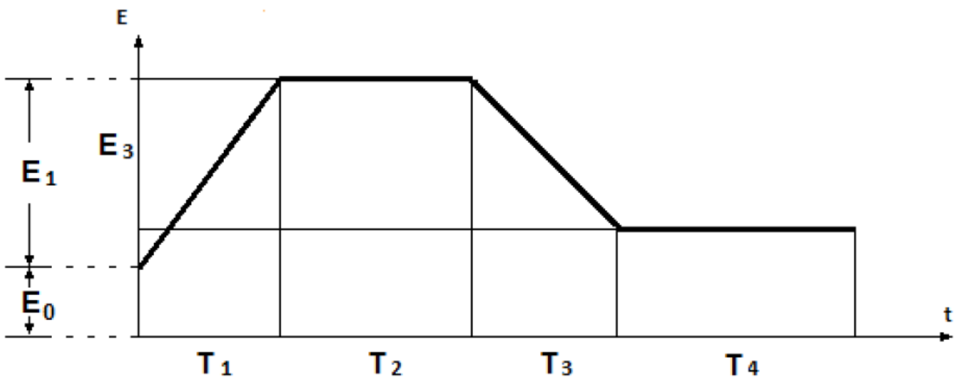


*Figure 3: Typical ESS charging/discharging cycle (IEC 62933-2)*

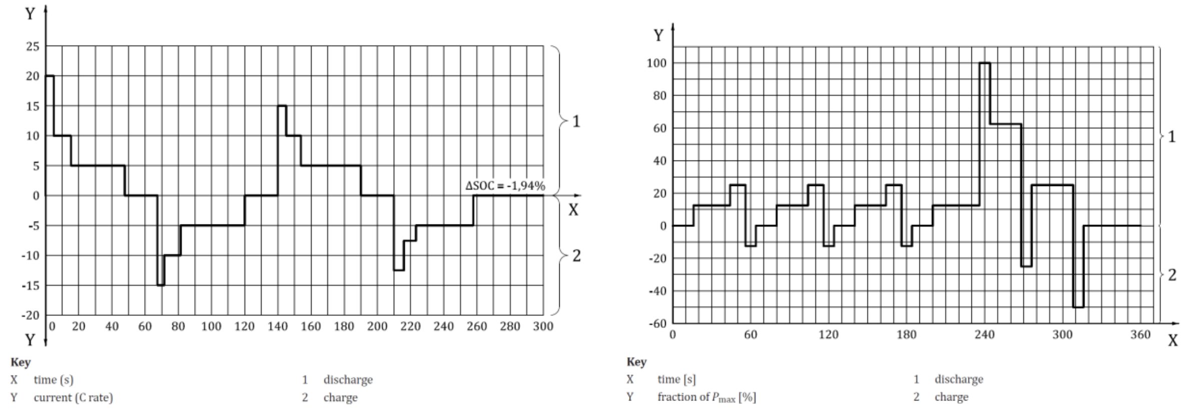


*Figure 4: Cycle test profile PHEV (left) and BEV (right) (discharge-rich) (ISO 12405-4)*

The **application service energy (AS)** (kWh) is the total energy required by the application over its lifetime in kWh. With the lifetime of an application (13 years), the number of annual full cycles $FC_a$ (FC/a) (e.g. 60 FC/a), a rated energy of 80 kWh and 80% DOD it can be calculated as follows:

$$AS = Lifetime\ application * FC_a * E_{rated} * DOD$$

$$= 13 * 60 * 80 * 80\% = 49{,}920\ kWh$$

This formula can be used for all types of applications, when the number of annual full cycles is given. For EVs, given that data on annual all-electric vehicle kilometres travelled (VKT) (e.g. 14,000 km), energy consumption of the vehicle (0, 20 kWh/km) and recovery braking (20%) is available, the following formula can be used:

$$AS_{EV} = Lifetime\ application * annual\ all\text{-}electric\ VKT * energy\ consumption * (1 + recovery\ braking$$

$$= 13 * 14{,}000 * 0{,}20 * (1 + 20\%) = 43{,}680\ kWh$$

If the AS is higher than the $Q_{FU}$ of the battery used in that specific application, more than one battery is required for that application, and thus, a battery replacement is required. The following formula is applied for the calculation of the number of batteries needed to fulfil the application service:

$$N_{bat} = \frac{AS}{Q_{FU}} = \frac{43{,}680}{96{,}000} = 0.46$$

Since that figure is lower than one, in that example, there is no need for a battery replacement.

The actual lifetime (service life) of a battery, as a simplification, is determined by the minimum of cycle life and calendar life (in reality, a superposition of both aging effects takes place). Whichever is reached first, determines the end of life. Thus, it can be calculated as follows:

$$service\ life_{bat} = \min\{\mathrm{L_{Cyc}}; \mathrm{L_{Cal}}\mathrm{FC_a}\}$$

As explained above, when using batteries losses occur due to battery energy efficiency and self-discharge. With an average state of charge $SOC_{Avg}$ (%) of 50%, the losses can be calculated as follows:

$$\mathbf{Losses} = Q_{FU} * (1 - \eta_E) + SD * \underbrace{\min\left\{\frac{L_{Cyc}}{FC_a}; L_{Cal}\right\} * 12}_{\text{actual service life in months}} * SOC_{Avg} E_{Rated}$$
$$= 86{,}400 * (1 - 0{,}96) + 0{,}02 * \min\left\{\frac{1{,}500}{60}; 15\right\} * 12 * 50\% * 80$$
$$= 3{,}840 + 192 = 4{,}032$$

For the exemplary figures chosen, the impact of a battery's energy efficiency on its direct energy consumption is a lot higher than the effect of self-discharge. Further, $E_{Rated}$, DOD, cycle life as well as calendar life, but also the actual annual utilisation of the battery shows high impact on the AS and thus, on the direct energy consumption of a battery.

#### 3.1.1.2.2. Key parameters for the calculation of battery energy efficiency

As we could show in chapter 3.1.1.2.1, the energy efficiency of a battery has strong impact on its direct energy consumption. Consequently, the battery energy efficiency will be reviewed more detailed. The key parameters of a battery that are required for calculating its efficiency are the following:

- **Voltaic efficiency $\eta_V$ (%)** can be defined as ratio of the average discharge voltage to the average charge voltage. The charging voltage is always a little higher than the rated voltage in order to drive the reverse chemical (charging) reaction in the battery (Cadex Electronics 2018).
- **Coulombic efficiency $\eta_C$ (%)** is the efficiency of the battery, based on charge (in coulomb) for a specified charge/discharge procedure, expressed by output charge divided by input charge (ISO 11955).
- With V, I and T as average Voltage, average Current and Time for C Charge and D Discharge the **battery energy efficiency** can be calculated as follows (Recharge 2018):

$$\boldsymbol{Energy\ efficiency} = \left(\frac{V_D}{V_C}\right)\left(\frac{I_D * T_D}{I_C * T_C}\right) = (voltaic\ effiency)(coulombic\ efficiency)$$

Li-ion batteries have a coulombic efficiency close to 100% (better than 99.9% according to Gyenes et al. (2015)) (no side reaction when charged up to 100%). Consequently, the voltaic efficiency is the main lever concerning the battery energy efficiency. It is always below one because of the internal resistance of a battery, which has to be overcome during the charging process, leading constantly to higher charging voltages compared to discharging voltages. Consequently, a higher discharge voltage as well as a lower charge voltage, while all other parameters are kept unchanged, improve efficiency. Figure 5 shows charge and discharge voltages for two different cell chemistries (nickel manganese cobalt (NMC) and lithium iron phosphate (LFP)) in relation to the SOC and the resulting efficiency. It has to be mentioned however, that the scope of this study is not limited to those cell chemistries (see also Task 1 and Task 4). First it can be seen, that charge voltage is higher than discharge voltage for both cell chemistries. Second, the efficiency of NMC cells in monotonically increasing with SOC. Third, the efficiency of LFP decreases rapidly in the extremities (0 and 100% SOC) (Redondo-Iglesias et al. 2018a).

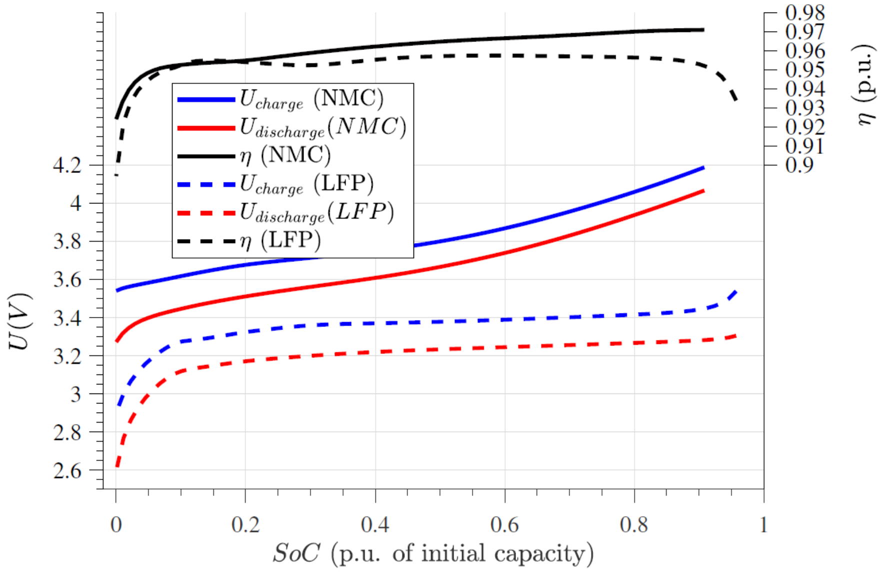


*Figure 5: Charge and discharge voltages (left y-axis) and efficiency (right y-axis) of fresh cells (Source: Redondo-Iglesias et al. (2018a)).*

Different cell chemistries and designs can be differentiated (see Task 4), which also differ in energy efficiency. According to Redondo-Iglesias et al. (2018a) for Lithium Iron Phosphate batteries an energy efficiency of around 95% can be assumed, while for Lithium Nickel Manganese Cobalt Oxide an energy efficiency of 96% at cell level is assumed. Recharge (2018) also assume 96% energy efficiency as an average. Including losses due to the BMS (thermal managements system, protection circuit module) leads, according to Schimpe et al. (2018) and expert interviews to a battery efficiency on system level, as defined within this study, of 92%.

Furthermore, it has to be noted that the energy efficiency strongly depends on the charge/discharge currents (C-rate, power) for given cell chemistry and design (see formula above).

However, it has to be mentioned that these statements are not generalizable. Battery cell characteristics depend on much more than the cathode material only. Any other component (e.g. anode, electrolyte, separator), size and format (cylindrical, pouch, prismatic; see Task 4) as well as the combination of materials and the manufacturing process largely influence the cell characteristics. Consequently, generalizable statements when comparing for example NMC and LFP cells, regarding cycle life or safety, can hardly be made and have to be treated with caution.

#### 3.1.1.2.3. Further parameters related to battery efficiency and affected energy

Besides the parameters that have already been described and discussed, further terms and definitions referring to batteries, battery efficiency and affected energy have to be introduced:

- **Energy E (kWh)** is the total number of kWh that can be withdrawn from a fully charged battery under specified conditions (similar to ISO 12405-1 "capacity").
- **State of health SOH (%)** defines the health condition of a battery; however, no definition can be derived from standards. It can be described as a function of capacity degradation, also called capacity fade (see ISO 12405-4) and internal resistance. Depending on the application, a battery can only be operated until reaching a defined SOH, thus, it relates to the service life of a battery.
- **Internal resistance R (Ω)** is the resistance within the battery, module, pack or system. It is generally different for charging and discharging and dependent on the current, the battery state of charge and state of health. As internal resistance increases, the voltaic efficiency decreases, and thermal stability is reduced as more of the charging/discharging energy is converted into heat.
- **Rated voltage $V_R$ (or nominal Voltage) (V)** is a suitable approximate value (mean value between 0% and 100% DOD) of the voltage during discharge at a specified current density used to designate or identify the voltage of a cell or a battery (IEC 62620).
- **Voltage limits $V_L$ (V)** define the maximum and minimum cut-off voltage limits for safe operation of a battery cell. The maximum voltage is defined by the battery chemistry. For Lithium-ion battery (LIB) cells of LCO, NCA and NMC type 4.2 V are typical voltages. For LFP type, it is 3.65 V. However, the voltages mentioned are operational limits that should be kept in order to reach a certain battery cycle life. There are also higher voltage limits that relate to safety aspects. The battery is fully charged when the difference between battery voltage and open circuit voltage is within a certain range.
- **Open circuit voltage $V_{OC}$ (V)** is the voltage across the terminals of a cell or battery when no external current is flowing. (UN Manual of Tests and Criteria).
- **Volumetric energy density (Wh/l)** is the amount of stored energy related to the battery pack or system volume and expressed in Wh/l (ISO 12405-4).
- **Gravimetric energy density (Wh/kg)** is the amount of stored energy related to the battery pack or system mass and expressed in Wh/kg (ISO 12405-4).
- **Volumetric power density (W/l)** is the amount of retrievable constant power over a specified time relative to the battery cell, module, and pack or system volume and expressed in W/l.
- **Gravimetric power density (W/kg)** is the amount of retrievable constant power over a specified time relative to the battery cell, module, pack or system mass and expressed in W/kg.

Figure 6 shows a typical data sheet of a battery system for use in heavy-duty vehicles. Most of the parameters and terms that have been introduced within that study can be found on that data sheet. The calendar life and the energy efficiency of the battery system, however, is not stated in the data sheet.

| ELECTRICAL DATA | AKASYSTEM 15 OEM 50 PRC | 2P AKASYSTEM 15 OEM 50 PRC | 3P AKASYSTEM 15 OEM 50 PRC | nP AKASYSTEM 15 OEM 50 PRC |
|---|---|---|---|---|
| Cell connection in module | 12s1p | 12s1p | 12s1p | 12s1p |
| Capacity | 50 Ah | 100 Ah | 150 Ah | n* 50 Ah |
| Energy | 33 kWh | 66 kWh | 99 kWh | n* 33 kWh |
| Technology | li-ion NMC | li-ion NMC | li-ion NMC | li-ion NMC |
| Nominal voltage | 661 V | 661 V | 661 V | 661 V |
| Voltage (max.) | 756 V | 756 V | 756 V | 756 V |
| Voltage (min.) | 540 V | 540 V | 540 V | 540 V |
| Discharging power max. (10s)* | 75...150 kW | 150...300 kW | 225...450 kW | n* 75...150 kW |
| Charging power max. (10s)* | 40...70 kW | 80...140 kW | 120...210 kW | n* 40...70 kW |
| Continuous power (RMS) < 15 min* | 50...75 kW | 100...150 kW | 150...225 kW | n* 50...75 kW |
| Continuous power (RMS) > 15 min* | 37...50 kW | 75...100 kW | 112...150 kW | n* 37...50 kW |
| Internal HV-Fuse | 200 A | 2x200 A | 3x200 A | n* 200 A |
| Power consumption in standby mode | 8 W | 16 W | 24 W | n* 8 W |
| Cycle life (depending on DoD, T, power)** | 1,600 - 3,000 cycles | 1,600 - 3,000 cycles | 1,600 - 3,000 cycles | 1,600 - 3,000 cycles |

**AKASYSTEM n 15 OEM 50 PRC: freely scalable according to your application**

*peak rating depending on fuse and cable / connector configuration ** long life cell

| MECHANICAL DATA | AKASYSTEM 15 OEM 50 PRC | 2P AKASYSTEM 15 OEM 50 PRC | 3P AKASYSTEM 15 OEM 50 PRC | nP AKASYSTEM 15 OEM 50 PRC |
|---|---|---|---|---|
| Coolant pressure max. | 2.5 bar | 2.5 bar | 2.5 bar | 2.5 bar |
| Coolant pressure drop (Water/glycol=50/50) | <400 mbar @ 300 l/h nom. 25 °C | <400 mbar @ 600 l/h nom. 25 °C | <400 mbar @ 900 l/h nom. 25 °C | <400 mbar @ n* 300 l/h nom. 25 °C |
| Operating temperature range | -25 to 60 °C | -25 to 60 °C | -25 to 60 °C | -25 to 60 °C |
| Recommended operating temperature | 15 to 35 °C | 15 to 35 °C | 15 to 35 °C | 15 to 35 °C |
| Protection classes | IP67 (IP6K9K possible) | IP67 (IP6K9K possible) | IP67 (IP6K9K possible) | IP67 (IP6K9K possible) |
| Weight (incl. contactor box) typical*** | 230...254 kg | 460...506 kg | 690...759 kg | n*230...n* 253 kg |
| Dimension (L x W x H) in mm (nominal) | 1,700 x 700 x 150 | 1,700 x 700 x 305 | 1,700 x 700 x 460 | 1,700 x 700 x n* 155 |

**AKASYSTEM n 15 OEM 50 PRC: freely scalable according to your application**

***depending on housing material

*Figure 6: Typical battery system data sheet (Source: Akasol (2018)).*

#### 3.1.1.3. Definition of base cases

Looking at the global battery demand (see Task 2), **EV** and **stationary ESS** stand out, especially referring to future market and growth potential. Besides the BEV and PHEV markets, large scale ESS also show high growth rates in future. A bit lower, but still substantial are growth rates for residential ESS according to Task 2 report. In EV applications, the main purpose of batteries is supplying electrical energy to electric motors that are providing traction for a vehicle. In stationary applications they balance load (supply and demand for electricity) and consequently store electrical energy received from the grid or directly from residential power plants (such as photovoltaic (PV) systems or block-type thermal power stations) or commercial power plants (renewable or non-renewable energy sources) and feed it back to the grid or energy consumers.

Since for the two mentioned fields of application, EV and ESS, numerous specific applications can be distinguished, they have to be narrowed down further. As the purpose of this report is to identify the impact of batteries on energy consumption, those applications should be selected for further analyses that have the highest energy consumption. For the **EV** field greenhouse gases (GHG) from road transport are regarded as a useful proxy for energy consumption. Figure 7 shows, that the highest share of GHG can be attributed to **passenger cars** with more than 60%. These are followed by **heavy-duty trucks and buses**. Light duty trucks, motorcycles and other road transportation play a minor role only and are therefore not considered further.

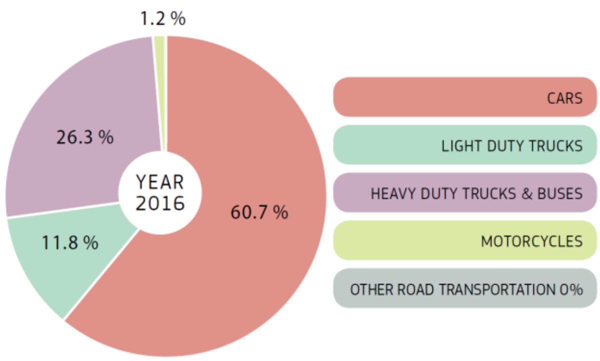


*Figure 7: GHG emissions from road transport in the EU28 in 2016 by transport mean [%] (Source: European Commission (2018)).*

In 2017 more than 15 mio. new passenger cars were registered in the EU28 (European Commission 2018) in contrast to less than 2 mio. light commercial vehicles/light duty trucks, which stresses the importance of passenger cars. Light commercial vehicles and light duty trucks weigh less than 3.5 tonnes and thus, are more similar to passenger cars, than to medium- or heavy-duty trucks. Due to the similarity of light commercial vehicles and passenger cars in terms of battery capacity, fuel consumption or annual mileage, light commercial vehicles are not considered as an own base case but considered to be represented by the passenger car base cases.[1] Passenger cars have, in terms of registrations but also in terms of GHG emissions, by far the highest share in road transport. For that reason and since many different passenger car segments exist, which should be represented in that study, two passenger car types are considered: small-sized cars and medium- to large-sized cars.

Furthermore, 370,000 medium-and heavy-duty trucks were registered in the EU28 in 2017, while only 42,000 buses and coaches were registered (European Commission 2018). Beyond that, the technical characteristics of buses, such as battery capacity, fuel consumption or annual mileage, do not differ significantly from the characteristics of HDT.[2] For that reason,

[1] Battery capacities of light commercial vehicles, which are already on the market, range between 20 kWh (Iveco Daily Electric, Nissan e-NV200 Pro, Streetscooter Work Box, Citroen Berlingo Electrique) and 40 kWh (EMOVUM E-Ducato, Mercedes-Benz eSprinter and eVito (Schwartz 2018). Furthermore, for the light commercial vehicle Renault Kangoo Z.E. Boblenz (2018) states a fuel consumption of 15,2 kWh/100km according to the NEDC which is converted to 19kWh/100km according to the EPA FTP. Finally, light commercial vehicles are driven 15,500 km on average per year in the UK (Dun et al. 2015) and 19,000 km in Germany (KBA 2018), which is just slightly higher than for passenger cars.

[2] The battery capacity of urban buses ranges between 80 kWh and 550 kWh (Electrek 2017; VDL Bus & Coach 2019), while most of the buses have a battery capacity of around 200 kWh. Aber (2016) states an average energy consumption of 125 kWh per 100 km and according to Papadimitriou et al. (2013) urban buses travel on average between 40.000 and 50.000 km a year, while coaches travel up to 60.000 km on average.

considering buses as an own base case would not lead to significant new insights, regarding the Ecodesign process.

Trucks can be further differentiated according to their gross vehicle weight (GVW) in medium-duty trucks (up to 16 tonnes GVW) and heavy-duty trucks (HDT) (more than 16 tonnes GVW). Since the registrations of HDT are three times higher than those of medium-duty trucks (European Commission 2018), the former will be in the focus of this study. HDT can be heavy-duty straight trucks, semi-trailer trucks, or tractor units, referred to as heavy-duty tractor units (HDTU).

Regarding **passenger cars, BEV and PHEV** are the most promising battery-related applications (Gnann 2015). For **HDT** also **battery-electric vehicles** seem to be very promising, while for **HDTU plug-in-hybrid solutions** seem to be promising (Wietschel et al. (2017)).

There are currently four potential main applications for **stationary ESS** (see also Task 2): PV battery systems, peak shaving, direct marketing of renewable energies and the provision of operating reserve for grid stabilization in combination with multi-purpose design (Michaelis 2018). Since PV battery systems, referred to as **residential ESS** and the provision of operating reserve and multi-purpose design, referred to as **commercial ESS,** seem to have the highest market potential (see Thielmann et al. (2015b) and Task 2), they will be in the scope of this study.

The most promising battery technology (see Task 4) for both fields of application, EVs as well as ESS are large-format lithium-ion batteries. This is due to their technical (in particular energy density, lifetime) as well as economic (cost reduction) potential. It has to be noted that the product scope is still the battery system as defined in section 3.1.1. However, the utilization of the battery, represented by a load profile for example, as well as battery capacity varies.

To sum it up the following applications are in the scope of this study and define **base cases**:

**EV applications:**

- passenger BEV (medium to large)
- passenger BEV (small)
- passenger PHEV
- battery-electric HDT
- plug-in-hybrid HDTU

**Stationary applications:**

- residential ESS
- commercial ESS

The base cases defined above have certain requirements concerning technical performance parameters, such as energy densities, calendar and cycle life, C-rates (fast loading capabilities) and tolerated temperatures, which will be defined in the following sections.

**Parameters for the definition of base cases**

Looking at the formula for the calculation of the direct energy consumption of batteries (see chapter 3.1.1.2.1), the following parameters have to be defined for all base cases:

- Rated battery capacity
- Depth of discharge
- Annual full/operating cycles base case
- Calendar life base case
- Energy efficiency battery

#### 3.1.1.3.1. Base cases for EV applications

**Rated battery capacity on application level**

The required and suitable rated battery capacity highly depends on the actual vehicle type. The bigger and heavier a car is, the larger the battery capacity should be. Currently for BEV 20 to 100 kWh (Tesla Model S and X) are common battery capacities, although larger battery capacities might be available for special sport cars. PHEV usually have a battery capacity of 4 to 20 kWh. Medium- to large-sized cars currently have a battery capacity between 60 and 100 kWh. Therefore, we take **80 kWh** for the **base case BEV (medium to large).** The current sales-weighted average of rated battery capacity for passenger **BEV** in Europe is 39 kWh, thus we assume **40 kWh** to be the battery capacity of **small-sized passenger BEV**. For passenger **PHEV** the average is at 12 kWh and stayed almost constant (see Figure 8). Therefore, we assume **12 kWh for PHEV**.

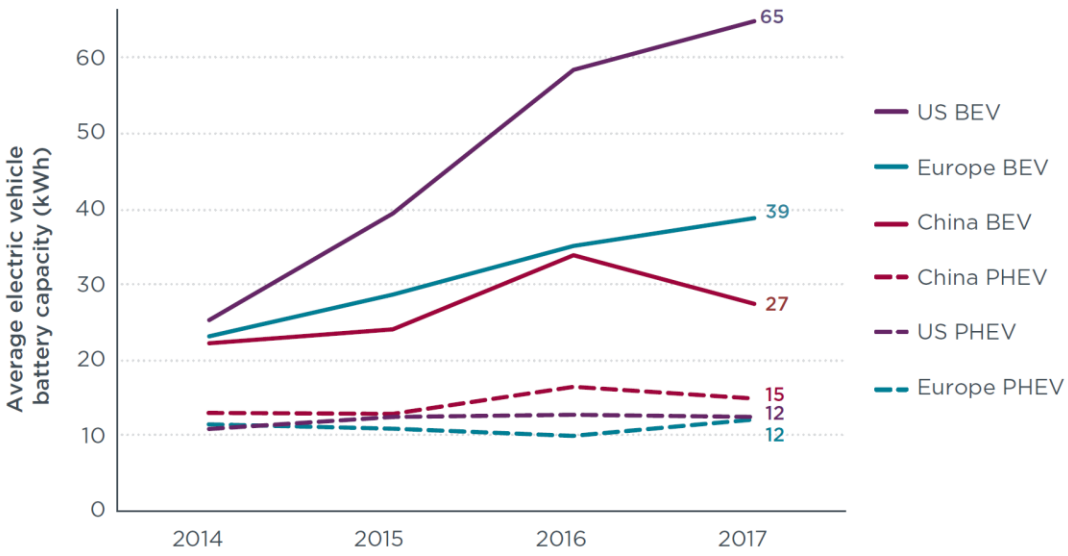


*Figure 8: Sales-weighted average of xEV battery capacities for passenger cars [kWh] (Source: ICCT (2018))*

In contrast to passenger cars, no battery-electric **HDT** (between 12 and 26 to gross vehicle weight (GVW)) is available on the market. So far, only some pre-series trucks are tested by selected customers (Daimler 2018; MAN Truck & Bus AG 2018). Nevertheless, truck OEM specified technical details for their announcements, ranging from 170 kWh battery energy of a DAF CF Battery Electric up to a Tesla Semi (HDTU) with 1,000 kWh battery capacity (Honsel

2018). Most of the battery capacities currently stated range between 200 and 300 kWh, however, a further increase can be expected for the future and thus, 360 kWh is assumed for the base case. According to Hülsmann et al. (2014) and Wietschel et al. (2017) for long range **HDTU** purely battery-electric trucks seem not to be a proper solution. They argue that range and costs of battery-electric HDTU are not competitive. As mentioned, some truck manufacturers however, such as Tesla (Tesla Semi) and Daimler (Freightliner eCascadia) announced HDTUs with ranges of 400 to 800 km being provided by a huge battery. Nevertheless, two drawbacks are linked with high battery capacities: First, because of their high weight, they significantly reduce payload, which is hardly acceptable for truck operators. Second, big batteries, besides their negative ecological impact, which is increasingly discussed in public and the limited availability of resources, are very expensive. Since in a business context (e.g. logistics service providers), economic aspects and as such especially the total cost of ownership of operating a truck are decisive, from the current point of view battery-electric trucks don't have a high market potential, thus plug-in hybrid HDTU are considered. Following Hülsmann et al. (2014) and Wietschel et al. (2017), a battery energy of **160 kWh** is assumed for PHEV **HDTU**.

**Depth of Discharge**Referring to Hülsmann et al. (2014) for BEV applications a DOD of 80% is assumed. For PHEV applications, 75% DOD seems to be reasonable, according to expert interviews.

**Annual full/operating cycles and calendar life base case**

The number of operating cycles[3] per year can be retrieved by dividing the all-electric annual vehicle mileage by the all-electric range of the vehicles. Thus, first the all-electric annual mileage of vehicles has to be determined, before the all-electric range and the calendar life of the base cases are defined.

*Annual mileage*

Although it is argued, that driving profiles of ICEV (internal combustion engine vehicles) and BEV or PHEV might differ (Plötz et al. 2017a) (on the one hand the range of EV is limited but on the other hand their variable costs are comparably low in contrast to their high fixed costs, resulting in high annual mileages being beneficial for EV) for this study it is assumed, that the same annual mileage and driving patterns apply to all powertrains. Further, for simplification reasons we do not thoroughly review distinct (daily) driving patterns and profiles but average annual and daily driving distances. However, taking Figure 9 into consideration it becomes clear that average values are just a rough approximation of the actual daily driving distances, which can vary greatly in size.

[3] For EV operating cycles are calculated, since data can be retrieved more easily than for the calculation of full cycles.

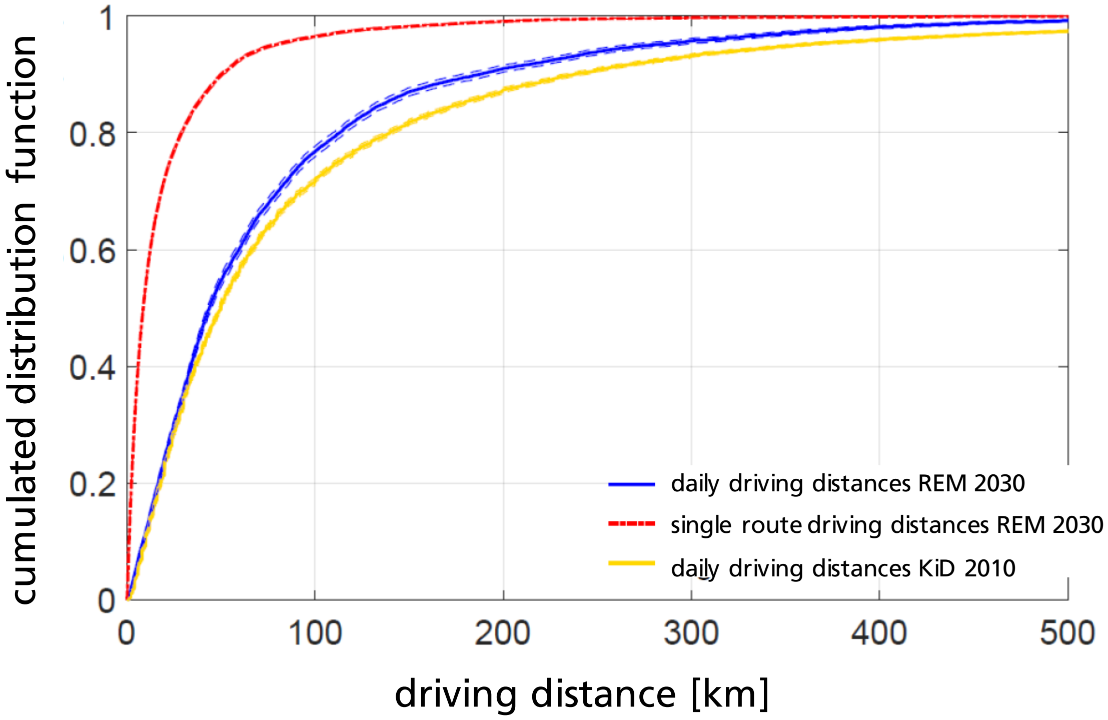


*Figure 9: Daily and single route driving distances of passenger cars in Germany (Source: Funke (2018)).*

The average vehicle kilometres travelled (VKT) per **passenger car** and year in the EU28 is approximately 14,000 km for medium-large passenger cars and 11,000 km for small passenger cars according to Papadimitriou et al. (2013). Further, the average retirement age of medium-large cars is around 13 years, while for small cars it is 14 years. However, the service life of EVs could be longer than that of ICEV because of less mechanical parts subjected to failure risk.

**HDT** drive on average **50,000 km** per year in the EU28 (Papadimitriou et al. 2013). Further, the average for **HDTU** is **100,000 km** per year. The typical operating life is **14 years** for **HDT** and **12 years** for **HDTU** in the EU(Papadimitriou et al. 2013).

*All-electric range and mileage*

For **BEV**, naturally the entire annual mileage is driven all electric. Plötz et al. (2017b) find, that in Germany each passenger car is used on **336 of 365 days** of the year, thus 40 km is the assumed daily all-electric mileage of a BEV passenger car. Further, the all-electric driven share of passenger **PHEV** is calculated by Plötz et al. (2017a) and it is about 40-50% with 40 km all-electric range. Since the base case PHEV's all electric range is 50 km (battery capacity multiplied with DOD, divided by energy consumption; required values to be discussed in the next paragraphs) 50% all electric mileage is assumed, leading on an annual basis to **7,000 km**. **HDT** drive on **260 days** per year (daily ~190 km all-electric for HDT and 380 km for HDTU) (Wietschel et al. 2017). Since the all-electric range of HDT is **240 km** (same calculation as for passenger PHEV) no intermediate charging is required. **HDTU** have an all-electric range of only **86 km**, thus intermediate charging is required for achieving high all-electric VKT. The HDTU however is continuously on the road, only making stops in order to account for mandatory periods of rest. A break of 45 to 60 minutes for fast charging should be sufficient, in order to fully recharge the battery, leading to a daily range all-electric range of 140 km, which might be increased further by mandatory breaks. Thus, we conclude, that 50,000 of the 100,000 kilometres per year might be driven all-electric by the HDTU.

The all-electric ranges of EVs can either be derived from measurements based on official test cycles or calculated by multiplying the rated energy by the DOD and dividing the result by the energy consumption of the vehicle (the latter approach is less accurate and it is therefore neglected). The energy consumption in that case also has to be derived from measurements according to official driving cycles.

*EV energy consumption*

The application service energy of a vehicle can roughly be differentiated in energy required for traction and energy required by ancillary consumers, such as entertainment systems, air conditioning or light machine, servo steering and ABS. Figure 10 shows the energy consumption [kWh] and distribution of a Nissan Leaf (2012) on a specific drive cycle (~12km). Around 30% of the energy provided to the electric motor can be fed back into the battery due to regenerative braking (explained below). However, for the base cases we assume 20% as a conservative assumption. The accessories load sums up to approximately 3%. However, it is important to note, that referring to these figures no cooling or heating of the driver cabin is included. This can increase energy consumption by around 25%.

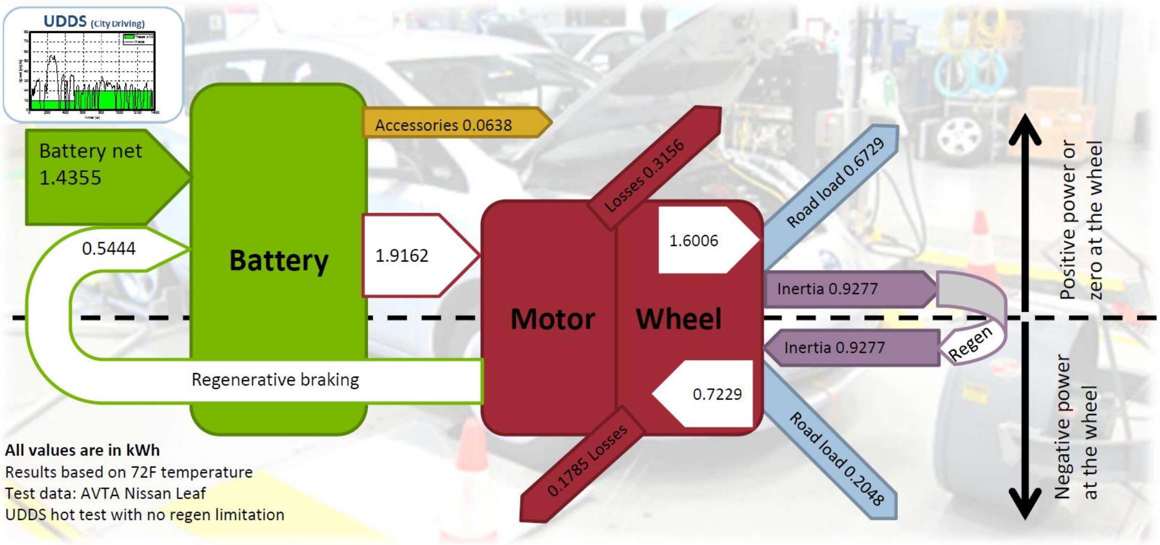


*Figure 10: Battery energy efficiency losses of Nissan Leaf (2012) (Source: Lohse-Busch et al. (2012))*

All of the energy consumed within a BEV (leaving out auxiliary lead-acid batteries), the total energy consumption of the vehicle has to be delivered by the battery, which is also true for the electric mode of PHEV.

The energy required by a vehicle for its traction can be calculated as follows (Funke 2018):

$$\int \frac{1}{\eta_{PT}} \left( \underbrace{\frac{1}{2} c_d \rho A v^2}_{aerodynamic\ drag\ resistance} + \underbrace{c_r m g}_{rolling\ resistance\ force} + \underbrace{ma}_{mass\ acceleration} \right) * v \ dt$$

With ηPT being the efficiency of the vehicle's powertrain (electric motor, gearbox, power electronics), cd as drag coefficient, ρ as density of fluid [kg/m3] (1.2 kg/m3 for air), A as characteristic frontal area of the body [m2], v as flow velocity [m/s] (driving speed), cr as rolling resistance coefficient, m as mass of body [kg], g as acceleration of gravity [$m/s^2$] and a as lengthways acceleration of the vehicle. When considering the traction energy requirements of a vehicle, one can see that it substantially depends on the vehicle's speed (to the power of three) but also on the vehicle's mass. This is where the **impact of the battery weight** on energy consumption becomes clear. Furthermore, **payload** plays an important role, especially for commercial vehicles. Since for example the battery weight of a Tesla Model S can be as high as 500 kg, an impact of battery weight on the traction energy consumption and consequently on the total fuel consumption can be expected. Detailed calculations cannot be part of that study, but as a rough estimation for each additional 25 kWh battery energy an increase in fuel consumption of 1 to 2 kWh/100km can be expected, while in future due to improvements of gravimetric energy density 0.5 to 1 kWh/100 km might be possible (Funke 2018).

What can also be seen from the formula presented is that vehicle speed and acceleration and consequently **individual driving behaviour** have a strong impact on fuel consumption.

*Energy consumption measured with standard tests*

For the assessment of passenger cars' emissions and fuel economy the **Worldwide Harmonized Light Vehicle Test Procedure** (WLTP) just recently replaced the **New European Driving Cycle** (NEDC) as reference drive cycle. It was established in order to better account for real-life emissions and fuel economy and it uses a new driving/speed profile (see Figure 11). The WLTP comprises 30 instead of 20 minutes of driving; it includes more than twice the distance and less downtime compared to the NEDC. Further, the average speed is 46.5 km/h instead of 34 km/h; also, a cold engine start is carried out, while air conditioning use is still not considered. Plötz et al. (2017a) argue, that fuel consumption of cars measured with the WLTP is closer to real-life fuel consumption, but it is still not accurate.

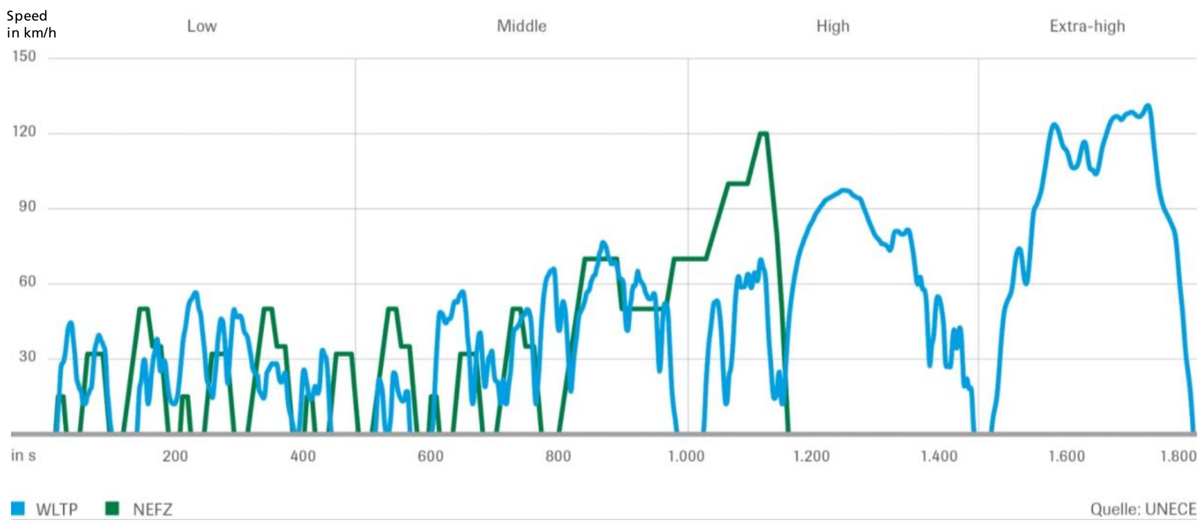


*Figure 11: Comparison of speed profiles for WLTP and NEDC (Source: VDA (2018))*

They consider the use of the **Federal Test Procedure** (FTP) of the U.S.-American Environmental Protection Agency (EPA) more accurate and very close to real-life behaviour (see speed profile in Figure 12). This is mainly because the FTP includes AC use and hot and cold ambient temperatures, both having big impact on the fuel consumption. That is why for the fuel consumption of the reference applications, if available, values measured with the FTP are used. According to Plötz et al. (2017a) the all-electric driving range, and thus also fuel consumption of vehicles measured with the NEDC can be assumed to be 25% lower than when measured with the FTP.

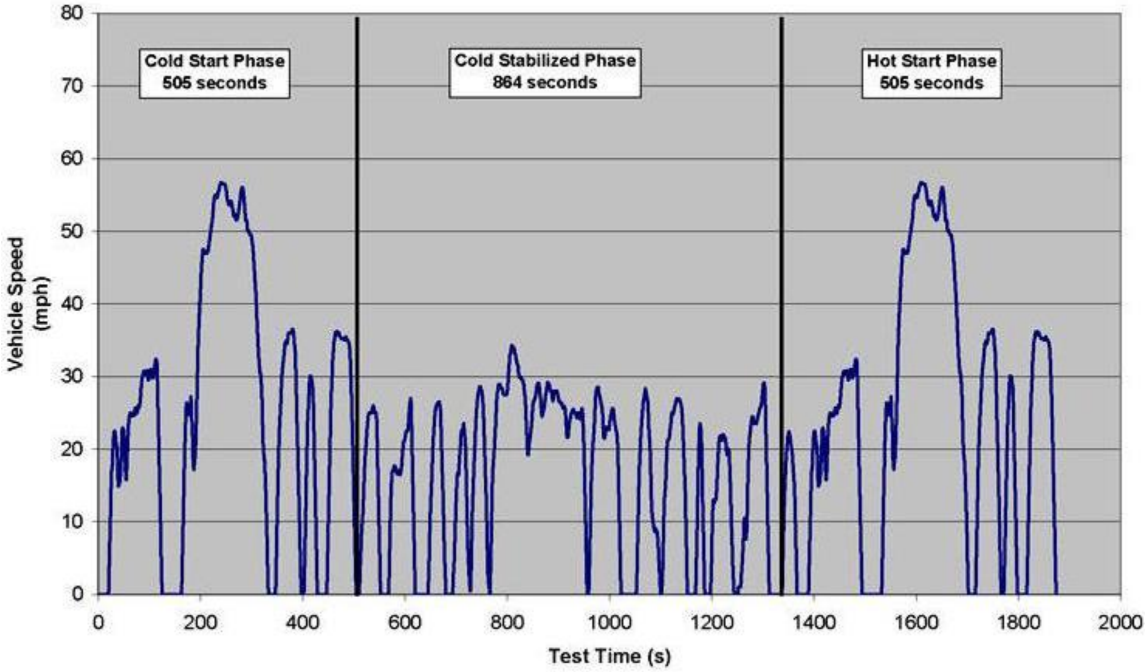


*Figure 12: Speed profile of EPA Federal Test Procedure (Source: EPA (2018)).*

Fueleconomy.gov (2018) provides a database of energy consumption of passenger BEV and PHEV. Analyzing the fuel consumption of medium-large and small BEV as well as PHEV and including efficiency gains in the near future, we assume that the base case BEV (medium and large) will consume 20 kWh/100km, while BEV (small) will consume 16 kWh/100km and PHEV around 18 kWh/100 km. No fuel consumption is specified for **HDT**, but from range specifications of the Daimler eActros a fuel consumption of **120 kWh/100km** can be derived. Comparing that figure to Hülsmann et al. (2014), Hacker et al. (2014) and Wietschel et al. (2017) it can be confirmed **.** For a **HDTU** a fuel consumption of **140 kWh/100km** can be derived from Wietschel et al. (2017) .

A big advantage of BEV and PHEV, that helps increasing the range, is the potential **brake energy recovery** (regenerative braking, or braking energy recuperation). During braking, a certain share of the kinetic energy can be recovered when using the electric motor as a generator, feeding back energy to the battery.

Gao et al. (2018) state that about 15% of battery energy consumption could be recovered with a 16t **battery-electric delivery truck**, while Xu et al. (2017) find, that 11.5% of the battery energy consumption could be recovered - **12%** is used as a conservative assumption. Furthermore Gao et al. (2015) find, that a plug-in electric **HDTU** (parallel-hybrid with diesel engine) is able to reduce total fuel consumption by 6 to 8% although there is not much kinetic energy recovery. The reason is associated with the more optimal utilization of the engine map. It is assumed, that the fuel consumption is reduced by **6%** on average through energy recovery, no matter if it is a plug-in-hybrid truck with a diesel engine, fuel cell or catenary system.

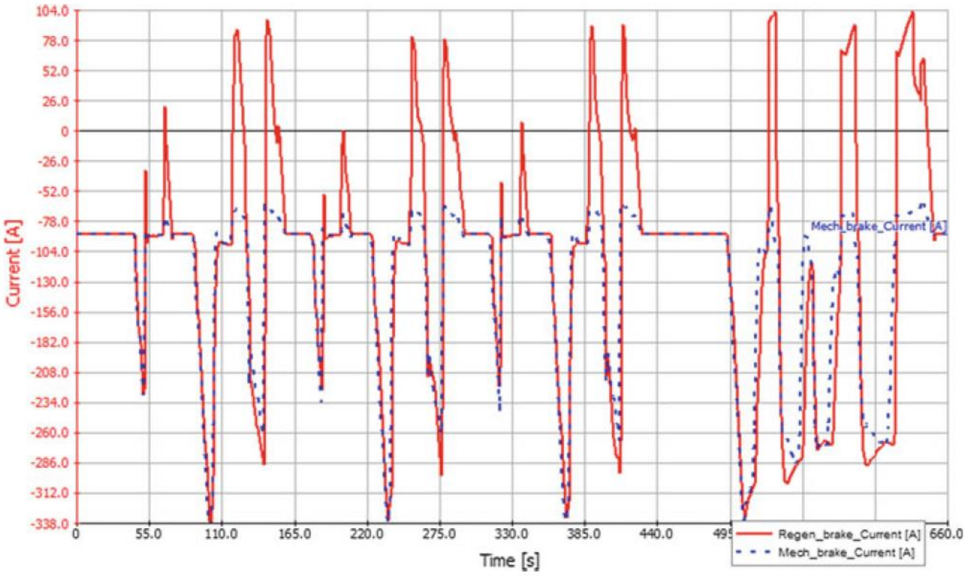


*Figure 13: Current change curves (Source: Xu et al. (2017))*

*Calendar and cycle life of battery*

It is desirable that the battery's cycle and calendar life coincides with the vehicle lifetime. Nevertheless, especially for high annual vehicle mileage, this might not be feasible, since for batteries that are used in BEV a cycle life of **1,500 full cycles** and for batteries used in PHEV a cycle life **2,000 full cycles** are assumed (according to experts), before the batteries reach EOL condition (assuming no calendar aging). Batteries for HDT and HDTU have to be designed for higher annual mileage, thus, **2,000 full cycles** are assumed for **BEV HDT** and **3,000 full cycles** for **PHEV HDTU** (based on expert interviews). Further, a maximum calendar life of the installed battery (assuming no cycling) of **20 years** seems reasonable for all EV applications according to experts (high power or high energy required). Those lifetime figures might require full or partial battery changes concerning the applications (see chapter 3.3.2).

An important aspect that would have impact on the battery's lifetime is the potential provision of demand side flexibility by BEVs and PHEVs. One option is controlled or smart charging of EVs regarding flexible timing and charging power, which is tested and partially already implemented (controlled/delayed/smart grid-to-vehicle G2V). Smart charging can be operated by smart charging devices or by the distribution grid operator. Smart charging devices can optimize the charging of EVs economically from a user perspective by profiting from flexible electricity tariffs. A positive side-effect can be a reduced capacity degradation of the EV due to on average reduced SOCs (González-Garrido et al. 2019). Grid operator controlled smart charging reveals load-shifting potential to the distribution grid operator. Having load-shifting potential at hand reduces required grid expansion, which is due to the additional load caused by EVs, but it might also lead to "un-optimal" charging, which could decrease battery lifetime. Another option is, that EVs, which are idle and connected to the grid could be used as flexible energy storage, feeding energy back into the grid (vehicle-to-grid V2G) for which EV owners would get a compensation. This would cause additional cycling and thus reduce the battery lifetime. EVTC (2017) was able to show that delayed G2V charging does not have negative impact on the battery, while González-Garrido et al. (2019) even showed a positive effect on the battery. Both studies agree, however, that V2G charging accelerates capacity degradation significantly. González-Garrido et al. (2019) state an increased degradation of 15 to 30% depending on V2G power, while Jafari et al. (2018) state an additional battery degradation of

14 to 37% depending on the type of service provided (frequency regulation, peak shaving or solar energy integration).

**Energy efficiency**

As already explained above, the energy efficiency of a battery depends on the operating conditions. Assuming optimum temperatures, provided by a TMS, C-Rate is the deciding factor. For BEV at an average C-rate for charging and discharging of 0.5C the energy efficiency of the battery is about 96%. This figure relates to DOE (2012) where it is stated, that at the most demanding drive cycle an average battery efficiency of 95% can be measured. Since the most demanding drive cycle is not the most representative drive cycle we assume a slightly higher efficiency of 96%. For PHEV the same energy efficiency is assumed.

As explained in section 3.1.1.2.1, the application service energy for EVs can be calculated by either using detailed data on actual vehicle and driving characteristics or by using an assumed number of full cycles. Taking all data and assumptions into account, an annual number of full cycles and thus charging of 120 can be estimated for all passenger cars it seems reasonable that they are charged on every third day. Because of the much more frequent use, for the HDT base case 300 full cycles and for the HDTU 600 full cycles can be assumed. Beyond that, many figures that have been discussed, such as battery energy efficiency, self-discharge, battery calendar or cycle life, energy consumption of the vehicle etc. were assumed to be static as they are defined in several battery, vehicle and ESS testing standards. It has to be mentioned, however, that those figures highly depend on the actual utilization of batteries, which change according to temperature and actual driving/load profiles of the applications, for example. In this section, those deviations are not taken into consideration.

The data discussed in the previous paragraphs is summed up in Table 1. We included application specific parameters such as lifetime, VKT, energy consumption, range, DOD and typical range of the battery capacity in that application. Further, we calculated the quantity of functional units according to section 3.1.1.1 and the application service energy as well as energy consumption due to battery energy efficiency and due to self-discharge according to section 3.1.1.2.1 for each application. Those figures are related to the strict product approach.

*Table 1: Summary of data required for the calculation of EV base cases*

| | **Passenger BEV (medium to large)** | **Passenger BEV (small)** | **Passenger PHEV** | **HDT BEV** | **HDTU PHEV** |
|---|---|---|---|---|---|
| Economic lifetime of the application [a] | 13 | 14 | 13 | 14 | 12 |
| Annual vehicle kilometres [km/a] | 14,000 | 11,000 | 14,000 | 50,000 | 100,000 |
| All-electric annual vehicle kilometres [km/a] | 14,000 | 11,000 | 7,000 | 50,000 | 50,000 |
| Energy consumption [kWh/100km] | 20 | 16 | 18 | 120 | 140 |
| Braking energy recovery in AS [% fuel consumption] | 20% | 20% | 20% | 12% | 6% |
| All-electric range [km] | 320 | 200 | 50 | 240 | 86 |
| Annual number of full cycles [cycle] | 120 | 120 | 120 | 300 | 600 |
| Maximum DOD (stroke) [%] | 80% | 80% | 75% | 80% | 75% |
| Typical capacity of the application [kWh] | 80 | 40 | 12 | 360 | 160 |
| Min capacity of the application [kWh] | 60 | 20 | 4 | 170 | n/a |
| Max capacity of the application [kWh] | 100 | 60 | 20 | 1,000 | n/a |
| Battery calendar life (no cycling) [a] | 20 | 20 | 20 | 20 | 20 |
| Battery cycle life (no calendar aging) [FC] | 1,500 | 1,500 | 2,000 | 2,000 | 3,000 |
| **Application Service Energy (AS) [kWh]** | **96,000** | **48,000** | **18,000** | **576,000** | **360,000** |
| **Maximum quantity of functional units (QFU) over application service life [kWh]** | **43,680** | **29,568** | **19,656** | **940,800** | **890,400** |
| Battery energy efficiency | 92% | 92% | 92% | 92% | 92% |
| **Energy consumption due to battery energy efficiency [kWh]** | **7,680** | **3,840** | **1,440** | **46,080** | **28,800** |
| Self-discharge rate [%/month] | 2% | 2% | 2% | 2% | 2% |
| Average SOC [%] | 50% | 50% | 50% | 50% | 50% |
| **Energy consumption due to self-discharge [kWh]** | **192** | **96** | **29** | **864** | **384** |

#### 3.1.1.3.2. Base cases for stationary ESS

**Rated energy**

Referring to Graulich et al. (2018) and Figgener et al. (2018) residential ESS have an average battery energy of approximately 10 kWh, although a range of 1 to 20 kWh is possible.

The battery energy and power of currently installed commercial ESS varies widely between 0.25 and 129 MWh (see Hornsdale Power Reserve (2018) and Task 2). For commercial ESS a trend towards bigger rated energies can be seen, thus a total application rated energy of 30,000 kWh is assumed.

**Depth of Discharge**

According to Stahl (2017) the DOD of residential and commercial ESS is at 90%. However, that DOD is only relevant for some limited applications and thus, 80% are assumed.

**Annual full cycles and calendar life base case**

Batteries that are coupled with PV (residential ESS) are expected to be subject to 200 to 250 full cycles per year. The upper boundary is chosen for the base case, following expert interviews. These figures are average values that might represent central Europe. Of course, in Scandinavian countries these figures would be much lower, while in southern European countries, such as Spain or Italy these figures would be higher.

It also has to be noted, that the number of cycles might increase in future, when these residential ESS are allowed to provide grid services, such as primary frequency control on top of self-consumption. In some EU member states the regulation is about to change, in order to allow residential ESS to provide grid services. There is a lack of empirical data on how many cycles would be added. According to experts 50 to 80 additional cycles per year are realistic, which could be increased to up to one daily grid service cycle (365 annual cycles in total) for revenue-optimising residential actors.

Thielmann et al. (2015b) state, that calendar life of a battery and the PV system should coincide, which is 15 to 25 years for the latter. Thus, 25 years are assumed. Consequently, less than 5,000 full cycles would be required. For German residential ESS Holsten (2018) confirm on average around 400 full-load hours of use per year and thus 200 full cycles. Figure 14 shows a typical daily load profile of a residential PV system coupled with an ESS. The battery is charged during daytime and the stored energy is consumed during the night. Further, Holsten (2018) determine a figure of around 450 full-load hours per year for commercial ESS which corresponds to 225 full cycles. However, we assume 250 cycles, since demand for flexible ESS might increase in future due to the increasing share of renewable energy generation. Figure 15 shows the load profile of a commercial ESS, depicting the high fluctuations of feed-in and feed-out.

**Cycle life and calendar life battery**

For residential ESS a cycle life of the battery of 8,000 cycles and for commercial ESS of 10,000 cycles seems to be feasible (Holsten 2018), in combination with a calendar life of 25 years for residential and commercial ESS (expert interviews).

**Energy efficiency**

As in EV applications, an energy efficiency of 96% is assumed.

Since residential ESS are usually operated within private houses, ambient conditions are no critical issue and the operating temperature can be expected to be little under room temperature. The same applies to commercial ESS. Gravimetric and volumetric energy density are also only of minor relevance, because space and weight in private houses or commercial sites are not as limited as in EV for example (Thielmann et al. 2015b).

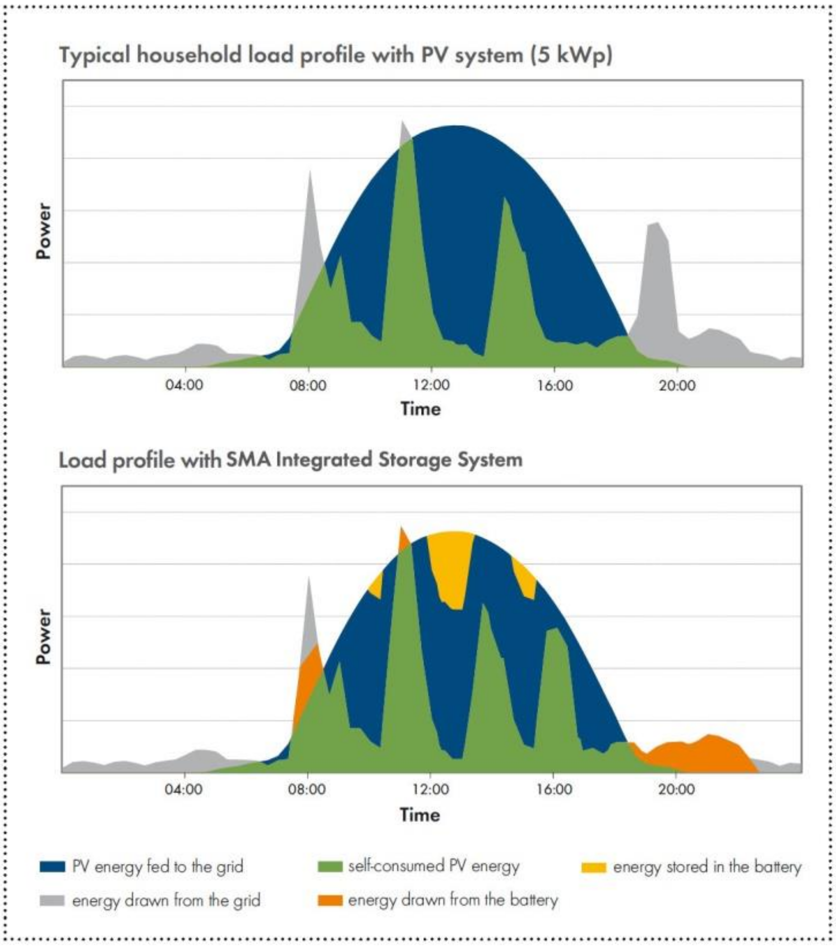


*Figure 14: Household load profile of PV with and without battery (Source:(SMA 2014) SMA (2014) )*

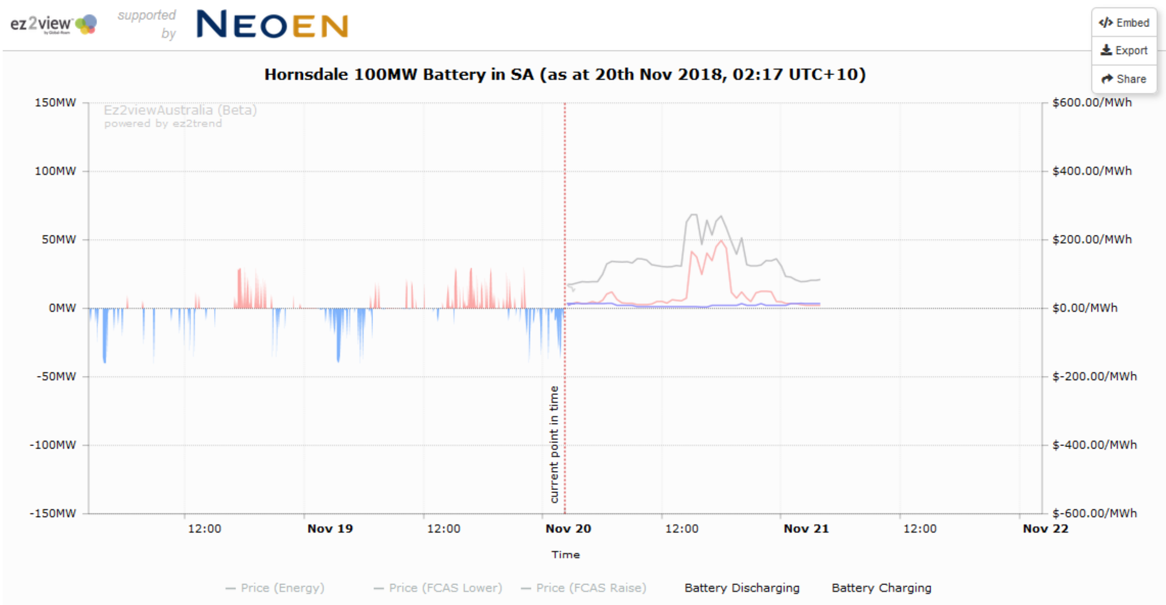


*Figure 15: Load profile of commercial ESS (source: Hornsdale Power Reserve (2018))*

The data discussed in the previous paragraphs is summed up in Table 2. We included application specific parameters such as lifetime, annual full cycles, DOD and typical range of the battery capacity in that application. Further, we calculated the quantity of functional units according to section 3.1.1.1 and the application service energy as well as energy consumption due to battery energy efficiency and due to self-discharge according to section 3.1.1.2.1 for each application. Those figures are related to the strict product approach.

*Table 2: Summary of data required for the calculation of ESS base cases*

| | **Residential ESS** | **Commercial ESS** |
|---|---|---|
| Economic lifetime of the application [a] | 20 | 20 |
| Annual full cycles [FC/a] | 250 | 250 |
| Maximum DOD (stroke) [%] | 80% | 80% |
| Typical system capacity [kWh] | 10 | 30,000 |
| Minimum system capacity | 2.5 | 250 |
| Maximum system capacity | 20 | 130,000 |
| Battery calendar life (no cycling) [a] | 25 | 25 |
| Battery cycle life (no calendar aging) [FC] | 8,000 | 10,000 |
| **Application service energy** | **40,000** | **120,000,000** |
| **Maximum quantity of functional units ($Q_{FU}$) over battery service life** | **64,000** | **240,000,000** |
| Battery system energy efficiency | 92% | 92% |
| **Energy consumption due to battery energy efficiency [kWh]** | **5,120** | **19,200,000** |
| Self-discharge rate [%/month] | 2% | 2% |
| Average SOC [%] | 50% | 50% |
| **Energy consumption due to self-discharge [kWh]** | **30** | **90,000** |

#### 3.1.1.3.3. Summary of standard test conditions for EV and ESS battery packs and systems

Two standards that are widely used for the testing of EV batteries are IEC 62660 and ISO 12405. While IEC 62660 refers to cells testing, ISO 12405 refers to systems testing (see MAT4BAT 2016, EnergyVille 2019 and Annex to Task 1 "Analysis of available relevant performance standards & methods in relation to Ecodesign Regulation for batteries and identification of gaps" for further details). The standards related to EVs are depicted in Table 3, whereas the standard related to ESS is depicted in Table 4.

*Table 3: Standard test conditions for EV (Source: based on MAT4BAT Advanced materials for batteries (2016), EnergyVille (2019) and Annex to Task 1)*

| Test | Application | Test conditions IEC 62660-1:2010 | Test conditions ISO 12405-4:2018 |
|---|---|---|---|
| Energy efficiency | BEV/PHEV | @100%, 70% SOC<br>@-20°C, 0°C, 25°C, 45°C<br>Charge according to the manufacturer and rest 4 hours<br>discharge BEV @C/3, HEV @1C | @ 65%, 50%, 35% SOC<br>@ 0°C, 25°C, 40°C<br>12s charge pulse @Imax (or 20C) and rest 40s then 16s discharge pulse @0.75 Imax (or 15C) |
| | BEV | Fast charging<br>@25°C | Fast charging<br>@0°C, 25°C |

| | | | |
|---|---|---|---|
| | | Charge @2C to 80% SOC and rest 4 hours<br>Charge @2C to 70% SOC and rest 4 hours | Charge @1C and rest 4 hours<br>Charge @2C and rest 4 hours<br>Charge @Imax and rest 4 hours |
| **Self-discharge** | BEV/PHEV | Stored @45°C, conditioned @25°C @50% SOC<br>Determination with 1C<br>Duration 28 days, checkup 28 days | |
| | BEV | | @25°C, 40°C<br>@100% SOC<br>No load for 48h, 168h, 720h |
| | PHEV | | @25°C, 40°C<br>@80% SOC<br>No load for 24h, 168h, 720h |
| **Cycle life** | BEV/PHEV | Stored @45°C, conditioned @25°C @SOC window 100%-20% and 80%-25%,<br>Different BEV and HEV profiles<br>Check-up every 28 days at 25°C<br>End of test if C(current)<0.8C (initial) or 6 months | |
| | | | @25°C - 40°C according to TMS<br>@SOC window 100%-20%<br>different BEV profiles<br>Check-up every 28 days @25°C<br>Limits during check-up to be defined before |
| | | | @25°C - 40°C according to TMS<br>SOC window 80%-30%<br>different PHEV profiles<br>Check-up every 28 days at 25°C<br>Limits during check-up to be defined before |
| **Storage life** | BEV/PHEV | Tested @20°C, checkup@25°C @100% SOC for BEV, @50% SOC for HEV<br>Discharge @C/3 for BEV, 1C for HEV<br>Check-up every 42 days, end after 3 repetitions | |

*Table 4: Standard test conditions for ESS (Source: Annex to Task 1 and IEC 2015)*

| Test | Application | IEC 61427-2: 2015 |
|---|---|---|
| **Energy efficiency** | residential and commercial ESS | Calculate average of:<br>@ RT, max and min ambient temperature during enduring test with defined profile |
| **Waste heat** | | @ Max ambient temperature during endurance test with defined profile |
| **Energy requirements during idle state** | | @ RT during periods of idle state |
| **Self-discharge** | | @ RT<br>@ 100% SOC for UPS, 50% SOC for other applications<br>1C<br>Check-up every 42 days, end after 3 repetitions |
| **Service life** | | @ RT - 40°C according to TMS<br>@SOC window 100%-20%<br>with endurance test profile<br>Check-up every 28 days at 25°C |

### 3.1.2. Extended product approach

In chapter 3.1.1 we showed the importance of rated battery energy, depth of discharge or state of charge respectively, battery energy efficiency, self-discharge, cycle life and calendar life but also actual utilisation of batteries, stated as annual full cycles, on the direct energy consumption of batteries.

By now, the impact of these parameters was discussed from a global perspective and mainly in relation to technical standards. Thus, following the extended product approach, within this chapter the actual utilisation of batteries under real-life conditions will be discussed. Further, deviations of real-life utilisation from test standards are discussed.

Table 5 provides an overview of real-life deviations of EVs and ESS from standard test conditions and how they are considered.

*Table 5: Real-life deviations from standard test conditions*

| Potential deviation from standards | Explanation | How it is considered |
|---|---|---|
| Driving profiles or load profiles | Different load profiles of batteries in urban, freeway and highway traffic but also in different regions, for example, when used in grid stabilization | Only considered via average energy consumption measured with a specific test cycle<br>Only average cycles considered |
| Driving patterns | Different driving distances and duration on weekdays/ at weekend; load profiles for ESS vary over the years and within a year | Average daily driving distances and durations assumed per base case |
| Charging strategy | Charging C-rates, frequency and duration vary | Standard charge strategy defined for each base case |
| Temperature | Ambient temperatures vary (winter, summer, region, etc., even daily) | TMS is expected to be standard, thus not considered |

In general, the energy efficiency of a battery is influenced by load profiles (charging/discharging and SOC ranges while being under load), which are directly linked to driving profiles of electric vehicles or load profiles of stationary applications. Driving patterns and load profiles influence no-load losses and the required annual full cycles. Furthermore, they have impact on the charging strategy, which influences energy efficiency respectively. Temperature also has strong impact on a battery energy efficiency and lifetime.

Figure 16 shows how the speed profile of a car translates into other parameters profiles, such as cumulative energy consumption, cell current, cell power, cell voltage and SOC.

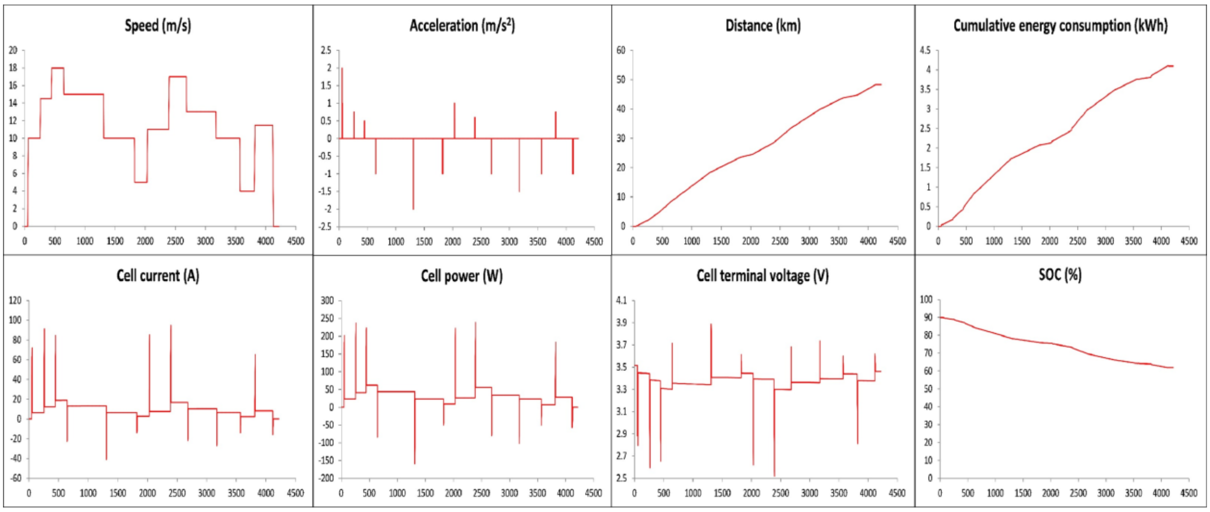


*Figure 16: Example of voltage, current and SOC profiles according to speed profile over time (in seconds) (Source: Pelletier et al. (2017))*

A speed profile that is supposed to be close to real-life utilisation of a passenger vehicle is the test cycle (speed profile) of the Worldwide Harmonized Light Vehicle Test Procedure (WLTP). Figure 17 shows the quite jagged WLTP test cycle, which clearly differs from the load profile of the efficiency test standards in Figure 4.

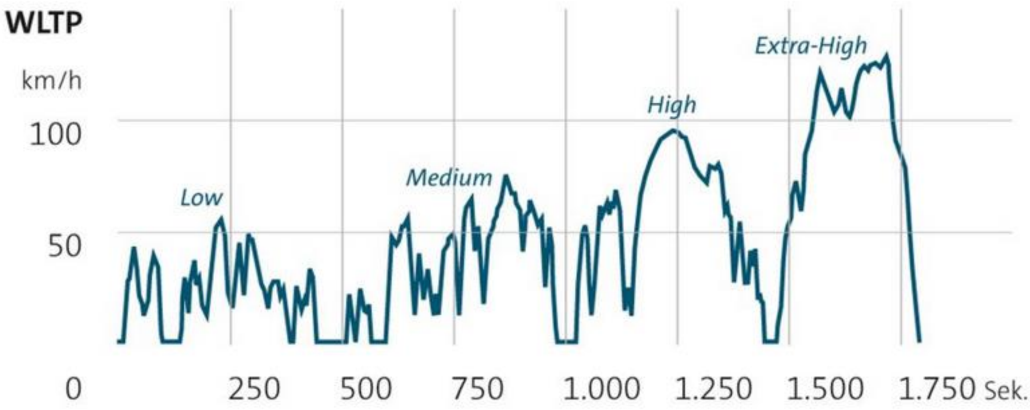


*Figure 17: Speed profile of WLTP test cycle (Source: SEAT UK (2019))*

Fast increasing and decreasing speed profiles induce high C-rates, which have negative impact on the batteries efficiency. Figure 18 shows the **influence of C-rate** on voltage during discharge. The higher the C-rate the faster the discharge voltage drops, leading to a lower average $V_D$ and voltaic efficiency and thus, low battery energy efficiency. Furthermore, the total battery capacity cannot be withdrawn at high C-rates.

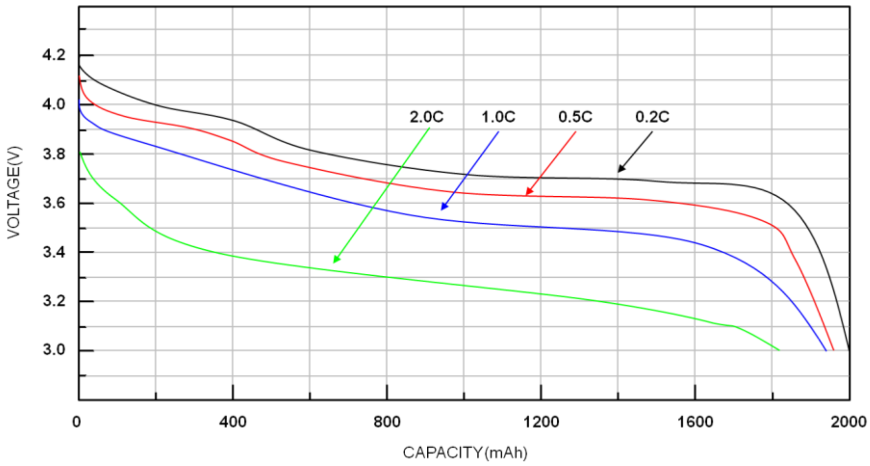


*Figure 18: Voltage change at different C-rate discharge (Source: Ho (2014))*

In Figure 19 a typical charging process can be seen. At the beginning, charge current is at 100%, while cell voltage increases slowly during the charging process. Battery capacity increases almost linearly at first. When reaching about 60% of the battery capacity the cell voltage reaches its maximum and stays on that level. While charge current starts decreasing down to zero the battery capacity increases until it reaches the rated capacity. Thereafter, a float charging voltage stabilizes the battery capacity and the SOC respectively.

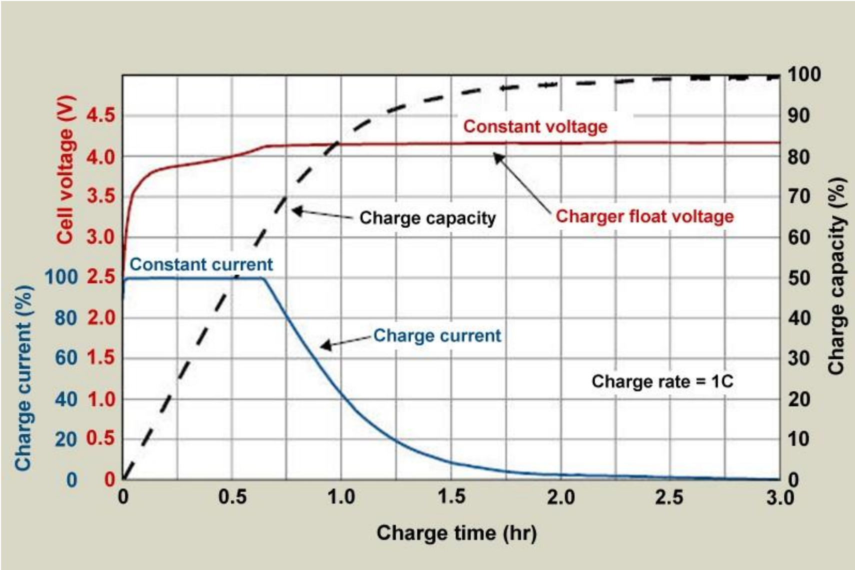


*Figure 19: Charging curve of a typical lithium battery (Source: Cadex Electronics (2018)).*

As stated above, a lower average charge voltage $V_C$ is beneficial for voltaic efficiency, thus, charging between a **SOC of around 20 to 70%** is beneficial for battery energy efficiency. Advised C-rates of LIB cells lie between 0.5C and 1C. Consequently, **fast charging**, at 2C or above are unfavourable.

In Figure 20 the **impact of different temperatures** during the discharging process on voltage and SOC can be seen. With increasing temperatures, the voltage drops slower, leading to higher $V_D$, and higher battery capacities can be withdrawn. However, high temperatures have a negative effect on the lifetime of a battery, which will be discussed later.

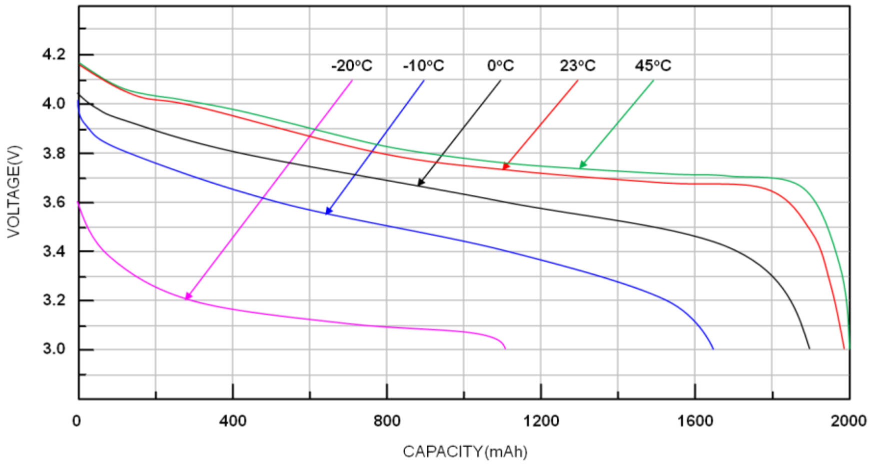


*Figure 20: Voltage change for discharge at different temperatures (Source: Ho (2014))*

Capacity losses of batteries can be reversible and irreversible. While irreversible losses are known as capacity fade, capacity degradation or aging respectively (which will be discussed in the next section), reversible capacity losses are known as **self-discharge**. Batteries that are stored at a specified SOC will lose capacity over time, but it is very difficult to differentiate between capacity losses due to self-discharge and capacity losses due to capacity fade (Redondo-Iglesias et al. 2018b). Nevertheless, it can be said, that self-discharge of all battery chemistries increases at higher temperatures (see Figure 21). With every 10°C temperature increase, the self-discharge effect typically doubles (Ho 2014).

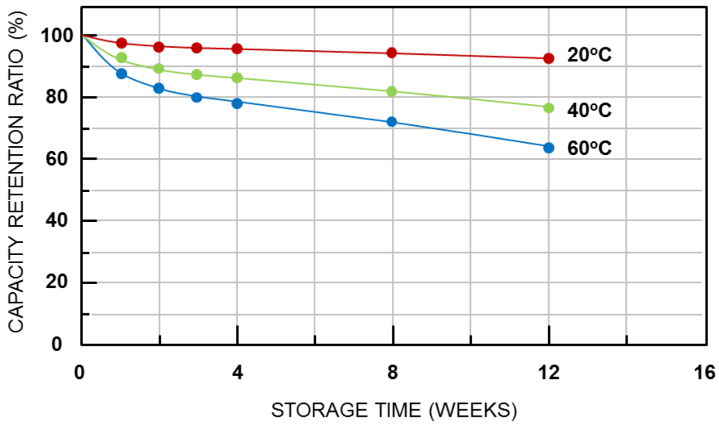


*Figure 21: Capacity retention at different temperatures (Source: Ho (2014)).*

Further, self-discharge depends on the battery's SOC. The higher the SOC the higher the self-discharge. A Lithium-ion battery has a self-discharge of 0 to 6.5% per month at an SOC between 30 and 65% depending on temperature (30-60°C) and of 2 to 20% at 100% SOC depending on temperature (30-60°C). As an average for lithium-ion batteries a self-discharge of maximum 2% at room temperature can be assumed even at 100% SOC (Redondo-Iglesias et al. 2018b).

### 3.1.3. Technical systems approach

As already mentioned, batteries are either part of vehicle or of a stationary (electrical) energy system, which comprise additional components such as a charger, power electronics (inverter, converter) and active cooling and heating systems. However, energy consumption of these components is considered as indirect losses and thus discussed in chapter 3.2.

### 3.1.4. Functional systems approach

In the functional approach the basic function of battery systems, the storage and provision of electrical energy, is maintained, yet other ways to fulfil that function and thus other electrical energy storage technologies are reviewed.

Alternative technologies to LIB used in EVs are fuel cells with hydrogen storage, nickel-metal hydride batteries (NiMH) or lead-acid (Pb) batteries.

**Proton exchange membrane fuel cells (PEM-FC)** are actually energy converters, which is why they can only be used in combination with (hydrogen) storage tank. The energy density of the PEM-FC is clearly above the energy density of today's and future LIB systems. The operating life however is still limited to approximately 6000 operating hours. In automotive applications, it is usually used in combination with pressurised storage of hydrogen. However, there are only few car models manufactured in series production.

**NiMH-batteries** are batteries, in which electrodes are made of nickel oxide hydroxide and a hydrogen storage alloy of nickel and so-called mixed metal with rare earth elements. The electrolyte is a potassium hydroxide solution. They are especially designed for hybrid-eletric vehicles. As traction battery, however, their potential is very low. Nickel and its supply chain are the big challenge. Since Nickel is very expensive, NiMH batteries are more expensive than LIB and beyond that, their environmental record is worse.

**Pb-batteries** are batteries with electrodes of lead and lead dioxide and an electrolyte of diluted sulphuric acid. They play an important role in emerging markets such as India to build low-cost vehicles and thus, to ensure cheap mobility for society. For the German and European market, they will not be used for traction purposes, but they are still state-of-the art for starter batteries. This is partly because they have already reached the end of their development potential, and in terms of their performance, for example, they are clearly behind lithium-ion batteries.

For stationary applications, mainly Pb-batteries, flywheel energy storage systems (FESS), sodium-sulphur (NaS) batteries and sodium nickel chloride ($NaNiCl_2$) batteries and redox-flow batteries (RFB) can be seen as alternatives to LIB (see also Figure *22* and Thielmann et al. (2015a)):

**Pb-batteries** are the benchmark technology for stationary applications in the range of up to 1 GWh and 20 MW. They are able store electricity for several minutes but also for several days. Because of their low investment costs in many stationary applications, they are state-of-the art. Their energy density however is quite low and their cycle life is limited. On the other hand, calendar life is between 10 to 20 years.

**FESS** store electrical energy in the form of kinetic energy by means of an electric machine, which accelerates a flywheel. They represent an economically interesting option for the storage of electrical energy, especially for those applications, where several charge and discharge cycles occur per day and thus accumulators, due to their limited number of charge/discharge cycles and super capacitors due to their high costs in relation to the storable energy, from an economic point of view are not advantageous. Their efficiency however is currently still low, which is why they are rarely used (Schulz et al. 2015).

**NaS/$NaNiCl_2$:** NaS batteries, in which electrodes are made from the elements mentioned above use as a solid-state electrolyte a sodium ion conductive ceramic. $NaNiCl_2$ batteries, usually also called a ZEBRA battery, use a solid-state electrolyte, which is supplemented by a combination of liquid and solid electrodes. The anode, which is separated by a separator from the exterior of the battery is made from liquid sodium, the cathode from sodium chloride or from sintered nickel, which is impregnated by a liquid saline solution of nickel chloride and sodium chloride. It requires high operating temperatures, which is why a heater in addition to a thermal insulation is used, since the otherwise; the cell would be constantly discharged. It can be used from 100kWh to 1 GWh and stores energy for 1h up to one week. The technology is available but not that present on the market, also because of its high costs for example in relation to Pb batteries.

**RFB** is a battery concept, which is based on the reduction and oxidation of electrolyte solutions that are pumped from storage tanks to a fuel cell like stack. They have a lower energy density than LIB and their systems are more complex. In stationary applications, they are especially relevant for large-scale installations, where their maintenance effort is adequate. One the one hand their cycle life is very high (> 10,000 cycles), on the other hand, little data on their long-term stability is available. Their requirements regarding operating conditions are quite demanding and costs are a little bit above Pb. RFB are mostly relevant for storing 100kWh up to some MWh for up to several days and solutions are already available.

To sum it up, for stationary applications currently Pb-batteries are state-of-the-art and are superior to LIB especially in terms of costs and calendar life. With improving performance and cost parameters however LIB, RFB and NaS-batteries can be an alternative, depending on power, energy and storage duration requirements.

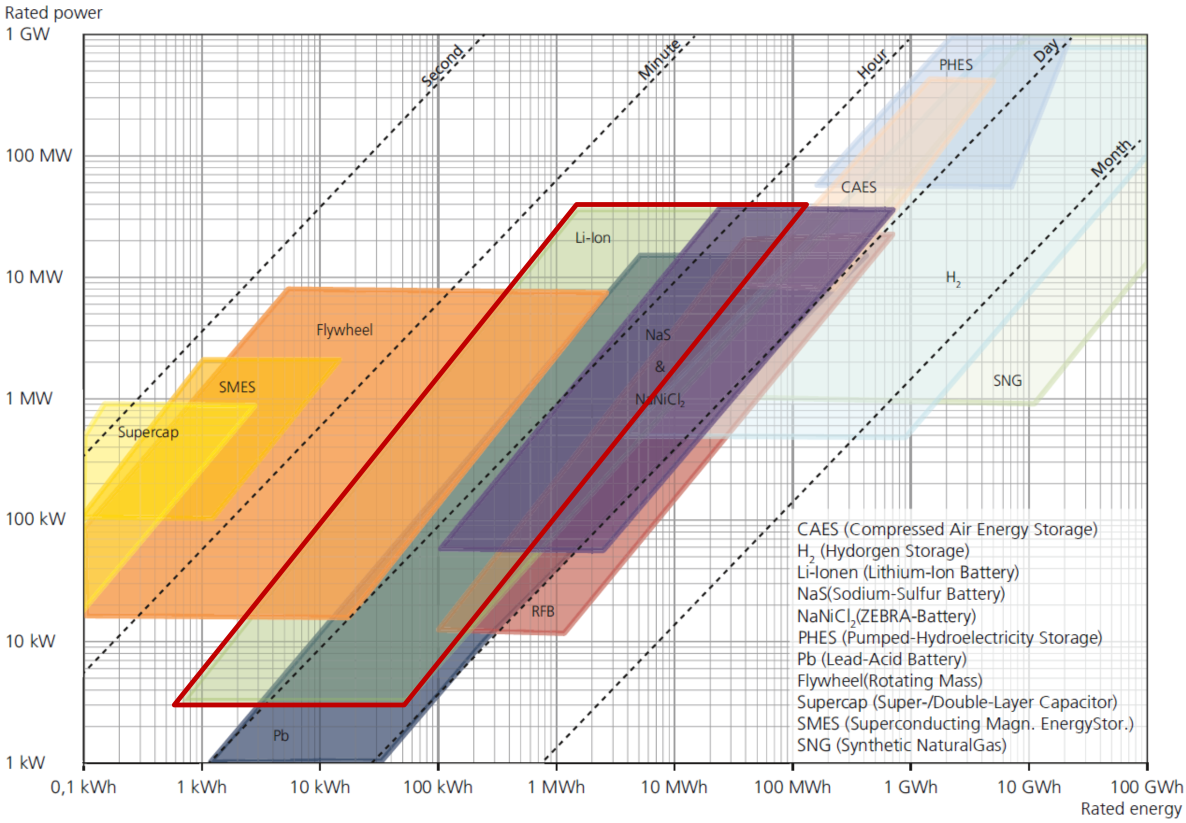


Figure *22*: Alternative stationary electrical energy storage technologies (Source: *Thielmann et al. (2015a)*)

## 3.2. Subtask 3.2 - System aspects in the use phase affecting indirect energy consumption

As mentioned before, batteries are part of vehicles or stationary energy systems. Consequently, further components that have impact on the energy consumption have to be considered. Power electronics (according to the system boundaries defined in Task 1), such as converters, inverters, electric engines and so on will not be included. One reason for that is that in EV as well as in stationary applications many different design options, which components to be used and how to combine them, are existent (BVES and BSW Solar 2017; Erriquez et al. 2018). Accordingly, indirect energy consumption of chargers as well as of active cooling and heating systems will be discussed in this section.

For EVs, a differentiation between regular (AC) charging and fast (DC) charging has to be made, since efficiencies of both charging types differ. While for AC chargers with 3.8 kW, which are suitable for passenger cars, a charger efficiency of 85% can be assumed (Lohse-Busch et al. 2012; Kieldsen et al. 2016), for AC chargers with 22 kW, that are suitable for trucks, an efficiency of 92% can be assumed (Genovese et al. 2015; Kieldsen et al. 2016). The efficiency of DC fast charging at 50 kW for passenger cars and 150 kW for trucks is assumed to be 93% (Genovese et al. 2015; Trentadue et al. 2018). Further, we assume, that passenger vehicles are charged with AC power for 80% of the time, since most of the day, they just stand idle and thus, there is enough time for slow charging, which is good for the battery lifetime. Trucks however spend more time on the road and thus, we assume 50% AC charging. ESS are charged DC only and based on expert interviews, a charger efficiency of

98% can be assumed. The parameters related to the calculation of direct and indirect energy consumption and all results are summed up in Table 6 for EVs and in Table 7 for ESS.

$$\left(1-\left(Share\ AC\ charge * \eta_{AC\ charger} + (1 - Share\ AC\ charge) * \eta_{DC\ charger}\right)\right) * \frac{Q_{FU}}{\eta_E}$$
$$= \left(1-(80\% * 85\% + (1-80\%) * 93\%)\right) * \frac{96{,}000}{0{,}96} = 13{,}400$$

*Table 6: Summary of data required for the calculation of EV base cases (indirect energy consumption)*

| | **Passenger BEV (medium to large)** | **Passenger BEV (small)** | **Passenger PHEV** | **HDT BEV** | **HDTU PHEV** |
|---|---|---|---|---|---|
| **Maximum quantity of functional units (QFU) over application service life [kWh]** | **96,000** | **48,000** | **18,000** | **576,000** | **360,000** |
| Battery energy efficiency | 92% | 92% | 92% | 92% | 92% |
| **Energy consumption due to battery energy efficiency [kWh]** | **7,680** | **3,840** | **1,440** | **46,080** | **28,800** |
| Self-discharge rate [%/month] | 2% | 2% | 2% | 2% | 2% |
| Average SOC [%] | 50% | 50% | 50% | 50% | 50% |
| **Energy consumption due to self-discharge [kWh]** | **192** | **96** | **29** | **864** | **384** |
| Charger efficiency AC [%] | 85% | 85% | 85% | 92% | 92% |
| Charge power AC [kW] | 3.8 | 3.8 | 3.8 | 22 | 22 |
| Charger efficiency DC [%] | 93% | 93% | 93% | 93% | 93% |
| Charge power DC [kW] | 50 | 50 | 50 | 150 | 150 |
| Share AC charge [%] | 80% | 80% | 80% | 50% | 50% |
| **Energy consumption due to charger energy efficiency [kW]** | **13,983** | **6,991** | **2,622** | **46,957** | **29,348** |
| Heating/cooling energy requirements [%] | 5% | 5% | 5% | 5% | 5% |
| **Energy consumption due to cooling and heating requirements [kWh]** | **4,800** | **2,400** | **900** | **28,800** | **18,000** |

According to Schimpe et al. (2018) the battery losses in stationary applications due to heating or cooling requirements amount to 5%. The same figure is assumed for EVs.

*Table 7: Summary of data required for the calculation of ESS base cases (indirect energy consumption)*

| | **Residential ESS** | **Commercial ESS** |
|---|---|---|
| **Maximum quantity of functional units (QFU) over application service life [kWh]** | **64,000** | **240,000,000** |
| Battery energy efficiency | 92% | 92% |
| **Energy consumption due to battery energy efficiency [kWh]** | **5,120** | **19,200,000** |
| Self-discharge rate [%/month] | 2% | 2% |
| Average SOC [%] | 50% | 50% |
| **Energy consumption due to self-discharge [kWh]** | **30** | **90,000** |
| Charger efficiency DC [%] | 98% | 98% |
| **Energy consumption due to charger energy efficiency [kW]** | **1,391** | **5,217,391** |
| Heating/cooling energy requirements [%] | 5% | 5% |
| **Energy consumption due to cooling and heating requirements [kWh]** | **3,200** | **12,000,000** |

## 3.3. Subtask 3.3 - End-of-Life behaviour

The aim of this subtask is to identify, retrieve and analyse data and to report on consumer behaviour regarding end-of-life aspects of batteries from an average European perspective.

As already explained in this study, batteries have a limited cycle and calendar life. The actual utilisation of batteries in terms of cycling and the conditions under which they are operated (specific C-rates, within certain SOC or DOD ranges, at specific temperatures) decrease a batteries capacity and thus energy permanently. Further, internal resistance of a battery increases over time, and consequently energy efficiency decreases. In summary, the SOH diminishes.

The lifetime of a LIB cell is subject to its actual utilisation, thus referring to the definition of the functional unit, the **cycle life** of battery cell can be specified by full cycles at a certain DOD. 1,000 to 2,000 full cycles are feasible for BEV at a DOD of 80%, while PHEV reach between 4,000 and 5,000 full cycles at 80% DOD (Thielmann et al. 2017). With increasing fast charging capabilities that result in high charging power the load and stress for the battery grows leading to increasing requirements concerning cyclical operating life. This is a very important aspect, especially in the light of the continuously increasing charging power that already reaches up to 500 kW (ChargePoint 2019). In general, with increasing charging power, the temperature of the battery while charging increases, which in turn accelerates battery aging or requires strong thermal management in order to prevent battery aging (Collin et al. 2019). It also has to be mentioned, that the cycle life requirements for heavy-duty trucks are a lot higher, since their annual mileage is higher and also their load profile is a lot more challenging compared to passenger cars.

**Service life and aging of batteries**

The service life of a LIB is defined as the time between the delivery date (beginning of Life, BOL) and the point of time (end-of-life, EOL) at which properties previously defined in standards or product specifications fall below a defined value due to aging. The end of life occurs, for example according to Part 4 of DIN 43539 "Accumulators; Testing; Stationary cells and batteries", if the maximum battery energy falls below 80% of the rated battery energy, which corresponds to a SOH of 80%. 80% are also stated in condition B in the cycle life tests in IEC-62660-1. Generally that value strongly depends on the application (Podias et al. 2018). The EOL condition for passenger EV is usually between 70 and 80%, while for trucks 80% are assumed, since a certain range is essential for economic operation. Residential and commercial ESS are used until 70% are reached.

Two metrics for the definition of service life can be distinguished (as described above): Calendar life and cycle life.

In practice, the combination of both influences the total service life of a battery. **Calendar life** is another important parameter (also for End of Life (EOL) analyses). No general statements can be made because it mainly depends on the actual utilisation of the battery and largely on the ambient conditions (temperature) under which batteries are stored. Around 15 to 20 years are current expected lifetimes, which are necessary in order to be able to reach the operating life of current ICEVs. The calendar life refers to a battery, which is not cyclized, i.e. the battery is not used in the respective application or if the battery is in bearing condition. Calendar life of a battery relates to the number of expected years of use. If not being used, within the battery interactions between electrolyte and active materials in the cell and corrosion processes can take place that affect the service life. Extreme temperatures and the cell chemistry as well as the manufacturing quality are further factors that can accelerate aging. **Cycle life** is defined by the number of full cycles that a battery can perform, before reaching EOL. Full cycles are to be distinguished from partial cycles. For the latter, a battery is not entirely discharged and charged, but only within a certain range referring to the SOC. Batteries like nickel metal hydride batteries show a so-called memory or lazy effect, when a lot of partial cycle are performed, leading to accelerated aging. Most lithium-ion cells however, do not show that effect (Sasaki et al. 2013).

**Aging** refers to the deterioration of the electrochemical properties (e.g. lower capacity, energy density etc.). Mostly, it is determined by the **energy throughput or cyclisation.** The more cycles a battery has performed, the lower the available capacity (see Figure 23). Further, **high performance requirements** during charge and discharge of the battery and high currents (high C-rates) result in high internal heat production, which might irreversibly damage the electrode materials, directly influence, and accelerate aging (see also Figure 23).

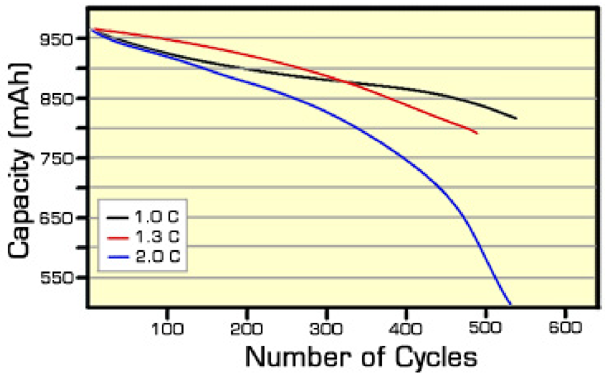


*Figure 23: Aging (decrease of capacity) over number of cycles at different C-rates (Source: Choi and Lim (2002)).*

Capacity decreases with time and internal resistance increases, which consequently leads to a power decrease. This is mostly due to side reactions, which take place during the charge and discharge processes in the electrolyte, such as stretching of active materials. Due to the utilisation of different materials, which are in contact to each other, a multitude of reactions might be possible. Additionally, ambient **temperature conditions** influence the increase of internal resistance and thus, potential service life as well. The higher the temperature, the faster the mentioned processes will proceed and in turn, lower service life (see Figure 24). Depending on the application and condition, active cooling might therefore be necessary.

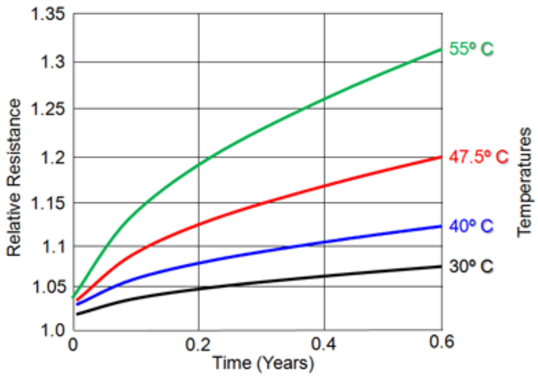


*Figure 24: Internal resistance over time at different temperatures (Source: Woodbank Communications (2005)).*

Figure 25 shows, how the **efficiency** and **capacity** of cells develops **under calendar aging** conditions (60°C, 100% SOC). For NMC cells efficiency decreases very quickly from 96% down to 87% within 190 days and within the same period capacity decreases by 37%. The LFP cell's efficiency, however, just decreases from 95% to 94% over a period of 378 days, while a capacity fade of 30% can be seen. Especially for NMC cells these analyses show the unfavourable impact of high temperatures and high SOC on calendar aging and energy efficiency (Redondo-Iglesias et al. 2018a).

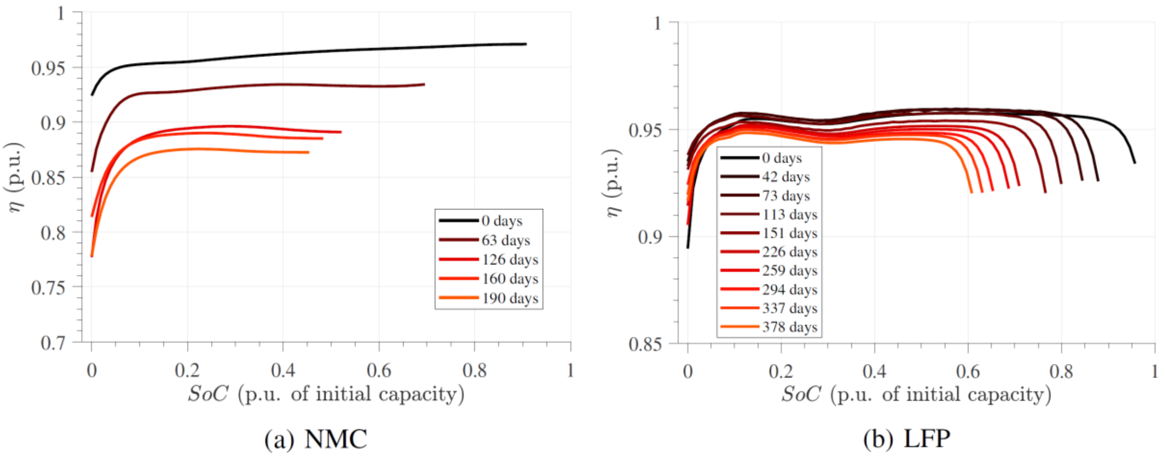


*Figure 25: Efficiency degradation of cells under calendar ageing conditions (60°C, 100% SOC) (Source: Redondo-Iglesias et al. (2018a)).*

As already discussed for the charging processes, the **SOC ranges** a battery is operated within largely influences the operating life. One the one hand narrow SOC ranges around 60% or 70% SOC significantly improve cycle life of batteries and on the other hand, they decrease capacity fade as Figure 26 shows.

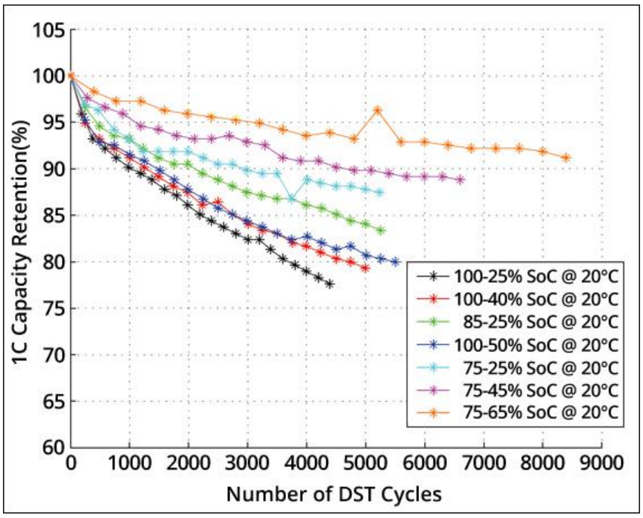


*Figure 26: Capacity loss as a function of charge and discharge bandwidth (Source: Xu et al. (2018)).*

Consequently, charging and discharging Li-ion only partially and at low C-rates prolongs battery cycle life and decreases capacity fade, which is also supported by Figure 27.

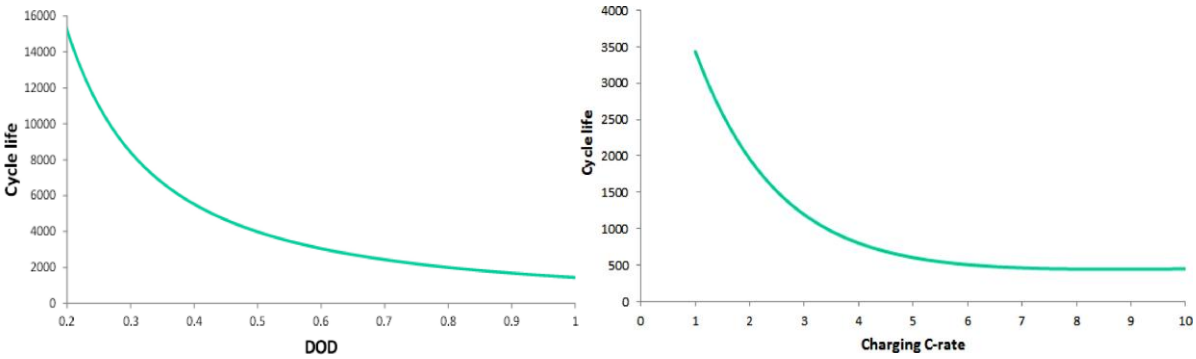


*Figure 27: Cycle life versus DOD and charging C-rate (Source: Pelletier et al. (2017))*

A battery is usually operated in an application until its EOL condition is reached. EOL was defined in Task 1 according to IEC 61960 and IEC 62660 as condition that determines the moment a battery cell, does not anymore reach a specified performance in its first designated application based on the degradation of its capacity or internal resistance increase. This condition has been set to 80% for electric vehicle application of the rated capacity.

Figure 28 shows how the capacity of a LIB-cell decreases over cycle life. In that case, the cell reaches EOL after approximately 500 cycles.

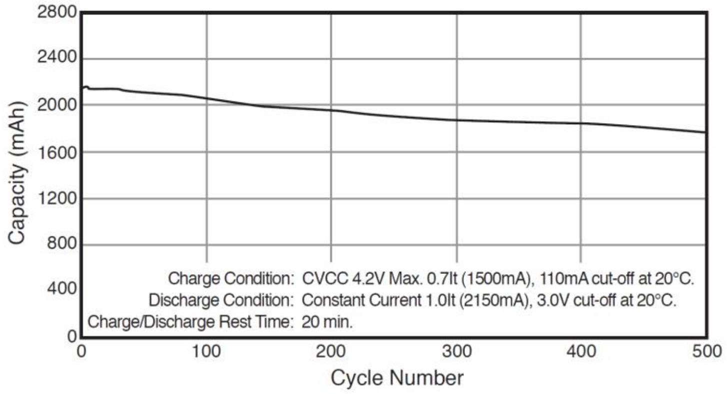


*Figure 28: Lifecycle characteristics of Panasonic CGR18650CG cylindrical cell (Source: Panasonic (2008))*

The impact of temperature and of DOD on the cycle life is depicted in Figure 29. With increasing DOD, cycle life shortens. The same applies for increasing temperatures, which accelerate the aging process (capacity loss/capacity fade) and lead to a lower number of full cycles.

Although having reached EOL condition for a certain application with a remaining capacity of 80% this does not necessarily mean, that a battery is not usable any more (Podias et al. 2018). The reduced capacity and energy efficiency restrict the further use, and also safety aspects have to be taken into consideration, since with enduring service life the risk of failure (electrical short, chemical chain reaction) increases.

Within this study, we discussed batteries that are utilised in either EV or stationary ESS applications, thus which are part of a bigger system or product respectively. For the discussion of EOL behaviour in this Task, a focus is set on the EOL behaviour of the applications/base cases in distinction from the EOL analyses in Task 4, which are focussed on the battery's EOL and on battery and material recycling.

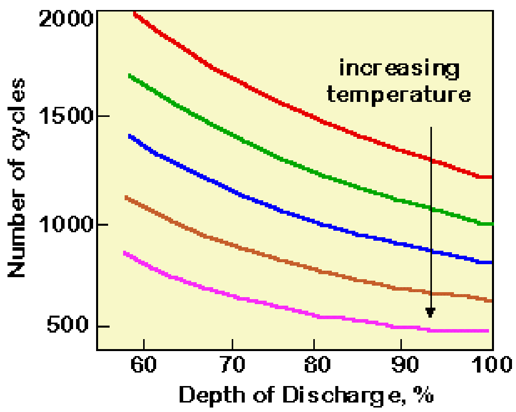


*Figure 29: Number of full cycles before EOL is reached over DOD and depending on temperature (Source: TractorByNet (2012)).*

In general, a LIB can pursue five ways after its first-use:

- remanufacturing
- reuse - battery is used again in the same application
- repurposing/second-use - battery is is used in another, different application, mainly stationary ESS applications. After their first use, the batteries are tested and prepared for use for energy storage in a second-use application.
- recycling - battery is "destroyed" in order to recover materials
- waste - batteries decompose on landfills

In the following sections, we focus on reuse and repurposing, since the other aspects will be covered in Task 4.

### 3.3.1. Product use & stock life

Table 8 shows a comparison of the service life of the base case EV applications and the batteries used within these applications. The stated service life of the batteries in full cycles and years has to be long enough, so that after the first use, the service life is not exhausted and there is remaining potential for second-use. That potential mainly refers to a second use in stationary ESS, since the EOL conditions are usually lower. Consequently, batteries used in ESS that reach their EOL are not considered to have second-use potential.

Regarding the service life in full cycles, passenger BEV batteries are not only able to provide the required number of full cycles for the application, but they exceed the requirements, which reveals **second-use potential**. PHEV, BEV HDT and PHEV HDTU batteries however are not able to provide the number of full cycles required for the application. An entirely different picture can be drawn regarding the service life in years. For all EV applications, the service life of the battery in years is longer than the application's life, thus second-use potential is given.

*Table 8: Comparison of service life of applications/base cases vs. maximum battery performance (data was drawn from the preceding sections)*

| | Service life (in full cycles) | | | Service life (in years) | | |
|---|---|---|---|---|---|---|
| | Application | Maximum battery performance | | Application | Maximum battery performance | |
| Passenger BEV (medium to large) | 683 | 1,500 | | 13 | 20 | |
| Passenger BEV (small) | 924 | 1,500 | | 14 | 20 | |
| passenger PHEV | 2,730 | 2,000 | | 13 | 20 | |
| HDT BEV | 3,267 | 2,000 | | 14 | 20 | |
| HDTU PHEV | 9,275 | 3,000 | | 12 | 20 | |

| | |
|---|---|
| | suitable for second-use |
| | to a certain extent suitable for second-use |
| | not suitable for second-use |

Four conclusions can be drawn from these figures:

- First, regarding passenger BEV, their batteries might be suitable for second-use in ESS, since battery service life in cycles as well as in years exceeds the application's service life.
- Second, for batteries used in passenger PHEV, their service life in cycle is exceed, whereas service life in years is not yet reached. Consequently, second-use potential might be given under certain circumstances, e.g. when the PHEV is not driven that much and thus, does not reach that number of cycles.
- Third, the battery service life in cycles of HDT BEV and HDTU PHEV is heavily exceeded, while service life in years is not yet reached. There might be few HDT and HDTU with low annual mileage and thus low application cycles, which might offer second-use potential. For the majority of batteries used in HDT and HDTU however, low potential for second-use is seen.
- Fourth, batteries in stationary ESS are used, until they reach the end of their life, whether in cycles or years. EOL condition is expected to be lower for ESS than for EVs, but at the time the shoulder point is reached (EOL), after which the capacity drops very fast, those batteries are not expected to be used in second-use applications. On the other hand, the lower EOL conditions of ESS allow the utilisation of second-use EV battery.

A promising way to increase calendar life of a battery, which seems to be critical for passenger cars, is to lower the SOC, when the application/vehicle is at rest (MAT4BAT Advanced materials for batteries 2016). Beyond that, it has to be noted that passenger car and truck manufacturers are expected to design the batteries in a way that they are able to last the vehicle's entire cycle and calendar life, which might increase second-use potential. However also the opposite might be the case, such that batteries last exactly as long as the vehicles, leading to almost none second-use potential.

### 3.3.2. Repair and maintenance practice

In general, a LIB can be considered maintenance free. If however, parts of the battery system have to be replaced due to failure, gaining access to a battery is differentially difficult, depending on the application.

Batteries used in EV are usually built in the vehicle's underbody and protected by a stable metal casing, thus requiring high effort for accessing and repairing batteries (see Figure 30). Due to the location of the battery pack within a vehicle, but also due to the high battery voltages, specialized experts are required for repair and maintenance. While the latter is also true for ESS, whether they are residential or commercial, the accessibility of ESS batteries a lot easier. In residential applications batteries are mounted to the wall (see Figure 31), whereas in commercial applications they are installed in factory like halls, thus being easily accessible.

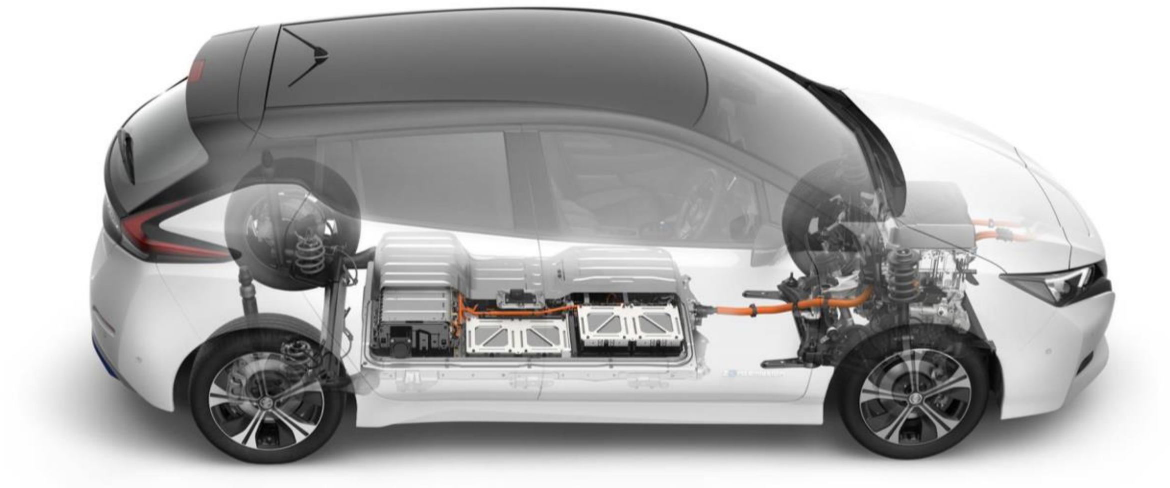

*Figure 30: Position of Nissan LEAF 40kWh battery (Source: Kane (2018))*

It can be expected, that in case of failure batteries in mobile applications and in commercial ESS will repaired, since otherwise the whole application's EOL would be reached, which from an economic point of view would be very unfavourable. For residential ESS, it seems possible, that they are replaced entirely. An advantage of the usual modular setup of batteries refers on the one hand to easy assembly of the components and on the other hand to simplified maintenance and interchangeability of individual modules. Lithium-ion cells are practically maintenance-free and a sophisticated BMS, balancing load and temperature evenly among all cells/modules, contributes significantly to this (Rahimzei et al. 2015). According to Fischhaber et al. (2016) replacing specific modules might also be a suitable measure to postpone a battery's EOL.

*Figure 31: Kreisel Mavero home battery (Source: Kreisel Electric (2018))*

In general, battery removability is stipulated in the Battery Directive. Nevertheless, the share of non-removable batteries and of batteries removable only by professionals is increasing, which often results in early EOL in the application (Stahl et al. 2018).

### 3.3.3. Collection rates, by fraction (consumer perspective)

The EU EOL Vehicles Directive 2000/53/EC and Battery Directive 2006/66/EC state, that vehicles and batteries have to be collected and recycled. Since disposal of waste industrial and automotive batteries in landfills or by incineration is prohibited, implicitly a collection and recycling rate of 100% is demanded.

However, the amount of batteries that are actually recycled varies according to the type of application and battery (see Figure 32). Currently, regarding the battery mass flow of batteries, LIBs are mainly found in the field of portable batteries. LIBs are included in the category "other batteries" and they sum up to approximately 37,000 t, thus representing around 18% of the mass flow. This will change significantly with the EV diffusion. Only 30% of "other" portable batteries are collected and recycled.

Regarding automotive batteries, which in that mass flow only comprise lead-acid batteries, the collection and recycling rate is over 92%, whereas for lead-acid batteries in industrial applications around 90% collection and recycling rate are achieved. Consequently, one could conclude, that a similar collection and recycling (or re-use) rate might be achievable for LIB in industrial and automotive applications. However, that would neglect that LIBs are not as easily removed from their applications as lead-acid batteries, which can be handled and transported comparably easy and whose recycling is profitable from an economic point of view. Consequently, comparable recycling rates will only be achievable by strong regulatory intervention.

For LIBs, there are currently several large-scale recycling facilities in Europe that do recycle cobalt, nickel, copper and aluminium. Since Cobalt is a critical raw material for the EU, its recovery is essential and also, its recovery is economically valuable. However, because of technological but also economic challenges, recovery of lithium is currently scarce: only some smaller facilities that have been built up in research projects are available. It should be pointed out that Umicore recently started the recovery of lithium from the slag fraction of its large-scale pyro metallurgical process (Stahl et al. 2018).

This could be subject to change, when the market of EVs and ESS and accordingly of LIB batteries to be recycled increases and/or further regulations on European level are enforced. According to Recharge (2018), it can be expected that 95% of EOL batteries are collected for second-use or recycling while 5% come to an unidentified stream.

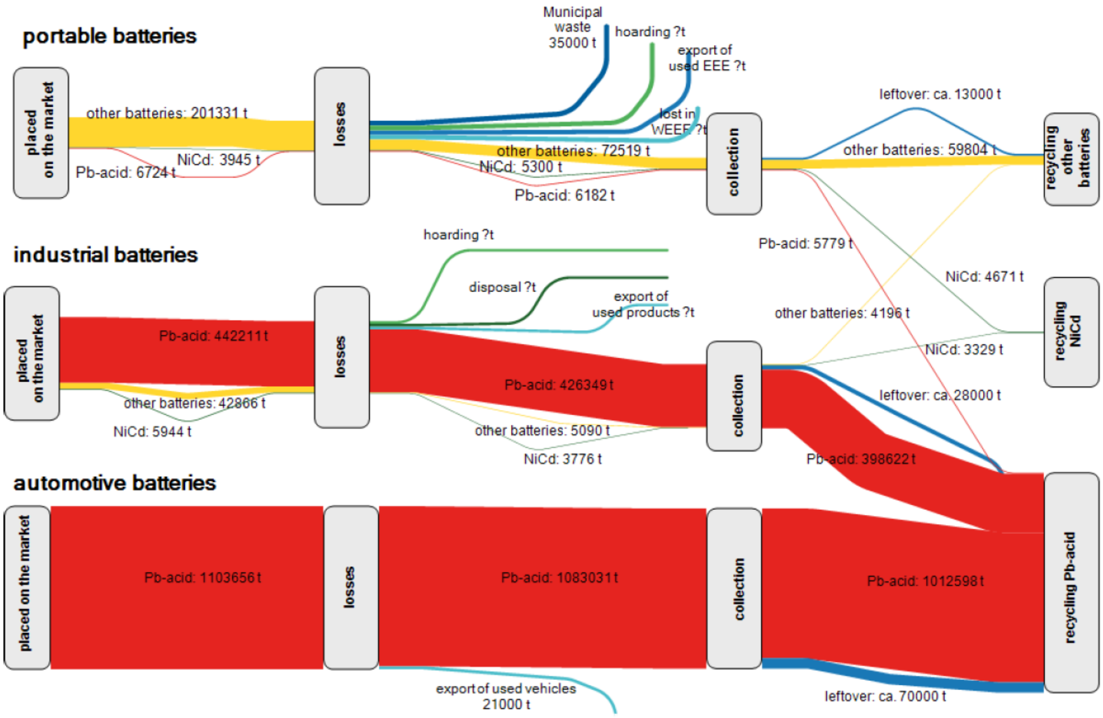


*Figure 32: Mass flow diagram of batteries for EU28 in 2015 [tonnes] (Source: Stahl et al. (2018))*

*Table 9: Assumptions referring to collections rates of EOL batteries (Source: Recharge (2018)).*

| Collection rate for second-use or recycling | Unidentified stream |
|---|---|
| 95% | 5% |

### 3.3.4. Estimated second hand use, fraction of total and estimated second product life (in practice)

The figures from Table 8 concerning the calendar life of applications already include second hand (second-use) utilisation time, thus only second-use applications are to be reviewed.

Currently within the EU Battery Directive, collection and recycling rates are stated. That does not address second-use applications, which are very promising. Due to missing definitions and regulations in the Directive concerning the re-use, preparation for re-use or second use, there is an unclear legal situation, primarily for battery producers (Stahl et al. 2018).

Fischhaber et al. (2016) assume that battery cells or modules with EOL capacity of 80% can be used down to an energy of 40% within a second-use application. A further utilisation might provoke a battery failure. Many experts however state, that already below 70% SOH the risk of a thermal runway increases significantly. Since the actual SOH of individual cells within a module after first-use is not known, time-consuming and thus expensive measurements and SOH-determination is required. According to Figure 33 starting in 2023, when first EV generations reach their EOL, a considerable market for second-use LIB starts to develop. Nevertheless, this requires the clarification of existing regulations and the introduction of supportive regulations.

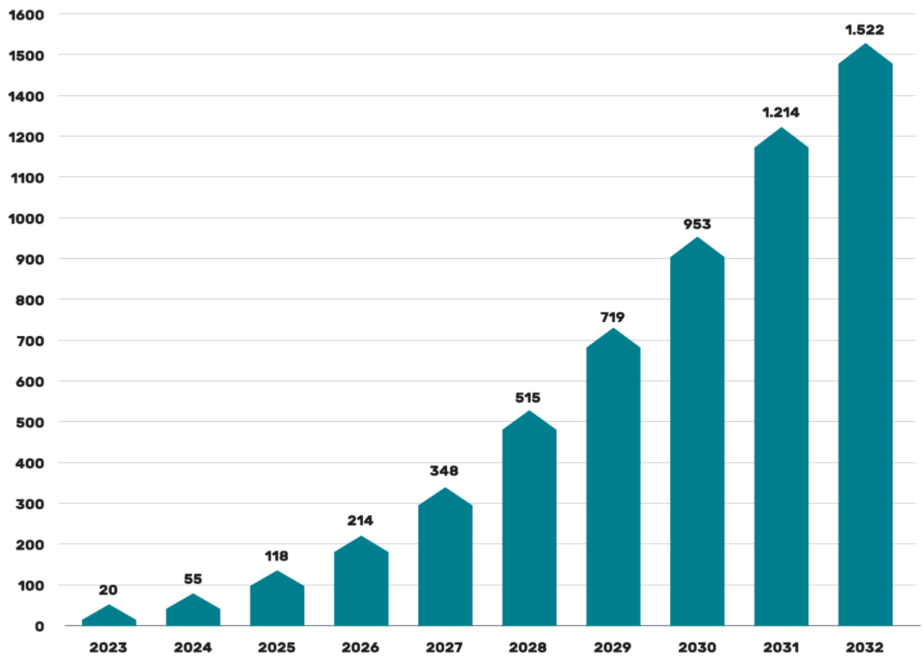


*Figure 33: Estimated global second-use-battery energy [GWh] (source: Berylls (2018)).*

An aspect that could accelerate a second-use market would be a specific design for second-use-applications already considered in the battery production. First, this relates to a facilitation of the dismantling of the battery system down to the cell, which might improve technical and economic feasibility of second-use. Second, this relates to an improved battery management system and SOH determination, so that the process of separating “good” cells (EOL not yet reached, SOH high enough for second-use) from “bad” cells (EOL reached, SOH too low for second-use) is facilitated. Further, that would reduce the risk of repurposing cells for second-life applications that could have still be used in the first-life application. Requirements for battery management and SOH determination, in a second-use context, are further elaborated and discussed in Task 7. According to experts, a range of 40 to 80 percent of first-life batteries might be reused.

## 3.4. Subtask 3.4 - Local Infrastructure (barriers and opportunities)

**The aim of this subtask is to identify barriers and opportunities relating to the local infrastructure needed for the operation of** batteries in EVs and ESS, e.g.:

- Energy: reliability, availability and nature
- Installers, e.g. availability, level of expertise/ training
- Physical environment, e.g. possibilities for product sharing

### 3.4.1. Energy: reliability, availability and nature

The demand for ESS in residential but especially in commercial applications largely depends on the availability and costs of technologies for renewable energy generation. The cheaper PV systems get, the more residential ESS might be sold. An increase of renewable energy, which is highly fluctuating and dependant on weather conditions will lead to a more instable electricity grid and require more commercial ESS to stabilize the grid or to compensate fluctuations in energy generation and consumption. Further EVs as well as ESS could be used for providing demand-side flexibility, however this would depend on the availability and conditions of time-dependent electricity tariffs for demand-side-flexibility applications. Further new market designs for financing the grid might be required, due to increasing decentralised energy generation and storage.

### 3.4.2. Charging Infrastructure for EV

For EVs, the availability and costs of charging infrastructure have a high impact on batteries energy efficiency. An increasing charging power might lead to faster battery aging, which reduces overall battery efficiency. Further, a high density of charging infrastructure might lead to lower battery capacities, since the distances between charging points decreases. Beyond that, the impact on load profiles and therefore on durability, e.g. fast charging vs. overnight charging, as well as on peak demand in grids might be an issue

### 3.4.3. Installation, e.g. availability and level of know-how

The limited availability of qualified personnel or suitable maintenance and repair infrastructure, especially for battery replacements, might be a barrier to second-life and repurposing concepts.

### 3.4.4. Lack of trust in second-hand products

Especially end customers might not be willing to buy second-hand product (used EVs/batteries) because they do not trust in their quality and well-functioning. However, the use of second-life batteries might also have a positive impact on a company's sustainable image.

### 3.4.5. Availability of CE marking and producer liability in second-life applications

A big, yet still unsolved issue is the question of CE marking in second-life applications and the question of liability. The cell OEM and the car OEM know best, via BMS or other systems, how the battery has actually been used and can make a good estimate on the battery's state of health. However, they do not want to be liable in case of failure or damage.

## 3.5. Subtask 3.5 – Summary of data and Recommendations

The summary of all important data and assumptions can be found in Table 10.

Further, we want to address the consistency and compliance of that study with the Product Environmental Footprint Pilot. The definition of the battery system and its components is consistent with the PEF approach, especially since the thermal management system and chargers are not in the primary scope of neither PEF nor our study. Also all vehicle and energy system components are beyond the scope. The wording, but also the calculation formulas for application service energy and quantity of functional are derived from the PEF and only slightly adapted and facilitated. However, it has to mentioned, that the PEF is not designed for the consideration of second-life applications.

Based on the analysis in this task, several main observations can be made:

- Power electronics (inverter, converter etc.) and drivetrain efficiency are not to be included in the product scope, however they will have substantial impact on the overall efficiency.
- Further, the charger is also not to be included in the product scope, since it is not built together with the battery and usually provided by another supplier.
- The active cooling/heating system is mostly closely linked to the battery and might even be provided by the battery supplier. However, regarding cooling and heating systems, car manufacturers consider the vehicle as an entire system and besides the thermal management of the battery; the passenger compartment has to be adequately tempered. For the vehicle's thermal management system currently also thermal heat pumps are discussed, thus energy consumption can hardly be differentiated to the battery and passenger compartment
- However, the substantial losses due to charger and cooling and heating requirements might be worth a deeper analysis.

*Table 10: Summary table of all relevant data (Sources according to the preceding section*

| | **Passenger BEV (medium to large)** | **Passenger BEV (small)** | **Passenger PHEV** | **HDT BEV** | **HDTU PHEV** | **Residential ESS** | **Commercial ESS** |
|---|---|---|---|---|---|---|---|
| Economic lifetime application [a] | 13 | 14 | 13 | 14 | 12 | 20 | 20 |
| Annual vehicle kilometres [km/a] | 14,000 | 11,000 | 14,000 | 50,000 | 100,000 | | |
| All-electric annual vehicle kilometres [km/a] | 14,000 | 11,000 | 7,000 | 50,000 | 50,000 | - | - |
| Fuel consumption [kWh/100km] | 20 | 16 | 18 | 120 | 140 | - | - |
| Recovery braking [% fuel consumption] | 20% | 20% | 20% | 12% | 6% | - | - |
| All-electric range [km] | 320 | 200 | 50 | 240 | 86 | - | - |
| Annual number of full cycles [cycle] | 120 | 120 | 120 | 300 | 600 | 250 | 250 |
| Maximum DOD (stroke) [%] | 80% | 80% | 75% | 80% | 75% | 80% | 80% |
| Typical system capacity [kWh] | 80 | 40 | 12 | 360 | 160 | 10 | 30,000 |
| Minimum system sapacity [kWh] | 60 | 20 | 4 | 170 | n/a | 2,5 | 250 |
| Maximum system capacity [kWh] | 100 | 60 | 20 | 1,000 | n/a | 20 | 130,000 |
| **Application Service Energy** | **43,680** | **29,568** | **19,656** | **940,800** | **890,400** | **40,000** | **120,000,000** |
| **Quantity of functional units (QFU) over application service life** | **96,000** | **48,000** | **18,000** | **576,000** | **360,000** | **64,000** | **240,000,000** |
| Battery cycle life (no calendar aging) [FC] | 1,500 | 1,500 | 2,000 | 2,000 | 3,000 | 8,000 | 10,000 |
| Battery calendar life (no cycling) [a] | 20 | 20 | 20 | 20 | 20 | 25 | 25 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| ŋcoul x ŋv = energy efficiency | 92% | 92% | 92% | 92% | 92% | 92% | 92% |
| **Energy consumption due to battery energy efficiency [kWh]** | **7,680** | **3,840** | **1,440** | **46,080** | **28,800** | **5,120** | **19,200,000** |
| Self-discharge rate [%/month] | 2% | 2% | 2% | 2% | 2% | 2% | 2% |
| Average SOC [%] | 50% | 50% | 50% | 50% | 50% | 50% | 50% |
| **Energy consumption due to self-discharge [kWh]** | **192** | **96** | **29** | **864** | **384** | **30** | **90,000** |
| Charger efficiency AC [%] | 85% | 85% | 85% | 92% | 92% | | |
| Charge power AC [kW] | 3.8 | 3.8 | 3.8 | 22 | 22 | | |
| Charger efficiency DC [%] | 93% | 93% | 93% | 93% | 93% | 98% | 98% |
| Charge power DC [kW] | 50 | 50 | 50 | 150 | 150 | | |
| Share AC charge [%] | 80% | 80% | 80% | 50% | 50% | | |
| Battery efficiency charge [%] | 94% | 94% | 94% | 94% | 94% | | |
| **Energy consumption due to charger energy efficiency [kW]** | **13,983** | **6,991** | **2,622** | **46,957** | **29,348** | **1,391** | **5,217,391** |
| Heating/cooling energy requirements [%] | 5% | 5% | 5% | 5% | 5% | 5% | 5% |
| **Energy consumption due to cooling and heating requirements [kWh]** | **4,800** | **2,400** | **900** | **28,800** | **18,000** | **3,200** | **12,000,000** |

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