Modeling and simulation of electric vehicles - The effect of different Li-ion battery technologies

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Abstract — Limited range is one of the main drawbacks of battery electric vehicles. Especially at low temperatures the range is reduced due to low battery capacity and power as well as additional energy demand for auxiliaries. In order to compare different battery technologies regarding their in-vehicle performance, a model based approach is chosen. Several battery technologies are modeled and implemented into a simulation environment for vehicle systems. In addition, varying test cases are defined to analyze the battery characteristics and impact on the vehicle performance. For example, simulation results show that the energy demand of the power train rises significantly in urban surroundings and low ambient temperature conditions. This is due to the fact that recuperation of brake energy is limited by the reduced battery power capability. Furthermore, the efficiency of the battery and the power train is analyzed regarding varying temperatures, battery sizes and driving cycles. Eventually, the electrical range taking into account different driving cycles, temperatures, and auxiliary loads is studied. *EVS25 Copyright*.

Keywords— Modeling, simulation, Li-ion, battery electric vehicle, energy consumption, thermal effects

1. Introduction

Using the electric vehicle in combination with renewable energy sources is a promising option to reduce emissions and save fossil fuel resources [1]. However, on the other hand there are still some problems that have to be solved. Besides cost and life time issues, the limited traveling range is one of the main drawbacks of battery electric vehicles. Especially at low temperatures the range strongly decreases due to the lower capacity and power capability of the battery. Furthermore, the increased auxiliary energy demand for heating of the passenger cabin and battery increases significantly when ambient temperatures are low.

To solve these problems, industry and research organizations develop different Li-ion battery technologies. In order to compare these battery technologies regarding their suitability for battery electric vehicle applications, a model based approach is chosen and described in the following. Therefore, different battery technologies are modeled and validated by measurements (see chapter 2). In the next step, the battery models are implemented into the vehicle system simulation library AlternativeVehicles. By applying several test cases, such as temperatures, driving cycles, and battery sizes (see chapter 3), the battery technologies are compared regarding their impact on vehicle energy demand, electrical range, and energy efficiency (see chapter 4).

2. Battery modeling

For the modeling of the battery, three very different technologies have been considered:

- $LiNi_xMn_yCo_zO_2$ vs. graphite (NMC)
- $LiFePO_4$ vs. graphite ($LiFePO_4$)
- $LiCoO_2$ vs. titanate (titanate)

NMC based batteries are a compromise of more or less standard electrode materials with respect to safety, capacity, power, and cycling stability. They are available for a wide range of applications, ranging from small laptop batteries to large traction batteries [2-3].

Batteries based on $LiFePO_4$ show superior safety characteristics. Furthermore, they are expected to have a high cycle life while being able to provide a significant power. The flat open circuit voltage and the oftentimes low inner resistance allow a rather quick charging of the battery compared to e.g. conventional NMC based batteries.

Table 1 Technical data for modeled batteries.

Parameter	$LiFePO_4$	NMC	Titanate
Nominal capacity [Ah]	2.3	2.45	0.135
Nominal voltage [V]	3.3	3.6	2.3
End of charge voltage [V]	3.6	4.2	2.8
End of discharge voltage [V]	2.0	2.5	1.8

Titanate based batteries are said to have the highest expected life times; they operate over a wide temperature range and are able to deliver high power.

Due to their availability, small batteries have been tested in the lab. Since the electrical behavior is not determined by the size, but by the chemistry and cell design parameters like the ratio of active material to conductor material the results can be used to assess larger traction batteries. The technical data of the modeled batteries is given in Table 1.

2.1 Modeling approach

Equivalent circuit models are widespread for simulating lithium-ion batteries. They reach from ideal models with constant voltage source and inner resistance to models based on impedance spectroscopy being able to capture the dynamics of the double layer capacities and diffusive effects within the battery [4-9].

For models based on impedance spectroscopy the effort of parameterization is high and temperature effects are often neglected. Since temperature has a significant influence on the battery efficiency and actual capacity, it cannot be neglected when simulating driving cycles for an electric vehicle. Hence, a stationary modeling approach has been chosen.

The model consisting of three equations describes the open circuit voltage, the inner resistance in case of charging, and the inner resistance in case of discharging:

$$U_0 = f_1(SOC, T_{AMB}) \quad (1)$$

$$R_{cha} = f_2(SOC, T_{AMB}, I_{BAT}) \quad (2)$$

$$R_{dis} = f_3(SOC, T_{AMB}, I_{BAT}) \quad (3)$$

The open circuit voltage is dependent on the state of charge and the ambient temperature; the inner resistances depend on the state of charge, the temperature, and the current. The proposed model results in the equivalent circuit depicted in Figure 1. The model may be charged or discharged; the terminal voltage is calculated by the open circuit voltage and the ohmic losses within the battery.

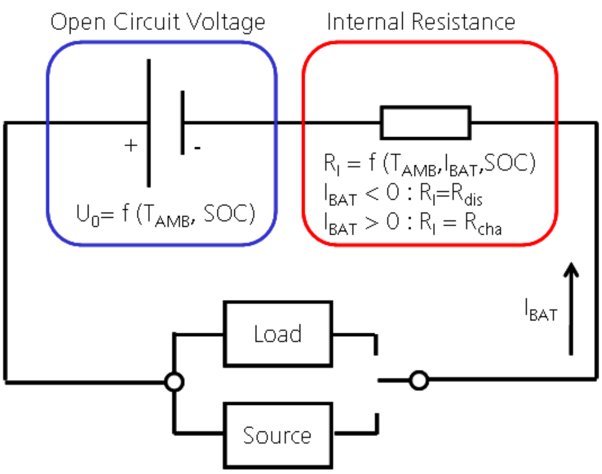

Figure 1 Equivalent circuit model. State of charge and temperature influence the open circuit voltage, the inner resistance is additionally influenced by the battery current.

2.2 Parameter estimation

In order to parameterize the modeled batteries, pulsed discharge and charge currents are used, for the determination of both the open circuit voltage and the inner resistance. A basic voltage response to these pulsed current tests is depicted in Figure 2.

The measurement delivers results for one current and one temperature at all state of charge levels. For different currents and temperatures several measurements are necessary. This procedure has several advantages: non expensive equipment can be used and therefore several measurements can be performed in parallel. Open circuit voltage and inner resistance are determined in one measurement. The correct value of the inner resistance can easily be determined through the quasi-stationary state following each pulse.

The values are used as input for the fitting of the function in the equations 1 to 3.

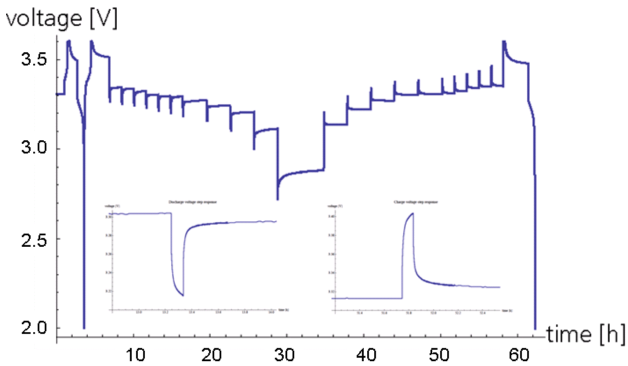

Figure 2 Basic measurements for determination of inner resistance and open circuit voltage of the battery. The test starts with a capacity test followed by a full charge. After the full charge the actual pulse test starts. The small pictures within the figure show the voltage response in case of a discharging current pulse on the left side and in case of a charging current pulse on the right side.

Figure 3 shows an example for a function resulting from the measurements and the parameter estimation. The open circuit voltage for the NMC based battery has a strong state of charge and a weak temperature dependence. Similar functions result for the remaining parameters and batteries.

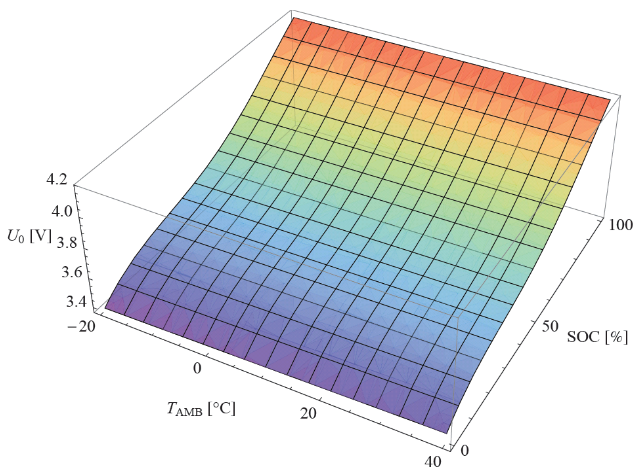

Figure 3 Modeled open circuit voltage for the NMC based battery, depending on the ambient temperature and the state of charge.

2.3 Model validation

For validation purposes current profiles close to electric vehicle applications have been applied to the batteries. These result in highly dynamic discharge profiles and rather constant currents during the charging phase.

A temperature profile ranging from -20 °C to 40 °C has been superimposed to current profile. The resulting voltage response in comparison to the simulation result is depicted in Figure 4.

It can be seen that high deviations appear especially for the beginning resting phases since the stationary model immediately switches to the stationary state, resulting in the maximum errors shown in Table 2. However, these voltage responses are completely negligible since no current is flowing and since the efficiency and capacity of the batteries are not influenced.

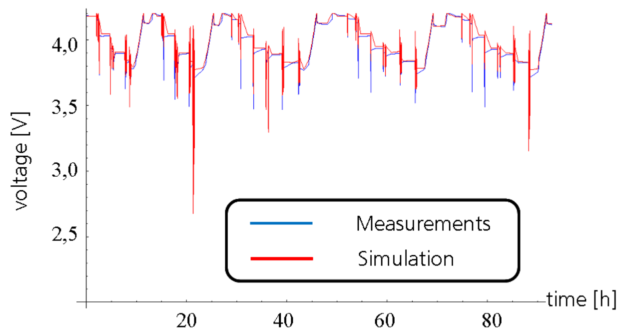

Figure 4 Validation profile for NMC based battery. The graph shows very accurate results for different temperatures within the limitations of a stationary battery model.

For the NMC and the $LiFePO_4$ based batteries the resulting average errors are very low. For the titanate based batteries the parameterization has been more difficult due to the higher inner resistance of the specific battery. For small and constantly flowing currents like those in stationary applications the results have been even more accurate.

Table 2 Error values from validation for the three modeled lithium-ion battery types.

Parameter	$LiFePO_4$	NMC	Titanate
Mean absolute error [mV]	32.5	26.3	52.0
Mean relative error [%]	0.98	0.68	2.01
Max absolute error [V]	0.37	0.60	0.52
Max relative error [%]	11.3	18.2	20.2

3. Vehicle modeling and simulation

This chapter describes how the battery models are used in combination with the AlternativeVehicles Library to investigate the impact of different battery technologies on the vehicle performance. Therefore, in the first section a short introduction into the simulation language Modelica and the AlternativeVehicles Library is given. In the following section different test cases are defined. For example initial temperatures, drive cycles, and battery capacities are varied.

3.1 AlternativeVehicles Library

The AlternativeVehicles Library, which has been developed by DLR Institute of Vehicle Concepts [10], is based on the object-oriented modeling language Modelica. Modelica is a non-proprietary standard which allows modeling of complex physical systems consisting of components from varying physical domains, e.g. mechanics, electrics, electronics, hydraulics, thermodynamics and control theory. Contrary to Matlab/Simulink, Modelica is an equation based language. The models are described by differential, algebraic, and discrete equations. Additionally, it is also possible to implement block diagrams in order to model control systems.

Due to physical connectors, Modelica models are well-arranged. The physical connector consists of a flow and a potential variable describing the energy flow between different subsystems. For example, electrical voltage and current are the potential and the flow variable of an electrical connector. In Modelica, models can be implemented in a graphical and a textual way. Figure 5 shows an example of an entire battery electric vehicle model. The electric and mechanical parts are divided by the electric drive. In Figure 5 electrical connections are indicated by blue and mechanical rotational connections by gray lines.

Another feature of Modelica is the expandable connector which allows the modeling of bus systems. Signals can be added and read in any sub-model where the signal is needed. In the vehicle model the yellow expandable connectors are used to exchange control and status data between the different components. Further information about Modelica can be found in [11].

The Modelica library AlternativeVehicles has been developed to analyze different alternative power trains regarding their efficiency, energy demand, and driving performance. Furthermore the impact of different subcomponents on the entire vehicle system, e.g. energy storages and electrical motors, can be investigated. The AlternativeVehicles Library contains many components which are necessary to model alternative power trains. Main components are electrical energy storages, electric drives, electrical converters, fuel cell systems, engines, transmissions, and auxiliaries like air conditioning compressors.

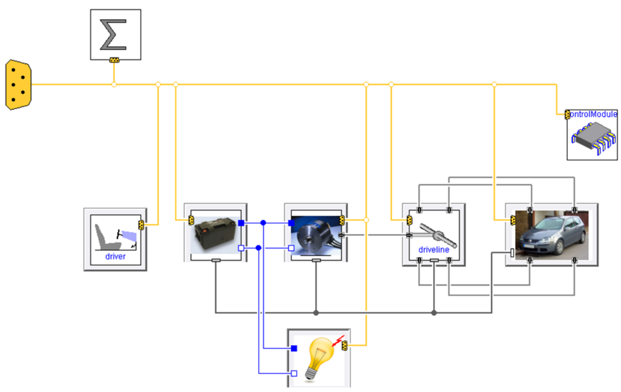

Figure 5 Graphical view of a Modelica battery vehicle model.

Besides these component models the AlternativeVehicles Library contains ready to use vehicle models, e.g. conventional gasoline or diesel vehicles, hybrids, fuel cell hybrids, and battery electric vehicles.

Due to the fact that many models are based on the VehicleInterfaces Library [12] it is easy to use models from other automotive Modelica libraries like the Power Train Library, which has been developed by DLR Institute of Robotic and Mechatronics [13].

3.2 Vehicle definition and test cases

This section describes the definition of the basic vehicle parameters as well as the assumed parameters which are varied to investigate the use of different battery technologies.

For the following simulation-experiments a vehicle belonging to the compact class (like the Volkswagen Golf, see Table 3) is defined. Due to the comparatively low energy demand and the application in urban surroundings, the small and the compact class will be the main markets for battery electric power trains.

Table 3 Basic vehicle parameters.

Parameter	Unit	Value
Maximum velocity	km/h	150
Acceleration (0-100 km/h)	s	14
Air drag c_w x A	1	0.62
Kerb weight (ref. vehicle)	kg	1340
Rolling coefficient	1	0.01

Related to the modeled battery technologies in chapter 2, the defined vehicle model is equipped with a NMC, a titanate, and a $LiFePO_4$ battery. Beside the electrical characteristics one of the main differences is the energy and power density. The Li-Ion battery using NMC as cathode material has the highest energy density. On the opposite $LiFePO_4$–batteries have a very high power density and a medium energy density.

Table 4 Assumed battery parameters.

	$LiFePO_4$	NMC	Titanate
Cell energy density [Wh/kg]	108	196	65 (37.8)
Cell power density (con.) [kW/kg]	2	1	0,12
Mass factor cell to system	1,3	1,3	1,3
System energy density [Wh/kg]	83	151	50
Specific thermal capacity [kJ/kg K]	1	1	1
Usable capacity [%]	85	85	85

In order to define the energy density on the battery system level, a mass factor of 1.3 is specified. This means that the mass of the battery system is 1.3 times higher than the total cell mass. This mass factor considers all components which are needed to build up a battery system, e.g. battery housing, battery management, and thermal conditioning like cooling/heating. To reach an increased cycle life time, the usable capacity is limited to 85 % of the nominal capacity.

Based on the defined vehicle parameters (see Table 3) and the assumed battery parameters (see Table 4) the electric vehicle models are build up and dimensioned.

To compare the different battery technologies and their impact on the vehicle performance four parameters are varied. For each battery technology three battery sizes are defined (see Table 5). In order to make sure that the driving performance is reached, the electrical power train is adapted regarding the traction power for every battery size. The three battery technologies and sizes result in 9 basic battery vehicle configurations.

As mentioned above, the battery temperature is one main parameter which affects the battery characteristics. Hence, a wide range of initial temperatures from -20 to +20°C is chosen.

Table 5 Varied model parameters.

Parameter	Unit	Value
Battery capacities (small, medium and large)	kWh	15, 25 and 35
Battery start temperatures	°C	-20; -10; 5 and 20
Drive cycles	-	Artemis Urban Road, Motorway and NEDC
Auxiliaries	-	With and without Battery heating/cooling; 2 kW electrical, COP 2

Another crucial factor is the driving cycle. For example, within the New European Drive Cycle (NEDC) the mean velocity and acceleration is comparatively low. Therefore the Artemis Cycles are also applied [14]. Artemis driving cycles are divided into the three parts: urban, road, and motorway. The urban cycle is characterized by a low mean velocity as well as many strong acceleration phases. On the opposite the motorway cycle has a higher mean velocity and less acceleration and deceleration phases. The road cycle is comparable with the NEDC.

Last but not least the auxiliary load affects the battery characteristics. Especially the temperature conditioning of the battery itself is not negligible. Particularly at low temperatures the battery performance is rather low and an extra battery thermal conditioning is useful and necessary to achieve a higher charge and discharge power. However, for this conditioning additional energy is needed. This raises the question whether a higher range is reached with or without battery heating.

4. Simulation results and discussion

In this chapter the simulation results are shown and the key findings are discussed. Therefore, in the first section, the results of the vehicle dimensioning are shown. In the following sections all battery technologies are compared regarding their impact on vehicle energy demand, efficiency, and driving range.

4.1 Vehicle dimensioning

Based on the defined vehicle parameters the battery vehicles are dimensioned. The electrical drive power is chosen regarding the required maximum vehicle speed, the acceleration, and the vehicle mass which itself depends on the corresponding battery technology and size. All vehicles are dimensioned at a constant temperature of 20°C.

Table 6 Dimensioned battery vehicles with different battery technologies and sizes.

		$LiFePO_4$	NMC	Titanate
Max. velocity [km/h]		150	150	150
Acceleration (0-100) [s]		14	14	21/14.8/14
Battery capacity [kWh]		small: 15 / medium: 25 / large: 35		
Battery mass[kg]	small	181	100	300
	medium	301	166	500
	large	421	232	700
Vehicle mass [kg]	small	1418	1331	1543
	medium	1543	1403	1748
	large	1669	1475	1959
E-Motor power [kW]	small	55	55	65
	medium	60	60	70
	large	65	65	80

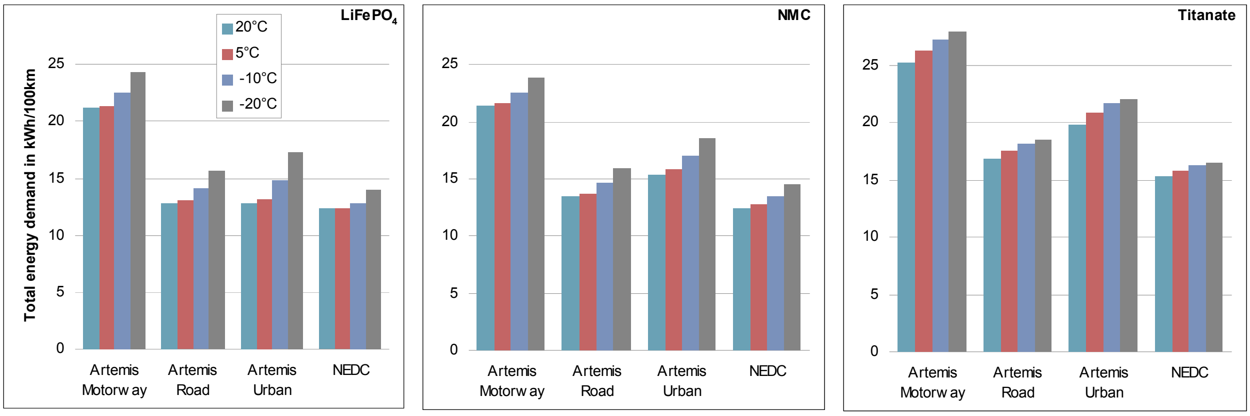

Figure 6 Simulation results of the total energy demand using the large sized batteries.

The vehicle mass is determined by subtracting the masses of all components which are part of the conventional power train, e.g. engine, transmission, and fuel storage. Subsequently, all major components of the electric power train like the electric drive, the power electronics, and the battery are added. Results of the dimensioning process show that the electric vehicles with titanate based Li-ion batteries are very heavy (see Table 6). In comparison to the reference vehicle with conventional power train (1340 kg) the masses of vehicles with titanate batteries is 200-600 kg higher and exceeding the gross vehicle weight, which is around 1800 kg in compact vehicle class. In this case usually reinforcements of the body structure are needed to guarantee the same safety and stiffness. Furthermore the simulated maximum acceleration from 0-100 km/h shows that the power capability is not sufficient for the small and medium titanate battery capacity.

4.2 Vehicle energy demand

In the following the total energy demand (see Figure 6) is calculated on the basis of the defined parameters and the dimensioned vehicle models above. The total energy demand (E_{Batt}) is determined by the required energy at the wheels (E_{Wheel}) and the losses of the electrical power train (see Figure 7). The main energy losses of the power train can be identified in the electrical motor and the battery. Main losses of the electrical motor ($E_{M,loss}$) are friction, iron and ohmic losses as well as switching losses within the inverter. The battery losses ($E_{B,loss}$) can be separated into reversible and irreversible losses. For the main part, the irreversible losses are named as Joule heat and represent the sum of ohmic and kinetic overvoltages of the battery [15]. In the battery model they are represented by the internal resistance.

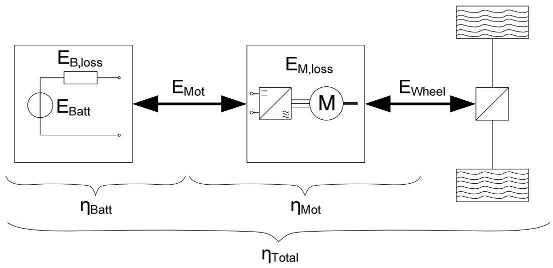

Figure 7 Energy flows between the main power train components.

Figure 6 shows that the total energy demand of the electric vehicle using a $LiFePO_4$ or NMC battery is lower in comparison to the titanate technology. This is due to the fact that the efficiency is higher because of the smaller inner resistance of $LiFePO_4$ and NMC batteries. In addition, the energy demand rises significantly for all investigated battery technologies when the temperature

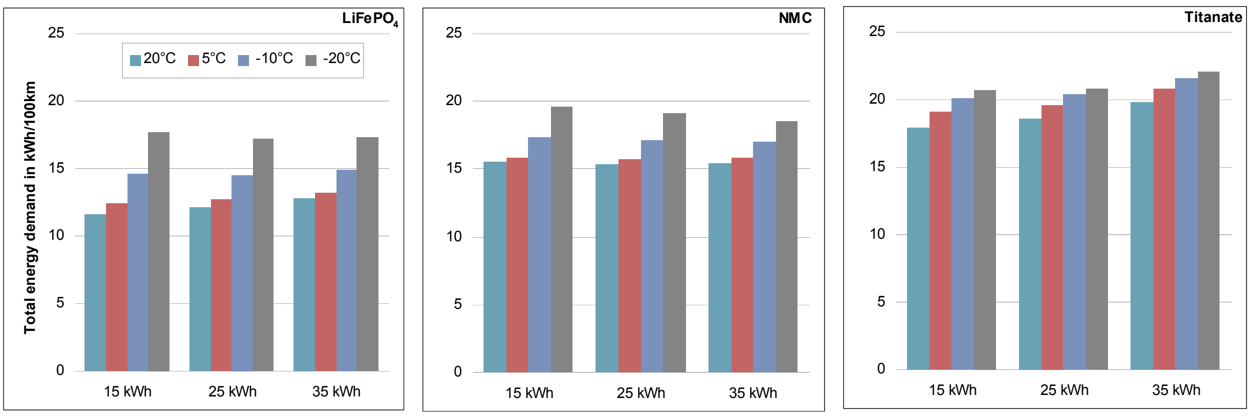

Figure 8 Simulation results of the vehicle energy demand driving the Artemis Urban cycle.

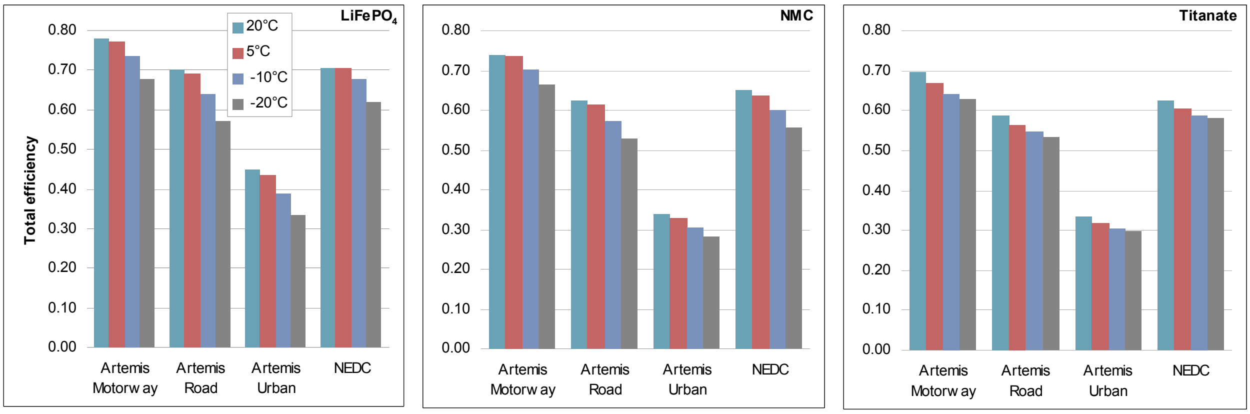

Figure 9 Simulation results of the total efficiency (η_{Total}) using the large sized batteries.

falls below 5°C. The increase of energy demand in the Artemis Urban cycle is comparably higher than in the other cycles. This characteristic can be explained by the higher rate and magnitude of acceleration/deceleration phases which lead to a higher amount of energy conversion losses.

Varying the battery size leads to two effects. On the one hand, the vehicle becomes heavier and therefore the driving energy demand increases. On the other hand, the power capability and efficiency is improved. Hence, more brake energy can be recuperated and less energy is converted into heat. Looking at the $LiFePO_4$ and titanate batteries shows that increasing the battery capacity results in a higher energy demand (see Figure 8). In contrast, the NMC battery more or less compensates the higher energy demand by the higher efficiency and power capability of the battery. This contrary effect can be explained by the higher energy density of the NMC technology in comparison to $LiFePO_4$ and titanate. This means the increase of the driving energy demand caused by the higher battery mass Table 3 is lower than the decrease due to the higher battery efficiency and power capability.

4.3 Vehicle efficiency

The vehicle efficiency shows how much energy is needed related to the required driving energy at the wheels. In combination with Figure 7 the total efficiency is determined by equations (4), (5) and (6).

$$\eta_{Total} = \frac{E_{Wheel}}{E_{Batt}} \tag{4}$$

$$E_{Batt} = E_{Mot} - E_{B,loss} \tag{5}$$

$$E_{Mot} = E_{Wheel} - E_{M,loss} \tag{6}$$

The highest efficiency is reached while driving the motorway cycle (see Figure 9). As mentioned above, in comparison to the urban cycle less energy conversions have to be performed due to less acceleration and deceleration phases and therefore a higher total efficiency is reached. Furthermore the efficiency is also dependent on the start temperature of the battery. Regarding the energy demand, the difference between 20°C and 5°C is rather small. The highest total efficiency (η_{Total}) is reached by using the $LiFePO_4$ batteries.

Another influence factor on the total efficiency is the battery size (see Figure 10). As already mentioned in section 4.2, the battery capacity directly affects the battery power capability and efficiency (η_{Batt}). If the capacity is enlarged, the inner losses decrease and thus the efficiency is raised. This effect can be observed best at cold temperatures (see Figure 10). Additionally due to the lower inner resistance the power capability is increased. The higher power capability itself directly affects the power train efficiency (η_{Mot}), since the electrical drive is able to recuperate more kinetic energy.

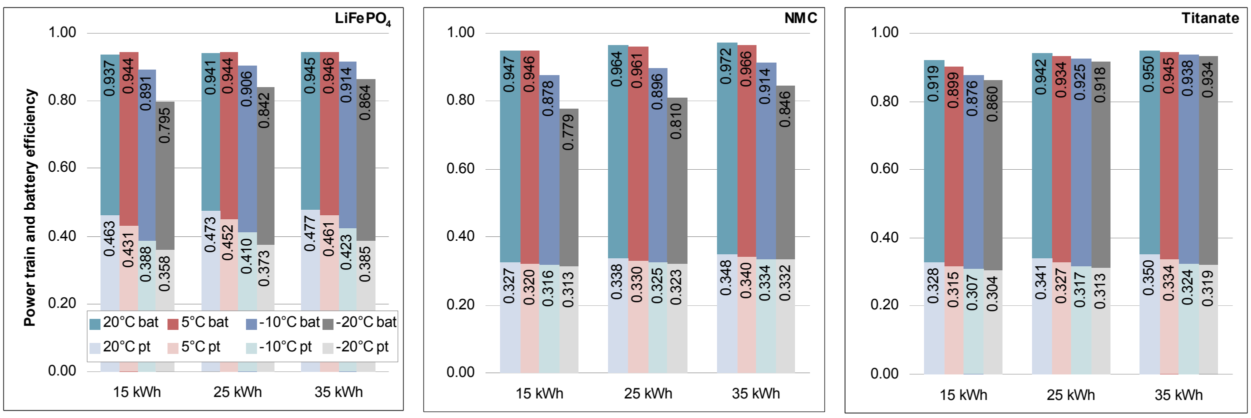

Figure 10 Simulation results of power train η_{Mot} (pt) and battery η_{Batt} (bat) efficiency driving the Artemis Urban Cycle.

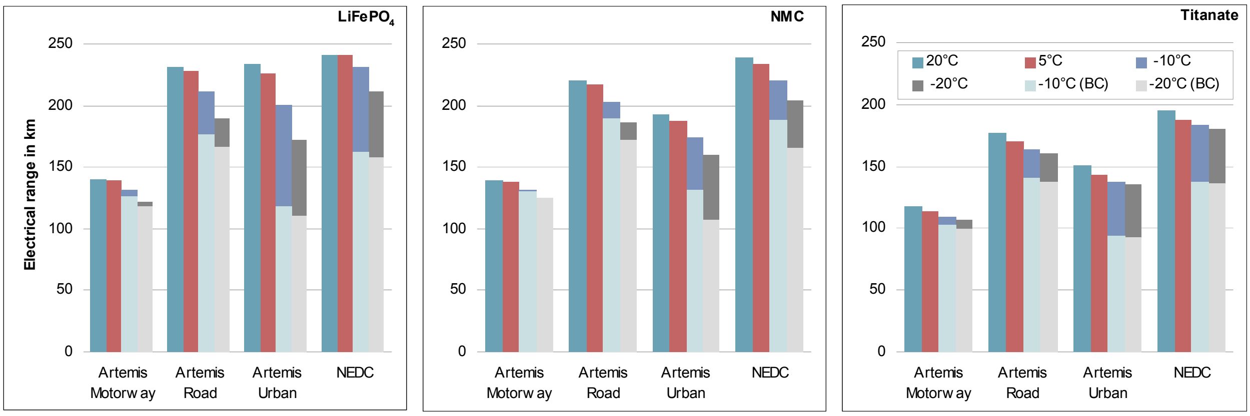

Figure 11 Simulation results of electrical range without and with battery temperature conditioning (BC) using the large batteries.

The simulation results in Figure 10 show that due to the higher battery power the power train efficiency using $LiFePO_4$ is significantly higher than the ones for NMC or Titanate. Furthermore, it can be seen that the battery efficiency of titanate is less temperature dependent than the $LiFePO_4$ or NMC technologies.

4.4 Vehicle range

Based on the simulated energy demand (see Figure 6) the 35kWh-battery vehicles would reach a range between 100 km and 240 km depending on the driven cycle and the used battery technology (see Figure 11).

To answer the question in section 3.2, asking whether and how the vehicle range is shortened or improved by using a battery temperature conditioning system further simulations are carried out. Therefore, the battery is heated until it reaches 5°C. The results in Figure 11 for -10°C and -20°C show that the reduction of the driving range is the lowest for the motorway cycle. Especially in the very short Artemis Urban cycle the range is shortened by around 30 % compared to the simulations without conditioning the battery temperature. This means that especially on short distances the startup heating of the battery is not improving the vehicle range or energy demand. Only on longer distances, repeating the drive cycles several times, the start up conditioning of the battery leads to an extended range and less energy demand.

However, if the vehicle is plugged in, the energy needed for thermal start-up conditioning of the battery could be supplied from the grid. Thus the vehicle range can be increased because no extra energy for battery conditioning is needed at the beginning of the drive cycle.

5. Conclusion

Modeling and simulation of battery electric vehicles has shown that the choice of battery technology has a high impact on the vehicle performance. Energy demand, efficiency, range, and acceleration performance are main parameters which are affected.

All investigated battery technologies ($LiFePO_4$, NMC, and Titanate) showed a high temperature dependency. Especially for temperatures ranging from -10°C to -20°C the energy demand rises significantly. Furthermore, the battery size and the utilized drive cycle have a strong influence on the energy demand and efficiency. Simulating the Artemis Urban drive cycle with a small sized battery showed that the best performance was reached using the battery with $LiFePO_4$ technology. Additionally simulation results have shown that temperature dependency can be lowered and efficiency and power capability can be raised by increasing the battery size. Particularly the NMC battery vehicle in the Artemis Urban cycle showed that with increasing the battery size and mass the energy demand is not raised. This means that the effect of higher power capability and efficiency compensates for the increased driving drag energy caused by the higher battery mass. This phenomenon can be explained by the lower specific power capability of the NMC battery in comparison to the $LiFePO_4$ battery: the small $LiFePO_4$ battery already has enough power to regenerate the brake energy. One must add that the results are correct for these specific batteries. While the specific energy density is rather fixed for the technologies, power density might vary significantly resulting in slightly differing results.

Eventually, the usage of a battery thermal conditioning was analyzed. The results show that a controlled and faster warm-up of the battery cannot improve the vehicle range. Especially for the Artemis Urban cycle with a short distance and with low mean velocity, the range is shortened by around 30 % in comparison to the model without battery thermal conditioning.

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