From the smoking exhaust to the clean socket

Design steps from the diesel-powered mobile machine to the all-electric mobile machine

Part 1

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1. Introduction

In recent years, the electrification of vehicles has progressed further and further. Besides climate change and rising energy costs, this change is also driven by the continuous improvement of components, both in terms of performance and price. This can be observed in particular in battery-powered passenger cars, which have significantly increased their market share.

The trend towards electrification in mobile machinery and commercial vehicles is not quite as clear, or less obvious in the consumers' perception. Yet it is precisely in this area that a high added benefit can be achieved, as mobile machines and commercial vehicles not only profit from the more accessible torque and the more precise control, but also from the higher efficiency.[1][2][3]

The requirements for the design and layout of a mobile machine are very complex: On the one hand, there are usually a large number of actuators that have to be operated by the energy source. For example, a straddle carrier has 4 drives, as well as a hoist. In addition, there are auxiliary drives for hydraulic components, air conditioning and other auxiliary systems. In many cases, there is also a requirement for very high availability. Additionally, there are a number of possible solutions and topologies that can be considered for electrification and that need to be evaluated.

In this series of white papers we want to highlight different aspects of the electrification of mobile machinery. The aim of this series is to provide readers with insights into the issues and processes involved in solving these challenges.

In this paper, we start with general considerations of the power and energy requirements of these applications to met the requirements.

We then look at various general approaches to solving the challenges and show how general considerations of power flows can already be used to make important design considerations independent of technology. This technique allows us to compare different technical realizations quantitatively with quiet low effort.

2. Power and Energy demand

An electrified mobile machinery is basically an electric energy storage system on the move. The storage medium can be fossil fuel, a hydrogen tank, or a battery. This stored energy is converted into electrical energy, which is then converted into kinetic energy. The main design question is how much energy we need to store and how much power do we need to provide.

Let us first look at the power and energy requirements of mobile machinery compared to other applications of electrical storage systems.

Figure 2-1 shows the demand for different applications. Mobile devices are applications that use electrical energy to operate without a mains connection. Example applications are the laptop or the mobile, as well as battery-powered tools. The power range goes up to a maximum of 1kWh and also the output just up to 1kW.

At the upper end of the power and energy scale are the stationary energy storage applications. They already start at a few killowatt hours and a power of a few kilowatts. These are typical home storage systems for the intermediate storage of solar power. However, they can reach into the megawatt range. These are then large-scale storage systems that are used for the power and energy market.

Between these two poles are the mobility applications. In Figure 2-1, we have distinguished between mobility applications such as eBikes, eScooters and automotive and mobile machinery.

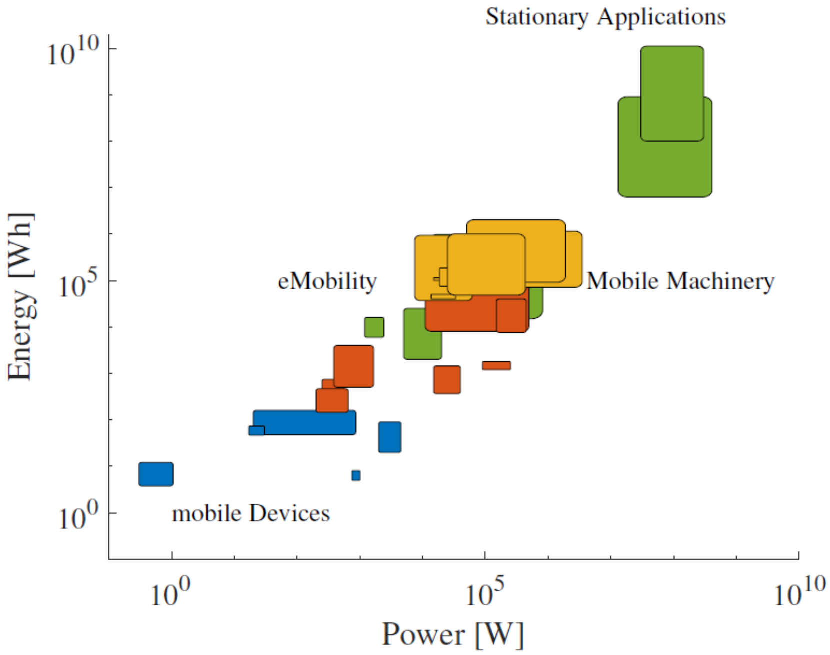


Figure 2-1: Energy and power demand of different energy storage applications. [4]

In electrical storage systems, a distinction is made between energy and power applications. The E-rate serves as a differentiation criterion here. The E-rate results from the ratio of power P and installed storage capacity κ.

$$E = \frac{P \cdot 1\text{h}}{\kappa\ [\text{Wh}]}$$

The E-Rate allows us to distiquish between power and energy application in a simple form. F.e. if we have a storage with a capacity of $\kappa = 5\text{kWh}$ and discharge it over one hour with 1kW, the E-rate is 1/5. This would be a typical energy application. In comparison to the installed capacity the charge power is very low. Mobiles and laptops are typical energy applications. On the one hand manufacturers increases the capacity of the energy storage and on the other hand they are decreases the power consumption to increase the intervals between charging operations.

If we discharge the storage of $\kappa = 5\text{kWh}$ with 20kW, the E-rate is 4. This would be a power application. An electrical screwdriver is a simple example for this type of application. It need very short periods of high power to screw, but it do not need to provide this power over a long period of time continuously.

The distinction between energy and power applications is relevant for the design of the storage system. Power applications require high currents. For electrochemical and chemical storage systems, a large cathode or anode surface is needed so that a large charge carrier exchange can also take place. In energy applications, on the other hand, it is necessary for the storage to have a lot of active material to store the energy. Figure 2-2 shows the E-rates for various mobile machines.

We see that most of these applications have E-Rats above 1, so they are power applications and not energy applications. The only exception is the wheel loader, which has an E-rate of ½.

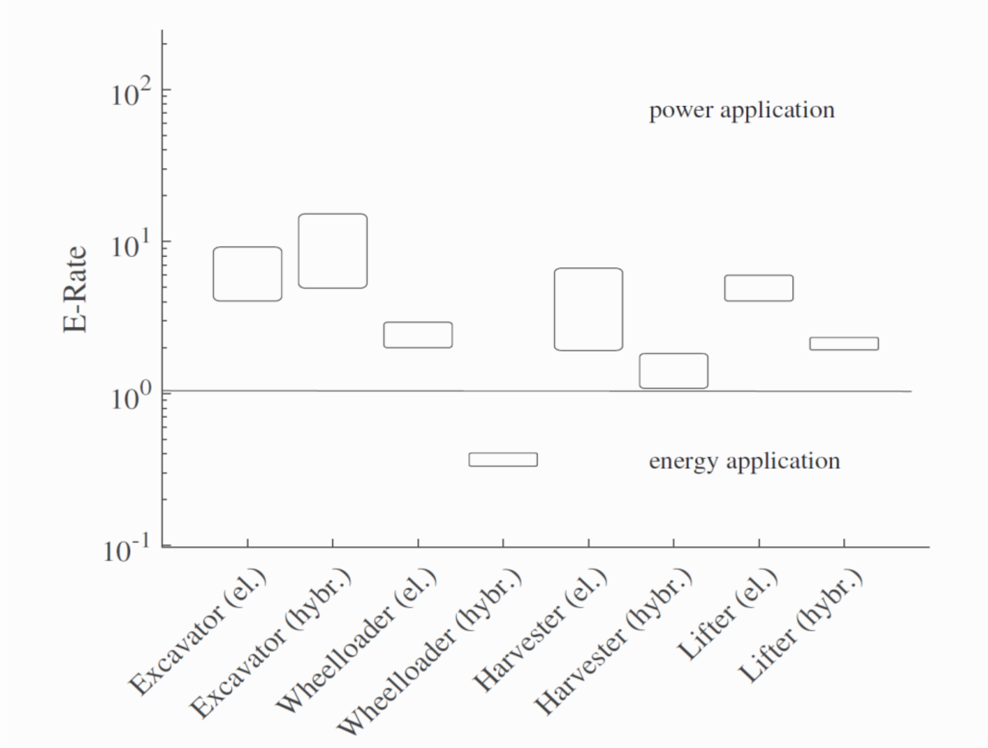


Figure 2-2: E-rates of some mobile machinery applications. [4]

3. Designcriteria for electrification of mobile machinery

There are many possible drive solutions for the electrification of mobile machines, some of which are shown in Table 3-1. For a better overview, the use of a gearbox and the associated additional degrees of freedom were not considered. One criterion for evaluating the various drive solutions is the efficiency. This is defined by the ratio of stored energy and consumed energy.

$$\eta = \frac{E_{\text{out}}}{E_{\text{in}}}$$

For example, if we have a drive solution that has an efficiency of 33%, this means that of one kilowatt hour of stored energy, only 330 watt hours are used. Hence if we were to transport a liter of fuel, we convert one third of it into kinetic energy. The remaining two thirds dissipates in form of heat or friction losses. The associated weight, or volume, is transported along with it, but is not converted into work.

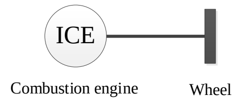
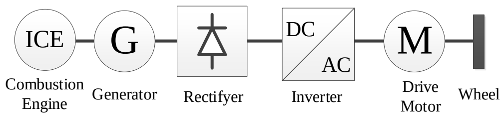
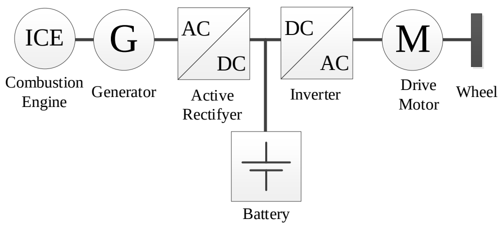
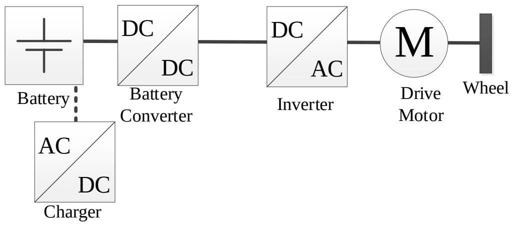
Combustion Engine		$\eta = \eta_{\text{ICE}} = 30\%$
Diesel Electric		$\eta = \eta_{ICE} \cdot \eta_{\text{G}} \cdot \eta_{\text{R}} \cdot \eta_{\text{Inv}} \cdot \eta_{M}$ $= 45\% \cdot 96\% \cdot 97\% \cdot 95\% \cdot 92\% = 36\%$
Diesel hybrid engine		$\eta = \eta_{ICE} \cdot \eta_{\text{G}} \cdot \eta_{\text{AFE}} \cdot \eta_{\text{B}} \cdot \eta_{\text{Inv}} \cdot \eta_{M}$ $= 45\% \cdot 96\% \cdot 97\% \cdot 92\% \cdot 95\% \cdot 92\% = 33\%$
Full electric Engine		$\eta = \eta_{C} \cdot \eta_{B} \cdot \eta_{\text{Inv}} \cdot \eta_{M}$ $= 98\% \cdot 92\% \cdot 95\% \cdot 92\% = 78\%$

Table 3-1: Different types of powertrains and an estimate of their efficiency.

Let us now look at different types of propulsion shown in Table 3-1 in detail. The baseline is the combustion engine, where a fuel is converted into thermal energy and then into kinetic energy via a combustion process. The efficiency cannot be greater than that of the Carnot process. In reality, this efficiency is even worse, since the efficiency is additionally influenced by the operating point and the translating mechanics. Therefore, operational efficiencies of more than 30% are rarely observed.

In a diesel-electric drive, the kinetic energy generated in the combustion engine is converted into electrical energy, which is then converted into kinetic energy via an inverter and an electric motor. The additional energy conversion stages reduce the overall efficiency with their efficiencies, but since the operating point of the combustion engine can be optimized here, a higher efficiency can be achieved.

The disadvantage of a diesel-electric drive is that the energy flow only goes from the diesel generator to the consumer. Braking processes, where theoretically the electric drive can transfer the kinetic energy back into electric energy, cannot be optimized. This is possible with a diesel hybrid engine. Here, too, the generator is operated at an optimized operating point. However, there is a battery that can be charged by the generator and by recuperation. In direct comparison with the diesel-electric system, the efficiency is a little lower, which is due to the fact that the energy goes through an additional conversion stage.

The next solution is the all-electric powertrain. Here the internal combustion engine is replaced by a battery. The overall efficiency within the vehicle is highest here, as different electrical forms of energy can be converted with very high efficiency. But we have to be aware, that the battery needs to be charged and this charging process also includes losses.

With such a large number of possible powertrain solutions, which also have different parameters, the design of a powertrain is relatively complex. One would have to consider and vary the parameters of the different conversion stages for each type of drive. This complexity can be reduced

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considerably by using an additional abstraction level and leads to the application of power flow diagrams, for the description of electrical storage systems [4]–[7] This approach is described in the next section.

4. The Power flow diagram

The basic idea of using a power flow diagram is that any electrical storage system is used to convert stored energy into electrical or kinetic power. Figure 4-1 shows a power flow diagram for a diesel-electric powertrain. The diagram consists of power nodes between which power is transported. There are three types of nodes: sources, sinks and the storage. With A_B we describe the power flow from node A to node B. Since such a power flow is not ideal, the losses must be included. For this purpose, each power node is provided with an efficiency $\eta_{AB}(A_B)$ [4], [6]–[8].

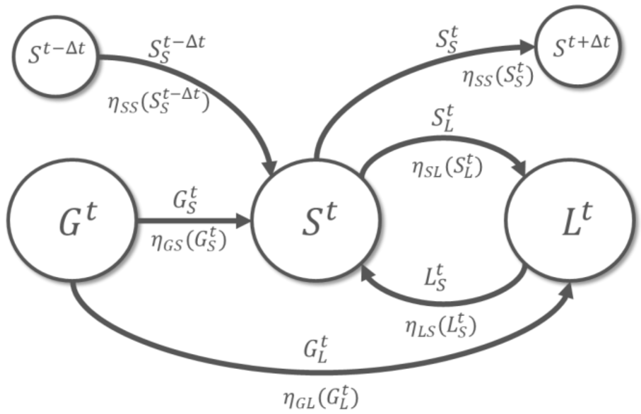

Figure 4-1: Example of the power flow diagram of a diesel-electric powertrain.

The advantage of this description is that each technical realization only differs in the range of possible values for A_B and the efficiency $\eta_{AB}(A_B)$ of the underlying technology.

Another special feature is the storage node, which draws stored power from the past and transports unused power into the future.

For a more detailed description of the technology, we refer to the literature. At this point, we would like to show an example of how such an efficiency is created from individual component information. Let us consider the power flow from the battery to the load. In our example, the load is a torque T, which is to be generated at a certain speed ω. The power flow describing this process is S_L, which is linked to the efficiency $\eta_{SL}\ (S_L)$. The total efficiency of the power flow results from the efficiencies of the individual components:

$$\eta_{\text{tot}}(T,\omega) = \eta_{\text{inv}}(U,I) \cdot \eta_{\text{motor}}(T,\omega)$$

Figure 4 2 shows the efficiencies and the combined efficiencies.

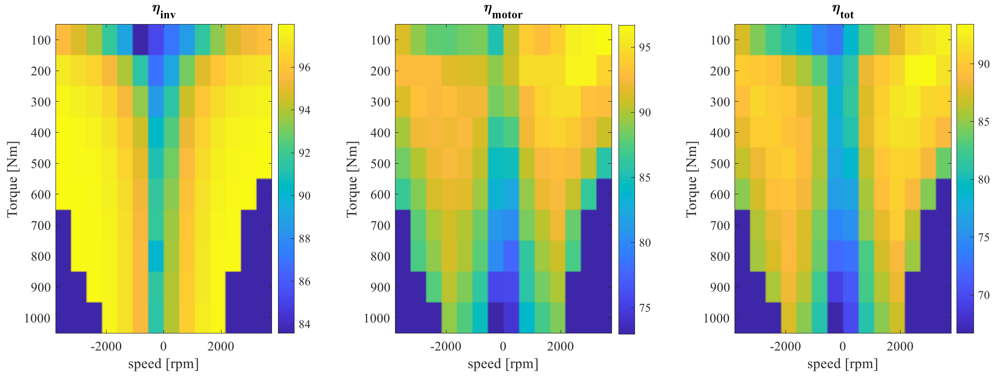

Figure 4-2: Example for the determination of the efficiency $\eta_{SL}(S_L)$ based on component efficiencies

Unfortunately, time series for torque and speeds are not always available for the load profiles that describe how the vehicle is to be used. In order to be able to carry out a simplified analysis, which is sufficient for the system analysis in the first step, it makes sense to represent η_{WR} and η_{motor} as a function of the power. In our example, we take the maximum efficiency at the given power and thus obtain a description that depends solely on the power.

In the following, we will now show how design decisions can be made with the help of a power flow diagram. For this purpose, we will consider the example of a hybrid fuel cell truck. This is to be equipped with a lithium ion battery that is used for recuperation. In this analysis, we do not want to consider the harmful influence of power fluctuations on the fuel cell. The design of the battery to dampen these fluctuations is examined in more detail in [9].

Figure 4-3 shows both a technical realization and the power flow diagram. In the technical implementation considered here, both the fuel cell and the battery are connected to the DC link via their own DC/DC converter. This supplies the drive motor.

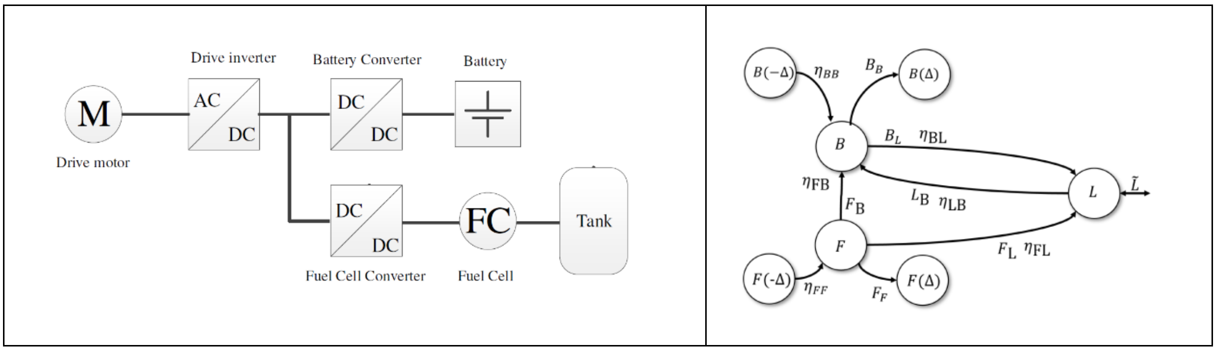

Figure 4-3: Example application of a fuel cell truck with a battery as intermediate storage. As well as the corresponding power flow diagram [4]

The power flow diagram of the hybrid fuel cell truck abstracts the overall system. It divides the system into three power nodes. The node for the fuel cell F, the battery B and the traction load L. The information about the power electronic components used is mapped by the transmission efficiencies [4], [9]

The following equations describe the system:

$$0 = \eta_{LB}L_B + \eta_{FB}F_B + \eta_{BB}B(-\Delta) - (B_B(\Delta) + B_L)$$

$$0 = \eta_{FF}\,F(-\Delta) - (F_B + F_L)$$

$$\tilde{L} = \eta_{BL}B_L + \eta_{FL}F_L - L_B$$

The 1st equations describe the power flows to and from the Lithium ion battery. The 2nd equation the power flows of the fuel cell and the 3rd equation the power flow towards and from the load. Here, $\tilde{L}$ is the load profile of the application. Note, that the two storage nodes, the fuel cell F and the lithium ion battery B have also power flow from the past and into the future.

The design of a hybrid fuel cell truck with the help of the power flow diagram is carried out in several steps. The starting point is a load profile $\tilde{L}$, which describes the use of the vehicle. Figure 4-4 shows such a load profile.

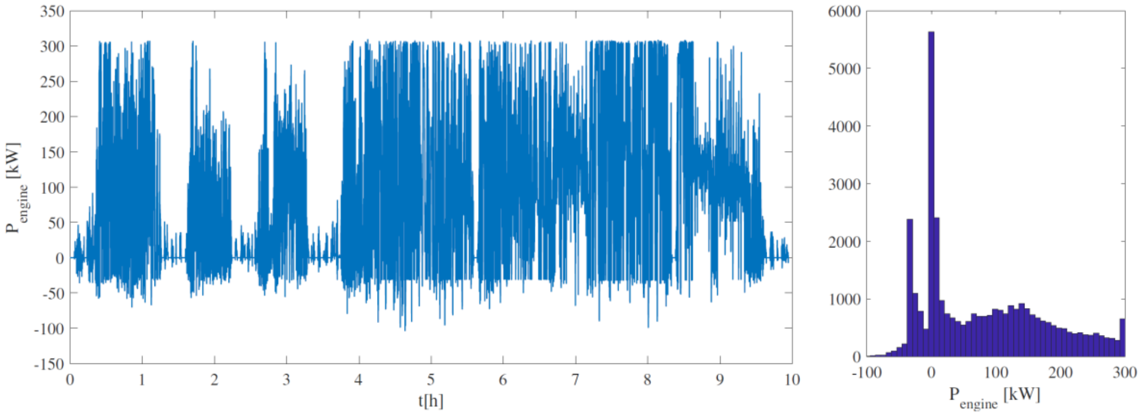

Figure 4-4: Load profile of the hybrid fuel cell truck [4]

Next, the technology is described. In the power flow diagram, this means that the transmission efficiencies $\eta_{BB}, \eta_{BL}, \eta_{LB}, \eta_{FB}, \eta_{FL}$ and η_{FF} are described.

Then the maximum transfer powers have to be defined. For each power transfer from A to B, A_B then applies: $A_B \in [0, A_B^{\max}]$

The last step is to define an optimisation criterion. This describes the goal of our design. For mobile machines, an obvious criterion is the reduction of losses. Since a loss of transmitted power, must be compensated by carried stored energy. (Recall that in an internal combustion engine we use less than half of the stored energy for movement, the rest is given away in the form of dissipated heat. So we have to store more than twice as much energy in the vehicle than we really need).

$$\min Y : (1 - \eta_{BB}(B_B))B_B + (1 - \eta_{BL}(B_L))B_L + (1 - \eta_{LB}(L_B))L_B + (1 - \eta_{FB}(F_B))F_B + (1 - \eta_{FL}(F_L))F_L + (1 - \eta_{FF}(F_F)F_F$$

The task is now to determine the optimal power flow for each point of the load profile. This can be done heuristically via a defined strategy or by solving the optimisation task [10]–[13].

In this simple example we have worked with a heuristic strategy [4]. The lithium ion battery always has priority. If the power stored in the battery is not sufficient, the fuel cell is used.

We now want to address the question of how much capacity we need for the battery. We have three different types of cells at our disposal. These differ in the maximum charge rate, expressed as the E-rate. The E-rate ranges from 1E to 4E. At 1E, we can charge a battery with 4kWh storage capacity for one hour with 4kW. At 4E, we can charge the battery with 4kWh in a quater of an hour with 16kW.

We now proceed by varying the storage capacity of the battery. The E-rate of the battery enters the power flows F_B and L_B. If we assume that the power electronics are designed accordingly, the maximum charging power of the battery also defines the maximum size of these power flows.

$$F_B, L_B \in \left[0, \frac{\kappa \cdot \mathrm{E}}{1\mathrm{h}}\right]$$

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We want to determine quantitatively how well a certain type of battery with a certain capacity supports recuperation. To do this, we define the recuperation rate. This represents the ratio of the recuperation rate at infinite power and capacity R_{∞} and the measured recuperation $R_{\kappa,E}$.

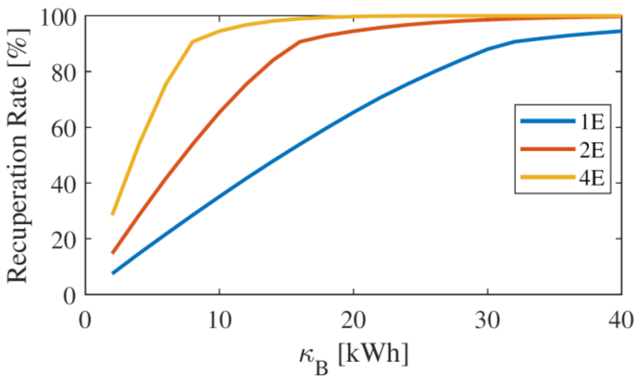

Figure 4-5: Recuperation rate as a function of the battery capacity and the E-rate.[4]

Figure 4-5 shows the results of this calculation. As expected, the recuperation rate increases with the capacity of the battery and the E-rate. The curves have a characteristic behaviour. For small capacities, the recuperation rate increases linearly and rapidly. This is because every additional kilowatt hour is also used for recuperation. From approx. 30kW, the curve flattens out significantly. Each additional kilowatt-hour increases the recuperation rate slightly. This must be the case, as can be seen from the power histogram in Figure 4-4. Here we can also see that recuperation with a power of more than 30kW occurs less frequently.

With the help of this data, we can now determine how large the battery must be. If we assume that we do not want to store 100% but only 90% of the recuperation power, the required storage capacity is 32kWh, 16kWh or 8kWh. Depending on whether we want to use a 1E, 2E or 4E cell. If we are interested in storing 98% of the recuperation power, we need 52kWh, 28kWh or 14kWh.

5. Conclusion

For the design of storage systems, and mobile utility vehicles can be considered as moving storage systems, the use of the power flow diagram is a simple way to evaluate different technical realisations with little effort.

Since this analysis is only carried out at the level of power and stored energy, not all questions that are of interest in the design of such a system can be answered. In particular, the interaction of battery, inverter and electric motor at different operating points requires more detailed consideration. We will go into this in more detail in Part 2.

Bibliography

[1] A. Lajunen, P. Sainio, L. Laurila, J. Pippuri-Mäkeläinen, and K. Tammi, "Overview of powertrain electrification and future scenarios for non-road mobile machinery," *Energies (Basel)*, vol. 11, no. 5, 2018, doi: 10.3390/en11051184.

[2] M. Liukkonen, A. Lajunen, and J. Suomela, "Feasibility study of fuel cell-hybrid powertrains in non-road mobile machineries," *Autom Constr*, vol. 35, pp. 296–305, 2013, doi: 10.1016/j.autcon.2013.05.019.

[3] K. Tammi, P. Sainio, and D. Student, "Hybrid and electric Non-Road Mobile Machines (NRMM) For further interest on NRMM roadmap," 2017.

[4] A. U. Schmiegel, *Energy Storage Systems*, vol. in Press. Oxfort: Oxford University Press, 2022.

[5] A. U. Schmiegel, "Residential PV Storage Systems - storage size matters - Residential PV Storage Systems," 2013.

[6] A. U. Schmiegel, *Energiespeicher für die Energiewende*. München: Hanserverlag, 2019.

[7] A. U. Schmiegel and A. Kleine, "Upper economical performance limits for pv storage systems," in *28th European Photovoltaic Solar Energy Conference*, 2013, pp. 1–20.

[8] A. Kleine and A. U. Schmiegel, "Optimized Operation strategies for PV Storages systems - Yield limitations, optimized battery configuration and the benefit of a perfect forecast," *Energy Procedia*, vol. 46, pp. 104–113, 2014, [Online]. Available: http://dx.doi.org/10.1016/j.egypro.2014.01.163

[9] A. U. Schmiegel, "Design consideration for a hybrid Fuel cell truck," 2022.

[10] J. Kukkaro, "Straddle Carrier Electric Powertrain Optimization," no. August, 2016.

[11] P. Hangga and T. Shinoda, "Motion-Based Energy Analysis Methodology for Hybrid Straddle Carrier Towards Eco-Friendly Container Handling System," *Journal of the Eastern Asia Society for Transportation Studies*, vol. 11, no. 0, pp. 2412–2431, 2015.

[12] D. Chen, W. Niu, W. Gu, and N. Schofield, "Game-based energy management method for hybrid RTG cranes," *Energies (Basel)*, vol. 12, no. 18, 2019, doi: 10.3390/en12183589.

[13] *Energy management for vehicular electric power systems*.

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