

Design of the Energy Storages for a (Battery) Electric Commuter Train

Schmetz, Roland¹, Struck, Alexander¹

¹Rhine-Waal University of Applied Sciences, Cleves

Abstract

The use of battery-powered electric commuter trains instead of those which are propelled by internal combustion engines on only partially (or non) electrified railway lines can save considerable amounts of energy and can avoid exhaust emissions to a large extent with comparatively low investment costs. As path to these goals, the railway line, the operating and the trains are modeled for a particularly interesting, real-life example. Then, for the generated models, it is shown how the energy demands of model-compliant (battery) electric commuter trains can be calculated and how their energy storages can be designed. The models and the procedure can also be applied for a large number of comparable dimensioning cases when defining further railway lines, operating and commuter train models, corresponding parameterization as well as the occasionally necessary addition of slope and curvature resistances. The calculation of energy demands and the design of energy storages, however, show that there are a large number of different alternatives for technical specifications as well as decisions relevant to energy efficiency and business management, too. To determine the most suitable solutions, further measures such as the investigation of the effects of intelligent modifications to the underlying models, the development and implementation of computer-aided simulations as well as the construction and testing of real (battery) electric commuter trains make sense.

Keywords: Battery, electric, battery electric, train, commuter train, recuperation, energy, Rhine-Waal University, Cleves, Nijmegen, energy demand, energy storage, electrification, railway, railroad, railway line, railway track, battery electric multiple unit, BEMU

1 Introduction

In discussions about a future, more sustainable energy supply, measures to increase energy efficiency do not always receive adequate attention. Energy, which is not needed at all, is the most environmentally friendly energy and, with a predicted share of two-thirds, almost the key to reach the German Federal Government's targets "Halving primary energy demand" and "Reducing electricity demand by one quarter" by 2050, which were defined in 2010. If the highly probable transition to e-mobility on the road by 2050 is excluded, which will have a favorable effect on primary energy demand as a result of improved conversion factors, and only moderate increases in demand are implied, the aforementioned electricity savings target could already be achieved alone by the measures listed in **Table 1**.

Table 1: Saving Potentials for Reducing Electric Power Demand by a Quarter

Current Demand	Saving Potential	Archievable Savings	Remaining Demand
591 TWh ¹	Energy-efficient Electric Motors (by 2020) ²	27 TWh	564 TWh
564 TWh	Energy-efficient Electric Motors (beyond 2020) ³	11 TWh	553 TWh
553 TWh	Complete Transition to LED-Lightning ⁴	~60 TWh	493 TWh
493 TWh	Enforcement of a Power Factor of 0,95 ³	48 TWh	445 TWh
445 TWh	Use of High Voltage DC Transmission (HVDC) ⁴	~20 TWh	425 TWh
425 TWh	Speed and Load Control of Drives		???
???	Optimisation of Power Semiconductors		???
???	Use of Superconductors		???
???	Further Saving Potentials, e.g. Energy-efficient Household Appliances		???

¹gross electricity demand (useable energy) 2014 according to the annual report of the German Arbeitsgemeinschaft Energiebilanzen e.V. ²according to EU directive 640/2009 ³according to the German Zentralverband der Elektroindustrie (ZVEI)

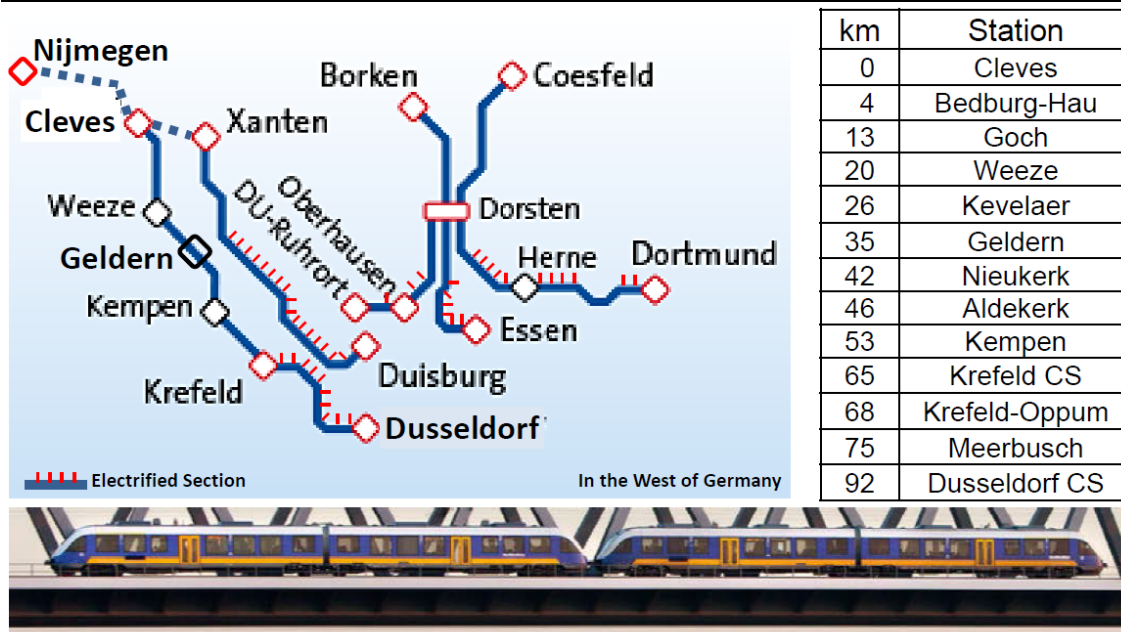
⁴according to own extrapolation (DC: direct current)

From powertrain engineering, however, it is additionally known that the energy demand can often be significantly reduced by reducing friction and moving masses and, if possible, recuperating the energy required for unavoidable acceleration and lifting operations of the remaining (large) masses. In the transport sector, especially city buses, trams and commuter trains have a great potential for recuperation of kinetic (but also potential) energy due to their typical, strongly intermittent load profiles. This is the reason why some public transport companies already use (battery) electric city buses, which can (sometimes additionally) be supplied from occasionally existing direct current (DC) electricity grids. Likewise, some (battery) electric trams with the same property are already being tested [1]. In contrast, for railway applications only trials of diesel-electric hybrid commuter trains are known so far [2]. With regard to the currently fiercely focused emissions of internal combustion engines and the finite nature of fossil fuels, however, diesel-electric hybrid commuter trains do not represent a sustainable development goal anymore. In view of the increasing number of passengers and for protection of the environment, organizations such as the German Verkehrsverbund Rhein-Ruhr (VRR) are rather striving for the further expansion of the electrified railway network. Thus in its current plan for regional transport [3], the VRR calls repeatedly for the electrification of the 65 km long, non-electrified section of the left Rhine railway line (Nijmegen/NL-) Cleves-Geldern-Krefeld (-Dusseldorf/Cologne). This situation, the meanwhile usual tender for the operation of regional railway lines in rather smaller lots for periods of fifteen years, for which often own, specific trains are procured, as well as a number of other particularly typical features which simultaneously simplify the necessary calculations, are motivation according to [4] and [5] to investigate for this railway line once the use of (battery) electric commuter trains (BECTs) and carry out a design of the required battery storages.

2 Present Situation and Modeling

2.1 Present Situation

Meanwhile, the left Rhine railway belongs with its northern section Cleves-Geldern-Krefeld (the former connection from Nijmegen/NL to Cleves was cut in 1991) and the section Krefeld-Dusseldorf to the diesel network Niederrhein/Ruhr/Münsterland (also called Niers/Rhine/Emscher-network) according to the left part of **Figure 1**, which contains yet some more strong frequented, but only partially electrified railway lines.



Alstom-Diesel Commuter Train (DCT) consisting of two single train units of type LINT 41 on the Rhine Bridge close to Dusseldorf

Legend: CS: Central station - References: www.nordwestbahn.de and www.bahn.de/kursbuch

Figure 1: Diesel-network Niederrhein/Ruhr/Münsterland with the northern section of the left Rhine railway and a diesel commuter train (DCT)

The operation of this diesel network is awarded since December 2009 until November 2024 to the German railway company NordWestBahn GmbH based in Osnabrück (meanwhile except the railway line Dorsten-Herne-Dortmund, which is again operated by German railway company Deutsche Bahn AG since 2014). Especially on the railway line Cleves-Geldern-Krefeld-Dusseldorf quite high train and passenger kilometers are provided despite a series of infrastructure, train reliability and organizational problems. In addition, not least due to the founding of the Rhein-Waal University of Applied Sciences in Cleves, this railway line has experienced a strong increase in passenger numbers and train travels (compression of the former hourly rhythm to a half-hourly rhythm on workdays since the annual timetable of December 2009, additional train travels in the morning hours since the annual timetable of December 2014 - despite strong capacity constraints due to the 35 km long missing second track in the section Cleves-Geldern and train shortage, additional late train travels on weekends and 24/7-operation at major events since the annual timetable of December 2016). In regular service, the railway line is operated exclusively by Alstom LINT 41 diesel commuter trains (DCTs), which operate on average across all travels in double traction (as shown in the lower part of Figure 1). Nevertheless, and despite additional increases to triple traction during peak hours standing passengers (even in the first class) are not the

exception but more likely in the southern part of the non electrified section of this railway line because of completely occupied seats. Therefore, several local authorities and political parties vehemently demand (in the meantime) the complete electrification (and the reconstruction of the second track in the section Cleves-Geldern). According to the German newspaper Rheinische Post of March 7, 2016, the network branch of the German railway company Deutsche Bahn AG estimates the cost for the electrification and reconstruction of the second track to about EUR 500 million [6]. Upon request in June 2016, about EUR 155 million from this money are needed for the (double-track) electrification. This figure, consisting of costs of EUR 2 million/km (double-track) and additional costs of EUR 25 million for two transformer stations including traction power lines, is in principle also confirmed by the spokesman of the German passenger association Pro Bahn [6]. It also roughly corresponds to the cost of EUR 12 billion proposed by the German company Siemens AG in promoting its eHighway concept in 2012 for the electrification of a highway backbone network with a length of 6000 km, but including the direct DC converter stations for feeding. In contrast, only about EUR 1.25 million/km (in the case of obviously existing transformer stations) are necessary for the fully projected completion of the electrification of the double track city line S 28 from Kaarst to Mettmann according to the standard Re 100, which is actually under construction [7]. Even with the use of this lower figure, the cost of electrification of the part Cleves-Geldern-Krefeld would still be in the order of EUR 100 million, a sum which, despite the rather dense traffic of light passenger trains, cannot be justified with regard to the actual cost of fuel and the return on investment, since the cancellation of freight and heavy passenger trains two decades ago. In addition, there would be the need to carry out a so-called planning approval procedure, in which, according to experience, many objections can arise, which elimination can lead to further, substantial cost increases.

2.2 Modeling

Model of the Railway Line

On the railway line Cleves-Geldern-Krefeld-Dusseldorf, including the start and end stations, there are thirteen stations in the distances according to the table in the right part of Figure 1. All trains stop at all stations. Since there are no significant topographical obstacles on the left lower Rhine, despite the fact that the Rhine-Maas watershed has to be crossed twice, the railway line can be considered as straightforward and level, so that no slope and curvature resistances must be taken into account in the following

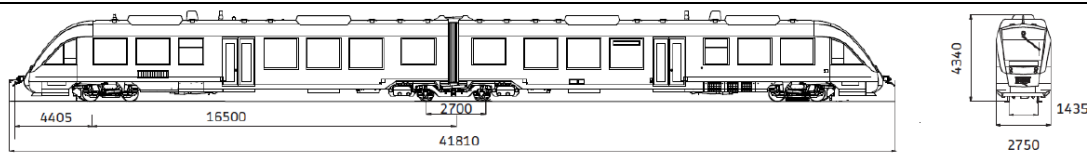
calculations. Although the railway line is designed for a maximum speed of 140 km/h in the examined section, it is driven in normal operation only with a top speed of 120 km/h. For the sake of simplicity and estimation to the safe side, it is assumed for all travels between the stops that all trains accelerate as quickly as possible to the maximum speed of 120 km/h, which then is maintained as long as possible, before the trains brake down with a deceleration of -1.13 m/s^2 . In reality, however, there are some shorter sections with speed restrictions, in particular the use of the sidings in case of the regular train encounters at the stations Bedburg-Hau and Weeze as well as the direction tracks in the stations Kevelaer and Krefeld CS.

Operating Model

According to the December 2014 timetable published on <http://www.bahn.de/kursbuch>, and the offsetting of the reduced service on some public holidays with the additional morning partial rides, and the added weekend travels since the annual timetable of December 2016 there take place an average of 16.5 train travels per day exclusively on Mondays to Fridays, another train travel on Mondays to Saturdays and another seventeen trains travels daily, all for both directions. This results in an operating model with 10790 train travels per year and direction or a total of 21580 train travels of 92 km each per year. Therefore, almost 0.6 million train-kilometers out of the almost 2 million train-kilometers per year are done under the catenary and about 1.4 million train-kilometers take place on the non-electrified part of the line.

Train Models

Based on the technical data of the Alstom diesel trains LINT 41 used in regular operation, double tractions of two single units according to **Figure 2** are defined here as train models both for propulsion by internal combustion engines and for (battery) electric propulsion. These two train models are referred to DCT in case of propulsion by internal combustion engines and to (Battery) Electric Commuter Train (BECT) in case of propulsion by (battery) electric drives. The BECT, for which the design of the energy storages is to be investigated here, should be an as much as possible equal built, virtual twin of the DCT, but with drive systems per single train unit according to **Figure 3** consisting of one high voltage part, one controlled rectifier, one common DC-rail, four inverter drives distributed to the four driven axles and one or more energy storages instead of the two internal combustion engines, the two gear transmissions and the two fuel tanks. This BECT, which consists of two single train units, is dimensioned to provide the same performance as the DCT. Beyond these settings, its further specification takes place step by step in the sections 3 and 4.



Common technical data:

- Dimensions according to drawing
- Aerodynamic drag coefficient $c_d = 0,5$
- Front section $A = 10 \text{ m}^2$
- Number of seats and stands: 136 and 120
- Possible operation modes:
Single, double and triple traction
- Standard operating mode: Double traction
- Average operating mass in double traction
 $m = 2 \times 75 \text{ t} = 150 \text{ t}$
- Maximum velocity: $v_{\max} = 120 \text{ km/h}$
- Stepwise constant accelerations:
 $a_{\text{I}} = 0,80 \text{ m/s}^2$ for $v = 0 \dots 20 \text{ km/h}$
 $a_{\text{II}} = 0,53 \text{ m/s}^2$ for $v = 20 \dots 35 \text{ km/h}$
 $a_{\text{III}} = 0,35 \text{ m/s}^2$ for $v = 35 \dots 55 \text{ km/h}$
 $a_{\text{IV}} = 0,23 \text{ m/s}^2$ for $v = 55 \dots 80 \text{ km/h}$
 $a_{\text{V}} = 0,15 \text{ m/s}^2$ for $v = 80 \dots 120 \text{ km/h}$
- Constant braking deceleration:
 $d = -1,13 \text{ m/s}^2$

Specific technical data:

- | Single diesel train unit | Single (battery) electric train unit |
|--|--|
| • Axle arrangement: Bx' 2' By' | • Axle arrangement: Bo' 2' Bo' |
| • Load per driven wheelset: 11 t | • Electric power to transformer with rectifier or from energy storages via common DC-rail to four inverters with traction motors |
| • Load per not driven wheelset: 15,5 t | • Drivetrain efficiency: $\eta = 0,9$ |
| • Rated power of diesel engines: $P = 2 \times 315 \text{ kW}$ | |
| • Drivetrain efficiency: $\eta = 0,8$ | |

References: www.nahverkehr-franken.de/rbahn/648-techdat.html, www.fahma-rheinmain.de/content/taunus_technik.html
 measurements by students

Figure 2: Technical Data of the Single Train Units of the Train Models

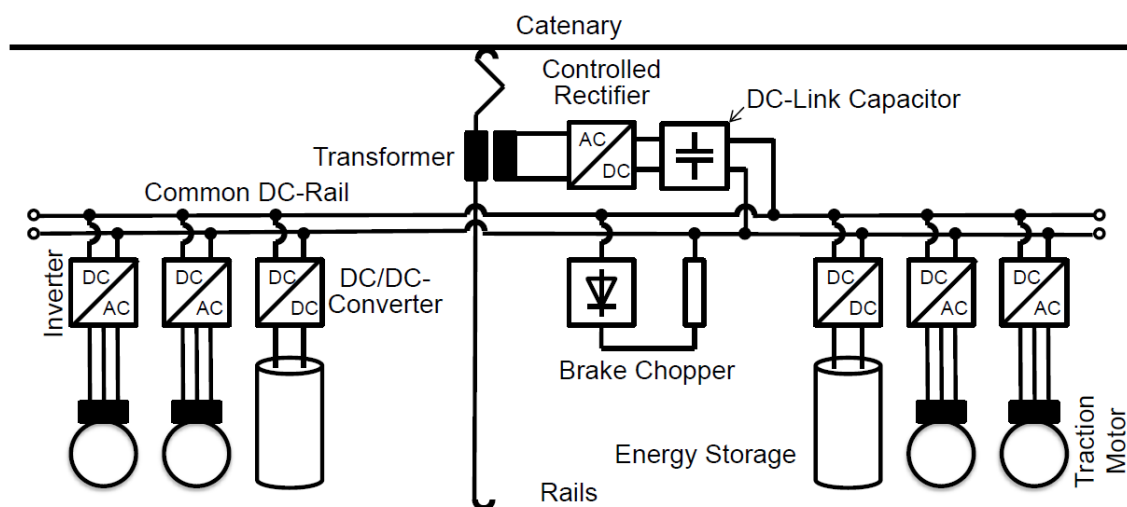


Figure 3: Drive Scheme of a Single (Battery) Electric Train Unit

3 Calculation of Energy Demands

The calculation of energy demands is based on the DCT. For this purpose, the driving resistance to be overcome must be determined first. In principle, the driving resistance is composed of the components rolling resistance, slope resistance, acceleration

resistance and aerodynamic drag [8], if the breakaway resistance is neglected, which only occurs for a very short moment at start. In case of railways, the resistance when passing through track curves must also be taken into account. But here it can be excluded as well as the slope resistance due to the above-defined railway line model. This results in the formula (1) for the driving resistance given in the upper left part of **Figure 4**. With the data of the DCT defined above and excluding the acceleration resistance according to formula (2), the speed-dependent driving resistance can be calculated, which is represented by the lower graph in the right part of this figure.

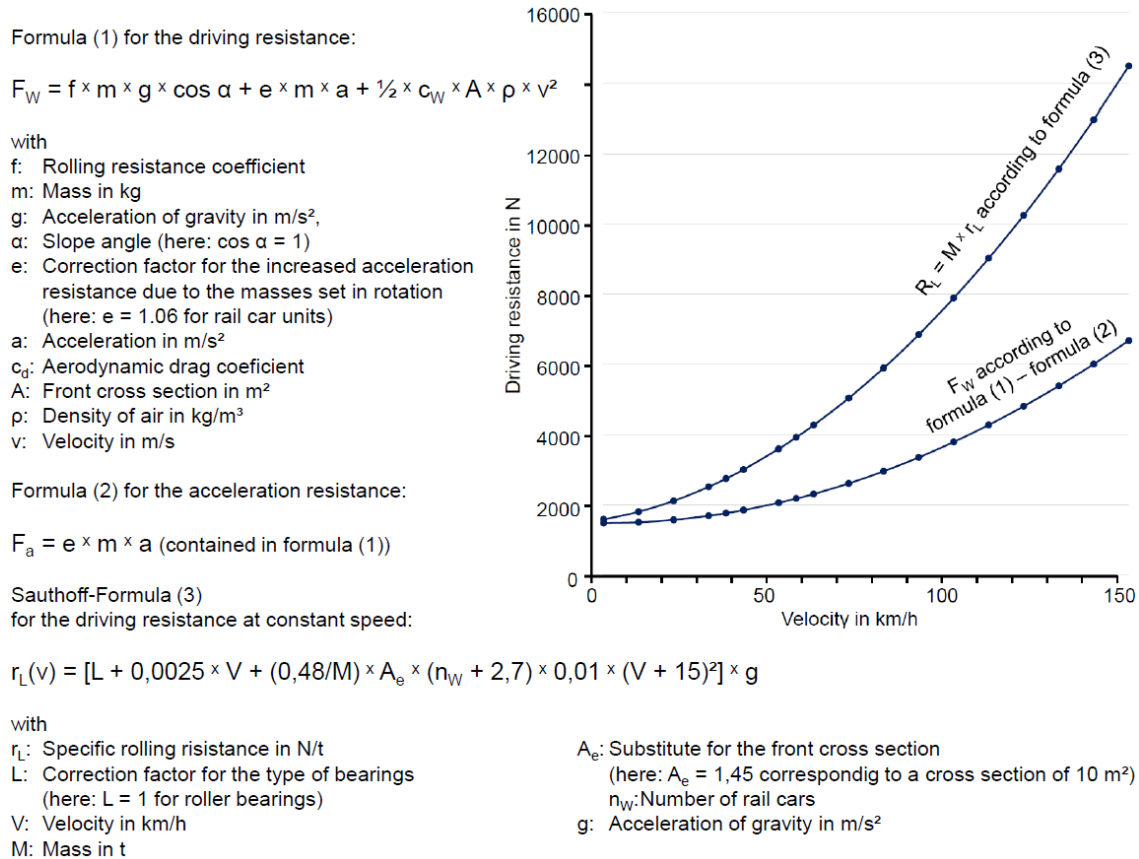


Figure 4: Driving Resistances as a Function of Speed

Because the formula (1) for the calculation of the driving resistance is rather complicated in praxis, in Germany there are additionally Strahl's formulas for the calculation of the driving resistance of freight trains and the also quite complicated Sauthoff formula for the calculation of the driving resistance of passenger trains (formula (3) in the lower left part of figure 4), valid for calculations at constant (final) speeds [8]. In the Sauthoff formula, the rolling resistance and the aerodynamic drag are combined by reference to the weight force to a speed-dependent driving resistance r_L ,

which then only has to be multiplied by the mass of a train to obtain its overall driving resistance at a constant speed.

Since the Sauthoff formula (3) considers in addition to the components due to the difference of the formulas (1) and (2) also the increase of the rolling resistance coefficient due to the type of wheel bearings and the current speed, the effects of the length of a train, its induced aerodynamic undertow and a mean headwind on the aerodynamic drag, it delivers a stronger speed-dependent graph for the driving resistance according to the upper graph in Figure 4 than the difference of the formulas (1) and (2). Therefore, for the purpose of an estimation to the safe side, here the Sauthoff formula is used for the determination of the energy demands for overcoming the driving resistances. The results according to Sauthoff's formula, however, must be increased by the acceleration resistances due to formula (2), which have to be overcome after each stop for the acceleration from standstill to the maximum travel speed of 120 km/h.

By analogy with the five-step transmissions of type Ecomat 5HP902 made by the German company Zahnradfabrik Friedrichshafen AG (ZF) which are actually installed in the LINT 41 trains and assuming a suitably matched combustion engine characteristic, it can be assumed for the DCT according to Figure 2, that the accelerations in the five steps are sectionally constant. Similar to normal operation, this leads to distances of 3000 m for each acceleration process after departure and after each stop as well as to the respective distances that can be traveled at the maximum speed of 120 km/h, and to the related energy demands according to **Table 2**. In contrast, the braking distances before each stop take only 500 m, and during each of the related braking phases, another 0.9 kWh of energy are needed to overcome the driving resistance. These energy demands, however, support the necessary withdrawal of kinetic energy during the braking phases. But they lead to a reduction in the recuperable energy, too.

In addition, the idling demands during standstill and braking phases must be taken into account for the DCT, during which electrical drive systems can largely be switched off or used for recuperation. Under the usual assumption that 10% of the indicated power is needed to overcome the internal friction in the four internal combustion engines of the DCT with an effective power of 315 kW, thus 35 kW each, these energy demands are at a total of 2.3 kWh per minute idle. Furthermore, it has to be taken into account, that for proper operation the internal combustion engines must be run in each case at least five minutes before departure from the starting station and after arrival at the destination

station, and during the standstill and braking phases within the travel distances. Therefore, the related idle demands are listed in Table 2, too.

Table 2: Energy Demands for a Travel from Cleves to Dusseldorf in kWh

km	Station	Driving ¹	Acceleration	Braking	Idling ²
0	Cleves	0	0	0	11,5
4	Bedburg-Hau	7,0	24,5	0,9	12,65
13	Goch	21,3	24,5	0,9	3,45
20	Weeze	15,6	24,5	0,9	5,75
26	Kevelaer	12,7	24,5	0,9	3,45
35	Geldern	21,3	24,5	0,9	3,45
42	Nieukerk	15,6	24,5	0,9	3,45
46	Aldekerk	7,0	24,5	0,9	3,45
53	Kempen	15,6	24,5	0,9	3,45
65	Krefeld CS	29,8	24,5	0,9	5,75
68	Krefeld-Oppum	4,9	24,5	0,9	3,45
75	Meerbusch	21,3	24,5	0,9	3,45
92	Dusseldorf CS	44,0	24,5	0,9	12,65
Σ		216,1 kWh	294,0 kWh	10,8 kWh	75,9 kWh

¹Energy demands to overcome the driving resistances during the acceleration and constant speed phases (without energy demands for the accelerations)

²Energy demands during standstill and brake phases

These energy demands for idling have to be increased by the requirements of the auxiliary drives yet. In case of the DCT, these requirements are taken into account with an average power demand of 50 kW for driving of generators for the on-board electrical system, compressors for the air brake systems, coolant pumps and fans for the waste heat of the internal combustion engines, and the lubrication of the gear transmissions. Another average power demand of 25 kW (corresponding to 50 kW only during the warmer half of the year) is added to drive the air conditioning compressors. Under the above operating conditions, this results in an additional energy demand of 125 kWh per train travel (corresponding to 1.25 kWh/min) for the auxiliary drives.

The same demand for the auxiliary drives is also assumed for the BECT. In the first instance, this may be surprising, since only for the DCT can be assumed that all the heat required for heating during the colder half of the year can be obtained from the cooling circuits of the internal combustion engines, while in the BECT even in case of use of

liquid-cooled electric motors, inverters and battery storages including their management systems only the half of the heat is available, and therefore an additional electrically heating is necessary. But these assumptions are permissible with regard to the more efficient supply of energy to the on-board electrical system, the omission of the pumps for the lubrication of the gear transmissions and the same average power demand for driving the compressors of the air conditioning systems.

Not listed in Table 2 is the energy that could theoretically be recuperated when braking a (modified) DCT, for example by means of flywheel energy storages or, in case of the BECT, by restoring it to the batteries. It results from reducing the kinetic energy of 24.5 kWh supplied to the train models during each acceleration phase by the energy of 0.9 kWh required during each braking operation to overcome the driving resistance. Thus it is theoretically 23.6 kWh during each braking process or 283.2 kWh for a full train travel. But, since no recuperation is provided in the technical design of the DCT selected here, for the DCT it is not be examined further at this point.

With the energy demands for the single operating phases determined in this way, a total energy demand of 838.5 kWh, calculated as shown in **Figure 5**, is obtained, corresponding to 201.4 liters of diesel fuel per train travel or 4.35 million liters of diesel fuel corresponding to 210 TJ of primary energy per year for operation with DCTs versus 436.9 kWh per train travel respectively 9.43 GWh corresponding to 85 TJ primary energy per year for operation with BECTs. In addition, the maximum savings potential can be quantified to 125 TJ of primary energy per year or 2.08 million liters of diesel fuel equivalents while avoiding the undesirable exhaust emissions. At the same time, the energy demand per train travel of a BECT represents the starting point for the electrotechnical design of its energy storages in the next section.

4 Electrotechnical Design of the Energy Storages

Determination of the capacity

From Table 2 and Figure 5 can be calculated that the BECT requires for a travel on the considered railway line from the charging point in the starting station to reach the electrified part of the railway line model a total energy of 298.4 kWh. This amount of energy must be available in the batteries of the BECT at the begin of such a travel. In fact, the batteries must have a much higher nominal capacity as they lose capacity by aging, and should not be charged to their upper capacity limit or deeply discharged during normal operation. In addition, the energy demand of the battery management system must be taken into account, while here for simplification the rather low

discharge losses are added to the charging losses. These facts are considered by surcharges of 25% (corresponding to 74.6 kWh) for a 20% capacity loss during the service life of the batteries and a further 53.9% surcharge (equivalent to 201 kWh) for duty cycle operation with a limit of 90% capacity for charging and a limit of 25% capacity for discharging. It is assumed that, with a remaining capacity of 25% in normal operation, there is also a sufficient reserve for any emergencies. This means that the BECT must have a total nominal battery capacity of 574 kWh.

Energy demands per travel of the Diesel Commuter Train (DCT)¹:

Driving phases	270.1 kWh ²
Accelerations	367.5 kWh ²
Idling	75.9 kWh
Auxiliary drives	125.0 kWh
	<u>838.5 kWh</u> $\approx 201.4 \text{ l diesel fuel}^3 \approx 9.73 \text{ GJ(PE)}^4$

Total demand for 21580 travels/a: $\approx 4.35 \text{ Mio l diesel fuel} \approx 210 \text{ TJ (PE)}^4$

Energy demands per travel of the (Battery) Electric Commuter Train (BECT)¹:

Driving phases	240.1 kWh ⁵
Accelerations	326.7 kWh ⁵
Idling	0.0 kWh
Auxiliary drives	125.0 kWh
Recuperable energy	- 254.9 kWh ⁶
	<u>436.9 kWh</u> $\approx 3.93 \text{ GJ (PE)}^7 \approx 105 \text{ l DFE}^8$

Total demand for 21580 travels/a: $\approx 9.43 \text{ GWh} \approx 85 \text{ TJ (PE)}^7$

Savings potential/a: $\approx 125 \text{ TJ (PE)}$ respectively 2.08 Mio l DFE⁹

- Legend: ¹: with coverage of the energy demands during the braking phases by removing kinetic energy
²: after correction by the drive train efficiency $\eta_{\text{DCT}} = 0.8$
³: for specific demand $e = 0.2 \text{ kg/kWh}$, density $\rho = 832.5 \text{ kg/m}^3$ and calorific value $H_u = 43 \text{ MJ/kg}$
⁴: Primary Energy (calculated with the conversion factor $f_p = 1.35$)
⁵: after correction by the drive train efficiency $\eta_{\text{BECT}} = 0.9$ (driving and recuperating)
⁶: after subtraction of $12 \times 0.9 \text{ kWh}$ for the braking processes and correction according to ⁵
⁷: Primary Energy (calculated with the conversion factor $f_p = 2.5$)
⁸: DFE = Diesel Fuel Equivalents, calculated from 436.9 kWh with e and ρ according to ³
⁹: DFE = Diesel Fuel Equivalents, calculated from $(201.4 - 105) \text{ l DFE} \times 21580 \text{ travels/a}$

Figure 5: Total Energy Demands and Savings Potential

Configuration of the Energy Storages

Before continuing the electrotechnical design of the energy storages, the electric drive system of the BECT must be specified more precisely. For this purpose, the requirements for the largely identical designs of the DCT and the BECT and same performances have to be taken into account. In addition, the efficiencies listed in Figure

5 and some common, but here not further explained rules for the dimensioning of electric drives must be considered. Then, for example, eight 500 V three-phase asynchronous traction motors with 100 kW continuous power each are sufficient to drive the eight axles of a BECT. Furthermore, there are eight at least two-fold overloadable traction inverters required which are highly suitable for operation in the field weakening range, and which require a DC-link voltage of at least 710 V on the input side under full load and under these conditions. Overall, this results in eight single electric drives, which are connected in each single train unit on the input side expediently via a common DC-rail and a common, controlled rectifier with a high voltage part as shown in Figure 3, and regarding their control via a common data bus. Any opportunities for simplification of this basic structure should not be discussed at this point. Furthermore, it is assumed that the batteries are connected via their own DC/DC-converters to the common DC-rail, with which the charge and discharge of the batteries can be controlled in both the battery electric and the pure electric operation. Any potential measures to save these DC/DC-converters should not be examined here either. With regard to the number of batteries, and for reasons of a good mass distribution and low line losses, it is assumed that four batteries with a capacity of 143.5 kWh each are provided in the vicinity of the four pairs of axle drives of the BECT. These four batteries, for example, can be installed at the locations of the internal combustion engines and gear transmissions of today's DCTs.

Due to the relevant occupational safety regulations like DGUV-I 8686, which apply in Germany, the four batteries should be designed as packs of fifteen stacks of 48 VDC each in series and with a sufficient number of stacks in parallel. Such battery stacks are usually constructed from single lithium-ion or lithium-iron phosphate battery cells. The characteristics and technical data of two suitable battery cells are shown in **Figure 6**. Here lithium iron phosphate battery cells are chosen to manufacture the battery stacks because of their larger working temperature range, their suitability for higher currents, their nearly constant discharge voltage and their not shown, but commonly higher cycle stability, in spite of their lower capacity. Due to the increasingly large-scale production of high-performance energy storages for electric vehicles, there are now also other, fairly quickly available, sufficiently safe and cost-effective alternatives [9], which require adequate attention, too.

A favorable structure of the single battery stacks results, for example, from the arrangement of 240 battery cells of type YT26650FP according to figure 6 in 16S15P configuration (thus sixteen battery cells in series and fifteen in parallel each), which, for example, can be monitored with the aid of chips like Infineon-Aurix of type SAK-TC

277 T. Then, a battery stack has an open circuit voltage of 51.2 VDC, a discharge current of 300 A at a voltage of 48 VDC and a capacity of 1.92 kWh. To obtain one single battery pack with a capacity of 143.5 kWh, fifteen of these battery stacks must be connected in series and each five in parallel, so that there are totals of 72,000 battery cells and 6000 management chips needed for the four required battery packs. In view of these figures, it becomes evident that in the real construction of the battery packs, additional effort is required to handle the heat released, above all during the charging and discharging processes, in the form of an efficient thermal management, which, however, can not be discussed here for reasons of scope. But a rough consideration of

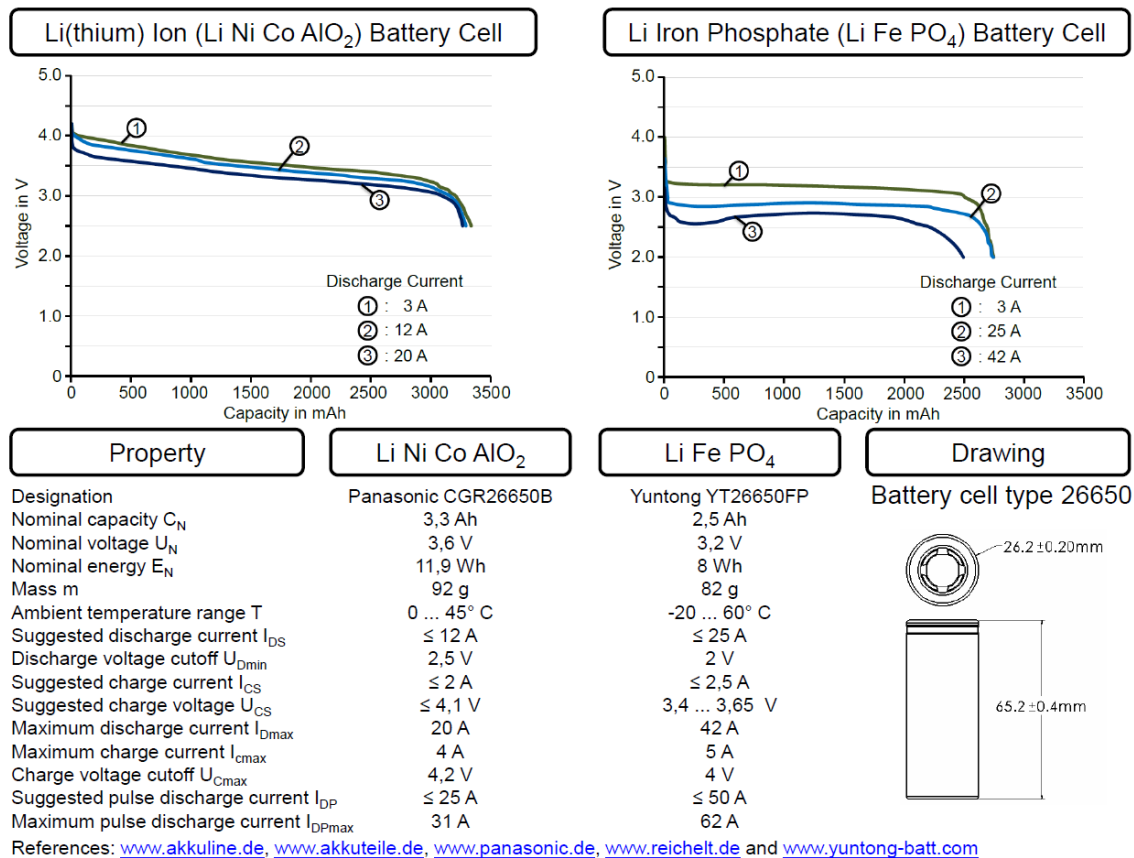


Figure 6: Characteristics and Technical Data of Different Battery Cells

the need for cables, circuit boards, cooling lines and mounting material in addition to the battery cells and management chips results in an overall specific energy density of about 65 Wh/kg and a mass of about 2.2 t per battery pack. Even with the assumption of same masses of the drive systems of the DCTs and the BECTs, this leads to a mass increase of approximately 3 t per single train unit in spite the masses of the half-full fuel tanks are saved. But, when arranging the battery packs at the location of the internal combustion engines of the DCTs, the higher mass causes an increase in the axle loads of the driven axles, which is train-specific even beneficial. Only for reasons of

simplification, a recalculation of the energy demand of the BECT which is slightly increasing due to the larger masses may be just dispensed here.

Check of the Charge and Discharge Cycles

With the highest suggested charging current of 2.5 A at an average charging voltage of 3.4 V per battery cell, the net charging power can be assumed to 8 W due to charging losses within the batteries. Therefore, a charging time of 32 minutes is necessary for the required supply of each 74.6 kWh of energy to the four battery packs in regular operation after each travel, which can be shortened to a 16-minute quick charge in a few cases of heavy delays. Thus, a sufficient charging time is always ensured on the electrified part of the underlying railway line model even when trains run each half hour or delay-related shortenings of the fifteen-minute reverse time in the destination station are necessary.

In contrast, a sufficient charging time in the starting station, which is in the not electrified section of the railway line model, can only be ensured if the reverse times per train are increased from fifteen to 45 minutes. In particular, when the trains have to run in an half-hourly rhythm due to the operating model, this requires the procurement of an additional BECT. For this purpose, an adjustment of the operating model and the installation of two sufficiently robust charging stations, each as about 150 m long catenary sections, are required. Because of the favourable position of the starting station, the two charging stations can be connected with just 250 m long underground cables to a nearby substation of the regional 110 kV power grid.

Further modifications (or measures which harm the energy efficiency) of the BECT are necessary if the energy recovery during braking is investigated. Because for a deceleration of a BECT with $-1,13 \text{ m/s}^2$ (both the railway-technical and the electro-technical admissibility of such a brake down in pure regenerative braking require separate checks) there is a braking power of almost 5900 kW required during the first second. After that, the braking power decreases by 200 kW with each additional second during each almost thirty-seconds long braking process. Due to the supportive driving resistance, the assumed reverse efficiency of the drive system of 90% and total charging losses of about 1 W per battery cell, but without taking into account the damping effect of the inductances of the electric motors and any filters, the real initial braking power can be assumed as 5000 kW, which decreases then by 170 kW per second. While the recovery of this braking power into the catenary on the electrified railway line section is not a particular problem, the reduced braking power during battery operation only falls after 26 seconds below the nominal net charging power of 540 kW, which is permitted

for the four battery packs in normal operation (**Figure 7**). Even with the permission of quick-charging, which reduces the lifetime of the battery packs, the then permissible maximum net charging power of 1080 kW is not enough to absorb the recuperable braking energy. To solve this problem at least the measures listed in Figure 7 come into question.

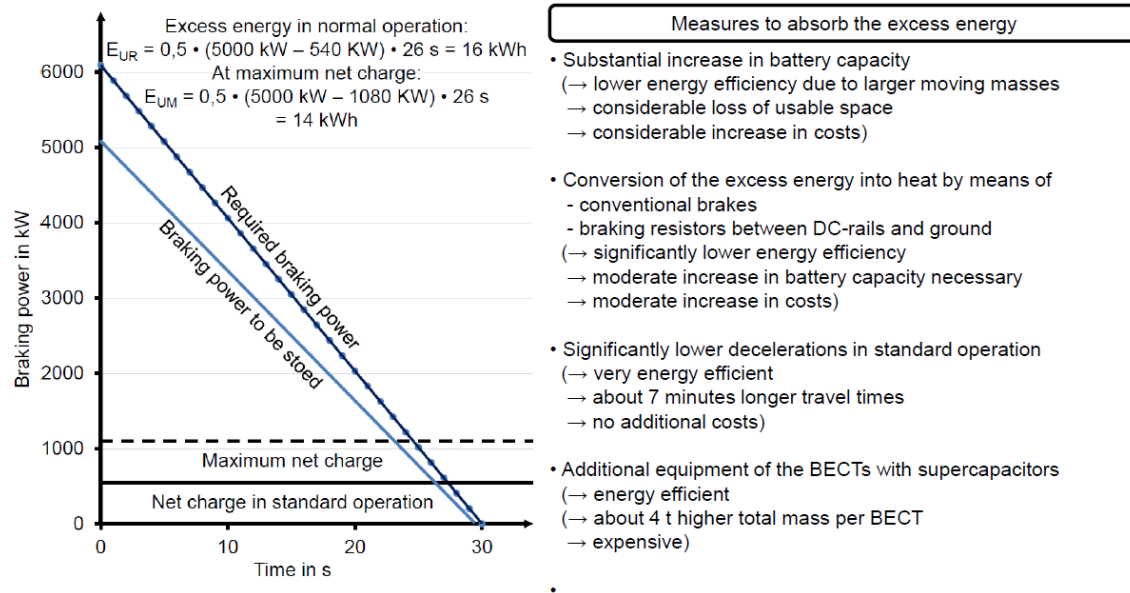


Figure 7: Braking Performance and Measures to Absorb the Excess Energy

The wide range of possible measures according to Figure 7 shows that this is the actual problem of the design of the energy storages. Since the reason for the investigation is precisely the increase of energy efficiency (and the associated positive environmental effects), the first two measures do not have to be further investigated. Although the third measure is still feasible under the premises set here, it permanently uses almost all of the time reserves built into the operating model and thus lead to a particularly high susceptibility to delays (or to the need for procurement of another two additional BECTs). Likewise, only a slight acceptance of the longer travel times on behalf of the passengers as well as the resulting passenger migration can be expected. But even the last of the measures listed in Figure 7, the coverage of the high storage requirements by means of special short-term storages such as supercapacitors (hereinafter referred to as supercaps), implies considerable disadvantages. For storing the excess energy of 16 kWh per braking process in regular operation, for example, at least 232 pieces of suitable Eaton supercaps of type XLM-62R1137-R are required, which can be arranged in four groups parallel to the four battery packs, and, for the best use of their capacity, can be connected via separate DC/DC-converters to the common DC-rails of the single train units. As a result, apart from an increased space requirement, the mass of a BECT

increases by another 4 t and its price in the order of EUR 250,000.-. Therefore, all the measures listed in Figure 7 lead only to suboptimal solutions. Better solutions may be achieved if, in addition to minor adjustments to the operating and train models made so far, greater adjustments are allowed.

This becomes evident in the review of the highest power demands during the discharge cycles, which each occur at the end of the five single acceleration stages of the defined train model. These power demands can be calculated from the installed total power of the DCTs as 1120 kW, respectively 280 kW per battery pack, taking into account the efficiency assumptions shown in figure 2 and neglecting the needs of the auxiliary drives. The single battery packs, indeed, can provide a continuous discharge power of 1080 kW (as maximum even more than 2000 kW) when they are assembled from five parallel battery stacks. This means that the previously designed energy storages are also suitable for the operation of BECTs with a much higher installed drive power, which either let accomplish shorter driving times due to faster accelerations or a waiver of the installation of additional supercaps by shifting the acceleration and braking profiles without travel time extensions. In any case, it is to be expected that larger-sized electric drives will be required in order to slow down the BECTs in normal operation as far as possible in a regenerative manner.

5 Conclusions

In the previous sections, it was demonstrated for a real case, how the overall energy demand for a BECT can be calculated, its energy storages can be designed and its technical realization can be accomplished. It was also shown that in this manner great benefits in terms of energy demands can be achieved and exhaust emissions can be largely avoided. But it has also become clear that a large number of different alternatives exists for technical specifications as well as for decisions regarding energy efficiency and economic aspects. For implementation, therefore, not only further, considerable effort is required to determine the best possible configuration of train units, energy storages and electric drives, but fully developed BECTs will need investments for additional trains and charging infrastructures. An additional, periodic investment requirement will also be created by the not yet investigated, but limited service life of the energy storages. Because in case of the underlying operating model already 2500 full load cycles occur per year. Nevertheless, in order to achieve an economically necessary minimum service life of energy storages in the order of a half concession period, thus 7.5 years, a special emphasis has to be laid on the careful charging and

discharging of the energy storages, especially for part load cycles, in conjunction with a proper design and adequate battery management. Although a number of key figures and real components have already been identified in the previous sections and further missing information has been determined by internet research, an investment calculation was not carried out here because of the still insufficient database. According to an evaluation of the advertising of a well-known manufacturer at the Innotrans-fair in the German capital Berlin in September 2016 [10], this manufacturer expects, under the assumptions and figures given there, as well as by offsetting the also advertised, lower maintenance costs against any interest rates, and from a purely monetary point of view, at best an amortization within 28 years. In contrast, the tendency here is more likely to lead to a payback period in the order of ten years in the best case.

References

- [1] Bombardier Transportation GmbH. 2016. "Battery-Powered Tram Sets Reach Record": Information from November 9, 2015. Accessed August 25, 2016. <http://www.eurailpress.de/news/alle-nachrichten/single-vi/news/batteriebetriebene-strassenbahn-stellt-reichweitenrekord-auf.html> (in German)
- [2] Kache, M. 2014. "Diesel Hybrid Rail Cars." In: Railway Technology Review (ETR) 63. (December): 50-3. (in German)
- [3] Verkehrsverbund Rhein-Ruhr (VRR), 2016: Regional Transport Plan: 92. (in German)
- [4] Müller-Hellmann, A. 2014. "Electric trains - even on non-electrified lines!?" In: Railway Technology Review (ETR) 63. (May): 3. (in German)
- [5] Siemens AG. 2016. "Mireo - The Train that Intelligently Combines it All.": Siemens Publication No. MOML-B1021-00-7600, Munich, 7.
- [6] Settnik, A. 2016. "Half a Billion Euros for the Second Track?": Information from March 7. Accessed July 28, 2017. <http://www.rp-online.de/nrw.staedte/goch/halbe-milliarde-fuers-zweite-gleis-aid-1.5816112> (in German)
- [7] Dipl.-Ing. H. Vössing GmbH. 2015. "Electrification S 28.": Project Flyer, Duisburg, 1-2. (in German)

- [8] ABB Henschel Lokomotiven GmbH. 1993. "System Technology - Railway Vehicle Technology.": ABB Henschel Lokomotiven GmbH Publication, Mannheim, 118-23. (in German)
- [9] Beck Automation GmbH. 2017. "Multifunctional Power Storage Systems.": Product Flyer, Würzburg, 1-4. (in German)
- [10] Bombardier Transportation GmbH. 2016. "Talent 3 - Train Benchmark Battery versus Diesel versus Fuel Cell": Advertising from September, 2016. Accessed August 14, 2017. <http://www.drehscheibe-online.de/foren/read.php?2,7999143>, also to be found under <http://www.ice-treff.de/index.php?mode=thread&id=455465>

Authors



Schmetz, Roland

studied mechanical engineering at the Technical University Aachen (RWTH) from 1981 to 1986 and then economics. In 1987 he received the Springorum Medal and in 1991 his doctorate at the Fraunhofer Institute of Production Technology (IPT). He then worked for eighteen years as managing partner of a company for agricultural machinery and tractors until his appointment as Professor of Powertrain Engineering at the Rhein-Waal University of Applied Sciences in Cleves. In 1982 he was one of the initiators and from 1982 to 1989 one of the record holders for the longest model train in the world. From 1992 to 1998, he designed, patented and directed the project to build the world's first diesel-electric, series-hybrid, agricultural tractor with power electronic inverter-technology and a host of other novel features.



Struck, Alexander

Alexander Struck studied physics from 1997 to 2002 at the Technical University Braunschweig, the University of Umeå (Sweden) and at the University of Hamburg. After a research stay at the Montan University Leoben (Austria) he received his doctorate in 2005 at the University of Hamburg. After working at the University of Genova (Italy) and the University of Kaiserslautern from 2006-2010, he took over the charge of battery simulation at the Fraunhofer Institute for Manufacturing Technology and Applied Materials Research in Oldenburg. In 2012, he accepted the call to become Professor of Theoretical

