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Standardized Sizing for Alternative Drivetrains in Rail Vehicles: A Modular Approach for Enhanced Efficiency and Cost Reduction

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Abstract

In the development of alternatively powered rail vehicles, determining the appropriate sizes for fuel cells and batteries poses significant risks and challenges for manufacturers and operators. This study focuses on establishing a standardized approach for sizing components of alternative drivetrains within a modular energy system. The objective thereby is to increase production volume, lower costs, and streamline the customization of energy systems for optimized usage.

To define these component sizes, an analysis of German regional rail transport routes was conducted. Based on this analysis, battery and fuel cell powered drivetrains were automatically designed using a simplified operational strategy. Subsequently, the calculated sizes of batteries and fuel cells were statistically analysed. The obtained results were compared with existing initiatives for modular fuel cell and battery component sizes. Based on this a *Modular Power Pack* was concluded, which should serve the suitability for future rail application.

Keywords: alternative powertrains, fuel cell, hydrogen, battery, dimensioning, energy optimization, module sizes, modular power pack

1 Introduction

The high costs of batteries and fuel cells pose a challenge in developing alternative drivetrains for rail vehicles. Additionally, the railway sector faces a dilemma with demanding technology requirements and low purchase volumes. Resolving these issues is crucial for advancing alternative propulsion technologies in rail vehicles, making them both technologically advanced and cost-effective for broader adoption.

Under these circumstances standardized dimensions for the components of alternative powertrains are very important. Due to a lack of empirical knowledge in dimensioning batteries for railway application this process becomes a big risk. Therefore, this paper proposes the implementation of a standardized sizing strategy for batteries in rolling stock. This strategy, tailored to specific needs, is designed to streamline development processes, thereby reducing associated risks.

2 Methods

First of all, various areas of application for alternatively powered rail vehicles are discussed and the powertrain topologies to be examined are defined. Based on this wide range of use cases, simulations were executed with generic and pre-defined vehicles, and a simplified operating strategy. The results of this is a representative power demand profile for each use case. On basis of this statistical calculations are made to derive generic battery module sizes and fuel cell module sizes. These will be compared with other publications. *Figure 1* shows the steps to derive the *Modular Power Pack.*

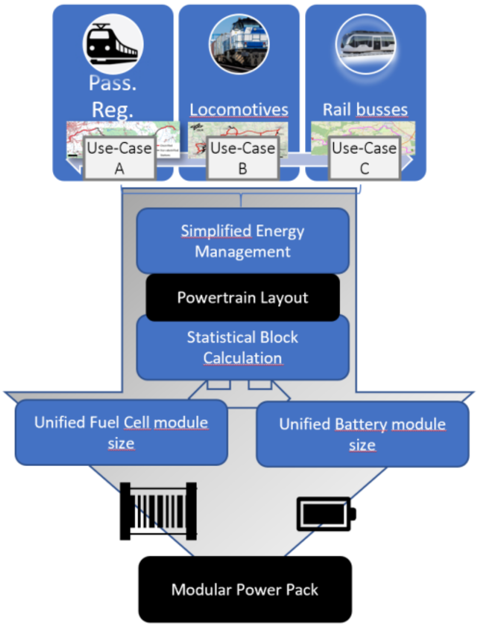

Figure 1: Modular Power Pack estimation based on three use cases and vehicle types: passenger regional train, shunting locomotives, rail busses

2.1 Use case definition

Alternative drives in rail vehicles are suitable on non-electrified or partially electrified lines on which retrofitting is not feasible for economic reasons. This is particularly the case on lines with a very low frequency and/or construction and authorization difficulties.

In Germany, numerous local public transport routes lack full electrification. A study by the DLR reveals that about 500 regional rail lines utilize diesel-powered trains. Roughly 57% of these lines have approximately 90% of their length without electrification. Additionally, 28.5% of these routes are shorter than 58 km. [1] The amount shows the importance of investigating future solutions for alternative drive train concepts, since infrastructural actions to electrify are cost intensive and take a long time to be realized.

In this paper three relevant fields of application are outlined and described. These are passenger regional trains, shunting locomotives and rail busses.
The power requirements for passenger lines were investigated using a generic passenger train, which has a mass of almost 100 tons. The average track length of generic regional profiles is 80 km. For this use case the power requirement at the wheel of 1000 kW was needed to operate the train.

A route selection from a previous study is used to simulate shunting operations. In this study two typical application profile categories were investigated. These are shunting-heavy mixed operation and regional line transport within an operational range of 100 km continuous journey. The power requirement profiles were examined by the vehicle type Vossloh DE18 or a MaK G 1206, covering 180 days of data operated with varying loads. This effected in a required power result for shunting locomotives with less than 2000 kW at the wheel. [2]

The route selection for the rail busses is based on the findings of a study, which aims for reactivating peripheral areas to the rail network. Rail busses lately have gained in popularity in proofing the rising interest in this use case. [3] [4] [5] The study mentioned investigate typical lines with less than 30 km track length. [6]

Ten artificial lines are simulated with a generic vehicle, which weighs less than 50 tons resulting in a required power demand of less than 500 kW. *Table 1* summarizes the power demand of the different use cases.

Use Case	**Average track length**	**Power requ. at wheel**
A: Passenger Regional Train	80 km	< 1000 kW
B: Shunting Locomotives	25 km	< 2000 kW
C: Rail busses	30 km	< 500 kW

Table 1: Summary of the use cases and their power requirements

2.2 Drivetrain topologies

In this paper, the pure battery drive, the battery-overheadline (OL) drive, the fuel cell drive and the fuel cell-OL drive are analysed.

In Battery Multiple Units' (BMU) drivetrain topology, the entire energy demand is provided by the battery. Here, recharging can take place by conduction. This form of alternative drive is an exception in the rail vehicle sector and it is only suitable for special applications and for shorter distances. Because of the missing overhead connectivity special recharging options need to be considered. The recharging could be managed by a third rail or similar solutions. [7] In this case the onboard transformer might be optional, which effects in a lighter vehicle. Only stationary recharging is considered for this drivetrain topology in this paper. Therefore, the operating strategy purely relies on the battery. *Figure 2* is showing the drivetrain topology including the auxiliary converter, the electric motor and the necessary converters.

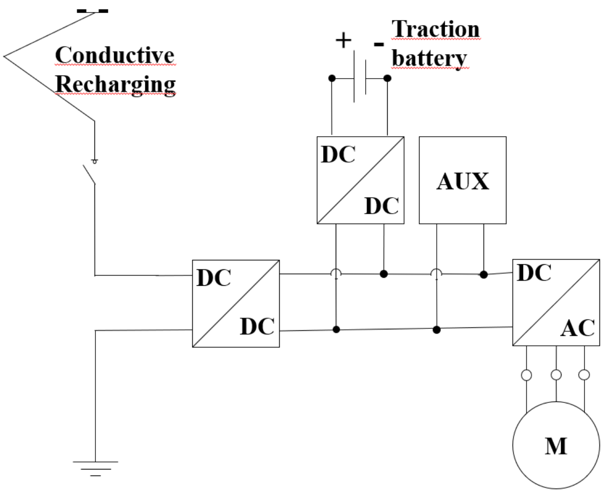

Figure 2: Powertrain of BMU

The Battery Electric Multiple Unit (BEMU) currently represents the largest number of alternatively powered rail vehicles. It can travel using the traction battery in limited sections without overhead contact lines and recharge under overhead contact lines or use them on sections with overhead contact lines. However, the OL equipment and the battery technology requires a large installation space and a correspondingly large number of components onboard. The topology of the BEMU can be seen in *Figure 3*.

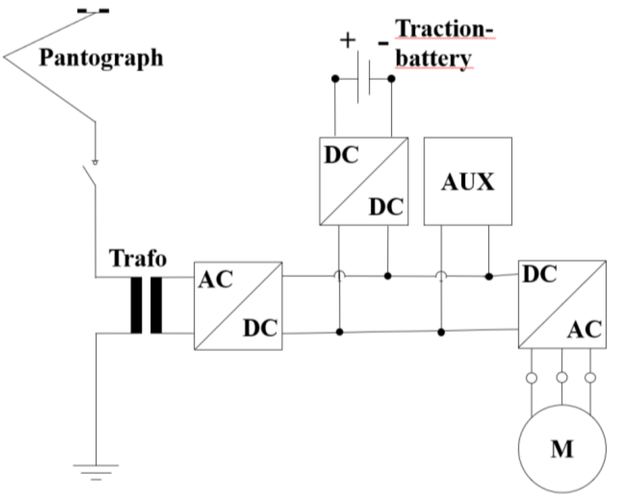

Figure 3: Topology of a BEMU

The operating strategy for the BEMU depends on the track length and the availability of the overhead contact lines. This powertrain layout is suitable for the majority of routes. The typical range, which is operated solely on battery traction is 80 km (see Use Case A).

The fuel cell drivetrain fully relies on the energy content in the hydrogen storage and the battery system. This drivetrain is potentially to be used for the Use Case B in shunting locomotives. The layout can be seen in *Figure 4*. The operating strategy hereby is dependent on the initial dimensioning of the fuel cell stack and the traction battery.

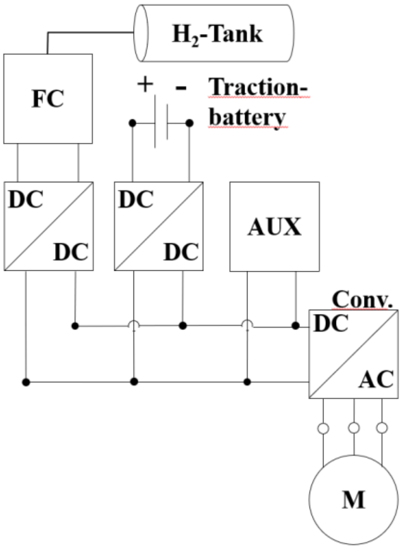

Figure 4: Fuel Cell Drive

The last drivetrain, which is relevant for dimensioning the modular power pack is the fuel cell-OL drive. Currently there are projects investigating the potential of this drivetrain in regional passenger trains. One of them is the EU funded FCH2Rail project, which demonstrates the vehicle on public train lines in Spain. [8]

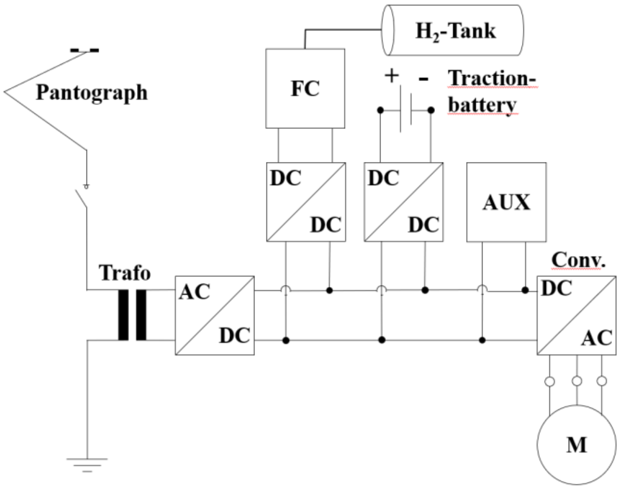

Figure 5: Fuel cell-OL equipped with a pantograph

2.3 Operating Strategies and dimensioning of components

The operating strategies of the powertrain serve as the foundation for dimensioning the components battery and fuel cell. The energy management strategy is described in the papers [9], [10] and builds on the automised dimensioning algorithm by the inhouse software HybridizationTool. The Tool is able to cope with all mentioned drivetrains in 2.2 and respects the boundary conditions of the battery type and if wished, the fuel cell and the availability of OL. The HybridizationTool works in three steps:

1) Pre processing: Analyzing the service profile to derive the power requirements of the track and the vehicle
2) Calculation and dimensioning: iteratively dimensioning the battery and if necessary the fuel cell size based on the boundary conditions of the battery type and the fuel cell
3) Post Processing: checking the applicability of the components on the track

All of the steps apply the power distribution between the battery and fuel cell, which is described in [11]. The boundary conditions of the components were chosen for Low Temperature Fuel Cells (LT PEM FC) and the battery types Lithium Titanate Oxide (LTO), Lithium Iron Phosphate (LFP) and Nickel Manganese Cobalt (NMC).

2.4 Statistical dimensioning of modular power pack

The pooled simulation results from Use Case A-C are used in the final step to derivate the modular power pack. Modules are here defined according to the standard for lithium ion batteries IEC 62928:2017 as "*Energy storage device consisting of one or more electrically connected cells*". [12] These module sizes are statistically calculated. The method is illustrated in *Figure 6*.

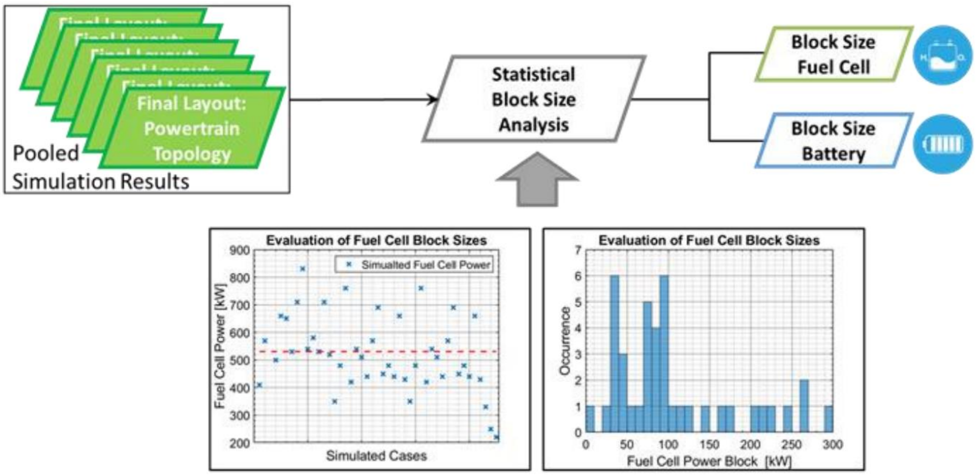

Figure 6: Module Size derivation [13]

Figure 6 shows that across all generated data sets the mean value is calculated for the fuel cell power and battery capacity. This resulting average serves as the reference point (red dotted line in *Figure 6*) for potential standardized core components. Subsequently, the variance from this reference to each simulated component (depicted as blue dots in *Figure 6*) is calculated. Utilizing the absolute deviation from this established baseline, we determine potential module sizes. [13] For the final module size the smallest derived median is taken as a module, since this allows the suitability for all drivetrains and use cases by scaling the amount. The resulted module sizes are compared to available modules on the market.

3 Results

The following chapters present the results. Starting with the component dimensions and the comparison to available component sizes on the market. Continuing with the simulation of a BEMU with the established module sizes and a varying number of modules.

3.1 Component dimensioning and statistical analysis

The component dimensions analysis receives as input the required dimensions of the powertrain based on the powertrain topology. The battery module sizes for the drivetrain topologies BMU and BEMU are summarized *Figure 7*.

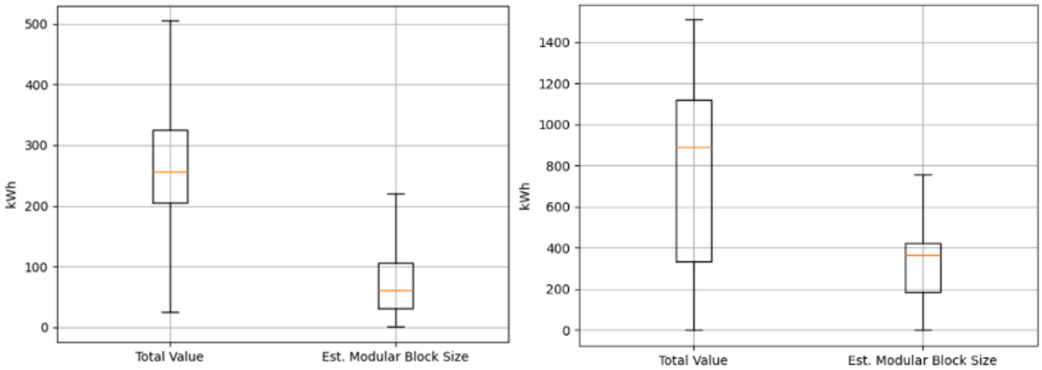

Figure 7: Box plot of the battery dimensions (kWh) for the vehicle types BMU (left) and BEMU (right)

The figure shows an established modular size window, which is in between 34 kWh to 103 kWh for the BMU. The suggested module size is 66 kWh here. Looking at the BEMU the box plot window shows values, which start from 195 kWh to 410 kWh. The suggested module size here is 366 kWh.

Looking at the fuel cell vehicles the fuel cell module sizes were calculated for the fuel cell and the dedicated battery module sizes. These are shown in *Figure 8*.

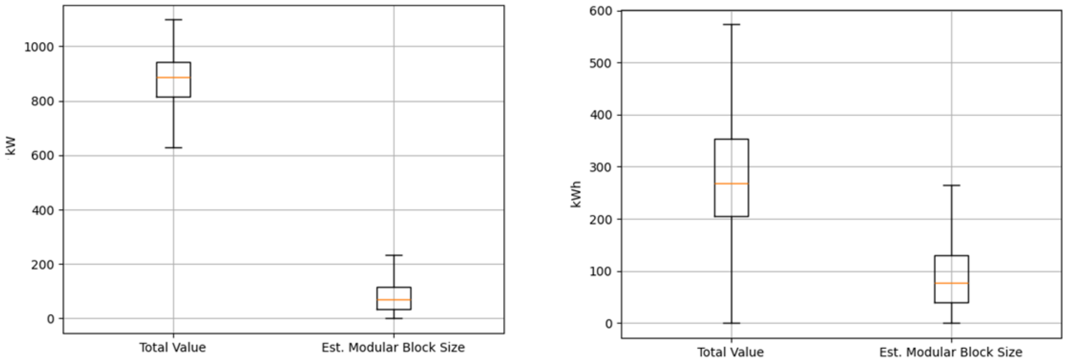

Figure 8: Box plot of the fuel cell dimensions in kW (left) and the dedicated battery dimensions in kWh (right)

The lower quartile for the fuel cell modular module size is hereby 60 kW. The upper quartile is 110 kW. The median fuel cell module size is 75 kW. For the battery dimensions the upper quartile is120 kWh and the lower quartile is 44 kWh. The median battery module size is 75 kWh.

In *Table 2* the results of the smallest module sizes for battery and fuel cell across all drive train types are summarized.

Type	**Fuel Cell**	**Battery**
Median	75 kW	34 kWh

Table 2: Median of fuel cell modules and battery based on statistical calculation

3.2 Market comparison

This chapter shows the available battery module sizes on the market. These shall be compared to the statistical module sizes derived in chapter 3.1. *Table 3* shows a summary of available battery modules.

Battery module (available on the market)	**Provider**	**Cell type**	**Technology**	**Module size [kWh]**
Battery System 9 AKM 150 CYC	Borgwarner	Cylindrical cells	NMC	98 [14]
Battery System 15 OEM 50 PRC	Borgwarner	Prismatic cells	NMC	33 [15]
M3 Energy Module	leclanche		NMC	4,7 [16]
Bordline Max 500 UHP	ABB		LTO	17,7 [17]
SCiB™ Battery System	Toshiba	Prismatic cells	LTO	60 [18]
Modular high energy LFP battery	forseepower		LFP	36 /55 [19]
PULSE 15	forseepower		LTO	14,6 [20]
FLEX PLUS	forseepower		NMC	52/56 [21]
INTILION Zellmodul	Hoppecke	Prismatic cells	LFP	6,1 / 9,2 [22]

Table 3: Available Battery Modules on the Market

The available market battery modules show that there are different approaches for sizing the battery modules. NMC battery modules start at 4 kWh and end at 98 kWh module sizes. LTO batteries show a range from 14,6 kWh to 20 kWh. Modules with LFP technology are available from 6,1 kWh up to 55 kWh.
Calculating the median for the listed battery module sizes a value of 33 kWh results.

Fuel cell module (on the market)	**Provider**	**Fuel Cell type**	**Module size [kW]**
FCmove-XD	Ballard	LT PEM	120 [23]
FCmove-HD+	Ballard	LT PEM	100 [23]
FCmove-HD	Ballard	LT PEM	70 [23]
FCmove-MD	Ballard	LT PEM	45 [23]
TFCM2-B/F	Toyota	LT PEM	60 [24]
TFCM2-F	Toyota	LT PEM	80 [24]

Table 4: Fuel cell modules on the market

Looking at available Fuel Cell modules the systems from Ballard and Toyota shows a range from 45 kW to 120 kW. Ballard is defining a range of four different module sizes, which are designed for different use cases. These are medium to heavy duty as well as more performance oriented systems like the FCmove-XD. [23]
Calculating the median for the listed fuel cell modules a power of 65kW results. *Table 5* summarizes the median values for batteries and fuel cells.

Type	**Fuel Cell**	**Battery**
Median	65 kW	33 kWh

Table 5: Median of fuel cell modules and battery modules on the market

4. Comparison: Module Sizes

Comparing between the fuel cell module sizes derived from statistical calculations and the median market fuel cell module size, as well as the comparison between statistically derived battery module sizes and the median market battery module size gives several insights:

For fuel cell module sizes, the study reveals that the lower quartile for fuel cell modular size is 60 kW, with an upper quartile of 110 kW and a median size of 75 kW. In contrast, the median fuel cell module size available on the market stands at 65 kW. This comparison suggests that the median market fuel cell module size closely aligns with the statistically derived median size, indicating a degree of consistency between market offerings and statistically derived sizes.

Turning to battery module sizes, the study's statistical analysis unveils an upper quartile of 120 kWh, a lower quartile of 44 kWh, and a median module size of 66 kWh. In comparison, the median battery module size available on the market is 33 kWh, which is half the size of the calculated value.

5 Conclusions and Contributions

The present study aims to establish a standardized method for sizing components of alternative drivetrains within a modular energy system, with the goal of increasing production volume, reducing costs, and enhancing the adaptability of energy systems for optimized usage. Through a detailed analysis of German regional rail transport routes, alternative drivetrains were automatically designed, and the sizes of batteries and fuel cells were statistically analyzed. The results of this investigation were compared with existing standardized module sizes for fuel cell and battery components. This comparison reveals a correlation between market offerings and statistically derived sizes. Based on this a *Modular Power Pack* can be established, which includes a battery module size of 33 kWh -45 kWh and a fuel cell module size of 65 kW -75 kW.

The comparative analysis with available market sizes for battery and fuel cell systems shows alignment in terms of the identified median values. The findings highlight the potential of a standardized approach for modular energy systems in rail transportation. By implementing these standardized modules, rail vehicle manufacturers and operators could benefit from improved efficiency and cost-effectiveness, leveraging established sizes to reduce costs.

In upcoming work, the optimal module amount for different use cases is iterated based on the established *Modular Power Pack* sizes mentioned. This will be investigated for battery vehicles first. Hereby a special focus will be to investigate the optimal amount in dependence of the use case and the cell chemistry and their unique characteristics. Additional research on fuel cell hybrid powertrains will be included as well using the established fuel cell module size. Under these circumstances detailed efficiency and cost analysis will be made and concluded in energy management optimization.

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