Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 72 (2023) 64–71

Transportation Research Procedia

www.elsevier.com/locate/procedia

Transport Research Arena (TRA) Conference

New light rail vehicle and drivetrain concepts for catenary free operation of branch lines

Sebastian Reimann[a]*, Peter Gratzfeld[a]

[a]*Karlsruhe Institute of Technology, Institute of Vehicle System Technology, Institute of Rail System Technology, Rintheimer Querallee 2,Building 70.04, Karlsruhe, 76131, Germany*

Abstract

This paper proposes a new light rail train concept suitable for battery-only, hydrogen and diesel operation of branch lines. A simulative methodology is presented, analyzing these drivetrains within the new train concept. The simulation features a detailed train model, including a propulsion and an auxiliary model. System effects such as the use of waste heat for heating the train are considered, analyzing the drivetrain options in detail. 31 railway lines in Germany and France are analyzed taking various environmental conditions into account. The drivetrains are compared assuming climate neutral operation based on hydrogen and diesel made from electricity. The battery train is the most energy-efficient solution, followed by hydrogen which can be an option on longer tracks. The diesel train needs twice as much energy as the hydrogen train, which makes it not economically suitable.

Keywords: Rail transport; New vehicle concepts; Alternative drive trains; Simulation; Battery Electric Multiple Units; Hydrogen Electric Multiple Units

1. Introduction

The European Green Deal proposes climate neutrality by 2050. To achieve this goal sustainable and smart mobility is needed, cf. European Commission (2019). Rail transport already has the ability for climate neutral mobility due to the possibility of using electricity from renewable sources directly if catenary wires are present. Despite this long-known technology, rail transport connecting rural with urban areas often depends on trains with internal combustion engines and diesel due to a lack of electrification. Only 53.1% of German and 58.5 % of French railway lines are electrified. The EU average is at 53.7 %, cf. European Commission (2021).

---

* Corresponding author. Tel.: +49-721-608-4-5855.
E-mail address: sebastian.reimann@kit.edu

10.1016/j.trpro.2023.11.323

Climate neutrality on the one hand and the lack of electrification on the other hand is driving railway business into the use of new drive train technologies such as battery-electric trains (BEMU), hydrogen trains (HEMU) or diesel-electric trains (DEMU) with alternative climate friendly fuels.

While these technologies are emerging, it is difficult for railway operator to choose which drivetrain technology suits their requirements best. The optimal technology depends on the track itself, the operation profile, the timetable, energy costs, acceptance by operators and passengers as well as the available trainsets. Over the 30-year lifetime of a trainset these parameters are changing making it even more difficult to choose the optimal technology.

By looking at different track characteristics, so called branch lines with a maximum speed of about 100 km/h and often curvy and steep tracings can be found to be a key operation area of trains with alternative drivetrains in the future. These lines are connecting rural areas with main lines where passengers change for connection to city centers. These branch lines often do not show big passenger numbers and have only limited service. Full electrification of these lines is often not an economical option in the years to come. Small and efficient trainsets based on alternative drivetrains will be the future of these lines.

The current developed trainsets by Siemens (2020), ALSTOM (2021), Stadler Rail Group (2019) and CAF Briginshaw (2021) are electric trains (EMU) or diesel trains (DMU) that are further equipped with batteries or a hydrogen drivetrain, to achieve the climate friendly operation. These trains were often developed for mainline high capacity routes not suiting the requirements of branch lines in an optimal manner.

The goal is therefore to develop a train concept with a small capacity of approximately 100 passengers and a lightweight design. The passenger number allows a flexible and cost efficient operation, since the capacity can be adapted according to the demand by coupling multiple trains. The lightweight design allows efficient driving and cheap and efficient building and maintaining of infrastructure since a lightweight design allows the train to run on lines with reduced axle loads. Overall, a light rail vehicle concept is needed.

In this paper a new train concept for these branch lines is presented and all possible drivetrain concepts are systematically analyzed. Analogous to the currently proposed trains by the industry, not a totally new train is developed since this is too cost inefficient. The branch line train concept which is presented here is based on the tram-train concept in operation in Karlsruhe and other cities in Germany and France. Tram-train trains are light rail vehicles which are able to run on tram infrastructure in the city center as well as on train infrastructure on normal trainlines. The maximal axial load is 11,5 t. Their power supply can be DC, AC or an internal combustion engine (ICE). The train can often switch between two different power supplies ensuring wide operational possibilities.

The literature contains numerous feasibility studies by research institutes, transport companies and train manufacturers on the use of alternative drive systems on various routes. Bauermeister et al. (2021) analyze the climate friendly operation of railway lines in Austria and Hungary. BEMU-drivetrains and, after electrification, EMU-drivetrains were found to be the most feasible solution. For energy demand-calculation, a simplified energy model is used. The emission free operation of railway lines in Germany are analyzed in Klebsch et al. (2020). The energy demand of the proposed trainsets is calculated with simplified equations. This study also concludes that BEMU-drivetrains are best for the proposed operation. In Laverick and Hoffrichter (2019), BEMU and HEMU drivetrains are compared for service on a 14 km trainline going from San Bernardino to Redlands in California. A simulation assuming constant component efficiencies as well as constant auxiliary loads is carried out. The study finds that the HEMU drivetrain is most feasible, taking future extensions of the line into account. Based on the study one Stadler Flirt HEMU trainset was ordered. A study focusing on the use of fuel cells is Ruf et al. (2019). Three railway lines in France, Spain and the Netherlands are analyzed presenting the potential for fuel cells in the railway sector.

Overall, these studies lack a detailed train simulation that includes precise drivetrain as well as auxiliary consumers models. If the train model is not accurate the overall result is poor and system effects such as the use of the fuel cells waste heat aren’t considered. As Otto et al. (2020) mention, the auxiliary energy demand can vary between 20 – 50 % of the total energy demand of the train mainly depending on the outside temperature. Assuming constant and in most cases worst case auxiliary power loads leads to a false interpretation of the train’s energy demand. These energy demands are often the basis of total cost of ownership calculations leading to high costs for trainsets with alternative drive systems. Within this paper the focus is on a precise train model as well as considering systems effects to gain a good understanding for the proposed different drivetrain configurations.

2. Vehicle and drive train concept

The vehicle and drivetrain concept is derived from a tram-train vehicle that is in operation in Karlsruhe, Germany. The vehicle in operation is a three-car trainset with a DC-only energy supply. The vehicle has four asynchronous machines (ASM) with a power of 145 kW each. It is equipped with three heating, cooling and ventilation systems (HVAC) for passenger comfort. It operates on three tram-train lines of length 46, 45 and 30 km. The tram-train is part of an intensive data analysis program described in Otto et al. (2020) which leads to highly accurate simulation models.

The proposed light rail vehicle with alternative drivetrains for the catenary free operation contains only two passenger cars. The middle car is switched into a technology car, in which the extra technology is placed that is needed for the BEMU, the HEMU or the DEMU. Introducing an extra technology car is also done by railway manufacturers, for example Stadler in the FLIRT and WINK platform. With the extra technology car, the overall axial load doesn't extend 11,5 tons. Figure 1 shows the proposed configuration, displaying in yellow the space for the extra technology, and in red the seat configuration. Passengers can walk through the technology car, accessing the other part of the train. The train can hold 76 sitting and 92 standing passengers. It has a maximum speed of 100 km/h and an empty mass of 62 tons.

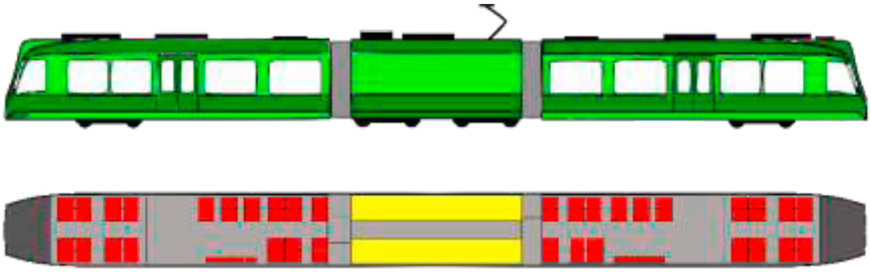

Fig. 1. Proposed light rail vehicle with a technology car

Figure 2 shows the drivetrain configuration for the BEMU. The drivetrain contains all technical equipment necessary for AC-power supply as well as a 350 kWh battery and a DCDC converter. The AC line converter is designed to charge the train while driving (including acceleration) and during standstill.

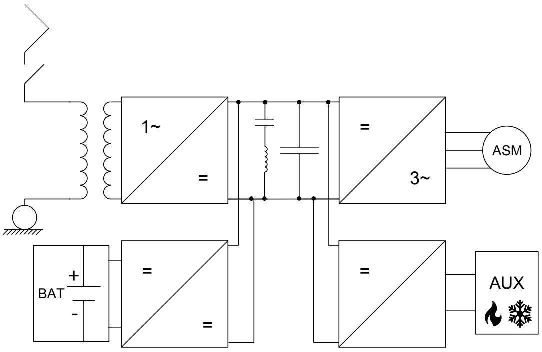

Fig. 2. BEMU drivetrain configuration

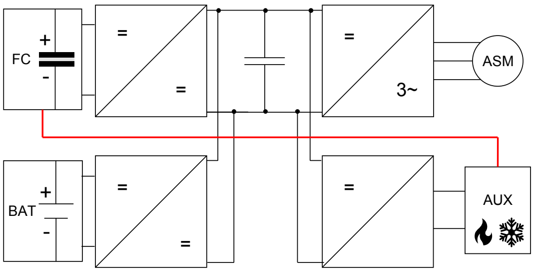

Fig. 3. HEMU drivetrain configuration

The HEMU drivetrain configuration is shown in Figure 3. It contains two 200 kW fuel cells and one 90 kWh battery. The battery is used for peak load compensation and for storing energy recovered from regenerative breaking. A power load management system is installed, limiting the dynamic load of the fuel cell in order to expand the fuel cell's lifetime as well as increasing the fuel cell's efficiency. Within the figure it is indicated in red that the waste heat of the fuel cell can be used for the auxiliary system to heat the train compartment. Since the blowout temperature of the heating system is restricted, the amount of waste heat that can be used at a time is limited to 75 kW. In addition to the auxiliary system of the BEMU drivetrain, a fuel cell cooling system is added.

Figure 4 shows the DEMU drivetrain configuration. The DEMU drivetrain is similar to the HEMU drivetrain containing a 90 kWh battery and the possibility to use 75 kW of waste heat from the internal combustion engine. Instead of the fuel cell, it contains an internal combustion engine with a nominal power of 375 kW and a synchronous engine as generator. The power management system tries to operate the internal combustion engine in an optimal operation point, thus increasing the efficiency of the internal combustion engine. Furthermore, the internal combustion engine is shut down at stations to reduce local emissions close to passengers.

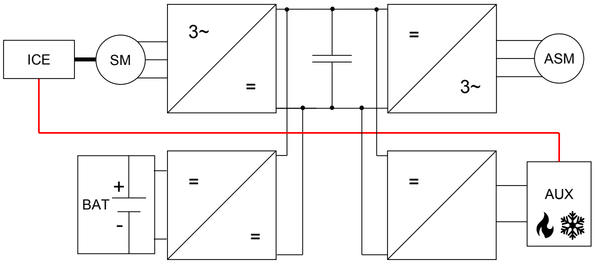

Fig. 4. DEMU drivetrain configuration

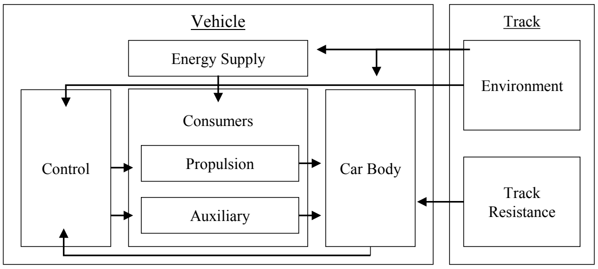

Fig. 5. Model overview

3. Simulation Model

The simulation model is built using the modelling language Modelica. The model is object oriented dividing the overall model into multiple sub- and subsubmodels. The overall model consists of the vehicle- and the track model. The vehicle model can be divided into the control-, consumer-, car body- and the energy supply model. The track model is built using the environment- and the track resistance model. All dependencies are displayed in figure 5. The model has been developed at our institute over the past years. First, the model was developed for a diesel hybrid train by Haag et al. (2017). Later the scope was extended to BEMU vehicles, Reimann et al. (2020).

3.1. Vehicle model

To gain a highly accurate vehicle model, the vehicle model is based on the tram train model where a lot of data is present to parameterize the model. The propulsion model is based on efficiency fields measured during real live operation of the tram train vehicle. Since the propulsion system does not require any changes for the proposed BEMU, HEMU or DEMU train, the propulsion model can be used as is. The propulsion model has a coefficient of determination (R^2) of 95.5 %.

The auxiliary model consists of all auxiliary consumers of the train. The biggest part is the HVAC system that calculates the heating load considering the outside temperature the outside dewpoint temperature as well as the solar radiation. The auxiliary model of the tram train model has an R^2 value of 90.3 %. The model is adapted for the BEMU, HEMU and DEMU train model. Instead of three HVAC systems, only two are considered: one for each passenger car. Furthermore, a cooling system is modelled considering water cooling for the battery and the fuel cell. The internal combustion engine is air cooled. A heat exchanger is modelled exchanging heat between the coolant and the intake air of the HVAC system to reduce the necessary heating. This heat exchanger is switched off during the HVAC operation modes ventilation and cooling.

A driver model and an auxiliary control model is within the control model block. The driver model sets the driving lever while minimizing the gap between a target speed and the current speed at each track meter. The target speed is precalculated for each track meter. The auxiliary control model operates the auxiliary consumers. It adjusts the inside temperature of the train compartment to minimize the gap between the pre-set target temperature declared in DIN EN 14750-1 and the temperature inside the train compartment.

The energy supply model consists of the following, depending on the BEMU, HEMU or DEMU setup: AC energy supply, the battery, the fuel cell and the internal combustion engine. The batteries are modelled using real live data from electric busses, as described in Bauer et al. (2021) and the combustion engine is based on data from a diesel-electric train, Haag et al. (2017). Due to a lack of real live data the fuel cell and the AC energy supply are modelled using data from literature.

Within the car body model, the actual location of the train, the speed and the acceleration are calculated. The temperature is modelled using one heat capacity which is reduced in comparison to the tram train model since the train compartment is smaller.

3.2. Track model

The track model consists of all specifications made in DIN EN 50591:2019-12. Within the track resistance model the curvature and the slope at each track meter serves as an input, calculating the speed dependent track resistance. The model is parameterized with measurements done with the tram train vehicle during real operation. Since the BEMU, HEMU or DEMU weight doesn't change significantly from the tram train weight, this model is used without any change. Within the environment model the pre-calculated target speeds as well as the variables for temperature and solar radiation needed for the train compartment model are stored in look up tables.

4. Simulated Scenario

To gain representative results the simulated scenarios have to represent a wide range of track and environment scenarios. In total, 31 tracks in Germany and France are analyzed. Figure 6 shows a map of the analyzed tracks. The tracks are chosen randomly while considering an even distribution within the geographical landscapes of France and Germany. Therefore, different tracks are represented in the analysis, which are for example flat and long as well as curved and steep. The data needed for this analysis is taken from open source data: SNCF RESEAU (2020) and Deutsche Bahn AG (2019).

Fig. 6. Analysed tracks (red) in Germany and France

Besides the information about the track, such as curvature, slope and heights, environmental data such as the temperature and the solar radiation is needed. Furthermore, operational parameters, i.e. number of passengers and proposed speed have to be specified.

In a first step, a worst-case scenario is simulated analyzing if all train configurations specified in Chapter 2 are able to operate on the analyzed tracks. For BEMU trains the need for recharge opportunities is analyzed. The worst-case scenario contains a full vehicle, cold outside conditions as well as track speeds that are necessary to fulfill today's timetable. If track speeds are higher than 100 km/h the timetable is adjusted.

The HEMU and DEMU configuration are able to operate on all tracks due to the train configurations power and acceleration speed being oriented to the diesel trains that run on these branch lines today. For the BEMU configuration some recharge opportunities are necessary: It is assumed that every track endpoint is electrified, allowing the train to recharge while being on idle time at the endpoint. If that is not enough for operation, 5 km of track are assumed to be electrified, allowing the BEMU train to operate on all 31 lines. More than these two infrastructural measures are not necessary. The results of the worst-case scenarios are not representative for the overall train operation since the worst-case scenario is only happening rarely. Specific train configurations for each track are not further investigated. If a track is not that challenging, a smaller battery or smaller fuel cells could be a suitable solution to reduce cost.

A reliable comparison can be reached by analyzing mean environment conditions: For the temperature model, the data is collected from the Copernicus Climate Change Service, Climate Data Store: Hersbach et al. (2018). For each day in 2020 at 12:00 am, 6:00 am, 12:00 pm and 6:00 pm the parameters temperature, dewpoint temperature, solar radiation and direct solar radiation are collected. Representative values for each parameter are calculated building the mean over each season. These values are then used as inputs to the simulation.

Overall for the comparison, 992 simulations, 31 tracks · 2 (inbound and outbound) · 4 seasons (spring, summer, fall, winter) · 4 times (12:00 am, 6:00 am, 12:00 pm and 6:00 pm), are calculated for each drivetrain configuration.

5. Results

Exemplary results from railway line 1100 going from Puttgarden to Lübeck in Germany on a spring day scenario at 6:00 am are displayed in Figures 7 – 9. They show the state of charge of the battery (BEMU), the hydrogen demand (HEMU) and the diesel demand (DEMU) as well as the total and the auxiliary energy demand and the simulated speed profile. The total energy demand is calculated assuming that the heating value of hydrogen is 33.3 kWh/kg and that of diesel is 11.8 kWh/kg.

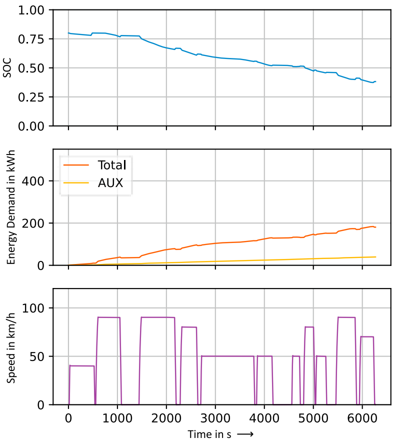

Fig. 7. Simulation results BEMU

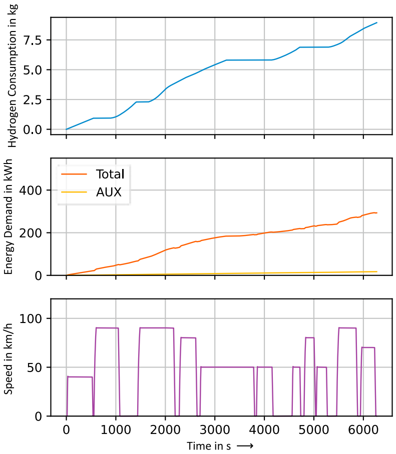

Fig. 8. Simulation results HEMU

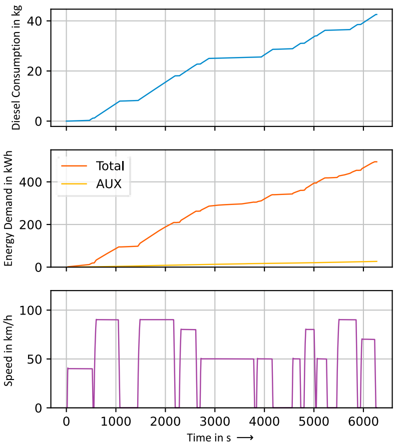

Fig. 9. Simulation results DEMU

Analyzing all lines and scenarios, the energy demand per km respectively the hydrogen and diesel consumption per km is calculated and displayed in Figure 10 - 12. To show the range of results, boxplots for each configuration are displayed. Since the diesel consumption varies more between the tracks, there are outliers in the DEMU boxplot. Outliers are displayed with circles.

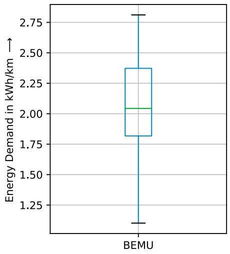

Fig. 10. Simulation results BEMU

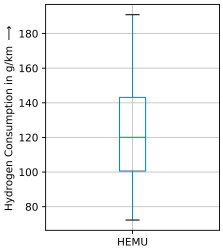

Fig. 11. Simulation results HEMU

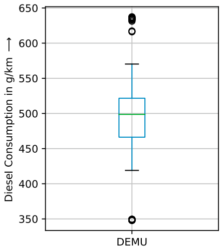

Fig. 12. Simulation results DEMU

Figure 13 compares the total energy needed by the train configurations, again using the heating value of hydrogen and diesel. If electric energy is the primary energy source of all three train configurations, hydrogen and diesel have to be generated first. Hydrogen can be generated using an electrolysis with an efficiency of 70 %, cf. Leopoldina (2018). To obtain diesel, hydrogen is further processed using for example the Fischer-Tropsch process also with an efficiency of 70 %, cf. Leopoldina (2018). By assuming these efficiencies, Figure 14 shows the necessary energy supply for the operation. If this energy supply is climate neutral, all three proposed drivetrain configurations can be considered climate neutral.

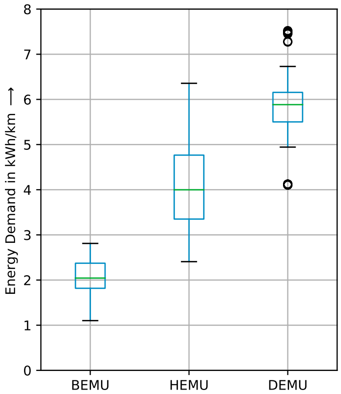

Fig. 13. Total energy demand

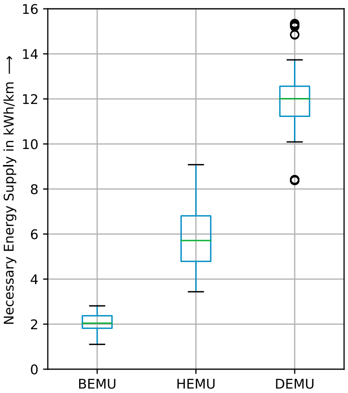

Fig. 14. Necessary energy supply

6. Conclusion

The simulation results in Figures 7 - 9 are showing in detail the advantages and disadvantages of the proposed drivetrain configurations. The efficiency of the fuel cell is about 55 % at its bests point, while the diesel engine has an efficiency of about 40 % at its best point. This increases the energy demand for these configurations significantly. The auxiliary demand is the highest for the BEMU train, since no waste heat is used to heat the train compartment. This effect is the largest in winter while in summer when the AC is running the auxiliary demand of the DEMU is the largest. Because heating is less efficient than cooling the effect in winter is more important. The SOC graph indicates that recharging at the last stop is necessary. This has to be considered while planning the timetable. The hydrogen and the diesel consumption indicate the necessary fuel tank size. For the hydrogen train, this can become a challenging topic.

Considering all simulations (Figures 10 – 12) the variety within the results is displayed. This variety is due to different track profiles and simulated environmental conditions. For the DEMU configuration the variety is the largest. This is due to the previously described local emission free power management system. If a track has lots of stations, this management system switches the internal combustion engine on and off very frequently, resulting in a non-optimal operation point of the engine during operation. Compared to other trains with the same primary energy source, all configurations show a very energy-efficient train operation due to the lightweight design as well as the possibility to store a lot of braking energy back into the battery due to its good charging ability. Figure 10 displays the energy demand of the BEMU train. With a demand of about 1.25 up to 2.75 kW/km, this train configuration is the most energy efficient solution. This is due to the efficient drivetrain components and the direct use of electrical energy, without the inefficient storage of energy in chemical fuels.

By using the heating value of hydrogen and diesel, the energy demand of the train configurations can be compared to the BEMU train, see Figure 13. The HEMU train is half and the DEMU train is a third as efficient as the BEMU train, which is due to the efficiency of the fuel cell and the internal combustion engine. The use of the waste heat is not compensating this efficiency gap between BEMU and HEMU / DEMU. This is also partly due to the extra power needed for cooling the fuel cell and the internal combustion engine, which increases the auxiliary energy demand.

For a climate neutral operation of all three trainsets, the primary energy source of all three configurations can be renewable electric energy. Figure 14 compares the then necessary energy supply. With that, the HEMU system is a third and the DEMU is only a sixth as efficient as the BEMU system.

Overall the BEMU technology is the most energy-efficient technology if a BEMU train set is able to operate on the line. The HEMU technology is a suitable alternative if for example the track is too long or too steep for BEMU operation and the mentioned electrification is too costly or cannot be executed in a reasonable time. The DEMU operation with alternative climate friendly fuels uses double es much energy than the HEMU setup, without bringing a big advantage over the HEMU configuration. This is probably in most cases not economically beneficial and should not be followed.

Future work is to develop strategies to further enhance the energy efficiency of the BEMU trains. Using energy efficient heat pumps for heating and operating the train's auxiliaries in an optimal manner can reduce the energy demand of the BEMU trains. Furthermore, the idea to use waste heat can also be implemented within the BEMU train by using waste heat of the traction motors and the battery for heating the train compartment.

References

ALSTOM, 2021. Emission-free train solutions to deliver railway decarbonisation. [Online] https://www.alstom.com/press-releases-news/2021/11/emission-free-train-solutions-deliver-railway-decarbonisation, accessed 26.04.2022.

Bauer, R., Reimann, S., Gratzfeld, P., 2021. Modeling of Traction Batteries for Rail Applications Using Artificial Neural Networks in IEEE Transportation Electrification Conference & Expo (ITEC). Chicago, IL, USA, IEEE, pp. 826–831.

Bauermeister, M., Claus, E., Laurent, F., Diebel, T., Nakkash, N., 2021. Alternative Antriebe im öffentlichen Verkehr. KCW GmbH. [Online] http://vvnb.at/fileadmin/CONTENT/Downloads/Aktuelles/2021-04-26_-_Low_Carb_Mobility_-_Studie_alternative_Antriebe.pdf, accessed 26.04.2022.

Briginshaw, D. 2021. CAF to build more than 60 battery-powered EMUs for Germany, in International Railway Journal, 6/24/2021. [Online] https://www.railjournal.com/passenger/light-rail/caf-to-build-more-than-60-battery-powered-emus-for-germany/, accessed 26.04.2022.

Deutsche Bahn AG, 2019. Geo-Streckennetz. Geoinformationen zu Strecken des Schienenverkehrsnetz. [Online] https://data.deutschebahn.com/dataset/geo-strecke.html, accessed 26.04.2022.

DIN EN 14750-1, 08.2006. Bahnanwendungen - Luftbehandlung in Schienenfahrzeugen des innerstädtischen und regionalen Nahverkehrs - Teil 1: Behaglichkeitsparameter; Deutsche Fassung EN 14750-1:2006.

DIN EN 50591:2019-12, 12.201. Bahnanwendungen - Fahrzeuge - Spezifikation und Überprüfung des Energieverbrauchs; Deutsche Fassung EN 50591:2019.

European Commission 2019. The European Green Deal. Brussels. [Online] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52019DC0640&from=EN, accessed 26.04.2022.

European Commission, 2021. EU Transport in figures. [Online] https://op.europa.eu/o/opportal-service/download-handler?identifier=14d7e768-1b50-11ec-b4fe-01aa75ed71a1&format=pdf&language=en&productionSystem=cellar&part=, accessed 26.04.2022.

Haag, S., Eller, M., Gratzfeld, P., 2017. Methodical design of a hybrid propulsion for short-distance railcars. In Elektrische Bahnen 115 (5), pp. 230–237.

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Soci, C., 2018. ERA5 hourly data on single levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS).

Klebsch, W., Guckes, N., Heininger, P., 2020. Bewertung klimaneutraler Alternativen zu Dieseltriebzügen. Wirtschaftlichkeitsbetrachtungen am Praxis-Beispiel ›Netz Düren‹. VDE Verband der Elektrotechnik Elektronik Informationstechnik e. V., Frankfurt am Main.

Laverick, N., Hoffrichter, A., 2019. ZEMU Concept Feasibility Study. Detailed Evaluation of Battery and Hydrogen Technologies for the Arrow Service. Mott MacDonald. Los Angeles.

Leopoldina 2018. Coupling the different energy sectors - options for the next phase of the energy transition. Position paper. München, Halle (Saale), Mainz: German National Academy of Sciences Leopoldina; Union of the German Academies of Sciences and Humanities. [Online] https://www.acatech.de/publikation/sektorkopplung-optionen-fuer-die-naechste-phase-der-energiewende/, accessed 26.04.2022.

Otto, P., Tesar, M., Gratzfeld, P., 2020: Design and Evaluation Examples of a Data Acquisition System for Light Rail Applications in 33rd World Electric Vehicle Symposium & Exposition.

Reimann, S.; Jost, F.; Gratzfeld, P. 2020. Multiphysics Simulation of a Battery Electric Train Operation in TRA2020 Book of Abstracts. [Online] https://publikationen.bibliothek.kit.edu/1000106014, accessed 26.04.2022.

Ruf, Y., Zorn, T., Akcayoz N., Andrae, P., Erofeeva, S., Garrison, F, Schwilling, A,. 2019. Study on the use of Fuel Cells and Hydrogen in the Railway Environment. Shift2Rail. [Online] https://shift2rail.org/wp-content/uploads/2019/05/Study-on-the-use-of-fuel-cells-and-hydrogen-in-the-railway-environment_final.pdf, accessed 26.04.2022.

Siemens, 2020. Siemens Mobility receives first order for battery-powered trains Munich. [Online] https://press.siemens.com/global/en/pressrelease/siemens-mobility-receives-first-order-battery-powered-trains, accessed 26.04.2022.

SNCF RESEAU, 2020. OPEN DATA SNCF: Lignes par type. [Online] https://ressources.data.sncf.com/explore/dataset/lignes-par-type/export/?location=6,46.69508,2.48494&basemap=jawg.transports, accessed 26.04.2022.

Stadler Rail Group, 2019. Stadler supplies 55 battery-operated FLIRT trains for the Schleswig-Holstein local transport association. Berlin. [Online] https://www.stadlerrail.com/media/pdf/2019_0702_media%20release_flirt%20akku_en.pdf, accessed 26.04.2022.