Technological, Economic and Ecological Assessment of Powertrain Technologies in the Railway Sector

Maximilian Weber[1], Christian Zinner[1], Patrick Pertl[1], Alexander Trattner[1,2]

[1] HyCentA Research GmbH, Inffeldgasse 15, A-8010 Graz, +43 316 873 9500, office@hycenta.at, www.hycenta.at

[2] Institute of Thermodynamics and Sustainable Propulsion Systems, Inffeldgasse 19, A-8010 Graz, +43 316 873 30001, institut@ivt.tugraz.at, www.itna.tugraz.at

Abstract: To manifest locally zero-emission operation in the railway sector, the classic electric trains are not always the most favorable option. The optimum powertrain technology in terms of technological, economic, and ecological targets is subject to various aspects. Depending on the specific circumstances, the methodology outlined in this paper allows for the identification of the most suitable variant through a technology-neutral assessment. Considering both the vehicles and infrastructures, the approach with a scientifically sound and validated database is a valuable tool in aiding an informed decision on the favorable alternative.

Keywords: Decarbonization, Alternative Propulsion Systems, Life Cycle Assessment, Dynamic Investment Calculation, Use-Value Analysis, Technology Comparison

1 Introduction

Rail transport holds the potential to be one of the most environmentally friendly forms of mobility. Nevertheless, only about 56 % of the European railway network is electrified, employing catenary lines to enable the operation of locally emission-free electric-powered railcars [1]. As a consequence, 44 % is still largely served by diesel-powered trains, resulting in the emission of large quantities of greenhouse gases and air pollutants.

Given the aggravating climate conditions [2], the European goal is to gradually decarbonize all sectors and to achieve climate neutrality by 2050 [3]. With a standard operating life of 30 years for railcars [4], existing DMU (Diesel Multiple Unit) must be replaced by sustainable propulsion systems within the next 10 years. Electrification of the affected lines is therefore a logical choice; however, it incurs significant costs for the acquisition and maintenance of the catenary line. To compensate for this, the operation of EMU (Electric Multiple Unit) requires a high driving frequency and substantial transport capacity. This often does not apply to especially regional lines in sparsely populated regions [5,6].

Accordingly, alternative technologies such as BEMU (Battery Electric Multiple Unit) and HEMU (Hydrogen Electric Multiple Unit) are becoming appropriate possibilities to close the gaps in electrification with zero local emissions. A major challenge for the converting of existing diesel-powered lines is that there is a need for new vehicles and additional infrastructure. As the various technologies all have their advantages and disadvantages, a universally optimal solution regardless of the area of application does not exist. Instead, the technologies must be evaluated on a case-by-case basis considering the specific boundary conditions.

Decarbonizing the rail passenger traffic has been addressed in several publications. Pagenkopf et al. [7] focus on the vehicles and examines the availability and suitability of battery-electric and hydrogen-electric trains for use on non-electrified routes. In a rather simplistic way, reference is made to the costs of purchase as well as the costs and emissions during operation. A key message is that alternative forms of propulsion still face a lack of competitiveness against conventional technologies. In turn, Herbert and Scholz [8] and Pertl et al. [9] discuss the infrastructures required for an decentralized hydrogen-based operation of railcars. They primarily concentrate on the economic and operational conditions of renewable hydrogen production regarding potential areas of application. Both studies conclude that hydrogen technology will become competitive by 2030. Moreover, they expect considerable cost reductions in the long term, which could boost the use of hydrogen in the rail sector. A consideration of vehicles and infrastructures can be found in Wille et al. [4], Klebsch et al. [5,6], Müller [10], Wittemann and Meinelt [11] or Frank and Gnann [12]. In these, the technological and economic evaluation of alternative propulsion systems is carried out on the basis of specific examples. The quintessence is that the use of electric-powered trains via catenary line will continue to be the most suitable option for a majority of applications in the future. Nevertheless, the battery-electric and hydrogen-electric trains represent promising variants to serve in one case shorter distances of 40 to 100 km and in the other case longer distances of up to 1000 km.

With respect to profound decision-making as to which alternative is in favor, this paper addresses a technology-neutral comparison of vehicles and infrastructures. The technologies are subjected to a comprehensive and holistic analysis, taking into account technological, economic and ecological aspects. As part of the proposed toolchain (see section 2), the evaluation is based on a longitudinal dynamics simulation of the vehicles as well as a life cycle assessment and a dynamic investment calculation of the technologies. Applying the specified boundary conditions (see section 3), individual criteria such as greenhouse gas emissions, costs, powertrain mass/volume, driving range and refueling/recharging time are estimated by means of a valid database (see section 4). A use-value analysis finally helps to identify the benefits and drawbacks of each technology.

2 Methodology

2.1 Longitudinal Dynamics Simulation

The starting point for this toolchain is a longitudinal dynamics simulation of the vehicles. In this paper, it is primarily used to calculate the power/energy demand of the vehicle, which results from overcoming all the driving resistances and supplying the propulsion system plus auxiliary consumers. These auxiliary units encompass components such as those of the powertrain, HVAC (Heating, Ventilation and Air Conditioning) or thermal management. The total required power is thus composed of the power of the electric machine and the power of the auxiliary consumers. This power must be provided by the on-board energy storage system. Taking into account the efficiencies of the corresponding components, the energy demand results from integrating the power over time. In fact, the actual energy consumption experiences seasonal fluctuations due to heating or cooling of passenger cabins in winter and summer. This paper focuses on the energy demand during the transition period, as it is representative of the average annual energy consumption of the investigated railway route.

2.2 Life Cycle Assessment

The toolchain also includes a life cycle assessment to evaluate the environmental footprint in terms of resource demands and greenhouse gas emissions of each technology. Beside the vehicle, the analysis considers the required infrastructure. The basis for the analysis is an accurate database using reliable figures from the latest academic publications, newest manufacturer information and sound expert knowledge. As these values are subject to variations, a baseline scenario is defined to represent the state of the art, plus an optimistic and a pessimistic scenario to cover those ranges of uncertainty.

The life cycle assessment applied here refers to the principles and guidelines of ÖNORM EN ISO 14040 [13] and ÖNORM EN ISO 14044 [14]. It consists of a definition of the scope, a life cycle inventory, a life cycle impact assessment, and an interpretation of the results. Depending on the purpose, it can be carried out for either all or single life cycle phases. Figure 1 depicts a complete life cycle, which is divided into (a) pre-use or production phase including extraction and processing, (b) use phase including operation and maintenance as well as (c) post-use or end-of-life phase including recycling and disposal [15,16].

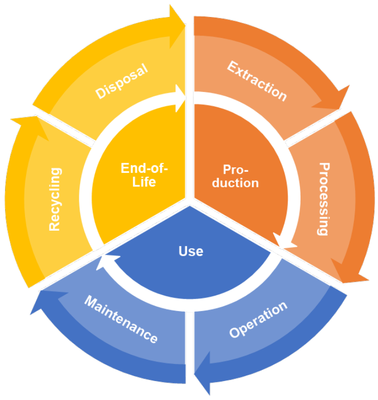


Figure 1: Life cycle phases

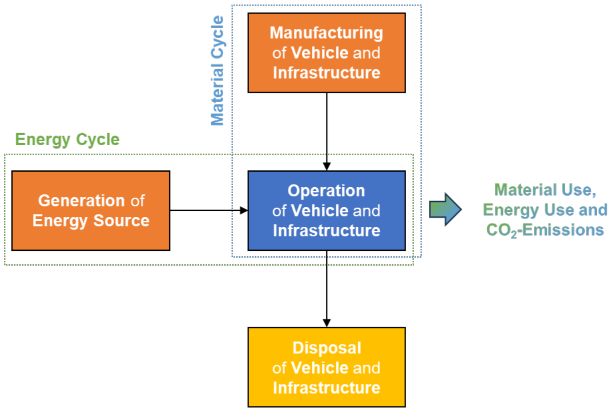


Figure 2: Life cycle inventory

However, this paper focuses on a simplified evaluation as some aspects are not considered due to lack of consistent data. First, only resource demands and greenhouse gas emissions are quantified, with the environmental impact assessment being neglected. Second, the analysis is limited to the pre-use and use phases and excludes the post-use phase. As shown in Figure 2, the approach involves the materials and energy sources required for production and operation of the vehicles and infrastructures. The greenhouse gas emissions, expressed in CO_2-equivalents, are calculated from the carbon footprints of the materials and energy source used. The materials are allocated to the emissions generated from “cradle-to-gate” during extraction and processing. In the case of energy sources, the emitted greenhouse gases are made up of indirect CO_2-emissions from production (“well-to-tank”) and direct CO_2-emissions from operation ("tank-to-wheel”).

2.3 Dynamic Investment Calculation

To determine the specific expenses of purchasing and operating the vehicles plus infrastructures, the database is expanded to include corresponding monetary values. The existing wide cost ranges are again taken into account with the baseline, optimistic and pessimistic scenarios. According to ÖNORM M 7140 [17], the cost analysis is performed individually for CAPEX

(CAPital EXpenditures), i.e. capital-based expenses (investment) and OPEX (OPerational EXpenditures), i.e. operation-based expenses (maintenance) and consumption-based expenses (energy). Both form the TCO (Total Costs of Ownership). However, the time value of expenditures changes, especially over long observation periods. With this in mind, the costs are calculated dynamically taking into account interest and inflation [18]. Future payments are therefore compounded at

$$i_r = \frac{1 + i_n}{1 + j} - 1, \qquad \text{Equation 1}$$

where the real interest rate i_r is the nominal interest rate i_n adjusted for the inflation rate j. Assuming a nominal interest rate of 2.5 % [19] and an inflation rate of 2.0 % [20] in the medium to long term, this results in a real interest rate of 0.49 %. Annual expenses E_t at time t are incurred for reinvestment, maintenance, and energy. Reinvestment takes place if a component reaches its end-of-life within the observation period. In this paper $T = 30$ years is defined, as this corresponds to the typical operating life of railcars. The future value of the expenses is computed according to

$$E_t = E_0 \cdot (1 + i_r)^t. \qquad \text{Equation 2}$$

At the end of the observation period, components may have a residual value that needs to be discounted. Considering the initial investment I_0, the lifetime t_l and the residual useful life t_r of each component, the revenue R_T is given as

$$R_T = -I_0 \cdot \frac{t_r}{t_l} \cdot (1 + i_r)^{(T - t_r)}. \qquad \text{Equation 3}$$

2.4 Use-Value Analysis

A use-value analysis is essential for the systematic evaluation of technologies using multiple criteria. For the scientific comparison of the vehicles and infrastructures, this paper proposes a classification in rail-specific technical and operational, economic, and ecological aspects. The rating scale applied ranges from 0 to 5, with a score of 0 indicating an unsatisfactory result and a score of 5 an excellent result. The technical aspect includes criteria such as powertrain mass/volume, constructional effort, technological maturity, and durability; the operational aspect comprises criteria such as driving range, recharging/refueling time, grid stress, timetable stability and synergy effect. When assessing the economic aspect, capital and operational expenses are taken into account, while the ecological aspect is considered in terms of resource use, greenhouse gas and particle emissions plus area demand. The figures used to evaluate the individual criteria are part of the database used.

3 Boundary Conditions

3.1 Railway Route

The comparison of technologies is performed using the example of the “Mühlkreisbahn” in Austria, which is still operated by conventional diesel railcars. The railway route is a regional railway line with a relatively long and steep track and poses highly dynamic requirements. It is a standard-gauge, single-track line with a distance of around 60 km. The height difference between the lowest and highest point is more than 350 m (see Figure 3), which results in a maximum inclination of roughly 50 ‰. The route includes a total number of 19 stations. Given a maximum speed of currently 80 km/h, the operating time per cycle is around 75 min. Trains depart from both terminus stations every 120 min. Four vehicles, including breakdown reserves, are needed for regular operation. With three trains in alternating operation, this results in 6 cycles and 355 km per train. The data is taken from the study by Pertl et al. [9].

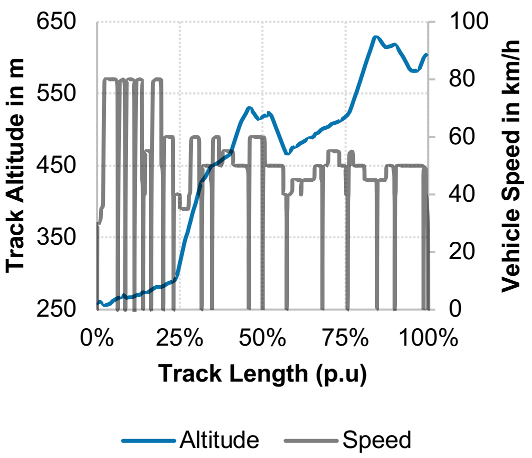


Figure 3: Altitude and speed profile

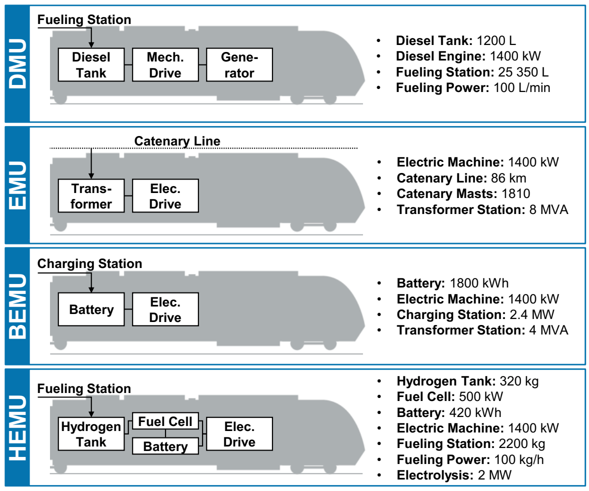


Figure 4: Specifications of technologies

3.2 Specifications

In conducting the energy demand of the vehicle, the commercial software AVL CRUISE™ M is used to model each propulsion system. These models include all relevant components as well as vehicle-related parameters (e.g. maximum acceleration and speed, mass, length, etc.) and track-related parameters (e.g. altitude, inclination, wind, temperature, etc.). Except for the propulsion system, the vehicles are considered identical, i.e. the powertrain models only differ in their components. The specifications of the vehicles (see Figure 4) enable at least a round trip without the need for recharging or refueling. Accordingly, the BEMU and HEMU are assumed to have a higher mass than the DMU and EMU. The efficiencies are described by corresponding characteristic curves depending on the actual operating point. With respect to operation, the efficiency ranges are 30 to 40 % for the DMU, 80 to 90 % for the EMU, 72 to 81 % for the BEMU and 40 to 50 % for the HEMU [4,5,10,12].

The energy demand of the vehicle represents the basis for calculating the energy demand of the infrastructure, which depends on the efficiency, power rating and operating time of the respective facility. The efficiency ranges applied are 85 to 90 % for the DMU, 94 to 96 % for the EMU, 88 to 93 % for the BEMU and 72 to 81 % for the HEMU. The efficiency of the electrolysis is taken into account at 60 to 70 % [4,5,10,12]. The specifications of the infrastructures (see Figure 4) ensure a short recharging or refueling time and in the special case of DMU and HEMU a sufficient supply of fuel.

Another important aspect is the lifetime of the vehicle and infrastructure components. Due to operational ageing, these components may be renewed or replaced within the period under consideration. As a result, this is reflected in increased emissions or costs. The DMU does not need any major replacements in terms of vehicles and infrastructure within 30 years. The same applies to the EMU for the vehicles; concerning its infrastructure, components of the catenary line with higher wear and tear must be replaced within 20 years, while all other components last 50 years or longer. However, the BEMU and HEMU necessitates more frequent replacement. In the instance of using an LTO (Lithium Titanium Oxide) battery, replacement is required after 20,000 cycles for the BEMU and after 60,000 cycles for the HEMU. When utilizing PEM (Polymer Electrolyte Membrane) technology for the HEMU, fuel cells must be replaced after 30,000 hours and the electrolysis after 80,000 hours of operation [4,5,12,21–25].

3.3 Energy Sources

Beyond the energy demand of vehicles and infrastructure, the energy source plays a substantial role in the process of comparing the technologies. On the one hand, aspects such as the carbon footprint and costs are greatly influenced by where the energy comes from and how it is generated and distributed. On the other hand, the production and transport of energy have an eminent impact on issues such as availability or resilience.

Regarding climate and environmental protection, it is only rational to pursue operations based on renewable energies in the medium to long term. Such energy sources, devoid of local emissions of greenhouse gases and air pollutants, become imperative for future applications. The analyses conducted in this work have revealed that utilizing electricity from the energy mix still involves considerable amounts of CO_2 through indirect emissions. For the sake of simplicity, only electricity from renewable energies is taken into further account. However, operation exclusively on the basis of renewable energies cannot be taken for granted at present. Renewable hydrogen is not available on the market in the quantities required for train operation and must be produced decentralized. But even the electricity drawn from the grid is not yet fully renewable. As of today, the supply of renewable electricity is only possible in direct coupling with a renewable power generation plant. This fact needs to be considered when deciding on a propulsion system.

For the following comparison, an emission factor of 321 kg(CO_2)/MWh for conventional diesel and 14 kg(CO_2)/MWh for renewable electricity is applied [26]. In addition, costs of 147 to 204 €/MWh for fossil diesel [4,5,8,10,12,27] and 126 to 239 €/MWh for renewable electricity including grid fees, taxes and levies [4,5,8,10,12,28–30] are assumed. In the case of hydrogen production on-site, it should be highlighted that e.g. in Austria or Germany the electricity supply is currently exempt from grid fees if the electrolysis system is drawn directly from a renewable power generation plant without using the public grid. Taking into account the typical price composition, hydrogen can be produced at around 40 % lower electricity costs [22,31].

4 Results

4.1 Energy Consumption

The energy consumption of vehicles and infrastructure has a significant influence on the carbon footprint and costs of the different technologies. The relevant boundary conditions for determining the energy demands were discussed in the previous section. Table 1 provides the resulting energy consumption of the vehicles and infrastructures related to the total mileage of the vehicles, considering the efficiencies in the baseline scenario. While the results from the optimistic and pessimistic scenario are not explicitly presented, they are factored into the quantification of the CO_2-emissions and costs. The same applies to the energy demands of electrolysis. Since hydrogen production lies beyond the system boundary defined, it is excluded from Table 1. The decrease in efficiency due to degradation was neglected.

Table 1: Specific energy consumption of technologies

Technology	DMU	EMU	BEMU	HEMU
Vehicle	$17.8\ kWh/km$	$5.8\ kWh/km$	$6.5\ kWh/km$	$11.0\ kWh/km$
Infrastructure	$0.01\ kWh/km$	$0.3\ kWh/km$	$0.7\ kWh/km$	$1.2\ kWh/km$

4.2 CO_2-Emissions

In Figure 5 the results from the life cycle assessment are illustrated. The bar represents the baseline scenario, and both ends of the whisker indicate the optimistic and pessimistic scenario. As expected, the DMU causes the highest CO_2-impact. In contrast, the alternatives account for only 13 % to 26 % of the CO_2-emissions. Most of them are attributed to the vehicles, while the infrastructures take for a lesser share. The EMU stands as the sole exception, where the infrastructure has a higher carbon footprint than the vehicles. This is due to the enormous amount of material required to install the catenary system. Specifically, the quantities of concrete, steel, copper and aluminum add up to 75 to 147 t/km, which is 67 to 113 t(CO_2)/km [24,25,32,33]. In comparison, the emissions of the BEMU and HEMU are only half as low. The most significant contribution stems from the production of the vehicle body and the powertrain components. Attention should be directed towards the batteries at 58 to 177 kg(CO_2)/kWh, hydrogen tanks at 8 to 16 kg(CO_2)/kWh and fuel cells at 20 to 35 kg(CO_2)/kW, as these components demand certain quantities of critical elements characterized by high carbon footprint [34–41]. These include lithium, nickel, manganese, cobalt, titanium, phosphate, carbon fiber and platin. Additionally, Figure 6 illustrates the cumulated CO_2-emissions over time. Apart from the considerable annual CO_2-emissions caused by the DMU, the EMU has a substantial initial carbon footprint. The BEMU and HEMU are less conspicuous in both respects.

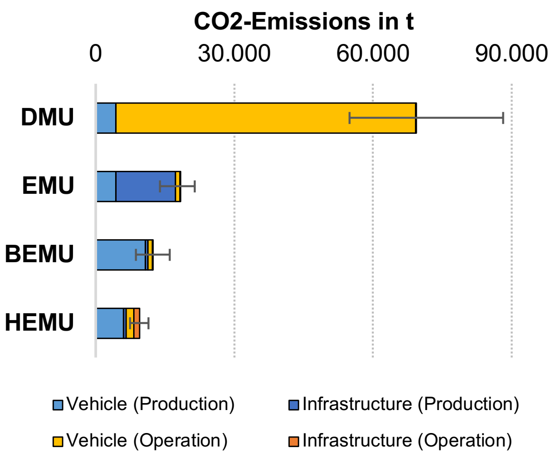


Figure 5: Total CO_2-emissions of technologies

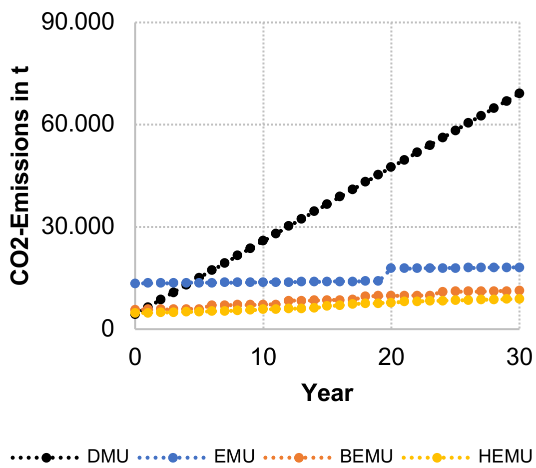


Figure 6: CO_2-emissions of technologies over time

4.3 Total Costs

Figure 7 shows notable differences in costs among the technologies. These stem from the unique expenses associated with vehicles and infrastructures, influenced by factors such as technological maturity, experience, availability, lifetimes as well as energy prices and mileage. Considering four vehicles each, except for the BEMU, which is calculated with five vehicles for timetable stability, the DMU has the lowest costs, while the EMU exhibits the highest costs; BEMU and HEMU are in between. The cost intensity of the EMU is primarily attributed to the extensive construction work involved in installing the catenary system, as indicated in [4,5,10,12] at 0.9 to 1.8 M€/km. Contrarily, the purchase of a four-part train examined here is lower priced at 7.1 to 10.6 M€. For BEMU, the purchase is around 9.4 to 12.0 M€, for HEMU around 10.1 to 12.8 M€ [5,7,8,10,12]. At 1.0 to 3.0 M€ per charging station or hydrogen station, their infrastructures are comparatively less significant [4,5,10,12,42,43]. Regarding operation, the expenses of the alternatives are in a similar range, with the EMU being the most cost intensive. Based on [4,5,8,10,12], the maintenance of the vehicles of EMU and BEMU are considered at 0.7 to 2.4 €/km, the HEMU at 0.9 to 2.7 €/km. For the maintenance of the infrastructures annual costs of 300 to 600 k€/a (EMU), 2.5 to 36 k€/a (BEMU) and 36 to 120 k€/a were used. In terms of energy, the electricity required for hydrogen production was assumed to be exempted from grid charges. The full price was applied for electricity drawn from the public grid. In Figure 8 also the progression of costs over time is depicted. The DMU shows a linear annual increase, which is almost the same for the HEMU at a higher cost level. Greater conspicuousness is observed in case of the BEMU and EMU, where the replacement of the batteries is just as evident as the replacement of parts of the catenary line. The considerable residual values of the catenary system after 30 years should also be acknowledged.

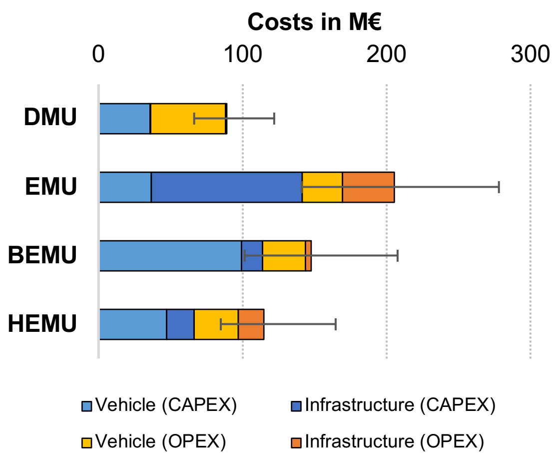


Figure 7: Total costs of technologies

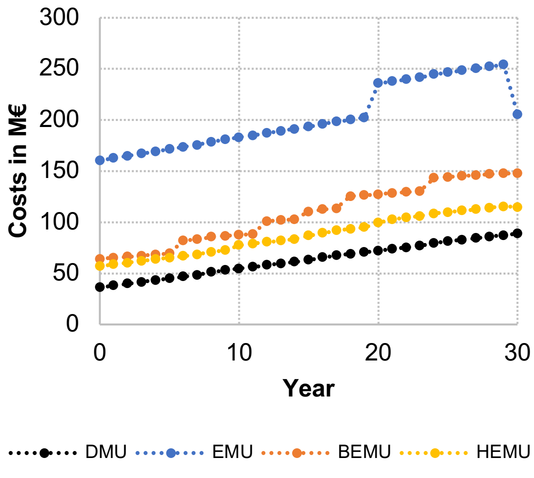


Figure 8: Costs of technologies over time

4.4 Technology Comparison

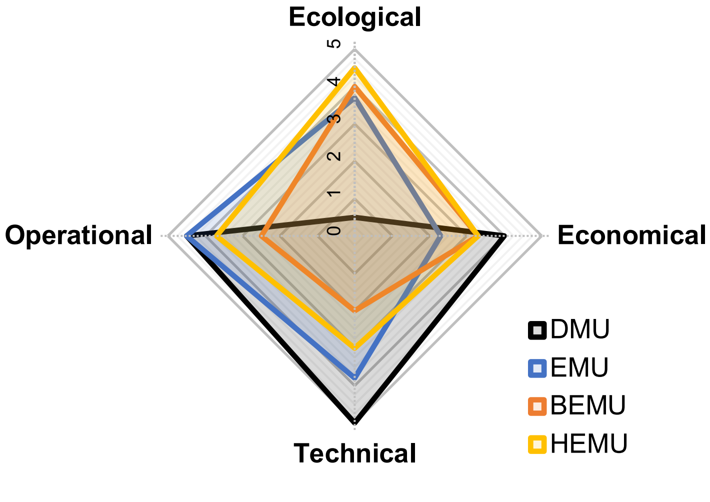
Limiting the comparison to CO_2-emissions and costs alone would be narrow-minded. Based on a use-value analysis, the assessment of the technologies is therefore extended to include the evaluation criteria presented in section 2.4. From technical, operational, economic, and ecological perspectives, this allows for a qualitative demonstration of the potential of the technologies. The final results are depicted in Figure 9 and discussed below.

Ecological: The assessment includes the CO_2-emissions discussed in section 4.2 as well as the particle emissions determined by [44,45] and area demands estimated from [24,25,32,33]. As becomes evident, the HEMU yields the most favorable score. In a direct comparison, the EMU exhibits CO_2-emissions twice as high, a 7.5 % greater particle load attributed to particle abrasion from the catenary line, and roughly a four times higher area demand for the construction of the catenary system. The lower rating for the BEMU is attributed to the higher number of vehicles and the larger battery.

Economical: When examining the capital and operational expenditures, the HEMU appears to be the most advantageous option among the alternatives. In consideration of the findings from section 4.3, this is mainly due to the significantly expensive infrastructure of the EMU, while the BEMU incurs higher costs primarily caused by the additional vehicle.

Technical: The BEMU and HEMU achieve the lowest scores, as they are disadvantageous in terms of their powertrain mass and volume. Assuming LTO batteries, PEM fuel cells and Type IV hydrogen tanks, the powertrain of the BEMU amounts to 31.8 t and 26.2 m³, that of the HEMU to 12.7 t and 24.3 m³. This makes them heavier and bulkier than the EMU, potentially influencing axle load and seating capacity. Furthermore, battery and hydrogen technology are yet less technologically mature and have shorter lifetimes.

Operational: With respect to performing an uninterrupted operation the EMU is generally more beneficial. For the HEMU, the tank capacity is adequate for daily refueling either before starting or after completing the timetable, with refueling taking around 23 min. In the case of the BEMU, there are limitations as recharging is necessary after each round trip, requiring about 45 min per charging process. The substantial load on the electricity grid can be considered a challenge for both EMU and BEMU. Moreover, the HEMU offers the highest potential for creating synergies with other forms of mobility within the region of application.



Ecological:
CO_2-emissions, particle emissions, area demand

Economical:
capital / operational expenditures

Technical:
powertrain mass / volume, constructional effort, technological majority, durability / reliability

Operational:
driving range, recharging / refueling time, grid stress, timetable stability, synergy potential

Figure 9: Comparison of technologies

5 Conclusion

In general, it can be stated that there is no single ideal alternative that is equally suitable for all diesel routes. Decision-makers seeking a new transport solution for their railway networks must evaluate the options on an individual basis. In terms of technological, economic, and ecological targets, the suitability of these alternative technologies depends on various aspects such as operating conditions, costs, or emissions savings. In addition to the necessity for renewable energy, e.g. the material and energy demands for the production and operation of vehicles and infrastructures are of crucial importance.

Hence, this paper addresses a comprehensive and holistic evaluation of the vehicles and infrastructures to fulfill the requirement of comparing different technologies on a scientific level in a neutral and transparent manner. The methodical toolchain proposed is based on a longitudinal dynamics simulation of the vehicles as well as a life cycle assessment, a dynamic investment calculation and a use-value analysis of the vehicles and infrastructures. Applying a valid database consisting of specific figures from latest academic publications, newest manufacturer information and sound specialist knowledge, this allows for a quantification of resources, greenhouse gas emissions and costs plus a determination of rail-specific technical and operational criteria such as powertrain masses/volumes, driving ranges and refueling/recharging times.

Within this paper, the approach was applied to the “Mühlkreisbahn”, a relatively long and steep railway track with a daily mileage of approximately 1040 km. The comparison was conducted using an observation period of 30 years, as this corresponds to the typical operating life of railcars. The classic diesel trains served as a benchmark; the classic electric trains as well as the new battery-electric and hydrogen-electric trains were examined as alternatives. Renewable electricity and hydrogen were assumed as energy sources. Taking into account the typical efficiencies and lifetimes of the components as well as the given boundary conditions, the hydrogen variant proved to be potentially the most favorable option for this scenario, followed by the catenary variant and the battery variant.

In summary, the methodology presented offers a technology-open assessment of the different propulsion systems and infrastructure facilities from a technological, economic, and ecological point of view. This allows the technologies to be compared with each other on the basis of technological, economic and ecological aspects. The results and findings can ultimately make a valuable contribution to supporting the decision-making process in terms of the most suitable alternative.

6 Acknowledgment

The authors would like to thank the Austrian Research Promotion Agency (FFG) for funding and managing the project “WIVA P&G HyTrain” (FFG Nr. 885087). Special thanks are extended to AVL List GmbH for supporting the research activities by providing software as part of the “AVL University Partnership Program”.

7 References

1. Statista. Share of the rail network which is electrified in europe. Available online: https://www.statista.com/statistics/451522/share-of-the-rail-network-which-is-electrified-in-europe/#statisticContainer.
2. Pörtner, H.-O.; Roberts, D.C.; Poloczanska, E.S.; Mintenbeck, K.; Tignor, M.; Alegría, A.; Craig, M.; Langsdorf, S.; Löschke, S.; Möller, V.; et al. Summary for Policymakers. In *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working*

Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; Pörtner, H.-O., Roberts, D.C., Poloczanska, E.S., Mintenbeck, K., Tignor, M., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., Eds.; pp 3–34.
3. EC. The European Green Deal.
4. Wille, N.; Pfaff, R.; Nolte, R.; Vetter, M.; Hohn, M.; Tappert, T. Innovatives Triebfahrzeug: Identifizierung von Forschungsansätzen und technischen Grundlagen zur Entwicklung eines leiseren, umweltfreundlicheren und betriebswirtschaftlich darstellbaren innovativen Triebfahrzeugs für bislang nicht elektrifizierte Netze **2020**.
5. Klebsch, W.; Guckes, N.; Martin, J. Bewertung klimaneutraler Alternativen zu Dieseltriebzügen **2020**.
6. Klebsch, W.; Heininger, P.; Martin, J. Alternativen zu Dieseltriebzügen im SPNV **2019**.
7. Pagenkopf, J.; Schirmer, T.; Böhm, M.; Streuling, C.; Herwartz, S. Marktanalyse alternativer Antriebe im deutschen Schienenpersonennahverkehr **2020**.
8. Herbert, T.; Scholz, R. Wasserstoff-Infrastruktur für die Schiene **2016**.
9. Pertl, P.; Gyurica, M.; Trattner, A.; Vopava, Julia, Kienberger, Thomas; Zauner, C.; Böhm, Hans, Tichler, Robert; Landgraf, Matthias, Zeiner, Martina; Veit, P. HYTRAIL Hydrogen Technology for Railway Infrastructure **2019**.
10. Müller, A. Wissenschaftliche Bewertung von alternativen, emissionsarmen Antriebskonzepten für den bayerischen SPNV: Technische und wirtschaftliche Bewertung alternativer Antriebskonzepte **2017**.
11. Wittemann, N.T.; Meinelt, F. Bewertung von konventionellen und alternativen Antrieben für den Rheinland-Pfalz Takt 2030 unter besonderer Betrachtung des Pilotprojekts „Pfalznetz“: Alternative Antriebskonzepte Pfalznetz **2019**.
12. Frank, F.; Gnann, T. Alternative Antriebe im Schienenverkehr **2022**.
13. Austrian Standards. ÖNORM EN ISO 14040: Umweltmanagement - Ökobilanz - Grundsätze und Rahmenbedingungen **2021**, 34.
14. Austrian Standards. ÖNORM EN ISO 14044: Umweltmanagement - Ökobilanz - Anforderungen und Anleitungen **2021**, 68.
15. Merschak, S.; Hehenberger, P.; Bachler, J.; Kogler, A. Data Relevance and Sources for Carbon Footprint Calculation in Powertrain Production **2022**, doi:10.1007/978-3-030-62807-917.
16. Wong, E.Y.C.; Ho, D.C.K.; So, S.; Tsang, C.-W.; Chan, E.M.H. Life Cycle Assessment of Electric Vehicles and Hydrogen Fuel Cell Vehicles Using the GREET Model - A Comparative Study. *Sustainability* **2021**, *13*, 4872, doi:10.3390/su13094872.
17. Austrian Standards. ÖNORM M 7140: Betriebswirtschaftliche Vergleichsrechnung für Energiesysteme nach dynamischen Rechenmethoden **2021**, 35.
18. Konstantin, P.; Konstantin, M. *Praxisbuch Energiewirtschaft*: *Energieumwandlung, -transport und -beschaffung, Übertragungsnetzausbau und Kernenergieausstieg;* Springer Vieweg Berlin, Heidelberg: Berlin, Heidelberg, 2023.
19. Fielitz, U. Prognose des EZB-Leitzins für 2023, 2024, 2025 bis 2030. Available online: https://www.mehrwertsteuerrechner.de/notenbanken/ezb-leitzins/prognose/.
20. Statista. Prognosen zur Inflationsrate in Österreich bis 2028. Available online: https://de.statista.com/statistik/daten/studie/290144/umfrage/prognosen-zur-entwicklung-der-inflationsrate-in-oesterreich/.

21. ABB. Bordline Max 700-HP: High power battery for transportation. Available online: https://library.e.abb.com/public/69a1060b719249ad9769512ece0d6e77/ABB_BORDLINE%20Max%20700-HP_RevB.pdf?x-sign=LIYteSGJDi2Gw5HsafhppJ9LOrSK3tNoP7G8Ka2EjlZA5D+h3oDVqfRkQuQ5b11C.
22. Frontier Economics. Grundlage für die Positionierung zu Wasserstoff: Bericht für Österreichs Energie **2021**.
23. Waymann, N.; Heckmann, J.; Pyschny, H. Wirtschafsfaktor Ladeinfrastruktur **2021**.
24. Mottschall, M.; Bergmann, T. Treibhausgas-Emissionen durch Infrastruktur und Fahrzeuge des Straßen-, Schienen- und Luftverkehrs sowie der Binnenschifffahrt in Deutschland **2013**.
25. Schmied, M.; Mottschall, M. Treibhausgasemissionen durch die Schieneninfrastruktur und Schienenfahrzeuge in Deutschland **2010**.
26. Umweltbundesamt. Berechnung von Treibhausgas (THG)-Emissionen verschiedener Energieträger. Available online: https://secure.umweltbundesamt.at/co2mon/co2mon.html.
27. Statista. Durchschnittlicher Preis für einen Liter Diesel in Österreich 2023. Available online: https://de.statista.com/statistik/daten/studie/796450/umfrage/durchschnittlicher-preis-fuer-einen-liter-diesel-in-oesterreich/.
28. BMK. Energie in Österreich: Zahlen, Daten, Fakten **2023**.
29. VERBUND AG. Integrierter Geschäftsbericht **2022**.
30. BNETZA. Marktuntersuchung Eisenbahnen **2022**.
31. Bullmann, T.; Gollnick, C.; Schorpp, J.; Oswald, H. Wasserstoff: DIHK-Faktenpapier **2020**.
32. Tuchschmid, M.; Knörr, W.; Schacht, A.; Mottschall, M.; Schmied, M. Carbon Footprint and environmental impact of Railway Infrastructure **2011**.
33. Brunner, N.; Hofmann, I.; Koller, S.; Meusberger, M. Treibhausgasemissionen durch Schieneninfrastrukturbau: Ermittlung von Emissionskennwerten für die Bewertungsprozesse im Zuge der Erarbeitung des Zielnetzes 2040 **2022**.
34. Helms, H.; Fehrenbach, H.; Biemann, K.; Kämper, C.; Lambrecht, U.; Jöhrens, Julius, Meyer, Kerstin. Klimabilanz von strombasierten Antrieben und Kraftstoffen **2019**.
35. O'Connell, A.; Pavleno, N.; Bieker, G.; Searle, S. A Comparison of the Life-Cycle Greenhouse Gas Emissions of European Heavy-Duty Vehicles and Fuels **2023**.
36. Wietschel, M.; Moll Cornelius; Oberle, S.; Lux, B.; Timmerberg, S.; Neuling, U.; Kaltschmitt, M.; Ashley-Belbin, N. Klimabilanz, Kosten und Potenziale verschiedener Kraftstoffarten und Antriebssysteme für PKW und LKW **2019**.
37. Sternberg, A.; Hank, C.; Hebling, C. Treibhausgas-Emissionen für Batterie- und Brennstoffzellenfahrzeuge mit Reichweiten über 300 km **2019**.
38. Buberger, J.; Kersten, A.; Kuder, M.; Eckerle, R.; Weyh, T.; Thiringer, T. Total CO2-equivalent life-cycle emissions from commercially available passenger cars. *Renewable and Sustainable Energy Reviews* **2022**, *159*, 112158, doi:10.1016/j.rser.2022.112158.
39. Kawamoto, R.; Mochizuki, H.; Moriguchi, Y.; Nakano, T.; Motohashi, M.; Sakai, Y.; Inaba, A. Estimation of CO2 Emissions of Internal Combustion Engine Vehicle and Battery Electric Vehicle Using LCA. *Sustainability* **2019**, *11*, 2690, doi:10.3390/su11092690.

40. Fritz, D.; Heinfellner, H.; Lambert, S. Die Ökobilanz von schweren Nutzfahrzeugen und Bussen: Bewertung ausgesuchter Anwendungsfälle alternativer Antriebskonzepte hinsichtlich Reduktionspotenzial von CO2-Emissionen und Energieverbrauch **2022**.
41. Bekel, K.; Pauliuk, S. Prospective cost and environmental impact assessment of battery and fuel cell electric vehicles in Germany. *The International Journal of Life Cycle Assessment* **2019**, *24*, 2220–2237, doi:10.1007/s11367-019-01640-8.
42. Cihlar, J.; Villar, A.; Wang, A.; Melgar, F.; Jens, J.; Rio, P. *Hydrogen generation in Europe*: *Overview of costs and key benefits;* Publications Office of the European Union: Luxembourg, 2020.
43. Siegemund, S.; Trommler, M.; Kolb, O.; Zinnecker, V.; Schmidt, P.; Windorf, W.; Zittel, W.; Raksha, T.; Zerhusen, J. E-Fuels Study: The potential of electricity based fuels for low emission transport in the EU **2017**.
44. Fruhwirt, D.; Sturm, P.; Bucca, G.; Bode, G.; Michael, S.; Rodler, J. Emissions from railways: Results of tests on a pantograph-catenary test bench. *Transportation Research Part D: Transport and Environment* **2023**, *117*, 103667, doi:10.1016/j.trd.2023.103667.
45. Heldstab, J.; Kljun, N. PM10-EMISSIONEN VERKEHR: Teil Schienenverkehr **2007**.