Alternatives to diesel multiple units in regional passenger rail transport

Assessment of systemic potential

VDE

Study

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Frankfurt am Main

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Publisher:
VDE Verband der Elektrotechnik
Elektronik Informationstechnik e. V.

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Design:
Kerstin Gewalt | Medien&Räume

Cover photos:
WK / WK
Bombardier / Alstom

19 August 2019

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Germany has one of the densest railway networks in the world. Every day, thousands of trains are used to transport millions of passengers safely and reliably. Long-distance travellers take it for granted that their ICE is electric. Despite all the delays and technical problems which regularly occur, even railway sceptics have no doubt that rail travel is the most environmentally friendly mode of transport. At present, though, this does not necessarily apply to regional passenger transport, since electric multiple units can only be used on railway lines that are fully electrified. However, this is not the case in many regions.

Forty per cent of the German rail network is not electrified

There are many gaps in the network of overhead lines (or catenaries) spanning the rail network in Germany. In sparsely populated regions, local railway lines are often not electrified at all. In other parts of the country there are electrification gaps in the lines, some of which measuring just a few kilometres in length. Electric multiple units require continuous stretches of catenary wire. It would therefore make sense simply to close the gaps in the overhead lines. However, the expected high maintenance costs for overhead lines can only be met through high service frequencies and passenger traffic volumes on the railway line which are high enough to make them economically viable. In many cases, however, the gaps are to be found in regions with low traffic volumes.

Diesel multiple units operate on many electrified regional transport lines

The lack of suitable alternatives has so far resulted in diesel multiple units being operated on many regional transport lines in order to bridge any electrification gaps. This results in an absurd situation in which over a third of the train kilometres travelled in Germany are clocked up by diesel trains with frequently low transport performance levels (in passenger kilometres) due to insufficient passenger numbers. This compromises the railway's environmentally friendly reputation. A large proportion of the diesel multiple units used in Germany are now more than 20 years old. There are hardly any emission-related restrictions on their use.

Decarbonisation of transport prohibits new orders of diesel multiple units

The public decision makers responsible for soliciting and ordering railway line services are under pressure to find a rapid solution to the diesel problem in regional passenger rail transport (SPNV). The typical operating life of multiple units is 25 to 30 years. Any new units deployed in the coming years will therefore be in operation until 2050 at least. 2050 is also the year in which all transport in Germany is to be completely decarbonised. It therefore no longer makes sense to order new diesel multiple units. The supply market has already adapted: it is increasingly focusing on alternative types of drive.

The search for alternatives to diesel is a complex challenge

What are the best replacements for diesel multiple units? Working this out is proving to be a complex, fundamental challenge. Various industries and organisations are directly or indirectly involved in the decision-making process. In addition to public decision makers, railway undertakings and vehicle manufacturers, these include infrastructure and energy companies, as well as representatives from universities and various associations.

In the course of 2018, VDE conducted structured interviews with representatives of these different groups in order to identify the scope of the decision-making task, and possible solutions. The results and final conclusions are presented in this study.

The electric motor is the basis of all possible alternative drive concepts

Compact electric motors, which deliver their power directly to the wheel axles of a multiple unit, are more efficient, more robust, lighter and quieter than any combustion engine could ever be. They are completely emission-free and climate-neutral if green electricity is used. The most suitable alternative to the diesel engines in multiple units is therefore the electric motor – as it has long been used in conventional catenary multiple units.

Full electrification of regional passenger rail services would not be economically viable

Complete electrification of the regional rail network would be an obvious, energy-efficient way of solving the railway diesel problem. However, this option is not economically viable for many diesel railway lines due to the low traffic volumes; the construction and maintenance costs of the additional overhead line infrastructure are high and the prescribed planning approval procedure is time-consuming. In addition, the infrastructure construction companies are currently at their capacity limits. According to experts, even the significant increase in the degree of electrification by 2025 contained in the coalition agreement of the federal government will require significant acceleration of the planning and implementation.

Fully electric, catenary-independent multiple units represent an advantageous alternative

There are firm plans to close the electrification gaps on certain diesel railway lines with high traffic volumes. Decision-makers are also considering fully electric multiple-unit trains featuring direct axle electric motor drives with on-board energy supply. One solution is the battery electric multiple unit, in which a large lithium-ion battery provides the traction current and can be recharged from the overhead line. Another is the fuel cell multiple unit, in which the electrical energy is generated from controlled oxidation of the hydrogen gas carried on-board. The only exhaust gas produced here is pure water vapour.

Zero emissions and climate neutrality are key evaluation criteria for new drives

Neither battery electric nor fuel cell multiple units produce local pollutant emissions. Both concepts are only climate-neutral if the traction battery is charged using green electricity or the hydrogen fuel is produced electrolytically using green electricity. In addition, their individual infrastructure and energy generation and supply requirements need to be factored into their environmental compatibility assessment: fuel cell trains need hydrogen refuelling stations, which in turn require a functioning hydrogen production industry. Battery trains that draw their charging current from charging stations or overhead lines have a similar traction current climate footprint to electric multiple units.

Hybrid drives are favoured by some as lower-risk bridging solutions

Some decision-makers doubt the maturity or mass-production suitability of alternative drives, as little experience has yet been gained in actual operation. They prefer reliable solutions with lower emissions than diesel-mechanical drives which can at the same time bridge the gap until the new technologies are ready for series production. One possible solution is diesel hybrids which draw electricity from batteries or the overhead line on certain routes, thus allowing them to run electrically. However, such concepts are technically complex and expensive to implement in the vehicles. In view of the agreed decarbonisation of transport by 2050, this would represent costly investment in a temporary solution. Instead, tests are currently being carried out on different versions of converted diesel fleets.

Synthetic fuel only has limited suitability as a low-emission, climate-neutral alternative

The hybrid diesel multiple unit basically has the potential to be an alternative in the long term if fossil diesel is replaced by equivalent synthetic fuel produced using renewable energy and ‘green’ hydrogen. This would represent a climate-neutral solution in terms of its ecological footprint. With the technologies available today, however, so much energy is required for synthesis that the use of such fuel could ultimately only be justified for air transport. Moreover, it does not help to eliminate local emissions.

There is no “ideal alternative” to the use of diesel multiple units

Regardless of the industry of the interviewees, or their specific interests, they all agreed that there is not just one best alternative to the diesel multiple unit. This conclusion is also confirmed by a neutral benefit analysis which was carried out as part of this study with the support of the participants. One finding is that the search for a suitable alternative requires each individual diesel railway line to be analysed on a case-by-case basis.

Battery-powered multiple units can bridge overhead line gaps without precluding subsequent electrification

Battery-powered multiple units are the best solution on low-traffic railway lines with catenary gaps of no longer than 40 to 80 kilometres, provided that the battery can be recharged sufficiently quickly via the pantograph on electrified sections. In the case of larger gaps, electrification islands may also be justified if they can be used as the basis for future electrification expansion.

Fuel cell trains represent a long-term alternative to the electrification of extensive stretches of railway line

Fuel cell trains are the best solution on railway lines with no catenary at all or which have gaps of significantly more than 80 kilometres. This presupposes that a hydrogen refuelling station network can be established and that refuelling trips are no more costly than those of diesel. Experts believe that, assuming no change in the framework conditions, the hydrogen price would have to fall significantly below 5 euros per kilogram for fuel cell trains to become economically viable.

Catenary multiple units will continue to be the ideal solution for electrified rail networks in the future

It is assumed that alternative drives will only be used on railway lines with low passenger transport capacity levels. In other cases, comprehensive electrification and operation of the lines with catenary multiple units is generally economically viable.

The present planning approval procedure hampers the rapid electrification of lines

The transport transition requires the existing rail network to be used more intensively through denser timetable frequencies. Electrification is an important prerequisite for this. The current planning approval procedure for electrification, line expansion and line reactivation projects is still very time-consuming but is to be reduced to well under 4 years. The Transport Planning Acceleration Act, which is currently at the implementation stage, provides a solution here.

1 Introduction and Motivation

According to the coalition agreement of the Federal Government from March 2018, transport in Germany is to be completely decarbonised, i.e. made climate-neutral, by 2050 [1]. This objective cannot be achieved simply by shifting or avoiding transport, or by improving efficiency levels. Additionally, solutions are needed for vehicles, drives, fuels and infrastructure to ensure greenhouse gas neutrality. A report published by the Federal Environment Agency in 2015 [2] states: Electrified railways powered by renewable energy represent a means of transport with a climate-neutral option at its disposal that only needs to be implemented. Yet electrification projects for regional passenger rail transport are by no means easy to implement. Here, as in road transport, battery or fuel cell-based drives represent workable alternatives.

Around half of the 5,100 passenger trains currently used in local transport run on diesel. Of these, about two-thirds are more than 20 years old. In road traffic, they would already be banned because of their fine particulate and NO_x emissions. Multiple units have a typical operating life of between 25 and 30 years, meaning that the purchase of new vehicles as replacements for old diesel units will also be included in future tendering procedures for regional passenger railway lines.

The regionalisation of the regional passenger rail system in the mid-1990s saw the establishment of a structure of responsibilities which has proved effective: the public decision makers appoint railway undertakings (EVUs) to operate the regional passenger railway lines within their area of responsibility. These EVUs have to compete with rivals from all over Europe in the tendering process.

In the past, EVUs bought or rented the required multiple units themselves. In most cases they ensured the availability of their vehicles by maintaining themin their own workshops. The introduction of EU Regulation 445/2011 made it mandatory for each multiple unit to be assigned an official maintenance entity (Entity in Charge of Maintenance, ECM). This can be operated by transport companies, vehicle manufacturers or other companies.

1.1 Problem

As a transport contractor, the public decision maker acts in the public interest to ensure that the passengers are offered an adequate timetable service (“Daseinsvorsorge” – provision of basic services). In addition, it is expected to provide the framework conditions which offer the most energy-efficient and environmentally friendly local transport possible. The EVU undertakes to ensure the safe and trouble-free yet cost-effective operation of the railway lines assigned to it in accordance with the specifications of the public decision maker. The proven electric and diesel multiple unit models of the vehicle manufacturers, which are in strong competition with each other, have so far been able to perform this task effectively.

The situation has now become more complicated, however. The acquisition of new diesel multiple units is not only critical because of the diesel problem. Only a few models are available nowadays on the vehicle market. Even companies which specialise in train rental no longer offer diesel multiple units. Instead, all vehicle manufacturers are now promoting electric multiple units which draw their drive energy from batteries or fuel cells, i.e. run with practically no need for overhead lines, and can thus replace diesel multiple units.

As attractive as alternative drives may be technologically, they also represent a considerable challenge for established decision-making structures. Any decision in favour of an alternative requires a comprehensive understanding of the technical characteristics and requirements in terms of vehicle operation and maintenance, and not least their infrastructural prerequisites. Ultimately, neither the public decision makers nor the EVUs have the depth of knowledge required to make a full assessment of the alternatives. And the manufacturers have not yet received sufficient feedback on the maturity of their vehicles in regular operation.

It is still unusual for public decision makers and railway undertakings to regard manufacturers as anything more than vehicle suppliers. New relationships are increasingly being established between customers, operators and manufacturers in regional passenger rail transport, as shown by the availability model established in NRW as part of the major Rhine-Ruhr-Express (RRX) transport and infrastructure project. In this concept, also known as the lifetime model, the manufacturer is not only responsible for delivering the vehicles, but also for maintaining them and ensuring their operational availability over 32 years. In operating the RRX lines assigned to them, the participating EVUs primarily perform a carrier function, i.e. they provide considerably less added value than they did in the previous situation. In return, the public decision maker, as manager and investor in this triangular relationship, assumes a considerable degree of responsibility for the associated risks. Not every public decision maker is fully able or willing to bear such a high and risk-laden responsibility, either technically or in terms of personnel.

A further challenge for all parties involved is that it would actually make sense to electrify some local railway lines previously served by diesel multiple units. It is difficult to achieve rapid results since electrification is usually decided at the federal level and corresponding projects must be taken into account in the Federal Transport Infrastructure Plan (BVWP). Even if all parties involved agree that a line should be electrified, the prescribed planning approval procedure and the resources of the infrastructure construction companies (which are currently very limited) prove to be major obstacles in terms of time and cost. According to DB Netz AG, the electrification of some key lines in Bavaria, for instance, could take up to 20 years, as each line must continue to be operated during the construction period.

1.2 BMVI funding project

→ Figure 1 served as the basis for discussions which the VDE[1] conducted in 27 consecutive one to two-hour interviews with representatives of organisations and sectors directly or indirectly involved in the field of regional passenger railways, see → Table 1.

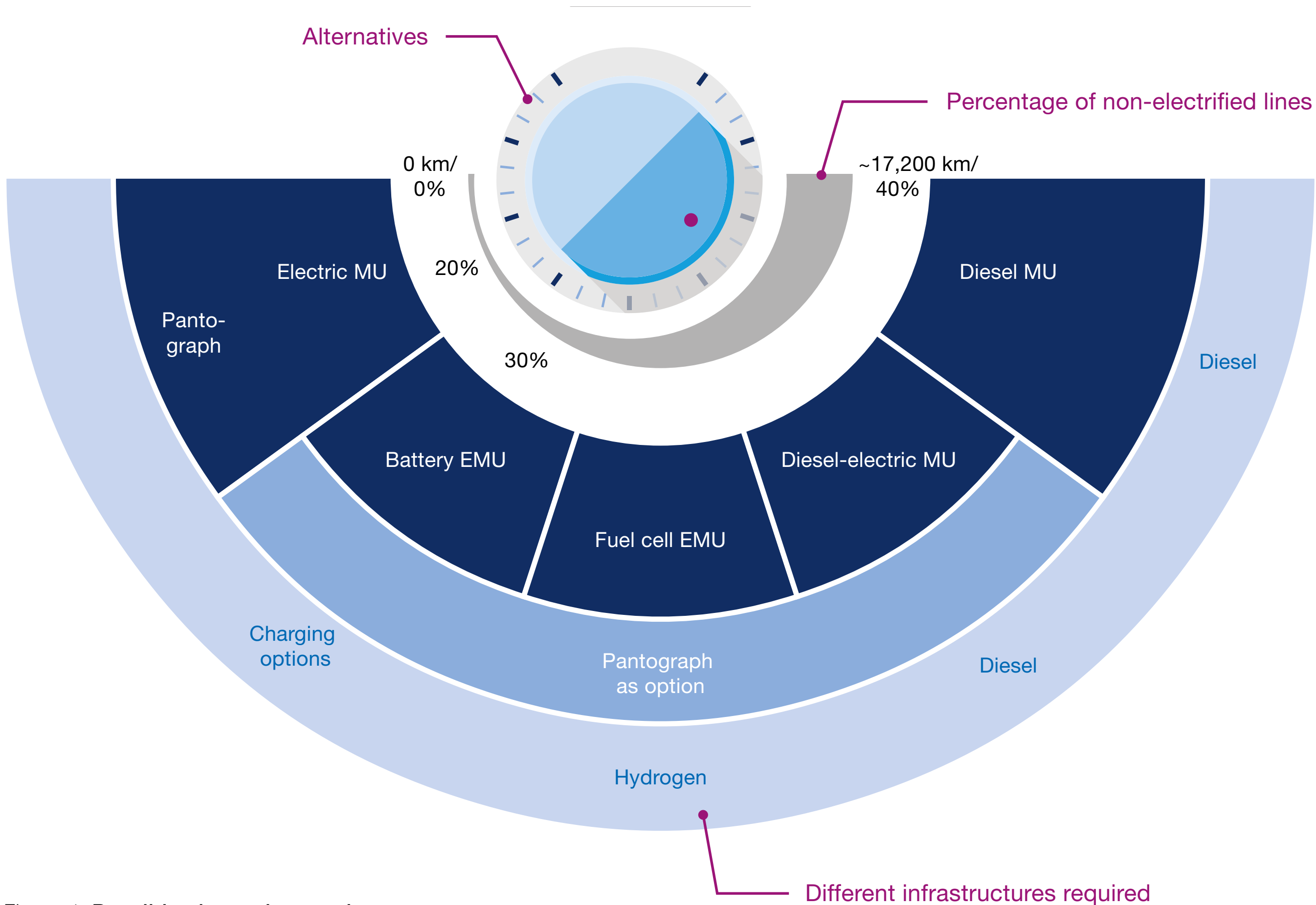


Figure 1 **Possible alternatives to the use of diesel multiple units in regional passenger rail transport**

1 Verband der Elektrotechnik Elektronik Informationstechnik e.V.; https://www.vde.com/

Public authority	EVU	Mainten-ance	Manufacturer	Infra-structure	Energy	Organisation/ University
BEG **LNVG** **NAH.SH** **NVR** **NWL- ZVM** **RMV/Fahma** **VBB** **VMS** **VRR** **VVO**	**Agilis**	Agilis				**Allianz pro Schiene** **BAG-SPNV** **DLR** **HTW** **TU Berlin** **TU Dresden** **VDV**
	DB Regio	**DB Regio**		**DB Netz**	**DB Energie**	
	BeNEX	BeNEX				
		Alstom	**Alstom**			
		Bombardier	**Bombardier**			
	NEB	NEB		**NEB**		
	SWEG	SWEG		**SWEG**		
		Siemens Mobility	**Siemens Mobility**			
		Stadler	**Stadler**			

Table 1 **Overview of the industries and organisations interviewed (bold = primary function of the interviewee)**

The result is a wide range of views, criticisms, expectations and recommendations from different perspectives. The authors have incorporated these in the various chapters of this study. It was agreed with the interviewees that no statements given on particular topics and issues would be assigned to an individual. All participants agreed to have their name and organisation or company disclosed. The alphabetical list can be found in → Annex 7.1.

The project: The VDE is aiding the “X-EMU” development project of Siemens Mobility GmbH, funded by the Federal Ministry of Transport and Digital Infrastructure (BMVI), by providing analyses and studies on various systemic aspects of technical, economic or social relevance that could influence the realisation of multiple units with alternative, emission-free drives. The present study is the result of the second part of a subproject subcontracted to the VDE [3].

1.3 Purpose and structure of the study

Aspects relating to the technological characteristics of the concepts in question and their technical implementation need to be taken into account in the search for suitable alternatives to the use of diesel multiple units in regional passenger rail transport. However, the different infrastructural requirements must also be compared with each other. Resource availability, environmental compatibility and systemic benefit are important aspects in the overall objective comparison, as are cost-effectiveness and operational friendliness.

In preparing the study, the authors conducted extensive online research and analysed the available publications on all relevant aspects. Based on this, they then held talks with a total of 38 people from the railway sector in order to obtain their individual assessments and to ascertain the extent to which their industry is affected by the various aspects. The results are featured in this study.

Chapter 2 first looks at the historical decisions made in the decade following reunification and at the legal foundations that determined the current structure of the regional passenger railway system. Special focus is placed on the role of the organisations and companies directly or indirectly involved in the regional passenger rail system in the search for alternative solutions to diesel multiple units. In particular, financing by the Federal Government and the role of state-owned companies are examined.

Chapter 3 looks at the possibilities of electrifying rail lines as an alternative to today's diesel networks. Electric drives in the form of energy-efficient and environmentally friendly solutions which do away with the need for electrification are described in **Chapter 4**. The main focus here is on their technological characteristics and their implementation in vehicles and infrastructure, to the extent that this is necessary for an understanding of them. Various vehicle models from the relevant manufacturers are taken as examples.

The discussions with the interested parties revealed that the process of choosing an alternative to diesel trains is complex and is also influenced by individual preferences. For this reason, the authors applied a method known as benefit analysis in order to facilitate objective decision-making. They used a set of criteria already introduced in [4]. Publicly available data based on these criteria had already been used to evaluate the properties of the various concepts and to carry out an initial benefit analysis. For the present study, the authors reviewed the evaluation data from [4] and compared it with the statements given by the experts. At a workshop with the interview participants, the weightings of all criteria in the decision-making process were recorded in order to improve the benefit analysis on the basis of the revised evaluation data.

Chapter 5 describes the application of this benefit analysis and examines in detail the resulting potential of the various alternatives.

Chapter 6 brings the study to a close with a summary, supplemented by recommendations for further action in the search for alternatives to existing diesel railway lines in regional passenger rail transport.

2 Challenges of regional rail passenger transport

The rapidly growing levels of car and HGV traffic on the roads since the 1950s have eroded the importance of the railway as a mode of transport for passengers and goods. Since the reunification of Germany, the network of federal trunk roads has expanded continuously to its total length of 51,000 kilometres today. The motorway network has grown by 24 per cent to 13,000 kilometres [5]. The extent to which the government neglected the rail transport system is evident from the fact that the rail network shrank by 14 per cent over the same period, from 44,000 kilometres to 38,500 kilometres today (incl. non-federally-owned lines), as a result of decommissioning[2]. According to Allianz pro Schiene (Pro-Rail Alliance) [6], the share of rail passenger transport in 2016, at 96 billion passenger-kilometres (pkm), was only about 8.3 per cent of the total transport capacity, in comparison with 83.8 per cent accounted for by private motorised transport.

2.1 Reform of regional rail passenger transport

Following German reunification in 1990, the highly indebted Deutsche Bundesbahn of West Germany inherited the GDR's Deutsche Reichsbahn, which had a huge investment backlog at that time. The Railway Restructuring Act, which came into force in 1994, brought about both legal and organisational restructuring of the two official railways. This federal resolution, which has since gone down in history as a reform of the railways, saw the Deutsche Bundesbahn and the Deutsche Reichsbahn merge in 1994 to form Deutsche Bahn AG, the privately-organised railway company of the Federation.

Responsibility for urban, suburban and regional transport, referred to collectively as regional passenger rail transport,[3] was transferred from the Federation to the federal states. A central component of the railway reform was the opening up of the railways and the granting of non-discriminatory access to the rail network for railway undertakings (EVUs) in order to reduce the costs of the rail system through competition. In 1996, the Regionalisation Act also transferred the financial responsibility for the regional passenger rail service to the 16 federal states. In order to implement this operationally, some states such as Lower Saxony, Schleswig-Holstein and Bavaria founded regional public transport companies organised under private law. Others, such as North Rhine-Westphalia, Hesse or Saxony, transferred their competence to local authority associations or transport associations. Maintenance and financing of the rail infrastructure and the stations remained the responsibility of the federal government and are now taken care of by the federal company DB Netze.

Competition introduced by the railway reform led to an improvement in the quality of the regional passenger rail service, which includes all Interregio-Express (IRE), Regional-Express (RE), Regionalbahn (RB) and S-Bahn lines. The passenger transport capacity [4] increased by 88% between 1994 and 2017 to 57 billion pkm, the operating capacity[5] by 35% to 673 million train kilometres. The capacity utilisation of the railway lines thus increased by 50%. It is assumed that regional passenger rail transport will continue to grow in importance in the coming decades [7].

2.2 Decarbonisation of transport

Germany's 2050 Climate Protection Plan in response to the climate protection agreement reached in Paris in 2015 includes a voluntary commitment to achieve at least an 80 per cent reduction in CO_2 emissions by 2050. In the transport sector, this goal can only be met if combustion engines can be consistently replaced by motors powered by electricity from renewable energy sources instead of fossil fuels. The necessary transition in the automotive sector has been somewhat sluggish to date, however the rail sector is much further advanced: the standard drive concept here has long been the electric motor powered by traction current drawn from an overhead line. It is therefore not surprising that politicians are now refocusing on the railway as an environmentally friendly mode of transport. In the coalition agreement of the Federal Government from March 2018, it was agreed to achieve CO_2-free mobility, i.e. the complete decarbonisation of transport, by 2050. Transport is thus to be shifted to other, more environmentally and climate-friendly modes, preferably to rail.

2 NE stands for "nichtbundeseigene Eisenbahn" (non-federally owned railway)

3 See General Railway Act (AEG) §2 Para. 12

4 Number of passengers × average distance travelled, usually in relation to one year [passenger-kilometres = pkm]

5 Number of trains × average distance travelled, usually in relation to one year [train kilometres = tkm]

The prerequisites for this now need to be put in place:

- Doubling the capacity of the rail network by 2030,
- Raising the level of German rail network electrification to 70% by 2025,
- Increasing the electrically-driven transport capacity of the regional passenger rail service to 90% by 2025,
- Putting no diesel multiple units or diesel locomotives into service after 2025.

2.3 Public decision makers as visionary purchasers

Devolution of the responsibility for regional passenger rail transport also changed the relationship between the regional government level (public decision makers) and the railway undertakings (EVUs). A “customer-supplier system” was introduced in which the public decision maker determines the scope of the regional rail transport service on behalf of its federal state. It places orders with one or more EVUs as “suppliers” following a (generally) public tendering process.

The revenue from ticket sales alone would not be sufficient to finance the entire regional rail transport system. For this reason, since 1996 the Federal Government has made so-called regionalisation funds available to the federal states each year. These amounted to around EUR 8.4 billion in 2018 and are shared out among the “Länder” based on a fixed distribution ratio. The total amount is increased annually by 1.8%. The most densely populated federal state, NRW, and Bavaria as one of the largest, for example, currently receive in excess of EUR 1 billion. The eastern German Länder also receive additional regionalisation funds. These funds (so-called “concession fees”) are used for the purchase of train services, investments in rail infrastructure and the purchase of new rolling stock.

The strategic orientation of the 27 public decision makers acting on behalf of their Länder (→ Figure 2) is the responsibility of the Federal Government and the relevant ministries. These targets include mobility, environmental and climate objectives, and implementation of the measures necessary to achieve these objectives by the public decision makers and EVUs. The search for alternatives to diesel multiple units is making the preparation of new transport contracts considerably more difficult than before. When ordering transport services, the authorities previously left it to the relevant railway undertakings to procure new rolling stock, the availability and maintenance of which caused few problems in the case of conventional drives.

The prestige Rhein-Ruhr-Express (RRX) project in North Rhine-Westphalia, in which five different public decision makers are involved, is a prime example of the complex range of responsibilities falling to public decision makers today. In addition to the responsible transport association Rhein-Ruhr (VRR), these five authorities are the local transport associations Rheinland (NVR) and Westfalen-Lippe (NWL), as well as SPNV-Nord of Rheinland-Pfalz and NVV of Nordhessen. The RRX is intended to improve regional transport by providing more frequent services and increased transport capacities on core routes in densely populated North Rhine-Westphalia. The operating capacity of 14.6 million train-kilometres per year to be distributed across the new RRX lines was awarded to the international transport companies Abellio and National Express following a Europe-wide tendering process for the transport contracts.

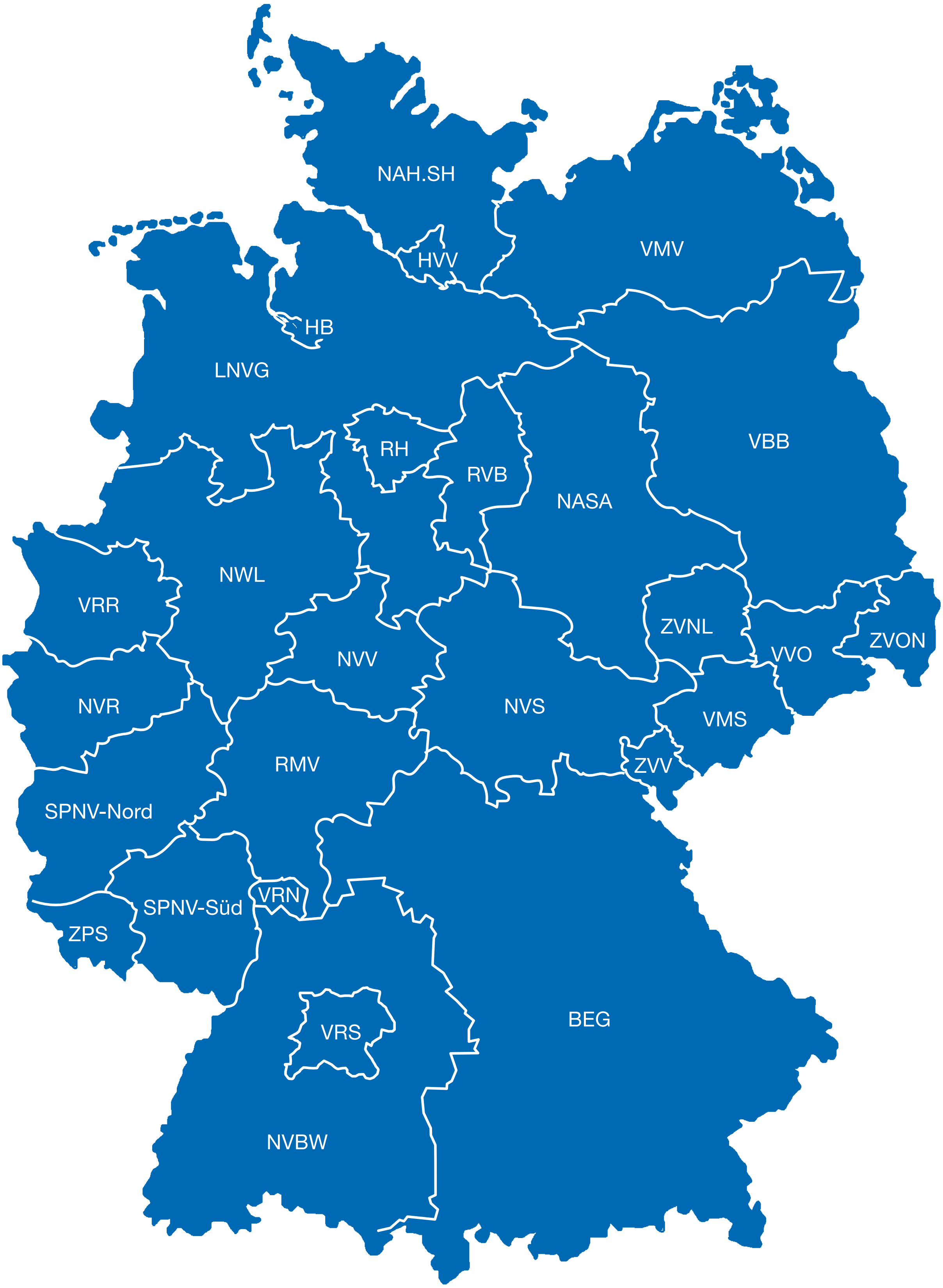


Figure 2 **The public decision makers in Germany [8]**

Many of the RRX lines are already electrified and carry dense traffic. The rail infrastructure needs to be expanded at various points, however, as the trains are now expected to run at higher speeds. The required high-performance electric multiple units with increased passenger capacity were put out to tender throughout Europe.

Figure 3 **RRX double-decker electric multiple unit Desiro HC in Hamm (photo: WK)**

The winner of the contract was Siemens Mobility with its four-car Desiro HC (High Capacity) double-decker electric multiple-unit train, a total of 82 of which are to be delivered by 2020. The first RRX trains began running in December 2018 as the Rhein-Hellweg-Express on the RE 11 line between Düsseldorf and Kassel-Wilhelmshöhe – see also → Figure 3.

The RRX trains have been purchased by the participating transport associations. They lease the trains to the two EVUs. The manufacturer Siemens Mobility has undertaken to maintain the vehicles for 32 years. It has set up its own facility in Dortmund for this purpose and guarantees 99 per cent availability.

This concept, known as the availability model, is now also stipulated by public decision makers in tendering processes for the purchase of multiple units with alternative drives. In contrast to the RRX case, the technologies behind the new drives and their interaction with other vehicle components, as well as the way in which the drive energy is delivered, have not yet been tested. Innovative drive concepts for railways can therefore carry considerable economic risks, which smaller railway undertakings in particular can scarcely be expected to shoulder. Thus, the public decision makers have no choice but to purchase the vehicles themselves and lease them to theEVUs. The public decision makers feel justified in leaving the long-term maintenance of their vehicles to the manufacturers and, in the case of fuel cell trains, also in requiring them to provide the hydrogen fuel. It is unclear what will happen in cases where hydrogen refuelling stations are also to be used by vehicles of other manufacturers.

2.4 “Carrier-only” railway undertakings?

One reason for opening up the railways to more competition in regional passenger rail transport was to keep the costs of rail operations as low as possible. DB Regio AG, which was founded in 1999 as a wholly-owned subsidiary of Deutsche Bahn AG, still dominates the local transport market as a rail transport company with a current market share of 67%. As a result of its historical monopoly, it operates its own fleet of vehicles and also takes care of vehicle maintenance in its workshops. Some public decision makers believe that, in this constellation, DB Regio is too inflexible and costly to cope with the significant increase in operating and transport capacity expected in the regional passenger rail system. They would prefer companies that are more flexible and that can focus on their actual role as carriers and offer this service at a lower cost.

Many smaller railway undertakings currently operate diesel railway lines in more remote areas. How such lines are operated can be illustrated by an example: In October 2008, Bayerische Eisenbahngesellschaft (BEG) awarded the Hamburg-based holding company BeNEX the contract for the Upper Franconia diesel network. BeNEX then founded Agilis Verkehrsgesellschaft, which has been operating the diesel network with 38 Regio-Shuttle RS1 diesel multiple units since June 2011. → Figures 4 and 5

Figure 4 **Diesel network Upper Franconia and electrified network Franconia (2011) [9]**

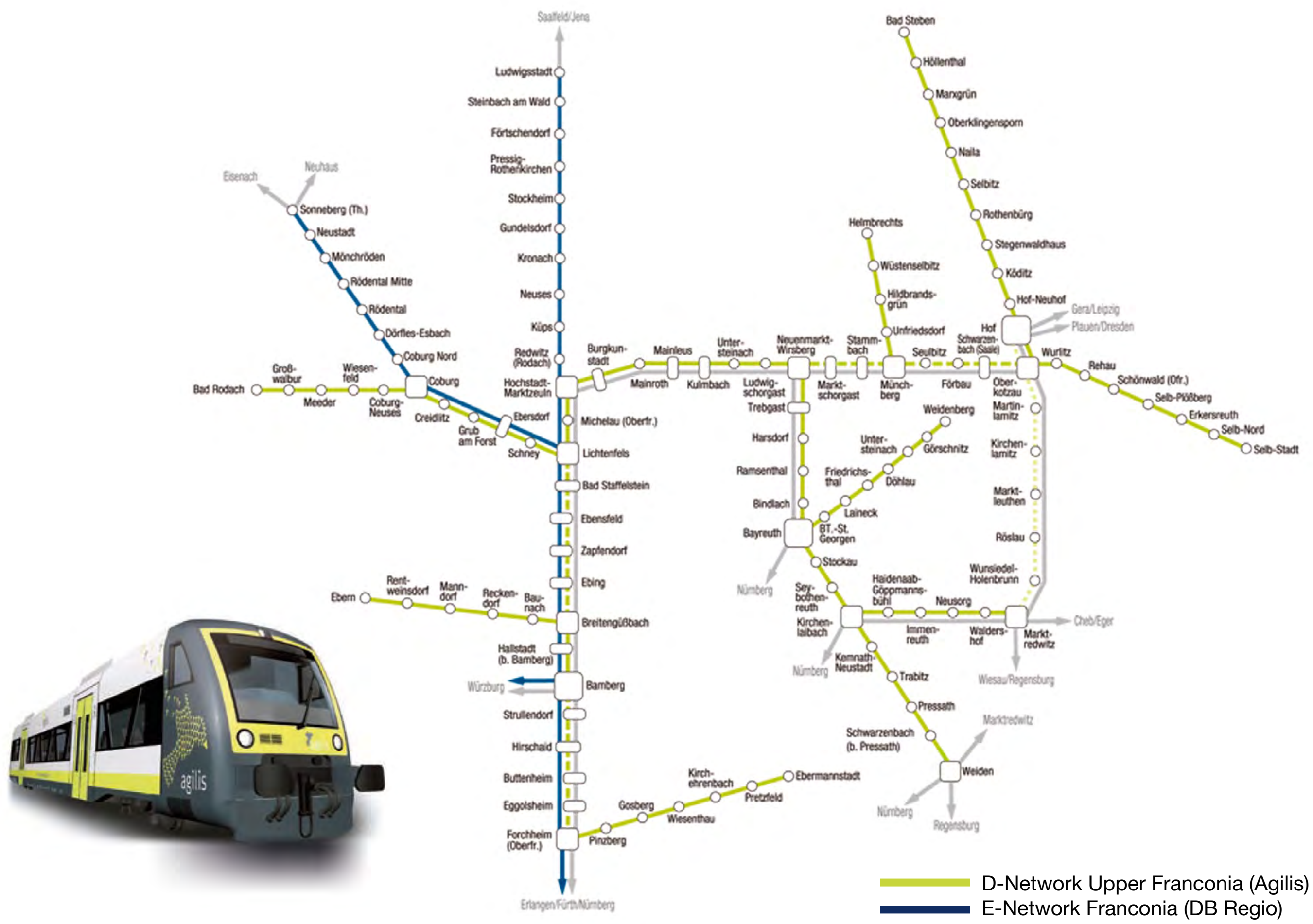


Figure 5 **Regio Shuttle RS1 of DB Regio in operation at Lake Constance (photo: WK)**

Agilis-V serves the 102 stops of the Upper Franconia diesel network, distributed over a track length of 429 km with the type RS1 diesel vehicle, which is valued by passengers and operators alike for its superior running dynamics. It thus delivers the 4.5 million train kilometre operating capacity commissioned by BEG. Continuous hourly cycles are run on almost all routes. The vehicle workshop for the network is located in Marktredwitz. The owner of the diesel multiple units is BeNEX GmbH, which takes care of their provision, planning and maintenance. Maintenance is carried out in its own workshops. In this constellation, Agilis is certainly not a pure carrier, but has a similar role to that of DB Regio.

DB Regio, with a turnover of EUR 6.4 billion and 22,000 employees, has lost a handful of regional networks, such as the diesel network in Upper Franconia, to smaller EVUs such as Agilis-V in recent years. The company was particularly affected by losing out in the prestigious RRX project in North Rhine-Westphalia, where the companies Abellio and National Express, which acted as 'pure carriers', were awarded the contract.

Despite all the criticism of DB Regio, it should not be overlooked that this company has far more possibilities and experience than its competitors (which are generally less well capitalised) when it comes to specifying the precise requirements for vehicles with alternative drive systems, running such vehicles and keeping them maintained.

DB Regio is keen to demonstrate its effectiveness in the EcoTrain project sponsored by the BMVI. The background to this is that DB Regio currently operates around 1,300 (more than half of all) diesel multiple units in its regional passenger rail service. The majority of these are relatively new and will therefore continue to be in use for a long time [10]. The intention is to convert part of this fleet into diesel-electric hybrids. These are to run on a combination of diesel and electricity, with reduced diesel consumption on lines without an overhead line and electrically from the catenary on overhead line sections. The option of obtaining the required energy from a large lithium-ion battery at stops with no overhead line should be included. See → Figure 6.

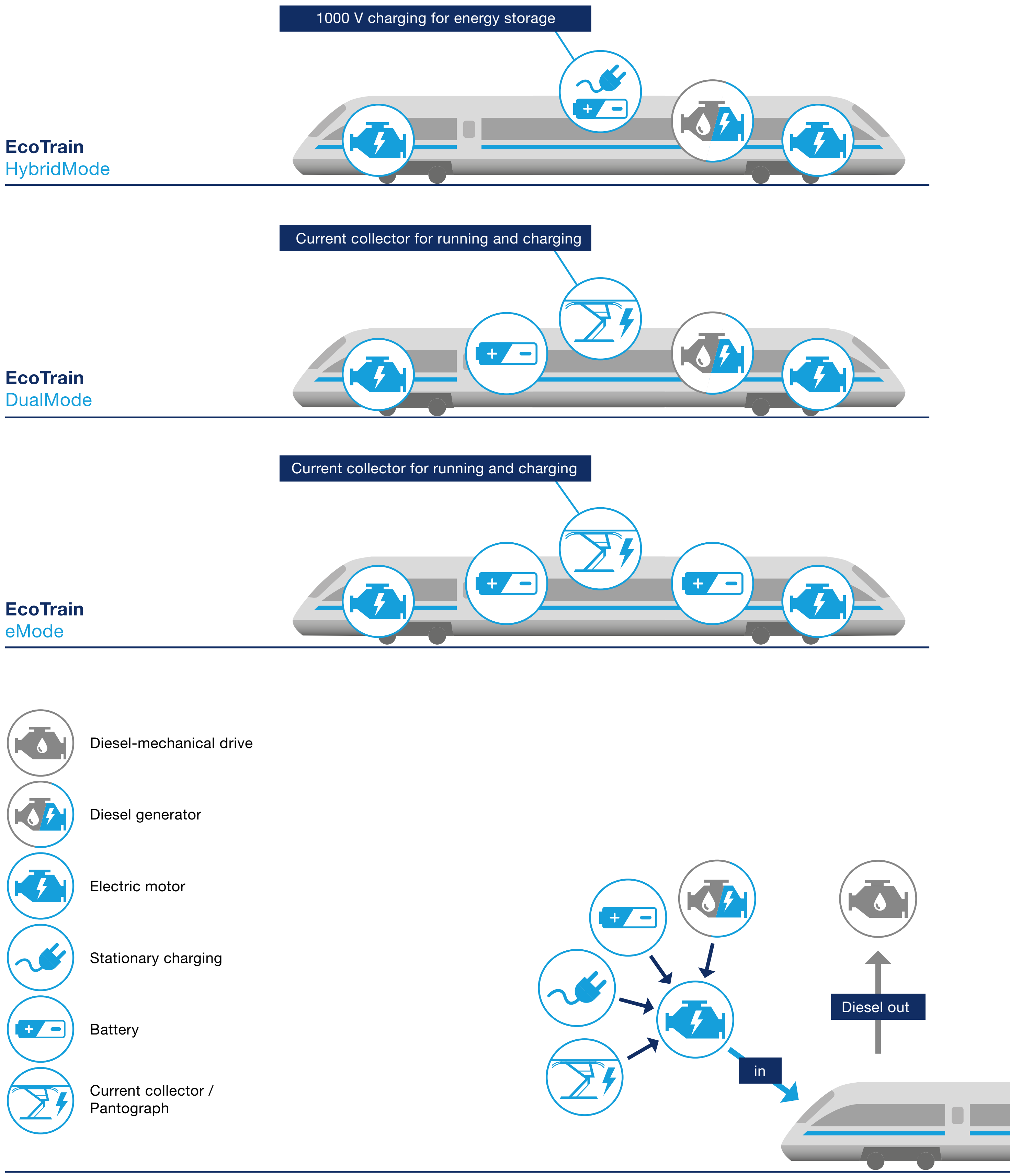


Figure 6 **DB Regio's EcoTrain concept [as shown in 10]**

2.5 Manufacturers as innovators and maintenance providers

The Germany-based manufacturers also enjoy success internationally. They are described below in alphabetical order and their portfolios are outlined in brief.

ALSTOM

The French company Alstom (turnover: EUR 7.9 billion) trades in Germany as Alstom Transport Deutschland GmbH (turnover: EUR 400 million). It is based in Salzgitter, the site of the former Linke-Hofmann-Busch GmbH (LHB), which was absorbed into the Alstom group in 1998.

Coradia LINT is the Alstom family of diesel multiple units, available in four different lengths: one, two and three carriages (LINT 27, 41, 54, 81). A total of 750 LINT trains are in service in the German rail network. (→ Figure 7)

Coradia Continental is the name of the Alstom family of electric multiple units. The 1440 series of this vehicle type is used as S-Bahn trains in various regions. (→ Figure 8)

In Braunschweig, Alstom maintains and modernises commuter trains (→ Figure 9) – including models made by other manufacturers. Verkehrsverbund Mittelsachsen (VMS) purchased 29 Coradia Continental electric multiple units for the Central Saxony electrified network, made them available to the operator Transdev in 2016 and entrusted Alstom with lifelong maintenance of the vehicles.

Figure 7 **Alstom Coradia LINT 54 diesel multiple unit from NWB**

Figure 8 **Alstom Coradia Continental electric multiple unit of operator HLB (photo: WK)**

Figure 9 **Alstom service facility for passenger multiple units and electric locomotives in Braunschweig [12]**

Despite all the concerns surrounding diesel engines, Alstom diesel multiple units are still very much in demand. As the operator of the Augsburg II diesel network commissioned by BEG, Bayerische Regiobahn recently acquired 28 new LINT 41 diesel vehicles. These will be used on three railway lines in Upper Bavaria and Swabia from the end of 2022 [12].

Figure 10 **Alstom Coradia iLINT fuel cell multiple unit (Photo: Alstom)**

Vehicles with alternative drive systems were evidently ruled out here, although Alstom now also offers multiple units with fuel cell drives. This train type is based on the LINT platform and is marketed under the model name **Coradia iLINT** (→ Figure 10). Alstom developed this train at its Salzgitter site in Germany with BMVI subsidies in order to offer its customers a long-term alternative that matches the operating performance of diesel multiple units in terms of range and seating capacity. Alstom also offers vehicle maintenance and servicing for this type of train.

Alstom unveiled its fuel cell multiple unit at InnoTrans 2016 in Berlin, where it received initial letters of intent (LoIs) from various public decision makers. The Coradia iLINT was tested with passengers on the route between Buxtehude and Bremerhaven at the beginning of 2018 and received approval from the Federal Railway Authority in July 2018 [13]. Subsequent operational tests have been carried out here on two pre-series vehicles since the end of 2018.

Despite the positive media response, customers have so far been reluctant to place orders. Upcoming calls for transport service proposals will not specify the type of alternative drive technology, as doubts remain about the future economic viability of the fuel cell-based multiple unit concept. It is also expected that Alstom, as the only supplier of an officially approved fuel cell train to date, will provide the necessary hydrogen gas.

BOMBARDIER

The Canadian company Bombardier Transportation (turnover: USD 16.3 billion) is headquartered in Berlin, Germany, and trades under the name Bombardier Transportation GmbH (turnover: USD 10 billion). The production site is in Hennigsdorf, the location of the former largest plant of Daimler-Chrysler Rail Systems (ADtranz), which was taken over by Bombardier.

Figure 11 **Bombardier TALENT diesel multiple unit of operator NEB [14]**

Figure 12 **TALENT 2 electric multiple unit of operator National Express (photo: WK)**

TALENT is the Bombardier family of diesel multiple-unit trains, available in two, three and four carriage versions. Just under 800 trains of this type are in service in the German rail network. (→ Figure 11)

TALENT 2 is the name of the Bombardier family of electric multiple units. 440 trains of this type are in service in Germany. (→ Figure 12)

Figure 13 **Bombardier TALENT 3 battery-powered multiple unit (Photo: Bombardier)**

Since 2004, Bayerische Oberlandbahn (BOB) has been using three three-carriage TALENT diesel multiple units to support its service during rush hours. BOB ordered six more multiple units for the 2013 timetable change. Vehicles with emission-free drive technologies were not available at that time. In the meantime, Bombardier has used BMVI subsidies to develop a battery-powered multiple unit at its Hennigsdorf plant which is based on the TALENT 3 electric MU platform and is sold under the model name **TALENT 3** BEMU. (→ Figure 13)

Bombardier unveiled the BEMU to the public at its factory premises in Hennigsdorf in 2018 to coincide with the InnoTrans in Berlin. For technical reasons this vehicle type has a limited range compared to diesel or fuel cell trains, yet the BEMU attracted positive media interest.

Even in the case of the battery-powered multiple unit, customers are still holding back. Current transport bidding processes do not commit themselves to a particular type of technology, revealing the uncertainty that still exists among decision-makers with regard to battery or fuel cell trains.

SIEMENS

Mobility GmbH

The Mobility division of Siemens AG (turnover: EUR 8.8 billion) was spun off from the Group as Siemens Mobility GmbH in August 2018 in preparation for the planned merger with Alstom. At the beginning of 2019, however, the merger was ruled out by the EU.

Desiro Classic is a two-carriage diesel multiple unit from the Siemens Desiro family, manufactured by Siemens Mobility. 320 trains of this type are in service in the German rail network. (→ Figure 14)

Desiro ML is the electric multiple unit of the Desiro family; its successor is the Mireo, which was presented in 2018. **Desiro HC** is the double-decker electric multiple unit of the Desiro family. (→ Figure 15; see also → Figure 3)

The Desiro Classic diesel multiple-unit is still in frequent use in Germany, but is no longer in production. DB Regio could revamp its existing Desiro-Classic fleet by upgrading its multiple units to diesel-electric hybrids in the EcoTrain project.

Figure 14 **Siemens Desiro Classic diesel multiple unit of operator DB Regio (photo: WK)**

Figure 15 **Desiro ML electric multiple unit (CityJet for ÖBB) at InnoTrans 2016 [15]**

Figure 16 **Battery CityJet-Eco multiple unit from Siemens/ÖBB, variant of Desiro-ML [16]**

Figure 17 **Mireo platform from Siemens Mobility (computer graphics) [17]**

With the support of the ÖBB (Austrian Federal Railways), Siemens Mobility successfully launched its Desiro ML-based battery train prototype (CityJet Eco). This vehicle will go into passenger service in the ÖBB transport network from summer 2019. (→ Figure 16)

In 2018, Siemens Mobility launched a modular traction platform based on Mireo (→ Figure 17) for the development of vehicles with alternative drive technologies. Siemens Mobility is developing a fuel cell train (Mireo Plus H) as part of a BMVI-funded project. Siemens has launched an independent project to develop a battery-driven multiple unit (Mireo Plus B) on this platform.

STADLER Rail AG / Pankow GmbH

Stadler Rail AG (turnover: CHF 2.2 billion) trades in Germany as Stadler Pankow GmbH (turnover: EUR 300 million) on the site of the former Adtranz plant where the well-known **Regio-Shuttle RS1** was developed and manufactured. This successful diesel multiple unit was taken over by Stadler (→ Figure 5 in 2.4) and, thanks to its “over-motorisation”, is still used today on highly frequented lines with no continuous overhead line. A total of almost 500 vehicles of this type are in operation.

The **Diesel GTW** is a two-carriage diesel-electric multiple unit which was created in a consortium together with Adtranz and Bombardier for Hessische Landesbahn and Usedomer Bäderbahn. (→ Figure 18)

FLIRT is a four-carriage electric multiple unit which enjoyed its first success in Germany; almost 1,700 units have since been sold worldwide. (→ Figure 19)

Figure 18 **Stadler Diesel GTW 2/6 of operator Usedomer Bäderbahn [18]**

Figure 19 **Stadler FLIRT electric multiple unit of operator Eurobahn (photo: WK)**

Figure 20 **Stadler battery-powered multiple unit FLIRT 3-AKKU (photo: Stadler)**

Figure 21 **Narrow-gauge fuel cell multiple unit for Zillertal (computer graphics) [20]**

In a project privately funded by the Stadler family, Stadler developed the AKKU-FLIRT, a battery-powered multiple unit based on the **FLIRT 3** generation, in a relatively short time. (→ Figure 20)

In May 2018, the Austrian narrow-gauge railway operator Zillertalbahn placed an order with Stadler Rail for five fuel cell multiple units. These are scheduled to go into service from 2022. [19] → Figure 21 shows a representation of the design study.

2.6 DB-Netze – a "bound" federal enterprise

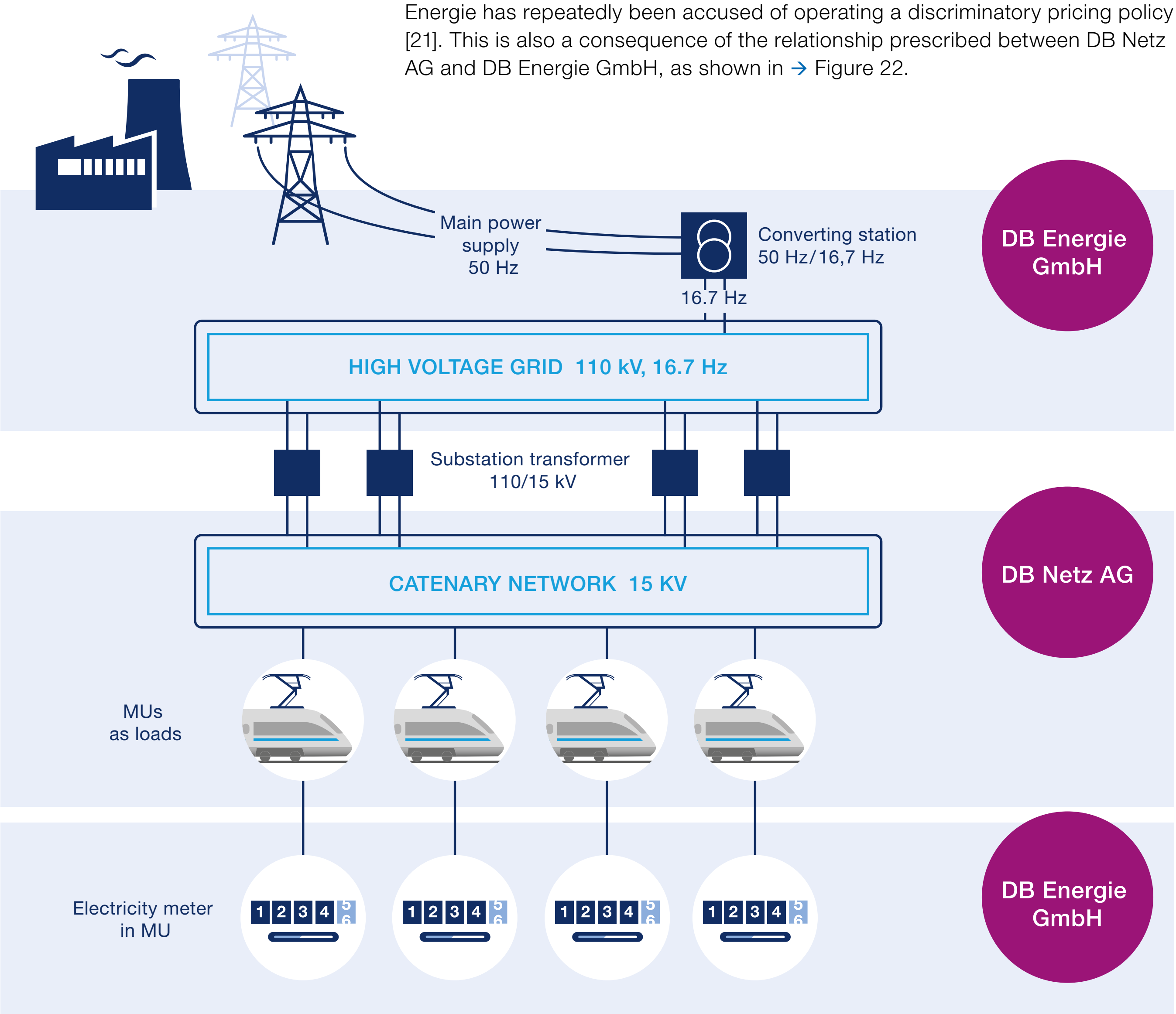
The federal-owned enterprise Deutsche Bahn AG is both a multitude of railway undertakings (EVU) which have long-distance and local passenger transport and also rail freight transport as its key business fields. So far, Deutsche Bahn has only been exposed to free competition in the local transport sector.

Figure 22 **Interaction within DB networks (based on [21])**

DB Regio AG is the relevant entity here and is the market leader, but is now increasingly exposed to competitive pressure from small, flexible transport companies, many of which are subsidiaries of large railway companies in neighbouring European countries.

In addition, Deutsche Bahn is a very large railway infrastructure company which is responsible for DB's entire route network, including all stations and the traction current (Bahnstrom) network as well as all facilities required for reliable railway operation. Reflecting this, the business unit (brand name: DB Netze) is divided into DB Netz AG, DB Energie GmbH and DB Station & Service.[6]

DB Netze is commissioned by the Federal Government to operate the rail infrastructure. Its task is to grant the DB Group companies and all competitors fair and impartial access to the infrastructure. With regard to traction current, DB Energie has repeatedly been accused of operating a discriminatory pricing policy [21]. This is also a consequence of the relationship prescribed between DB Netz AG and DB Energie GmbH, as shown in → Figure 22.



6 DB Netze also includes Deutsche Umschlaggesellschaft Schiene-Straße (DUSS mbH) which operates transhipment stations in Germany.

The traction current is based on a comprehensive supply system operated by DB Energie GmbH. It has its own power plants and stations for the conversion of 3-phase 50 Hz standard current into single phase 16.7 Hz traction current. It also has 110 kV high voltage lines for connecting the power plants and converting stations to the substations where the high voltage is converted into the required 15 kV catenary voltage.

The catenary which supplies power to the vehicles falls within the remit of DB Netz AG at the point where it leaves the substation. This makes DB Netz the owner and operator of the catenary network. The financing of this is based on the train path price (and corresponding federal funds) and not on the price of the traction current purchased [21]. DB Energie only assumes responsibility again within the vehicle itself: here, electricity meters measure the electricity which is consumed and fed back.

In the local transport sector, some of DB Regio's competitors felt discriminated against in the past because, as smaller electricity consumers, they received a much lower discount on the electricity price [21]. In addition, the higher power recovery efficiency of their generally more modern vehicles was not adequately rewarded. With regard to this example, it should be noted that the regulation has since been changed. The traction current network was opened for transit on 1 July 2014. This gives all railway undertakings a free choice of traction current supplier.

It is not possible to resolve issues such as the electrification of railway lines in regional passenger rail transport as a means of replacing diesel vehicles with electric multiple units, or of putting vehicles with alternative drives onto the rails, within the current structure of DB Netze: infrastructure-related issues fall within their remit, whereas vehicle issues do not.

The position towards alternative battery and fuel cell drive systems for multiple units is correspondingly complex. Would it not be preferable if the initiative for producing and supplying hydrogen, or for the partial electrification of lines to permit the charging of battery-powered multiple units lay with DB Netze? Today, this initiative lies exclusively with regional authorities and innovative vehicle manufacturers. The German Federal Network Agency and the Federal Railway Authority are currently clarifying whether charging stations should be assigned to the lines, i.e. whether DB Netze is responsible for them. A fundamental decision on the legal classification is expected in the near future. It is understandable that DB Netze is now asking how it should finance the necessary infrastructure investment. Through higher track use charges for vehicle concepts whose cost-effectiveness and future viability have not yet been ascertained?

2.7 Associations and alliances as rail lobbyists

Allianz pro Schiene

The **Allianz pro Schiene** (Pro-Rail Alliance) sees itself as a necessary counterweight to the car lobby and was founded specifically for this purpose in 2000. Convinced that rail transport is environmentally friendly, safe and economically efficient, and that it also provides affordable mobility for the general public, the alliance is committed to significantly increasing the market share of passenger and freight rail transport. Its members include non-profit organisations such as environmental associations, consumer organisations, trade unions and universities; supporting members include public decision makers, railway transport companies, railway construction companies and manufacturers.

Allianz pro Schiene believes that it is important to take a differentiated view of suitable alternatives to diesel trains. It does not limit its purview here to regional, long-distance or freight transport. The electrification of the German rail network itself is of central importance to the alliance. This is not only an environmentally-friendly measure, it also helps achieve the necessary long-term increase in the rail network capacity. The example of Rastatt shows how important electrification can be: In 2017, subsidence of a railway line led to a line closure which paralysed freight traffic for weeks because there were no diversion lines with a catenary.

Allianz pro Schiene attracted the attention of politicians by recommending an accelerated programme in the form of Elektromobilität Schiene 2025 (Rail Electromobility 2025) which went far beyond the projects envisaged in the Federal Transport Infrastructure Plan (BVWP) 2030, see also [6]. The main statements concerning electrification in Chapter 3 refer to these proposals.

VDV Die Verkehrsunternehmen

Verband Deutscher Verkehrsunternehmen (VDV – Association of German Transport Companies) is an industry association which, according to its own claim, engages in dialogue with politicians and business representatives. It represents roughly 600 public passenger and rail freight transport companies in Germany.

The VDV sees electromobility as a good means of becoming climate-neutral and locally emission-free, and sees great potential in local public transport. It argues in favour of transferring more traffic to the railways in cases where this represents a more favourable option. From an economic point of view, diesel multiple units represent a cheaper solution compared to the alternatives. The question is whether it is possible to factor in CO_2 emissions in order to arrive at a fair comparison. The hybridisation of diesel multiple units is a first step towards overcoming the diesel problem.

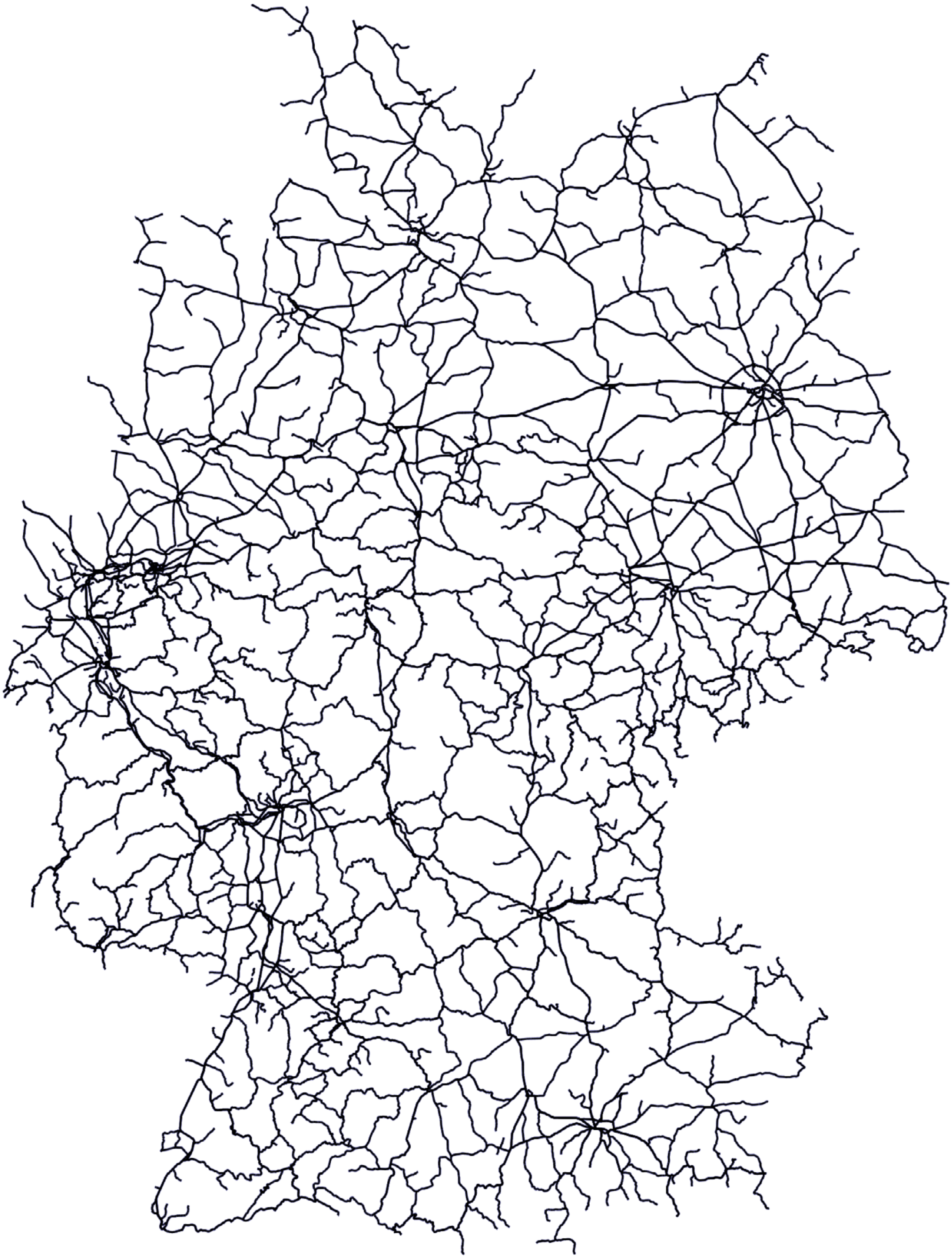
With regard to the further electrification of the rail network, the VDV shares the views of Allianz pro Schiene [22]. The introduction of alternative drives must be assessed using the same criteria as those for electrification. Accordingly, fuel cell multiple units (with their accompanying hydrogen infrastructure) do not actually qualify here. It would be more effective to focus on increasing energy efficiency and supporting diesel engines with batteries that absorb recuperation energy and kick in at peak loads. The VDV believes that synthetic fuel makes more sense than hydrogen, as it is suitable for normal combustion engines yet has a carbon-neutral effect in terms of its ecological footprint if produced using renewable electricity.

3 Electrification instead of diesel railway lines

3.1 Status quo and demand

The full decarbonisation of transport in Germany by 2050 is a declared political goal which enjoys broad support among the population. The rail system is well equipped for this: Electric multiple units which draw their drive energy from the overhead line run on fully electrified railway lines. The share of renewable energy in the German electricity mix is 40 per cent at present. It was 57 per cent in the traction current network in 2018 and, according to DB Energie, is set to rise to 80 per cent by 2030.

Figure 23 **German railway network [23]**



Federal state	Diesel network	Lines	Total length	Operational capacity	EVU	Public decision maker
Baden-Wurttemberg	Ortenau	Netz 8	180 km	2,100 T tkm[1]	SWEG	NVBW
Bavaria	Augsburg II	BRB	250 km	~2,600 T tkm	Bayer. Regiobahn	BEG
Berlin-Brandenburg	Heidekrautbahn		60 km	~650 T tkm	NEB	VBB
Hesse	Taunus-Bahnen	RB 12/12/15/16	80 km	~900 T tkm	HLB	RMV
Mecklenburg-Vorpommern	Warnov		~130 km	1,400 T tkm	DB Regio	VMV
Lower Saxony	Lüneburger Heide	RB 32/37/38	158 km	~1,600 T tkm	erixx	LNVG
North Rhine-Westphalia	Kölner Dieselnetz	RB 23–25/30, RE 12/22, S23	~340 km	7,200 T tkm	DB Regio	NVR
Rhineland-Palatinate	Südwest, Los 1		292 km	3,000 T tkm	DB Regio	SPNV-Süd
Saxony	Erzgebirgsbahn		233 km	2,400 T tkm	DB Regio	VMS
Saxony-Anhalt	DISA		~800 km	9,000 T tkm	Abellio	NASA
Schleswig-Holstein	Marschbahn	RE 6	230 km	2,700 T tkm	DB Regio	NAH.SH
Thuringia	Südthüringen, Los A	R 41/42/48	170 km	2,000 T tkm	Südthüring. Bahn	NVS

1 T tkm = 1,000 train kilometres

Table 2 **Examples of diesel networks in the federal states**

The railway network operates a total of approx. 34,000 kilometres of railway lines and, at 108 rail metres per km^2, is one of the densest networks in the world. However, the degree of electrification, at 59 per cent, is only average in Europe. Limited electrification affects regional passenger rail transport in particular. In federal states such as Lower Saxony, Bavaria or Schleswig-Holstein there are still extensive stretches of railway line with no catenary. In other regions, there are still electrification gaps in the busy regional rail network. Some of these are sections of track left out of the construction and expansion of S-Bahn networks around larger cities. These non-electrified sections, many of which are only a few kilometres long, are one reason why diesel multiple units are still deployed in networks even in the most densely populated regions, such as North Rhine-Westphalia. → Table 2 shows examples of diesel networks in the federal states.

In 2017, the German regional passenger rail service had a total operating capacity of 673 million train kilometres (tkm). This translated into a total transport capacity of 57 billion passenger-kilometres (pkm). About one third of the operating capacity (~225 million tkm) was accounted for by diesel railway lines which contributed transport capacity of less than 6 billion pkm, i.e. only about 10 per cent, cf. also [24].

A study conducted by the German Aerospace Center (DLR) in Berlin found that (at least) 469 of the approximately 1,000 regional passenger rail lines in Germany are served by diesel multiple units because they contain sections with no overhead line. → Figure 24 is based on data derived from [25] and shows the distribution of the diesel railway lines, listed from longest to shortest in kilometres. The green parts of the columns represent lines with, and the blue parts lines without a catenary. A detailed analysis shows that the diesel railway lines have a 23 per cent degree of electrification on average. Diesel-powered journeys under an overhead line are correspondingly common.

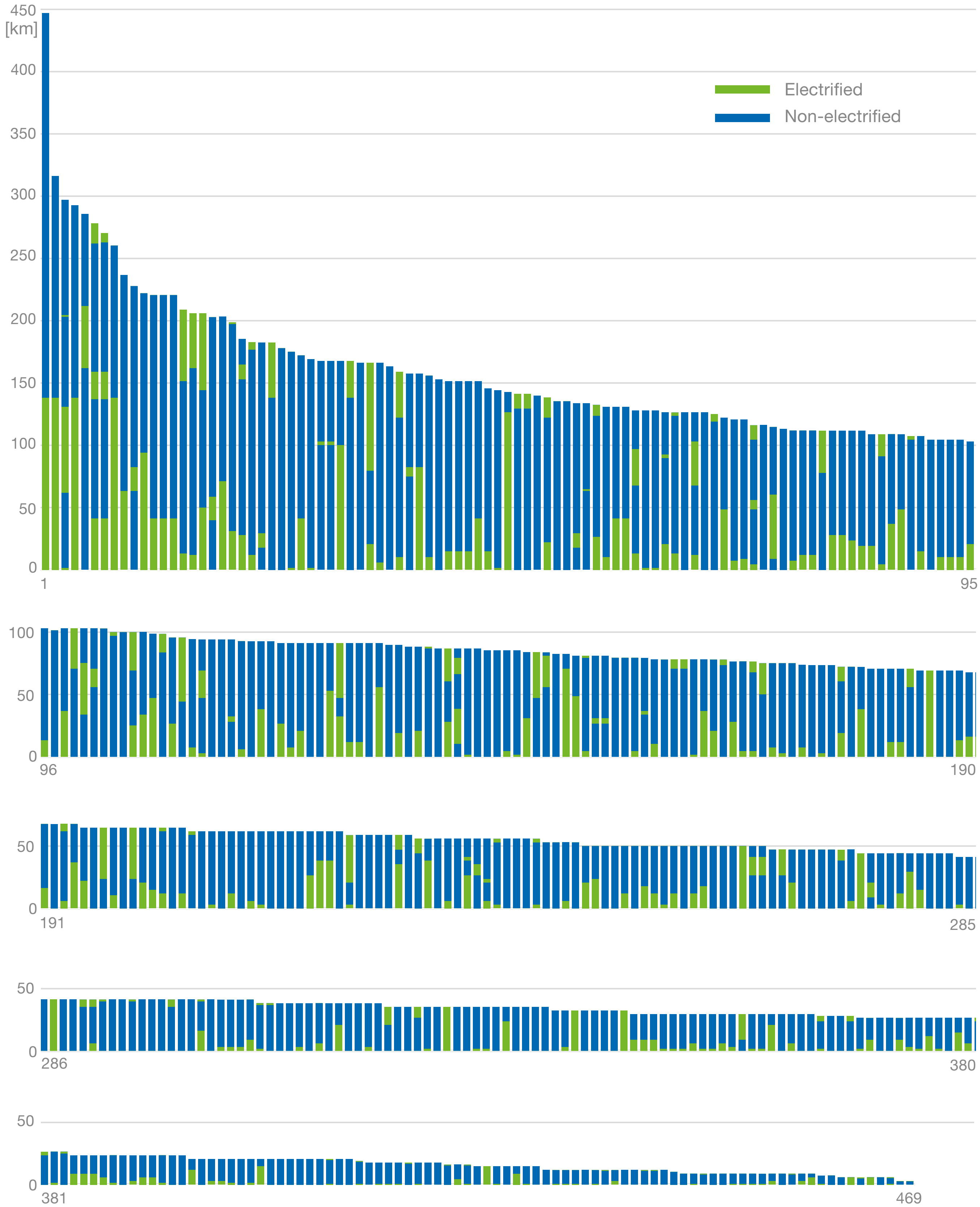


Figure 24 **Regional passenger railway lines served by diesel MUs [25] – the diesel railway lines are numbered from 1 to 469 on the horizontal axis**

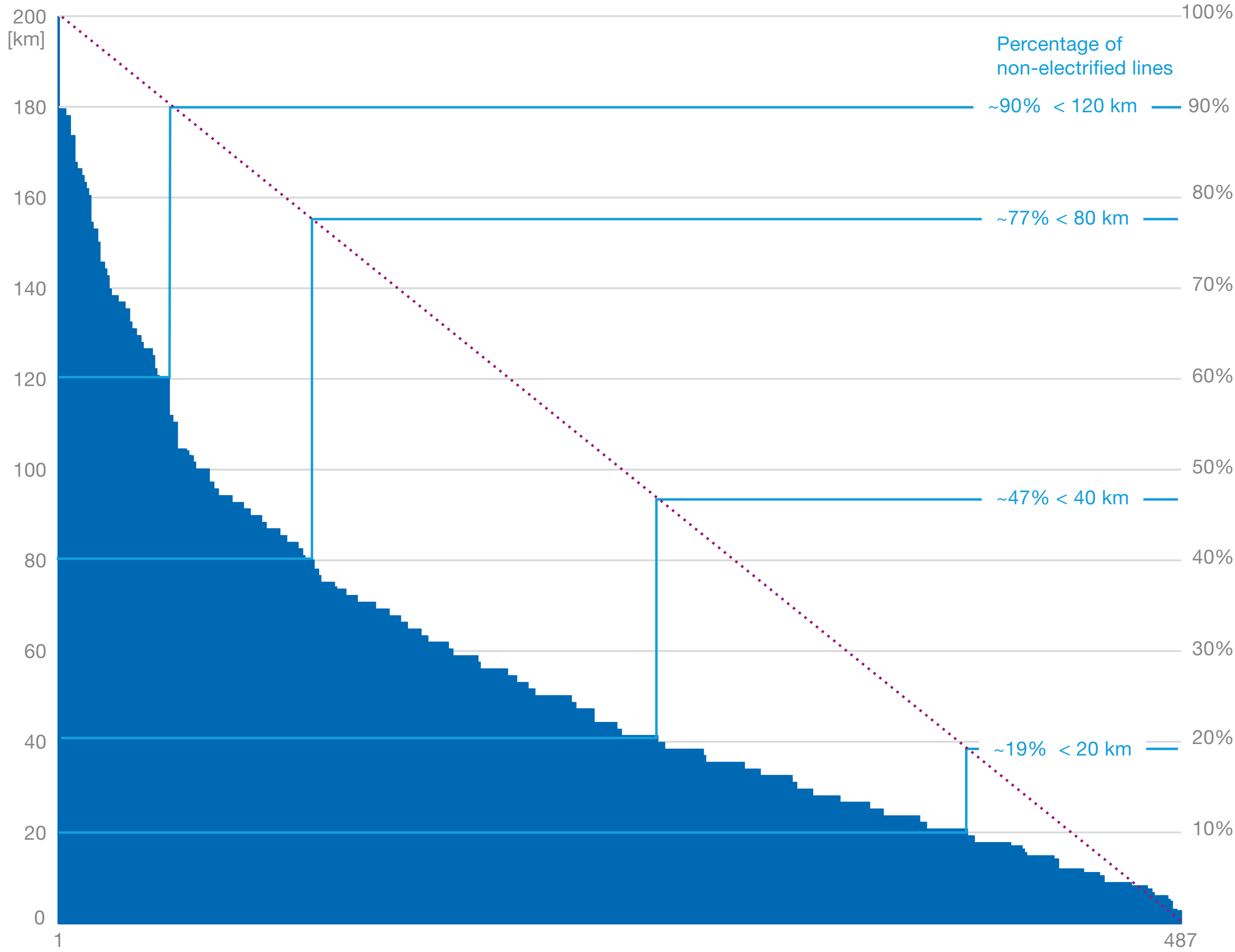


Figure 25 **Distribution of the length of non-electrified regional passenger railway lines (as shown in [25]) – the different sections are numbered on the horizontal axis**

The distribution of non-electrified sections on regional passenger railway lines, again listed by decreasing length in kilometres, is given in → Figure 25. The graph shows the statistical probability of a section of non-electrified track having a length below a given number of kilometres. Accordingly, about half of all non-electrified sections of diesel railway lines are shorter than 40 kilometres, and about three quarters of these lines are shorter than 80 kilometres.

Despite knowing the degree of electrification in the regional passenger rail transport system and the extent of diesel vehicle use, it is no easy matter for the decision-makers to draw the right conclusions with regard to decarbonisation and the transfer of more traffic from road to rail.

A moderate level of electrification is expressly desired at the political level, as can be seen from the coalition agreement of 14 March 2018. Rail transport is covered in part 4, Transport:

"By 2025 we want to have electrified 70 per cent of the rail network in Germany. We intend to electrify regional railway lines by means of a funding initiative. [...]"

Implementing this promise, on the other hand, is a major challenge for many of those involved. The necessary infrastructure measures are complex and costly, and the construction capacities of the infrastructure companies are currently very limited. These are 'regionally significant' public investments, making it mandatory to carry out a planning approval procedure. The regional planning procedure is time-consuming and associated with high personnel costs, as are the expansion planning, environmental assessment, risk assessment, economic feasibility study and hearings. The period from application including work phases LP1 to LP4 (according to HOAI[7]) through to implementation can take four to eight years, even in the case of smaller electrification projects.

The electrification of diesel railway lines can be achieved in various ways – as explained in the following sections.

3.2 Gap closures with overhead lines

An economic feasibility study carried out by TU Dresden in 2017 [26] shows that the electrification of densely trafficked routes (≤ every 30 minutes) is the ideal solution, as Bayerische Eisenbahngesellschaft (BEG), which commissioned the report, concluded. Even with a 60-minute service frequency, closing electrification gaps is still the most sensible measure if the gaps constitute no more than 50% of the railway line[8] and a large proportion of the electrification work (85%) is easy to carry out [26]. → Figure 24 shows that this could be the case for 7 per cent of railway lines – depending on the service frequency.

Electrification measures are also part of the 2030 Federal Transport Infrastructure Plan (BVWP), the instrument of federal transport infrastructure planning. This includes projects declared as 'ongoing and already contracted' that are currently being implemented. But there are also 'urgent and potential' electrification projects for which the demand has already been identified or which are still at the assessment stage. The increase in the degree of electrification to 70% by 2025, i.e. the political target, corresponds to an expansion of 3,300 kilometres (based on the current 20,100 km). This is almost 600 kilometres more than was planned in the 2030 BVWP.

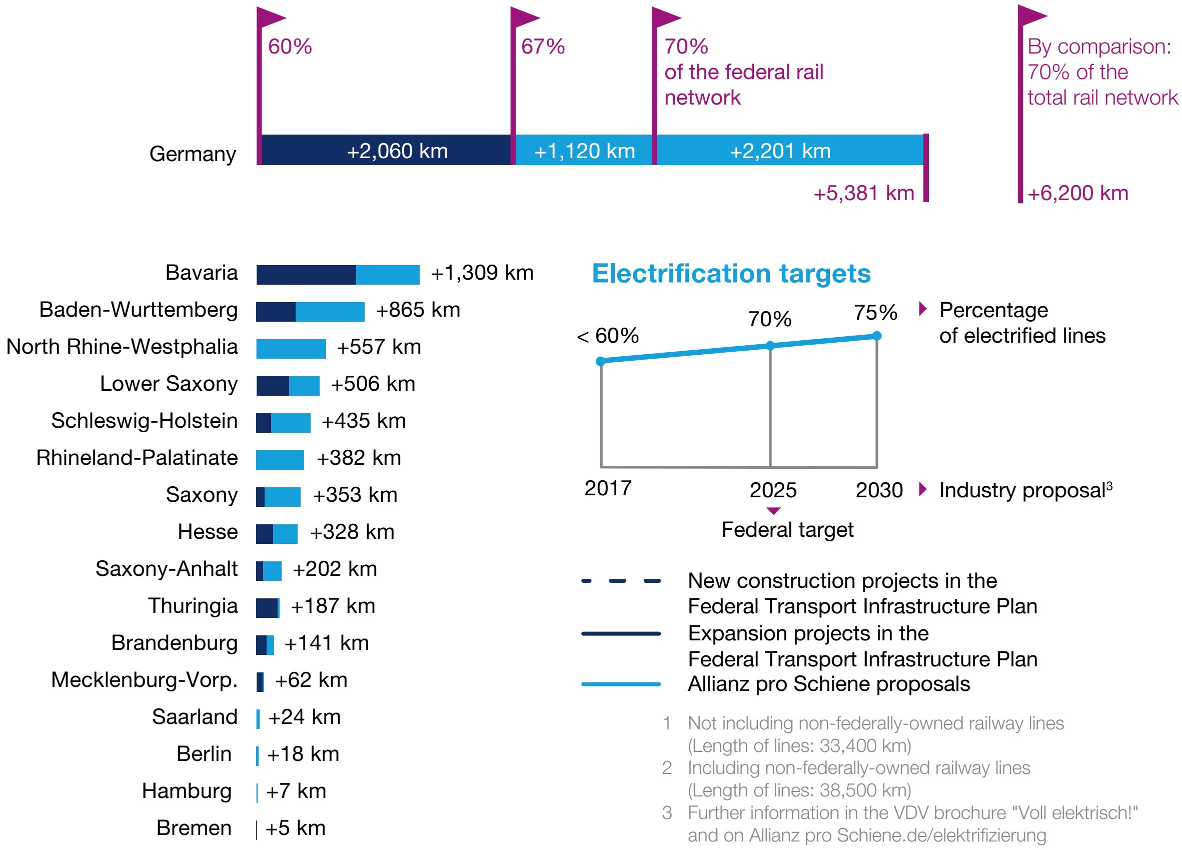
In 2018 Allianz pro Schiene and the Association of German Transport Companies proposed further major projects besides those included in the BVWP [27] [22]. This would allow the degree of electrification to be increased to 75% by 2030, see also → Figure 26.

7 Fee structure for architects and engineers: LP1–LP3 = Basic evaluation, drafting, cost calculation; LP4 = Approval planning

8 A standard length of 100 km is analysed in this study.

Figure 26 **Gap closure proposals for different federal states (according to [27])**

70 per cent of German railway electrified by 2025
Proposals for achieving this goal



1 Not including non-federally-owned railway lines (Length of lines: 33,400 km)
2 Including non-federally-owned railway lines (Length of lines: 38,500 km)
3 Further information in the VDV brochure "Voll elektrisch!" and on Allianz pro Schiene.de/elektrifizierung

3.3 Partial electrification of line sections

If the field is restricted to just electric or diesel multiple units, the only alternative for railway lines with no catenary at present is continuous electrification. Partial electrification would be pointless. Battery-powered multiple units, however, require overhead lines for charging the vehicles' batteries. On line sections which are longer than the guaranteed minimum range of such trains, partial electrification is required to provide the necessary charging infrastructure.

Even though the primary motivation for constructing these electrification islands is to charge the battery trains, experts believe that their technical structure should be based on that of the normal overhead line infrastructure:

Battery-powered multiple units must also be able to drive through the electrification island while charging via the pantograph; any requirement to stop for charging would be highly disadvantageous. It would make sense to provide cheap traction current in the electrification island. The option of connecting such islands to other islands and also to the overall network at a later date without having to completely rebuild them should also be taken into account. The electrification islands should therefore meet the approval standard so that they can be used by even more powerful electric multiple units in future, i.e. to draw higher current levels.

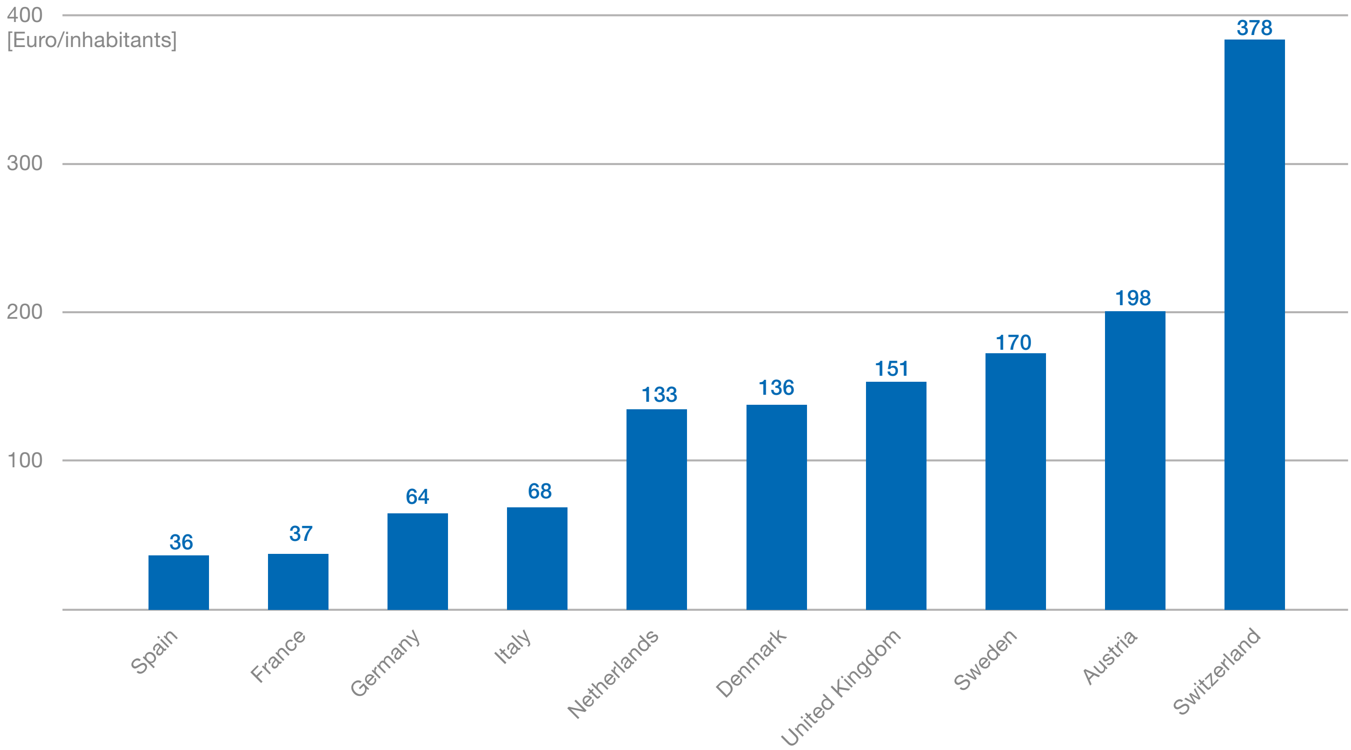
3.4 Full electrification of railway lines

Partial electrification of railway lines to operate battery powered multiple units can be regarded as an interim solution aiming at achieving full electrification of these lines in the long-term. Such solutions provide neither gap closure nor partial electrification in the proper sense. But here, too, the findings of the TU Dresden study are relevant: If the service frequency is ≤ 30 minutes, full electrification of a hitherto non-electrified railway line can make economic sense.

3.5 Full electrification as a vision for the entire rail network

Full electrification of the entire German rail network would make economic sense in view of the energy transition (which is already underway) and the transport transition (which is now becoming a necessity). Electrification costs are estimated at EUR 1 to 2 million per kilometre, which means that an increase in the level of electrification – from 59% today to 100% in the future – would cost up to EUR 30 billion. In fact, at EUR 64 per inhabitant, expenditure on rail transport was relatively low in Germany in 2016 compared with many other European countries (→see Figure 27).
In Switzerland, which is now fully electrified, spending was almost six times higher, at EUR 378 per capita. Compared to the rest of Europe, there is still plenty of room for improvement in Germany, and €30 billion for full electrification, for example, would represent around €360 per inhabitant.

Figure 27 **Investment in rail infrastructure in 2016 (according to [6])**



Ultimately, full electrification is a political issue. There would certainly be benefits for the economy as a whole; however full electrification would probably not be economically viable unless it was financed entirely from public funds.

Switzerland achieved full electrification within 20 years by adopting technical simplifications such as the use of wooden masts and other measures. Now, however, Switzerland is also interested in alternative types of drive. There, too, a handful of routes are incurring rising maintenance costs due to the ageing overhead line infrastructure.

4 Electric drives instead of diesel engines

No clear opinion emerged on the electrification of regional passenger railway lines in the VDE interviews with railway sector stakeholders. There are strong arguments in favour of different options such as closing smaller catenary gaps, or electrifying entire railway lines that previously had no overhead lines, or creating electrification islands, or even providing the entire rail network with overhead lines in the long term. Nevertheless, all participants were in agreement in both the interviews in 2018 and the final workshop in February 2019 on one aspect: electric motors are much more efficient and lighter, require less maintenance and, above all, are more environmentally friendly than even the latest generation of diesel engines. Any decision on alternatives to diesel multiple units is ultimately not based on the drive systems themselves, but on the concept-specific differences in the delivery and use of the drive energy and the efficiency level of the energy source production. Here it is also important to compare the environmental impact of energy production and consumption both locally and globally. Aspects such as these are covered in Chapter 5.

The various multiple unit concepts are described and compared below in terms of the functioning of their characteristic technology components, the typical vehicle structure, the key vehicle properties and the provision and conversion of energy into kinetic energy.

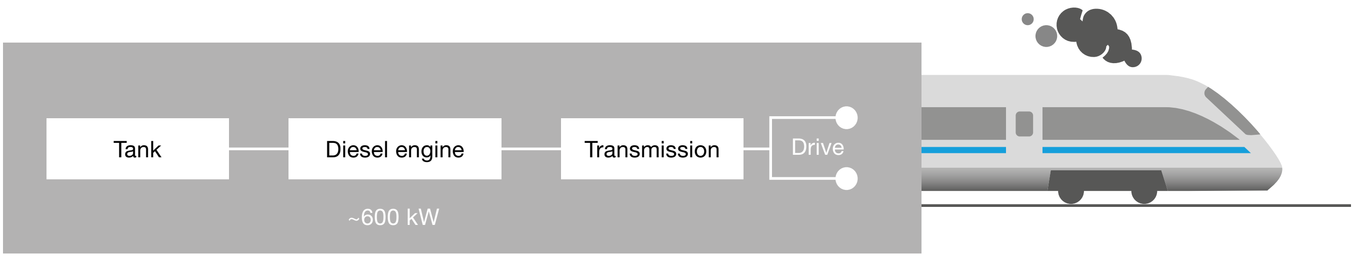
4.1 Diesel and diesel-hybrid multiple units

4.1.1 Diesel-mechanical drive

The drive form in diesel multiple units is usually diesel-mechanical, i.e. the power of the engine is transmitted to the wheels via a transmission system. The diesel engines have similar performance data to large HGVs or buses. Engine manufacturers include companies such as MAN, Iveco or MTU.

Figure 28 **VT 642 diesel multiple unit with 2 x 275 kW output (Euro II) (photo: PH)**

Diesel MU



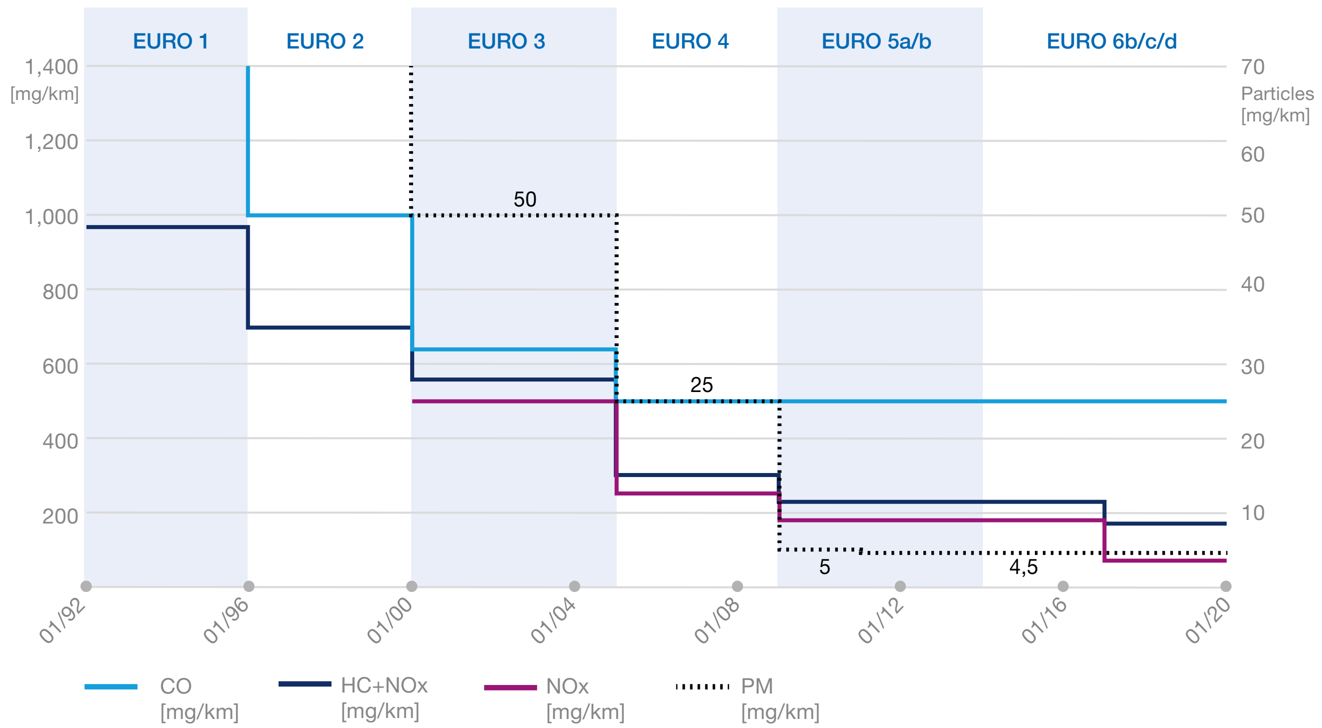
Series	VT 632	VT 642	VT 643	VT 648/623	VT 650
Type	**LINK II**	**Desiro Classic**	**Talent**	**LINT 41**	**Regio Shuttle**
Manufacturer	Pesa (PL)	Siemens	Bombardier	Alstom	Stadler / Adtranz
In operation	?	320 units	780 units	429 units	497 units
No. of carriages	2	2	3	2	1
Vehicle length	43.7 m	41.2 m	48.4 m	41.8 m	25.5 m
Seating/standing spaces	126 / 112	110 / 110	137 / 160	129 / 120	71 / 94
Power output	2 × 390 kW	2 × 275 kW	2 × 315 kW	2 × 315 kW	2 × 265 kW
Unladen weight	~65 t	68.2 t	57.0 t	63.5 t	37.7 t
Power-to-weight ratio	12.9 kW/t	8.1 kW/t	11.1 kW/t	9.9 kW/t	12.9 kW/t
Acceleration	≤0.8 m/s²	≤1.1 m/s²	≤1.0 m/s²	≤0.6 m/s²	≤1.2 m/s²
Speed	120–140 km/h	120 km/h	100–140 km/h	120–140 km/h	120 km/h
Tank size		2 × 600 l		2 × 800 l	2 × 770 l
Range			800-1,500 km		
Exhaust norm	Euro IIIB	Euro II	Euro II	Euro IIIB	Euro II
Diesel engine	MTU	MAN / MTU			Iveco / MAN

Table 3 **Structure and overview of technical data of diesel multiple units**

The Siemens Desiro Classic multiple unit, for example (→ Table 3), which has been used by Deutsche Bahn since 2000 in the form of the VT 642 series, is driven by two 6-cylinder diesel engines (with exhaust turbocharging and charge air cooling), each delivering an output of 275 kW at a speed of 1,900 revolutions [28]. The power-to-weight ratio of this diesel-powered vehicle is 8.1 kW/t based on an unladen weight of 68.2 tonnes, and allows acceleration of up to 1.1 m/s². The transmission system used is 5-speed automatic.

Five examples of diesel multiple units currently on the market can be found in → Table 3.

Like passenger cars, buses and HGVs, diesel multiple units must also comply with exhaust emission standards. Their comparatively very long operating life of 25 to 30 years makes it difficult to comply with exhaust gas regulations, which are being tightened in ever shortening cycles. Euronorm 6 applies to new diesel cars today, → see Figure 29.



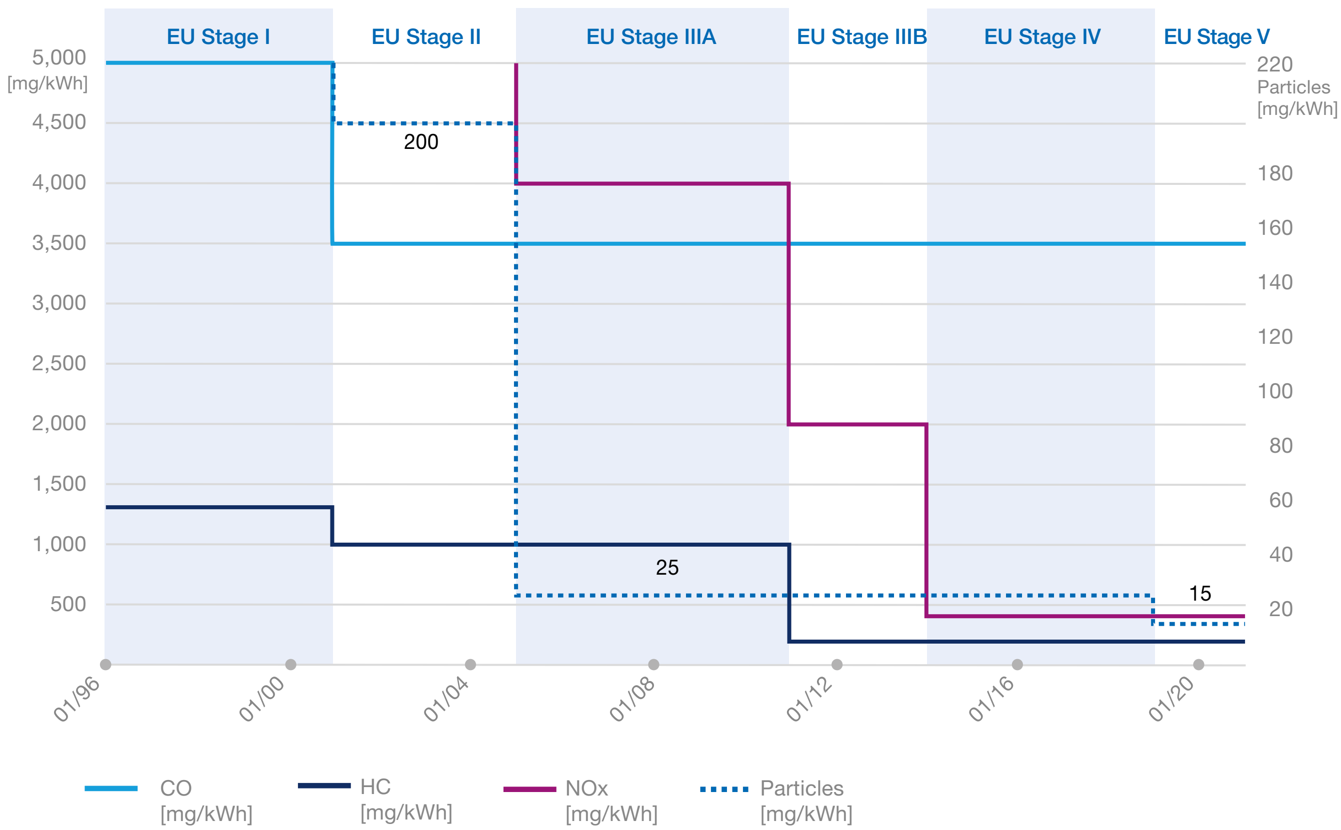


Figure 29 **(top) Development of limits for diesel passenger cars (type approval)**

Figure 30 **(bottom) Development of limits for diesel multiple units (engine class RLR)**

The exhaust emission limits for passenger cars are distance-based, and are therefore measured in mg/km. For diesel multiple units, they are based (like HGVs and buses) on the work performed by the engine, i.e. expressed in mg/kWh. → Figure 30 gives an overview of the development of exhaust emission limits for diesel multiple units to date. The Desiro Classic multiple unit, for example, complies with Euro Stage II.

Newer generation diesel multiple units meet the requirements of Euro IIIB. This specifies a soot particle limit of 25 mg/kWh. NO_x emissions must not exceed 2000 mg/kWh. According to the experts, it is not possible to retrofit the Regio Shuttle RS1, for example, in order to comply with the newer exhaust emission values.

Diesel-electric MU

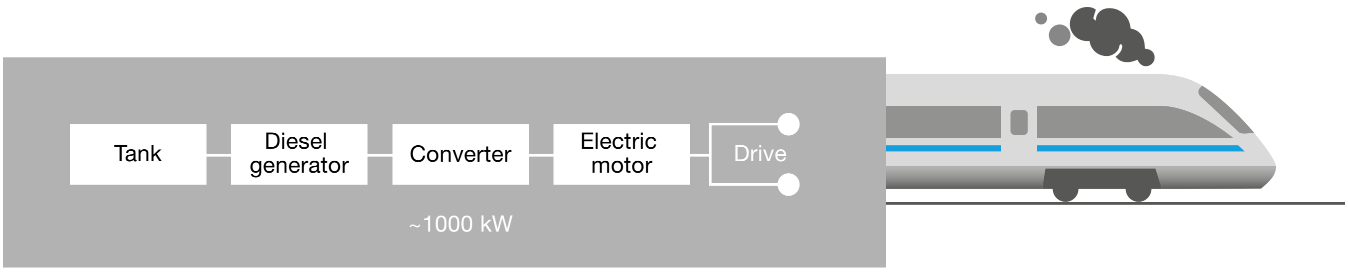


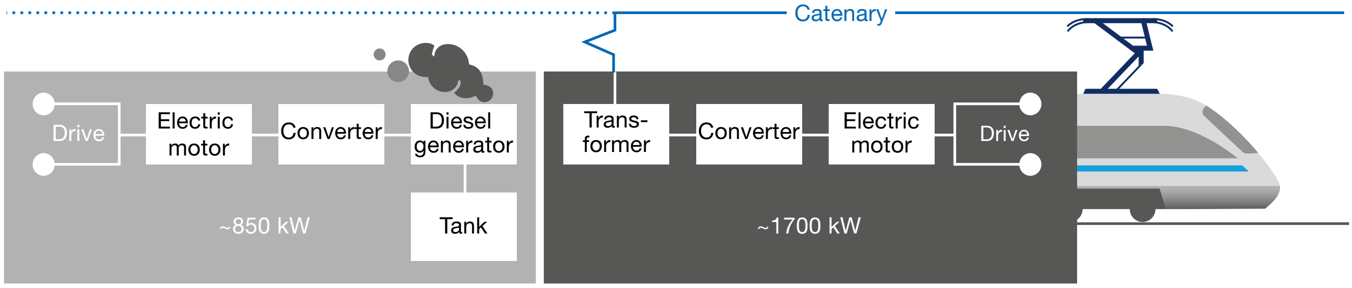
Figure 31 **Structure of diesel-electric multiple units**

4.1.2 Diesel-electric drive

Like all combustion engines, diesel engines deliver their highest energy conversion efficiency within a narrow speed range. A transmission system (including a mechanical clutch) is required when setting off under load. For higher loads, as is the case with heavy locomotives, it is common to use a diesel engine to generate the power for the electric motors that drive the vehicle. This ensures that the diesel engine can always be operated in the optimum range, and thus more economically. (→ Figure 31)

Bombardier also offers the Talent diesel multiple unit as a diesel-electric variant with significantly greater power. Stadler's diesel GTW was diesel-electric from the outset, but went out of production in 2018. In fact, basically for cost reasons, only a few diesel-electric multiple unit models are now left on the market.

Dual mode MU



(simplified representation)

Diesel hybrid MU

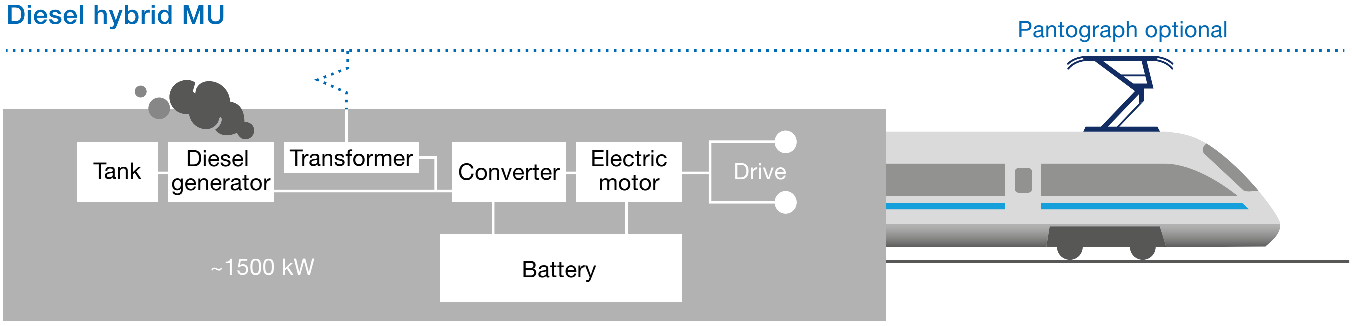


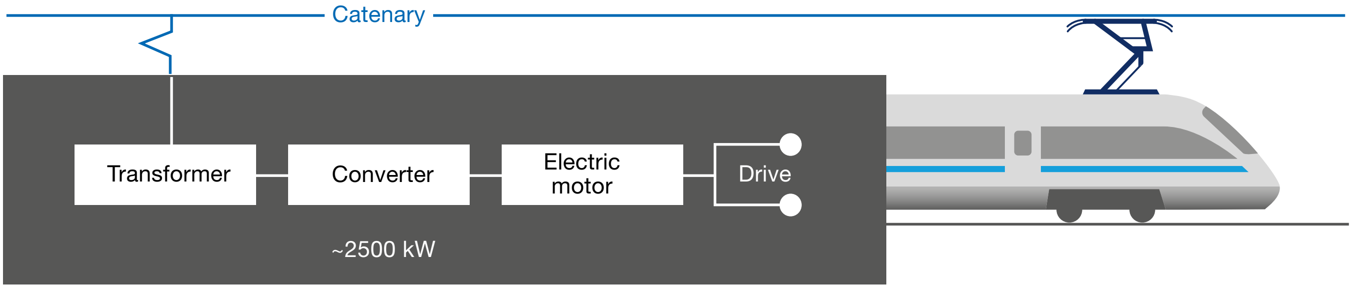
Figure 32 **Structure of dual-mode and diesel hybrid multiple units**

4.1.3 Diesel-hybrid drive

Alstom's Coradia Polyvalent, the Stadler FLIRT bimodal and a variant of the Bombardier AGC (Autorail à Grande Capacité) are examples of multiple units with dual mode drives. On stretches of track with no overhead lines, the power is provided diesel-electrically, i.e. a diesel generator generates the electricity for the electric motors. Wherever overhead contact lines are available, the vehicle can switch to pure electric multiple unit mode. (→ Figure 32)

Such a concept can be made hybrid if, as in the case of the EcoTrain, a sufficiently large lithium-ion battery is also provided which uses the regenerated braking energy to relieve the strain on the diesel generator and even allows the diesel engine to be switched off temporarily at stops where there is no overhead line.

Electric MU



Series	ET 442	ET 429	ET 430	ET 460	ET 440
Type	**Talent 2**	**FLIRT 3**	**(S-Bahn)**	**Desiro ML**	**Coradia Continental**
Manufacturer	Bombardier	Stadler	Alstom/Bomb.	Siemens	Alstom
in operation	400 units	1,694 units(1)	188 units	786 units	218 units
No. of carriages	4	4	4	3	4
Vehicle length	72.7 m	74.7 m	68.3 m	75.2 m	73.3 m
Seating/standing spaces	225 / not stated	219 / n.s.	184 / 296	259 / n.s.	240 / 186
Power output	3,030 kW	2,720 kW	2,350 kW	2,600 kW	2,880 kW
Unladen weight	150 t	120 t	119 t	120 t	140 t
Power-to-weight ratio	20.2 kW/t	22.7 kW/t	19.7 kW/t	21.7 kW/t	20.6 kW/t
Acceleration	≤ 1.2 m/s²	≤ 1.2 m/s²	≤ 1.2 m/s²	≤ 1.2 m/s²	≤ 1.2 m/s²
Speed	160 km/h	120–200 km/h	140 km/h	160 km/h	160 km/h

(1) International

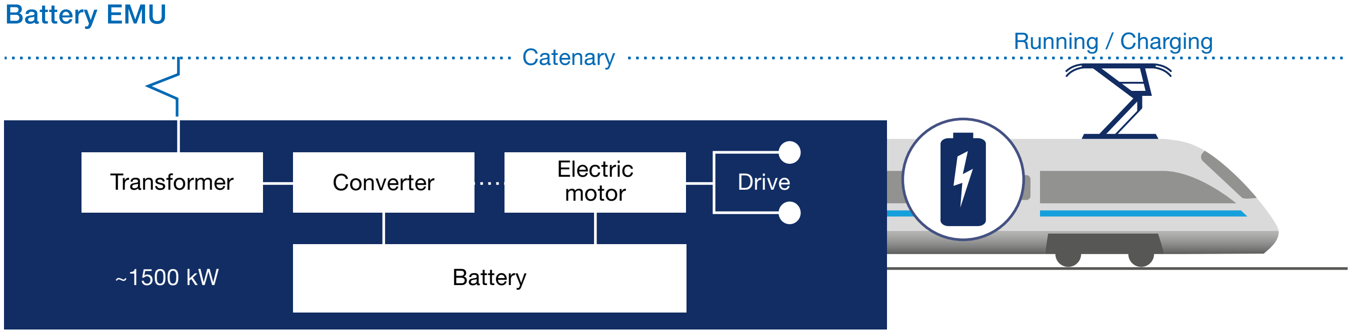
Table 4 **Structure and overview of technical data of electric multiple units**

4.2 Catenary electric multiple units

Electric multiple-unit trains draw their drive energy via a contact wire, in most cases in the form of an overhead line (catenary). Here electrical energy is provided as single-phase 15 kV voltage alternating at 16.7 Hertz.

The pantograph current collector bracket connects the overhead line to the vehicle's electrical system. The track serves as the return conductor for the circuit. A transformer reduces the 15 kV voltage to the a lower level suitable for the current converters. The purpose of these components is to generate the three phase current for the electric motors by direct and pulse rectification. Even today's electrical multiple unit trains can feed their braking energy back into the grid via the overhead line.

Five examples of electric multiple units currently on the market can be found in → Table 4.



Type	Talent 3 BEMU	Mireo Plus B	FLIRT 3 AKKU
Manufacturer	Bombardier	Siemens Mobility	Stadler
No. of carriages	3	2-3	3
Vehicle length	56.2 m	47 / 63 m	58.6 m
Power output	1,520 kW	1,700 kW	~1,500 kW
Range	40-60 km	80-100 km	80 km
Acceleration	≤ 1.0 m/s²	≤ 1.1 m/s²	≤ 1.0 m/s²
Speed	140 km/h	160 km/h[(1)]	140 km/h

(1) if magnetic brakes available

Table 5 **Structure and overview of technical data of battery MUs**

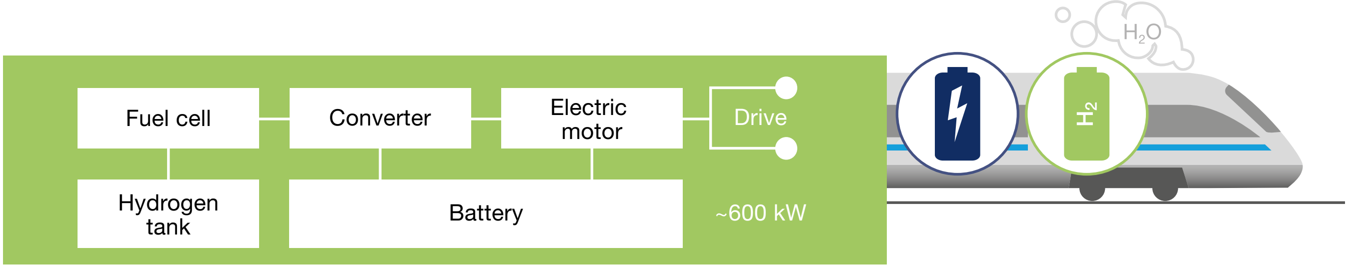
4.3 Hybrid battery-catenary multiple units

Battery-powered multiple units – such as those supplied by the manufacturers Bombardier, Siemens Mobility and Stadler – have the same design as electric multiple units but also have a large lithium-ion battery on board. This battery turns such vehicles into hybrids and, provided that the battery is sufficiently large for the gaps, allows them to run on routes that are not continuously electrified.

The battery is charged via the train's pantograph which makes contact with the contact wire e.g. when stationary at electrified stations or while running on sections with an overhead line. While the battery-powered multiple unit is running beneath the contact wire, it can use the energy it draws both to recharge the battery and to power the vehicle directly in electric multiple unit mode. The energy recuperated during braking can be stored in the battery or fed back into the overhead line network, as in normal electric multiple units.

Three examples of battery-powered multiple unit models can be seen in → Table 5.

H2-BZ multiple unit



Type	Coradia iLINT	Mireo Plus H	Narrow gauge[1] H_2 BZ multiple unit
Manufacturer	Alstom	Siemens Mobility	Stadler Rail
No. of carriages	2	2-3	4
Vehicle length	54.3 m	47 / 63 m	76 m
Power output	544 kW	1,700 kW	1,400 kW
Range	600-1,000 km	600-1,000 km	approx. 600 km
Acceleration	≤ 1.0 m/s²	≤ 1.1 m/s²	≤ 1.0 m/s²
Speed	140 km/h	160 km/h[2]	80 km/h

1 Information shows customer-specific requirements
(2) if magnetic brakes available

Table 6 **Structure and overview of technical data of fuel cell multiple units**

4.4 Hybrid hydrogen-battery multiple units

The new battery-powered multiple units introduced by the manufacturers are ultimately hybridisations of existing electric multiple units. Fuel cell multiple units, by contrast, have a similar design to that of a diesel-electric hybrid with battery. The diesel generator is replaced by a fuel cell stack which converts the gaseous hydrogen stored in pressure tanks into water vapour in a controlled chemical reaction with atmospheric oxygen, and delivers the released energy as electric current (and heat). This energy is used to drive the electric motors. A lithium-ion battery is also used to deliver dynamic power bursts in order to meet the operational power peaks required for acceleration. This battery is used for the intermediate storage of braking energy, as is also the case with battery-powered multiple units.

Three examples of fuel cell multiple units can be seen in → Table 6.

5 Benefit analysis for comparison of alternatives

Advantages and disadvantages can be given for each of the alternatives to diesel multiple units used in the regional passenger rail system considered in the previous chapters. The criteria on which such an assessment is based depend ultimately on the reviewers' expectations and the perspective of the interest group they represent. → Figure 33

For the public decision makers, overarching aspects such as energy efficiency, compatibility with the objectives of the energy transition, the resulting necessity of sector coupling, local emission avoidance, climate protection or the planned expansion of infrastructure are relevant criteria that justify the use of an alternative. The weight they ascribe to each of the criteria also depends on their personal experience and underlying attitude.

A railway undertaking will regard the criteria mentioned by the public decision maker as "nice-to-have" factors, but for rail transport companies, criteria such as vehicle availability, safety and above all cost-effectiveness over the period of use, are ultimately decisive, especially when it comes to alternatives to their diesel multiple units. Conversely, the latter are the main criteria for the public decision makers when assessing the performance of an EVU.

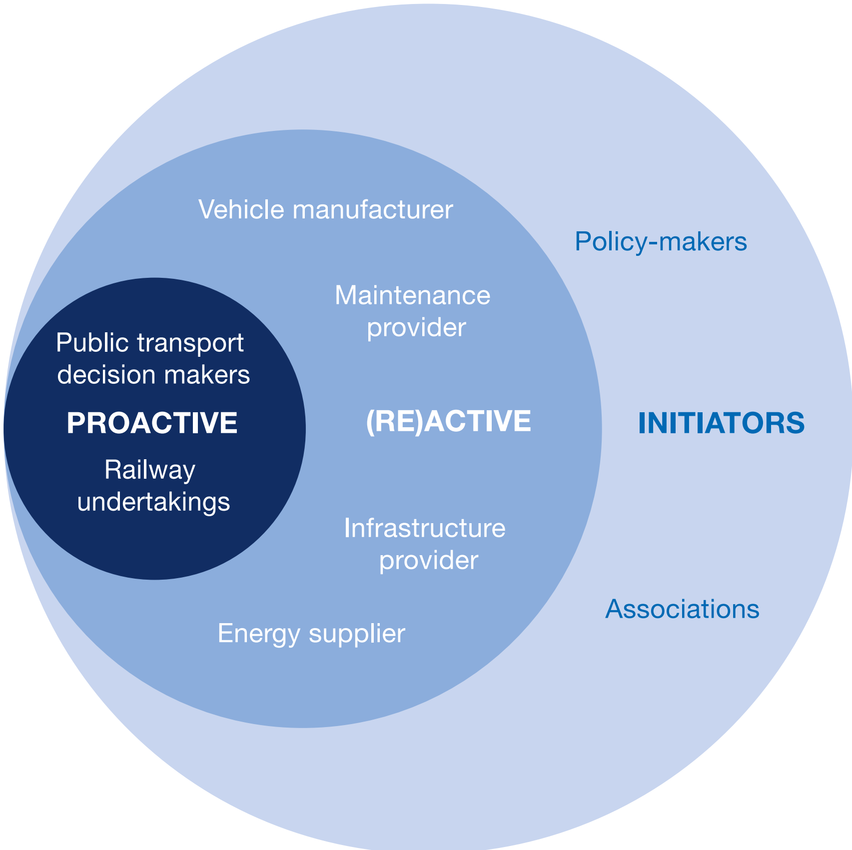


Figure 33 **Stakeholders and roles in the decision-making process**

The DB Netze division of Deutsche Bahn AG, which is responsible for the management and maintenance of railway lines, catenaries and stations as well as for the provision of traction current or diesel, has different criteria. These include in particular the financial viability of infrastructure adjustments, the availability of necessary construction and installation capacity and the possibility to adjust railway line or station prices, all of which are decisive with regard to possible alternatives.

Vehicle manufacturers or maintenance workshops will weight the criteria completely differently based on their particular perspectives.

Given the expected long-term effects and high costs, it is scarcely justifiable to make a snap yet binding decision in favour of an alternative based simply on a 'gut' feeling. This is making the situation difficult for many decision-makers at the moment: they are setting up projects in an attempt to test the different drive concepts in regular operation in the hope of being able to convince themselves of their suitability and cost-effectiveness, but also, if necessary, to backtrack and choose a different technology. Each is monitoring what "the others" are doing.

The following, however, represents a practical solution. Instead of making decisions intuitively, a tried and tested procedure that is known in decision theory as benefit analysis [29] can be used to solve the decision-making problem.

The following sections contain a brief description of the methodology and the chosen study framework followed by a presentation of a number of criteria that are suitable for assessing the potential utility of the possible alternatives and for obtaining a neutral and objective assessment of their prospective use in 2025 and beyond. The criteria considered here are somewhat theoretical in nature, and the analysis ultimately yields a conceptual assessment. In practice, however, public decision makers and EVUs are looking for suitable alternatives for existing diesel railway lines which are best suited to the corresponding route profiles, timetables, number of passengers, electrification plans, etc. Such aspects will be taken into account in the next subproject (probably in autumn 2019) in which decision-makers will provide data on diesel railway lines in order to carry out specific benefit analyses. The results will constitute factually substantiated recommendations for alternatives on specific lines.

5.1 Methodology and study framework

As indicated at the beginning, the search for a suitable alternative to diesel multiple units is a multi-dimensional decision-making problem. Benefit analysis offers a means of arriving quickly at a viable solution by breaking the problem down into subproblems which can be assessed more easily by applying simple arithmetic. The principle is shown schematically in → Figure 34.

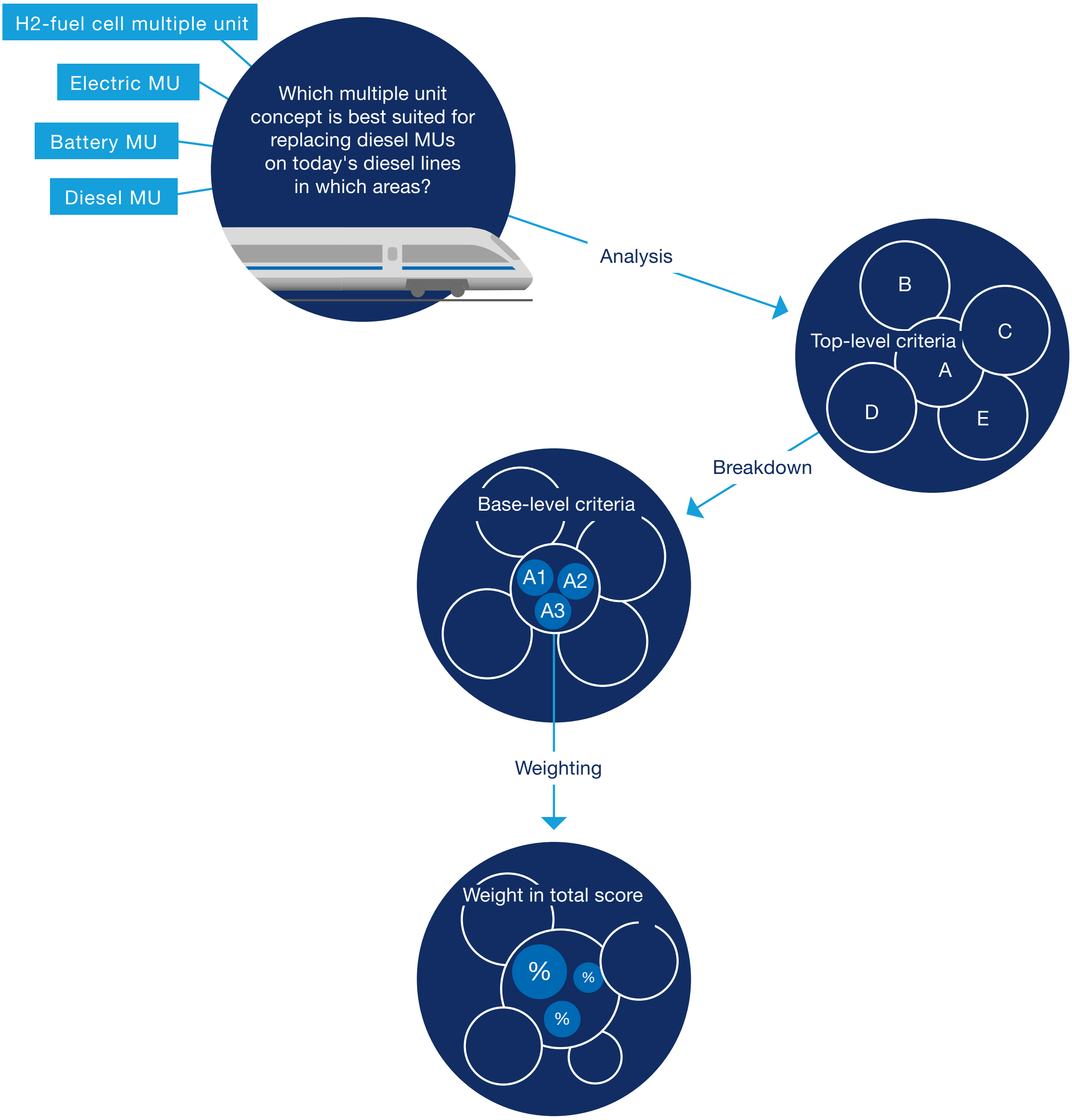


Figure 34 **Preparation of benefit analysis**

In addition to the diesel-mechanical (DM) multiple unit concept, the benefit analysis includes the following alternatives:

- Electrification, enabling the use of conventional catenary (overhead line – OL) multiple units,
- Battery-catenary hybrid (BOH) multiple units,
- Hydrogen-battery hybrid (WBH) multiple units.

Diesel variants such as those with diesel-electric drives or hybrid extensions using a pantograph or battery are not considered here, as they are more energy-efficient and have lower local emissions than diesel multiple units, but can only be climate-neutral if synthetic fuels are used.

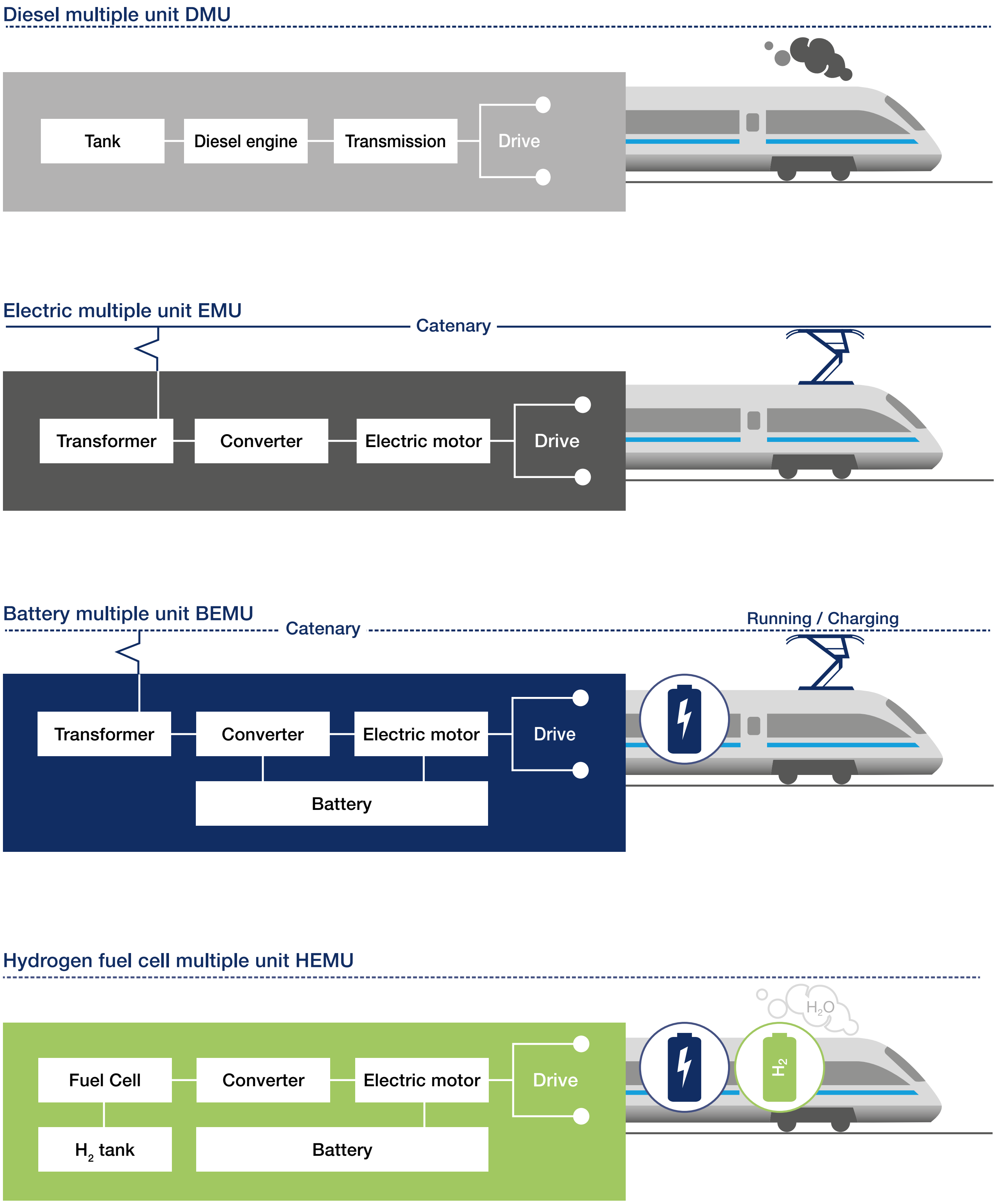


Figure 35 **Model types considered in the benefit analysis**

Basic suitability as a replacement for diesel multiple units is implicitly assumed for all three alternatives. The authors consider the following aspects to be decisive in their evaluation:

1. Operational friendliness
2. Cost-effectiveness
3. Environmental compatibility
4. Systemic benefit
5. Resource availability
6. Infrastructure friendliness.

The four model types shown in → Figure 35 meet these criteria to varying degrees as a result of their specific properties and requirements. Each of the six top-level criteria is complex and multi-layered, making it desirable to break each one down into more easily manageable sub-criteria, as described in → Figure 34. It makes practical sense to divide the top-level criteria into two levels of sub-criteria, i.e. to divide them first into subgroups of criteria ("mid-level criteria"), each of which is broken down further into a number of base-level criteria. Not every subcriterion carries equal weight, i.e. it does not influence the degree to which the parent criterion is fulfilled to the same extent. These differences are taken into account in the form of individual weightings.

5.2 Compilation of the evaluation criteria

All criteria are defined below as precisely as possible and explained in detail. Their clarity is essential for correct assessment of the potential of each alternative. The wordings may appear somewhat cumbersome in certain cases. This is due to the fact that points from 0 to 10 have to be awarded for the evaluation, with 0 representing ***very bad*** and 10 ***very good***.

Note: Diesel multiple units have a typical operating life of 25 years. Since rail transport is to be completely decarbonised by 2050, it will no longer make sense to buy new diesel multiple units after 2025. For a fair comparison of the various drive alternatives, it is therefore assumed that by 2025 the specific technologies will have reached their required maturity and the vehicles (together with the necessary quantities of the relevant energy sources) will be available. 2025 is therefore taken as the reference year for the evaluation.

5.2.1 Operational friendliness in 2025

Operational friendliness refers to the suitability of the multiple unit concept for daily use in regional passenger rail transport. For the railway undertaking, operational friendliness is essential in order to fulfil the transport contract with the public decision maker and to guarantee reliable operation of the railway line. → Figure 36

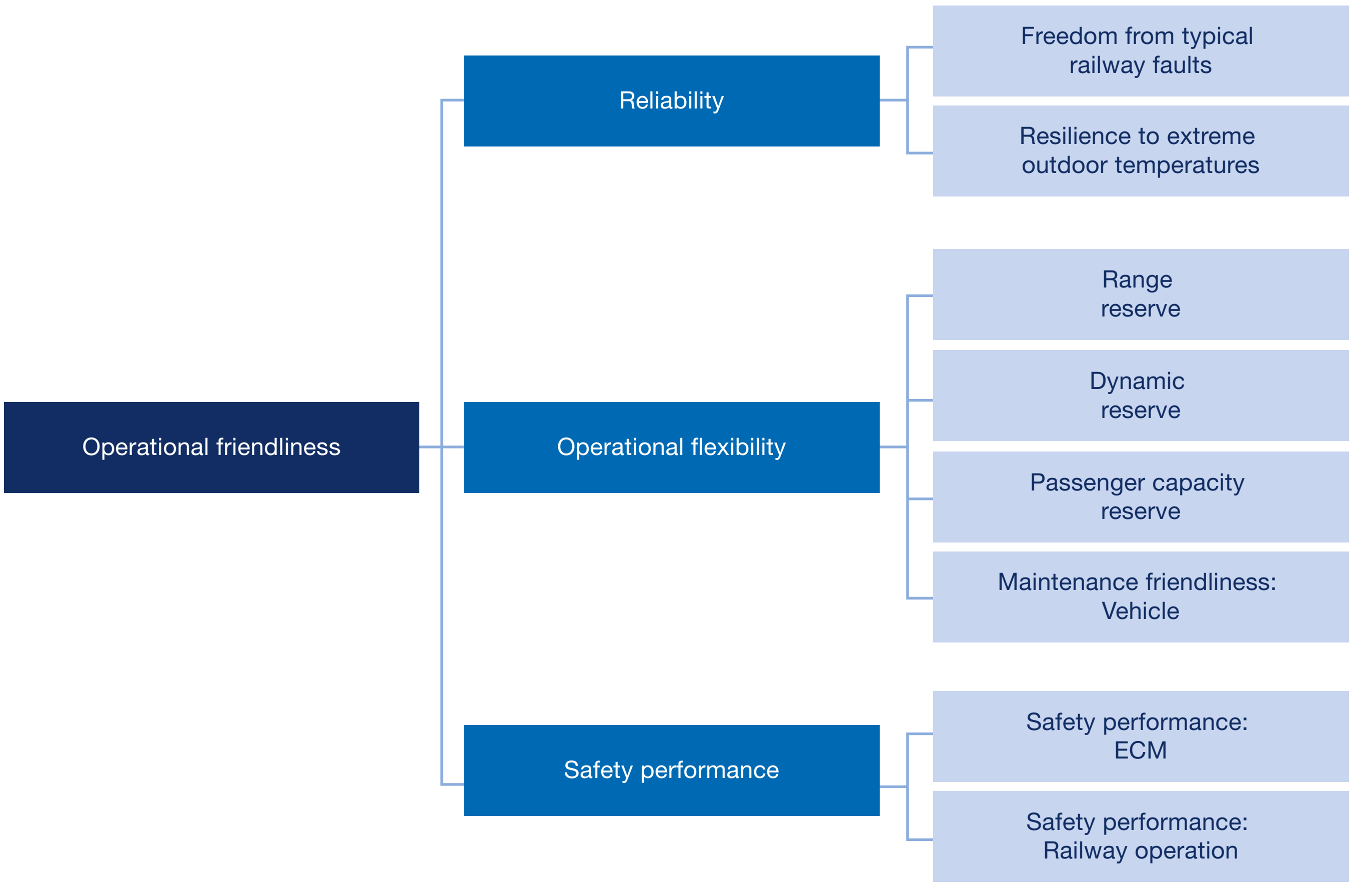


Figure 36 **Operational friendliness and associated sub-criteria, according to [4]**

Operational friendliness is broken down into a total of eight base-level criteria; these are condensed into three “mid-level” criteria. These are reliability, operational flexibility and safety performance. They are defined as follows.

Reliability

The reliability criterion describes the resilience of the multiple unit concept to external influences that could cause delays or impaired operation. An analysis of the causes of actual delays in train operation published in 2012 [30] shows that technical faults in trains are relatively frequent at 11.5%, faults in the overhead line at 1.1% are less frequent (→ Figure 37). Both types of failure result in average delays of a quarter of an hour each. Technical faults in trains using a mature drive technology can generally be assumed to be independent of the type of drive. In the event of an overhead line fault, however, multiple units which can function without a catenary have the advantage.

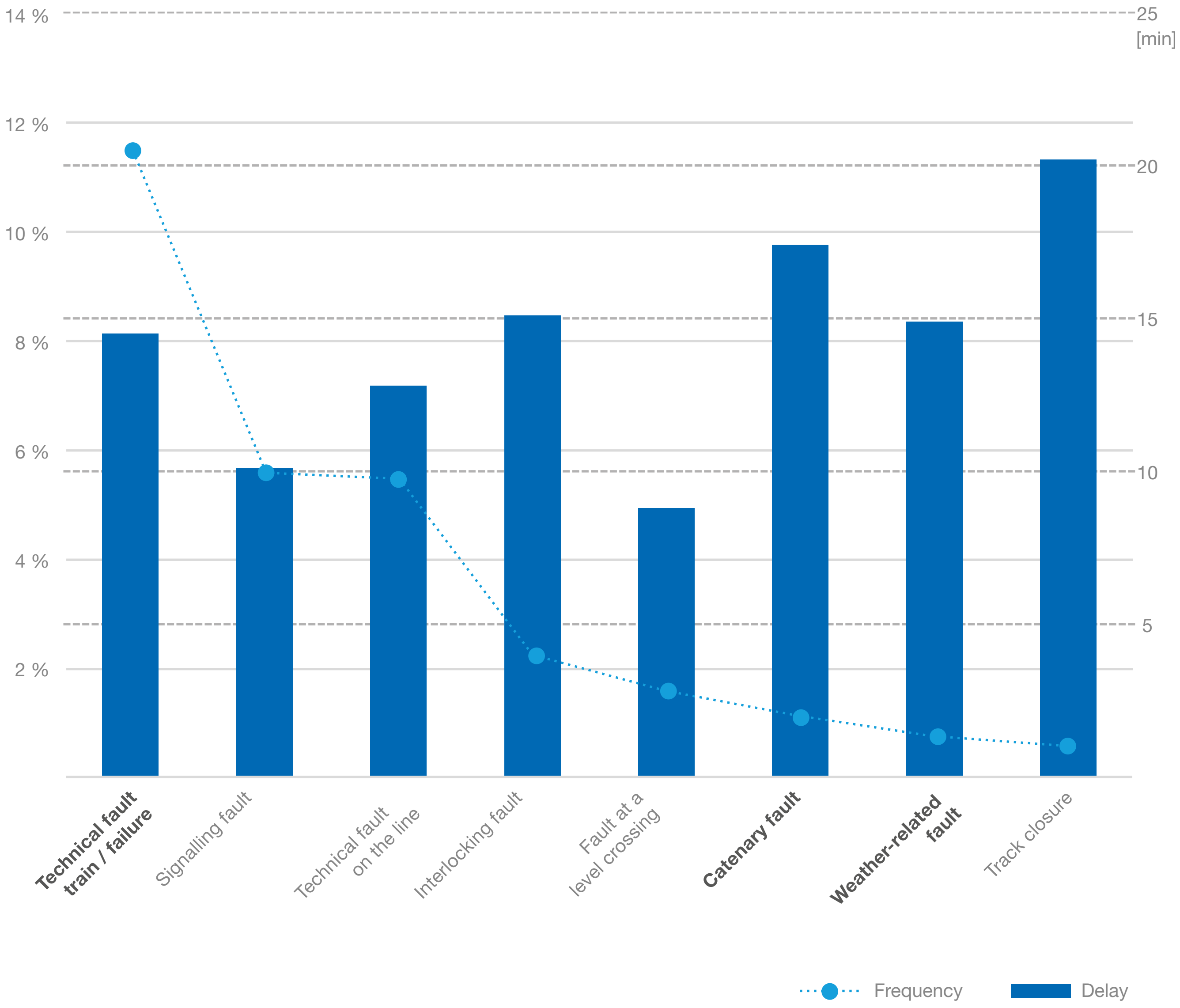


Figure 37 **Faults causing longer delays in railway operation, according to [30]**

At less than 1%, weather-related failures are relatively rare. However, the delays they cause are significant, at an average of 15 minutes each. The greatest seasonal weather influence is the outdoor temperature: it can be very cold in winter and very hot in summer. Drive technology that is sensitive to extreme outside temperatures constitutes a disadvantage. Increased energy consumption, which has an impact on the range, is another major drawback.

Base-level criteria: Reliability

- Freedom from typical railway faults
- Resilience to extreme outdoor temperatures

Operational flexibility

The criterion of operational flexibility describes the extent to which the drive technology can be used to operate a railway line in the face of changed circumstances, for example when detours have to be made, delays compensated or increased passenger volumes accommodated. This also includes rapid return to service after maintenance or repair.

Base-level criteria: Operational flexibility

- Range reserve
- Dynamic reserve
- Passenger capacity reserve
- Maintenance friendliness: Vehicle

Safety performance

The safety performance criterion describes the extent to which the drive technology is suitable for keeping down the costs required for dealing with specific hazards such as high voltages, power current, toxic substances etc. It is relevant during operation and also for repair and maintenance work in a workshop.

Base-level criteria: Safety performance

- Safety performance in ECM
- Safety performance in railway operation

5.2.2 Cost-effectiveness in 2025

There are many criteria which determine the cost-effectiveness of the drive technology. Ultimately, these are the expected costs for the acquisition of the vehicles and for their operation and maintenance until the end of the transport contract or the operating life of the vehicle. Added to this are the costs for infrastructure installation and maintenance, as well as energy costs.

Base-level criterion: Cost-effectiveness

- Cost performance

The cost performance describes the potential for keeping down the costs of the drive technology in railway operation to ensure that it has a positive economic impact over the contract or operating life. It is important to note here that the present analysis covers non-electrified or only partially electrified lines that tend only to have relatively light traffic levels. Only in such circumstances can vehicles with alternative drive systems compete economically with caenary multiple units.

5.2.3 Environmental compatibility in 2025

A multiple unit drive system is deemed to be environmentally compatible if emissions of toxic substances and noise pollution caused by engine and driving noise can be avoided. At the global level, the technology is environmentally compatible if emissions of climate-damaging gases such as CO_2 can be avoided in the manufacture of the components and the energy source, as well as in operation. The efficiency of the production and use of energy is a further aspect of environmental protection. The criteria for assessing environmental compatibility are global and local emissions avoidance and energy efficiency (→ Figure 38)

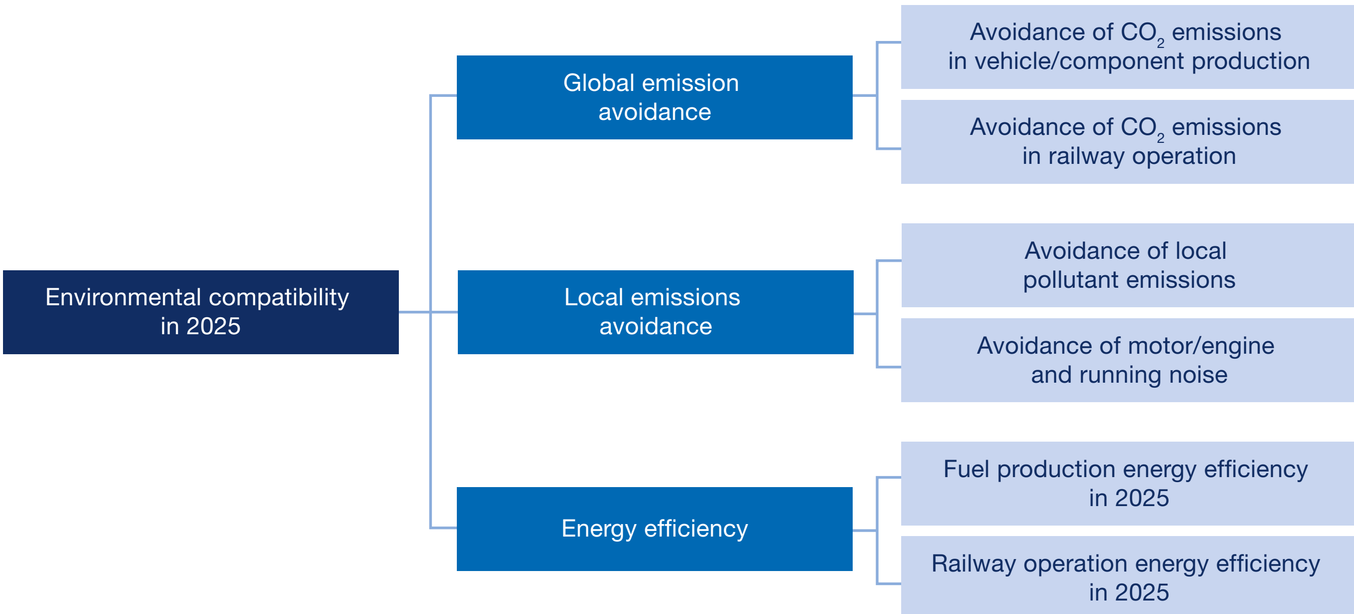


Figure 38 **Environmental compatibility and associated sub-criteria, according to [4]**

Global emissions avoidance

The global emissions avoidance criterion describes the extent to which climate-damaging gases are likely to be emitted (e.g. in tCO_2 equivalents per year) during the manufacture of the vehicle (and its specific technological components), as well as during operation over its operating life.

Base-level criteria: Global emissions avoidance

- Avoidance of CO_2 emissions in vehicle and component production
- Avoidance of CO_2 emissions in railway operation

Local emissions avoidance

The local emissions avoidance criterion describes the extent to which the multiple unit drive concept emits substances that are hazardous to health (e.g. NO_x, fine particulates) during operation and generates obtrusive engine or running noise.

Base-level criteria: Local emissions avoidance

- Avoidance of local emission of pollutants
- Avoidance of motor/engine and running noise

Energy efficiency

The energy efficiency criterion describes the efficiency with which the multiple unit concept is expected to generate the required drive energy and convert it into kinetic energy when in operation (in 2025).

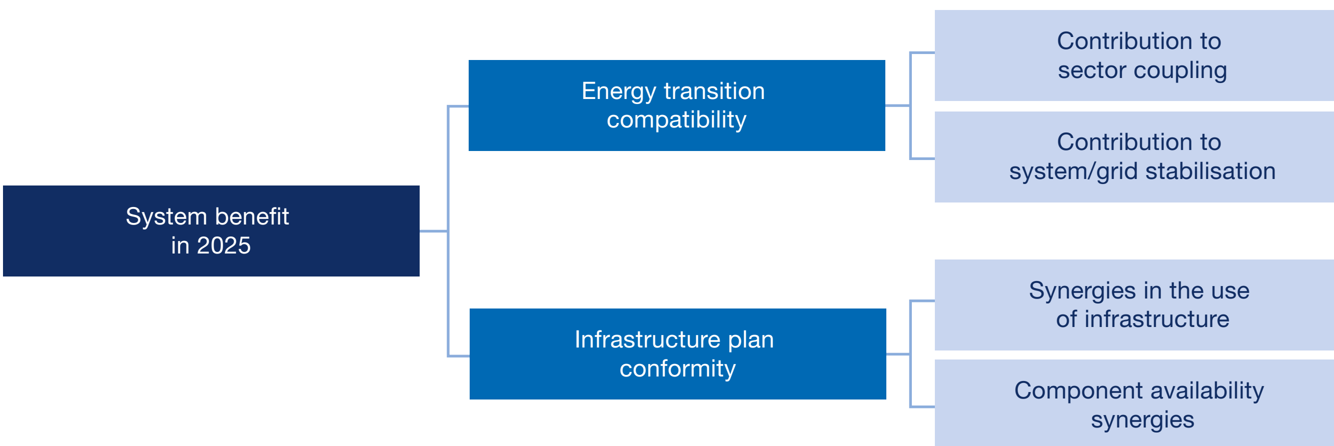
Base-level criteria: Energy efficiency

- Energy efficiency in fuel production in 2025
- Energy efficiency in railway operation in 2025

5.2.4 Systemic benefit in 2025

Introducing a new multiple unit drive concept is not an end in itself, but is based on generally accepted fundamental objectives. These include the energy transition and the transport transition. Associated with this is the coupling of the energy production/distribution and transport sectors. The transport

Figure 39 **Systemic benefit and associated sub-criteria, according to [4]**



transition will involve shifting some of the passenger and freight traffic from the road to the railway. The infrastructure expansion required for this therefore has an impact on the assessment of the multiple unit concept. Key criteria for evaluating the systemic benefit are therefore energy transition compatibility and infrastructure plan conformity.

Energy transition compatibility

The energy transition compatibility criterion describes the extent to which the multiple unit concept is expected to meet the energy transition targets in 2025, i.e. use of renewable energy, sector coupling and power grid stabilisation.

Base-level criteria: Energy transition compatibility

- Contribution to sector coupling
- Contribution to system or grid stabilisation

Infrastructure plan conformity

The infrastructure plan conformity criterion describes the extent to which the introduction of the multiple unit drive concept coincides with the plans of the Federal Government and the Länder for the expansion of the transport infrastructure. For example, there is a systemic benefit if the electrification of a regional passenger railway line is also advantageous to freight traffic, or if it allows the rerouting of long-distance trains in the event of line closures. A hydrogen refuelling station, for example, which can be used for both trains and buses with fuel cell drives, would also be beneficial for the system. Increasing the availability of compatible vehicle and infrastructure technology components for different applications represents a further criterion.

Base-level criteria: Infrastructure plan conformity

- Synergies in the use of infrastructure
- Synergies in technology components for infrastructure and vehicles

5.2.5 Resource availability in 2025

In order to be considered as a potential multiple unit concept, the associated technology components must have achieved technical maturity by 2025 and the vehicles must be ready for deployment. Sufficient quantities of the relevant energy source must be available by this time.

A total of four base-level criteria are assigned to resource availability; these are grouped together to form the mid-level criteria: energy and rolling stock procurement, see → Figure 40.

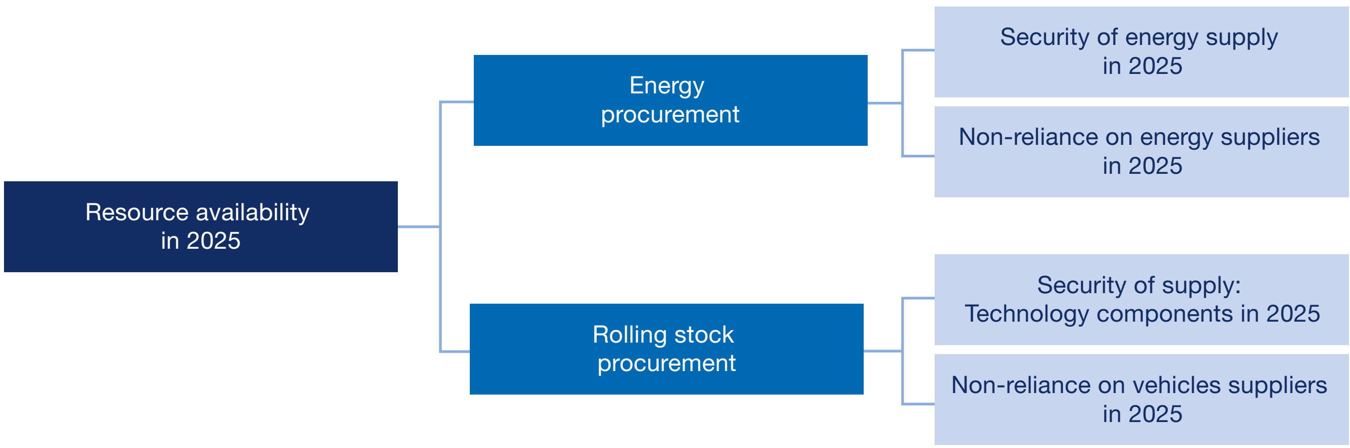


Figure 40 **Resource availability and associated sub-criteria, according to [4]**

Energy procurement

The energy procurement criterion describes the extent to which the energy required for the multiple unit concept can be generated and made available in 2025, plus the number of potential energy suppliers.

Base-level criteria: Energy procurement

- Security of energy supply in 2025
- Non-reliance on energy suppliers in 2025

Rolling stock procurement

The rolling stock procurement criterion describes the extent to which the technology components required for the multiple unit concept (e.g. fuel cells) will be available in 2025, plus the number of potential vehicle manufacturers.

Base-level criteria: Rolling stock procurement

- Security of technology component supply in 2025
- Non-reliance on vehicles suppliers in 2025

5.2.6 Infrastructure friendliness in 2025

As a rule, it is not in the public interest if the introduction of the new multiple unit concept requires a completely new infrastructure. For this reason, it is regarded as an advantage if the costs for the provision or use of infrastructure arising from the introduction of the concept can be kept low.

A total of four base-level and two mid-level criteria are assigned to infrastructure friendliness. The latter are infrastructure economy and infrastructure cost avoidance.
→ Figure 41

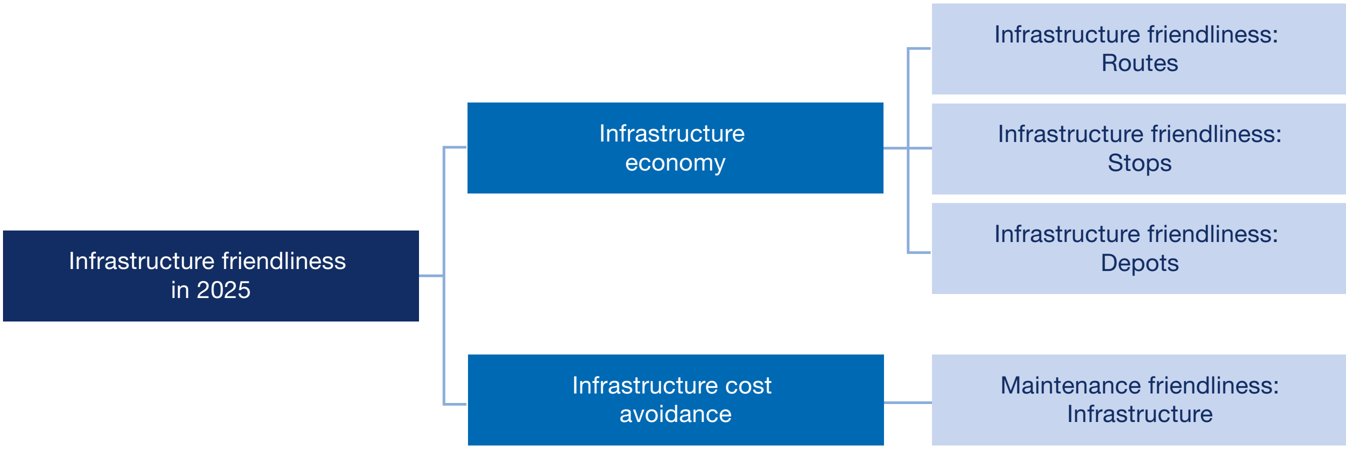


Figure 41 **Infrastructure friendliness and associated sub-criteria, according to [4]**

Infrastructure economy

The criterion of infrastructure economy describes the extent to which the multiple unit concept avoids further expansion of the infrastructure.

Base-level criteria: Infrastructure economy

- Infrastructure friendliness - Routes
- Infrastructure friendliness - Stops
- Infrastructure friendliness - Depots

Infrastructure cost avoidance

The criterion infrastructure cost avoidance describes the extent to which the multiple unit concept is suitable for avoiding ongoing additional costs for infrastructure maintenance.

Base-level criteria: Infrastructure cost avoidance

- Maintenance friendliness - Infrastructure

5.3 Scoring of multiple unit concepts at base-level criteria level

The following → figures 42 to 45 provide a schematic representation of the four multiple unit concepts, i.e. including the respective vehicle type, the associated infrastructure and the equipment required for operation and maintenance, as well as the production sites and the distribution of the required drive energy. Icons provide a rough overview of the properties to be evaluated: particular strengths are indicated by plus signs; weaknesses by minus signs. These representations have no claim to completeness. The complete picture is provided in → tables 7 to 14: the number of points (0-10) awarded for each of the 27 base-level criteria are given there, plus reasons.

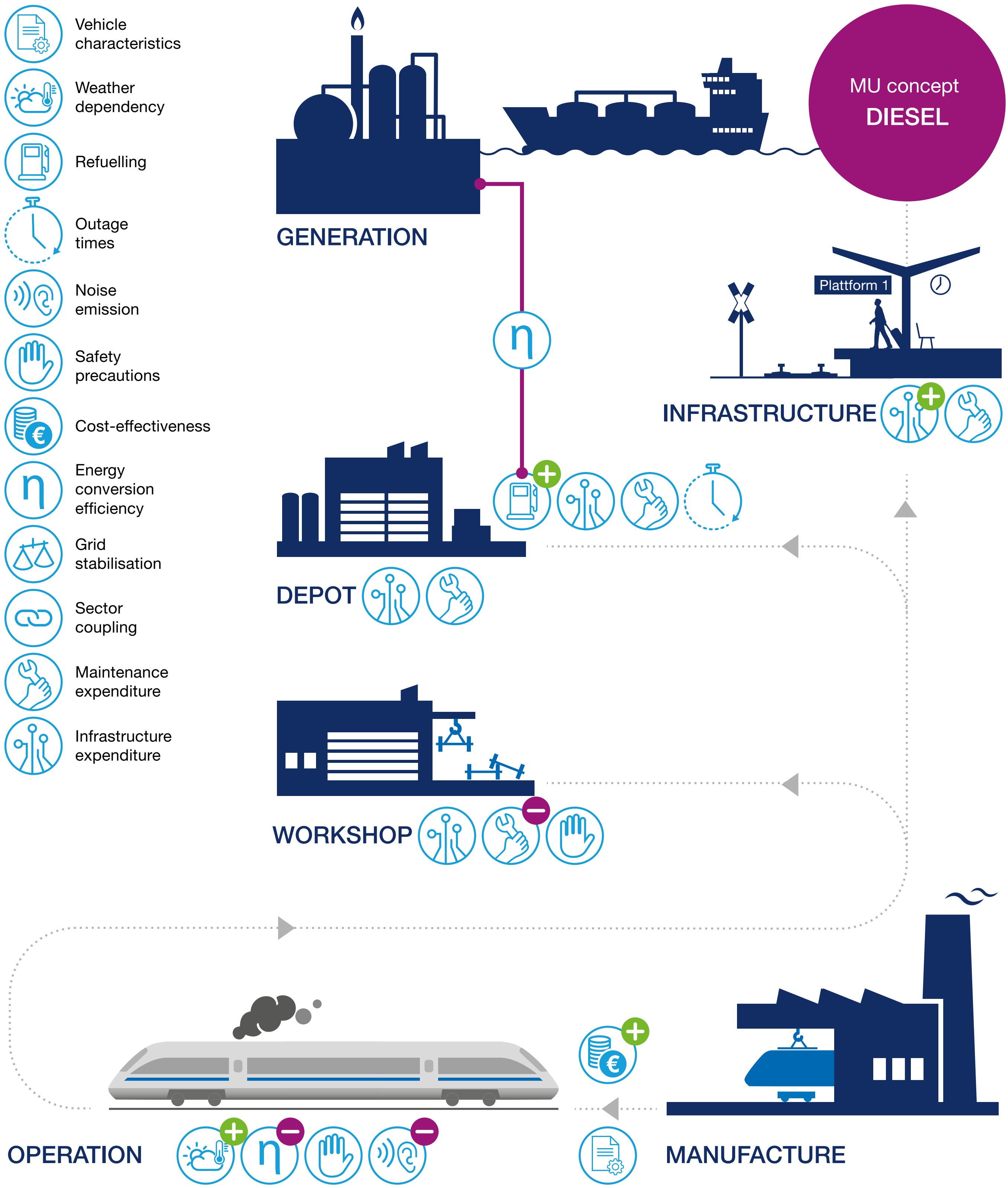


Figure 42 **Diesel multiple unit (DM) concept shown within landscape model**

Diesel multiple unit	(1) Operational friendliness (2) Cost-effectiveness in 2025	Points
Freedom from typical railway faults	Catenary faults have no influence on operation, detours are possible. No other specific advantages with regard to typical railway faults.	7
Resilience to extreme outdoor temperatures	Waste heat from the engine used to support heating. The cooling system has simple technical design. The vehicle is resilient to heat and cold (down to -40 °C).	8
Range reserve	The high energy density of diesel and the large tank allow ranges of up to 1,600 km. The vehicle can be used on all types of lines.	8
Dynamic reserve	The diesel engines used are not particularly powerful and usually allow only low acceleration and speed levels (depending on weight).	3
Passenger capacity reserve	There is a relatively small range of carriage sizes for diesel multiple compared to EMUs. Multiple traction is necessary to cope with any increase in capacity demand.	7
Maintenance friendliness: Vehicle	The high mechanical stress on the drive requires power pack (engine unit) replacement every three years. Oil, air filter etc. must be changed regularly.	3
Safety performance: ECM	Workshop personnel's extensive experience of handling flammable and toxic diesel keeps down the risk levels.	7
Safety performance: Railway operation	Experience with diesel keeps operational hazards within limits. Fire risk, fire behaviour and environmental hazards are nevertheless critical.	6
Cost performance	Infrastructure maintenance costs are relatively low. Suitable for low frequency traffic and lines with no catenary. Diesel price/environmental regulations endanger cost-effectiveness.	8

Table 7 **Evaluation of the diesel MU concept with regard to base-level criteria for (1) and (2), according to [4]**

Diesel multiple unit	(3) Environmental compatibility in 2025	Points
Avoidance of CO_2-emissions for vehicle/ comp. prod.	The production of diesel engines generates comparatively low CO_2 emissions. Recycling processes are fully developed.	10
Avoidance of CO_2 emissions in railway operation	During operation, the combustion of diesel leads to high CO_2 emissions.	0
Avoidance of local emission of pollutants	The combustion of diesel to drive a vehicle produces local pollutants which can have an irritant and environmentally damaging effect.	0
Avoidance of engine and running noise	The engine emits considerable noise levels during idling and when setting off. While running, the main problem is wheel-rail noise.	2
Fuel production – Energy efficiency in 2025	The engine conversion efficiency in the production and supply of diesel is 90%.	10
Railway operation – Energy efficiency in 2025	The efficiency of the conversion of the energy stored in the diesel fuel into kinetic energy is only 33%.	3

→

Diesel multiple unit	(4) Systemic benefit in 2025	Points
Contribution to sector coupling	The energy and transport sectors are not integrated.	0
Contribution to system/ grid stabilisation	There is no interface for stabilising fluctuations in the electricity grid caused by renewable energy.	0
Synergies in infrastructure use	Refuelling facilities are accessible via tracks and are available to all rail vehicles. There are no synergies with other sectors.	3
Synergies arising from component availability	Infrastructure and vehicle components are mature, available in the right quantity and quality, but there is no potential for technological improvement.	5
Diesel multiple unit	**(5) Availability of resources in 2025**	**Points**
Security of supply: Energy in 2025	A sufficient choice of refineries is available. Diesel is easy to store and transport. Little can be done to influence the development of diesel prices.	7
Non-reliance on energy suppliers in 2025	DB Energie is the only nationwide supplier of diesel fuel. Free choice of supplier is possible if refuelling stations are owned.	8
Security of supply: Technology components 2025	Vehicles currently available use standardised components. Their availability is assured and their lifetimes are predictable.	10
Non-reliance on vehicles suppliers in 2025	Established manufacturers offer a broad range of diesel multiple units. In the medium term, the market will shrink as there are signs of a move away from diesel solutions.	7
Diesel multiple unit	**(6) Infrastructure friendliness in 2025**	**Points**
Infrastructure friendliness – Route	Deployment of the vehicle requires no new infrastructure measures.	10
Infrastructure friendliness – Stops	Deployment of the vehicle requires no new infrastructure measures.	10
Infrastructure friendliness – Depots	The entire refuelling infrastructure is located in the depot. Investment costs remain moderate thanks to centralisation and use of simple components.	6
Maintenance friendliness: Infrastructure	The infrastructure is centralised, making it operation-friendly and requiring little maintenance. Refuelling is simple and possible without blocking routes.	10

Table 8 **Evaluation of the diesel multiple unit concept with regard to base-level criteria for (3) to (6), according to [4]**

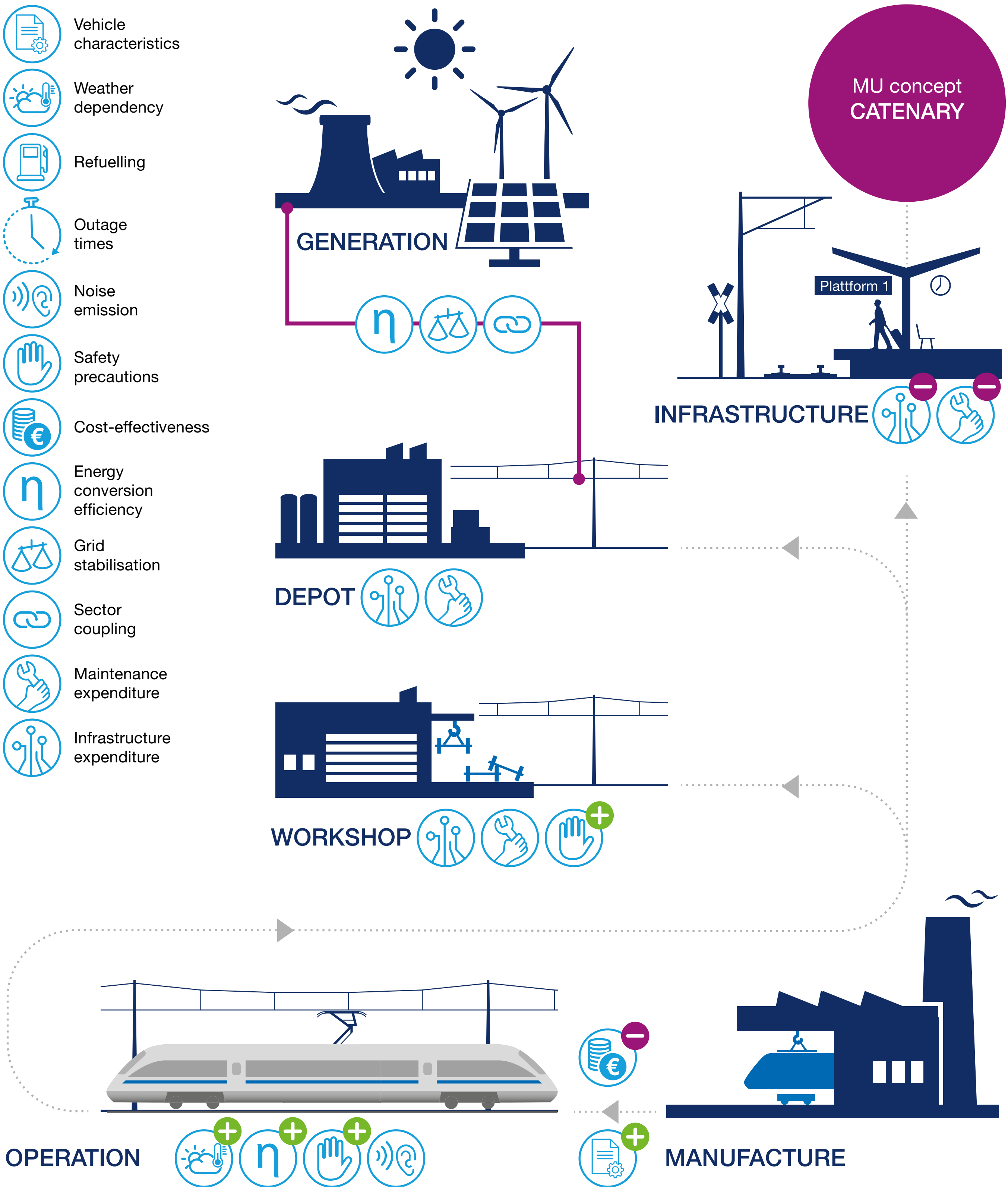


Figure 43 **Catenary MU (OL) concept shown within landscape model – evaluation after complete electrification of a diesel railway line**

OL multiple unit	(1) Operational friendliness (2) Cost-effectiveness in 2025	Points
Freedom from typical railway faults	OL faults (frequency ~1%) can cause serious delays (> 15 min). Diversions are only possible using routes with OL.	3
Resilience to extreme outdoor temperatures	Energy for cooling/heating drives and interiors is obtained from OL without affecting the performance of the drives themselves.	10
Range reserve	Continuous energy supply from OL offers unlimited range, i.e. no refuelling trips necessary. Routes without OL cannot be used.	9
Dynamic reserve	Powerful electric motors allow rapid acceleration and high speeds. Additional energy can be obtained from the OL for power peaks.	10
Passenger capacity reserve	Compact vehicle superstructure allows a wide range of compartment sizes and a high degree of flexibility in the purchase decision.	10
Maintenance friendliness: Vehicle	Electric motors do not have to be replaced within their lifetime. The relatively simple vehicle superstructure keeps maintenance costs low.	10
Safety performance: ECM	During maintenance, the energy supply can be disconnected mechanically. No hazardous chemical substances need to be handled.	10
Safety performance: Railway operation	The energy supply can be disconnected mechanically in the event of a fault. There is no increased fire risk e.g. because of fuel.	10
Cost performance	Electrification is a costly investment with additional maintenance costs. Cost-effectiveness requires high transport performance or intensive line use, which is doubtful on most routes.	4

Table 9 **Evaluation of OL multiple unit concept with regard to base-level criteria for (1) and (2), according to [4]**

OL multiple unit	(3) Environmental compatibility in 2025	Points
Avoidance of CO_2 emissions for vehicle/comp. prod.	The CO_2 equivalent in the manufacture of multiple unit electric motors is higher than that of diesel engines.	8
Avoidance of CO_2 emissions in railway operations	In using OL electricity, railways are following the renewable energy trend. Renewables will account for around 70% of the traction current mix in 2025.	9
Avoidance of local pollutant emissions	The energy obtained from the OL is converted into kinetic energy by electric motors, with no emission of pollutants.	10
Avoidance of engine and running noise	When idling and setting off, it is only auxiliary units which cause noise emissions. While running, the main problem is wheel-rail noise.	8
Fuel production – Energy efficiency in 2025	The efficiency of the DB railway power network will rise to ~78% by 2025.	9
Railway operation – Energy efficiency in 2025	Vehicles convert fuel energy into kinetic energy with around 80% efficiency. Recuperation increases the overall efficiency to 96%.	10

→

OL multiple unit	(4) Systemic benefit in 2025	Points
Contribution to sector coupling	The OL couples the energy sector to the transport sector and thus allows nationwide distribution of renewable energies.	10
Contribution to system/ grid stabilisation	Vehicles convert energy into kinetic energy without intermediate storage, i.e. they do not contribute to grid stabilisation.	0
Synergies in infrastructure use	Any necessary OL expansion is beneficial for the regional passenger rail system and for rail freight. It has not so far been possible for external (non-railway) applications to access the OL.	5
Synergies arising from component availability	Components of the OL system and vehicle technology are universally available. There are hardly any synergies with other sectors.	5
OL multiple unit	**(5) Availability of resources in 2025**	**Points**
Security of supply: Energy in 2025	The supply of traction current is secure and independent of the form of generation. The greater the share of renewables in the electricity mix, the lower the dependency on raw materials.	9
Non-reliance on energy suppliers in 2025	The traction power grid was opened up to other energy suppliers in 2014. Increased competition will reduce the dominance of DB Energie.	8
Security of supply: Technology components 2025	Commercially available vehicles use standardised components with assured availability and predictable service lives.	10
Non-reliance on vehicles suppliers in 2025	The market offers a broad portfolio of electric multiple units from established manufacturers based in Germany and Europe.	10
OL multiple unit	**(6) Infrastructure friendliness in 2025**	**Points**
Infrastructure friendliness – Route	Deployment of the vehicle requires gapless electrification. This includes (visually obtrusive) masts, contact wires and substations.	3
Infrastructure friendliness – Stops[1]	Stop points must have OLs to be accessible. The installation of OLs in railway stations is comparatively simple and aesthetically non-critical.	4
Infrastructure friendliness – Depots[1]	Depots require OLs in order to be accessible. The installation of OLs in/around depots is comparatively simple and aesthetically non-critical.	5
Maintenance friendliness: Infrastructure	Maintenance of the OL infrastructure is relatively costly and time-consuming. The relevant track is occupied during OL maintenance work.	2

1 The assigned point values seem to some experts too high as the provision of catenary is costly in case of track switches!

Table 10 **Evaluation of OL multiple unit concept for (3) to (6), according to [4]**

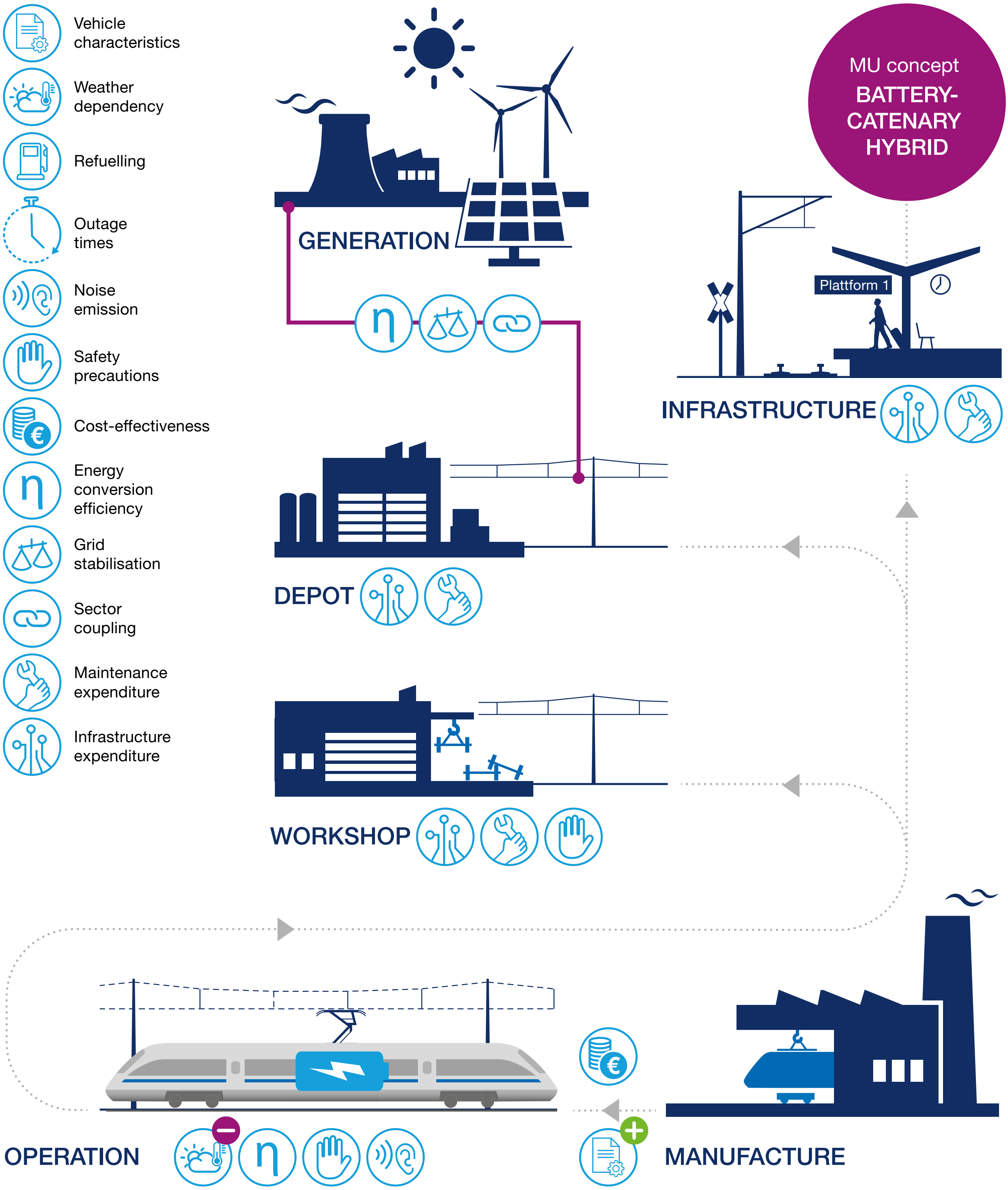


Figure 44 **Battery-powered multiple unit (BOH) concept shown within landscape model**

Battery-powered multiple unit	(1) Operational friendliness (2) Cost-effectiveness in 2025	Points
Freedom from typical railway faults	OL faults can be compensated to a limited extent. The short range requires the availability of functioning charging points.	5
Resilience to extreme outdoor temperatures	Extreme outdoor temperatures require preheating or cooling of the battery. Increased energy consumption is at the expense of range.	4
Range reserve	Ranges of up to 80 km are possible; charging via OL. Close vehicle-infrastructure dependency makes use on other routes more difficult.	3
Dynamic reserve	Powerful electric motors enable relatively high acceleration rates and speeds, but always at the expense of range.	5
Passenger capacity reserve	Limited range of compartment sizes available. The passenger capacity can be increased by means of multiple traction.	4
Maintenance friendliness: Vehicle	The battery is maintenance-free. Heavy-duty use shortens the battery life. Battery replacement after 8-15 years.	8
Safety performance: ECM	The battery is maintenance-free and remains sealed. Battery components are highly flammable. Complete absence of voltage is not possible.	5
Safety performance: Railway operation	The battery can easily be disconnected from the vehicle electrical system.	8
Cost performance	Where OLs exist there are no additional infrastructure costs for charging. The vehicle is particularly suitable for routes with low traffic frequencies and short OL gaps.	8

Table 11 **Evaluation of the battery-powered multiple unit concept with regard to base-level criteria for (1) and (2), according to [4]**

Battery-powered multiple unit	(3) Environmental compatibility in 2025	Points
Avoidance of CO_2 emissions for vehicle/comp. prod.	The materials used in the production of traction batteries and electric motors are associated with increased CO_2 emissions.	2
Avoidance of CO_2 emissions in railway operation	Charge current from the OL factors in the increasing share of renewables, which will rise to about 70% by 2025. Energy conversion efficiency disadvantages in battery use lead to higher consumption.	8
Avoidance of local emission of pollutants	No local pollutants are produced by the drive, as the chemical reactions in the battery take place without emitting pollutants.	10
Avoidance of engine and running noise	The power drawn from the battery does not contribute to noise levels. Otherwise, the operating noise levels correspond to those of OL multiple units.	8
Fuel production – Energy efficiency in 2025	The efficiency of the DB railway power network will rise to ~78% by 2025.	9
Railway operation – Energy efficiency in 2025	The efficiency of the conversion of electrical energy into kinetic energy is 86–96% (incl. recuperation).	8

→

Battery-powered multiple unit	(4) Systemic benefit in 2025	Points
Contribution to sector coupling	Vehicles allow renewable energies with high-level energy conversion efficiency to be distributed throughout the country.	9
Contribution to system/ grid stabilisation	Operational running reduces power peaks for the OL and substations. Direct use of the energy provided reduces the contribution to grid stabilisation.	2
Synergies in infrastructure use	Charging devices or the OL cannot be accessed by non-railway applications. The infrastructure can be used for other train applications.	4
Synergies arising from component availability	Battery and charging infrastructure component synergies exist with buses and HGVs. Availability and prices are constantly improving.	10
Battery-powered multiple unit	**(5) Availability of resources in 2025**	**Points**
Security of supply: Energy in 2025	The reliability of the energy supply corresponds to that of OL multiple units. The increasing share of renewable energy creates independence from international sources.	9
Non-reliance on energy suppliers in 2025	The traction power grid was opened up to other energy suppliers in 2014. Increased competition will reduce the dominance of DB Energie.	8
Security of supply: Technology components 2025	Battery suppliers use the same (mostly Asian) cell manufacturers. Train and car manufacturers compete for cell suppliers.	3
Non-reliance on vehicles suppliers in 2025	The numbers of suppliers and vehicle models are still limited. A broad range of different vehicles is expected to be launched by 2025.	3
Battery-powered multiple unit	**(6) Infrastructure friendliness in 2025**	**Points**
Infrastructure friend-liness – Route	It may be necessary to expand parts of the OL infrastructure in order to travel longer distances. Measures can spoil the appearance of the environment.	6
Infrastructure friendliness – Stops	Existing stopping points, even those without an OL, can be used. Improved accessibility and technical conditions simplify any local electrification that may be necessary.	7
Infrastructure friendliness – Depots[1]	Depots need charging stations or overhead lines. The investment costs required for this are relatively high.	4
Maintenance friendliness: Infrastructure	OL equipment or charging stations incur maintenance costs. The locations may be distributed. OL maintenance work can block the relevant tracks.	5

1 The assigned point values seem to some experts too low as only few depots are concerned

Table 12 **Evaluation of the battery-powered multiple unit concept with regard to base-level criteria for (3) to (6), according to [4]**

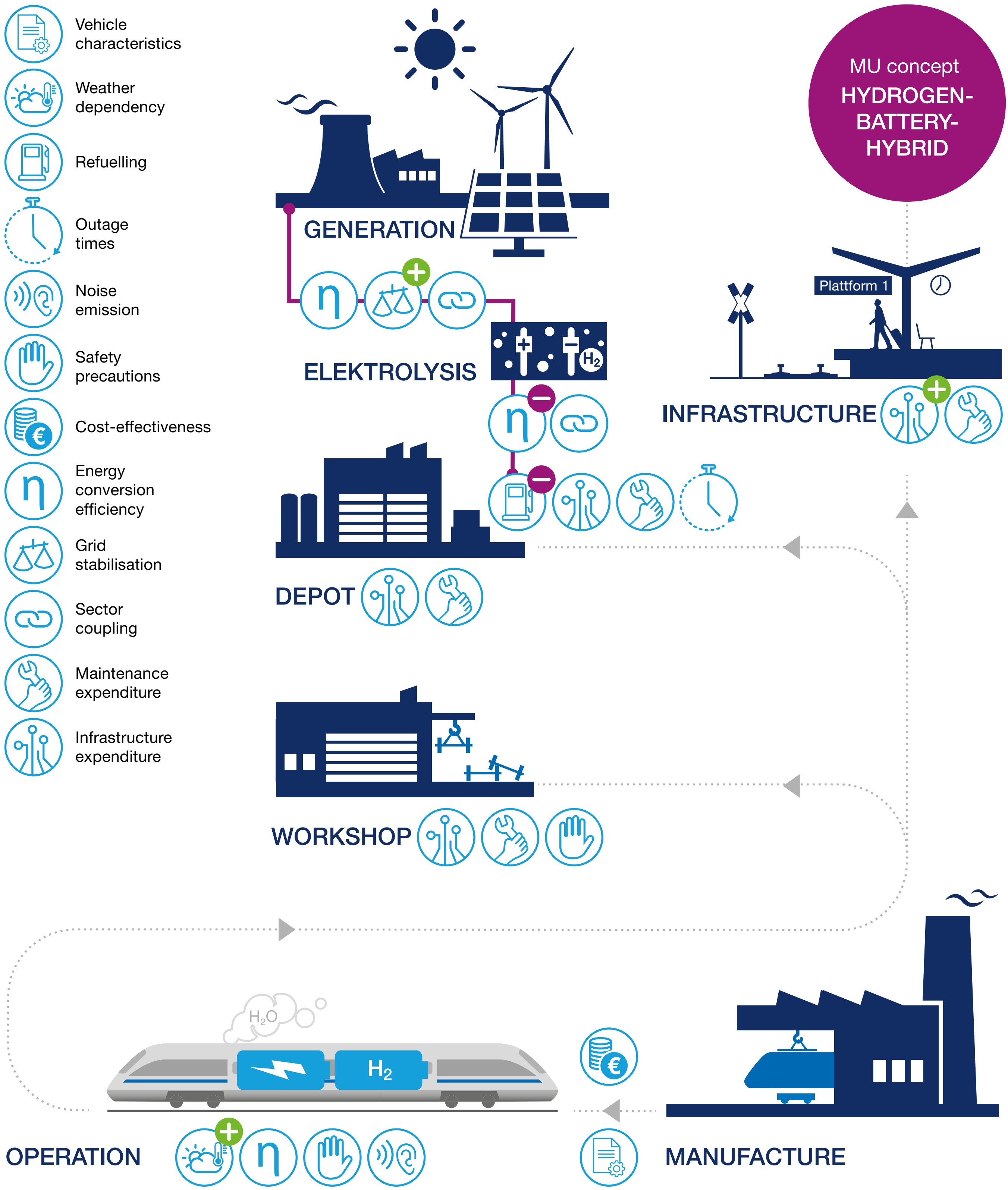


Figure 45 **Fuel cell multiple unit (WBH) concept shown within landscape model**

Fuel cell multiple unit	(1) Operational friendliness (2) Cost-effectiveness in 2025	Points
Freedom from typical railway faults	OL faults have no influence on operation. Detours are possible. No other advantages with regard to typical railway faults.	7
Resilience to extreme outdoor temperatures	The vehicle is resilient to heat and cold (down to -20 °C). Cooling requires a complex system. Fluctuations can be compensated with more fuel.	8
Range reserve	Depending on the size of the hydrogen tanks, ranges of around 1,000 km are possible. The vehicle can thus be used on all types of line.	7
Dynamic reserve	Powerful electric motors enable relatively high acceleration rates and speeds.	7
Passenger capacity reserve	Long ranges require long carriage variants/multicarriage vehicles. Improvements are expected in tanks with higher hydrogen pressure values.	4
Maintenance friendliness: Vehicle	The maintenance costs for fuel cell systems are relatively high. Fuel cells must be replaced after 4-8 years, batteries after 8-15 years.	5
Safety performance: ECM	Hydrogen is highly flammable, but not toxic. The energy source can be fully and simply disconnected. High gas pressure in the tank is controllable.	6
Safety performance: Railway operation	During operation, there are strict safety requirements and predefined emergency procedures. Hydrogen is highly flammable, but evaporates quickly and is therefore safer than diesel.	5
Cost performance	Infrastructure costs are relatively low, since there is no OL. Costs for local infrastructure and the hydrogen price must be viable for low frequency operation on the line.	8

Table 13 **Evaluation of fuel cell multiple unit concept with regard to base-level criteria for (1) and (2), according to [4]**

Fuel cell multiple unit	(3) Environmental compatibility in 2025	Points
Avoidance of CO_2 emissions for vehicle/ comp. prod.	The production of fuel cells, batteries, electric motors and pressure tanks is associated with increased CO_2 emissions.	1
Avoidance of CO_2 emissions in railway operations	Energy is used to produce the hydrogen consumed in operation. There are advantages to electrolysis using renewable energy despite the relatively low efficiency level.	5
Avoidance of local pollutant emissions	Electricity for train operation is generated by the reaction of H_2 with air O_2 in the fuel cell. The only exhaust gas which is created is pure water vapour (H_2O)	10
Avoidance of engine and running noise	Fuel cells operate quietly. Compressors and fans create noise when starting up. Otherwise, wheel-rail noise dominates.	7
Fuel production - Energy efficiency in 2025	In 2025, the energy conversion efficiency of hydrogen production using public grid electricity was only 42%.	4
Railway operation - Energy efficiency in 2025	Conversion of the energy stored in the hydrogen into kinetic energy has an efficiency level of around 55% (incl. recuperation).	5

→

Fuel cell multiple unit	(4) Systemic benefit in 2025	Points
Contribution to sector coupling	By using renewable energy for electrolytic hydrogen production, the operation contributes indirectly to sector coupling.	5
Contribution to system/ grid stabilisation	The system relevance of hydrogen grows with the share of renewable energy. Time-decoupled energy storage in hydrogen, and electricity generation in vehicles promote the integration of renewables into the power grid.	10
Synergies in infrastructure use	The provision of hydrogen yields synergies with other utilisation paths. These simplify the establishment of redundant hydrogen sources and supply chains.	9
Synergies arising from component availability	Hydrogen technology components can also be found in bus applications. Improved availability and lower prices can therefore be expected.	10
Fuel cell multiple unit	**(5) Availability of resources in 2025**	**Points**
Security of supply: Energy in 2025	Various processes are available for hydrogen production. Hydrogen transport requires local supply structures. Systemic redundancy is difficult.	4
Non-reliance on energy suppliers in 2025	Grey/green hydrogen is provided by vehicle manufacturers/partners. There is currently no free choice of supplier or free-market pricing system.	1
Security of supply: Technology components 2025	There are only a few suppliers of fuel cells. Multiple unit and automotive manufacturers compete for fuel cells suppliers.	3
Non-reliance on vehicles suppliers in 2025	The numbers of suppliers and vehicle models are still limited. A broader range of vehicles is expected to be available by 2025.	3
Fuel cell multiple unit	**(6) Infrastructure friendliness in 2025**	**Points**
Infrastructure friendliness - Route	Deployment of the vehicle requires no new infrastructure measures.	10
Infrastructure friendliness - Stops	Deployment of the vehicle requires no new infrastructure measures.	10
Infrastructure friendliness - Depots	A new refuelling infrastructure must be provided in the depots, with corresponding investment costs.	0
Maintenance friendliness: Infrastructure	Infrastructure maintenance can be organised centrally, with no obstruction of tracks. Increased susceptibility to faults (especially in the refuelling system) limits the infrastructure friendliness.	7

Table 14 **Evaluation of the fuel cell multiple unit concept with regard to base-level criteria for (3) to (6), according to [4]**

5.4 Weighting of the base-level and mid-level criteria

The basic procedure for the benefit analysis is shown in → Table 15. The degrees of fulfilment of two alternatives with regard to the top-level criterion H1 are considered here as examples. Points are awarded at the level of the base-level criteria. At the level above this, a mid-level score is yielded as a scalar product of the alternative's scores within the relevant base-level criteria group with the corresponding base-level weighting[9] (%). At the level of the top-level criteria, each top-level score is yielded in turn as a scalar product of the mid-level scores and the corresponding mid-level weightings. This ensures that each base-level criterion feeds in to the overall score based on its importance.

It is evident that not only the individual scores, but also the associated weightings must be determined carefully if an accurate assessment of the various multiple unit concepts is to be obtained. For this reason, the authors used the final workshop with the participants of the interviews carried out in 2018 to ascertain the relevance of the various base-level criteria. An online survey tool was used for this purpose, allowing each participant to participate in the criteria voting during the workshop.

Table 15 **Criteria weighting principle, and example**

Top-level criterion	Top-level score (HN) for Alternative 1	Top-level score (HN) for Alternative 2	Mid-level criterion	Weighting Mid-level	Mid-level score (MN) for Alternative 1	Mid-level score (MN) for Alternative 2	Base-level criterion	Weighting Base-level	Score Altern. 1	Score Altern. 2
H1	$\text{A1-HN}_1 = \alpha_{H1M1} * \text{A1-MN}_{11} + \alpha_{H1M2} * \text{A1-MN}_{12} + \alpha_{H1M3} * \text{A1-MN}_{13}$	$\text{A2-HN}_1 = \alpha_{H1M1} * \text{A2-MN}_{11} + \alpha_{H1M2} * \text{A2-MN}_{12} + \alpha_{H1M3} * \text{A2-MN}_{13}$	H1M1	α_{H1M1}	$\text{A1-MN}_{11} = \text{A1-N}_{111} * \alpha_{H1M1B1} + \text{A1-N}_{112} * \alpha_{H1M1B2}$	$\text{A2-MN}_{11} = \text{A2-N}_{111} * \alpha_{H1M1B1} + \text{A2-N}_{112} * \alpha_{H1M1B2}$	H1M1B1	α_{H1M1B1}	A1-N_{111}	A2-N_{111}
							H1M1B2	α_{H1M1B2}	A1-N_{112}	A2-N_{112}
			H1M2	α_{H1M2}	$\text{A1-MN}_{12} = \text{A1-N}_{121} * \alpha_{H1M2B1} + \text{A1-N}_{122} * \alpha_{H1M2B2} + \text{A1-N}_{123} * \alpha_{H1M2B3} + \text{A1-N}_{124} * \alpha_{H1M2B4}$	$\text{A2-MN}_{12} = \text{A2-N}_{121} * \alpha_{H1M2B1} + \text{A2-N}_{122} * \alpha_{H1M2B2} + \text{A2-N}_{123} * \alpha_{H1M2B3} + \text{A2-N}_{124} * \alpha_{H1M2B4}$	H1M2B1	α_{H1M2B1}	A1-N_{121}	A2-N_{121}
							H1M2B2	α_{H1M2B2}	A1-N_{122}	A2-N_{122}
							H1M2B3	α_{H1M2B3}	A1-N_{123}	A2-N_{123}
							H1M2B4	α_{H1M2B4}	A1-N_{124}	A2-N_{124}
			H1M3	α_{H1M3}	$\text{A1-MN}_{13} = \text{A1-N}_{131} * \alpha_{H1M3B1} + \text{A1-N}_{132} * \alpha_{H1M3B2}$	$\text{A2-MN}_{13} = \text{A2-N}_{131} * \alpha_{H1M3B1} + \text{A1-N}_{132} * \alpha_{H1M3B2}$	H1M3B1	α_{H1M3B1}	A1-N_{131}	A2-N_{131}
							H1M3B2	α_{H1M3B2}	A1-N_{132}	A2-N_{132}

Top-level criterion	Top-level score (HN) for Alternative 1	Top-level score (HN) for Alternative 2	Mid-level criterion	Weighting Mid-level	Mid-level score (MN) for Alternative 1	Mid-level score (MN) for Alternative 2	Base-level criterion	Weighting Base-level	Score Altern. 1	Score Altern. 2
H1	6.9	5.9	H1M1	27%	7.4	4.7	H1M1B1	57%	7	3
							H1M1B2	43%	8	7
			H1M2	30%	6.7	7.2	H1M2B1	33%	7	9
							H1M2B2	33%	8	7
							H1M2B3	17%	5	5
							H1M2B4	17%	5	6
			H1M3	43%	6.7	5.7	H1M3B1	27%	6	5
							H1M3B2	73%	7	6

9 The sum of the weightings within a top-level criteria group is 100%.

The weightings of the criteria therefore stem exclusively from the online survey of the participants. The 21 participants of the workshop represent six public decision makers, three railway undertakings and four manufacturers. Infrastructure providers, energy suppliers, researchers, consultants, associations and politicians were also represented. The points were awarded step by step, i.e. the participants entered the base-level criteria weightings (as %) that they considered appropriate following an explanation of each of the base-level criteria of the parent mid-level criterion (e.g. operational flexibility under operational friendliness). The averages of the scoring results (all participants or differentiated by sector) can be found in → Table 16 and → Table 17. The average weightings of the mid-level criteria within the parent top-level criteria (e.g. operational friendliness) are given in → Table 18.

Table 16 **Assessment of the relevance of the base-level criteria by workshop participants (Part 1)**

Operational friendliness	**Reliability**		**Operational flexibility**				**Safety performance**	
	Freedom from typical railway faults	Resilience to extreme outdoor temperatures	Range reserve	Dynamic reserve	Passenger capacity reserve	Maintenance friendliness	Safety performance: ECM	Safety performance: Operation
All participants	**58%**	42%	**34%**	30%	11%	25%	36%	**64%**
Public decision maker	**62%**	38%	33%	**36%**	15%	17%	29%	**71%**
EVU	50%	50%	23%	33%	10%	33%	43%	**57%**
Manufacturer	**66%**	34%	35%	24%	6%	35%	50%	50%
Govt/Associations	**68%**	33%	28%	28%	15%	**30%**	28%	**73%**
Research/Consulting	**73%**	27%	30%	**32%**	13%	25%	43%	**57%**
Infrastructure/Energy	25%	**75%**	**53%**	22%	5%	20%	23%	**77%**

Environmental compatibility	**Global emissions avoidance**		**Local emissions avoidance**		**Energy efficiency in 2025**		**Cost-effectiveness**	**Cost performance**
	Avoidance of CO_2 emissions: Veh./comp. prod.	Avoidance of CO_2 emissions: railway operations	Avoidance of local pollutant emissions	Avoidance of engine/ running noise	Efficiency: Fuel production	Efficiency: Railway operation		Cost performance
All participants	25%	**75%**	**61%**	39%	40%	**60%**		100%
Public decision maker	30%	**70%**	**69%**	31%	47%	**53%**		100%
EVU	18%	**82%**	**58%**	42%	47%	**53%**		100%
Manufacturer	24%	**76%**	**55%**	45%	30%	**70%**		100%
Govt/Associations	18%	**83%**	43%	**58%**	19%	**81%**		100%
Research/Consulting	15%	**85%**	**58%**	42%	40%	**60%**		100%
Infrastructure/Energy	40%	**60%**	**73%**	27%	50%	50%		100%

The greatest value is bold in each case

Note: The workshop discussion, especially of the base-level criteria for “operational flexibility”, prompted the authors to reword some criteria retrospectively in order to avoid possible misunderstandings. For example, they chose “Dynamic reserve” instead of “Technical performance”, or “Range reserve” instead of “Concept-specific range/refuelling trips”.

Systemic benefit	Energy transition compatibility		Infrastructure plan conformity	
	Contribution to sector coupling	Contribution to system/ mains stabilisation	Synergies from Infrastructure use	Synergies from component availability
All participants	**64%**	36%	**54%**	46%
Public decision maker	**63%**	38%	**53%**	47%
EVU	**52%**	48%	**57%**	43%
Manufacturer	**76%**	24%	44%	**56%**
Govt/Associations	**63%**	38%	**68%**	33%
Research/Consulting	**55%**	45%	**63%**	37%
Infrastructure/Energy	**70%**	30%	50%	50%

Resource availability	Energy procurement		Rolling stock procurement	
	Security of supply: Energy	Supplier non-reliance: Energy	Security of supply: Tech.comps.	Supplier non-reliance: Vehicles
All participants	**63%**	37%	**55%**	45%
Public decision maker	**64%**	36%	48%	**53%**
EVU	**65%**	35%	**63%**	37%
Manufacturer	**68%**	33%	**60%**	40%
Govt/Associations	**73%**	28%	**83%**	18%
Research/Consulting	**52%**	48%	**53%**	47%
Infrastructure/Energy	**55%**	45%	37%	**63%**

Infrastructure friendliness	Infrastructure economy			Infrastructure cost avoidance
	Infrastructure friendliness: Route	Infrastructure friendliness: Stops	Infrastructure friendliness: Depots	Maint.-friendly infrastructure
All participants	**45%**	21%	34%	100%
Public decision maker	**59%**	20%	21%	100%
EVU	**42%**	25%	33%	100%
Manufacturer	22%	21%	**57%**	100%
Govt/Associations	**58%**	3%	**40%**	100%
Research/Consulting	**55%**	21%	**24%**	100%
Infrastructure/Energy	33%	**35%**	**32%**	100%

The greatest value is bold in each case

Table 17 **Assessment of the relevance of the base-level criteria by workshop participants (Part 2)**

Resource availability	Operational friendliness			Cost-effectiveness	Environmental compatibility			Systemic benefit		Resource availability		Infrastructure friendliness	
	Reliability	Opera-tional flexibility	Safety perform-ance	Cost perform-mance	Global emissi-ons avoidan-ce	Local emissi-ons avoi-dance	Energy efficiency in 2025	Energy transition compati-bility	Infra-structure plan conformity	Energy procure-ment	Rolling stock procure-ment	Infra-structure economy	Infra-structure cost avoidance
All participants	**42%**	28%	31%	100%	29%	34%	**37%**	54%	46%	45%	55%	55%	45%
Public authority	**53%**	23%	24%	100%	27%	**43%**	30%	**57%**	43%	33%	**68%**	51%	49%
EVU	**38%**	30%	32%	100%	35%	**40%**	25%	50%	50%	55%	45%	**62%**	38%
Manufacturer	33%	33%	**34%**	100%	26%	31%	**43%**	**56%**	44%	**60%**	40%	56%	44%
Govt/ Associations	**58%**	28%	15%	100%	35%	30%	35%	**59%**	42%	34%	**66%**	**70%**	30%
Research/ Consulting	**40%**	38%	22%	100%	20%	27%	**53%**	50%	50%	52%	48%	53%	47%
Infrastructure/ Energy	24%	18%	**58%**	100%	39%	22%	39%	53%	47%	43%	**57%**	50%	50%

The greatest value is bold in each case

Table 18 **Assessment of the relevance of the mid-level criteria by workshop participants**

The weighting results show that top-level criteria which relate directly or indirectly to operation were consistently rated higher than those that relate to infrastructure, power generation or vehicle production. At the level of the mid-level criteria, reliability was gauged by operational flexibility, energy efficiency by avoidance of local emissions, and vehicle availability by energy procurement.

5.5 Potential of multiple unit concepts

The combining of the top-level criteria scores described in Section 5.2.6 with the weights presented in Section 5.4 can be represented in the form of network diagrams, as shown in → Figure 46. The potential of the four multiple unit concepts under consideration can be clearly seen here.

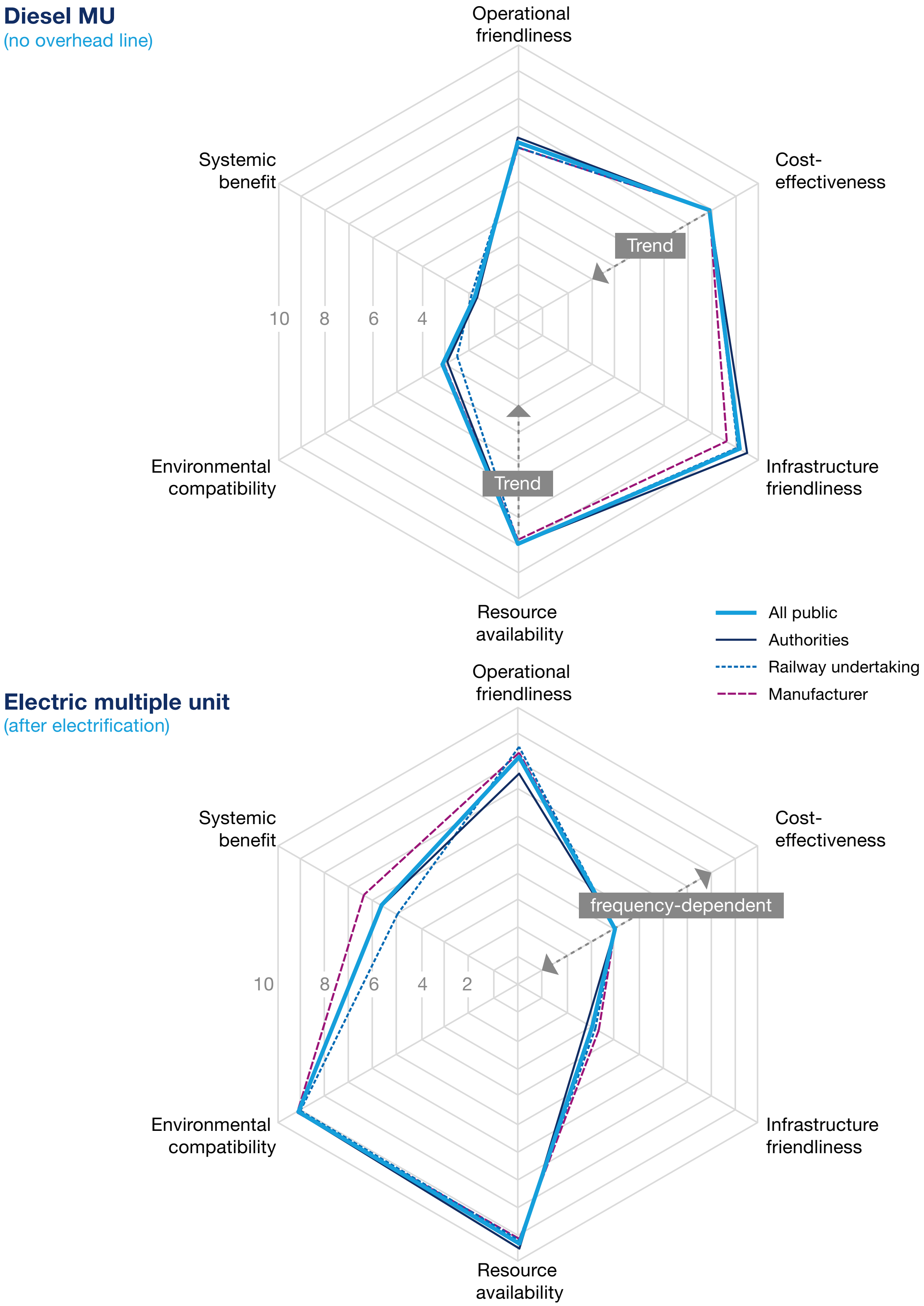
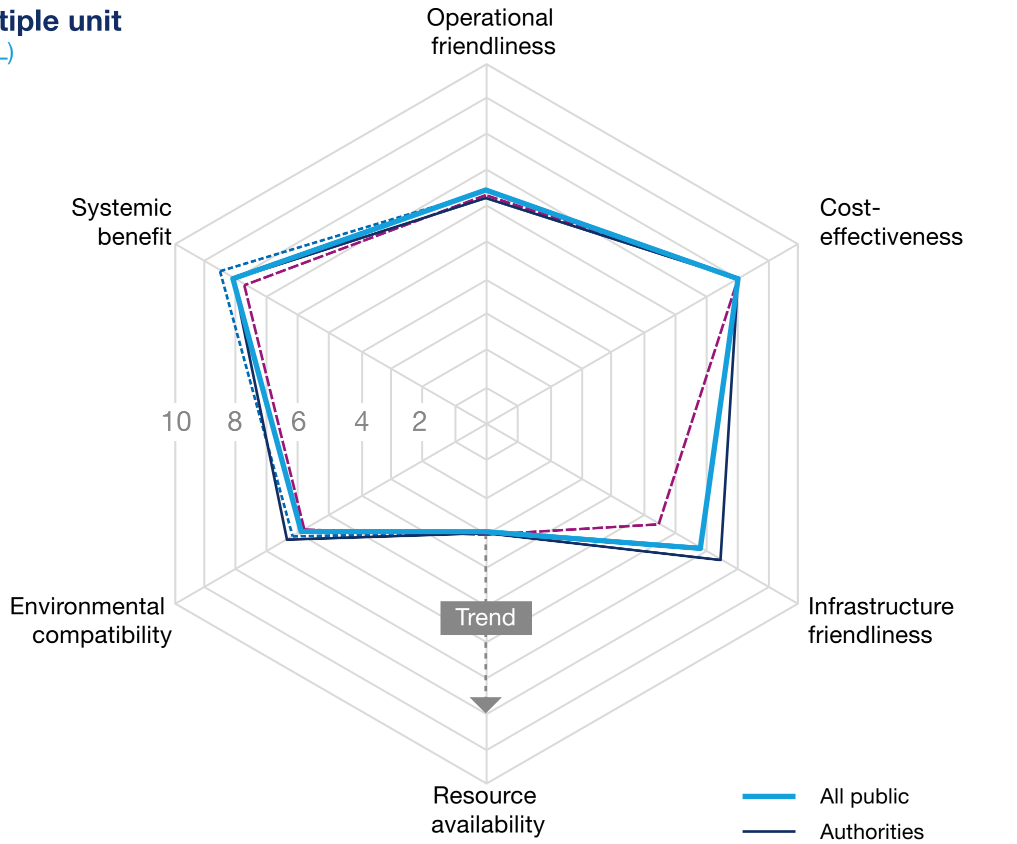
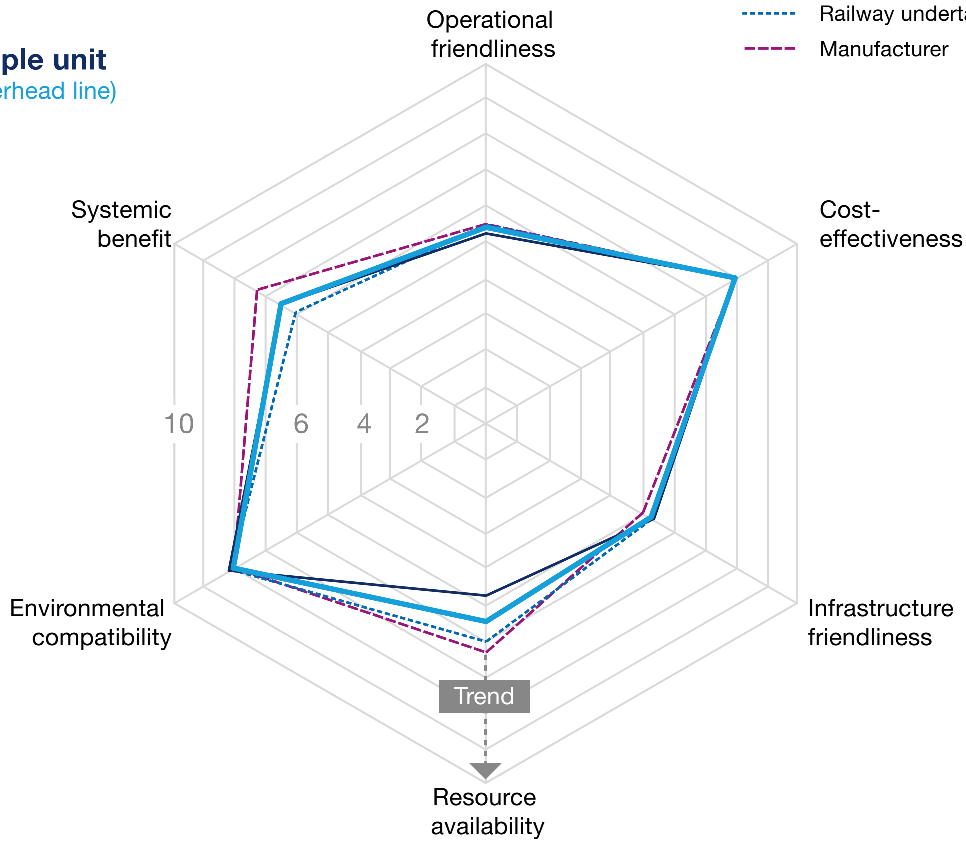


Figure 46 **Potential of the four multiple unit concepts (horizon 2025 and trends), chart based on [4]**

Fuel cell multiple unit
(hydrogen, no OL)



Battery multiple unit
(charging via overhead line)



If the network diagram of the diesel multiple unit is compared with that of the electric multiple unit, it becomes apparent that the two complement each other perfectly – assuming the conditions of today's regional passenger rail system, of course, i.e. with partially electrified railway lines. This explains the current status quo. Vehicle concepts based on alternative drive systems must also take this into consideration. The network diagrams for the fuel cell and battery-powered multiple units show that both have the potential to be alternatives to the current situation – especially when considered together. The predicted trends for the period after 2025 support this view.

The following can be stated regarding the individual drives:

The use of diesel multiple-unit trains on lightly frequented railway lines is feasible as long as overriding issues such as environmental compatibility or systemic benefit do not exclude them. The illegal manipulation of exhaust gas values, referred to in the media as the "diesel scandal", will result in further environmental regulations and bans. Diesel subsidies are likely to be abolished, which will increase the price of diesel. The cost-effectiveness of diesel vehicles will thus deteriorate, and it is conceivable that there will be a further decline in the diesel vehicle market.

The closure of electrification gaps on regional passenger railway lines is the first choice – especially with regard to environmental compatibility and operational friendliness – provided that the lines in question have sufficiently high traffic capacity (with service frequencies of under 1 hour) and that the necessary construction work can be completed quickly.

Fuel cell multiple units and battery-powered multiple units are technically viable alternatives on diesel railway lines in the regional passenger rail system. The advantage of fuel cell multiple units is that they do not require any overhead lines, i.e. in principle they can directly replace diesel units, provided that hydrogen refuelling facilities are available. The use of (green) hydrogen represents a major systemic benefit, i.e. it supports the energy transition and sector coupling. A disadvantage is the low energy conversion efficiency in combination with the proportion of fossil-based electricity used in hydrogen production as well as in converting the energy stored in hydrogen into kinetic energy. It is probably only a matter of time (2025+) before the present disadvantages (the limited choice of vehicles and the lack of production facilities and hydrogen refuelling stations) are overcome.

The great technical similarity with (catenary) electric multiple units and the possibly associated partial electrification as a charging infrastructure measure represent clear advantages of battery-powered multiple units, especially since they do not rule out the option of continuous electrification of current diesel railway lines in the future. The efficient conversion of electrical energy into kinetic energy without the need for indirect conversion to a different energy source is also advantageous. The relatively short range of the battery makes the battery-powered multiple unit concept unique as it requires the characteristics of individual lines to be taken into consideration. This limits its operational flexibility on different railway lines.

Diesel variants such as those with diesel-electric drives or hybridisations (such as pantographs or batteries) were not considered in this benefit analysis, as they ultimately only represent intermediate solutions. Diesel hybrid multiple units in particular, which are based on elaborate conversions of existing diesel multiple units, are difficult to assess in view of their complex technical construction, their costs and uncertain market demand.

5.6 Conclusion of benefit analysis and outlook

The representations of potential advantage shown in → Figure 46 prove that the use of benefit analysis to evaluate multiple unit concepts yields plausible results that can then be evaluated. A prerequisite for this is that the concepts can be awarded points to evaluate their fulfilment of base-level criteria and that the relevance of the individual criteria can be realistically assessed. It also emerged, however that, based on the generally formulated conditions, no clear recommendation can be made for a particular multiple unit concept, since the advantages and disadvantages of the various concepts are more or less balanced. Müller & Stephan endeavoured in [26] to make an economic evaluation of the alternative drive concepts (including diesel hybrids). To this end, they carried out an analysis of the expected costs over the entire life cycle of the vehicle (life cycle costs – LCCs). They chose an existing railway line of approximately 100 kilometres as the model line. Their results can be summarised as follows:

The economic evaluation of alternatives for a diesel railway line requires knowledge of (a) its traffic frequency, (b) the degree of pre-electrification and (c) the percentage of line sections that are difficult to electrify.

Table 19 **Results of the business analysis by Müller & Stephan (qualitative representation)**

<table>
<tr><th>Traffic freq. 0.5 h</th><th colspan="5">70% easy to electrify</th><th colspan="6">85% easy to electrify</th></tr>
<tr><td>Already electrified:</td><td>0%</td><td>20%</td><td>50</td><td>80%</td><td>100%</td><td>0%</td><td>20%</td><td>50%</td><td>80%</td><td>90%</td><td>100%</td></tr>
<tr><td>1st choice</td><td colspan="2">BOH</td><td colspan="2">OL-EMU</td><td>OL-EMU</td><td colspan="5">OL-EMU</td><td>OL-EMU</td></tr>
<tr><td>2nd choice</td><td colspan="2">OL-EMU</td><td colspan="2">BOH</td><td>OL-EMU</td><td colspan="5">BOH</td><td>OL-EMU</td></tr>
<tr><td>Least favourable choice</td><td colspan="5">WBH</td><td colspan="6">WBH</td></tr>
<tr><th>Traffic freq. 1 h</th><th colspan="5">70% easy to electrify</th><th colspan="6">85% easy to electrify</th></tr>
<tr><td>Already electrified:</td><td>0%</td><td>20%</td><td>50</td><td>80%</td><td>100%</td><td>0%</td><td>20%</td><td>50%</td><td>80%</td><td>90%</td><td>100%</td></tr>
<tr><td>1st choice</td><td colspan="2">Diesel hybrid</td><td colspan="2">BOH</td><td>OL-EMU</td><td colspan="2">Diesel hybrid</td><td>BOH</td><td colspan="2">OL-EMU</td><td>OL-EMU</td></tr>
<tr><td>2nd choice</td><td colspan="2">BOH</td><td>Dual mode</td><td>OL-EMU</td><td>OL-EMU</td><td colspan="2">BOH</td><td>OL-EMU</td><td colspan="2">BOH</td><td>OL-EMU</td></tr>
<tr><td>Least favourable choice</td><td>OL-EMU</td><td colspan="4">WBH</td><td colspan="6">WBH</td></tr>
<tr><th>Traffic freq. 2 h</th><th colspan="5">70% easy to electrify</th><th colspan="6">85% easy to electrify</th></tr>
<tr><td>Already electrified:</td><td>0%</td><td>20%</td><td>50%</td><td>80%</td><td>100%</td><td>0%</td><td>20%</td><td>50%</td><td>80%</td><td>90%</td><td>100%</td></tr>
<tr><td>1st choice</td><td colspan="3">Diesel hybrid</td><td>BOH</td><td>OL-EMU</td><td colspan="3">Diesel hybrid</td><td>Dual mode</td><td>BOH</td><td>OL-EMU</td></tr>
<tr><td>2nd choice</td><td colspan="4">Dual mode</td><td>OL-EMU</td><td colspan="3">Dual mode</td><td>BOH</td><td>OL-EMU</td><td>OL-EMU</td></tr>
<tr><td>Least favourable choice</td><td colspan="3">OL-EMU</td><td colspan="2">WBH</td><td colspan="2">OL-EMU</td><td colspan="4">WBH</td></tr>
</table>

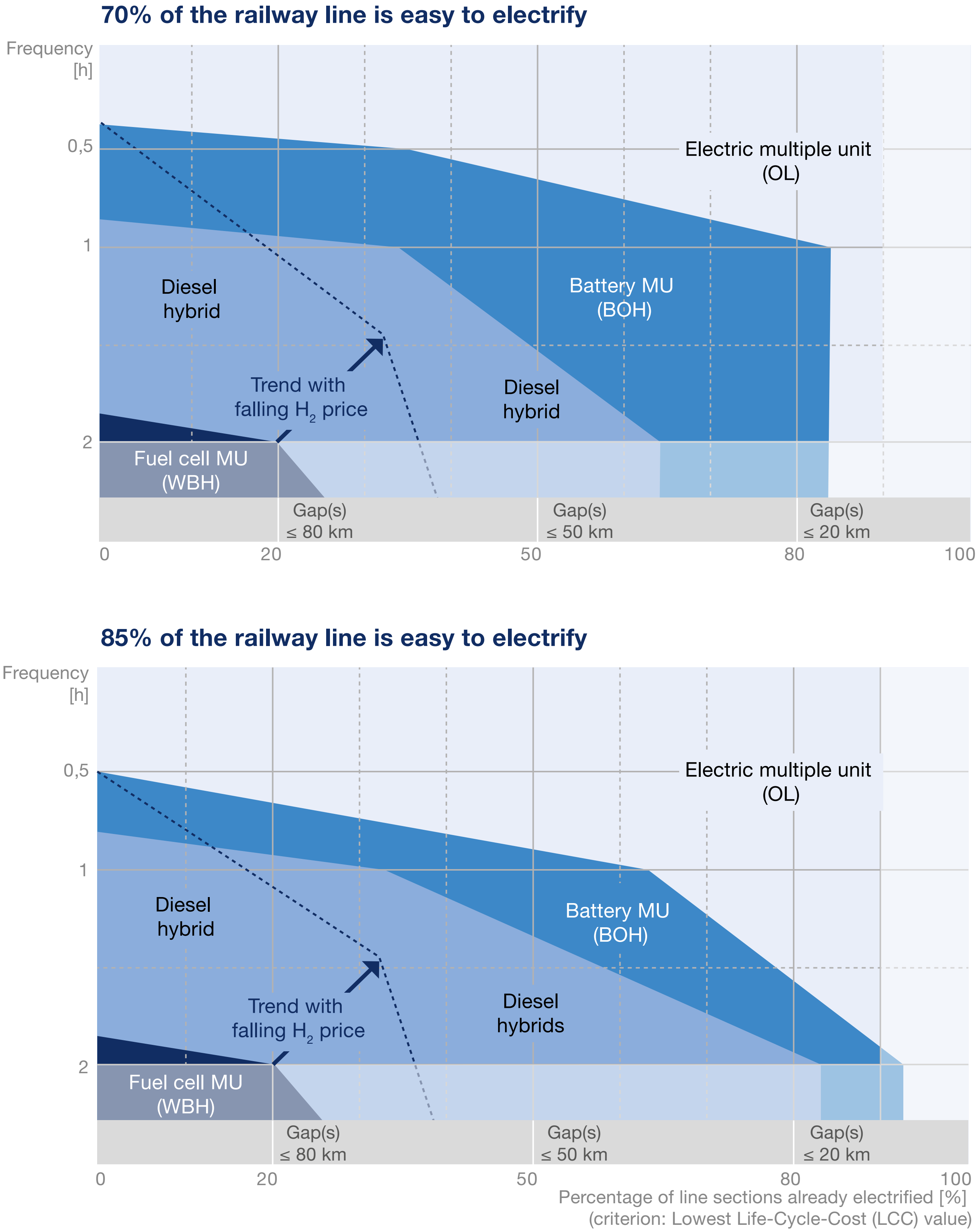


Figure 47 **Visualisation of the LCC considerations of the alternatives, based on [4]**

Traffic frequency is the most powerful factor here: In the case of dense traffic (frequency ≤ 0.5h), complete electrification of the railway line is the best option. In the case of a 1h frequency, the best alternative from an economic perspective depends on the existing degree of electrification and the projected costs for completing the electrification. Interestingly, the study concludes that diesel hybrids are the cheapest option for degrees of electrification of below 25%, while the fuel cell train is regarded as the least economical solution in all cases. The reasons for this negative assessment are as follows: (1) Electrolytically produced hydrogen costs more than € 5/kg; (2) the high-tech fuel cell and dynamic battery components have a short operating life; (3) the required new hydrogen tank infrastructure is relatively costly. This assessment does not take into account the possibility that significant progress could be made in the development of the technological components in the coming years. The systemic benefit of 'green hydrogen' is not taken into account, either. → Table 19 gives a qualitative summary of the results of the Müller & Stephan study.

→ Figure 47 shows a representation of these qualitative results. Reflecting the objectives of the present study, the focus in the graph is on rating the emission-free alternatives, i.e. the diesel variants are neither first nor second choice here. This moves the fuel cell multiple unit (WBH) up into first place, covering a large part of the diesel multiple unit segment. It is also important to note that the model route is 100 kilometres in length. If there is a 60% degree of pre-electrification, for example, no gap to be bridged can be more than 40 kilometres in length. A battery-powered multiple unit would certainly not have to stop for intermediate charging on this route.

Today, diesel multiple units (DM) are often deployed on infrequently used railway lines with low pre-electrification in cases where there are no environmental aspects to consider. Depending on the hydrogen price, fuel cell trains (WBH) basically have the potential to replace diesel multiple units directly on such lines. Hydrogen obtained by steam reforming from natural gas already costs less than € 2/kg [31] today. The price of electrolytically produced hydrogen will be based on this in the long term. The broken line in → Figure 47 indicates that falling hydrogen prices could improve the cost performance of the fuel cell train to such an extent as to make it a viable alternative to diesel on regional passenger rail services with higher traffic frequencies instead of electric or battery trains. The suitability of the battery-powered multiple unit, on the other hand, decreases as an alternative to diesel as the pre-electrification level of the railway line increases. This is because the electric multiple unit is the first choice at high pre-electrification levels.

A purely economic evaluation of the alternatives clearly does not yield a universally applicable recommendation for a particular multiple unit concept, either. In practice, recommending a low or zero-emission concept for a particular railway line presupposes that certain information about the line is available. According to the authors, this includes:

- Length, plus elevation and curve profile of the railway line in question
- Length of the non-electrified sections of the railway line
- Location and spacing of stops
- Travel and round-trip times on the railway line
- Service frequency, daily/weekly timetable
- Acceleration and braking distances, permissible speeds on the railway line
- Power consumption of auxiliary units for heating, air conditioning, lighting, Wi-Fi etc.
- Stopping times at stations and turning times
- Number of parallel tracks (1/2/n tracks)

The following additional information is needed for a more detailed analysis:

- Number of multiple units used on the railway line
- Parking times for multiple units (e.g. overnight etc.)
- Required passenger capacity on the railway line (including reserve buffer if necessary)
- Platform access heights at the stops along the railway line
- If applicable, location of diesel refuelling stations / location of the nearest depot along the railway line
- If applicable, location of hydrogen production sites (electrolysis, natural gas reforming) or hydrogen pipelines

If complete electrification of the railway line is regarded as an option, the following additional information is also of interest:

- Existence of an electrification plan
- Interior height and length of tunnels on the railway line
- Number of level crossings for special vehicles (e.g. heavy loads)
- Number of days of freight traffic on this line

The next (third) subproject will carry out further, more specific benefit analyses on the basis of the information provided on a number of representative diesel railway lines in different federal states. The result will be a further study, the success of which will again depend to a large extent on the willingness of the parties directly or indirectly involved in the decision-making process to participate in workshops and individual interviews.

6 Summary and recommendations

Alternatives to diesel railway lines must be considered on an individual basis

There is no single alternative which is equally ideal for all diesel railway lines in Germany. Decision-makers about to put a new transport contract out to tender for their railway networks have no alternative but to analyse each individual diesel railway line to determine which alternative is indeed the best one in each case. Their choice also depends on whether any plans already exist for the railway line in question. They will have to ask themselves, for example:

- Are any changes in the number of passengers to be expected in the long term?
- Does the railway line compete with local roads or do the two complement each other for traffic?
- Is the route of interest for tourists or commuters?
- Is there a need to change the service frequency of the trains running on the line?
- Could the line potentially promote development in the region?
- Does it make long-term sense to electrify the entire railway line
- Do any regional structures already exist for hydrogen, and will there be any resulting synergies?

Which multiple unit alternative is included in the invitation to tender and is then included in the contracts with the transport companies depends, among other things, on the answers given by the public decision maker to such questions. When making its decision, it can assume that the alternative drives function as required within their specified area of application and comply with the applicable quality requirements, and that the technologies involved will continue to evolve. In addition, it can assume that the corresponding vehicle market will continue to expand.

It should be noted here that analysis of a single diesel railway line is not a sufficient basis for making a concrete decision in favour of a new multiple unit concept, especially when only small numbers of vehicles are involved. The decision should take into account the entire network which is being put out to tender, i.e. the use of the new vehicles in the fleet and their economic operation.

Mobility, environmental and climate objectives complicate the decision-making process

Any decision in favour of a new type of multiple unit concept is not easy and represents a significant challenge for all involved. It requires consideration of the politically and socially prescribed goals of mobility development, environmental and climate protection, it must safeguard regional rail transport as an essential public service, uphold standards of service, comfort and punctuality, ensure the provision and maintenance of the required infrastructure, the availability of vehicle fleets and, not least, the proper use of the regionalisation funds provided by the federal government.

There is potential for the public decision makers to be overwhelmed by the task and a risk of the process being influenced by biased interest groups. This makes it all the more advisable to de-emotionalise the decision-making process and arrive at solutions with the help of objective analytical methods. Benefit analysis represents such a method.

In addition to identifying ‘alternative drives’, other similarly complex decisions also need to be made

Identifying alternatives to diesel multiple units in regional passenger rail systems is an example of a complex decision-making problem. The digitalisation of the railways, the German timetable frequencies or the transfer of traffic to the railways represent similarly complex challenges. Here, too, decision-makers are faced with the problem of having to identify the best options for the future based on the information available today.

6.1 Role of the public decision maker

The reorganisation of duties and responsibilities in the regional passenger rail system has demonstrably led to improvements in the provision and profitability of its operation. The customer-supplier principle (cf. → Section 2.3), which separates the political from the business levels, has proven to be effective. The success can be seen in the increased transport and operating capacity.

The decisions which the public decision-makers have to make today are much more complex than they were in the past

Side effects of the successful increase in the attractiveness of local transport include increased congestion on the main routes, growing passenger dissatisfaction due to substandard quality and delays, as well as heightened expectations regarding the operation of secondary routes. The threat of diesel bans (including in railway stations) and the expectation that emission-free rail transport will also help bring about the decarbonisation of all transport by 2050 will increase the pressure, especially on the public decision makers.

In the past, decisions about vehicles for the regional passenger rail system were relatively simple. Powerful electric multiple units could be used on railway lines with a continuous catenary. If there was no catenary or if there were isolated gaps, diesel multiple units were the only viable option, despite most of these being less powerful and having lower passenger transport capacities. This disadvantage was no great problem, as these were usually secondary lines with low traffic levels anyway. The public decision makers have seldom had to consider the technical details of drive technologies and their energy supply.

The task is now considerably more complex for the public decision makers. The question is no longer simply: "Diesel or electric?" The following decisions also have to be made:

- Electrification – yes or no?
- Diesel-electric or diesel-mechanical?
- Dual-mode or diesel hybrid?
- Diesel or synthetic fuel?
- Hydrogen or battery?

Electrification is generally a federal matter. This immediately raises the question of when is the right time for talking to those responsible about the viability of electrification measures.

Regional interests take precedence over intensive consultation among the public decision makers

The difficulty of identifying low-emission or emission-free drive alternatives betrays the fact that the existing structures in regional passenger rail transport are not really suitable for complex decisions. This applies in particular in cases where in-depth technological and systemic knowledge is required but where it is also important to preserve the attractiveness of the regional passenger rail system and the economic viability of its operation.

The scope of the task and the risks attached are often overwhelming, especially for smaller public decision makers with only a minor share of regionalisation funds. The wheel has seemingly constantly to be reinvented at the regional level because there is no dialogue among the public decision makers, and not even a joint action plan – as the 27 interviews with stakeholders in the railway sector have shown. The relevant associations prefer to concentrate on fundamental issues such as investment in rail infrastructure, digitalisation, etc. They have few resources for dealing with technical coordination issues outside the working groups, for example with the BAG-SPNV.

Overburdening of public decision makers is changing the decision-making and influence structures

The public decision makers often feel abandoned by the politicians and the federally owned railway companies. In particular, if they are organised as special-purpose and transport associations at the local level, they lack the personnel to make important technology decisions. Indeed, they are already stretched to capacity working on the planning and administration of their local transport lines and on overseeing their partner EVUs.

This is the reason why the public decision makers responsible for making vehicle decisions rely so heavily on the technological expertise of the manufacturers. This dependence is also reflected in the fact that responsibility for maintenance and servicing, even in the case of electric multiple units, is increasingly being transferred to vehicle manufacturers, even though this is one of the core tasks of transport companies with their own workshops. In the case of alternative drives, this responsibility is to be transferred primarily to the manufacturers of the vehicles concerned in what is known as the availability model. In the case of fuel cell trains, the manufacturers are also expected to provide the hydrogen. This gives them complete responsibility for ensuring vehicle availability in rail operations.

Increased responsibility will require public decision makers to have considerably more personnel and expertise in the long term

The public decision makers carry an extraordinarily high level of responsibility today within the new constellation of transport companies and manufacturers. It is conceivable that the situation will ease again when the new technologies become established and sufficient varieties and numbers of vehicles are available. At that point, it would also make sense to re-entrust EVUs with the maintenance and servicing of the vehicles they use, especially as this would then lower the vehicle costs and business risks again. If, on the other hand, the situation does not ease, there will be no alternative to substantially raising the personnel numbers and expertise levels of the public decision makers on a lasting basis.

6.2 Potential for vehicle manufacturers

Alstom is one of the few manufacturers still producing and successfully selling diesel multiple units. All other manufacturers abandoned this market in recent years and are focusing on their future-proof electric multiple units. Diesel hybrids as low-emission alternatives to multiple units with diesel-mechanical or diesel-electric drives have not so far been deemed future-proof by the manufacturers, who have primarily been concerned with finding enough customers for bridging solutions.

The manufacturers‘ high levels of systemic competence and resourcefulness make them powerful partners

Only limited numbers of vehicles with alternative drive systems are available at the moment. They have been developed more or less on the manufacturers' own initiative, partly funded by the federal government. An important trigger for these activities was the mass availability of sufficiently large batteries and suitable fuel cells. The public decision makers or transport companies have issued scarcely any specifications either for low-emission or emission-free concepts. Accordingly, for many years the manufacturers had no choice but to act on their own initiative and promote their own new sustainable concepts.

When the time was finally ripe, thanks in part to the diesel scandal, everything had to change very quickly – as the manufacturers reported in the interviews. Some of the decision-makers now had wildly exaggerated expectations regarding the performance of the new concepts, even though the actual aim was simply to replace slightly inefficient diesel multiple units.

The flexibility and efficiency of the Germany-based vehicle manufacturers can be seen from how quickly they were able to produce their multiple units with alternative drive systems. The proficiency of the manufacturers is also reflected in their high system competence, which has made them influential advisors to the public decision makers. The manufacturers have designed the vehicles as technically equivalent replacements for conventional diesel multiple units. Many operators, however, require the performance of the overmotorised RegioShuttle RS1 to maintain their schedules. This cannot currently be achieved by any of the alternatives on lines with no catenary. There is therefore need for even greater coordination here.

The manufacturers benefit from the structural weakness of decision-making organisations

The willingness of the manufacturers to assume responsibility and risks pays dividends: they are then entrusted with maintaining and servicing the vehicles and can thus monitor the performance of their trains and exploit any suggestions for improvement improvement in their further development. Their participation in infrastructure development, for example in the case of hydrogen refuelling stations, gives them a further opportunity to expand their business activities into other fields. Of course, there is a danger that the public decision makers will have to return to the previous status quo and that manufacturers will have to limit themselves in future to their previous role as suppliers of vehicles in a highly competitive field.

6.3 The future of railway undertakings

Opening the rail network to more competition in regional transport was one of the main objectives of the rail reform in the 1990s. DB Regio was founded as a subsidiary of Deutsche Bahn AG in 1999 as a result. DB Regio AG inherited the entire vehicle fleet, the maintenance workshops and the skilled staff. The new competitors are companies which are much smaller, flexible and focused solely on running their services. That is why they are putting DB Regio under pressure, even if it still has a comfortable market share of 67 per cent today.

The focus of the EVUs could shift again towards more added value

It remains to be seen in which direction the tasks performed by the railway undertakings will develop in the future. Is the availability model of vehicle maintenance and servicing which favours the manufacturers now permanent? Will maintenance in this constellation meet the EVUs' needs and availability requirements in the long term? Is close interaction between vehicle operation and maintenance not essential for ensuring high operational quality? It seems likely that the EVUs will increase their added value again in the future for vehicles with alternative drive systems, especially once the new technologies have become established and increased demand has given rise to a broader range of models and manufacturers.

For the EVUs, this means maintaining their maintenance expertise. DB Regio's EcoTrain project represents an approach that generates and preserves such expertise.

Railway undertakings are more sceptical about current developments than the public decision makers

Up to now, EVUs have mostly been ignored when it came to choosing vehicle concepts for railway lines. They only become relevant upon winning the tender and concluding their transport contract with the public decision maker. At this late stage, they have no choice but to implement the decision taken by the public decision maker. It is therefore understandable that the railway undertakings are somewhat sceptical about current developments. The elimination of their maintenance function decreases their added value. Nevertheless, they remain the first point of contact for passengers when problems arise with the new vehicle technology. As necessary and effective as it is for railway undertakings to focus exclusively on running trains, it means that they can only set themselves apart from their competitors in the bidding phase by the price they offer and thus by personnel cost. It remains to be seen whether the challenges which lie ahead can be overcome in this way.

6.4 Infrastructure challenges

The electrification of a railway line can only be justified from an economic point of view if there are significant transport capacities which require high-frequency traffic. Non-electrified regional passenger railway lines, however, are mostly secondary lines with low traffic levels. The benefits that electrification also bring to long-distance and freight transport are difficult to quantify in economic terms and ultimately play no role in the cost-benefit assessment. Those in charge thus have three options:

- The route is already included in the Federal Transport Infrastructure Plan (BVWP);
- The route is given higher priority in the BVWP because it is rated as urgent;
- Electrification can be financed from regional funds.

The unpredictability of electrification projects necessitates a plan B as a fallback

A decision in favour of electrification is followed by a planning approval procedure in which it is impossible to set the completion time because it depends on various factors. This planning uncertainty means that the decision-maker must always have a plan B if the electrification cannot be completed by the end of the current transport contract.

The charging infrastructure for battery-powered multiple units requires advance planning

The infrastructure for battery-powered multiple units requires precise planning and, in the final analysis, checking of the manufacturer's data against the specified timetables, because the energy consumption of a vehicle on the catenary-free line sections depends to a large extent on the operational load profile.

Ideally, the gap to be bridged is so small that no additional overhead lines are required for battery charging. In the event of larger gaps, electrification islands may become necessary. The organisational effort involved here is no different to that for electrification of the entire line. The costs, on the other hand, are considerably lower because the sections to be electrified are much shorter.

Hydrogen refuelling stations for fuel cell trains are long-term planning projects

The infrastructure required for fuel cell trains also requires careful planning because the costs involved in producing hydrogen and making it available (as the energy carrier) cannot be justified in all locations. The first tests of these new multiple units have so far been carried out as part of funded projects or in regions where hydrogen is already available as an industrial gas near the lines. In many cases it is possible to install the refueling infrastructure on non-critical land where simplified licensing procedures apply which fall within the competence of the regional railway authorities.

The provision of hydrogen by vehicle manufacturers is not aviable long-term proposition. Instead, DB Netze (as DB Energie GmbH) could assume responsibility in the future for the necessary expansion of the hydrogen refuelling station infrastructure and the provision or production of hydrogen. The creation of charging facilities is comparatively transparent as a requirement, whereas the supply of hydrogen represents a new type of challenge. Suitable interfaces to the public power grid will become crucial in windy and sunny regions for the purpose of generating systemically beneficial hydrogen. It is therefore conceivable that the supply of hydrogen will in practice require completely new structures that are not necessarily part of the railway system. In addition, there are currently no standardised invoicing systems, such as those for traction current or diesel fuel. Furthermore, financing of the new infrastructure requires bilateral coordination.

6.5 Political cornerstones

Electrification of diesel railway lines:

The mobility requirements of the 21st century cannot be implemented on the basis of 20th century regulations. Transport transition and CO_2-free mobility are goals that can only be achieved with political support. The Planning Acceleration Act adopted by the Bundesrat at the end of 2018 is intended to streamline the prescribed planning and approval procedure [32]. With this in mind, electrification must be prioritised for diesel-powered regional passenger railway lines with high transport capacities.

Battery and fuel cell drives:

The heterogeneity of the diesel railway lines in the regional passenger rail system makes it necessary also to promote battery and fuel cell-based drives, i.e. it is not sufficient simply to speed up the electrification process. The development of alternative drive concepts through to series production readiness should be accompanied by further intensive funding. Implementation risks must be mitigated by political support.

6.6 Recommendations

Characterisation of individual diesel railway lines as preliminary systemic measure

Individual diesel railway lines can be objectively characterised on the basis of suitable evaluation criteria as a means of finding the best alternative. This allows implementation to be effectively accelerated, as the necessary partners are involved at an early stage and the process can be properly coordinated. In turn this allows target-oriented application of the Planning Acceleration Act.

The railway undertaking currently operating the line in question should be involved in the public decision maker's criteria-based characterisation of the diesel railway line because it is best placed to know the special features and challenges of the route. In addition, the manufacturer should also be involved in the individual characterisation, contributing its specific knowledge of all vehicle characteristics (and, where appropriate, its experience as a designated maintenance provider). Possible conflicts of interest should be avoided.

It is advisable to involve DB Netze at the characterisation phase for the assessment of any individual electrification measures or the provision of any hydrogen refuelling stations that may be required. This can help ensure that these measures are also incorporated at a sufficiently early stage in the overall infrastructure planning.

Nothing is more constant than the certainty that technologies change constantly[10]

Batteries and fuel cells are two technologies which will see rapid further development in the coming years due to their great market potential. These trends must not be lost sight of in the characterisation of diesel railway lines. In the future, battery-powered multiple units may well achieve much greater ranges than are currently considered possible. This would reduce the scope of deployment for fuel cell trains. At the same time, this could significantly improve the efficiency ratios (and thus the costs) in the production of hydrogen and in the operation of fuel cells. It could even call the justification for electrification into doubt.

→ Figure 48 gives an overview of possible trends in the further development of alternative multiple unit concepts.

10 Freely adapted from Charles Darwin (1809–1882)

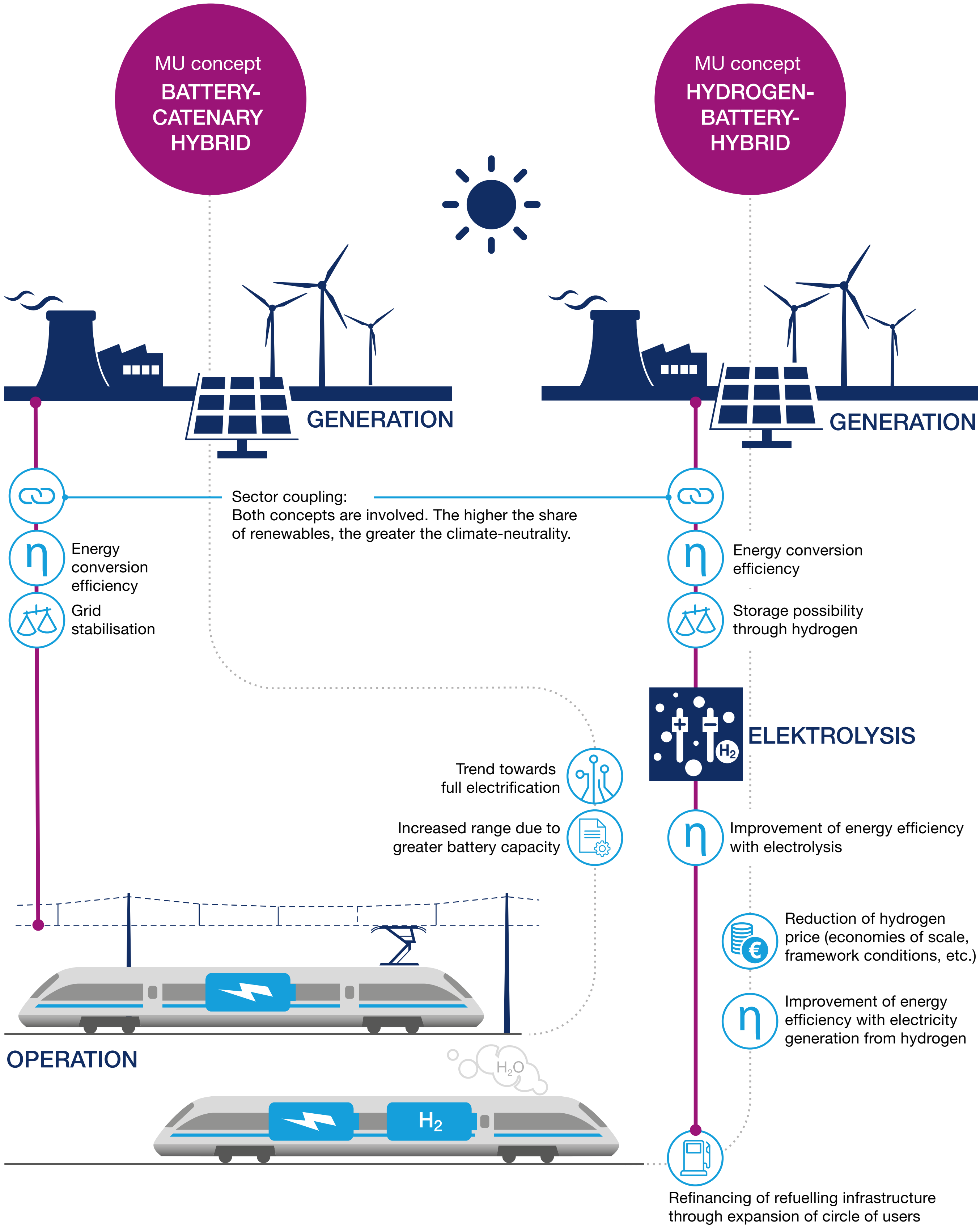


Figure 48 **Possible trends in the further development of CO_2-free concepts without gapless electrification**

7 Notes

Notes 7.1. Participants in the interviews and final workshop

Name	Company	Interview (in 2018)	Workshop (Feb. 2019)
Axel Hennighausen	Agilis, Regensburg	x	x
Dirk Flege	Allianz pro Schiene, Berlin	x	
Dr. Andreas Geißler	Allianz pro Schiene, Berlin	x	x
Peter Schumann	Alstom Transport Deutschland, Salzgitter		x
Michael Ritter	Alstom Transport Deutschland, Salzgitter	x	
Florian Liese	Bayerische Eisenbahngesellschaft (BEG), Munich	x	x
MR Markus Schell	Bavarian State Ministry for Housing, Construction and Transport, Department 53, Munich	x	x
Dr. Karsten Steinhoff	BeNEX, Hamburg	x	x
Sven Hornschuh	Alstom Transport Deutschland, Salzgitter		x
Stefan von Mach	Bombardier Transportation, Hennigsdorf	x	
Susanne Henckel	Bundesarbeitsgemeinschaft Schienenpersonennahverkehr (BAG-SPNV), Berlin	x	
Thomas Dill	Verkehrsverbund Berlin-Brandenburg (VBB), Berlin		x
Verena Löw	Verkehrsverbund Berlin-Brandenburg (VBB), Berlin	x	
Marcus Kliefoth	DB Energie, Frankfurt am Main	x	
Kai Wittig	DB Energie, Frankfurt am Main		x
Sebastian Zander	DB Energie, Frankfurt am Main	x	x
Burak Yilmaz	DB Netz, Frankfurt am Main		x
Heiko Noll	DB Netz, Frankfurt am Main	x	
Dr. Klaus Vestner	DB Regio, Frankfurt	x	
Johannes Pagenkopf	German Aerospace Center (DLR), Berlin	x	x
Toni Schirmer	German Aerospace Center (DLR), Berlin	x	
Joachim Michels	fahma, Hofheim am Taunus	x	x
Prof. Ronald Pörner	Hochschule für Technik und Wirtschaft (HTW), Berlin	x	
Thomas Nawrocki	Landesnahverkehrsgesellschaft Niedersachsen, Hannover	x	
Dieter Sandmann	Landesnahverkehrsgesellschaft Niedersachsen, Hannover	x	
Burkhardt Schulze	Nahverkehrsverbund Schleswig-Holstein (NAH.SH), Kiel	x	
Marcus Badow	Niederbarnimer Eisenbahn (NEB), Berlin	x	x
Kai Daubertshäuser	Rhein-Main-Verkehrsverbund (RMV), Hofheim am Taunus	x	x
Christian Engelmann	Siemens Mobility, Erlangen	x	
Cornelia Mager	Siemens Mobility, Erlangen		x
Jochen Steinbauer	Siemens Mobility, Erlangen	x	
Steffen Obst	Stadler Pankow, Berlin	x	x
Timo Jung	Südwestdeutsche Landesverkehrs-AG (SWEG), Stuttgart	x	
Prof. Markus Hecht	TU Berlin, Faculty V, ILS, Mechanical Engineering and Transport Systems, Rail Vehicles	x	
Pavel Boev	TU Berlin, Faculty V, ILS, Product Development Methods and Mechatronics	x	x

Name	Company	Interview (in 2018)	Workshop (Feb. 2019)
Ulrich Zimmermann	TU Berlin, Faculty V, ILS, Railways and Railway Operations	x	x
Carl-Roman Culemann	TU Berlin, Faculty V, ILS, Rail Vehicles	x	
Prof. Arnd Stephan	TU Dresden and Institut für Bahntechnik GmbH (Berlin)	x	
Martin Schmitz	Verband Deutscher Verkehrsunternehmen (VDV)	x	
Mathias Korda	Verkehrsverbund Mittelsachsen (VMS), Chemnitz	x	
Lutz Auerbach	Verkehrsverbund Oberelbe (VVO)	x	
Peter Krichel	Verkehrsverbund Rhein-Ruhr (VRR)		x
Georg Seifert	Verkehrsverbund Rhein-Ruhr (VRR)	x	
Lutz Oppermann	Zweckverband Nahverkehr Rheinland (ZV NVR)	x	x
Heiko Sedlaczek	Zweckverband Nahverkehr Rheinland (ZV NVR)	x	
Michael Geuckler	Zweckverband SPNV Münsterland, Münster	x	

Notes 7.2. Public decision makers in Germany

Abbreviation	Public decision maker	Head office
Baden-Wurttemberg		
VRN	Verkehrsverbund Rhein-Neckar GmbH	Mannheim
NVBW	Nachverkehrsgesellschaft Baden-Württemberg mbH	Stuttgart
VRS	Verband Region Stuttgart	Stuttgart
Bavaria		
BEG	Bayerische Eisenbahngesellschaft mbH	Munich
Berlin-Brandenburg		
VBB	Verkehrsverbund Berlin-Brandenburg GmbH	Berlin
Bremen		
HB	Senator für Umwelt, Bau und Verkehr des Landes Bremen	Bremen
Hamburg		
HVV	Hamburger Verkehrsverbund GmbH	Hamburg
Hesse		
RMV	Rhein-Main-Verkehrsverbund GmbH	Hofheim a.T.
NVV	Nordhessischer Verkehrsverbund GmbH	Kassel
Mecklenburg-Vorpommern		
VMV	Verkehrsgesellschaft Mecklenburg-Vorpommern mbH	Schwerin
Lower Saxony		
LNVG	Landesnahverkehrsgesellschaft Niedersachsen mbH	Hanover
RH	Region Hannover	Hanover
RVB	Regionalverband Großraum Braunschweig	Braunschweig
North Rhine-Westphalia		
VRR	Verkehrsverbund Rhein-Ruhr AöR	Gelsenkirchen
ZV NVR	Zweckverband Nahverkehr Rheinland GmbH	Cologne
NWL	Nahverkehr Westfalen-Lippe	Unna
Rhineland-Palatinate		
SPNV-Süd	Zweckverband SPNV Rheinland-Pfalz Süd	Kaiserslautern
SPNV-Nord	Zweckverband SPNV Rheinland-Pfalz Nord	Koblenz
Saarland		
ZPS	Zweckverband Personennahverkehr Saarland	Saarbrücken
Saxony		
ZVV	Zweckverband ÖPNV-Vogtland	Auerbach
ZVON	ZV Verkehrsverbund Oberlausitz-Niederschlesien	Bautzen
ZVMS	Zweckverband Verkehrsverbund Mittelsachsen	Chemnitz
VVO	Verkehrsverbund Oberelbe GmbH	Dresden
ZVNL	Zweckverband für den Nahverkehrsraum Leipzig	Leipzig
Saxony-Anhalt		
NASA	Nahverkehrsservice Sachsen-Anhalt GmbH	Magdeburg
Schleswig-Holstein		
NAH.SH	Nahverkehrsverbund Schleswig-Holstein GmbH	Kiel
Thuringia		
NVS	Nahverkehrsservicegesellschaft Thüringen mbH	Erfurt

Notes 7.3. Railway undertakings (according to BAG SPNV)

Abbreviation	Railway undertaking	Head office
Brandenburg		
HANS	Hanseatische Eisenbahn GmbH	Putlitz
NEB	Niederbarnimer Eisenbahn Betriebsgesellschaft mbH	Berlin
Baden-Wurttemberg		
BOB	Bodensee-Oberschwaben-Bahn GmbH & Co. KG	Friedrichshafen
HzL	Hohenzollerische Landesbahn AG	Hechingen
AVG	Albtal-Verkehrs-Gesellschaft mbH	Karlsruhe
SBB	SBB Deutschland GmbH	Konstanz
SWEG	Südwestdeutsche Verkehrs AG	Lahr
RNV	Rhein-Neckar-Verkehr GmbH	Mannheim
WEG	Württembergische Eisenbahn-Gesellschaft mbH	Waiblingen
Bavaria		
BLB	Berchtesgadener LandBahn GmbH	Freilassing
BZB	Bayerische Zugspitzbahn Bergbahn AG	Garmisch-Partenkirchen
BOB	Bayerische Oberlandbahn GmbH	Holzkirchen
BRB	Bayerische Regiobahn GmbH	Holzkirchen
AG-E	agilis Eisenbahngesellschaft mbH & Co. KG	Regensburg
AG-V	agilis Verkehrsgesellschaft mbH & Co. KG	Regensburg
DLB	Drei Länderbahn GmbH	Viechtach
Hesse		
DB	DB Regio AG	Frankfurt am Main
HLB	Hessische Landesbahn GmbH	Frankfurt am Main
CAN	cantus Verkehrsgesellschaft mbH	Kassel
RTG	RegioTram Gesellschaft mbH	Kassel
Mecklenburg-Vorpommern		
MBB	Mecklenburgische Bäderbahn Molli GmbH	Bad Doberan
UBB	Usedomer Bäderbahn GmbH	Heringsdorf
ODEG	Ostdeutsche Eisenbahn GmbH	Parchim
Lower Saxony		
WFB	WestfalenBahn GmbH	Bielefeld
NWB	NordWestBahn GmbH	Osnabrück
ERX	Erixx GmbH	Soltau
ME	metronom Eisenbahngesellschaft mbH	Uelzen
EVB	Eisenbahnen und Verkehrsbetriebe Elbe-Weser GmbH	Zeven
North Rhine-Westphalia		
RTB	Rurtalbahn GmbH	Düren
VIAS	VIAS Rail GmbH	Düren
ERB	eurobahn (Keolis Deutschland GmbH & Co. KG)	Düsseldorf
ABR-N	Abellio Rail NRW GmbH	Essen
NX	National Express Rail GmbH	Cologne
RBE	Rheinisch-Bergische Eisenbahn GmbH	Mettmann
VEN	Rhenus Veniro GmbH & Co. KG	Moers

Abbreviation	Railway undertaking	Head office
Rhineland-Palatinate		
TR	trans regio Deutsche Regionalbahn GmbH	Koblenz
VLEXX	Vier-Länder-Express (VLEXX GmbH	Mainz
WEBA	Westerwaldbahn des Kreises Altenkirchen GmbH	Steinebach-Bindweide
Schleswig-Holstein		
AKN	Altona-Kaltenkirchen-Neumünster Eisenbahn AG	Kaltenkirchen
NBE	nordbahn Eisenbahngesellschaft mbH	Kaltenkirchen
NEG	Norddeutsche Eisenbahngesellschaft Niebüll GmbH	Niebüll
SB	Saarbahn GmbH	Saarbrücken
Saxony		
SDG	Sächsische Dampfeisenbahngesellschaft mbH	Annaberg
CBC	City-Bahn-Chemnitz GmbH	Chemnitz
SBS	Städtebahn Sachsen GmbH	Dresden
FEG	Freiberger Eisenbahngesellschaft mbH	Freiberg
ABR-M	Abellio Rail Mitteldeutschland GmbH	Halle
PRESS	Eisenbahn-Bau- und Betriebsgesellschaft Pressnitztalbahn mbH	Jöhstadt
MRB	Mitteldeutsche Regiobahn (Transdev Regio Ost GmbH)	Leipzig
DBG	Döllnitzbahn GmbH	Mügeln
SOEG	Sächsisch-Oberlausitzer Eisenbahngesellschaft mbH	Zittau
Saxony-Anhalt		
DVE	Dessauer Verkehrs- und Eisenbahngesellschaft	Dessau
HEX	HarzElbeExpress (Transdev Sachsen-Anhalt GmbH)	Halberstadt
HSB	Harzer Schmalspurbahn GmbH	Wernigerode
Thuringia		
EB	Erfurter Bahn GmbH	Erfurt
STB	SüdThüringen GmbH	Erfurt
SWN	Stadtwerke Nordhausen GmbH	Nordhausen

International		
ÖBB	ÖBB Personenverkehr AG	(A) / Vienna
SNCB	Societe nationale des chemins de fer belges, societe de droit public	(B) / Brussels
KD	Koleje Dolnoslaskie sp.a.	(CS) / Legnica
CD	Ceske drahy, a.s.	(CS) / Prague
ADK	Arriva Danmark A/S	(DK) / Kastrup
DSB	Danske Statsbaner	(DK) / Copenhagen
SNCF	Societe nationale des chemins de fer francais, EPIC	(F) / Saint-Denis
CFL	Societe nationale des Chemins de fer luxembourgeois	(LUX) / Luxembourg
ANL	Arriva Openbaar Vervoer Nederland	(NL) / Leuwarden
PR	Przewozy Regionalne sp.z.o.o.	(PL) / Warsaw

Acronyms

Acronym	Name
BAG-SPNV	Bundesarbeitsgemeinschaft Schienenpersonennahverkehr (Federal Association for Regional Passenger Rail Transport)
BEMU	Battery Electric Multiple Unit
BMVI	Bundesministerium für Verkehr und digitale Infrastruktur (Federal Ministry of Transport and Digital Infrastructure)
BOH	Batterie-Oberleitungs-Hybrid (battery-catenary hybrid)
BVWP	Bundesverkehrswegeplan (Federal Transport Infrastructure Plan)
CO_2	Carbon dioxide
DB	Deutsche Bahn (German Railways)
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DM	Diesel-mechanical drive
DMU	Diesel Multiple Unit
ECM	Entity in Charge of Maintenance
EE	Erneuerbare Energien (renewable energy)
EIU	Eisenbahninfrastrukturunternehmen (railway infrastructure company)
EMU	Electric Multiple Unit
EVU	Eisenbahnverkehrsunternehmen (railway undertaking)
HEMU	Hydrogen Electric Multiple Unit
HGV	Large Goods Vehicle
kWh	Kilowatt hour
NMHC	Non-methane hydrocarbons
NO_x	Nitrogen oxides NO and NO_2
NRW	North Rhine-Westphalia
ÖBB	Österreichische Bundesbahn (Austrian Federal Railway)
OL	Overhead line (catenary)
pkm	Passenger kilometres (measure of passenger transport performance of trains)
RB	Regionalbahn (regional railway)
RE	Regionalexpress (regional express)
RRX	Rhine-Ruhr Express
SPNV	Schienenpersonennahverkehr (regional passenger rail transport)
THC	Total hydrocarbons
tkm	train kilometres – measure of operational performance of trains
VDV	Verband Deutscher Verkehrsunternehmen (Association of German Transport Companies)
WBH	Wasserstoff-Batterie-Hybrid (hydrogen-battery hybrid)

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