VDE Study

Evaluation of climate-neutral alternatives to diesel multiple units

Economic viability assessment based on the example of the ›Düren network‹

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Economic viability analysis based on the example of the ›Düren network‹
Frankfurt am Main

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Since the end of 2017 the technical-scientific German Association for Electrical, Electronic and Information Technologies (→ VDE) has been undertaking a neutral assessment of the economic viability of various alternatives as a replacement for diesel multiple units (→ DMUs) on regional rail passenger transport (→ SPNV) branch lines. The VDE decided not to limit its analysis to the technical details of vehicles with new drive types, but to focus above all on the systemic requirements that must be fulfilled in order to realise a particular alternative. It is also a priority for the VDE that its analyses take key social and political objectives – such as climate and environmental protection, the energy transition, sector coupling and mobility transitions – into account.

For the VDE, the search for alternatives represents a systemic issue

As a member of the BMVI[1]-funded X-EMU project the VDE is now publishing its third study in the series. The first investigation → [1] and → [2] explored suitable battery technologies for use in battery-powered multiple units. This concluded that the dynamic range and the level of reliability required by the railway sector are so extreme that they could only be met by LTO technology. However, LTO batteries are expensive and heavy. The automotive industry relies on more favourable technologies such as NMC which are falling in price and also enable higher travel distances. The VDE recommends a compromise that exploits the advantages of both technologies. The second study → [3] and → [4] was based on a detailed benefit analysis of diesel alternatives. The VDE supplemented this investigation with structured interviews of around 50 experts from the railway industry. A key finding was that the focus should be on fully electric solutions. This is because commuter trains are deployed for 25 to 30 years and complete decarbonisation of transport by 2050 ultimately rules out the introduction of hybrid interim solutions.

The VDE believes that, under certain conditions, both the direct and the indirect electrification of branch lines represent equivalent alternatives to diesel multiple units: *direct* in the sense of a continuous overhead line for the operation of electric multiple units (→ EMUs) or *indirect* in the form of vehicles with electric motors, the traction current of which comes from a battery (→ BEMU) or is provided by a fuel cell which allows the hydrogen carried on board to react in a controlled manner with air oxygen to form pure water steam (→ HEMU).

The VDE uses the ›Düren network‹ as an exemplary basis for its economic viability analysis

Before an actual decision can be made, it is necessary to investigate whether and under which conditions the various alternatives – BEMU, HEMU or EMU – are cost-effective. That is the purpose of this third investigation. To this end, the VDE has decided to dispense with its hitherto general approach and to conduct a detailed analysis of a concrete case study instead.

Zweckverband Nahverkehr Rheinland (ZV NVR, based in Cologne) is currently in a similar situation to many other public decision-makers: transport contracts for branch lines on which diesel vehicles previously ran are expiring; there is now an opportunity to replace them with environment and climate-friendly alternatives. For example, VRR[2] is looking for an alternative solution for its Niederrhein/Ruhr/Münsterland network, SPNV-Süd[3] needs a solution for its Palatinate network, as does ZVMS[4] for the Leipzig-Chemnitz line, which has not yet been electrified.

The VDE has taken the ›Netz Düren‹ (›Düren network‹) with its RB 21 Nord, RB 21 Süd and RB 28 lines as the basis for its economic viability analysis. For this it makes use of data on the ›Düren network‹, i.e. timetable, fleet size, operating capacity, speed limits, etc., provided by NVR as the public decision-maker and Rurtalbahn as the railway

1 Bundesministerium für Verkehr und digitale Infrastruktur (Federal Ministry of Transport and Digital Infrastructure)
2 Verkehrsverbund Rhein Ruhr, based in Gelsenkirchen
3 Zweckverband SPNV Rheinland-Pfalz Süd, based in Kaiserlautern
4 Zweckverband Verkehrsverbund Mittelsachsen, based in Chemnitz

infrastructure company (→ EIU) for 2026 (timetable year). The VDE supplemented this information with its own speed, acceleration and braking measurements for some trains and their stopping times at the stations.

The VDE calculated the energy demands of the multiple units on the ›Düren network‹ lines using simulations which are based on realistic speed profiles and take individual terrain profiles, auxiliary unit power values and idling requirements into account. It determined the fuel and electricity consumption of the vehicle types on the basis of the energy conversion efficiencies described in the literature for the individual technologies.

The VDE derived the costs for procuring and maintaining the vehicles and for replacing their technology components (such as power packs, batteries or fuel cells), as well as the costs required for the installation and operation of the additional infrastructure components such as overhead lines, electrification islands or refuelling stations, from the data provided by vehicle manufacturers, maintenance workshops or infrastructure operators. It used average values where differing cost information was available. The VDE has taken other non-critical data from other publications such as → [5]

In the case of the ›Düren network‹ there is basically a choice between fuel cell or battery-powered multiple units as suitable alternatives to diesel MUs. The VDE's analyses therefore focus primarily on comparing the HEMU and BEMU solutions. In order to be able to assess their *net benefit*, it also included DMUs and EMUs as (hypothetical) investment projects in the analyses. The vehicles are assumed to be either two or three-car vehicles but otherwise identical in terms of weight and passenger capacity (reference: multiple unit with 165 seats). It is also assumed that all vehicles will have the same level of technical maturity by the start date in 2026 and that the necessary infrastructure will be in place by then.

The VDE has chosen the net present value method for its economic viability evaluation

Investing in an alternative drive solution such as HEMU or BEMU only makes sense if there is a realistic chance of its delivering a positive economic result in the long term – supported, if necessary, by appropriate framework conditions and measures.

In order to assess which of the possible alternatives represents the most advantageous investment, the VDE chose the net present value method as its *dynamic investment calculation* approach → [6]. Here, only the specific costs for the relevant drive technology (which accrue over the life cycle of the vehicles) and the related infrastructure are taken into account. Accordingly, payments for personnel, administration or internal services, for example, are excluded. The relevant costs which are incurred each year are totalled in discounted form over the period under review, the investments are written down on a straight-line basis and their residual values included at the end of the period. The result is a negative capital value (*present value*) in euros. The drive solution with the smallest net present value is considered the most advantageous investment project.

The alternatives can be clearly differentiated between by their specific cost elements

In addition to train path and station charges, fuel and electricity prices also have a major impact on the economic viability of railway line operation. They are determined by the operating capacity of the vehicle fleet and thus account for a substantial share of the total costs.

The energy costs as well as those for vehicle procurement, replacement of key technology components and installation of the requisite infrastructure allow clear differentiation of the alternatives.

Sensitivity analysis is a central element of the VDE's economic viability analysis

The starting date in the future and the long-term nature of the examination diminishes the reliability of the economic viability analysis, especially with regard to fuel and electricity price changes, further development of the technologies or possible new social or political requirements. The authors supplement their simulations with a series of sensitivity analyses for the purpose of estimating the influence of the various parameters on the analysis results. To do this, they vary fuel and electricity prices, overhead line installation costs, track traffic frequencies, BEMU ranges, and vehicle prices and weights over a wide range, while examining the effect of each individual parameter.

Another critical parameter is the observation period. This is due to the ongoing operating costs which steadily accrue. Conversely the effect of acquisition and installation costs lessens over time. Inclusion of the residual values at the end of the period under consideration ensures that any alterations in the length of the period only cause negligible changes in the ratios of the resulting net present values of the alternatives.

Each of the fully electric alternatives has unique features

When considering the BEMU, it is important to know what percentage of the energy generated in the braking phases can be fed back to the battery for use in acceleration phases. Whether the range guaranteed by the vehicle manufacturers is sufficient for the ›Düren network‹ depends on where, how long and at what power level the batteries are recharged. Additional vehicles may be required to meet the operational requirements.

The provision of hydrogen fuel, the price of electrolytically produced *green* hydrogen, and in particular the efficiency and operational life of the fuel cell are decisive in the operation of the HEMU. In addition, the level of hydrogen consumption also depends on the extent to which, and the efficiency with which, the dynamic battery enables the use of recuperated braking energy.

EMUs recuperate part of their braking energy and feed it into the overhead line. They cannot use this energy directly for their own propulsion. In addition, the amount of energy fed back into the overhead contact line depends on the extent to which other trains can draw and actually use it at the exact same time. It is not possible to estimate how much the energy supplier will reimburse for this. The VDE therefore does not include the effect of recuperation in the net present value of EMUs, although it does mention it in its argumentation.

BEMUs and EMUs represent the most advantageous investments for the ›Düren network‹

At an electricity price of 12–14 ct/kWh in the traction power grid → [7] [8] [9] [10], the energy costs of BEMUs and EMUs yield a significant economic advantage over the HEMU solution. BEMUs and EMUs have the same net present value in the ›Düren network‹ because the sum of additional costs for BEMU vehicles, battery replacement and infrastructure costs for an electrification island coincidentally match those for full electrification of the three lines. Here the electrification island is assumed to cost €5 million and the overhead line 1 million €/km, including power transformation substation. From a figure of 1.5 million €/km the BEMU becomes a more advantageous investment project compared to the EMU. At 2 million €/km, the HEMU and the EMU are on a par in terms of their net present value. Electrification costs are therefore a sensitive valuation parameter.

The same applies to track traffic frequencies. It can be seen that, in 2026, only with the planned frequency of two trains per hour on RB 21 Nord and RB 21 Süd and a two-hourly frequency on RB 28 will the EMU and BEMU solutions have the same net present values. If a half-hourly cycle is also planned for RB 28, the EMU solution would clearly be the most advantageous investment project, assuming electrification costs of 1 million €/km.

The HEMU represents a system-supporting solution with higher efficiency-related costs

The energy demand of the HEMU is generally higher than that of the BEMU or EMU because of the position of the fuel cell between the fuel tank and wheel in the functional line. Assuming a price of 4.50 €/kg-H_2 for electrolysis hydrogen, the HEMU and DMU have equal resulting net present values if the diesel price rises to 1.46 €/litre – a realistic prospect in the medium term.

At a traction current price of 12 ct/kWh, the hydrogen price would have to fall below 1 €/kg-H_2 to bring the HEMU and BEMU solutions in line. It emerges that the real problem with the HEMU is not so much the fuel price as the high replacement costs. These costs stem from the price of fuel cells and dynamic batteries, but above all from the relatively short operating lifetimes of the fuel cells which are currently available. It is calculated that these will have to be replaced up to seven times over a period of 30 years.

In terms of infrastructure and operational requirements, there are strong similarities between the HEMU and DMU solutions. Given the importance of electrolysis hydrogen for the storage of renewable energy, the HEMU contributes not only to climate protection, but also to stabilisation of the power grid (*sector coupling*), which is necessary as part of the energy transition.

1 Introduction and Motivation

The age of combustion engine vehicles is coming to an end. This applies in particular to regional rail passenger transport (SPNV). Today, electric multiple units that draw their traction energy from overhead lines or conductor rails account for more than 80 per cent of the transport capacity[5].

As a result, up to 20 per cent of the transport capacity is provided by diesel multiple units, which are now mostly used on branch lines. Their mileage[6] here is by no means negligible: according to BAG-SPNV, it corresponds to roughly one third of the total capacity. This imbalance can be justified in terms of the provision of a basic service, but not in terms of climate protection. The lower the level of transport capacity provided, the higher the per capita emission of climate-damaging carbon dioxide, for example. Increasing concern about possible driving bans due to NOx emissions and particulate pollution has been instrumental in encouraging the responsible bodies to give serious consideration to environmentally friendly, long-term climate-neutral alternatives to diesel multiple units.

1.1 Problem

The time frame in which the decision for a suitable alternative needs to be made is determined by the end of the transport contract term for the diesel network and the remaining operating life of the diesel multiple units. Transport contracts are generally limited to 15 years and the useful life of diesel multiple units is set at 25 years. The political goal of full decarbonisation of transport in Germany by 2050 is creating significant pressure for action. As a result, no new diesel multiple units are to be put into operation after 2025.

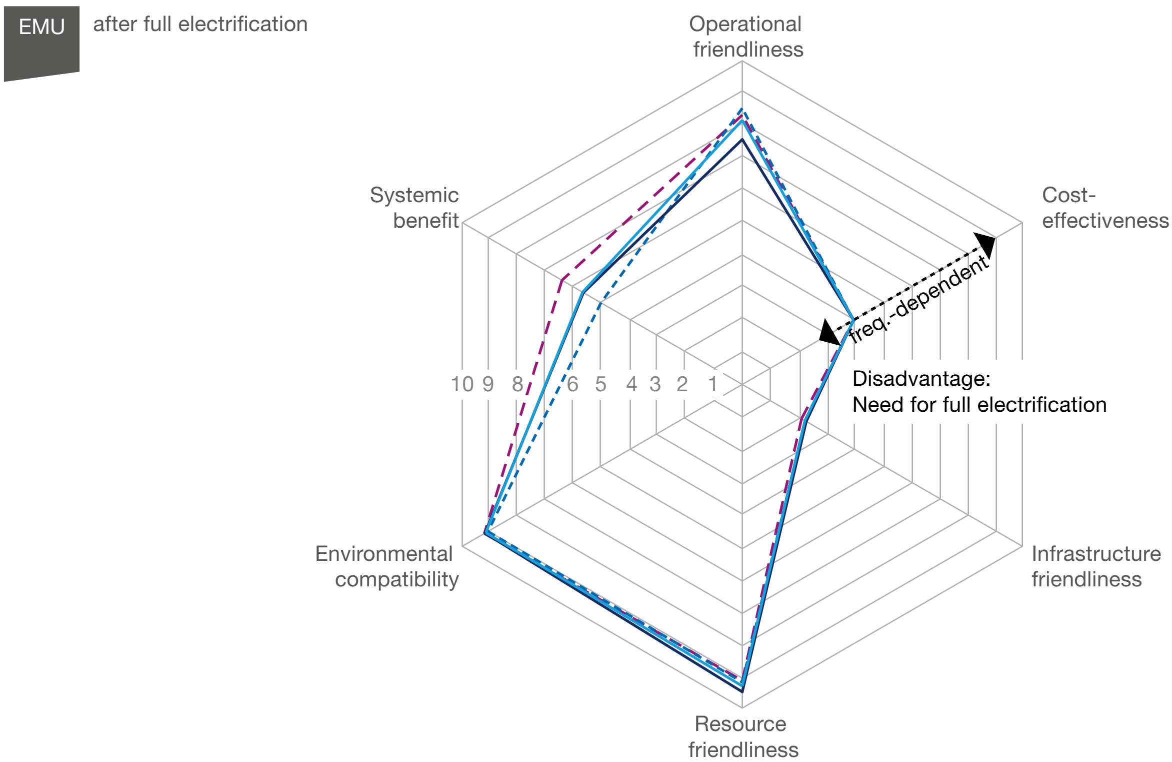
An alternative option to closing existing catenary gaps in the railway network infrastructure is to bridge these gaps in future with battery-powered multiple units, thus providing an electric service on lines previously reserved for diesel multiple units. As part of the BMVI-funded ›X-EMU‹ project, the VDE published a study in August 2018 → [1] which focuses on the high demands placed on the traction batteries used in multiple units. It examines which of the battery technologies and cells currently available are suitable for this purpose and highlights the major development trends up to 2030 and beyond.[7]

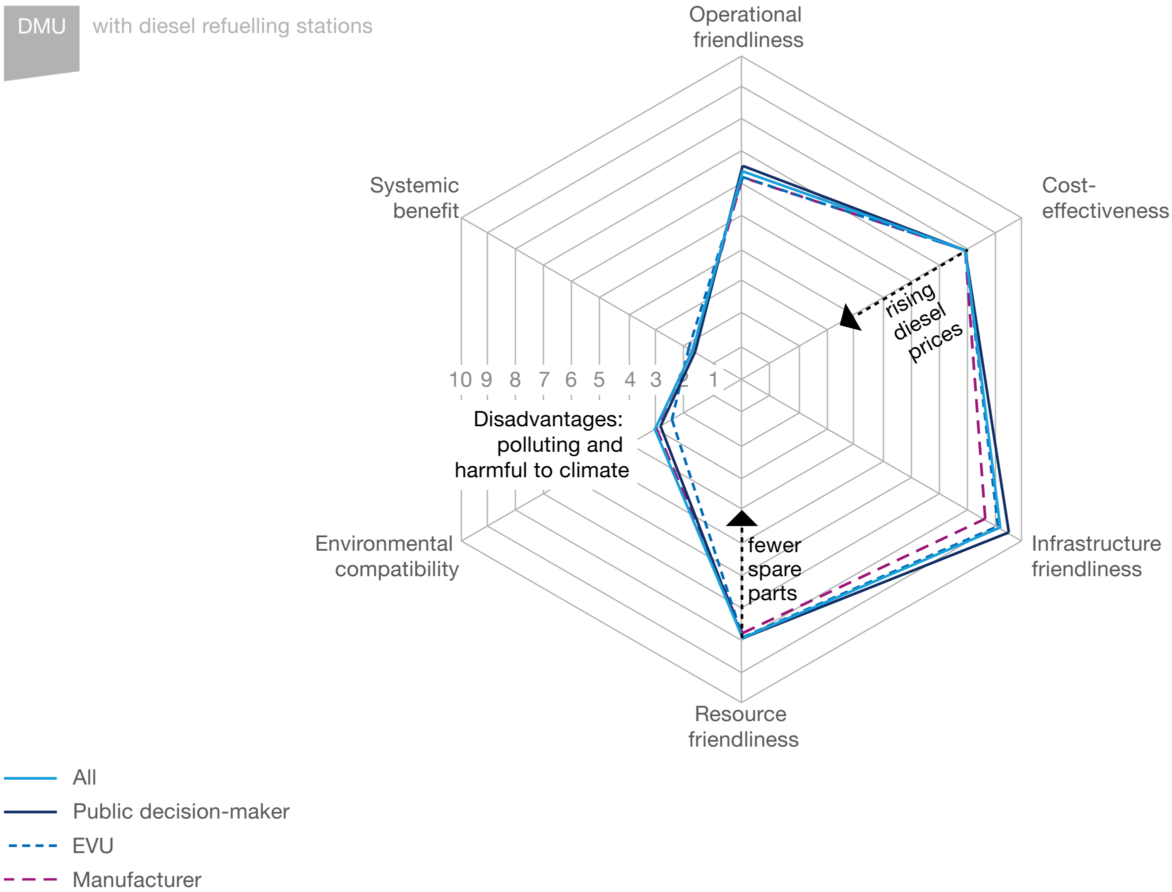
The battery-powered multiple unit has a limited range due to its technological constraints and, as such, is not the best alternative in all circumstances. In the case of railway lines which are largely non-electrified, or where there are larger gaps in the overhead contact line, the hydrogen-powered fuel cell multiple unit may prove the better alternative. By contrast, full electrification of certain railway lines may be the best option if they are already operating at high timetable frequencies or if much higher rates are planned for the future.

These alternative options were the subject of the second study published by the VDE in August 2019 → [3]. It records the systemic potential of the alternative solutions and evaluates them qualitatively on the basis of a benefit analysis. Intensive literature research, in-depth discussions with more than 50 experts from the railway industry and a constructive final workshop provided the information and data on which the analysis was based.[8]

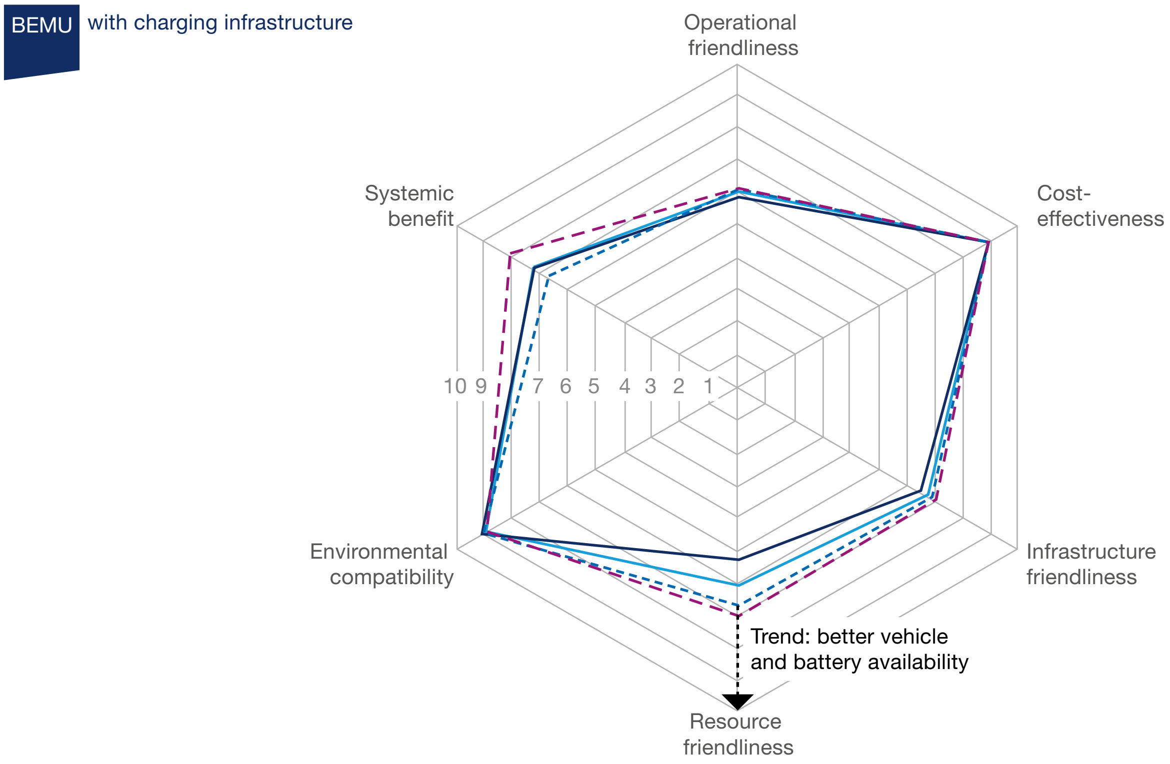
The main result is a presentation of the relative merits of the alternative solutions in the form of network diagrams based on six primary decision-making criteria. The disadvantages of the EMU option, i.e. of requiring full electrification and thus the additional expense of maintaining the resulting infrastructure, contrast with the disadvantages of the DMU, namely that it pollutes the environment and is not beneficial to the system, i.e. it contributes ultimately neither to the energy nor the transport transition. The two together represent the current accepted status quo → Figure 1. The respective network diagrams for BEMU and HEMU are shown in → Figure 2.

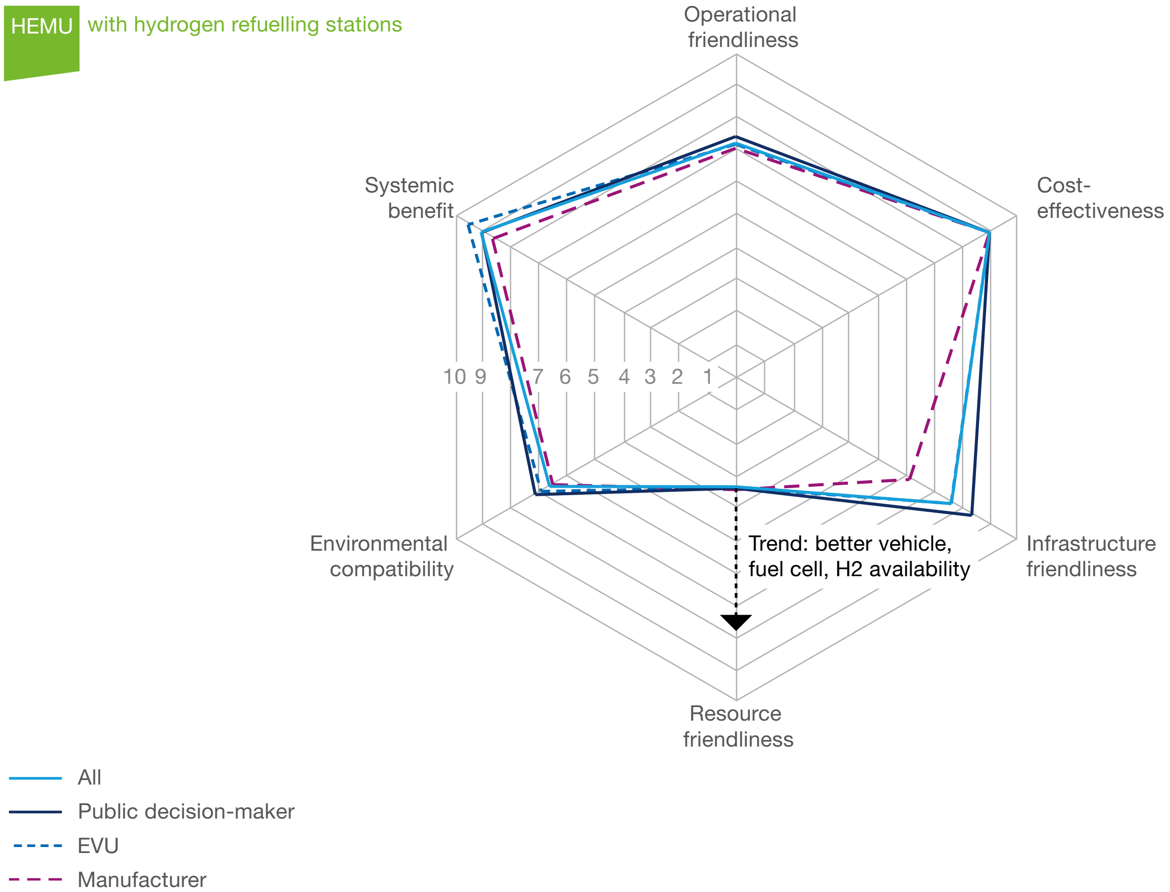
5 Also referred to as transport performance
6 Also referred to as operating capacity
7 The first study is available (free of charge) at https://shop.vde.com/de/10123-vde-study-battery-systems
8 The second study is available (free of charge) at https://shop.vde.com/de/alternatives-to-diesel-multiple-units-download





↑ Figure 1: Relative merits of the various multiple unit concepts (2025 horizon, and trends) – Part 1





↑ Figure 2: Relative merits of the various multiple unit concepts (2025 horizon, and trends) – Part 2

The BEMU and HEMU solutions emerge as suitable diesel alternatives – despite a number of disadvantages associated with their ease of operation and the availability of their technology components and energy sources, both of which must be improved → Figure 2, bottom. Both individually and jointly they represent an improvement on the previous DMU-based status quo.

The results yielded by the benefit analysis are helpful but ultimately insufficient to justify investment decisions in favour of specific diesel alternatives. In → [3], economic efficiency played an even more subordinate role. For the sake of simplicity, it was assumed that the costs of all solutions can be controlled in such a way as to make economic operation possible. Only in the case of the EMU is it assumed that full electrification of today's diesel lines makes little sense unless they are operated at sufficiently high timetable frequencies. In the case of branch lines with low traffic levels, the EMU solution is regarded as economically unfavourable.

In practice, the characteristics of the individual diesel networks and their railway lines must be taken into account and incorporated into an objective analysis and evaluation of the potential alternatives. This more differentiated approach is taken in this third VDE study.

1.2 BMVI funding 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 influence the realisation of multiple units with alternative, emission-free drives. The present study is the result of the third part of the project subcontracted to the VDE → [11].

1.3 Purpose and structure of the study

An important finding from the second VDE study → [3] was that it is impossible to identify the best alternative without considering the characteristics of the individual diesel lines. The real challenge therefore lies in recording and evaluating the specific characteristics of actual diesel networks and their individual railway lines based on real operating data. Accordingly, the authors are highly appreciative of the willingness of ZV NVR and Rurtalbahn as the railway infrastructure company (EIUs) to provide the necessary information and data on the ›Düren network‹ and thus contribute to the success of the present study.

Chapter 2 provides an overview of the regional transport networks in Germany, with a special focus on the diesel networks. **Chapter 3** contains updated technical information and data on diesel multiple units (DMUs), electric multiple units (EMUs), battery-powered multiple units (BEMUs) and fuel cell multiple units (HEMUs).

In **Chapter 4**, benefit analysis and the net present value method are presented as suitable approaches for evaluating alternative drive solutions. **Chapter 5** takes the ›Düren network‹, with its RB 21 Nord, RB 21 Süd and RB 28 lines, as an interesting basis for a viability analysis using the net present value method. **Chapter 6** looks at the extent to which the findings from the ›Düren network‹ are applicable to other diesel networks, and ends with a conclusion.

2 Regional passenger transport networks in Germany

According to a market study by the German Federal Network Agency → [12], rail passenger transport in Germany generated 98 billion passenger kilometres (pkm)[9] in 2018. 57 billion passenger kilometres of this were accounted for by regional rail transport. With an average travel distance of 21 kilometres, this corresponds to a transport volume of 2.7 billion passengers. The regional passenger rail transport (SPNV) system provided 691 million train kilometres (tkm)[10] of operating capacity for this. Total turnover was 11.1 billion euros.

Regional passenger rail transport includes a total of roughly 1,000 lines in the form of regional, regional express or suburban railways. Around half of these regional transport lines currently operate diesel multiple units due to a lack of (or incomplete) electrification. DB Regio, for example, has around 4,500 DMUs, making up roughly one third of its multiple unit fleet → [13]. Diesel multiple units are used primarily in rural regions with lower traffic volumes. Here, they account for an estimated 17 per cent of the total transport capacity of the regional rail transport system, i.e. roughly 10 billion passenger kilometres (derived from → [14]). For each individual diesel line, this corresponds to an average transport capacity of 20 million pkm – with an average operating capacity of 0.69 million tkm across all regional transport lines.

The following sections present the operating capacity of regional rail transport planned in the federal states until 2033 based on the current competition roadmap, and look at the future of today's diesel networks where binding decisions have in some cases already been made in favour of fuel cell or battery-powered trains.

2.1 Planned operating capacity

According to the 2019 competition roadmap → [15], the Federal Association for Regional Passenger Rail Transport (BAG SPNV) expects the operating capacity commissioned for the period from 2019 to 2033 to exceed 750 million tkm. Of this, 179 million tkm – almost 25 per cent – will be diesel or diesel + electric[11]. Battery-powered vehicles (BEMUs) will contribute 31 million tkm, fuel cell vehicles (HEMUs) 5 million tkm. For a total of 54 million tkm, it is still undecided whether BEMU, HEMU or hybrid solutions will be used in the future, or whether a decision will be made in favour of EMUs following full electrification. → Table 1.

2.2 Diesel networks today and in the future

At present, the public decision-makers and federal states seem to favour the BEMU solution in a choice between battery or fuel cell drives. However, the high proportion of decisions which are still outstanding means that this does not yet indicate a clear trend.

The early adopters of the BEMU solution are NAH.SH in Schleswig-Holstein, VRR in Nord Rhine-Westphalia and SPNV-Süd in Rhineland-Palatinate. The HEMU solution is supported by LNVG in Lower Saxony and RMV in Hesse. Both BEG in Bavaria and the state of Thuringia are reluctant to use alternative drives.[12]

By far the largest proportion of regional rail transport capacity, 484 million tkm, is accounted for by electric multiple units running beneath overhead lines. The largest contract totals (covering all traction types) are recorded by BEG (161 million tkm) and NVBW (113 million tkm) in Baden-Württemberg, followed by Berlin-Brandenburg (78 million tkm) and VRR (77 million tkm), all of which function as federal state-owned public decision-makers.

→ Table 2, → Table 3 and → Table 4 provide an overview of all networks which deploy diesel vehicles – including the relevant operating capacity and contract periods. An overview of the lines belonging to these networks is given in the → Appendix 7.2.

9 Transport capacity (transport performance) = number of passengers x average distance travelled, usually within one year

10 Operating capacity (mileage) = number of trains x average distance travelled, usually within one year

11 BEG (Bavaria) deploys trains with electric locomotives between Munich and Hof. These are then replaced by diesel locomotives from Regensburg. VRR (Hesse) uses so-called RT trains, which run as trams within the Kassel area and as diesel vehicles else-where. Diesel-electric multiple units are planned as part of a Franco-German bid in Rhineland-Palatinate and Baden-Württemberg → [33].

12 Explanations of all acronyms are given in the Appendix, → Acronyms.

2019–2033	EMU	DMU	Diesel/ Electric	BEMU	HEMU	open	SUM
NVBW (BW)	95.0 m tkm	15.1 m tkm		2.0 m tkm		1.3 m tkm	**113.5 m tkm**
Verband Region Stuttgart			12.5 m tkm			13.5 m tkm	**26.0 m tkm**
BEG (BY)	91.0 m tkm	59.2 m tkm	10.8 m tkm				**161.0 m tkm**
VBB (BE/BB)							**0.0 m tkm**
Berlin and Brandenburg	72.2 m tkm	5.0 m tkm			0.7 m tkm	0.2 m tkm	**78.1 m tkm**
RMV (HE)	26.2 m tkm	7.8 m tkm			1.8 m tkm		**35.9 m tkm**
NVV (HE)	4.4 m tkm		2.3 m tkm			2.3 m tkm	**9.0 m tkm**
LNVG (NI)	28.8 m tkm	22.9 m tkm			2.7 m tkm		**54.5 m tkm**
Province of Groningen		0.3 m tkm					**0.3 m tkm**
NVR (NW)	13.0 m tkm	9.1 m tkm					**22.1 m tkm**
NWL (NW)	14.4 m tkm					13.5 m tkm	**27.9 m tkm**
VRR (NW)	66.6 m tkm	1.5 m tkm		6.1 m tkm		2.4 m tkm	**76.6 m tkm**
SPNV-Nord (RP)	12.9 m tkm					6.5 m tkm	**19.4 m tkm**
SPNV-Süd (RP)	1.2 m tkm	1.2 m tkm	3.7 m tkm	4.6 m tkm			**10.6 m tkm**
ZPS (SL)	2.9 m tkm		2.3 m tkm	0.5 m tkm			**5.7 m tkm**
VVO (SN)	5.1 m tkm	4.1 m tkm					**9.1 m tkm**
ZVMS (SN)	7.5 m tkm	0.3 m tkm	1.8 m tkm			2.2 m tkm	**11.8 m tkm**
ZVNL (SN)	15.2 m tkm					2.5 m tkm	**17.7 m tkm**
ZVON (SN)		3.3 m tkm					**3.3 m tkm**
ZVV (SN)		3.0 m tkm					**3.0 m tkm**
NASA (ST)							**0.0 m tkm**
Saxony-Anhalt	21.2 m tkm	1.1 m tkm				9.4 m tkm	**31.7 m tkm**
NAH.SH (SH)	7.0 m tkm	7.8 m tkm		18.0 m tkm			**32.8 m tkm**
TLBV (TH)		0.3 m tkm					**0.3 m tkm**
Thuringia		10.6 m tkm	0.4 m tkm				**10.9 m tkm**
TOTAL	**484.5 m tkm**	**145.3 m tkm**	**33.7 m tkm**	**31.2 m tkm**	**5.2 m tkm**	**53.9 m tkm**	**753.8 m tkm**

↑ Table 1: Planned regional operating capacity until 2033
(federal states in brackets) → [15] [16]

NVBW (BW)	Networks (selection)		
Diesel	Netz 11 Hohenlohe – Franken-Untermain	3.4 m tkm	12/19 – 12/31
	Netz 11 Hohenlohe – Franken-Untermain	3.6 m tkm	12/31 – 12/44
	Netz 12 Ulmer Stern	1.7 m tkm	12/19 – 12/32
	Netz 12 Ulmer Stern	1.7 m tkm	12/32 – 12/44
	Zollern-Alb-Bahn	1.4 m tkm	12/21 – 12/33
	D-Netz Bodensee	1.3 m tkm	12/23 – 12/30
	Nordschwarzwald	1.7 m tkm	12/25 – 12/37
BEMU	Netz 8 Ortenau	2.0 m tkm	12/23 – 12/35
open	Ringzug Schwarzwald-Baar-Heuberg	1.3 m tkm	12/27 – 12/39
BEG (BY)	**Networks (selection)**		
Diesel	Augsburger Networks – Los 2	3.4 m tkm	12/22 – 12/33
	Expressverkehr Nordostbayern *	8.3 m tkm	12/23 – 12/30
	Regionalverkehr Oberfranken *	5.3 m tkm	12/23 – 12/35
	Regionalverkehr Ostbayern Übergang *	4.7 m tkm	12/23 – 12/25
	Regionalverkehr Ostbayern Übergang – Los 2 *	1.9 m tkm	12/23 – 12/26
	Regionalverkehr Ostbayern	4.7 m tkm	12/25 – 12/35
	Linienstern Mühldorf 2025+ *	7.5 m tkm	12/24 – 12/30
	Romantische Schiene *	7.5 m tkm	12/24 – 12/36
	Franken-Südhessen	6.5 m tkm	12/27 – open
	Allgäu-Schwaben	7.1 m tkm	12/29 – 12/30
D-/E-Locomotive	IR25 Interimsvertrag *	2.8 m tkm	12/22 – 12/23
	Expressverkehr Ostbayern Übergang – Los 1 *	2.1 m tkm	12/23 – 12/26
	Expressverkehr Ostbayern	4.0 m tkm	07/28 – open
VBB (BB)	**Networks**		
open	Netz Ostbrandenburg 2 *	6.3 m tkm	12/24 – 12/34
Berlin and Brandenburg	**Networks (selection)**		
Diesel	Netz Nordwestbrandenburg	2.4 m tkm	12/28 – 12/40
	Netz Spree-Neiße	1.9 m tkm	12/30 – 12/42
	Heidekrautbahn	0.7 m tkm	12/20 – 12/23
HEMU	Heidekrautbahn	0.7 m tkm	12/23 – 12/38
open	Netz Prignitz	0.2 m tkm	12/20 – open

* Status 2/2020

→

↑ Table 2: Overview of diesel networks and alternatives →[15] – Part 1

RMV (HE)	Networks		
Diesel	Wetterau West-Ost	1.6 m tkm	12/22 – 12/32
	Ländchesbahn *	0.6 m tkm	12/22 – open
	Lahntal/Vogelsberg/Rhön *	2.4 m tkm	12/23 – open
	Odenwald	2.1 m tkm	12/27 – open
	Niddertal	0.7 m tkm	12/27 – open
	Dreieich	0.5 m tkm	12/27 – open
HEMU	Taunus *	1.8 m tkm	12/22 – 12/32
NVV (HE)	**Networks**		
RT-vehicles	RT-Netz	2.3 m tkm	12/23 – 12/33
LNVG (NI)	**Networks**		
Diesel	Dieselnetz Niedersachsen-Mitte	4.5 m tkm	12/21 – 12/29
	Dieselnetz Niedersachsen-Mitte	4.5 m tkm	12/29 – open
	Weser-Ems	4.9 m tkm	12/26 – open
	DINSO I	4.1 m tkm	12/29 – open
	DINSO II	3.1 m tkm	12/29 – open
	RE 5 Cuxhaven-Hamburg	1.6 m tkm	12/27 – open
HEMU	Weser-Elbe	1.4 m tkm	12/21 – 12/23
	Weser-Elbe	1.4 m tkm	12/25 – open
NVR (NW)	**Networks (selection)**		
Diesel	euregiobahn (RB 20)	1.5 m tkm	12/21 – 12/25
Diesel	Kölner Dieselnetz	7.2 m tkm	12/13 – 12/33
open	Nordast Rurtalbahn (RB 21 Nord) **	0.6 m tkm	12/25 – open
	Südast Rurtalbahn (RB 21 Süd) **	0.5 m tkm	12/25 – open
	Eifel-Bördebahn (RB 28) **	0.3 m tkm	12/25 – open
NWL (NW)	**Networks**		
open	Netz OWL	5.4 m tkm	12/25 – open
	Netz westliches Münsterland	3.0 m tkm	12/26 – open
	Sauerlandnetz	5.1 m tkm	12/28 – open
VRR (NW)	**Networks**		
Diesel	Emscher-Münsterland-Netz 2021	1.5 m tkm	12/21 – 12/28
BEMU	Niederrhein-Münsterland-Netz	6.1 m tkm	12/25 – 12/40
open	S7	1.5 m tkm	12/28 – open
	Erft-Schwalm-Netz	0.9 m tkm	12/29 – open

* Status 2/2020 ** Source NVR

↑ Table 3: Overview of diesel networks and alternatives → [15] – Part 2

SPNV-Nord (RP)	**Networks**		
open	Hunsrück (Steilstrecke)	0.2 m tkm	12/29 – open
	Moselweinbahn	0.2 m tkm	12/29 – open
	Daadetalbahn	0.1 m tkm	12/29 – open
	Eifel-Westerwald-Sieg-Netz	6.1 m tkm	12/30 – open
SPNV-Süd (RP)	**Networks**		
Diesel	Pfalznetz Los 2	1.2 m tkm	12/23 – open
Diesel-Electric	Südwest-Grand Est	3.7 m tkm	12/24 – open
BEMU	Pfalznetz Los 1	4.6 m tkm	12/24 – open
VVO (SN)	**Networks**		
Diesel	VVO Dieselnetz	2.3 m tkm	12/21 – 12/31
ZVMS (SN)	**Networks**		
Diesel	Freiberg-Holzhau	0.3 m tkm	12/19 – 12/24
Diesel-Electric	Chemnitzer-Modell-Netz	1.8 m tkm	12/20 – open
open	SPNV-Netz Erzgebirge	2.2 m tkm	12/21 – open
ZVNL (SN)	**Networks**		
open	DNWS (RB 110)	1.0 m tkm	12/25 – 12/37
	DNWS (RB 113)	0.5 m tkm	12/25 – open
Saxony-Anhalt	**Networks**		
Diesel	Elster-Geiseltal	0.8 m tkm	12/19 – 12/32
open	Dieselnetz Sachsen-Anhalt	9.4 m tkm	12/32 – open
NAH.SH (SH)	**Networks**		
Diesel	Netz West	5.1 m tkm	12/25 – 12/34
	Netz Süd	2.7 m tkm	12/27 – 12/37
BEMU	XMU Ost	4.0 m tkm	12/22 – open
	XMU Nord	5.0 m tkm	12/23 – open
	XMU Nord/Ost	9.0 m tkm	12/32 – open
Thuringia	**Networks**		
Diesel	NeiTec-Netz Thüringen	4.6 m tkm	12/21 – 12/28
	Ebx 13 Zeulenroda-Hof	0.4 m tkm	12/22 – 12/24
	Dieselnetz Ostthüringen	5.4 m tkm	12/24 – 12/36
Diesel-Electric	OBS	0.4 m tkm	01/21 – 12/31

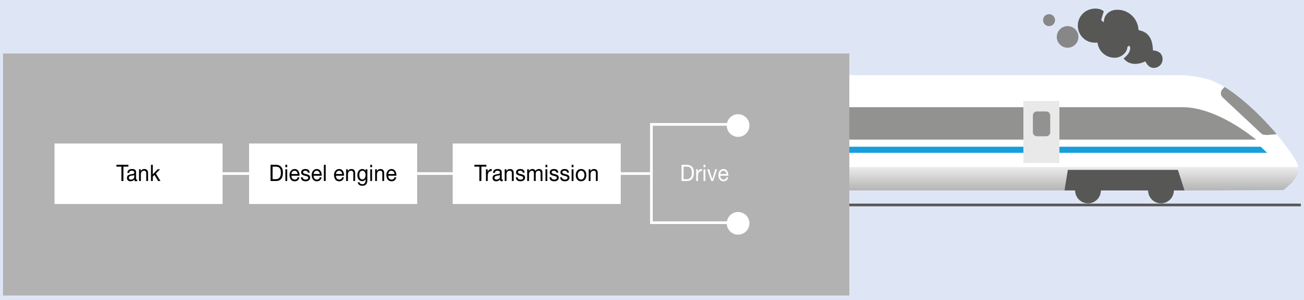
↑ Table 4: Overview of diesel networks
and alternatives → [15] – Part 3

3 The alternatives

In the past, it was comparatively easy for public decision-makers and railway undertakings to specify the type of traction to be used in the multiple units on the relevant lines: electric multiple units have always been used on fully electrified lines, for instance. If there was no overhead line, or it was incomplete, diesel vehicles were needed. In the 1990s, for example, Regio-Sprinter diesel multiple units from Siemens-DUEWAG were chosen if the timetable required particularly powerful vehicles for the acceleration phase and the lines were not electrified. Later, in the 2000s, the Regio-Shuttle from Stadler was the MU of choice. This could also provide multiple traction in case of higher traffic volumes. In cases where the dynamic requirements were less acute, modern diesel multiple units such as the Coradia LINT 54 from Alstom were chosen. For a technical comparison, see → Figure 3.

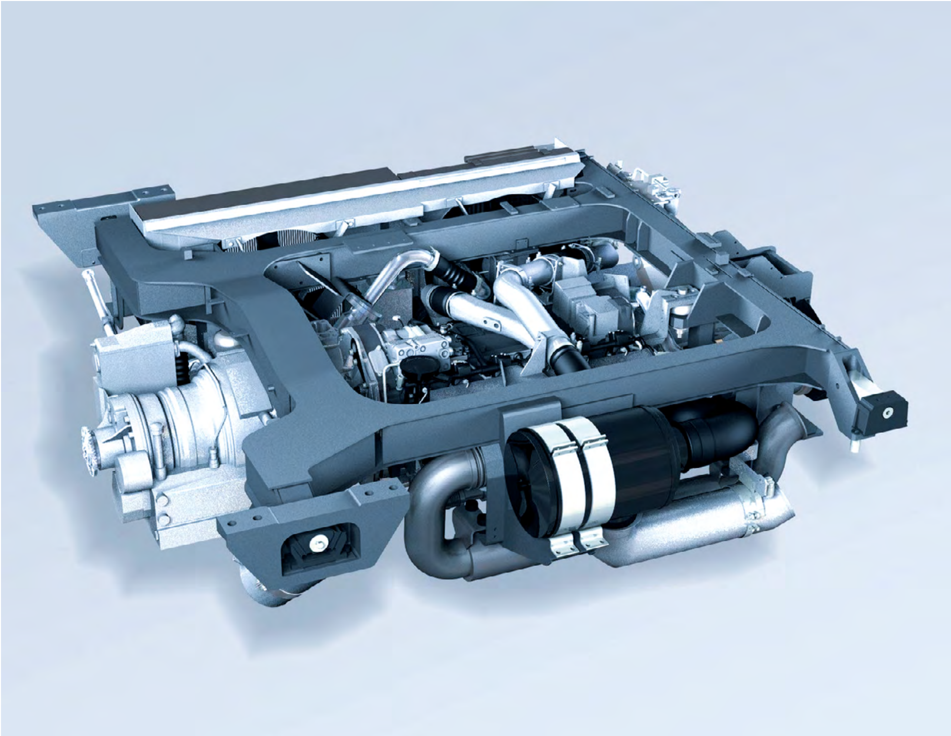
DMU

DMU	Regio Sprinter	Regio Shuttle RS1	Coradia LINT 54
	1-car	1-car	2-car
Length over headstocks	24,800 mm	25,000 mm	54,270 mm
Seating	84 spaces	79 spaces	165 spaces
Standing	100 spaces	85 spaces	184 spaces
Tare weight	49,200 kg	42,000 kg	98,000 kg
Engine capacity	2 × 198 kW	2 × 265 kW	3 × 390 kW
Maximum speed	120 km/h	120 km/h	140 km/h
Max. acceleration	1.10 m/s²	1.20 m/s²	0.60 m/s²
Manufacturer	Siemens/DUEWAG	Stadler Pankow	Alstom



Photos: NVR/Smilla Dankert · WK · WK

↑ Figure 3: Technical data – Diesel vehicles
(Source: Rurtalbahn GmbH)



Source: Rolls-Royce Power Systems

← Figure 4: MTU Power Pack Series 1800 for LINT multiple units (EU Stage IIIB, 2016)

Vehicles with diesel-mechanical drives require a transmission system in order to transfer the power from the combustion engine to the rails or road. In railway vehicles, drive trains with a diesel engine are also known as power packs. Two to three of these are installed in typical diesel multiple units and trains. Their exhaust gases are discharged through the roof. Ever more exacting requirements in terms of energy efficiency, vehicle stability and stricter emission standards have been the driving force behind the further development of this drive technology. Alstom's latest generation of diesel multiple units meets the *EU Stage V emissions standar*d → [17]. However, such major improvements are slow to gain acceptance given the extremely long operating life of these vehicles compared to HGVs.

The politically and socially advocated requirement to discontinue the use of rail vehicles with climate-damaging propulsion systems as soon as possible has made the decision-making process much more complex for those in charge of public transport: the choice of an alternative has become a system decision with long-term consequences. The authors believe that only vehicle solutions in which the drive is provided by electric motors, i.e. in which there is no reliance on combustion engines, constitute viable alternatives. One reason is that hybrid alternatives will not meet the goal of complete decarbonisation by 2050 and thus merely represent transitional solutions. The potential alternatives are therefore direct or indirect electrification: *Direct* in the shape of a continuous overhead line which allows the use of classic electric multiple units; *indirect* in the form of vehicles whose traction current is provided by batteries or fuel cells.

The list of possible alternatives is thus:

- Electric multiple unit (EMU)
- Battery-catenary hybrid (BEMU = Battery EMU)
- Hydrogen fuel cell-battery hybrid multiple unit (HEMU = Hydrogen EMU)

Their technical characteristics are set out below based on vehicles which are currently on the market or that will soon become available.

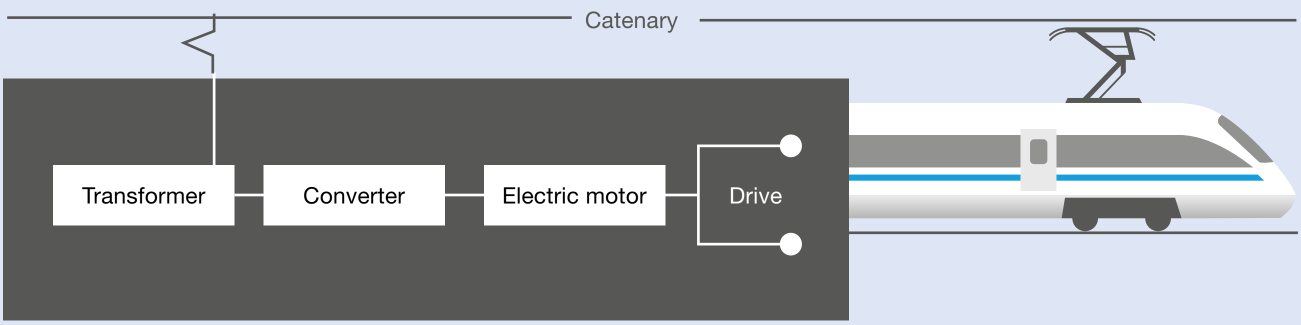
3.1 Electric multiple unit (EMU)

Electric multiple units (EMUs) draw their traction current from the overhead line. Housed in bogies, each electric motor drives one pair of wheels directly via the axle → Figure 6. The electricity is converted into kinetic energy with an efficiency level of over 90 per cent. The electric motors switch to generator mode during braking. The energy thus recuperated can be fed back into the overhead catenary, assuming that other electric multiple units are able to use it for acceleration at the same moment.

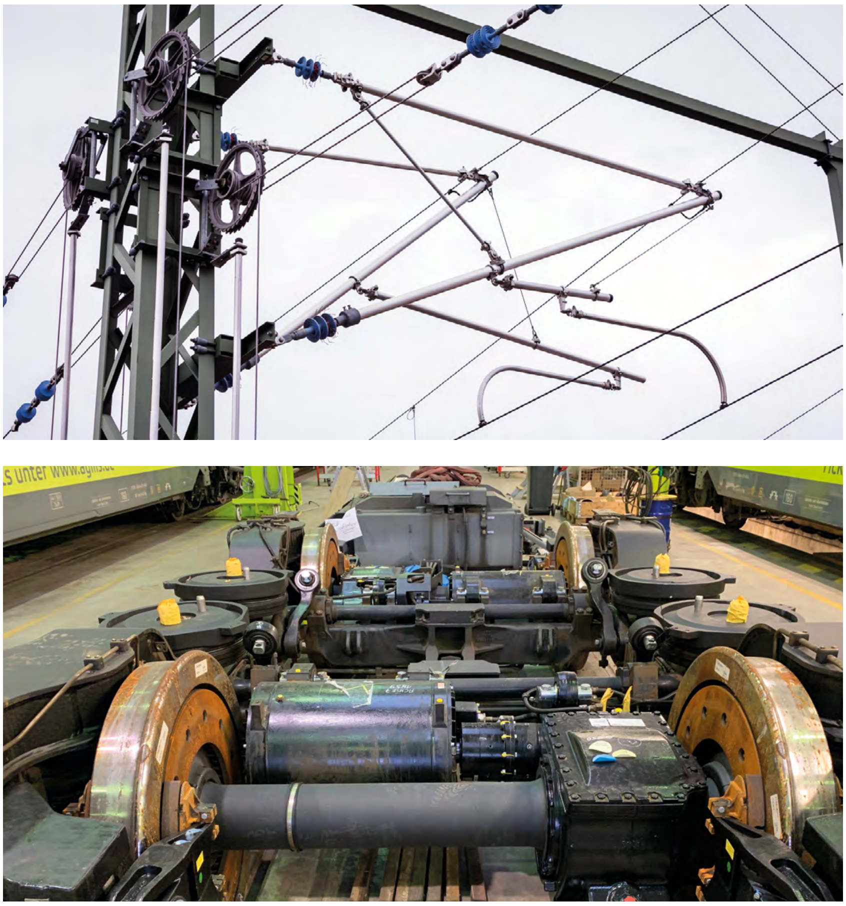
Photos: WK

EMU

EMU	TALENT 2	FLIRT 1	Desiro HC RRX
	3-car	3-car	4-car
Length over headstocks	56,200 mm	58,166 mm	105,252 mm
Seating	160 spaces	181 spaces	400 spaces
Standing	n/a	n/a	n/a
Operating mass	114,000 kg	105,200 kg	200,000 kg
Motor capacity	2,020 kW	2,600 kW	4,000 kW
Maximum speed	160 km/h	160 km/h	160 km/h
Max. acceleration	1.10 m/s^2	1.10 m/s^2	1.10 m/s^2
Manufacturer	Bombardier	Stadler Rail	Siemens-Mobility
	Source: Bombardier	Source: Stadler	Source: Siemens-Mobility



↑ Figure 5: Technical data for catenary electric multiple units (examples)



← Figure 6: Overhead line (catenary) and Jakobs bogie

Photos: NVR/Smilla Dankert · WK

3.2 Battery MU (BEMU)

The battery-powered multiple units (BEMUs) which are either currently available or have been officially announced by vehicle manufacturers have a similar structural design to that of conventional EMUs. They are equipped with large traction batteries that allow them to bridge gaps in the overhead line measuring from 80 to 120 kilometres (present situation). Roof-mounted pantographs enable BEMUs to act like EMUs on electrified lines; simultaneously they can rapidly recharge their batteries by drawing a power level of one megawatt or more.

The actual range of a BEMU on a stretch of track without catenary depends to a large extent on the installed battery capacity and the degree of load utilisation. More stringent running requirements or climatic peculiarities increase the energy demand and limit the battery capacity that can be used for operation, and thus the range. Manufacturers currently lack the long-term experience necessary for estimating the influence of such parameters on battery performance. This forces them to design the battery for specific routes on the basis of simulations of the relevant driving profiles. The usable capacity of a battery does not correspond to the nominal capacity specified in the data sheet. To achieve the longest possible operating life, a SoC (state of charge) window of 20 to 80 per cent should be maintained during operation. The capacity should therefore be designed such that the battery normally operates within a SoC window of 40–80%. Failures, extreme climatic conditions or other deviations from normal operation can be counteracted by designing in a buffer which temporarily allows more power than normal to be drawn without causing long-term damage. This renders unlikely the oft-feared stoppage of battery-powered trains due to an exhausted battery.

Braking energy recuperation significantly increases the energy efficiency of the BEMU, as it does not have to rely on there being another train in the vicinity that can use the recuperated energy for acceleration at the same moment. Instead, this energy can be used directly to recharge the traction battery.

↑ Figure 7: Battery-powered EMU TALENT 3

The disadvantage is that a BEMU is up to 10 per cent heavier than an EMU of the same design due to the high battery weight. The need for regular recharging of the battery throughout the day is another drawback, as it may necessitate changes to the original DMU operating solution. Further measures such as the installation of electrification islands for battery recharging may also be necessary.

From a systemic point of view, the BEMU solution is advantageous because it exploits the ever-growing share of renewable energy to the same extent as the EMU and will thus automatically become increasingly *greener*. It also represents a sensible interim solution on the way to full electrification (installation of continuous catenaries).

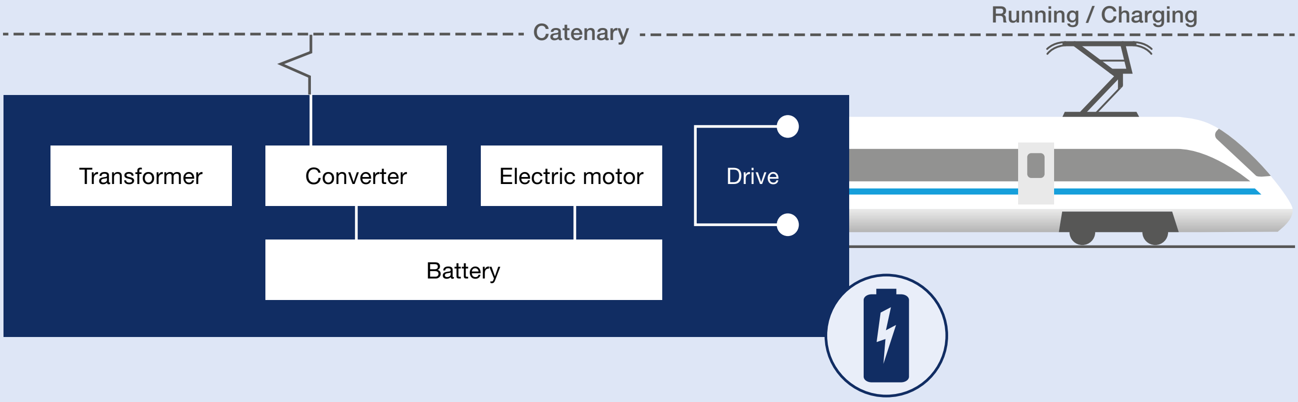
→ Figure 8 shows data for the following current BEMU models

- Bombardier's TALENT 3 BEMU → Figure 7 and → Figure 8 left, which was presented to the public at the InnoTrans trade fair in Berlin in 2018 as the first battery-powered multiple unit;
- The CityJet Eco → Figure 8 middle and → Figure 10, which Siemens-Mobility developed for the Austrian Federal Railways (ÖBB) on the basis of the Desiro ML electric multiple unit. It is being tested in regular passenger service on the Linz to Sankt Nikola-Struden route in Austria;
- The Mireo Plus B, which is available in 2 and 3-car versions. It is based on the Mireo Plus platform → Figure 8 right and → Figure 9, which itself was derived from the Mireo-EMU, albeit with shorter car lengths. In August 2019, NVBW placed an order with Siemens-Mobility for the delivery of 20 of these vehicles for NETZ 8 Ortenau, with a further requirement that they should be maintained and repaired over a period of 29.5 years → [16].

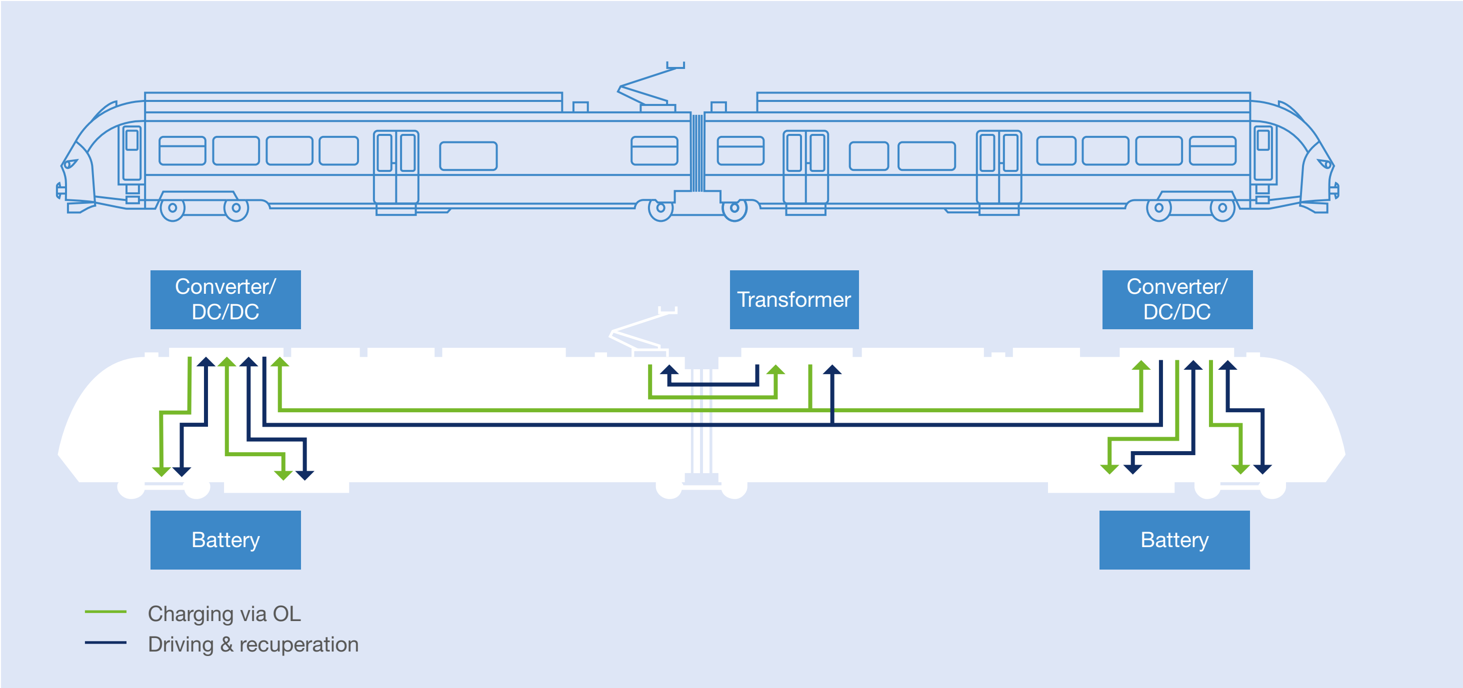
BEMU

Photos: Bombardier · Siemens · Siemens

BEMU	TALENT 3 BEMU	CityJet Eco	Mireo Plus B	Mireo Plus B
	3-car	3-car	3-car	2-car
Length over headstocks	56,200 mm	75,125 mm	62,900 mm	46,560 mm
Seating	165 spaces	244 spaces	155–194 spaces	105–139 spaces
Standing	n/a	n/a	n/a	n/a
Operating mass	> 100,000 kg	> 130,000 kg	124,500 kg	96,500 kg
Motor capacity	1,800 kW	up to 2,600 kW	2 × 850 kW	2 × 850 kW
Maximum speed	140 km/h	140 km/h	140 km/h	140 km/h *
in battery mode	n/a	100 km/h	n/a	n/a
Max. acceleration	1.10 m/s^2	1.00 m/s^2	1.00 m/s^2	1.10 m/s^2
in battery mode	n/a	0.77 m/s^2	n/a	n/a
Battery capacity	n/a	528 kWh	700 kWh	580 kWh
Battery range	100 km	80 km	120 km	80 km
Manufacturer	Bombardier	Siemens-Mobility	Siemens-Mobility	Siemens-Mobility
	Source: Bombardier	Source: Siemens-Mobility	Source: Siemens-Mobility	* 160 km/h with magnetic brakes



↑ Figure 8: Technical data currently available for battery-powered multiple units (02/2020)



↑ Figure 9: 2-car Mireo Plus B –
BEMU platform and energy flow diagram

↑ Figure 10: An ÖBB CityJet Eco BEMU
on the Linz – St.Nikola-Struden route (Oct. 2019)

Photo: Stadler · Computer graphics: Alstom

← Figure 11: Battery-powered EMUs FLIRT 3 Akku (above) and Coradia Continental BEMU (Computer graphics below)

No usable technical data was available to VDE on:

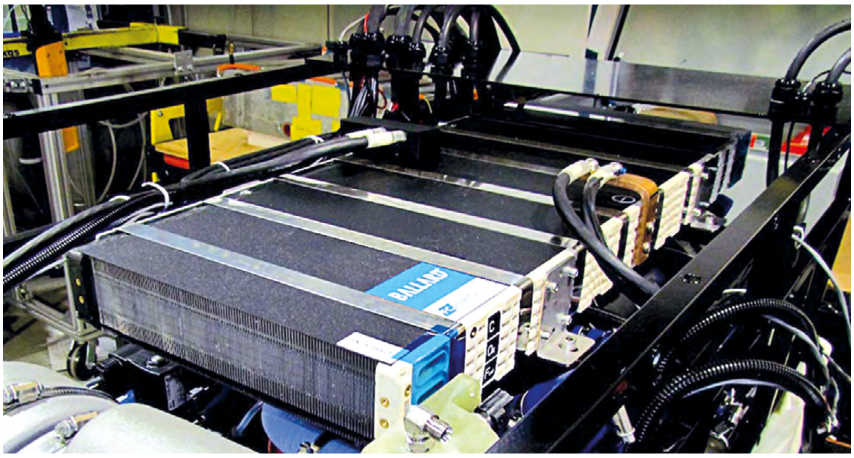
- FLIRT Akku – the Stadler BEMU based on the FLIRT-3-EMU → Figure 11 above. In October 2019, NAH.SH in Schleswig-Holstein and the manufacturer signed a supply contract for 55 vehicles for the XMU Nord and XMU East networks → [18]. This agreement requires Stadler to provide maintenance for these vehicles over a period of 30 years.
- Alstom BEMU based on Coradia Continental-EMU → Figure 11 below. In February 2020, the ZVMS transport association decided to purchase eleven vehicles of this type. These are to be used on the Leipzig-Chemnitz line from 2023 to 2028 and will be operated as EMUs once the full electrification of the line is complete. → [19]

3.3 Fuel cell multiple unit (HEMU)

From a technical viewpoint, the HEMU, like the BEMU, is a multiple unit with electric motor drive. The idea seems to have gained acceptance among customers and manufacturers alike that fuel cell multiple units should generally be used on routes with no or only intermittent overhead lines, i.e. no pantograph is needed on the roof. HEMU deployment therefore precludes EMU-mode operation on lines with an overhead catenary.

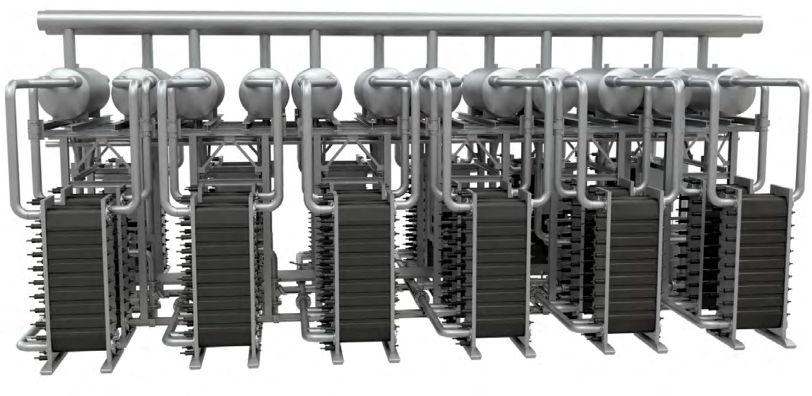
The body of the Alstom HEMU, → Figure 15 (left) and → Figure 16, corresponds to that of the Coradia LINT 54, a successful two-car DMU from Alstom. In designing this vehicle, Alstom was keen to retain its existing DMU operating concept. Accordingly, the main focus was on achieving a sufficiently long range, thus making it possible to minimise the number of strategically located hydrogen refuelling stations. The amount of power delivered by a DMU engine is relatively low compared to that of an EMU motor, yet this was still taken as the model power output. In the meantime, however, this very aspect is now often cited as an argument against the HEMU, even though the engine/motor power is not a specified technological requirement. Siemens Mobility has planned significantly higher drive power for its HEMU variant Mireo Plus H, → Figure 15 right.

In order to ensure dynamic operation in a HEMU, it is not sufficient for the power to be supplied exclusively by fuel cells, as these are not capable of delivering the high currents required for rapid acceleration. For this reason, the fuel cell stack → Figure 12 must be supplemented by a dynamic battery which is smaller than that found in a BEMU and is not used continuously. A technological disadvantage emerges here: the HEMU solution requires two technology components, namely a fuel cell and a battery – which has a corresponding impact on vehicle procurement and maintenance costs. A further disadvantage is the low efficiency of the process by which the energy stored in the hydrogen is converted into drive current. This means that a HEMU generally has a higher energy demand than that of a BEMU or EMU. In the reverse direction, too, the production of hydrogen by electrolysis, → Figure 13, is disadvantageous in terms of the overall energy balance.



← Figure 12: Fuel cell stack (Ballard Power)

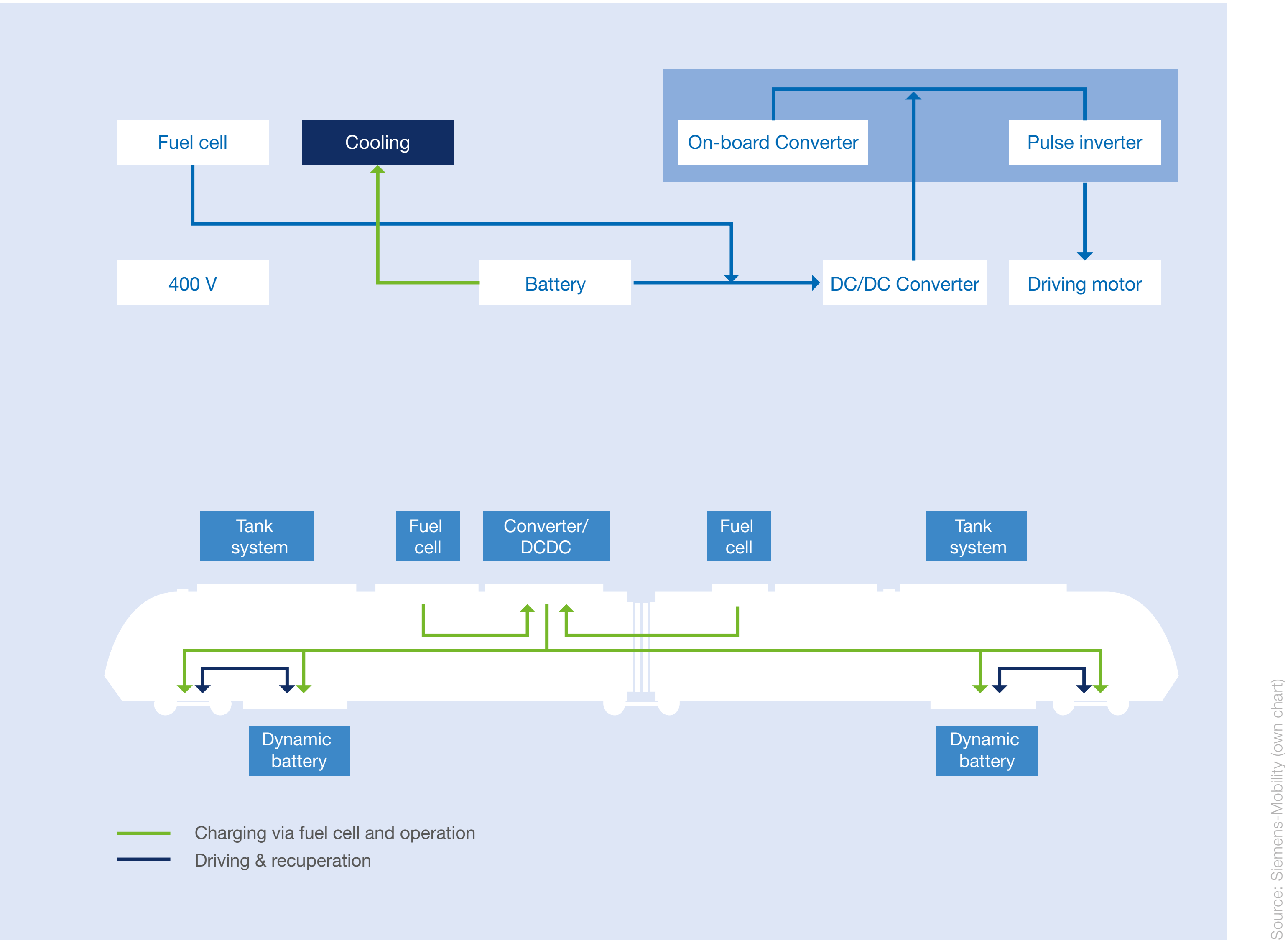
↓ Figure 13: Electrolyser (Siemens Silyzer 300)



The dynamic battery required by the system gives the HEMU the same advantage of being able to store its braking energy temporarily. This can then be used during acceleration phases and thus save hydrogen → Figure 14. The general discussion surrounding *green* hydrogen as the ideal storage option for renewable energy means that, despite its efficiency-related disadvantages, the HEMU solution is systemically advantageous because, like the BEMU solution, it encourages the energy transition, but it also supports the accompanying sector coupling.

→ Figure 15 shows data for two current HEMU models. These are:

- The Coradia → Figure 15 left which Alstom unveiled at InnoTrans 2016 in Berlin. This fuel cell-powered multiple unit will go into operation from 2022 in the Weser-Elbe network of the Lower Saxony regional public transport company LNVG, from 2023 in the Taunus network of the Rhine-Main transport association RMV and from 2024 on the Heidekrautbahn routes north of Berlin.
- The Mireo Plus H which, like the Mireo Plus B, is available in 2 and 3-car versions.

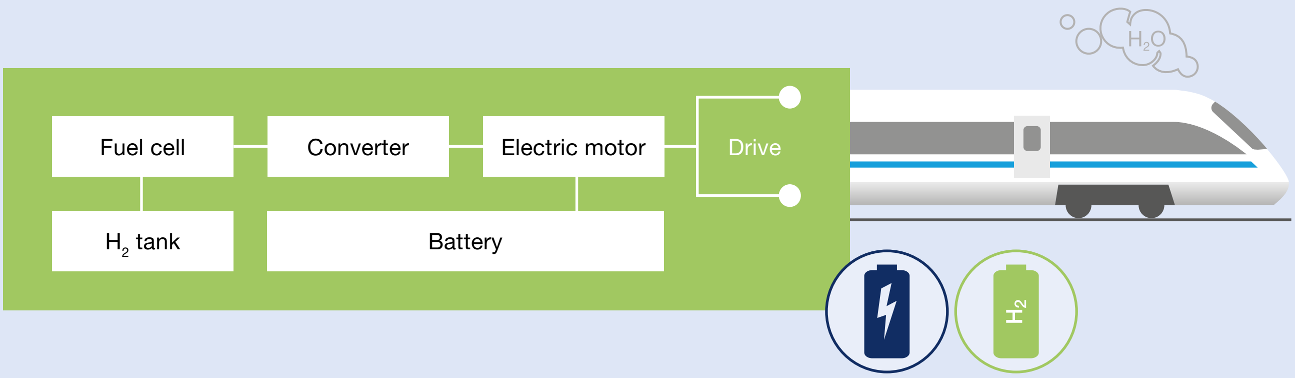


↑ Figure 14: 2-car Mireo Plus H –
HEMU-platform and energy flow diagram

Photos: Bombardier · WK · Siemens

HEMU

HEMU	Coradia iLINT 54 Type I [Type II]	Mireo Plus H	Mireo Plus H
	2-car	3-car	2-car
Length over headstocks	54,270 mm	62,900 mm	46,560 mm
Seating	153 [160] spaces	155–194 spaces	105–139 spaces
Standing	n/a	n/a	n/a
Operating mass	106,900 kg	> 120,000 kg	> 95,000 kg
Motor capacity	2 × 277 kW [2 × 367 kW]	2 × 850 kW	2 × 850 kW
Maximum speed	140 km/h	140 km/h	140 km/h *
Max. acceleration	1.10 m/s²	1.00 m/s²	1.10 m/s²
Fuel cell capacity	2 × 200 kW	2 × 200 kW	2 × 200 kW
Size of hydrogen tanks	260 kg	250 kg	130 kg
Vehicle range	1,000 km	900 km	550 km
Capacity of dynamic battery	n/a	2 × 175 kWh	2 × 175 kWh
Manufacturer	Alstom	Siemens-Mobility	Siemens-Mobility
	Source: Alstom	Source: Siemens Mobility	* 160 km/h with magnetic brakes



↑ Figure 15: Technical data currently available for fuel cell powered multiple units (02/2020)

Photo: WK

↑ Figure 16: Alstom Coradia iLINT on the RB 21 Süd line in Obermaubach (February 2020)

4 Decision-making methods

There is broad agreement among politicians and across society in general that diesel multiple units should not be used, even on relatively infrequently used branch lines, in the future. The public decision-makers and railway undertakings are thus now faced with making a systemic decision, the impact of which could have unknown effects on the cost-effective operation of the lines on which diesel trains used to run. Those responsible need to have the necessary technological and systemic knowledge in order to make the decision. This includes knowledge about such as aspects as: energy conversion efficiency, technical maturity and availability levels, renewable energies, long-term plans for the systemic coupling of power grids, mobility, industry and heat, and about the importance of hydrogen as a *green* energy source and its production through electrolysis. In addition, little experience has yet been accrued on the regular operation of BEMU or HEMU vehicles. This makes it extremely difficult for decision-makers to identify and select the best alternative for a diesel network based on *gut feelings*.

In its second study → [3], the VDE examined this complex issue and demonstrated how benefit analysis represents a suitable procedure for conducting an operational and economic assessment and comparison of the alternatives. The underlying methodology is explained in the following section.

In certain specific conditions, the direct or indirect electrification of today's diesel lines are equally favourable, meaning that a further procedure is needed to assess and compare the alternatives in terms of long-term investment based on capital value. Net present value analysis has proven to be a suitable valuation method here. The underlying principle is described in the second section of this chapter.

4.1 Benefit analysis

A benefit analysis is a decision theory technique → [20] which can usefully be applied when a system decision has to be made among a group of stakeholders and when various complex alternatives are available. The results are qualitative in nature, and their significance and general validity depend on the experience and statistical relevance of the people interviewed. A decision in favour of a particular alternative is usually based on a number of criteria, the non-fulfilment of which would lead to the exclusion of the option. This means that only those alternatives are considered which meet all the mandatory criteria. A comparison and qualitative assessment of the various alternatives can be made based on the respective degrees of fulfilment.[13] *Economic viability* is one of the fundamental decision-making criteria. The VDE's benefit analysis, however, is only based on a qualitative assessment, i.e. it assesses the potential of the alternative's long-term economic viability. The resulting conclusion would be insufficient as the basis for an investment decision, since the economic viability of a railway line also depends on the terrain through which it passes and the conditions under which the vehicles have to operate.

13 For the results, see Study → [3]. This is available as a free download

4.2 Net present value method

Investment in an alternative to an existing system which – as in the case of diesel vehicles on branch routes – has hitherto proved to be economically viable, only makes sense if it can yield a positive economic result in the long term (if necessary, supported by suitable framework conditions and measures).

One way is to base any investment decision in favour of a specific alternative on a comparative *dynamic investment calculation*. The formula described in → [6] is the basis for calculating the net present value:

$$C_0 = -I_0 + \sum_{t=1}^{n} \frac{R_t}{q^t} \pm \frac{L_n}{q^n} \qquad \boxed{\text{Formula 4.1}}$$

C_0 [€]	= Net present value = Present value of cash flows of an investment
$-I_0$ [€]	= Amount of investment at beginning of observation period
t [Year]	= Year t within period 0 to n years
n [Year]	= Useful life of investment object or length of observation period
R_t [€/Year]	= Return in year t (= Receipts minus expenditures)
$\frac{1}{q^t} = \frac{1}{(1+i)^t}$	= Discounting factor if t > 0 or compounding factor if t < 0
$q = 1 + i$ [%]	= imputed interest rate
L_n [€]	= Liquidation proceeds or expenditure in year n at end of observation period

The starting point of the comparative analysis is the assumption that each of the potential investment alternatives is beneficial in absolute terms. In other words, the sum of all revenues and costs (= expenditures; negative values) will be positive over the life cycle of the new vehicles and the additional infrastructure elements. The revenues prove to be less important for comparing the alternatives, as they are not technology-specific. On the cost side, too, there are various categories with the same expenditure levels for all investment alternatives (such as personnel, administration, internal services, train path and station charges). Thus, only the specific costs for the procurement and operation of the vehicles and the required infrastructure are relevant for an objective comparison.

The investment analysis in this study is carried out using the net present value method described in → [6]. Its successful application is demonstrated in → [5] and → [21], which confirms its suitability especially for economic and business-related assessments. Calculated over a defined period of time, the method determines the (negative) net present value based only on the relevant costs. The calculation assumes that the decision-maker acts as a *rational investor with economic objectives*, i.e. he will only decide to invest if the alternative is at least as advantageous as a corresponding investment on the capital market. In this case, the expenditures in the period concerned (based on their time of occurrence) and the expected residual values are discounted based on the applied calculation interest rate and thus linked as cash values to the present year 0 of the relevant period.

The calculation interest rate is decisive for the accuracy of the investment calculation. However, it is impossible to predict this accurately give the long period under consideration here. In financial mathematics, it is determined using the so-called nominal interest rate i_n and the price increase rate r. In the present study it was assumed that the nominal interest rate can be estimated as the average value of the current yield of fixed-interest securities over the past 15 years, → [22]. This would put it at 2 per cent. The current value of 1.5 per cent was taken as the rate of price increase. Based on the following formula

$$i = \frac{100}{100 + r} \times (i_n - r)$$

this yields an imputed interest rate of 0.49%.

At this point it should be noted that, since the same imputed interest rate is applied to all the alternatives, a change in this would affect the resulting net present values of the alternatives, but not their ratios.

It can be determined which of the alternatives would be the most advantageous investment project by comparing the resulting negative net present values: the lower (in absolute terms) the net present value of an alternative in the period under consideration, the more advantageous it is.

A challenge which this net present value analysis poses is the need for precise specification of certain parameters, such as fuel and electricity prices, route-specific energy demands per kilometre, replacement costs for high-tech components, etc. How decisive these parameters are for the result will be demonstrated in the next chapter, based on the example of the ›Düren network‹ and using sensitivity analysis.

Further important aspects are the lifetimes and depreciation periods to be applied to the various capital goods, as well as the period under consideration. According to the 1998 depreciation table for the “Passenger and goods transport (road and rail)” economic sector → [23], a depreciation period of (at least) 20 years is applied to multiple units, with the useful life rising to 35 years for electric drives. The present study assumes that new vehicles and additional infrastructure depreciate on a straight-line basis over their respective assumed useful lives. The residual values at the end of the period under consideration are added in discounted form to the resulting net present value. A maximum *transport contract duration* of 22.5 years[14], a *vehicle life* of 30 years and a *durable capital goods lif*e (e.g. for catenary masts) of 76 years were applied here.

14 this corresponds to 15 years plus additional maximum of 50% without re-tendering; see also footnote to → section 5.4.2

5 ›Düren network‹ – Economic assessment of the alternatives

Chapter 5 provides comprehensive information on the aims, implementation and evaluation of the viability analysis for the ›Düren network‹. → Section 5.1 looks at the history of the Rurtalbahn and the Bördebahn, where battery-powered rail buses were operated back in the 1980s, and presents ZV NVR and Rurtalbahn GmbH as the companies responsible for the current operations. → Section 5.2 provides an overview of the current operating programmes of the RB 21 Nord, RB 21 Süd and RB 28 lines, and also the programmes planned from 2026. The resulting fuel and power consumption levels of the different vehicle solutions are explained in → section 5.3 after a presentation of the VDE simulation model for calculating the energy demand on the three lines.

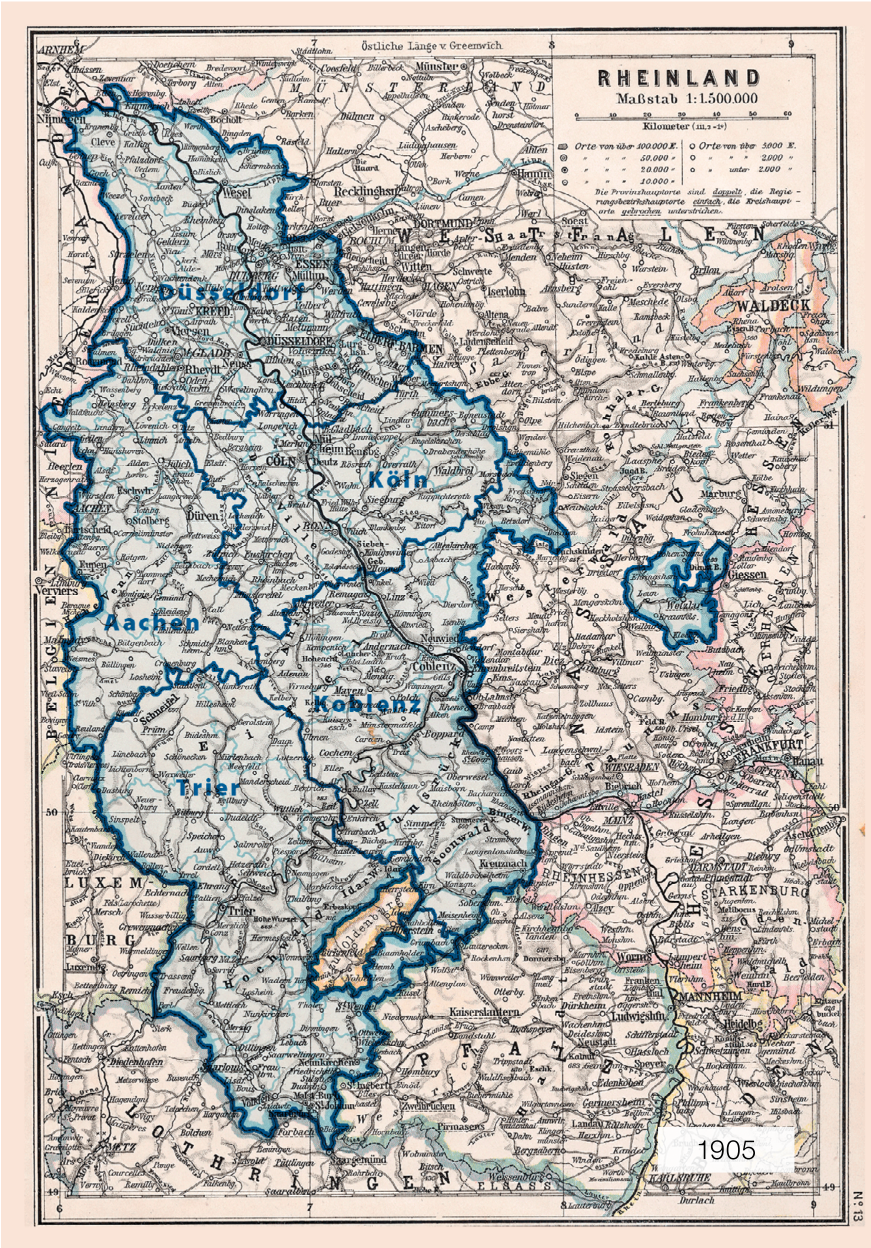
Taking this information as its basis, → section 5.4 then describes how the net present value method is used to determine which of the HEMU, BEMU or EMU solutions represents the most advantageous investment project for the ›Düren network‹.

5.1 Background

The origins of the three railway lines → [24] which comprise the current ›Düren network‹ date back to the second half of the 19th century when industrialisation was just beginning in the Rhine province (which belonged at that time to the Kingdom of Prussia) → Figure 17 and → Figure 18. Three railway companies were founded in 1836 as part of the development process for this region and the Ruhr area: the “Rheinische”, “Bergisch-Märkische” and “Köln-Mindener” companies. In 1856, the Rheinische Eisenbahn-Gesellschaft acquired the concession for the construction of a railway line along the Rur valley from Düren to Schleiden in the Eifel region. Its purpose was to facilitate the transportation of mined ores and also of smelting coal for the iron and steel industry. 1864 saw the inauguration of the Düren-Euskirchen *Bördebahn* passenger service. Work on the Düren–Jülich line began in 1873, with the first Düren–Lendersdorf–Maubach section opening in 1892 and the remaining stretch to Heimbach following in 1903.

→ Figure 17: The origins of the ›Düren network‹ in the Prussian province Rhineland (Part 1)

Source: https://de.wikipedia.org/wiki/Deutscher_Bund



← Figure 18: The origins of the ›Düren network‹ in the Prussian province Rhineland (Part 2)

Source: https://de.wikipedia.org/wiki/Datei:Rheinland_Regierungsbezirke_1905.png

5.1.1 Rurtalbahn

The Rurtalbahn serves the district of Düren along the River Rur. Its route comprises 29 closely spaced stops, seven of which are in the Düren urban area → Figure 20. The north branch (RB 21 Nord) of the railway connects Düren via Jülich to the town of Linnich, which is in the northern part of the district → Figure 19. The town of Heimbach in the south is connected to Düren via the south branch (RB 21 Süd). This route follows the many convolutions in the Rur from Untermaubach-Schlagstein to Heimbach – through picturesque forest and meadow landscapes.

Map section: Schweers + Wall / NVR · Photos: WK

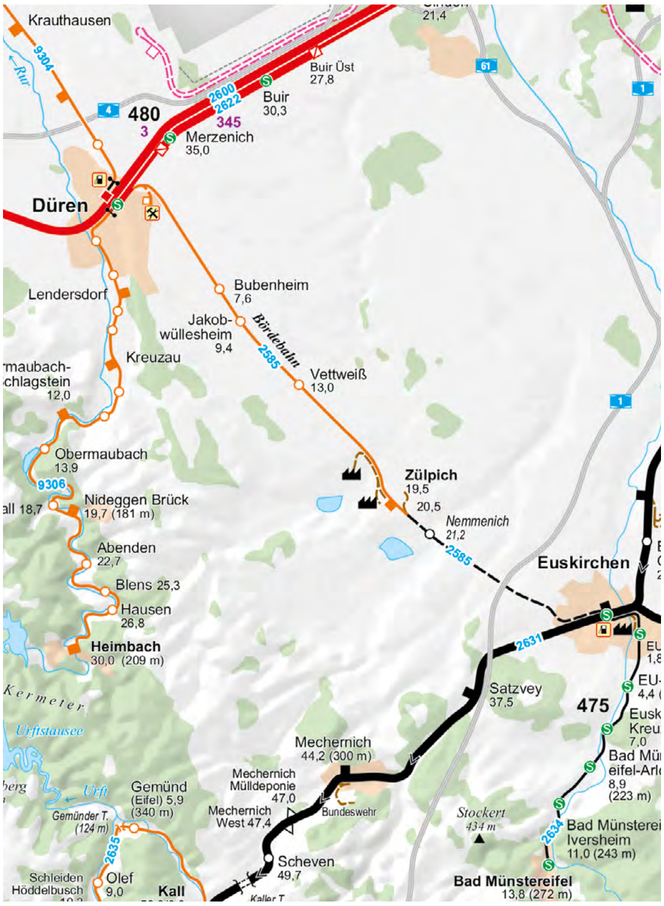
↑ Figure 19: RB 21 northern and southern branch

← Figure 20: RegioShuttle RS1 at Düren station

5.1.2 Bördebahn

The Bördebahn in its current form was created in 1979 by splitting the Düren–Bonn link and converting the Düren–Euskirchen line into a branch line, the scheduled operation of which was discontinued in 1983. There were increased efforts from 2008 to reactivate the line for local passenger operation in time for the planned *2014 State Horticultural Show* in Zülpich. The surprisingly strong demand, even among regular passengers, led to the formulation of a permanent reactivation plan, which was then finally agreed upon.

Falling within the remit of the NVR transport association, the line has been known as the RB 28 Eifel-Bördebahn since 2015. It connects the town of Düren with Euskirchen 30 kilometres away in the southeast, → Figure 21. This railway line runs predominantly in a straight line through rural areas, and is interrupted only by the premises of the paper manufacturer Smurfit Kappa Zülpich, the power plant of which burns lignite briquettes which are delivered to Zülpich Kappa station by freight trains on working days. RB 28 was used for passenger traffic on weekends and public holidays. Trains have been running daily at two-hour intervals on the route since December 2019. There are plans for a further increase in the frequency → Figure 22.



← Figure 21: RB 28 Eifel-Bördebahn

Map section: Schweeers + Wall / NVR · Photo: WK

Sorce: Press photo NVR

↑ Figure 22: Guests on the inaugural ride of the RB 28 on Monday, 16 December 2019:
G. Rosenke, Chief Administrative Officer (1), Dr. P. Peill, MdL (2), W. Spelthahn, Chief Administrative Officer (3), K. Voussem, MdL (4), Dr. R. Nolten, MdL (5), H. Kolvenbach, Association board member NVR (6), Dr. N. Reinkober, Managing Director NVR (7)

5.1.3 Historical multiple units

It took many years to reconstruct the railway installations along the Düren–Heimbach line (today RB 21 Süd) which had been destroyed during the Second World War. Not until October 1950 did the entire line open to rail traffic again. However, the growing number of cars and motorcycles on the roads gradually reduced its relevance. Starting in 1956, Deutsche Bahn simplified its railway operations, initially replacing its locomotive-hauled trains with diesel-powered VT 95 (BR 796) rail buses, → Figure 23.

Later, Deutsche Bahn replaced many of its VT 95s with battery-powered ETA 150.1 (BR 515) rail buses, → Figure 24. It had purchased a total of 232 of these between 1953 and 1965.

These vehicles were the technical successors of the “Wittfeld” accumulator railcar which the Royal Prussian Railway Administration had been using since 1907. The ETA 150 vehicles were equipped with lead batteries which delivered a total capacity of 548 kWh and a range of up to 400 kilometres – with a battery charging time of three hours → [25]. They had a top speed of 100 km/h. In the 1980s, battery-powered multiple units of this type were also used in Düren, for example on the line to Heimbach, as shown in → Figure 25. 24 years later, in February 2020, Alstom presented its iLINT 54 fuel cell train on this line → Figure 26.

← Figure 23: Diesel rail bus VT 95 in Landau railway depot (1978)

↓ Figure 24: Battery-powered ET 150 multiple unit in the Düren depot (1982)

Sources: Eisenbahnarchiv.de

Sources: Eisenbahnarchiv.de · Photo bottom: WK

← Figure 25: ETA 150 battery-powered multiple unit on RB 21 Süd: Heimbach 1986, Nideggen 1984, Obermaubach 1986

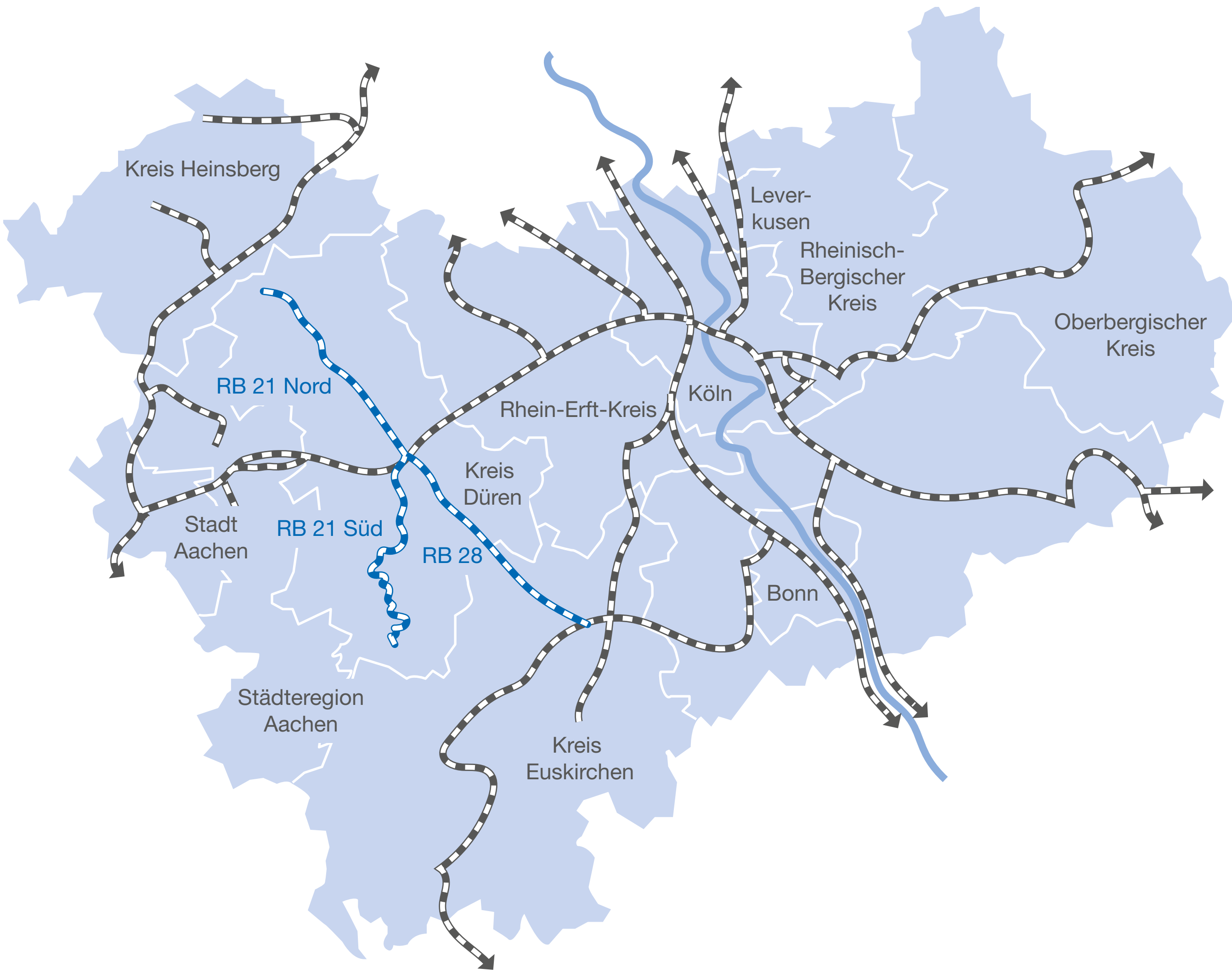
↓ Figure 26: iLINT 54 in Obermaubach

5.1.4 Rhineland Regional Transport Association (ZV NVR)

The territory of the Cologne-based Zweckverband Nahverkehr Rheinland (ZV NVR) includes the Rhineland part of North Rhine-Westphalia and covers the same area as the administrative district of Cologne → Figure 27. This includes the cities of Aachen, Bonn, Cologne and Leverkusen as well as the Düren, Euskirchen, Heinsberg, Oberbergischer, Rhein-Erft, Rhein-Sieg and Rheinisch Bergischer districts and the Aachen city region. The area covers approximately 7,400 km² and has 4.5 million inhabitants. 28 regional transport lines operate over a total length of roughly 1,550 kilometres. These lines have a total operating capacity of 26,8 million train kilometres per year, → [26].

NVR is searching for a suitable technical alternative to the diesel multiple units currently in operation on the RB 21 Nord (Düren–Linnich), RB 21 Süd (Düren–Heimbach) and RB 28 (Düren–Euskirchen) lines falling within its ›Düren network‹ (Netz Düren). The reason for this is that operation of these lines is shortly to be put out to tender. The current operator is the railway undertaking Rurtalbahn GmbH (RTB).

The stakeholders of ›Netz Düren‹ – i.e. NVR, Rurtalbahn and the district of Düren – have set themselves ambitious goals in the form of projects for the reactivation or expansion/addition of line sections, stops and new vehicles, aimed at achieving significantly higher operating capacity for considerably more passengers.



Source: www.nvr.de (own chart)

↑ Figure 27: Area of NVR
(marked blue the relevant lines of Netz Düren)

5.1.5 Rurtalbahn GmbH (RTB)

Dürener Kreisbahn took over operation of the Jülich–Düren (later *RB 21 Nord*) and Düren–Heimbach (later *RB 21 Süd*) railway lines from Deutsche Bahn in 1993. After changing the name to *Rurtalbahn*, it operated the lines at hourly intervals – initially using modernised Uerdingen rail buses. In 1995, Dürener Kreisbahn added 17 rapid-acceleration Regio-Sprinter multiple units from Siemens/DUEWAG (BR 654) to the Rurtalbahn fleet → Figure 28. This number was much higher than was actually required, meaning that some of the vehicles could be leased to other transport companies. In 2002, the passenger service between Jülich and Linnich was restored, enabling the trains to run now from Düren to Linnich → [24].

Based in the district town of Düren, the medium-sized company Rurtalbahn GmbH → [27] was founded in 2003 after Dürener Kreisbahn privatised the Rurtalbahn by selling 74.9% of its shares to R.A.T.H. GmbH. The current holding company, Kreis Düren, owns the remaining 25.1% of the shares.

Rurtalbahn GmbH (RTB) operates as a medium-sized, non-federally owned rail transport and infrastructure company (EVU|EIU) with its own vehicle fleet, depot and maintenance workshop. It is also the owner of the track installations in the ›Düren network‹. RTB is not a member of the “Tarifverband Bundeseigener und Nichtbundeseigener Eisenbahnen in Deutschland” collective bargaining association (TBNE).

In 2011, Rurtalbahn GmbH purchased five RS1 Stadler Regio Shuttles for 8.8 million euros to replace some of its outdated Regio-Sprinters. In 2016, RTB acquired three used RS1s from Ostdeutsche Eisenbahn, and also purchased three Alstom Coradia LINT 54 diesel multiple units for twelve million euros. In February 2019 RTB sold its last Regio Sprinters to the Czech Republic. Today, RTB is running its timetables with eight RS1s and three LINT 54s.

Photo: NVR/Smilla Dankert

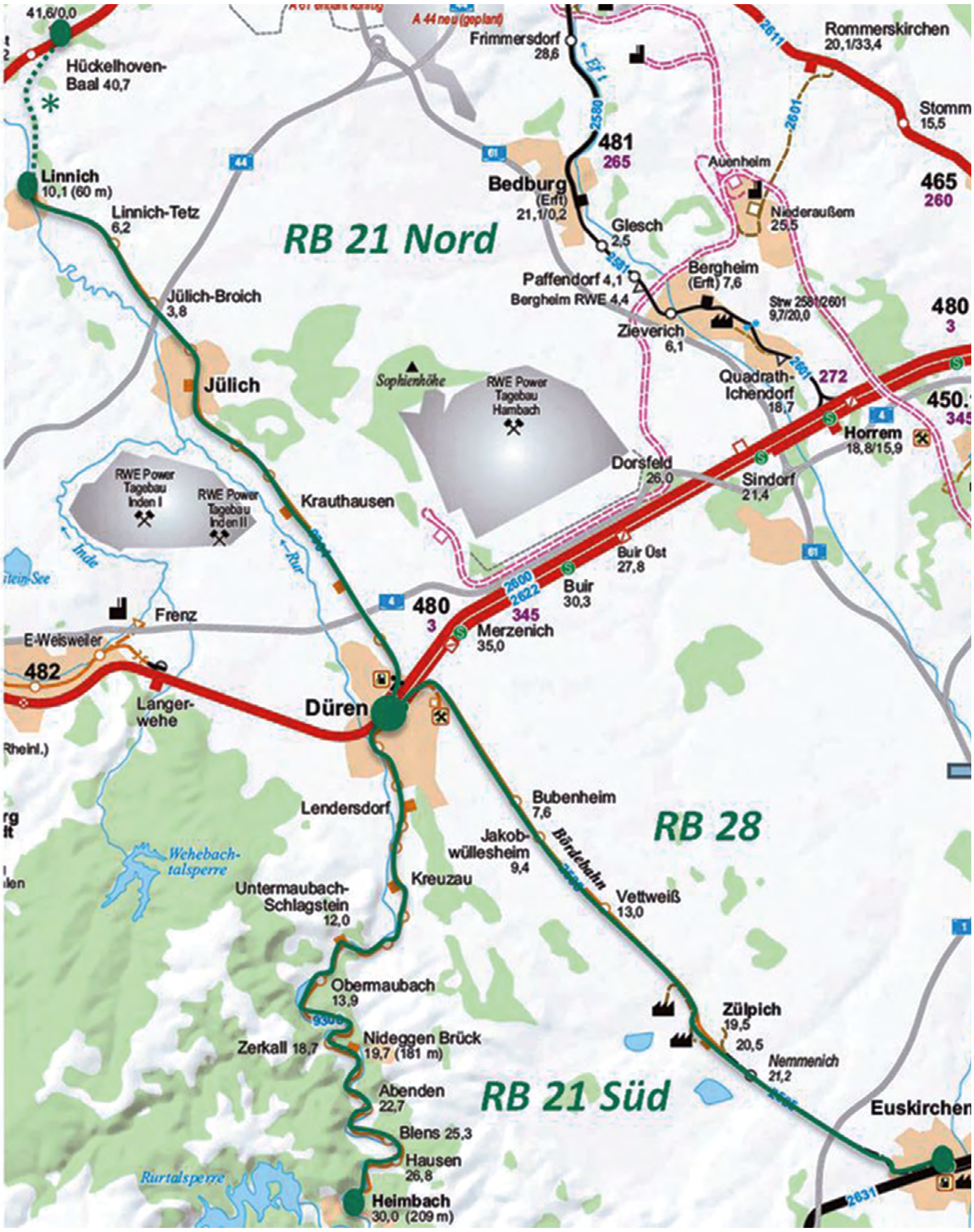
↑ Figure 28: RTB Regio Sprinter (in Heimbach), discontinued from February 2019

5.2 Current situation and plans

5.2.1 The ›Düren network‹

RB 21 Nord, RB 21 Süd and RB 28 form the ›Düren network‹ (Netz Düren), which is operated by Rurtalbahn GmbH (RTB) and for which NVR carries responsibility, see map → Figure 29.

By 2026, RB 21 Nord is to be lengthened to 31.5 kilometres through the addition of a 5.8 kilometre stretch between Linnich and Hückelhoven-Baal. The planned restoration and construction work is scheduled for completion in 2025. The infrastructure of the RB 28 line is currently being upgraded between Düren and Euskirchen to enable it to cope with faster train speeds and denser timetable frequencies.



← Figure 29: General plan of the ›Düren network‹ lines

Source: Schweers + Wall / NVR

Photos: WK

↑↑ Figure 30: Düren station – Electrified track 4/4a (left) and non-electrified track 23 (reight)

↑ Figure 31: RTB Regio Shuttle RS1 in Heimbach (left) and RTB Coradia LINT 54 in Jülich (right)

There is no catenary on any of the three lines, each of which is roughly 30 kilometres in length. Only track 4/4a in Düren station, assigned to lines RB 21 Süd and RB 28, is electrified. There are dedicated overhead lines for RE and S-Bahn traffic through Düren station. The RB 21 Nord line currently starts in Düren on the non-electrified track 23 → Figure 30.

Euskirchen station at the end of line RB 28 is to be fully electrified by 2028 as part of the electrification of the Bonn–Euskirchen–Kall/Bad Münstereifel lines.

The RTB fleet currently comprises three Alstom Coradia LINT 54 (BR 622) multiple units with 165 seats, and eight Regio Shuttle RS1 (BR 650) MUs (some double-traction), each with 79 seats, → Figure 31.

RTB currently provides an operating capacity of 904,385 train kilometres per year to the ›Düren network‹ with this fleet of vehicles. According to NVR, denser timetable frequencies are planned to yield a 44 per cent increase in this capacity by 2026, and the addition of the Linnich–Baal section will add a further 12 per cent, taking the total to 1,460,310 train kilometres. There are also plans to replace the fleet with new climate-neutral vehicles, i.e. battery or fuel cell-powered trains, whose weight, size and seating capacity will be modelled on the data of the LINT 54.

According to NVR, the transport contracts for RB 21 Nord, RB 21 Süd and RB 28 will expire simultaneously in December 2025 and will be put out to tender jointly for the 2026 timetable year.

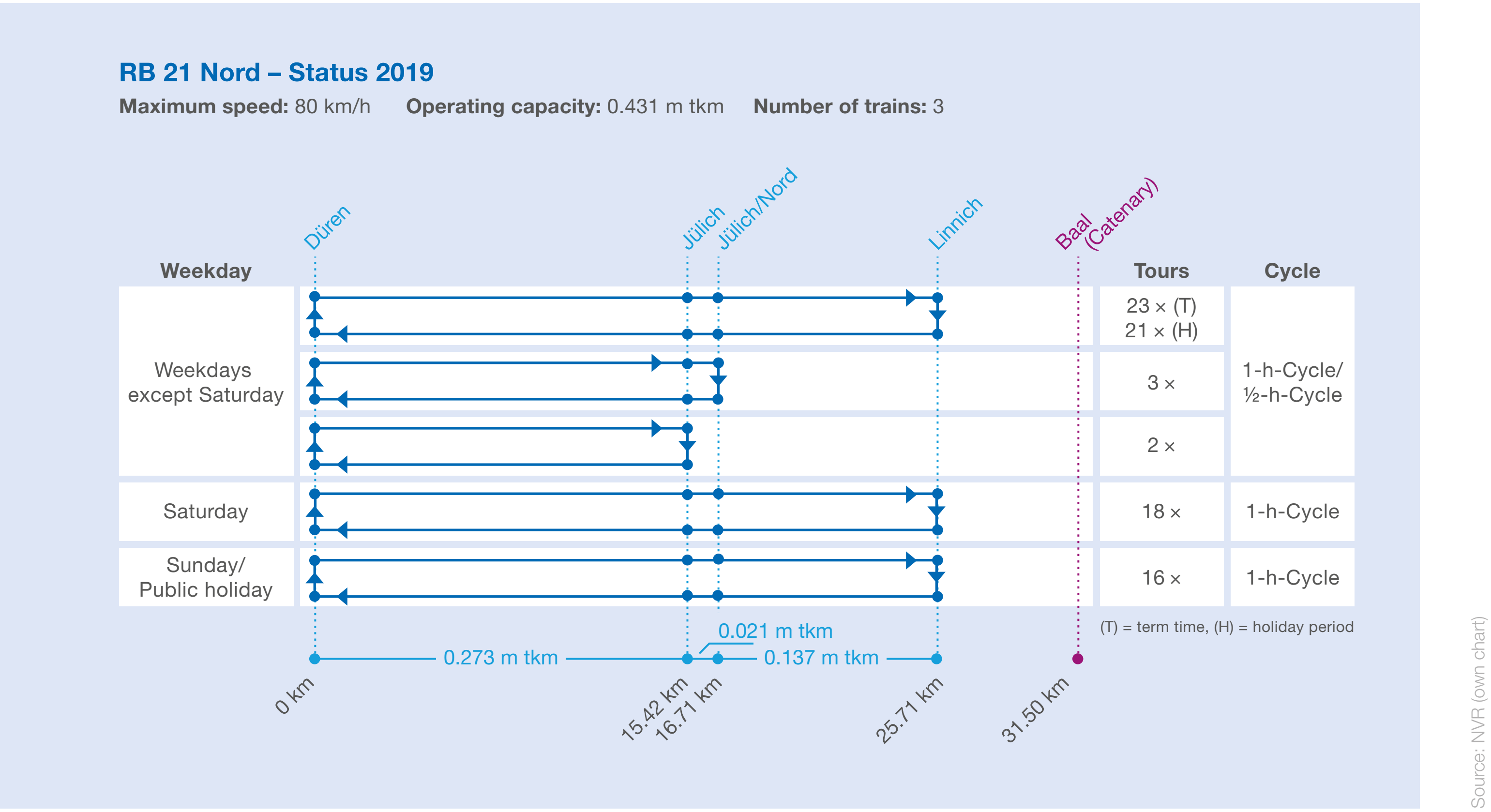
5.2.2 RB 21 Nord

The RB 21 Nord line connects Düren station via Jülich to Linnich station 25.71 kilometres away. The line comprises a total of thirteen stations, which are an average distance of 2.1 kilometres apart. There are six stops between Düren and Jülich; four of them are request stops. There are three request stops between Jülich/Nord and Linnich. The following three charts provide an overview of the current and planned operating programme of RB 21 Nord for 2026 and beyond.

Three trains (RegioShuttle RS1s or Coradia LINT 54s) currently operate on RB 21 Nord, each staggered by one hour. The timetable is so tight that the vehicles often have to accelerate at over 1 m/s^2 to keep to the schedule. The maximum permitted speed on the route is 80 km/h. For the short Düren–Jülich and Düren–Jülich/Nord routes, the total tour time of each train, including turnaround and waiting times, is 1 to 1.5 hours; for the long Düren–Linnich route it is 2 hours.

On weekdays, the Düren–Jülich and Düren–Jülich/Nord routes are operated every half hour in the morning and afternoon, and once per hour in the remaining times. On the Linnich line there is an hourly service in the mornings, afternoons and evenings, with a half-hourly service in the remaining times. On weekends and public holidays there are no short tours and Linnich has an hourly service. In a standard[15] year, this results in a total operating capacity of 430,881 tkm. This corresponds to 143,627 kilometres per train per year. The Düren–Jülich, Düren–Jülich/Nord and Jülich/Nord–Linnich routes have operating capacities of 272,811 tkm, 21,522 tkm and 136,548 tkm, respectively, → Figure 32.

↓ Figure 32: Operating programme of RB 21 Nord, status in 2019



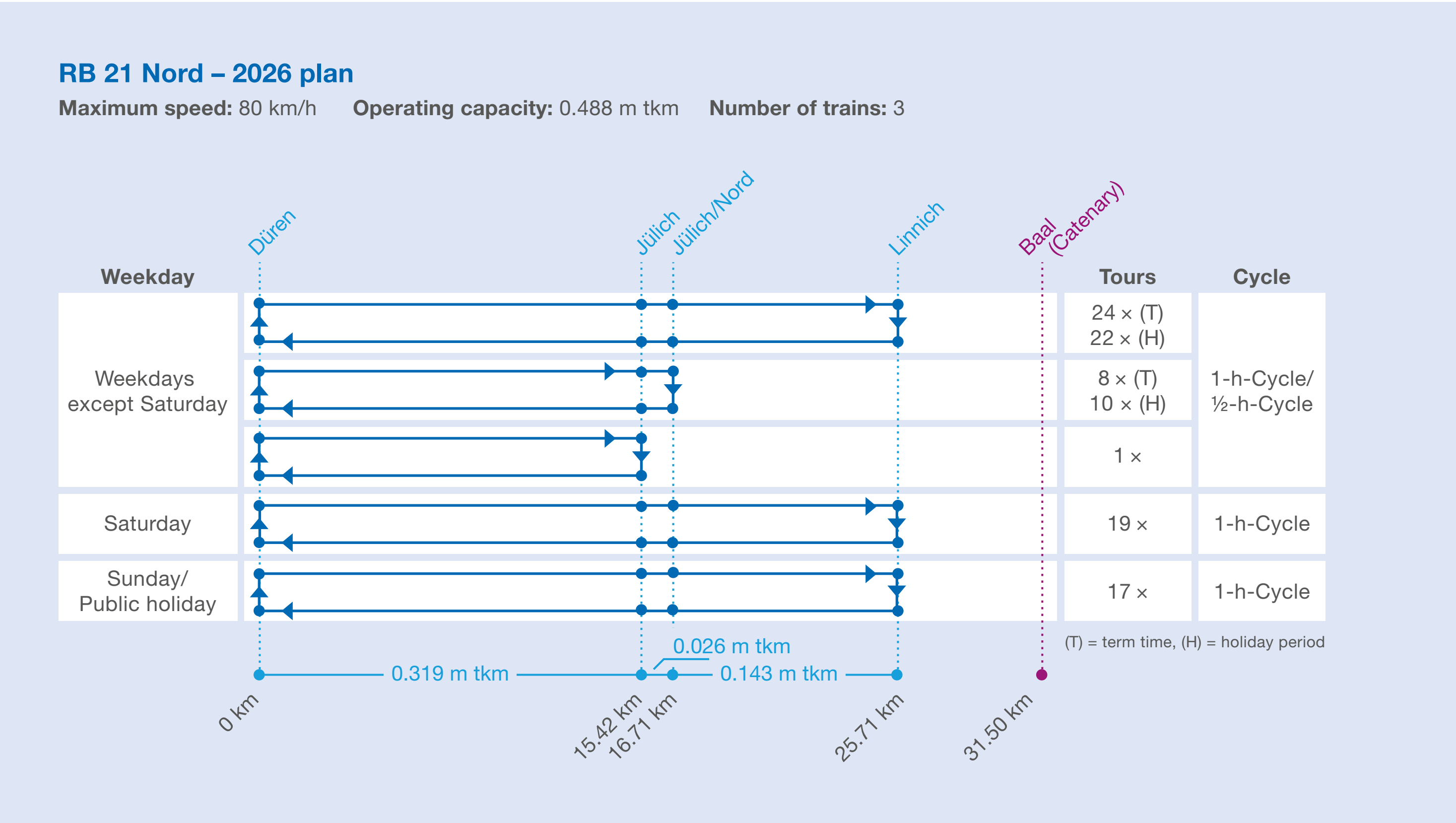
15 The standard year comprises 252 working days, 52 Saturdays and 61 Sundays and public holidays

As a designated branch route, RB 21 Nord is well utilised. According to Rurtalbahn GmbH, there are more than 5,000 passengers on standard weekdays.

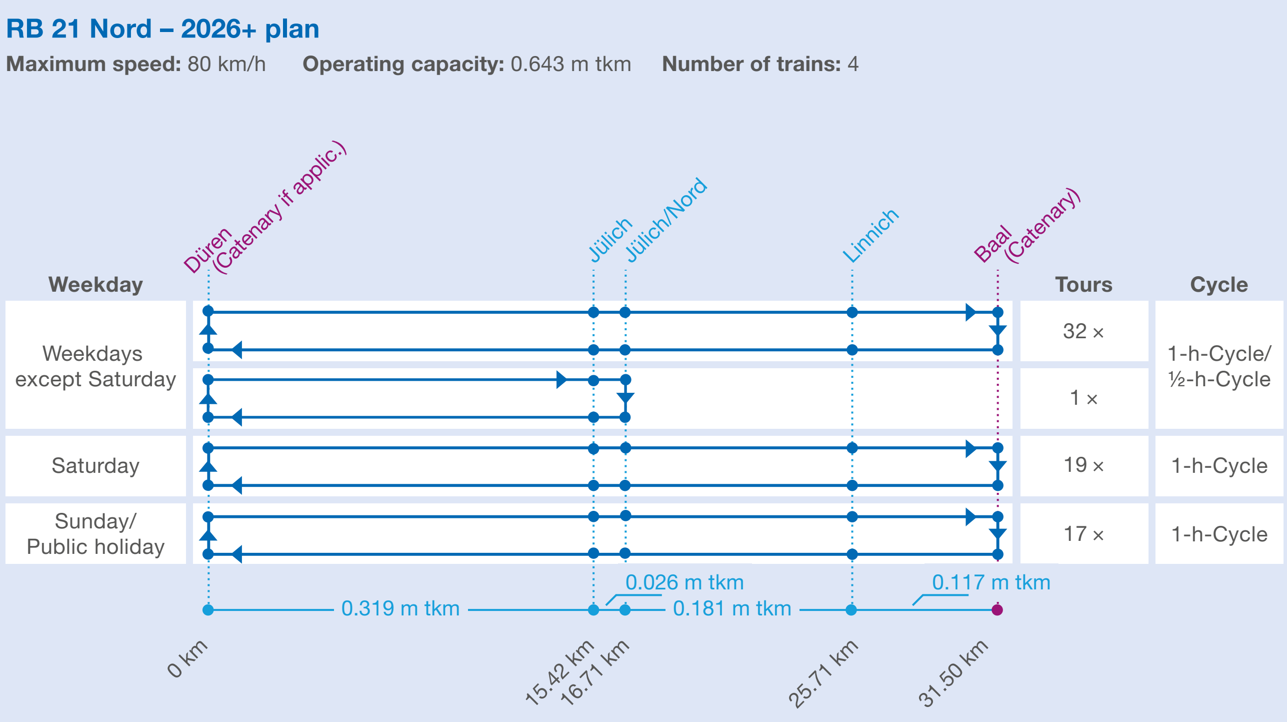
From 2026 traffic frequencies are to be increased, but without using additional trains, → Figure 33. This will be achieved by adding five short Düren–Jülich/N.–Düren tours on weekdays. An additional long Düren–Linnich–Düren tour is planned on all days. As a result, operating capacity will increase by thirteen per cent to a total of 488,064 tkm. This will increase the average annual mileage to 162,688 kilometres for each individual vehicle.

As mentioned above, the 5.79 kilometre section from Linnich to Baal station is to be restored and extended by the end of 2026. On weekdays, 32 long Düren–Baal–Düren tours and one short Düren–Jülich/N.–Düren tour are planned, → Figure 34. On weekends and public holidays there will be the same number of tours as before, but always to Baal. A further train will be required for this expansion. The extra concentration and expansion of traffic will yield a 32 per cent increase in operating capacity to 643,379 tkm – with an annual mileage of 160,845 kilometres per vehicle.

↓ Figure 33: Operating programme of RB 21 Nord, plan for 2026



Source: NVR (own chart)



Source: NVR (own chart)

↑ Figure 34: Operating programme of RB 21 Nord, plan for 2026+

5.2.3 RB 21 Süd

The RB 21 Süd line connects Düren station to Heimbach station 29.86 kilometres away via Untermaubach–Schlagstein. The line comprises a total of 17 stations, with an average spacing of 1.9 kilometres. There are eight stops on the Düren–Untermaubach line, five of which are request stops. On the remaining stretch to Heimbach there are six stops with four request stops. The following two charts provide an overview of the current and planned operating programme of this line for 2026.

A total of three RegioShuttle RS1 or Coradia LINT 54 trains are currently in operation on RB 21 Süd, each staggered by half an hour. For the short Düren–Untermaubach route, the total tour time for a train (including turnaround and waiting times) is one hour; for the long Düren–Heimbach route it is two hours. The schedule is so tight that the vehicles often have to accelerate at over 1 m/s^2 to keep to the timetable. The maximum permitted speed on the route is currently 70 km/h.

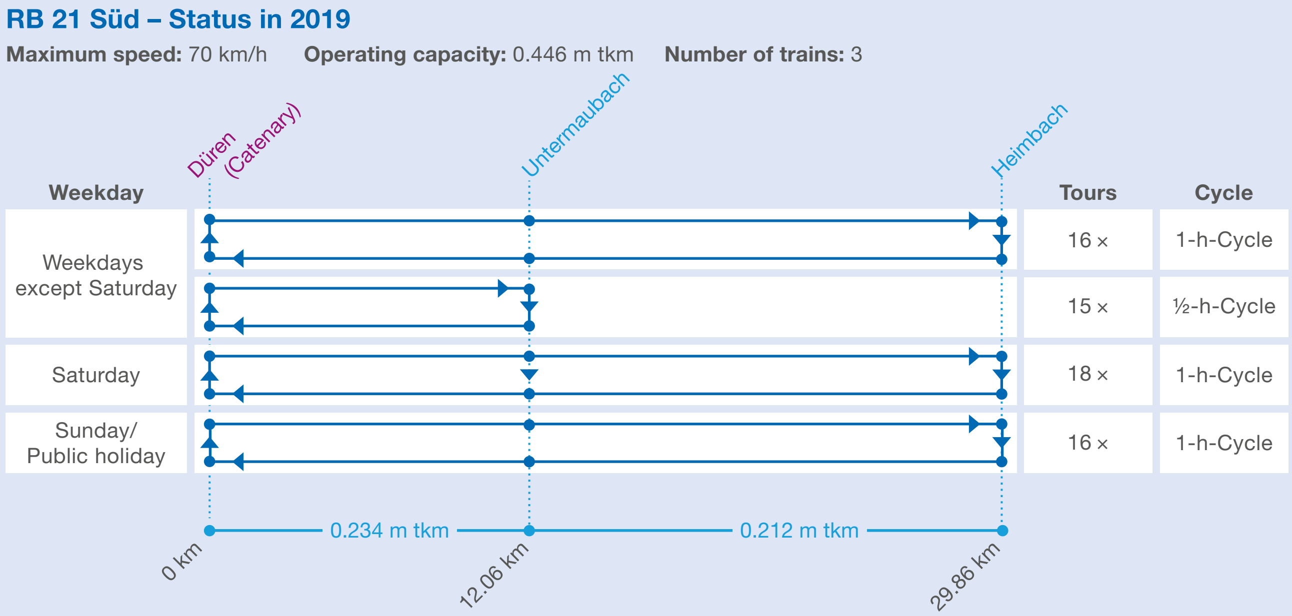
On weekdays, the 12.06 kilometre Düren–Untermaubach section is operated every half hour, the Düren–Heimbach section every hour, → Figure 35. On weekends and public holidays there are no short tours; there is an hourly service to Heimbach. In a standard year, RB 21 Süd has an operating capacity of 446,149 train-kilometres. This corresponds to an average mileage of 148,700 kilometres per train per year. On the Düren–Untermaubach and Untermaubach–Heimbach sections, operating capacities of 234,543 tkm and 211,606 tkm, respectively, are provided.

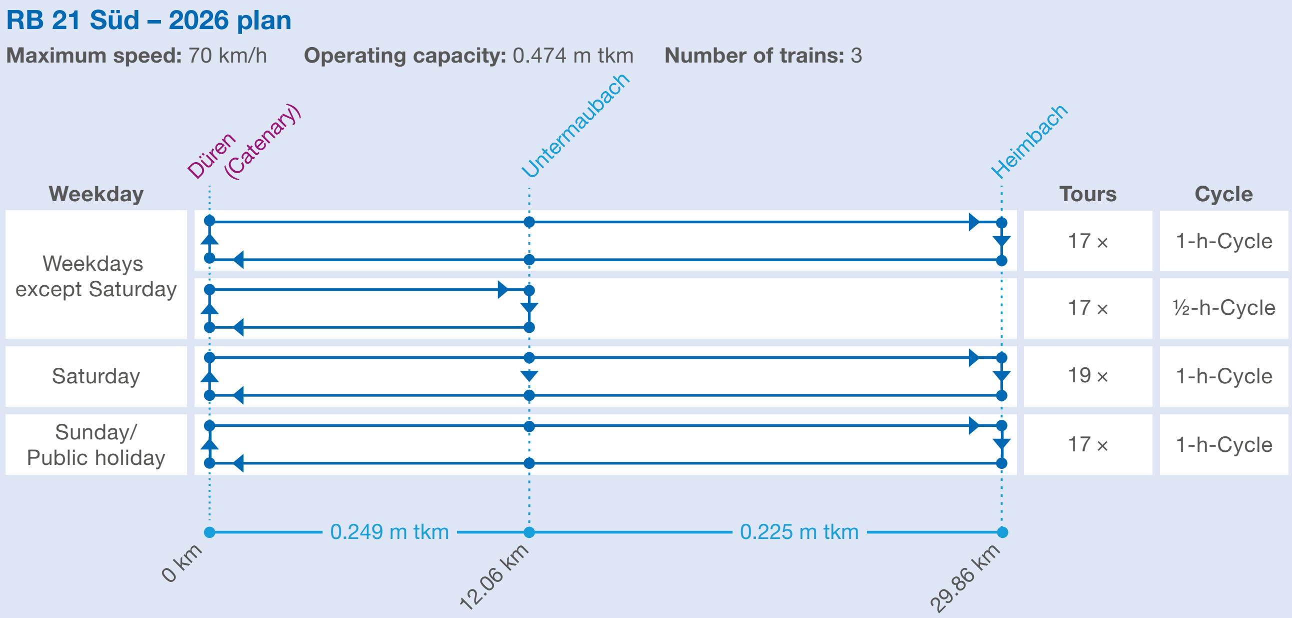
From 2026, there are plans to increase the traffic density without using additional trains → Figure 36. This will be achieved by adding two extra Düren–Untermaubach–Düren tours plus a long Düren–Heimbach–Düren tour on weekdays. In a standard year, this corresponds to a six per cent increase in operating capacity to 474,025 train-kilometres. The average mileage of each vehicle will increase to 158,008 kilometres per year.

RB 21 Süd, too, is apparently well utilised as a branch line. According to Rurtalbahn GmbH, there are more than 3,000 passengers on standard weekdays.

↓ Figure 35: Operating programme of RB 21 Süd, status in 2019

↓↓ Figure 36: Operating programme of RB 21 Süd, plan for 2026





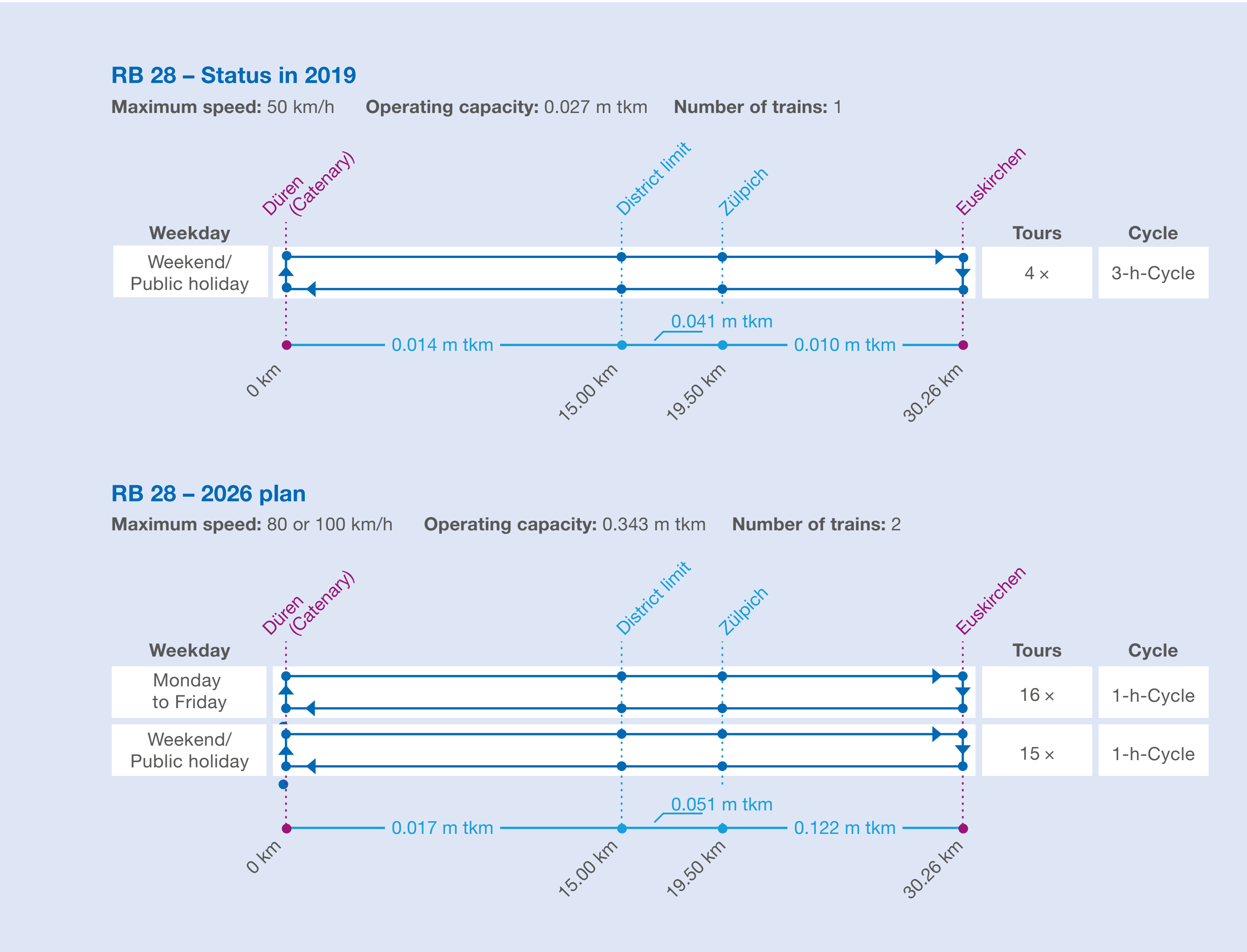
Source: NVR (own chart)

5.2.4 RB 28 Eifel-Bördebahn

The RB 28 line connects Düren station to Euskirchen station 30.26 kilometres away via Zülpich. The line comprises a total of eight stations, with an average spacing of 4.3 kilometres. Until November 2019, RB 28 only ran four times a day at three-hour intervals on Saturdays, Sundays and public holidays. One RegioShuttle RS1 vehicle was used for this. The speed was limited to 50 km/h. Until November 2019, trains had to stop for road traffic at all level crossings due to a lack of safety installations. The total tour time for each train was exactly three hours (including turning and waiting times). With four tours per day, this resulted in an operating capacity of 27,355 tkm.

In December 2019 the passenger service was extended to all weekdays, initially with six tours per day. Following the installation of modern safety equipment, 2026 will see a considerable increase in traffic density and expansion of overall traffic levels: an additional twelve tours will be made on Saturdays, with ten on Sundays and public holidays. In addition, a further 10 tours are planned on each weekday. As a result, operating capacity will increase by a factor of twelve to a total of 342,906 tkm. Despite this, the existing two trains will still suffice. The maximum speed currently under discussion is 80 or 100 km/h → Figure 37 provides an overview.

↓ Figure 37: Operating programme RB 28, status in 2019 and planned for 2026(+)



Source: NVR (own chart)

5.3 Energy demand of the vehicle fleet

The energy demand of a multiple unit on a railway line depends on its weight (including passengers), as well as on gradients, curve radii, acceleration and braking phases between stops, speed limits, wind direction and, where applicable, stretches of tunnel. The VDE has created a simulation model to calculate the fuel and electricity consumption of the vehicle fleet in the ›Düren network‹. This is described in the next section. The energy demands of auxiliary units, e.g. for heating, air conditioning, ventilation, lighting, etc., which can vary by season and climatic region, are also taken into account here. Even in stationary phases there is demand for energy when the drive motor is kept idling.

5.3.1 Simulationsmodell

The technology-independent, route-specific demand for kinetic energy can be calculated using the formulas given in the literature → [28] for the resistance forces that a rail vehicle has to overcome. A pragmatic solution here is the *synthetic formula* for calculating the tractive force:

$$Z_{Fzg} = W_B + (W_{St} + W_K) + W_{Luft} + W_{Stoß}) + W_R \qquad \boxed{\text{Formula 5.1}}$$

with the conditional equations

$W_B = m \cdot b \cdot \lambda$	Formula 5.2	Acceleration resistance [N]
$W_{St} = m \cdot g \cdot \sin\alpha$	Formula 5.3	Uphill resistance [N]
$W_K = m \cdot g \cdot f\left(\frac{1}{R}\right)$	Formula 5.4	Curve resistance [N]
$W_{Luft} = \frac{\varrho}{2} \cdot c_w \cdot A \cdot v^2$	Formula 5.5	Air resistance [N]
$W_{Stoß} = c_d \cdot m \cdot v$	Formula 5.6	Shock resistance [N]
$W_R = f_R \cdot m \cdot g$	Formula 5.7	Bearing friction and rolling resistance [N]

These include

m	= Service mass of vehicle incl.passengers [kg]
b	= Momentary acceleration [m/s^2]
λ	= Rotational mass supplement factor [ ]
g	= Gravitational acceleration [= 9.81 m/s^2]
$\sin\alpha$	= Incline [e.g. as ‰]
$f\left(\frac{1}{R}\right)$	= RÖCKL's approximation formula
c_w	= Drag coefficient [ ]
A	= Vehicle cross-sectional area [m^2]
ϱ	= Air density ≈ 1.25 [Ns^2/m^4]
v	= Momentary speed [m/s]
c_d	= Shock resistance coefficient [ ]

To ensure comparability of the BEMU, HEMU and EMU solutions, it is assumed that the respective vehicles are offered either as two-car (*train set*) or three-car (*articulated train*) vehicles and are otherwise identical in terms of weight and passenger seats (reference: Coradia LINT 54 with 165 seats). It is also assumed that they all have the same air resistance values, i.e. a realistic drag coefficient of c_w=0.5. This ensures that the vehicles differ only in their efficiency, the power requirements of their auxiliary units and, where applicable, their idling energy consumption.

The VDE inserted the tractional resistance → formulas 5.1 to 5.7 into a simulation model for the lines under consideration, RB 21 Nord, RB 21 Süd and RB 28, for which NVR as the public decision-maker and Rurtalbahn as the railway infrastructure undertaking (EIU) have provided timetables and line-specific data on gradients, stops, speed limits, and maximum acceleration and braking values. On the basis of this information, the VDE created a speed profile for the outward and return journey of each of the three lines, at a route resolution of 100 metres. The calculated profiles were verified based on speed measurements taken during test drives. This made it possible to calculate the demand for kinetic energy along the routes as follows:

On track element Δl (= 100 metres), work ΔA is expended to overcome the instantaneous traction resistance forces $W(v,l)$ acting on the vehicle $\Delta A = W \cdot \Delta l$. When cumulated over the entire length of the track, the total work required to overcome the resistance forces is $A = \sum(W \cdot \Delta l)$. In order to perform this work, energy is expended which the vehicle extracts from a source of energy. This is converted into motion at specific levels of energy conversion efficiency.

The following values for the energy conversion efficiency of drives can be found in the literature:

DMU: Diesel engines have energy conversion efficiency levels of up to 40 per cent → [29].

EMU: The drive train of an EMU has an energy conversion efficiency level of 85 per cent due to transformer and converter losses → [28].Part of the recuperated braking energy is fed back into the overhead line, but cannot be used directly for its own propulsion. The simulation only includes the vehicle itself, and does not take recuperation into account.

BEMU: At 85 per cent, a BEMU has the same energy conversion efficiency level as an EMU under an overhead line. In battery mode, this is reduced due to the 90 per cent efficiency level for intermediate storage of the current in the battery → [30]. The resulting energy conversion efficiency in battery mode is thus at least $0.9 \cdot 85\%$, i.e. approximately 77 per cent. In contrast to the EMU, the energy recuperated during electrical braking can be temporarily stored in the battery and used for the vehicle's own drive. This unique feature increases the energy efficiency of the vehicle. Recuperation and the use of the recovered energy is incorporated in the simulation.

HEMU: The HEMU draws its drive energy from a fuel cell. This generates the drive power by *consuming* the on-board hydrogen with an energy conversion efficiency level of around 60 per cent → [31]. Part of the energy is temporarily stored in a dynamic battery, which provides the high current levels needed for setting off and accelerating. The resulting tank-to-wheel energy conversion efficiency in battery mode is thus at least $0.6 \cdot 0.9 \cdot 85\%$, i.e. approximately 46 per cent. The battery also temporarily stores the recuperated braking energy. When this is used, it increases the vehicle's energy efficiency, as is the case in the BEMU. The simulation takes into account the hydrogen saved by using the braking energy stored in the battery.

5.3.2 BEMU and HEMU results

On the basis of the simulation model described in → Section 5.1.3, the VDE determined the *instantaneous value curves* for speed, traction resistance and the resulting energy demand of a vehicle on each of the three routes. Upon leaving the starting point, the vehicle halts at all stops. At the destination station it waits before turning and finally returning to the starting point. The VDE determined the expected specific current or fuel consumption of each vehicle on the basis of the energy conversion efficiency levels described in the literature. → Figure 38 shows how the energy demand varies on the RB 21 Nord, RB 21 Süd and RB 28 routes. This turns negative during the braking phases.

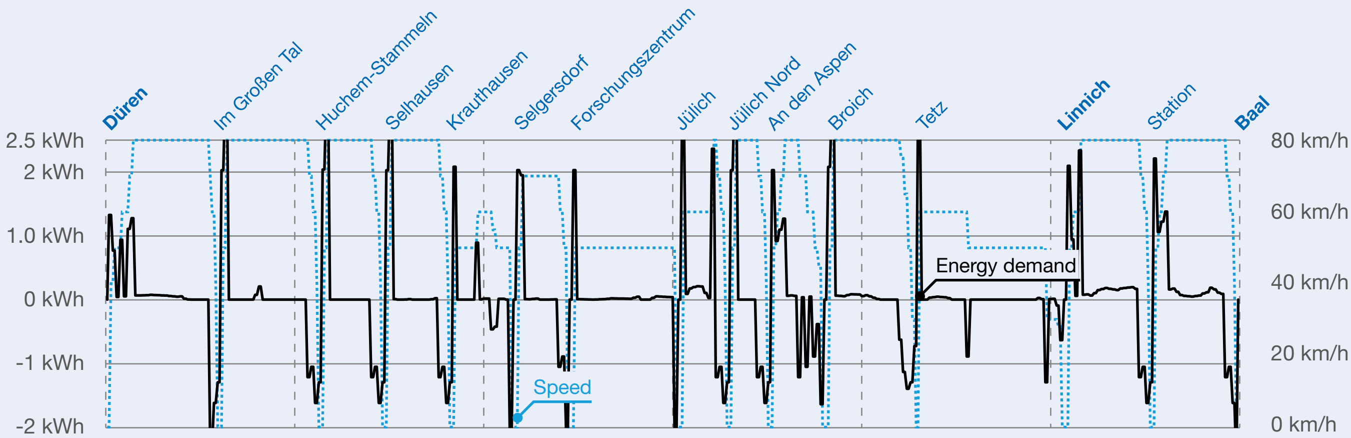
Note: A representation of all simulation results for BEMU, HEMU, EMU and DMU on the three railway lines RB 21 Nord, RB 21 Süd and RB 28 can be found in → Appendix 7.3.

→ Figure 39 shows how much electrical energy the BEMU vehicle consumes and recuperates on the ›Düren network‹ routes. The simulation takes into account both the use of the recuperated energy and the estimated power requirements for auxiliary units.

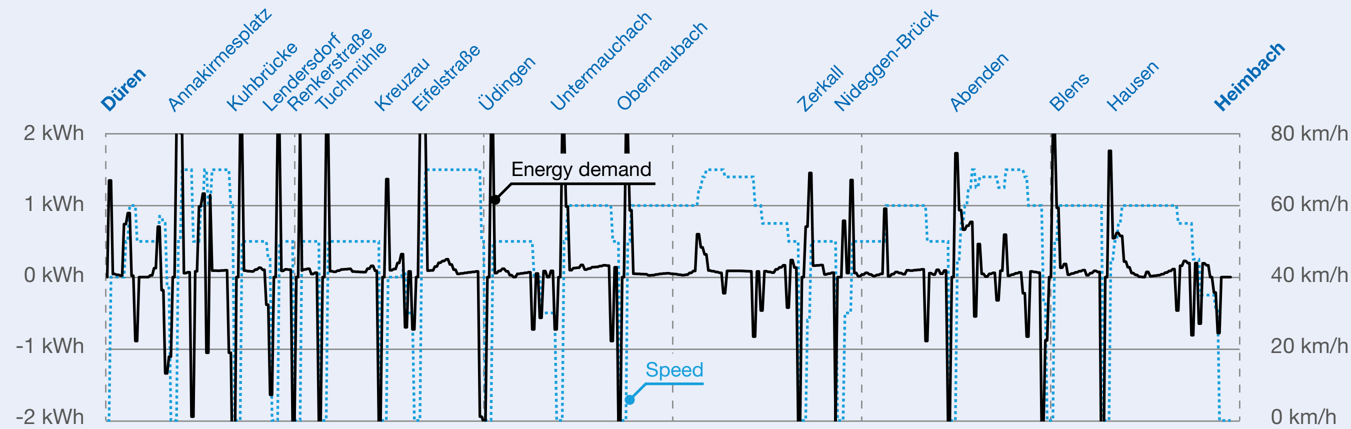
→ Figure 40 shows the expected hydrogen consumption of the HEMU vehicle on the ›Düren network‹ routes. The reduction in the hydrogen demand caused by using the electrical energy recuperated in the dynamic battery is factored in here, as is the estimated power demand of the auxiliary units.

Graphical representations of the diesel and power requirements of DMU and EMU vehicles can be found in → Appendix 7.3.

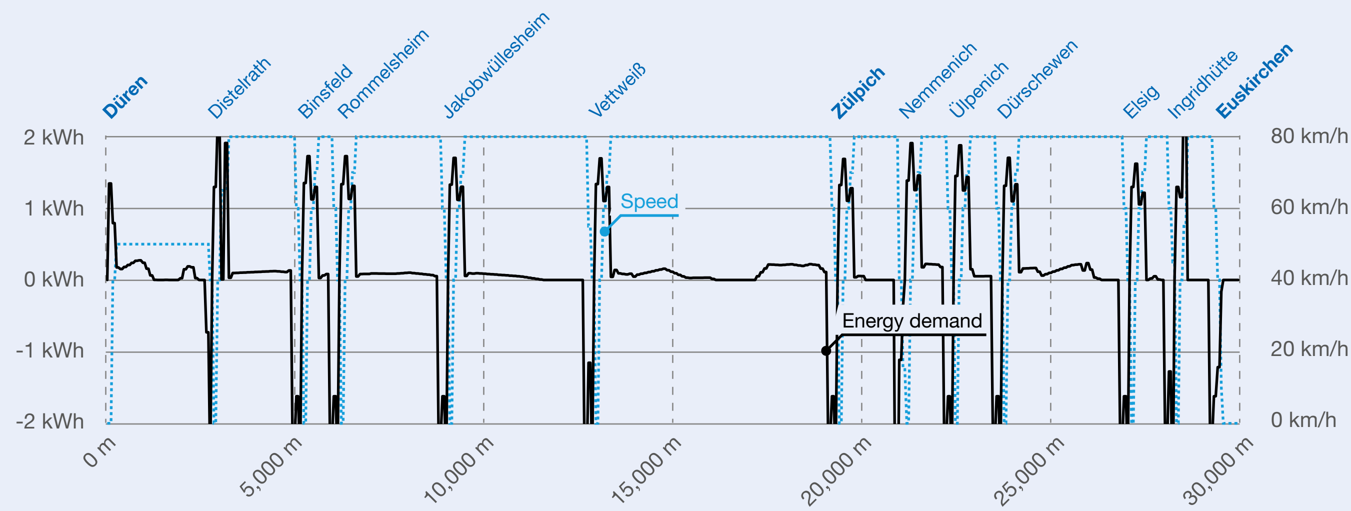
RB 21 Nord



RB 21 Süd

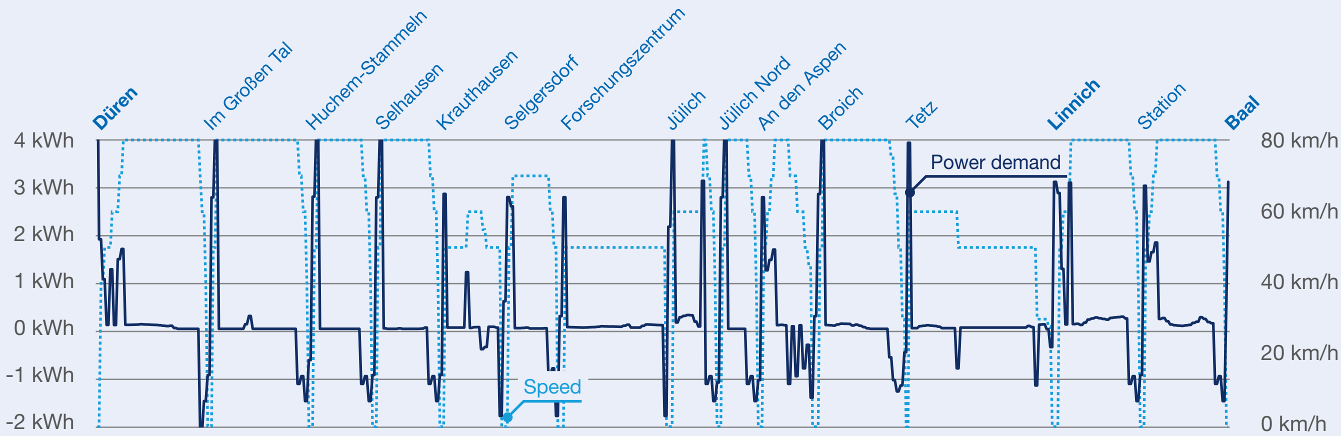


RB 28

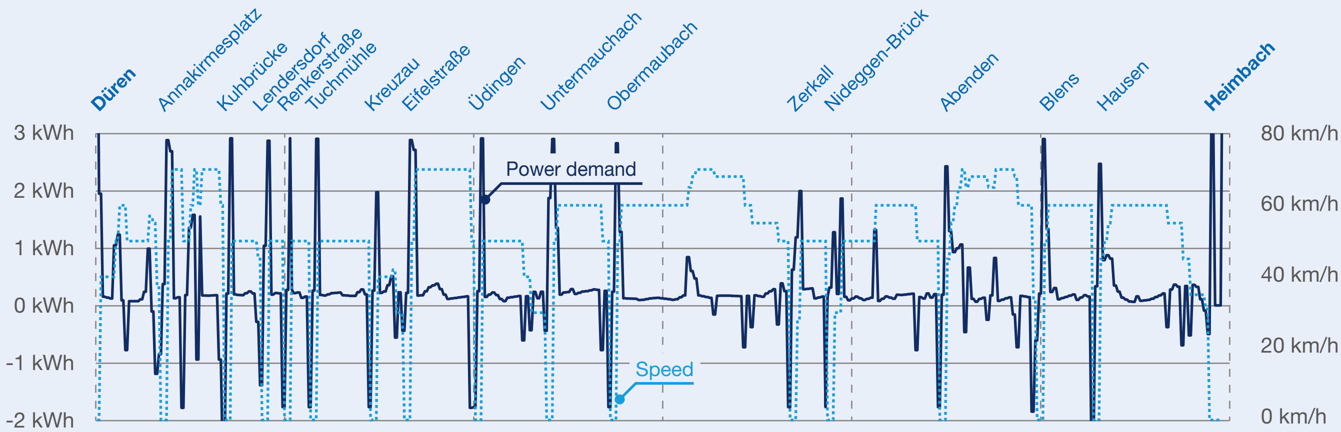


↑ Figure 38: Simulated energy demand for the ›Düren network‹ lines (2026+)

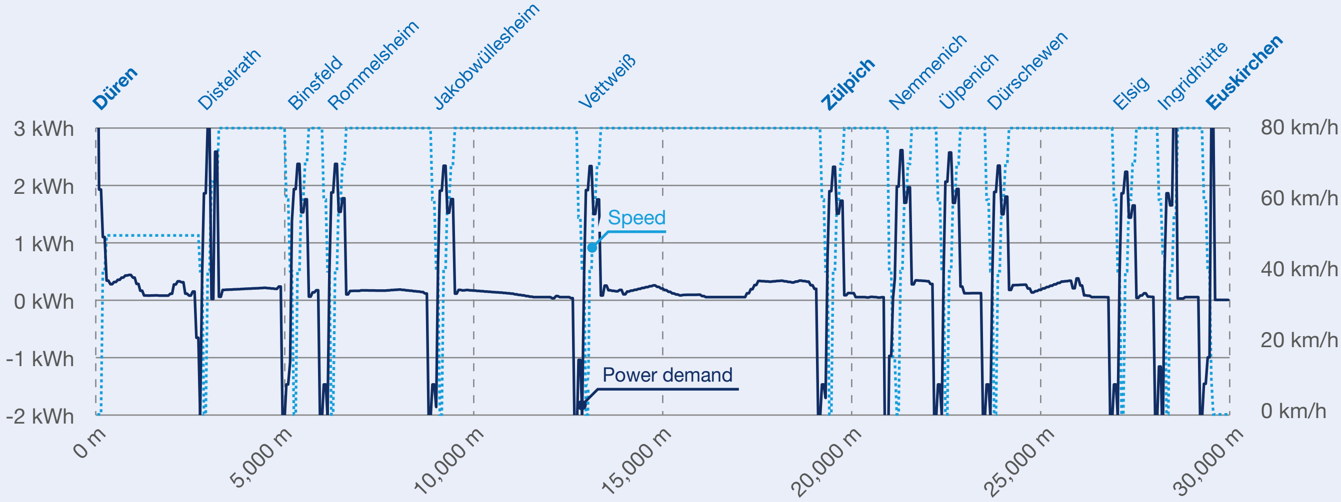
RB 21 Nord Power demand Ø 4.57 kWh/km incl. recuperation



RB 21 Süd Power demand Ø 5.24 kWh/km incl. recuperation

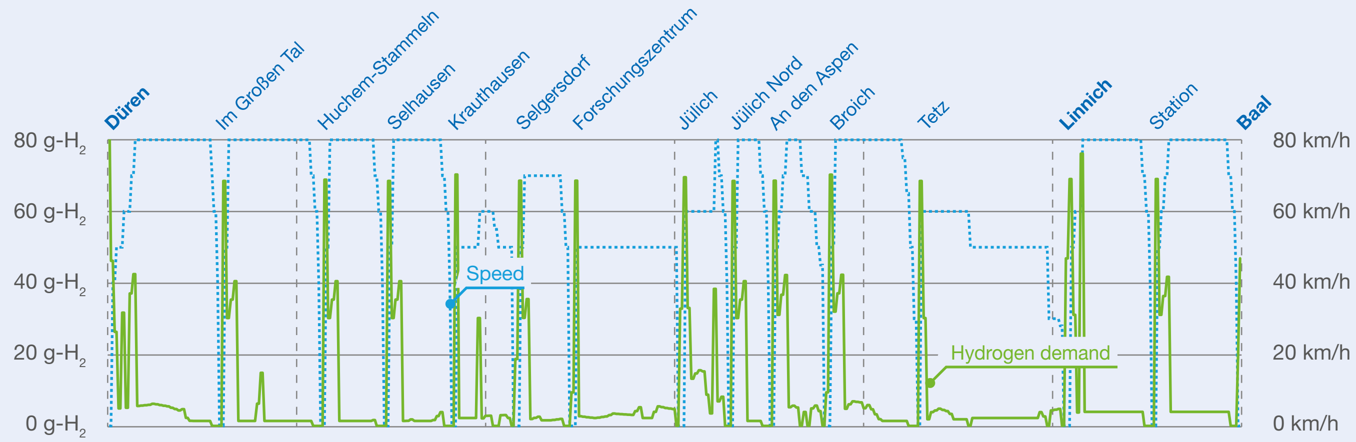


RB 28 Power demand Ø 5.27 kWh/km incl. recuperation

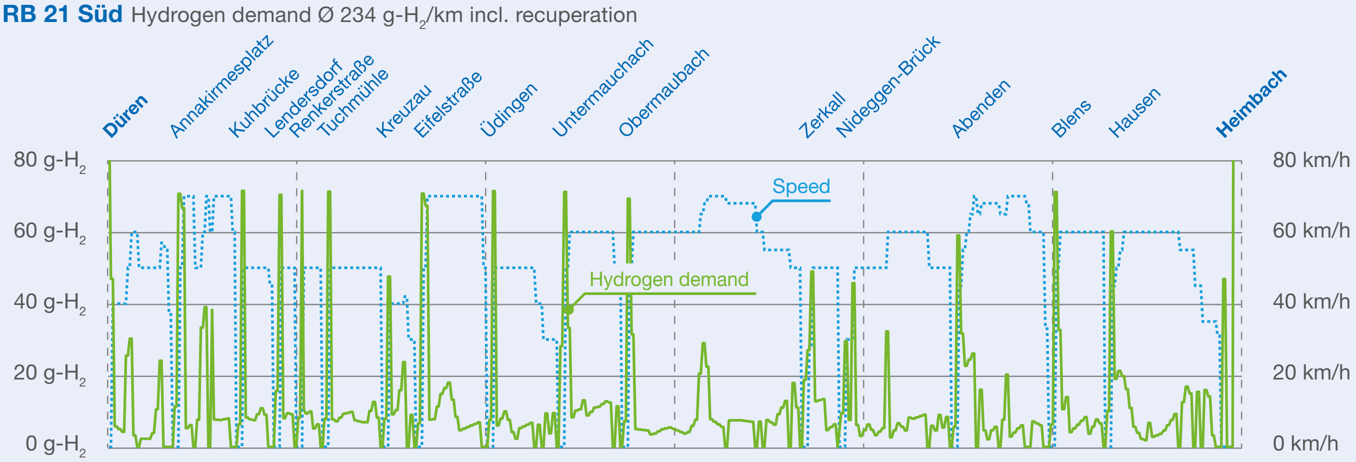


↑ Figure 39: BEMU power requirements on the ›Düren network‹ railway lines (2026+)

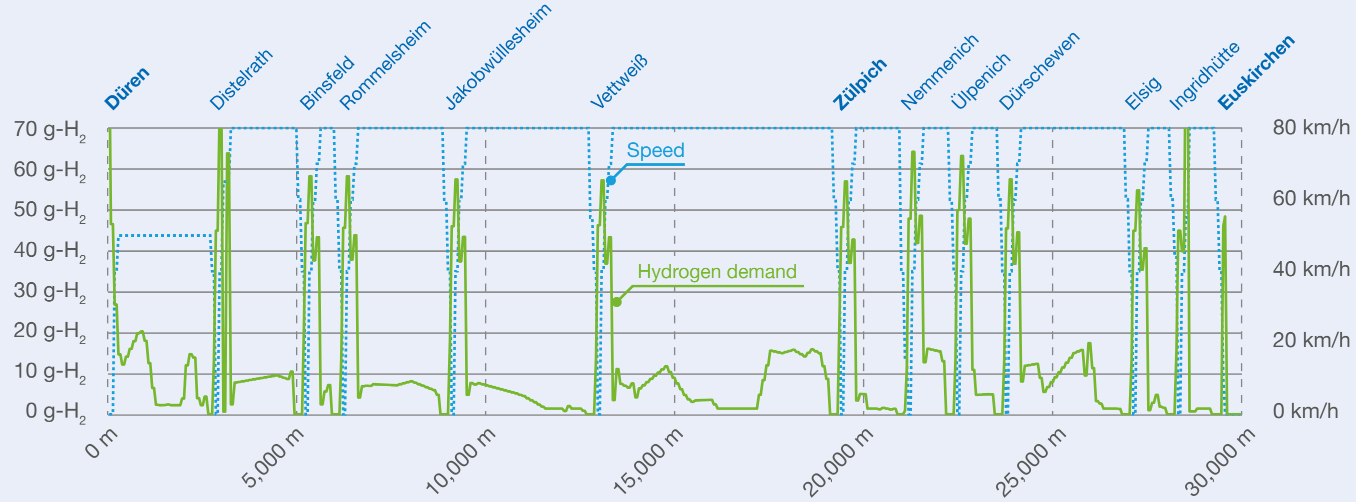
RB 21 Nord Hydrogen demand Ø 202 g-H_2/km incl. recuperation



RB 21 Süd Hydrogen demand Ø 234 g-H_2/km incl. recuperation



RB 28 Hydrogen demand Ø 253 g-H_2/km incl. recuperation



↑ Figure 40: HEMU hydrogen demand levels on the ›Düren network‹ railway lines (2026+)

5.4 Net Present Value analysis

The economic viability of the railway lines in the ›Düren network‹ is determined to a large extent by passenger demand and the revenue generated from ticket sales. The costs of purchasing, operating, maintaining and repairing the rolling stock and providing its traction power, as well as the costs of installing and maintaining the operational infrastructure, must be proportionate to this. In its viability analysis, the VDE therefore assumes that the operator, Rurtalbahn GmbH, is currently able to run the ›Düren network‹ (with eight Stadler RegioShuttle RS1 diesel multiple units and three Alstom Coradia LINT 54 diesel multiple units) cost-effectively – due in part to the subsidies agreed with the public decision-maker (concession fee[16]).

The energy costs for the vehicle fleet constitute one of the main cost items. As described in → Section 5.3, the energy demand of the individual multiple units depends on vehicle and line-specific characteristics as well as on the consumption levels of the auxiliary units. Converting these into electric power, hydrogen or diesel consumption presupposes knowledge of the energy conversion efficiency levels of each individual drive type. The average expected power and fuel requirements per vehicle on the ›Düren network‹ lines are shown in → Table 5.

	BEMU with recuperation	**HEMU** with recuperation	**EMU** w/o recuperation	**DMU**
	Ø Power demand	Ø H_2 demand	Ø Power demand	Ø Diesel demand
RB 21 Nord	4.57 kWh/km	202 g-H_2/km	7.48 kWh/km	1.68 l/km
RB 21 Süd	5.24 kWh/km	234 g-H_2/km	7.36 kWh/km	1.59 l/km
RB 28	5.27 kWh/km	253 g-H_2/km	7.96 kWh/km	1.74 l/km
Düren network	**5.03 kWh/km**	**230 g-H_2/km**	**7.60 kWh/km**	**1.67 l/km**

↑ Table 5: Average energy and fuel requirements on the ›Düren network‹ lines

Irrespective of the fact that the decision has basically already been made at the political level and in the public opinion to replace diesel operation with an environmentally friendly and climate-neutral solution as soon as possible, any alternative will have to be measured economically against the current DMU status quo. In the case of the ›Düren network‹, NVR believes that the question is ultimately one of whether to use fuel cell or battery trains in the future. The main focus of the economic viability analyses should therefore be on the HEMU and BEMU solutions. In order to be able to assess the net benefit of a particular alternative, the VDE has also incorporated DMUs and EMUs as (hypothetical) investment projects in the analyses.

To calculate the net present value, the VDE bases its comparative dynamic investment calculation on the general → formula 4.1 given in → Section 4.2. Receipts Et (= revenues) are set at zero in the formula, as are all expenditures A_t (= costs) which are clearly identified as non technology-specific. In addition, it is assumed that the residual bookkeeping value of capital goods at the end of the period of length n is greater than or equal to zero, i.e. positive liquidation proceeds L_n. Thus → formula 4.1 crystallises into → formula 5.8 for the description of the net present value of the technological alternative TA_i in the period $t = 1$ to n including the discounted expenditure flows $-A_t/q^t$ and the residual values L_n/q^n of the capital goods.

16 The concession fee is a regionalisation subsidy which is paid by the public decision-maker to the commissioned railway undertaking. The amount of this subsidy is proportional to the agreed mileage and was 12.18 €/tkm in 2016, according to BAG-SPNV.

$$C_0(\mathrm{TA_i}) = -I_0^{\mathrm{Vehicle}} + \frac{L_n^{\mathrm{Vehicle}}}{q^n}$$ Formula 5.8

$$+\sum_{t=1}^{n} \frac{-\mathrm{A}_t^{\mathrm{Energy}}}{q^t} + \sum_{t=1}^{n} \frac{-\mathrm{A}_t^{\mathrm{Maint.\,Veh.}}}{q^t} + \sum_{t=1}^{n} \frac{-\mathrm{A}_t^{\mathrm{Replacem.}}}{q^t}$$

$$+ -\mathrm{I}_0^{\mathrm{Infrastructure}} + \sum_{t=1}^{n} \frac{-\mathrm{A}_t^{\mathrm{Infrastr.\,Op.}}}{q^t} + \frac{\mathrm{L}_n^{\mathrm{Infrastructure}}}{q^n}$$

$$+ \sum_{t=1}^{n} \frac{-\mathrm{A}_t^{\mathrm{Path}}}{q^t} + \sum_{t=1}^{n} \frac{-\mathrm{A}_t^{\mathrm{Stations}}}{q^t}$$

C_0 [€] = Net present value

$\mathrm{TA_i}$ = Technological alternative considered (DMU, EMU, BEMU or HEMU)

$\mathrm{I}_0^{\mathrm{abc}}$ = Investment amounts for goods abc at beginning of observation period of length n

$\mathrm{L}_n^{\mathrm{abc}}$ = Residual values of goods abc at end of observation period

$\mathrm{A}_t^{\mathrm{xyz}}$ = Costs of type xyz in year t

$1/\mathrm{q}^{\mathrm{t}}$ = Discounting factor, where $\mathrm{q} = 1 + \mathrm{i}$ and i = imputed interest ratesee → Section 4.2

→ Formula 5.8 consists of three components. The sequence of terms in the first two lines comprises the technology-specific contributions to the net present value that are relevant for the railway undertaking (EVU) as operator of the railway lines. The second sequence of terms in the third row concerns the railway infrastructure undertaking (EIU) as investor and operator of the infrastructure. Together they yield a higher-level macroeconomic overview. The bottom line (blue) represents the costs for the use of train paths and stations that are relevant for the cost-effective operation of the lines. These constitute a sizeable proportion of the total costs, which is why the authors have taken the liberty of including them in the net present value analysis, although they are currently still independent of the alternatives under consideration. This raises the prospect of graduating the train path and station charges in the future depending on the technology used.

In order to compare the individual investment alternatives for the ›Düren network‹, the VDE, in consultation with NVR, chose the 2026 timetable year as the starting point for the period under consideration – including all operating data applicable from that year onwards. It was assumed that it will be possible to provide the relevant vehicles and install the associated overhead lines, electrification islands or hydrogen refuelling stations by 2025.

5.4.1 Data basis for the net present value method

Taking → formula 5.8 as the basis for calculating the net present value, all cost items are listed below, including their rates and start dates. These were collected in discussions with various vehicle manufacturers, railway undertakings, maintenance workshops and infrastructure companies. Averages were formed in cases where different values were given for the same item.

→ Table 6 contains the most important basic data on vehicles and infrastructure.

Vehicle pool	DMU	EMU	BEMU	HEMU	note
Procurement costs Useful life	3.50 m €/veh 25 years	4.30 m €/veh 30 years	6.20 m €/veh 30 years	6.90 m €/veh 30 years	3-car
Maintenance costs	1.20 €/tkm	0.80 €/tkm	0.85 €/tkm	0.95 €/tkm	based on mileage
Inspection cycle Inspection costs	8 years 260,000 €/RZ	8 years 230,000 €/RZ	8 years 230,000 €/RZ	8 years 245,000 €/RZ	
Replacement: Component 1 Replacement costs C 1 Replacement cycle C 1	PowerPack 166,000 € 3 years	Not applicable Not applicable Not applicable	Battery 1,300 €/kWh 8 years	Battery 1,300 €/kWh 8 years	Size – application-specific
Replacement: Component 2 Replacement costs C 2 Replacement cycle C 2	Not applicable	Not applicable	Not applicable	Fuel cell 2,000 €/kW 5 years	Size – application-specific
Energy price	1.20 €/l-Diesel 0.50 €/l-AdBlue	12.00 ct/kWh	12.00 ct/kWh	4.50 €/kg-H_2	from 2026 (assumed)
Infrastructure	**for DMU**	**for EMU**	**for BEMU**	**for HEMU**	**Note**
Procurement costs Useful life	350 T€/fuel st. 30 years	1 m €/OL km 76 years	5 m €/E-Island 76 years	1 m €/fuel st. 30 years	Service life
Operating Costs	20,000 €/year	250,000 €/year	~50,000 €/year	30,000 €/year	
Train path charge (TPS 2020) Station fee – stop Station fee – station	4.48 €/km 3.00 €/stop 5.00 €/stop	4.48 €/km 3.00 €/stop 5.00 €/stop	4.48 €/km 3.00 €/stop 5.00 €/stop	4.48 €/km 3.00 €/stop 5.00 €/stop	Non technology-specific Non technology-specific Non technology-specific

↑ Table 6: Basic data on rolling stock and infrastructure

The BEMU and HEMU are closely related to the EMU in terms of their structure. Nevertheless, their acquisition costs are generally higher because they also require costly technology components. In the case of the BEMU, these include a large traction battery with a capacity of over 500 kWh. The HEMU requires a large fuel cell stack with an output of over 400 kW, an additional dynamic battery and large hydrogen tanks. The expected replacement costs are correspondingly high, depending on the specified operating life of these components.

The maintenance costs of the DMU are higher than those of the alternatives, as the diesel engines are expensive to maintain and complete replacements of the engines are required at regular intervals over the operating life of 25 years.

In terms of infrastructure, the data set out in → Table 6 represent averages, except in the case of the refuelling station for the DMU: the changed requirements mean that the diesel refuelling station currently located at Düren station must now be moved by one kilometre. Costs of €300 thousand have been earmarked for this. In the case of the BEMU, it is assumed that only one recharging electrification island will be provided – in the Düren station.

The train path and station fees listed in → Table 6 are based on Rurtalbahn's 2020 price schedule. They are of a similar order to those of DB Netze, and are used to finance the operation and maintenance of the infrastructure. They are collected regardless of the propulsion technology used.

→ Table 7 and → Table 8 show all cost items relating to operation of the ›Düren network‹ lines with different vehicle solutions. The number of vehicles and the operating capacity values given in each case correspond to the information given in → Section 5.2 for 2026 for the RB 21 Nord line, extended to Baal.

General	RB 21 Nord (2026+)	RB 21 Süd (2026+)	RB 28 (2026+)	›Düren network‹
Line length	31.50 km	29.86 km	30.26 km	91.62 km
Share of fleet	4 vehicles(s)	3 vehicles(s)	2 vehicles(s)	9 vehicles(s)
Veh. reserve	1 vehicles(s)	1 vehicles(s)		2 vehicles(s)
Transport capacity	0.643 m tkm/year	0.474 m tkm/year	0.343 m tkm/year	1.460 m tkm/year
Mileage per veh.	0.161 m tkm/year	0.119 m tkm/year	0.171 m tkm/year	0.133 m tkm/year
DMU				
Veh. procurement	17.500 m €/30y	14.000 m €/30y	7.000 m €/30y	38.500 m €/30y
Veh. maintenance	0.772 m €/year	0.569 m €/year	0.411 m €/year	1.752 m €/year
Veh. inspection	1.300 m €/8y	1.040 m €/8y	0.520 m €/8y	2.860 m €/8y
Tract. energy costs	1.452 m €/year	0.909 m €/year	0.858 m €/year	3.219 m €/year
Train path costs	2.882 m €/year	2.124 m €/year	1.536 m €/year	6.542 m €/year
Station costs	1.124 m €/year	0.869 m €/year	0.510 m €/year	2.503 m €/year
Technology replacem.	0.268 m €/year	0.198 m €/year	0.143 m €/year	0.609 m €/year
Infrastruc. investm.	0.159 m €/30y	0.127 m €/30y	0.064 m €/30y	0.350 m €/30y
Infrastruc. operation	0.009 m €/year	0.006 m €/year	0.005 m €/year	0.020 m €/year
Refuelling journey costs	0.001 m €/year	0.001 m €/year	0.001 m €/year	0.003 m €/year
EMU				
Veh. procurement	21.500 m €/30y	17.200 m €/30y	8.600 m €/30y	47.300 m €/30y
Veh. maintenance	0.515 m €/year	0.379 m €/year	0.274 m €/year	1.168 m €/year
Veh. inspection	1.150 m €/8y	0.920 m €/8y	0.460 m €/8y	2.530 m €/8y
Tract. energy costs	0.654 m €/year	0.414 m €/year	0.316 m €/year	1.384 m €/year
Train path costs	2.882 m €/year	2.124 m €/year	1.536 m €/year	6.542 m €/year
Station costs	1.124 m €/year	0.869 m €/year	0.510 m €/year	2.503 m €/year
Infrastruc. investm.	31.500 m €/76y	149.300 m €/76y	30.260 m €/76y	211.060 m €/76y
Infrastruc. operation	0.110 m €/year	0.081 m €/year	0.059 m €/year	0.250 m €/year

↑ Table 7: Line-specific cost items for DMU and EMU, including infrastructure

General	RB 21 Nord (2026+)	RB 21 Süd (2026+)	RB 28 (2026+)	Düren network
Line length	31.50 km	29.86 km	30.26 km	91.62 km
Share of fleet	4 vehicle(s)	3 vehicle(s)	2 vehicle(s)	9 vehicle(s)
Veh. reserve	1 vehicle(s)	1 vehicle(s)		2 vehicle(s)
Transport capacity	0.643 m tkm/year	0.474 m tkm/year	0.343 m tkm/year	1.460 m tkm/year
Mileage per veh.	0.161 m tkm/year	0.119 m tkm/year	0.171 m tkm/year	0.133 m tkm/year
BEMU				
Veh. procurement	31.000 m €/30y	24.800 m €/30y	12.400 m €/30y	68.200 m €/30y
Veh. maintenance	0.547 m €/year	0.403 m €/year	0.291 m €/year	1.241 m €/year
Veh. inspection	1.150 m €/30y	0.920 m €/30y	0.460 m €/30y	2.530 m €/30y
Tract. energy costs	0.426 m €/year	0.277 m €/year	0.192 m €/year	0.894 m €/year
Train path costs	2.882 m €/year	2.124 m €/year	1.536 m €/year	6.542 m €/year
Station costs	1.124 m €/year	0.869 m €/year	0.510 m €/year	2.503 m €/year
Technology replacem.	0.481 m €/year	0.354 m €/year	0.256 m €/year	1.092 m €/year
Infrastruc. investm.	2.203 m €/30y	1.623 m €/30y	1.174 m €/30y	5.000 m €/30y
Infrastruc. operation	0.022 m €/year	0.016 m €/year	0.012 m €/year	0.050 m €/year
HEMU				
Veh. procurement	34.500 m €/30y	27.600 m €/30y	13.800 m €/30y	75.900 m €/30y
Veh. maintenance	0.611 m €/year	0.450 m €/year	0.326 m €/year	1.387 m €/year
Veh. inspection	1.225 m €/30y	0.980 m €/30y	0.490 m €/30y	2.695 m €/30y
Tract. energy costs	0.770 m €/year	0.467 m €/year	0.357 m €/year	1.595 m €/year
Train path costs	2.882 m €/year	2.124 m €/year	1.536 m €/year	6.542 m €/year
Station costs	1.124 m €/year	0.869 m €/year	0.510 m €/year	2.503 m €/year
Technology replacem.	0.913 m €/year	0.673 m €/year	0.487 m €/year	2.072 m €/year
Infrastruc. investm.	0.455 m €/30y	0.364 m €/30y	0.182 m €/30y	1.000 m €/30y
Infrastruc. operation	0.013 m €/year	0.010 m €/year	0.007 m €/year	0.030 m €/year
Refuelling journey costs	0.001 m €/year	0.001 m €/year	0.001 m €/year	0.003 m €/year
Recharge dyn. battery	0.021 m €/year	0.015 m €/year	0.011 m €/year	0.047 m €/year

↑ Table 8: Line-specific cost items for BEMU and HEMU, including infrastructure

5.4.2 Results of the net present value analysis

The VDE carried out a separate net present value analysis for each of the three ›Düren network‹ lines in order to compare and evaluate the four technology solutions: DMU, BEMU, HEMU and EMU. In consultation with NVR, the VDE chose four different observation periods:

15 years	Maximum duration of transport contracts with EVUs
22.5 years	Maximum exceptional duration under Article 4(4) of Regulation (EC) No 1370/2007[17]
30 years	Typical service life of multiple units with electric motor drives
70 years	The useful life of capital goods such as OL masts is used for orientation

The resulting net present values are given in → Table 9 – ordered by the length of the observation period. Blue ellipses in the left column (containing the sums for the network) high-light the smallest absolute net present values. This identifies the most advantageous investment project depending on the length of the observation period. According to this, BEMUs and EMUs prove to be equally advantageous. The two solutions vie for top position when it comes to the individual lines. With regard to the network as a whole, the longer the observation period, the more attractive the EMU becomes as a proposition, albeit within a narrow range. Factoring in the residual values of rolling stock and infrastructure evidently results in there being scant variation in the net present value ratios for DMU, EMU, BEMU and HEMU solutions over different observation periods. The VDE therefore limits itself to a period of 30 years in the further analysis.

→ Table 10 shows the resulting net present values ordered by cost type. Below the line containing the total net present values, two further lines provide information on how large the net present value is after deduction of the train path and station costs and what remains after deduction of the costs for infrastructure investment and operation. The latter net present values are the technology-specific costs that are only of concern to the EVU as operator of the railway lines.

15 years	**Network**	**RB 21 Nord**	**RB 21 Süd**	**RB 28**
DMU	-238.4 m €	-106.2 m €	-77.3 m €	-54.9 m €
EMU	-222.0 m €	-96.9 m €	-73.5 m €	-51.6 m €
BEMU	**-218.0 m €**	-97.3 m €	-72.9 m €	-47.7 m €
HEMU	-248.3 m €	-111.3 m €	-82.4 m €	-54.6 m €
22.5 years	**Network**	**RB 21 Nord**	**RB 21 Süd**	**RB 28**
DMU	-352.0 m €	-156.8 m €	-114.2 m €	-81.0 m €
EMU	-327.1 m €	-142.8 m €	-108.3 m €	-76.0 m €
BEMU	**-321.4 m €**	-143.5 m €	-107.5 m €	-70.4 m €
HEMU	-366.0 m €	-164.1 m €	-121.5 m €	-80.5 m €
30 years	**Network**	**RB 21 Nord**	**RB 21 Süd**	**RB 28**
DMU	-461.9 m €	-205.8 m €	-149.8 m €	-106.3 m €
EMU	-428.4 m €	-187.3 m €	-141.6 m €	-99.5 m €
BEMU	**-421.4 m €**	-188.4 m €	-140.6 m €	-92.3 m €
HEMU	-480.0 m €	-215.4 m €	-158.9 m €	-105.6 m €
70 years	**Network**	**RB 21 Nord**	**RB 21 Süd**	**RB 28**
DMU	-982.7 m €	-437.8 m €	-318.9 m €	-226.0 m €
EMU	-906.3 m €	-396.9 m €	-299.6 m €	-209.8 m €
BEMU	**-898.0 m €**	-401.7 m €	-299.6 m €	-196.7 m €
HEMU	-1022.8 m €	-459.2 m €	-338.5 m €	-225.0 m €

↑ Table 9: Total net present values for different observation periods

17 NVR 5.2.2020: "The duration may be extended by [...] 50% if this is necessary in view of the amortisation of assets. This is the case if the cost of the assets used is so high that it is not possible for the client or public service operator [...] to operate in an economically viable manner within the normal term of the contract."

30 years	Net present value	Network	RB 21 Nord	RB 21 Süd	RB 28
DMU	**Total**	**-461.9 m €**	**-205.8 m €**	**-149.8 m €**	**-106.3 m €**
	Total excl. T+S	**-210.2 m €**	**-94.3 m €**	**-66.6 m €**	**-49.3 m €**
	Total excl. T+S+I	**-209.3 m €**	**-93.9 m €**	**-66.2 m €**	**-49.1 m €**
	Vehicles	-46.0 m €	-20.9 m €	-16.7 m €	-8.4 m €
	Maintenance	-56.7 m €	-25.1 m €	-18.7 m €	-12.9 m €
	Energy	-89.6 m €	-40.4 m €	-25.3 m €	-23.9 m €
	Repl. of tech. comp.s	-16.9 m €	-7.5 m €	-5.5 m €	-4.0 m €
	Tanks	-0.1 m €	0.0 m €	0.0 m €	0.0 m €
	Train paths	-182.0 m €	-80.2 m €	-59.1 m €	-42.7 m €
	Stations	-69.7 m €	-31.3 m €	-24.2 m €	-14.2 m €
	Infrastructure	-0.9 m €	-0.4 m €	-0.3 m €	-0.2 m €
EMU	**Total**	**-428.4 m €**	**-187.3 m €**	**-141.6 m €**	**-99.5 m €**
	Total excl. T+S	**-176.7 m €**	**-75.8 m €**	**-58.4 m €**	**-42.6 m €**
	Total excl. T+S+I	**-126.0 m €**	**-57.7 m €**	**-41.8 m €**	**-26.5 m €**
	Vehicles	-47.9 m €	-22.0 m €	-17.2 m €	-8.8 m €
	Maintenance	-39.5 m €	-17.5 m €	-13.1 m €	-8.9 m €
	Energy	-38.5 m €	-18.2 m €	-11.5 m €	-8.8 m €
	Repl. of tech. comp.s	0.0 m €	0.0 m €	0.0 m €	0.0 m €
	Train paths	-182.0 m €	-80.2 m €	-59.1 m €	-42.7 m €
	Stations	-69.7 m €	-31.3 m €	-24.2 m €	-14.2 m €
	Infrastructure	-50.7 m €	-18.1 m €	-16.5 m €	-16.1 m €
BEMU	**Total**	**-421.4 m €**	**-188.4 m €**	**-140.6 m €**	**-92.3 m €**
	Total excl. T+S	**-169.7 m €**	**-77.0 m €**	**-57.4 m €**	**-35.4 m €**
	Total excl. T+S+I	**-166.0 m €**	**-75.3 m €**	**-56.1 m €**	**-34.5 m €**
	Vehicles	-69.1 m €	-31.7 m €	-24.8 m €	-12.7 m €
	Maintenance	-41.6 m €	-18.4 m €	-13.8 m €	-9.4 m €
	Energy	-24.9 m €	-11.8 m €	-7.7 m €	-5.3 m €
	Repl. of tech. comp.s	-30.4 m €	-13.4 m €	-9.9 m €	-7.1 m €
	Train paths	-182.0 m €	-80.2 m €	-59.1 m €	-42.7 m €
	Stations	-69.7 m €	-31.3 m €	-24.2 m €	-14.2 m €
	Infrastructure	-3.8 m €	-1.7 m €	-1.2 m €	-0.9 m €
HEMU	**Total**	**-480.0 m €**	**-215.4 m €**	**-158.9 m €**	**-105.6 m €**
	Total excl. T+S	**-228.3 m €**	**-103.9 m €**	**-75.6 m €**	**-48.7 m €**
	Total excl. T+S+I	**-226.4 m €**	**-103.1 m €**	**-75.0 m €**	**-48.3 m €**
	Vehicles	-76.9 m €	-35.2 m €	-27.6 m €	-14.1 m €
	Maintenance	-46.1 m €	-20.4 m €	-15.2 m €	-10.4 m €
	Energy	-44.4 m €	-21.4 m €	-13.0 m €	-9.9 m €
	Repl. of tech. comp.s	-57.7 m €	-25.4 m €	-18.7 m €	-13.5 m €
	Refuelling/charging	-1.4 m €	-0.6 m €	-0.4 m €	-0.3 m €
	Train paths	-182.0 m €	-80.2 m €	-59.1 m €	-42.7 m €
	Stations	-69.7 m €	-31.3 m €	-24.2 m €	-14.2 m €
	Infrastructure	-1.8 m €	-0.8 m €	-0.6 m €	-0.4 m €

↑ Table 10: Net present values by cost category for alternatives (period under consideration 30 years)

In the charts below, the different diagram diameters correspond to the ratios of the net present value sums.

→ Figure 41 shows the proportions of the different cost items contributing to the net present value of the ›Düren network‹. Train path and station fees are basically non technology-specific, i.e. their share remains constant in absolute terms. As explained elsewhere, the VDE has nevertheless included these costs in its analysis, as they represent dominant cost items and the net benefit of an alternative solution could be specifically enhanced through subsidies (e.g. of the train path fee) in the future.

→ Figure 42 shows a breakdown of the net present values without train path and station costs.

→ Figure 43 shows a further breakdown of the net present values without investment and operating costs for infrastructure.

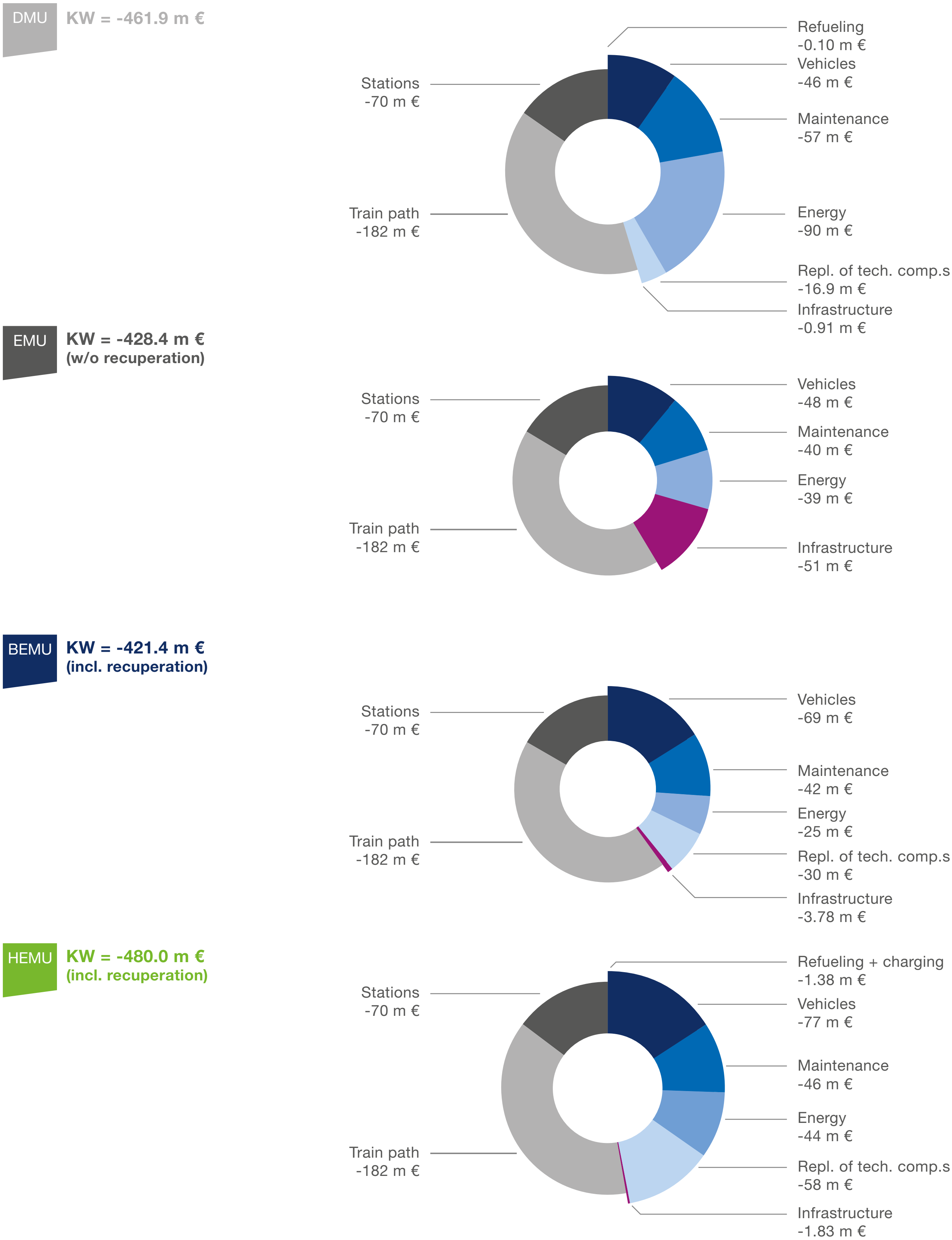
Comparison of the various pie charts shows that any assessment of economic viability is ultimately a question of perspective and the given framework conditions.

→ Figure 41 reveals that the economic viability of the railway line operation is determined to a large extent by the non technology-specific costs for train path and station use. Aside from these major cost blocks, different costs come to the fore depending on the individual technologies, as clearly emerges in → Figure 42. In the case of the DMU, it is above all the energy costs which determine the resulting net present value. In the case of the EMU, it is the cost of investing in full electrification. For the BEMU and HEMU, vehicle procurement costs and the cost of replacing their high-tech components account for a significant proportion of their net present value. The costs for installing electrification islands for the BEMU, on the other hand, are relevant but not dominant.

In the case of the HEMU, replacement of the high-priced fuel cell and dynamic battery components, plus the energy costs themselves, are responsible for rendering the resulting net present value clearly negative. The replacement costs ultimately depend on the quality and operating life of the fuel cell and battery. The energy costs are determined by the unfavourable energy conversion efficiency level and the price of hydrogen. The latter is assumed to be advantageous at 4.50 €/kg H2 for *green* hydrogen. The current price for electrolysis hydrogen is considerably higher. Therefore: a significant improvement in the operating life of the fuel cells and a more favourable hydrogen price would considerably raise the resulting net present value.

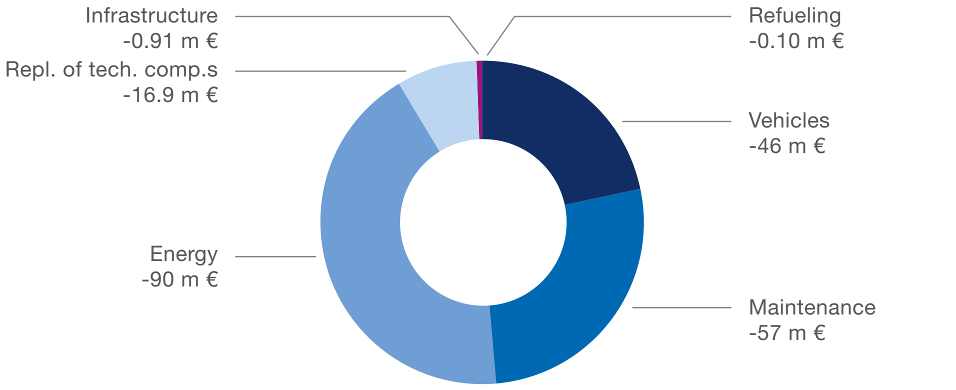
It is interesting to note that the BEMU and EMU, despite the differences in their various cost items, have very similar resulting net present values in the ›Düren network‹: the vehicle plus infrastructure costs for the EMU are the same as the vehicle plus replacement costs in the case of the BEMU. It should be noted that the energy costs of the EMU are ultimately lower than those of the BEMU. The simulation cannot, however, show the cost effect of the EMU recuperation into the overhead contact line, as the recuperation process assumes that there is another train nearby which can absorb the energy. The level of reimbursement from the energy provider thus remains an unknown factor.

→ Figure 43 shows that if the infrastructure is financed and provided by a *third party* and is therefore not taken into account in the net present value analysis, the proportions of the resulting net present values diverge even further.
In this case, the EMU is unparalleled in its status as an advantageous investment project. The BEMU is also highly advantageous. The resulting net present value of the HEMU corresponds to that of the DMU, although it should be noted that this is based on an assumed diesel price of 1.20 €/litre.

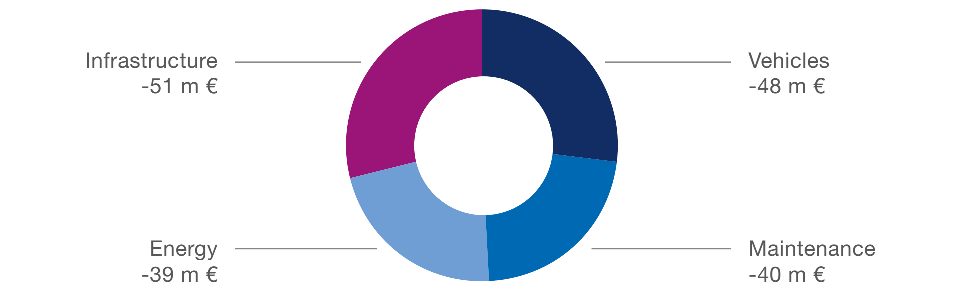


↑ Figure 41: Net present values for the ›Düren network‹ differentiated by cost type

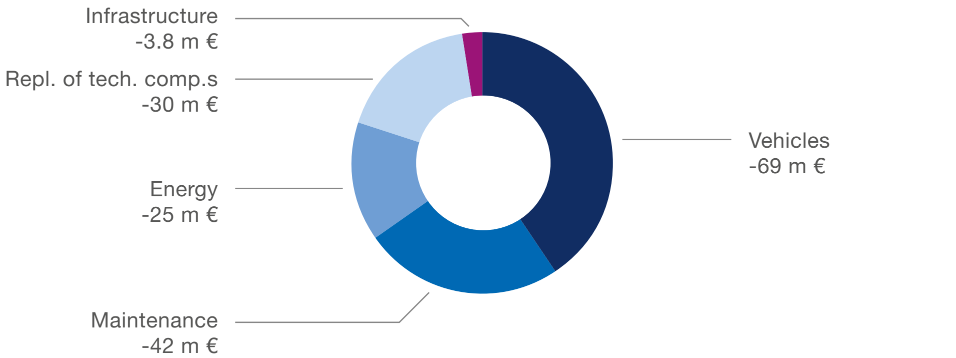
DMU **KW = -210.2 m €**



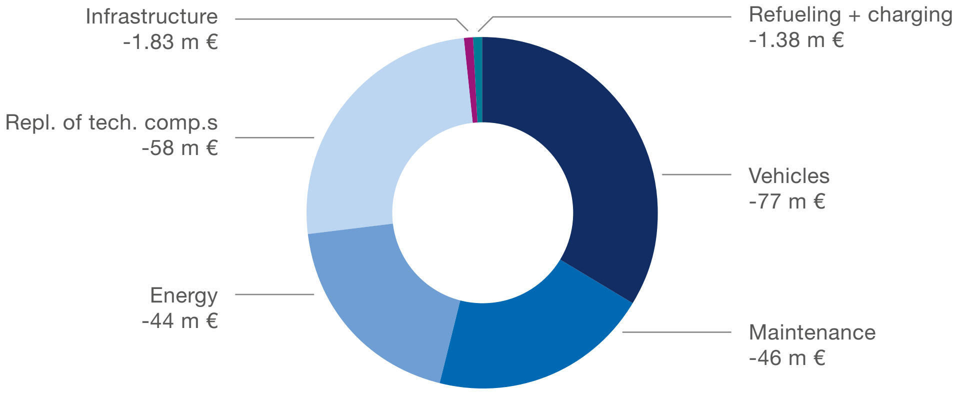
EMU **KW = -176.7 m €**
(w/o recuperation)



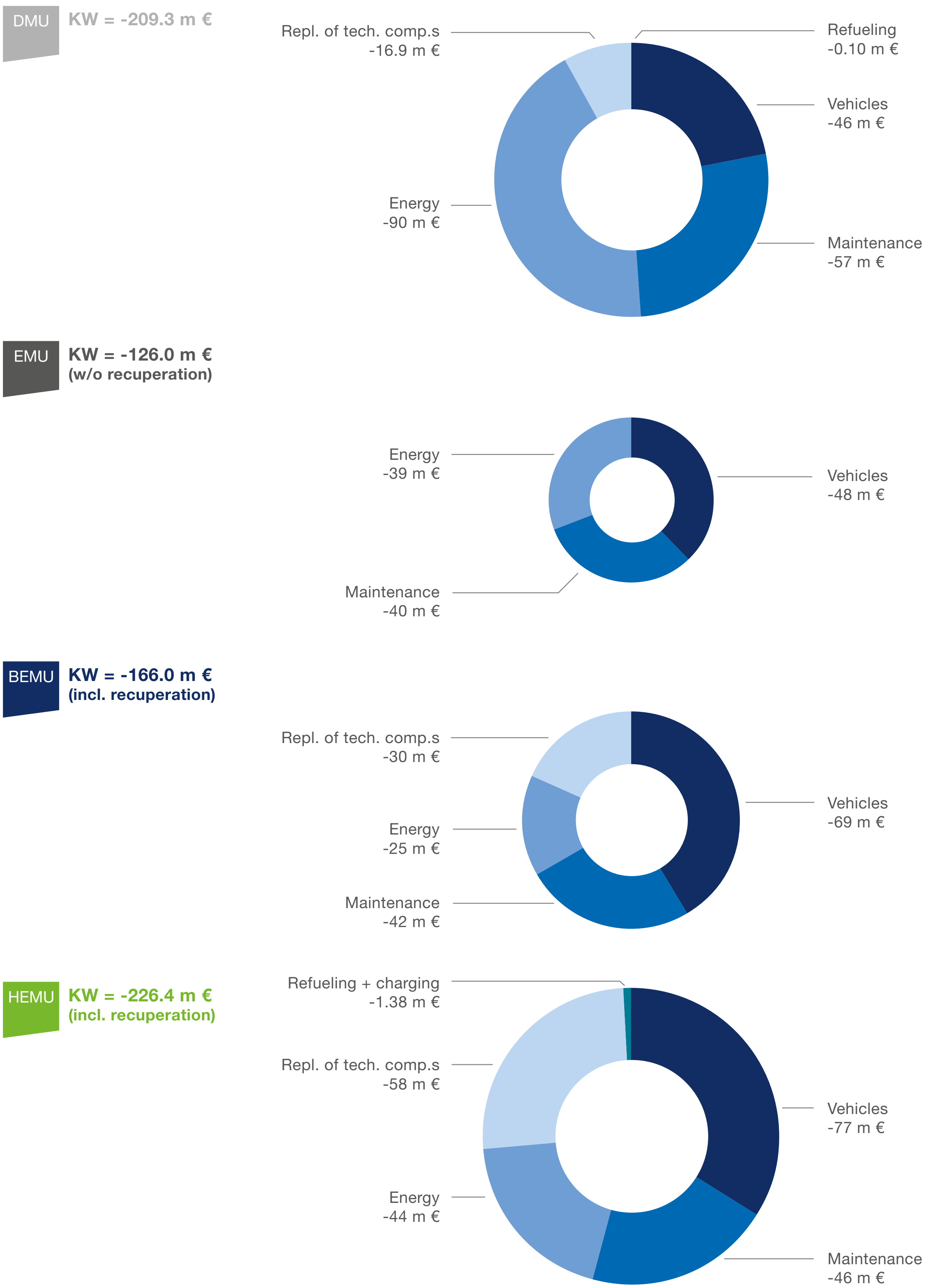
BEMU **KW = -169.7 m €**
(incl. recuperation)



HEMU **KW = -228.3 m €**
(w/o recuperation)



↑ Figure 42: Disaggregated net present values excluding train path and station costs



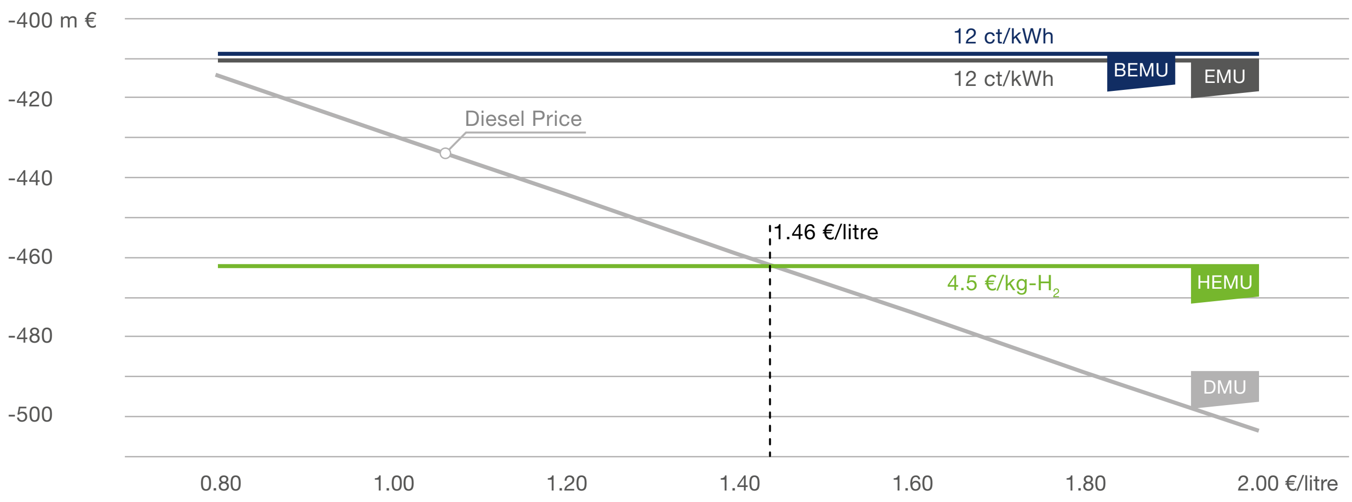
↑ Figure 43: Disaggregated net present values excluding train path, station and infrastructure costs

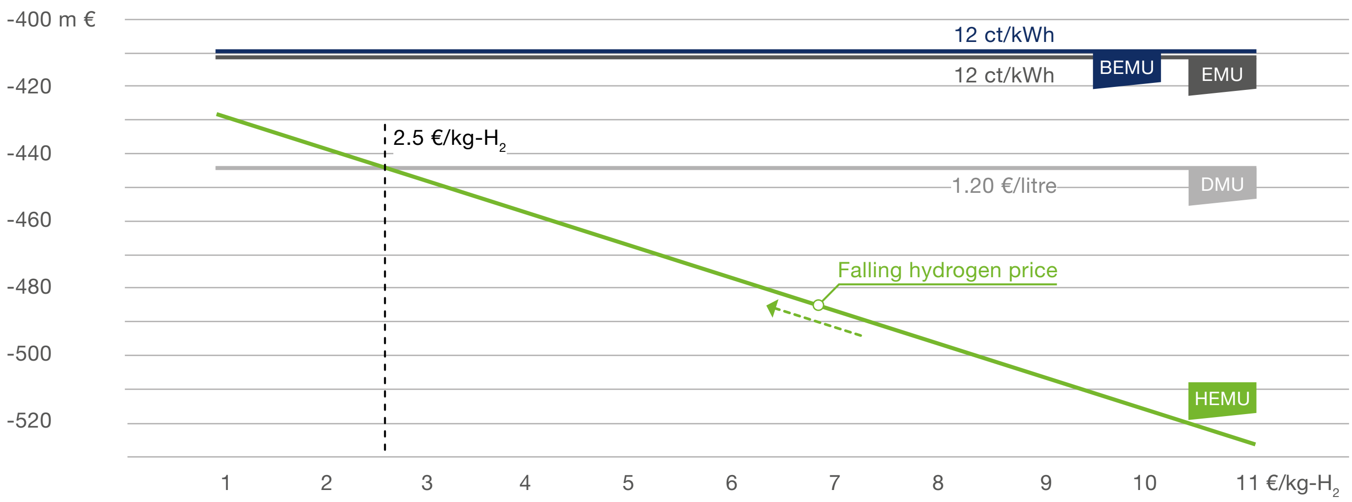
5.4.3 Sensitivity analysis

The findings given in → Section 5.4.2 are based on assumptions regarding, for example, applicable energy prices and electrification costs. Moreover, the statements are, strictly speaking, only applicable to the ›Düren network‹ with its specific line properties and operating conditions. For other networks and with other parameter values, different net benefit results could be obtained for a particular alternative. The VDE has investigated the extent to which the resulting net present values react to the various parameters by conducting a sensitivity analysis. The bandwidths within which the various parameters were varied are given in → Table 11.

PARAMETER	FROM	TO
Price: Diesel	0.80 €/litre	2.00 €/litre
Price: Electricity	10 ct/kWh	40 ct/kWh
Price: Hydrogen	1.00 €/kg-H_2	11.00 €/kg-H_2
Electrification costs	0.5 m €/km	2.0 m €/km
Size: BEMU fleet	+0 vehicles	+9 vehicles
Price: HEMU vehicle	EMU price + 0%	EMU price + 100%
Price: BEMU vehicle	EMU price + 0%	EMU price + 100%
Weight: BEMU	EMU weight + 0%	EMU weight + 50%
Weight: HEMU	EMU weight + 0%	EMU weight + 50%
Freq. in ›Düren network‹	1 train / 2h	3 trains / 1h

↑ Table 11: Parameters varied in the sensitivity analysis (observation period 30 years)



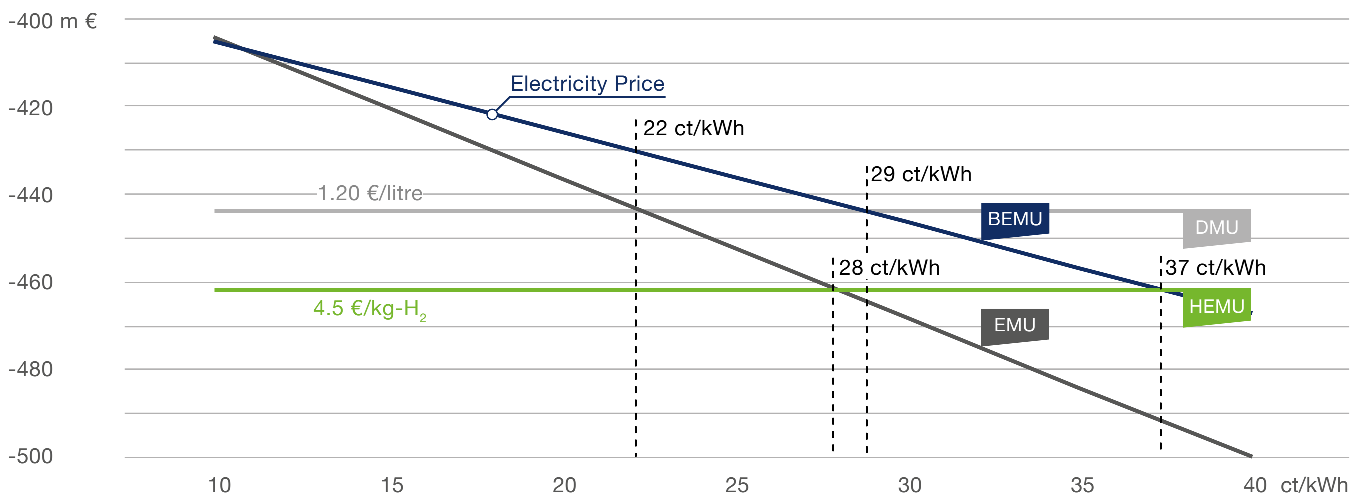


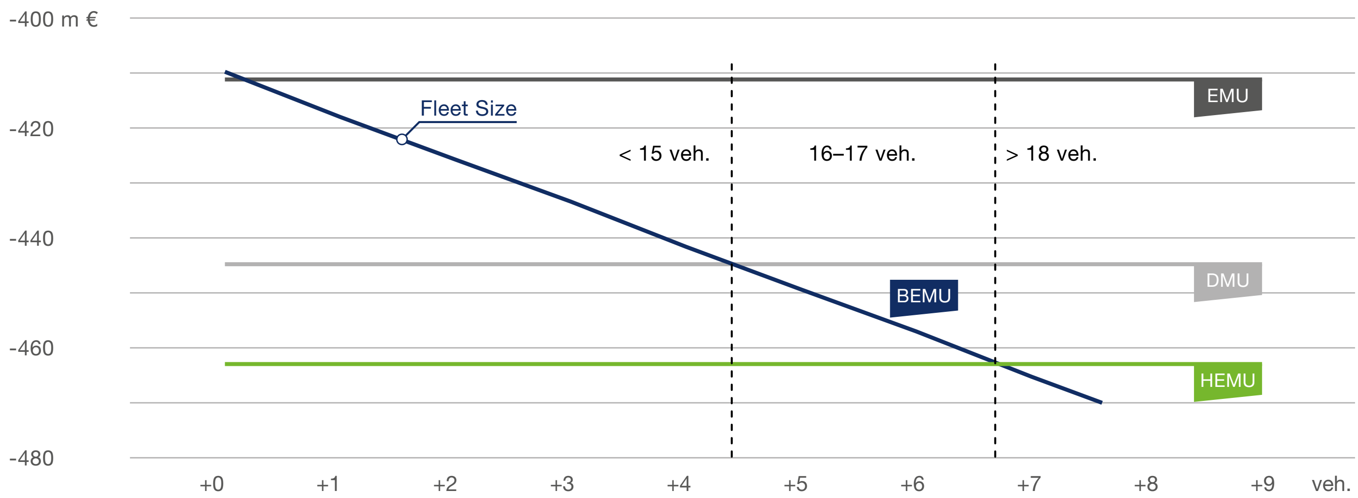
↑↑ Figure 44: Sensitivity analysis – Diesel price (reference: total net present value)

↑ Figure 45: Sensitivity analysis – Hydrogen price (reference: total net present value)

→ Figure 44 shows how the variation in the diesel price between 0.80 and 2.00 €/litre (with no change in the other energy prices) would affect the resulting total net present value of a possible investment in a new DMU fleet. According to this, the DMU and HEMU would be on a par at a diesel price of 1.46 €/litre – albeit assuming a price of 4.50 €/kg-H_2 for *green* hydrogen which has not yet been achieved.

→ Figure 45, by contrast, highlights how, taking all cost items in the net present value formula into account, the hydrogen price would have to fall below 2.50 €/kg-H_2 for the HEMU solution to be more advantageous than the DMU solution (at a diesel price of 1.20 €/litre). Accordingly, in terms of the ›Düren network‹, it would be unrealistic to expect a further reduction to put the hydrogen price on a par with EMU or BEMU.





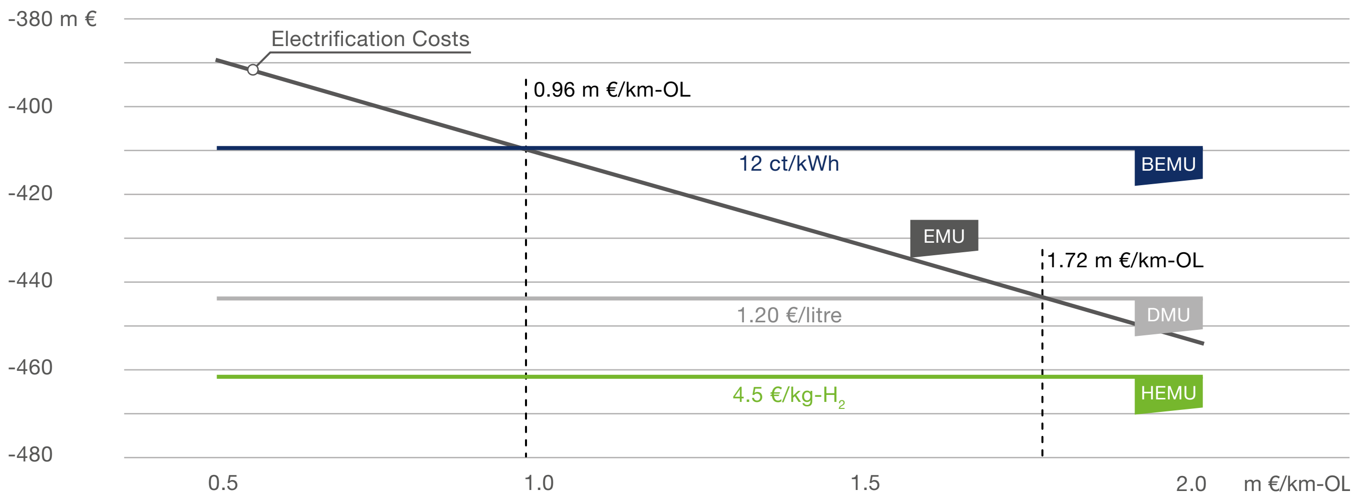
↑↑ Figure 46: Sensitivity analysis – Electricity price (reference: total net present value)

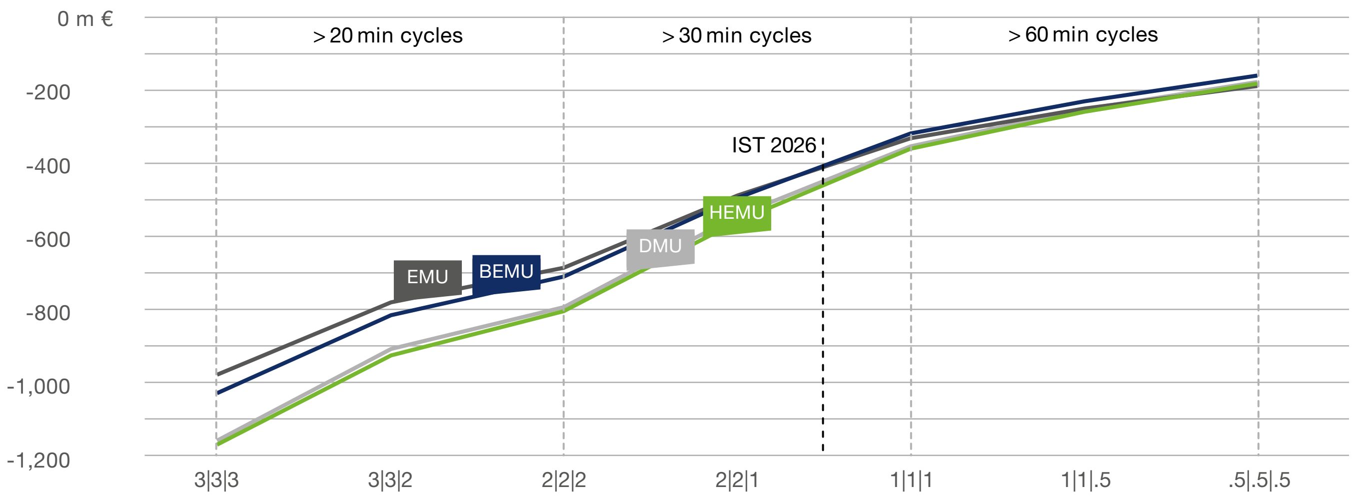
↑ Figure 47: Sensitivity analysis – BEMU fleet size due to limited range

The relative advantages of the EMU and BEMU solutions can be seen from the results of the electricity price variations, as shown in → Figure 46. Even without recuperation, the traction current price for the EMU solution could rise from 12 to 28 ct/kWh without making it more disadvantageous than the HEMU solution (at 4.50 €/kg-H_2). In the case of the BEMU solution, the conditions are even more favourable when recuperation is taken into account. Here, the electricity price could rise to 37 ct/kWh without the BEMU losing its advantage compared to the HEMU solution.

The result of the net present value analysis with regard to the net benefit of the BEMU and EMU solutions is so significant that there would be no change even in the face of wide varitions in the fuel and electricity prices.

How readily a BEMU fleet could be deployed in the ›Düren network‹ depends above all on the location of its charging infrastructure, the speed with which vehicles can be recharged there, and the amount of time the operating schedule allows for this. In borderline cases, it may be necessary for the operator to use more vehicles than was previously necessary with DMUs. → Figure 47 shows that the BEMU solution becomes significantly less advantageous as an investment project than the EMU solution if even one additional vehicle is required. However, it would take at least seven or more additional BEMUs to make the BEMU solution economically less attractive than the HEMU solution.





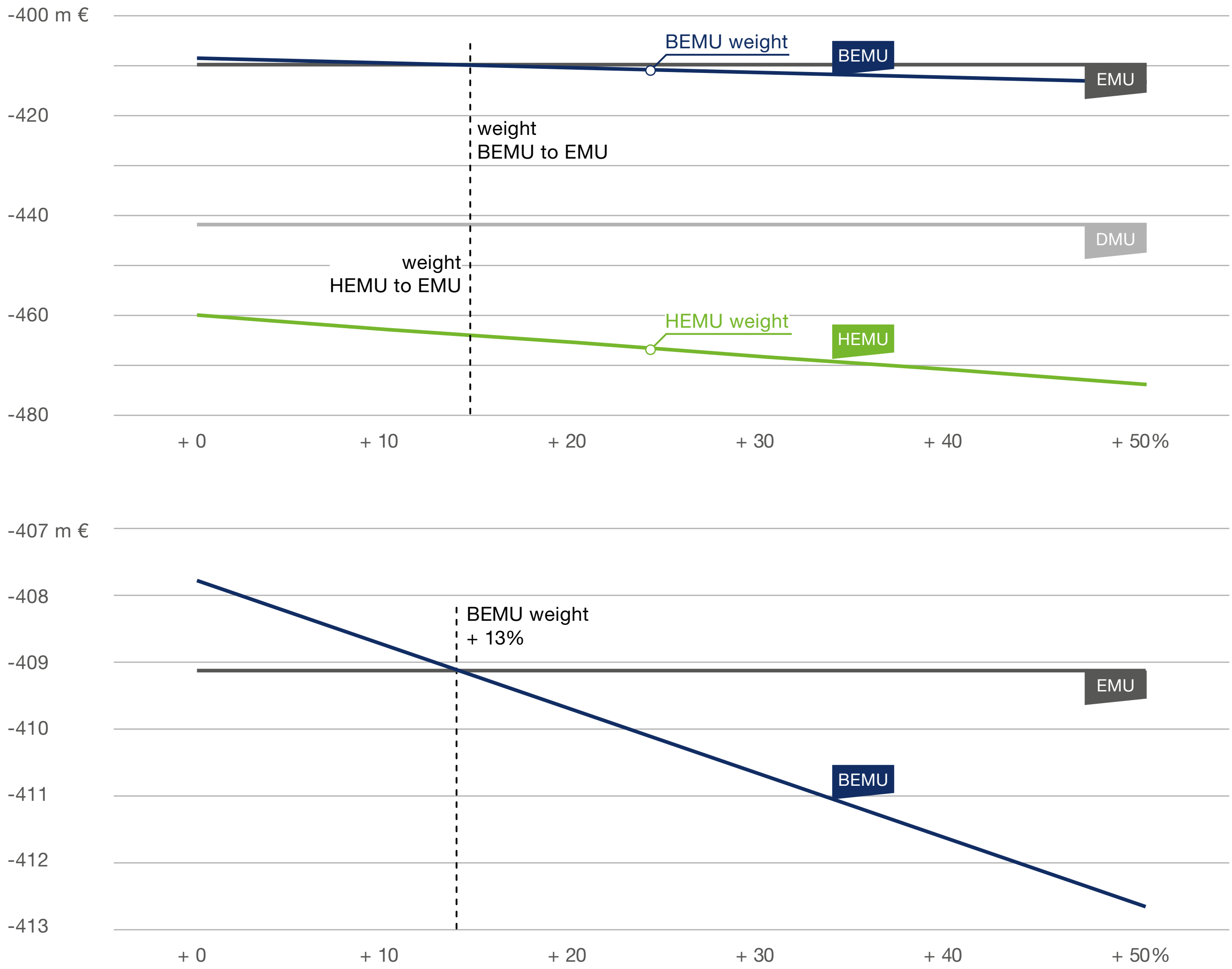
↑↑ Figure 48: Sensitivity analysis – Electrification costs of an EMU fleet

↑ Figure 49: Sensitivity analysis – Timetable frequency of the ›Düren network‹ lines

The net benefit of the EMU stems largely from the assumed electrification costs of 1 million €/km-OL (including substation). This begs the question of what the impact would be of significantly higher or lower production costs. The answer can be found in → Figure 48. According to this, the EMU and BEMU solutions are, coincidentally, more or less on a par at 1 million €/km. With considerably higher costs, the BEMU solution becomes by far the most advantageous investment project. From 2 million €/km, the EMU solution would be on a par with the HEMU solution. With electrification costs well below 1 million €/km, the net benefit of the EMU investment would be even more significant.

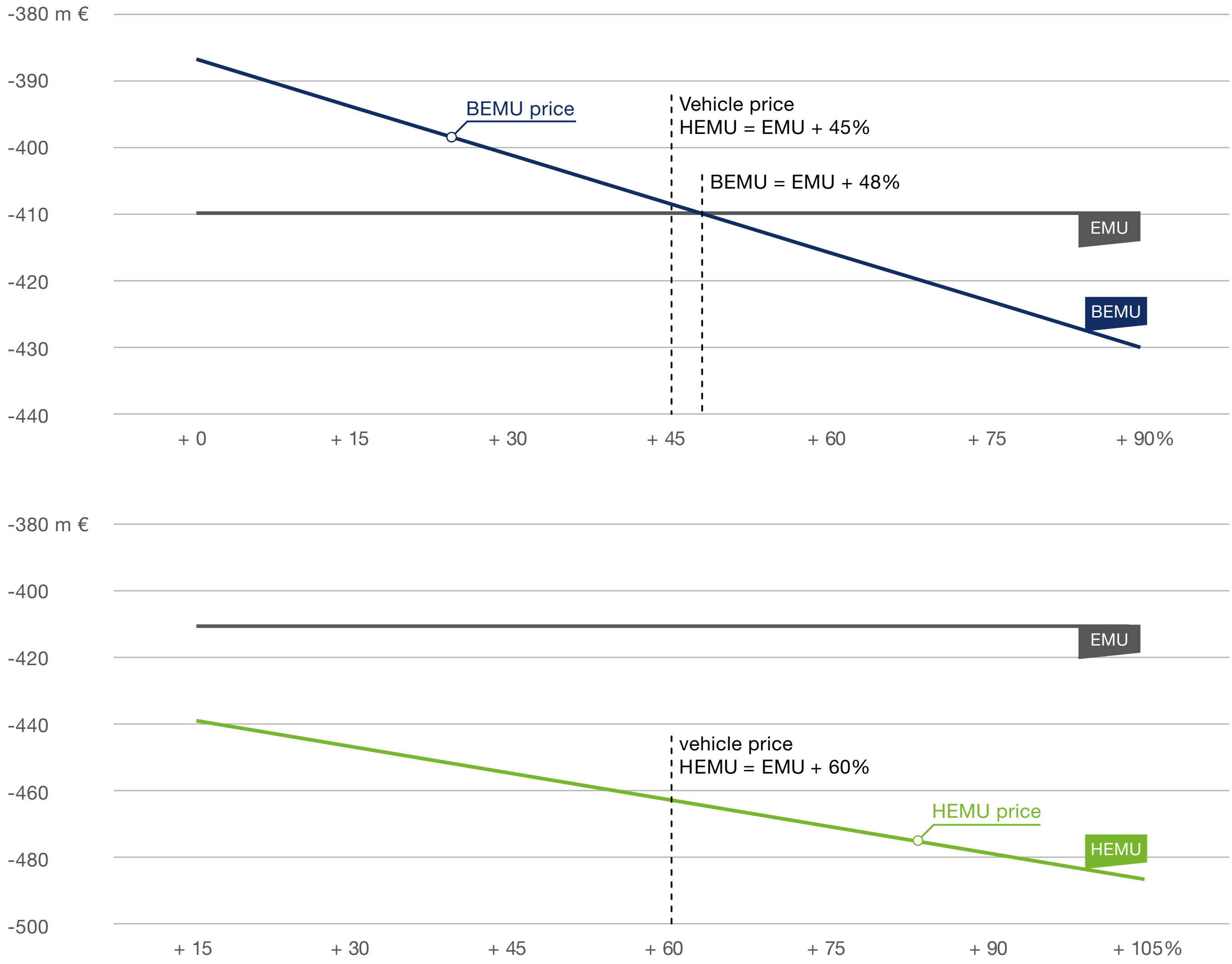
A key remaining question is the influence of the timetable frequency of the ›Düren network‹ lines on their net benefit, i.e. the resulting net present value. Up to this point, the analysis has assumed that the number of trains to be used per hour from 2026 onwards will remain unchanged, i.e. that there will be no changes in frequency in the next 30 years. → Figure 49 highlights the influence of different timetable frequencies on the net present value of the respective alternative. x|y|z stand for the number of trains used per hour on RB 21 Süd (x), RB 21 Nord (y) and RB 28 (z) – currently 2|2|.5 – meaning that the average interval is between half and one hour.

This confirms the assertion made for example in → [5] that full electrification becomes financially worthwhile with catenary electric multiple units and a timetable frequency of at least every half-hour. Evidently this also applies to the ›Düren network‹.



↑ Figure 50: Sensitivity analysis –
Weights of BEMU and HEMU vehicles

The weight and procurement prices of vehicles with alternative drive systems could pose potential problems. Indeed, the VDE analyses are based on the simplified assumption that all vehicles are the same weight, although the BEMU additionally carries a heavy battery, and the HEMU has large fuel cell stacks and a dynamic battery. The actual weights of the BEMU and HEMU are therefore likely to be at least 10 per cent higher than those of the comparable EMU model causing higher energy spendings. → Figure 50 shows that, given otherwise identical boundary conditions, the BEMU solution would lose its status as the most advantageous investment option to the EMU solution from an additional weight of 13 per cent.



↑ Figure 51: Sensitivity analysis –
BEMU and HEMU vehicle prices

The prices assumed for the BEMU and HEMU are estimates, extrapolated from known prices for EMU and DMU vehicles and taking into account the prices of batteries per kWh capacity and fuel cells per kW output. The VDE analyses assume that BEMU vehicles are 45 per cent more expensive than EMU vehicles of the same size and that HEMU vehicles are 60 per cent more expensive than EMU vehicles → Figure 51 shows that if the vehicles are 48 per cent or more expensive, the BEMU solution becomes less cost-effective than the EMU solution, despite recuperation.

In summary, BEMUs and EMUs represent two more or less equally advantageous investment projects for the ›Düren network‹. A decision in favour of one of the two options must be made on a strategic basis: Will the ›Düren network‹ be fully electrified in the long term because there are plans for higher timetable frequencies, for example? Or should overhead lines be dispensed with in the long term to protect the surrounding picturesque countryside?

6 Broader considerations and Conclusion

6.1 Cost leverage

At a total length of almost 90 kilometres, the ›Düren network‹, consisting of the RB 21 Nord, RB 21 Süd and RB 28 lines, is definitely not one of the largest diesel networks in Germany. However, it is a very interesting model for the VDE in view of its operating capacity (which is set to increase to 1.46 million tkm by 2026), and, according to Rurtalbahn, its above-average transport capacity. The sizeable stock of data which is available allows the alternative options to be examined and evaluated in detail. The resulting detailed findings can then – cautiously – be generalised and applied to other diesel networks.

The VDE's net present value analysis of the ›Düren network‹ reveals that, despite requiring full electrification, the overhead electric multiple unit (EMU) solution represents an extremely cost-effective investment project – provided that it can be completed without a need for excessive technical measures within the given time frame and that it is accepted by the *stakeholders*. According to NVR, the assumed overhead line installation costs in the order of €1/km-OL (including pro rata costs for an additional substation) are realistic in the case of the ›Düren network‹. It is unclear how the population will react if, for example, overhead lines are erected in the picturesque countryside of the RB 21 Süd route which is subject to a protection order.

If this *direct* form of electrification does not meet with approval, the battery-powered (BEMU) and the fuel cell (HEMU) multiple unit, as climate-neutral versions of *indirect* electrification, represent two further fundamentally viable investment alternatives. When assessing their net benefit using the net present value method, it should be borne in mind that various powerful levers can be used to exert significant influence on the resulting net present value, i.e. their net benefit. These apply both to the ›Düren network‹ lines and also to other diesel network lines. Up to three levers are listed below for each of the superordinate points (1–3), which are ordered according to the strength of their influence on the net present value. Differentiated by railway line and infrastructure operation, they are:

1. ***Technology-specific* costs related to vehicle pool and line operation:**

   Lever 1.1 Replacement of the various high-tech components
   Lever 1.2 Price and consumption of energy for realisation of operating capacity
   Lever 1.3 Procurement and replacement of fleet vehicles

2. ***Technology-specific* costs related to infrastructure installation and operation:**

   Lever 2.1 Installation and maintenance of the continuous overhead contact line
   Lever 2.2 Installation and maintenance of the overhead line charging infrastructure
   Lever 2.3 Installation, supply and maintenance of the refuelling station infrastructure

3. ***Non technology-specific* costs related to the operation of the railway lines:**

   Lever 3.1 Use of train paths
   Lever 3.2 Use of stations

Lever 1.1 Replacement of the various high-tech components:

Batteries and fuel cells for use in vehicles are based on sophisticated technologies that are constantly being refined.

When choosing a battery, vehicle manufacturers are faced with the challenge of selecting the most suitable cell technology for their application – as is explained in the VDE study from 2018 → [1]. Either they rely, like the automotive industry, on NMC/C technology, which offers the advantage of rising energy densities alongside falling cell prices. Or they decide in favour of NMC/LTO technology, which ostensibly has the disadvantage of lower (gravimetric) energy densities and higher cell prices. However, it is highly robust and is particularly suitable for application in multiple units with long operating lives, as the battery is extremely durable even in heavy-duty use and ideally only needs to be replaced once during the vehicle's operating life. The significantly higher battery-related vehicle acquisition costs are not critical in view of their relatively low leverage.

In contrast to batteries, fuel cells require regular maintenance for the replacement of individual defective stacks. Their production presumes a great deal of experience, meaning that only a few companies like Ballard or Hydrogenics have succeeded in mastering and developing this technology. Little is still known today about the actual operating life of fuel cells in multiple units. In HEMU applications, the fuel cell provides ranges far beyond those of BEMUs. An extra battery is required to provide the necessary driving dynamics when setting off and accelerating. During braking it should also absorb a sufficient amount of recuperated electricity to save hydrogen in the acceleration phases. Capacities of over 200 kWh are common today. Thus, the replacement costs of the HEMU solution are determined by two expensive technology components. In order to reduce these in the long term, there must be a fall in the price of the fuel cell per kilowatt of capacity, coupled with an increase in the operating life. Only in this way will the net present value and thus the relative net benefit of the HEMU solution improve to such an extent that it can compete with the BEMU solution in the long term.

Lever 1.2: Price and consumption of energy for realisation of operating capacity

Energy costs are another major lever that determines the relative net benefit of each potential investment project. Besides the energy price, which changes over the years, further decisive factors are energy efficiency, the use of recuperated braking energy and above all the intelligent coupling of technology-related efficiencies. Technological improvements in the coming years

Lever 1.3: Procurement and replacement of fleet vehicles

The installation of high-tech components will make vehicles more costly in any case. Interestingly, the influence of the significantly higher vehicle procurement costs is much less critical in comparison to the other cost items because they are only incurred once over the 30-year observation period, which mitigates their overall impact.

Lever 2.1: Installation and maintenance of the continuous overhead contact line

Electrification is a very expensive investment. It should be mentioned, however, that overhead contact lines have a very long operating life. This mitigates their influence on the net present value of the investment. The additional substation which may also be required is relatively difficult to estimate, and its installation could cost millions of euros. A particular leverage effect can be expected if the installation costs per kilometre of overhead line can be reduced, for example, by simplification and if additional substations can be avoided. An important prerequisite for deciding in favour of electrification is that the prescribed planning approval procedure can be carried out within the given time frame and with the decision-maker's existing staff.

Lever 2.2: Installation and maintenance of the overhead line charging infrastructure

The installation of electrification islands as part of the charging infrastructure for battery-powered trains is also an expensive investment, but much lower than that for full electrification. The leverage effect can be increased by simplifying the technical implementation and by avoiding additional substations. The planning approval procedure which this may involve is less complex.

Lever 2.3: Installation, supply and maintenance of the refuelling station infrastructure

Although the location of diesel or hydrogen refuelling stations (and their fuel supply) is extremely important for efficient operation, their costs have only a minor impact on the resulting net present value. Thus, the need for a refuelling infrastructure does not significantly affect the net benefit of investing in a HEMU project.

Lever 3.1: Use of train paths

The train path fee per kilometre in the private ›Düren network‹ is currently 4.48 €/km. In the DB's local rail network, the average charge according to TPS 2020 → [32] is 5.38 €/km. Thus the train path costs – as the product of the train kilometres travelled and this fee – are actually greater than the sum of the resulting replacement, energy and maintenance costs. It would therefore be possible to promote an alternative drive technology by reducing the train path charge by a moderate percentage.

Lever 3.2: Use of stations

The station fees charged per stop and station represent another significant proportion of the total costs. Here, too, it would be conceivable to promote a certain drive technology by making a slight reduction in the fee.

6.2 Conclusion

The net present value analysis levers as described in → Section 6.1 can be used as the basis for formulating general statements concerning the alternatives to diesel networks, and which are also applicable beyond the ›Düren network‹. Diesel networks basically differ in their individual line lengths, fleet sizes, operating and transport capacity, timetable frequencies, degrees of electrification, possible obstacles such as line crossings, tunnels, bridges, level crossings, gradients, curves or climatic conditions such as extreme weather or cold.

Line length and degree of electrification influence the costs of installing and operating the infrastructure, i.e. they affect the levers described in Lever 2.1 (Installation and maintenance of continuous overhead contact line) and Lever 2.2 (Installation and maintenance of charging infrastructure with overhead contact line). The longer the catenary-free sections are, the greater the influence of these levers on the resulting net present value, i.e. the more disadvantageous the EMU and BEMU solutions become. This negative impact becomes all the more serious if there are major technical difficulties that have to be overcome during electrification or the installation of an overhead line island. Accordingly, the decision between EMU, BEMU and HEMU will then tilt increasingly in favour of BEMU, and especially HEMU. In the case of lines with special energy demands, for example due to gradients or extreme climatic conditions, the BEMU solution is far less suitable than EMU or HEMU, which have comparatively unlimited energy reserves.

All other comparative and evaluative statements can be based on the knowledge gained from the ›Düren network‹, and then applied to other networks. The VDE has the necessary expertise to make such statements and will be pleased to offer this service to any public decision-makers, railway or infrastructure undertakings in the future.

7 Appendix

Appendix 7.1 Public decision-makers in Germany

Abbreviation	Public decision maker	State / Seat
VRN	Verkehrsverbund Rhein-Neckar GmbH	BW / Mannheim
NVBW	Nachverkehrsgesellschaft Baden-Württemberg mbH	BW / Stuttgart
VRS	Verband Region Stuttgart	BW / Stuttgart
BEG	Bayerische Eisenbahngesellschaft mbH	BY / München
VBB	Verkehrsverbund Berlin-Brandenburg GmbH	BE-BB / Berlin
HB	Senator für Umwelt, Bau und Verkehr des Landes Bremen	HB / Bremen
HVV	Hamburger Verkehrsverbund GmbH	HH / Hamburg
RMV	Rhein-Main-Verkehrsverbund GmbH	HE / Hofheim a.T.
NVV	Nordhessischer Verkehrsverbung GmbH	HE / Kassel
VMV	Verkehrsgesellschaft Mecklenburg-Vorpommern mbH	MV / Schwerin
LNVG	Landesnahverkehrsgesellschaft Niedersachsen mbH	NI / Hannover
RH	Region Hannover	NI / Hannover
RVB	Regionalverband Großraum Braunschweig	NI / Braunschweig
VRR	Verkehrsverbund Rhein-Ruhr AöR	NW / Gelsenkirchen
ZV NVR	Zweckverband Nahverkehr Rheinland GmbH	NW / Köln
NWL	Nahverkehr Westfalen-Lippe	NW / Unna
SPNV-Süd	Zweckverband SPNV Rheinland-Pfalz Süd	RP / Kaiserslautern
SPNV-Nord	Zweckverband SPNV Rheinland-Pfalz Nord	RP / Koblenz
SL	MS für Wirtschaft, Arbeit, Energie, Verkehr des Saarlandes	SL / Saarbrücken
ZVV	Zweckverband ÖPNV-Vogtland	SN / Auerbach
ZVON	ZV Verkehrsverbund Oberlausitz-Niederschlesien	SN / Bautzen
ZVMS	Zweckverband Verkehrsverbund Mittelsachsen	SN / Chemnitz
VVO	Verkehrsverbund Oberelbe GmbH	SN / Dresden
ZVNL	Zweckverband für den Nahverkehrsraum Leipzig	SN / Leipzig
NASA	Nahverkehrsservice Sachsen-Anhalt GmbH	ST / Magdeburg
NAH.SH	Nahverkehrsverbund Schleswig-Holstein GmbH	SH / Kiel
NVS	Nahverkehrsservicegesellschaft Thüringen mbH	TH / Erfurt

↑ Table 12: Public decision-makers responsible for regional public transport in Germany

Abbreviation	State
BW	Baden-Württemberg
BY	Bavaria
BE-BB	Berlin-Brandenburg
HB	Hansestadt Bremen
HH	Hansestadt Hamburg
MV	Mecklenburg-Vorpommern
NI	Lower Saxony

Abbreviation	State
NW	North Rhine-Westphalia
RP	Rhineland-Palatinate
SL	Saarland
SN	Saxony
ST	Saxony-Anhalt
SH	Schleswig-Holstein
TH	Thuringia

↑ Table 13: German federal states: Abbreviations

Appendix 7.2 Diesel networks in Germany

Network	Line section
Netz 11 Hohenlohe–Franken-Untermain	Würzburg–Lauda Aschaffenburg–Miltenberg–Wertheim Wertheim–Lauda–Crailsheim Crailsheim–Schwäbisch Hall–Hessental–Heilbronn Miltenberg–Walldürn–Seckach, Seckach–Osterburken
Netz 12 Ulmer Stern	Aalen–Ulm Munderkringen–Ehringen–Ulm
Zollern-Alb-Bahn	Tübingen–Albstadt-Ebingen–Sigmaringen Hechingen–Gammertingen–Sigmaringen
Nordschwarzwald	Pforzheim–Nagold–Horb Tübingen–Horb Pforzheim–Maulbronn Stadt
Netz 8 Ortenau	Offenburg–Freudenstadt/Hornberg Offenburg–Bad Griesbach Offenburg–Achern Achern–Ottenhöfen Biberach (Baden)–Oberharmersbach-Riersbach
Ringzug Schwarzwald–Baar–Heuberg	Schwarzwald–Baar–Heuberg
Augsburger Netze – Los 2	Langenneufach–Augsburg–Weilheim–Schongau–Augsburg–Eichstätt Stadt
Expressverkehr Nordostbayern	Nürnberg–Bayreuth/Hof Nürnberg–Weiden– Neustadt/Furth im Wald/Regensburg Schwandorf–Marktredwitz Coburg/Bamberg–Hof/Bayreuth
Regionalverkehr Oberfranken	Hof–Bad Steben Hof Mitte–Hof–Selb–Stadt mit Flügel Selb-Plößberg–Asch–Cheb–Marktredwitz Bamberg–Ebern Forchheim–Ebermannstadt Coburg–Bad Rodach Coburg–Lichtenfels–Bayreuth Bayreuth–Weiden Bayreuth–Marktredwitz Marktredwitz–Hof–Gutenfürst Hof–Münchberg
Regionalverkehr Ostbayern	Plattling–Bayrisch Eisenstein (–Klatovy) Zwiesel–Grafenau Zwiesel–Bodenmais Schwandorf–Furth i. Wald (–Domazlice) Cham–Waldmünchen Cham–Bad Kötztin–Lam Regensburg–Marktredwitz Marktredwitz–Schirnding (–Cheb)
Linienstern Mühldorf 2025+	Mühldorf (Obb.)–Simbach Mühldorf (Obb.)–Passau/Landshut/München Mühldorf (Obb.)–Burghausen Mühldorf (Obb.)–Salzburg Mühldorf (Obb.)–Rosenheim Mühldorf (Obb.)–Traunstein Traunstein–Traunreut München–Wasserburg Traunstein–Waging Prien–Aschau Neufahrn–Bogen

→

↑ Table 14: Assignment of regional rail transport networks and lines
Part 1 – Source → [15]

Network	Line section
Romantische Schiene	Dombühl – Dinkelsbühl – Wilburgstetten
Franken-Südhessen	Frankfurt – Würzburg – Bamberg Würzburg – Fulda/Lauda/Marktbreit/Nürnberg
Allgäu-Schwaben	Augsburg – Kempten (Allg) – Immenstadt – Oberstdorf/Lindau Augsburg – Memmingen – Bad Wörishofen Kempten (Allg) – Pfronten-Steinach Ulm – Kempten (Allg)
IR25 Interimvertrag	München – Furth – Prag München – Hof
Expressverkehr Ostbayern Übergang – Los 1	RE 2: (München –) Regensburg – Hof
Expressverkehr Ostbayern	München – Hof München – Furth im Wald – Praha
Netz Ostbrandenburg 2	RB 12: Berlin Ostkreuz – Templin RB 26: Berlin Ostkreuz – Werneuchen RB 26: Berlin Ostkreuz – Grenze DE/PL RB 35: Fürstenwalde – Bad Saarow RB 36: Frankfurt (O.) – König-Wusterhausen RB 54: (Berlin-Gesundbrunnen/Lichtenberg –)Rheinsberg RB 60: Eberswalde – Frankfurt (O.) RB 61: Schwedt – Angermund RB 62: Angermund – Prenzlau RB 63: Eberswalde – Templin
Netz Nordwestbrandenburg	Berlin – Neuruppin – Wittenberge
Netz Spree-Neiße	Cottbus – Forst (Lausitz) Cottbus – Görlitz – Zittau
Heidekrautbahn	Berlin Gesundbrunnen Berlin-Karow – Groß Schönebeck Schmachtenhagen
Netz Prignitz	RB 74: Pritzwalk – Meyenburg RB 73: Neustadt (Dosse) – Pritzwalk
Wetterau West – Ost	RB 46: Gießen – Gelnhausen RB 47: Friedberg – Wölfersheim-Södel – Hungen/Lich RB 48: Nidda – Friedberg (– Frankfurt) Lumbdatalbahn: Gießen – Lollar – Londorf
Ländchesbahn	RB 21: Limburg – Wiesbaden
Lahntal – Vogelsberg – Rhön	RB 45: Limburg – Fulda RB 52: Gersfeld – Fulda
Odenwald	RB 66: Darmstadt – Pfungstadt RE 80: Erbach – Darmstadt RB 81: Eberbach – Darmstadt RB 82: Eberbach – Frankfurt RE 85: Erbach – Frankfurt RB 86: Groß-Umstadt Wiebelsbach – Hanau RB 61: Dieburg – Frankfurt [Einzelf.]
Niddertal	RB 34: Glauburg-Stockheim – Frankfurt RB 48: Nidda – Frankfurt [Einzelf.]
Dreieich	RB 61: Dieburg – Frankfurt

→

↑ Table 15: Assignment of regional rail transport networks and lines
Part 2 – Source → [15]

Network	Line section
Taunus	RB 11: Bad Soden – Frankfurt.Höchst; RB 11: Kelkheim – Frankfurt.Höchst (Einzelf.) RB 12: Königstein – Frankfurt RB 15: Brandoberndorf – Frankfurt RB 16: Bad Homburg – Friedberg
RT-Netz	RT1: Hofgeismar-Hümme – Kassel Hbf – Holländische Str. RT4: Wolfhagen – Zierenberg – Kassel Hbf – Holländische Str. RT5: Melsungen – Kassel-Wilhelmshöhe – Kassel Hbf – Auestadion
Dieselnetz Niedersachsen – Mitte	Bünde/Herford – Löhne – Hameln – Hildesheim – Bodenburg Buchholz/N. – Hannover Bremen – Soltau – Uelzen
Weser-Ems	Osnabrück – Oldenburg – Wilhelmshaven Esens – Sande – Wilhelmshaven Osnabrück – Vechta – Delmenhorst – Bremen
DINSO I	Braunschweig – Schöppenstedt Northeim – Herzberg – Nordhausen Braunschweig – Salzgitter – Lebenstedt Braunschweig – Seesen – Herzberg Göttingen – Kreiensen – Bad Harzburg Bodenfelde – Northeim Einbeck-Mitte – Einbeck Salzderhelden – Göttingen
DINSO II	Braunschweig – Gifhorn – Uelzen Hannover – Goslar – Bad Harzburg Braunschweig – Vienenburg – Goslar / Bad Harzburg
RE 5 Cuxhaven – Hamburg	Hamburg – Cuxhaven
Weser – Elbe	Cuxhaven – Bremerhaven Bremerhaven – Buxtehude
die euregiobahn (RB 20)	Stolberg Hbf – Alsdorf – Herzogenrath – Aachen Stolberg Hbf – Eschweiler-Weisweiler – Langerwehe/Düren
Nordast Rurtalbahn	RB 21 Nord: Düren – Jülich – Linnich (– Baal)
Südast Rurtalbahn	RB 21 Süd: Düren – Untermaubach – Heimbach
Eifel-Bördebahn	RB 28: Düren – Zülpich – Euskirchen
Kölner Dieselnetz	RE 12/22 Köln – Gerolstein – Trier RB 23 Bonn – Euskirchen – Bad Münstereifel RB 24 Köln – Kall (– Gerolstein) RB 25 Köln – Marienheide – Lüdenscheid RB 30 Bonn – Remagen – Ahrbrück
Netz OWL	RE 82: Bielefeld – Detmold RB 67: Bielefeld – Warendorf – Münster RB 71: Bielefeld – Rahden RB 73: Bielefeld – Lemgo-Lüttfeld RB 74: Bielefeld – Paderborn RB 75: Bielefeld – Halle – Osnabrück RB 84: Paderborn – Kreiensen RB 85: Ottbergen – Göttingen
Netz westliches Münsterland	RB 51: Dortmund – Enschede RB 63: Münster-Zentrum Nord – Coesfeld RB 64: Münster – Enschede – Zwolle
Sauerlandnetz	RE 17: Hagen – Warburg – Kassel RE 57: Dortmund – Winterberg/Brilon Stadt RB 52: Dortmund – Lüdenscheid RB 53: Dortmund – Iserlohn RB RB 54: Unna – Neuenrade

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↑ Table 16: Assignment of regional rail transport networks and lines
Part 3 – Source → [15]

Network	Line section
Emscher–Münsterland–Netz 2021	RE 14: Essen-Steele–Borken/Coesfeld
Niederhein–Münsterland–Netz	RE 10: Kleve–Krefeld–Düsseldorf RE 14: Essen-Steele–Borken/Coesfeld RE 44: Kamp-Lintfort–Duisburg–Bottrop RB 31: Xanten–Moers–Duisburg RB 36: Oberhausen–DU-Ruhrort RB 41: Geldern–Krefeld–Neuss RB 43: Dortmund–Wanne.Eickel–Dorsten (optional)
S7	S7: Wuppertal–Solingen
Hunsrückbahn (Steilstrecke)	Boppard–Emmelshausen
Moselweinbahn	Bullay–Traben-Trarbach
Daadetalbahn	Betzdorf–Daaden
Eifel–Westerwald–Sieg–Netz	(1) Gießen–Limburg–Koblenz (2) Limburg–Koblenz–Andernach–Mayen (3) Zollhaus–Diez–Limburg (4) Andernach–Mayen–Kaisersesch (5) Limburg–Altenkirchen–Au–Betzdorf–Siegen–Kreuztal (6) Betzdorf–Siegen–Erndtebrück–Bad Berleburg (7) Limburg–Montabaur–Siershahn (8) Finnentrop–Olpe (9) Dillenburg–Slegen (10) Betzdorf–Herdorf–Haiger–Dillenburg
Pfalznetz Los 2	Kaiserlautern–Bad Kreuznach–Bingen Hinterwiedenthal–Bundenthal Kaiserlautern–Münchweiler–Landmeil–Monsheim
Südwest–Grand Est	Neustadt–Landau–Wissembourg–Straßbourg Mannheim/Karlsruhe–Wörth–Lauterbourg–Straßbourg Straßbourg–Kehl–Offenburg, Mulhouse–Mühlheim Metz–Forbach–Saarbrücken Straßbourg–Saargemünd–Saarbrücken Metz–Thionville–Trier
Pfalznetz Los 1	Kaiserslautern–Lauterecken Kaiserslautern–Kusel Kaiserslautern–Pirmasens Saarbrücken–Pirmasens Landau–Pirmasens Neustadt–Landau–Karlsruhe Winden–Bad Bergzabern Neustadt–Wissembourg Wörth–Lauterbourg Dillingen–Niedaltdorf Münchweiler–Monsheim (SP Ausflugsverkehr) Hinterweidenthal–Ost-Bundenthal (SP Ausflugsverkehr)
VVO-Dieselnetz	Dresden–Kamenz, Dresden–Königsbrück Heidenau–Altenberg Pirna–Sebnitz
Freiberg-Holzhau	Freiberg (Sachs)–Holzhau
Chemnitzer-Modell-Netz	C 1: Oelsnitz (Ezgeb.)-Stollberg-Chemnitz-Limbach-Oberfrohna C 2: Chemnitz–Burgstädt C 3: Chemnitz - Mittweida C 4: Chemnitz - Hainichen
SPNV-Netz Erzgebirge	(R 80 bzw. CM 5) Chemnitz–Annaberg-Buchholz–Cranzahl (R 81 bzw. CM 6) Chemnitz–Olbernhau (R 95) Zwickau–Aue–Johanngeorgenstadt

→

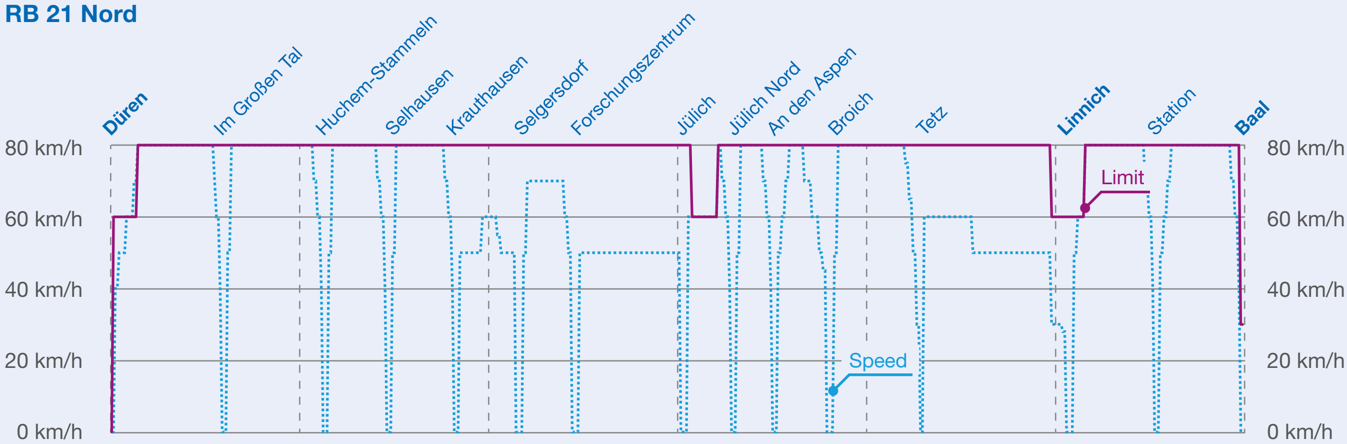
↑ Table 17: Assignment of regional rail transport networks and lines
Part 4 – Source → [15]

Network	Line section
DNWS	RB 110: Leipzig – Döbeln RB 113: Leipzig – Geithain
Elster-Geiseltal	RB 76: Weißenfels – Zeitz RB 78: Merseburg – Querfurt
Dieselnetz Sachsen-Anhalt	RE 4: Halle (Saale) – Halberstadt – Goslar RE 10: Magdeburg – Sangerhausen – Erfurt RE 11: Magdeburg – Halbertsadt – Thale RE 21: Magdeburg – Halberstadt – Goslar RE 31: Magdeburg – Halberstadt – Blankenburg RE 24: Halle (Saale) – Halberstadt RB 35: Wolfsburg – Stendal RB 36/RE 6: Wolfsburg – Magdeburg RB 41: Magdeburg – Aschersleben RB 43: Magdeburg – Oschersleben RB 44: Aschersleben – Halberstadt RB 47: Halle (Saale) – Bernburg RB 48: Magdeburg – Bernburg RB 50: Aschersleben – Dessau RB 77: Naumburg – Wangen RB 78: Merseburg – Querfurt
Netz West	Hamburg – Westerland (Sylt) Niebüll – Dagebüll
Netz Süd	Neumünster – Hamburg-Eidelstedt Ulzburg Süd – Norderstedt Mitte Elmshorn – Ulzburg Süd
XMU Ost	Lübeck Hbf – Kiel Hbf Lübeck Hbf – Lüneburg Kiel Hbf – Schönberger Strand
XMU Nord	Neumünster – Heide – Büsum Kiel Hbf – Husum Husum – Bad St. Peter-Ording Neumünster – Bad Oldesloe Kiel Hbf – Flensburg
XMU Nord/Ost	Lübeck Hbf – Kiel Hbf Lübeck Hbf – Lüneburg Kiel Hbf – Schönberger Strand Neumünster – Heide – Büsum Kiel Hbf – Husum Husum – Bad St. Peter-Ording Neumünster – Bad Oldesloe Kiel Hbf – Flensburg
NeiTec – Netz – Thüringen	Göttingen – Leinefelde – Erfurt – Jena – Gera – Glauchau Erfurt – Jena – Gera – Altenburg/Greiz Erfurt – Grimmenthal – Würzburg – Bad Kissingen
Ebx 13 Zeulenroda – Hof	Zeulenroda – Hof
Dieselnetz Ostthüringen	Leipzig – Gera – Saalfeld Gera – Greiz – Weischlitz Gera – Zeulenroda – Hof Saafeld – Hockeroda – Bad Lobenstein – Blankenstein Erfurt – Weimar – Jena – Gera Jena Saalbf – Orlamünde – Pößneck unt Bf (Apolda –) Weimar – Kranichfeld optional: Zeitz – Weißenfels
OBS	Rottenbach – Katzhütte Obstfelderschmiede – Lichtenhain – Cursdorf

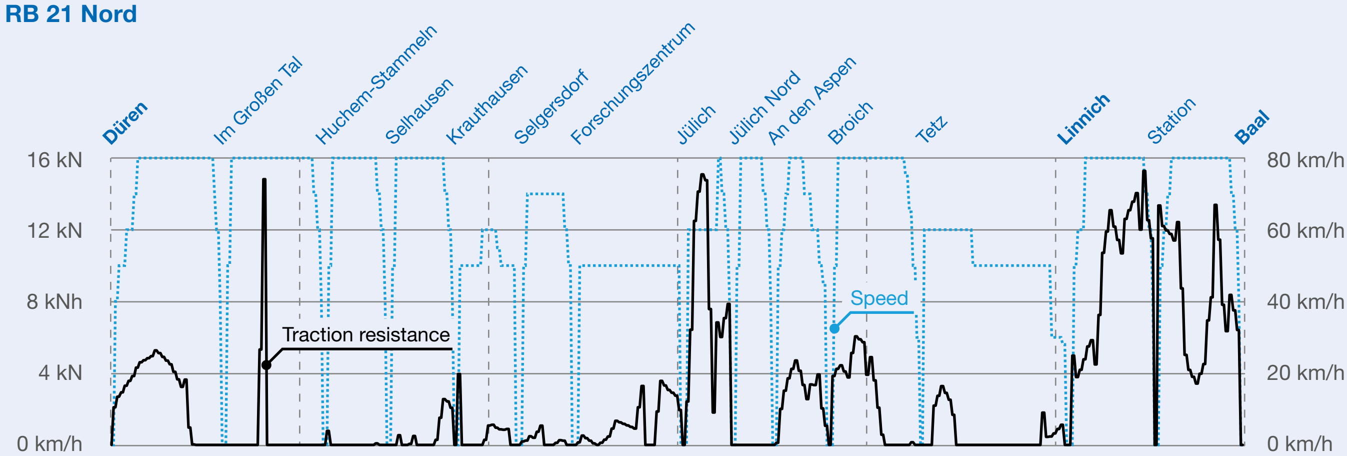
↑ Table 18: Assignment of regional rail transport networks and lines Part 5 – Source → [15]

Appendix 7.3 Graphs of all simulation results

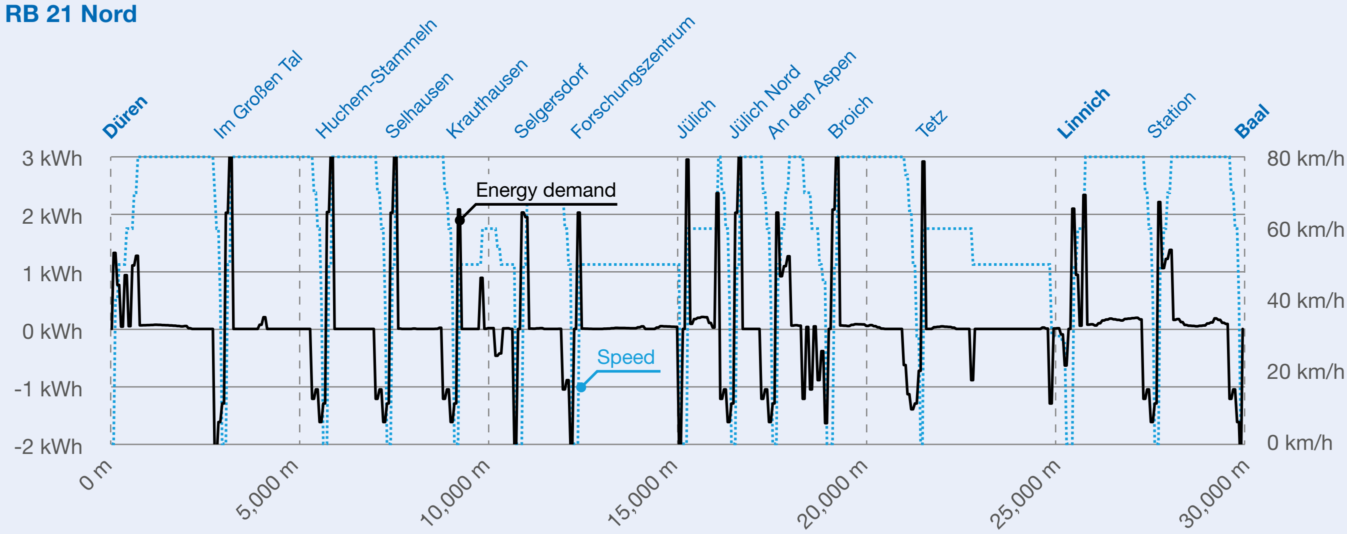
RB 21 Nord



RB 21 Nord

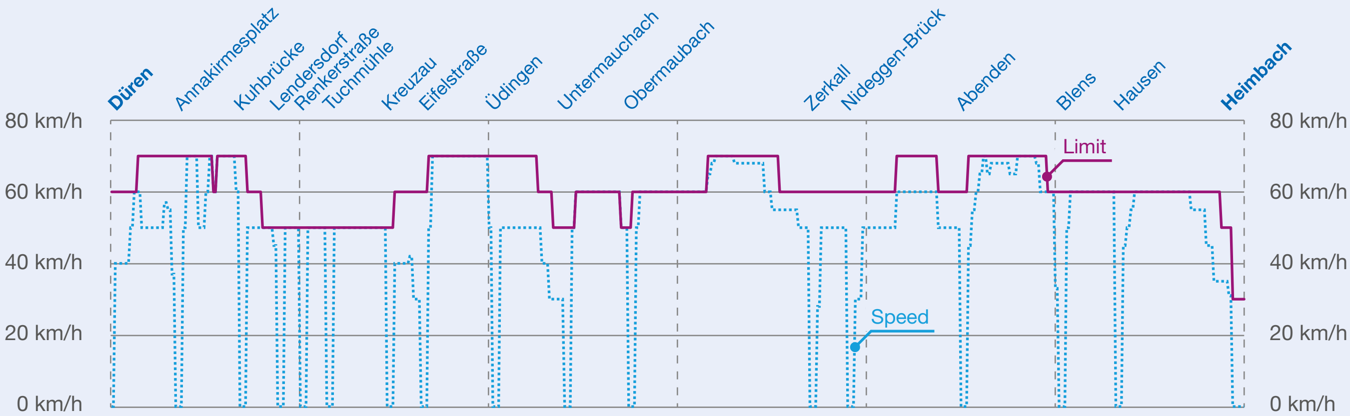


RB 21 Nord

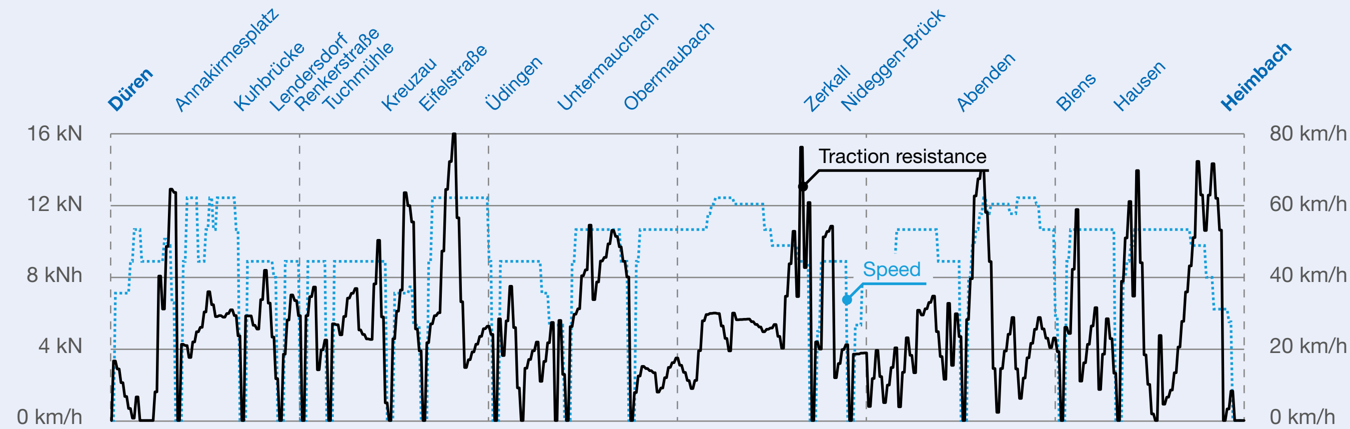


↑ Figure 52: RB 21 Nord –
Route, speed, traction resistance, energy demand (2026+)

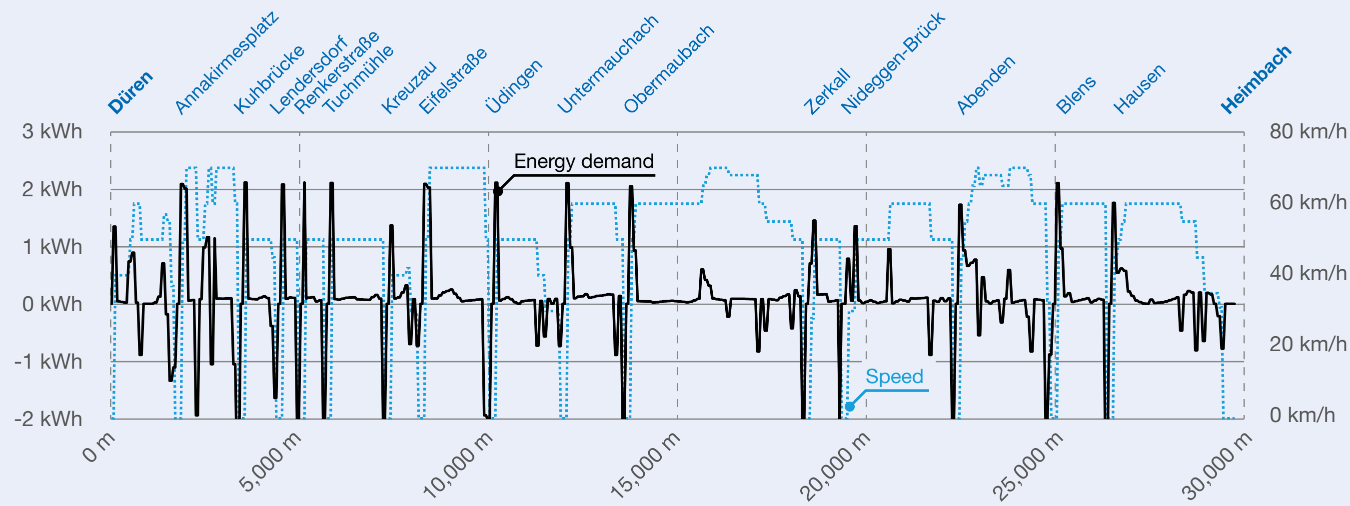
RB 21 Süd



RB 21 Süd

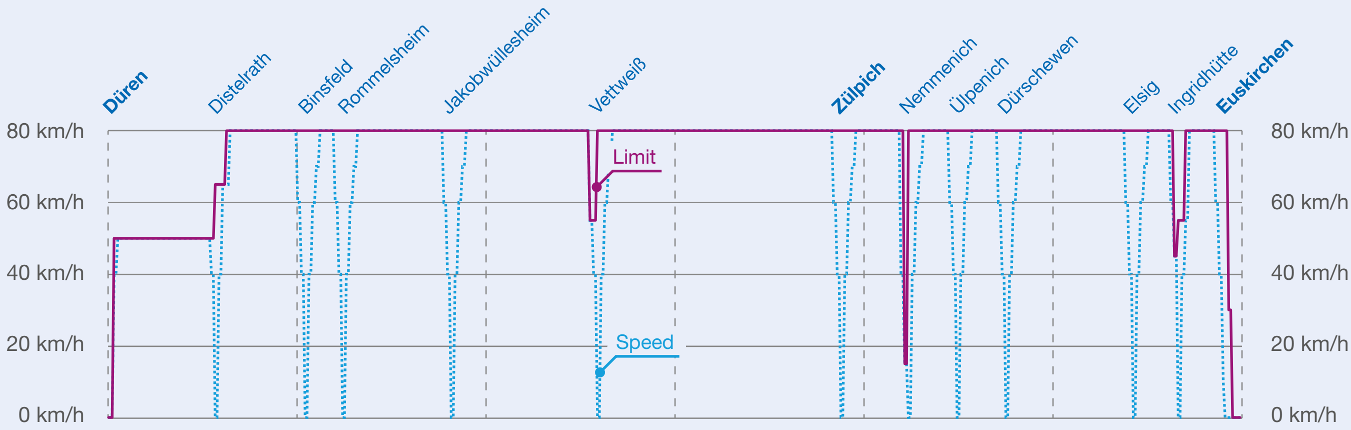


RB 21 Süd

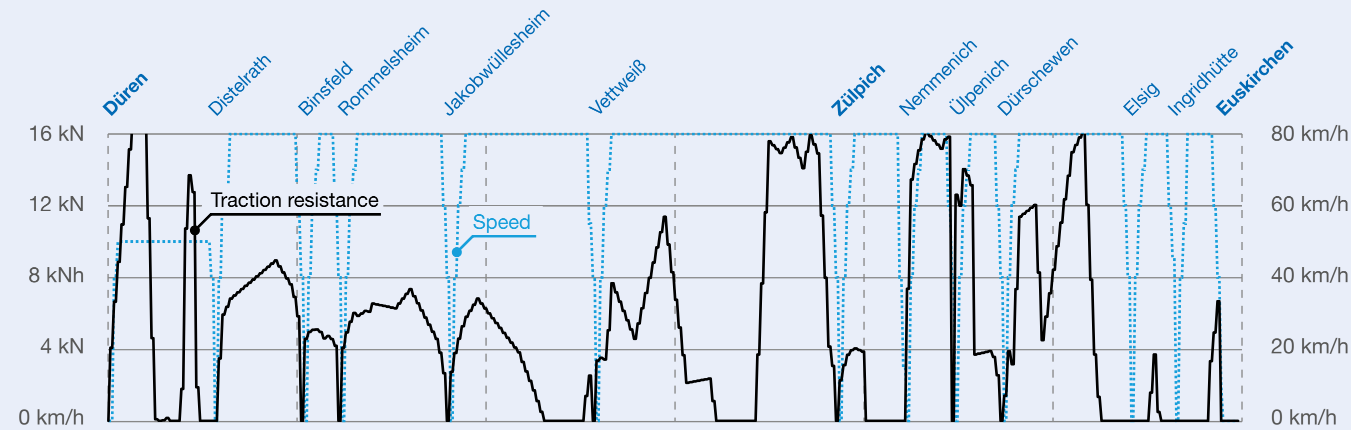


↑ Figure 53: RB 21 Süd –
Route, speed, traction resistance, energy demand (2026+)

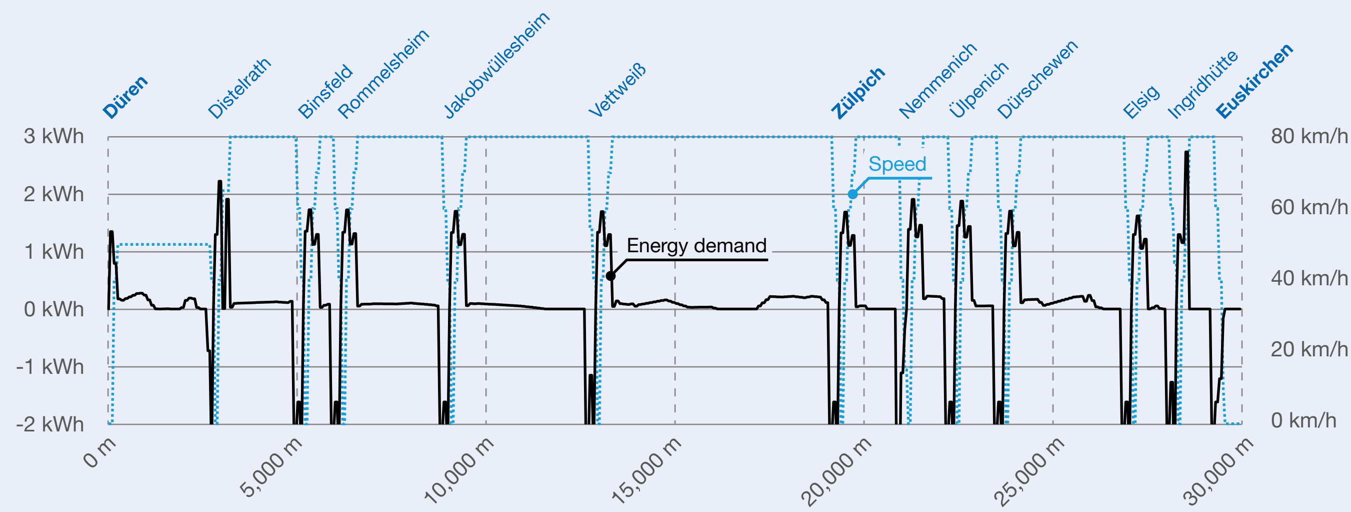
RB 28



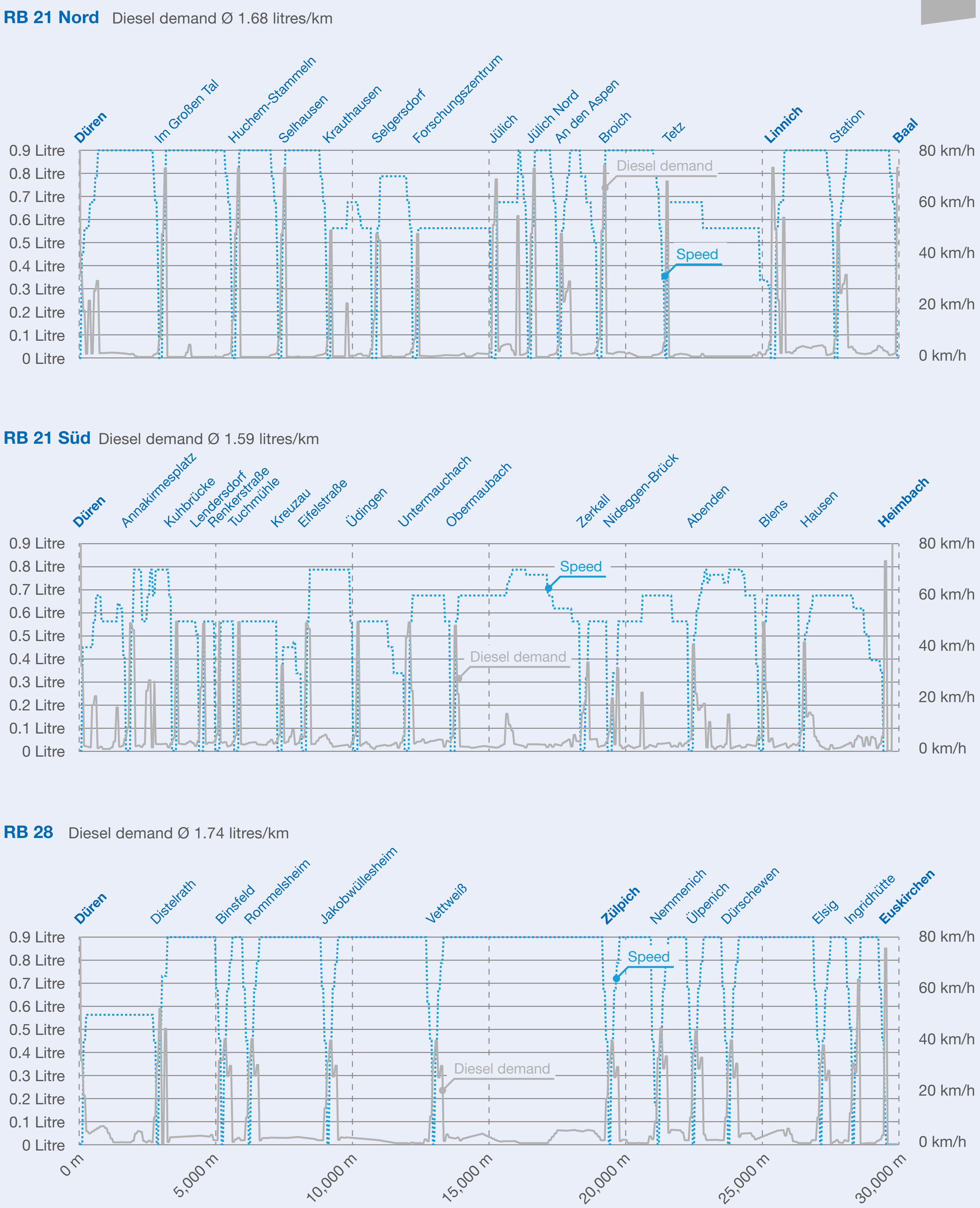
RB 28



RB 28

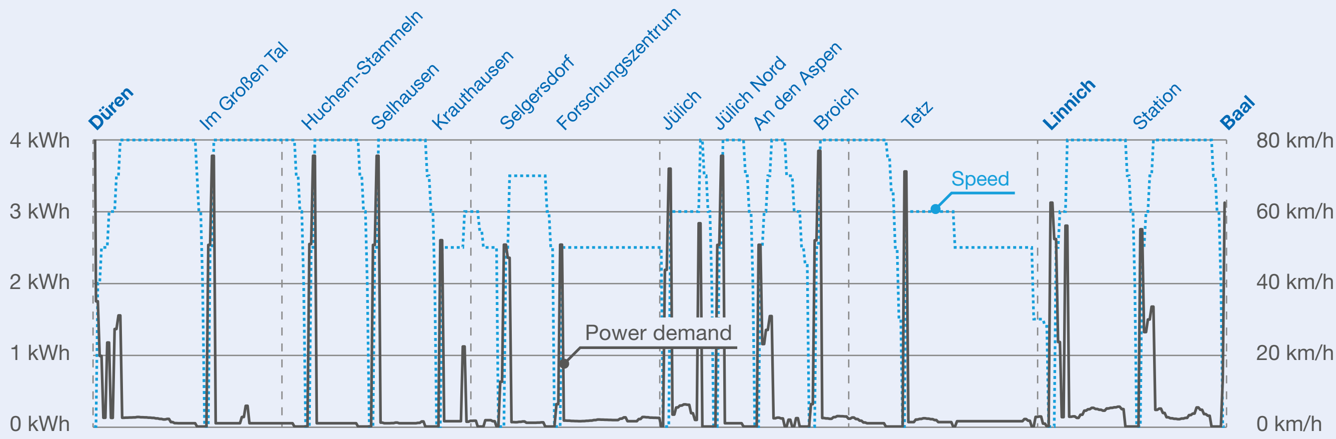


↑ Figure 54: RB 28 –
Route, speed, traction resistance, energy demand (2026+))

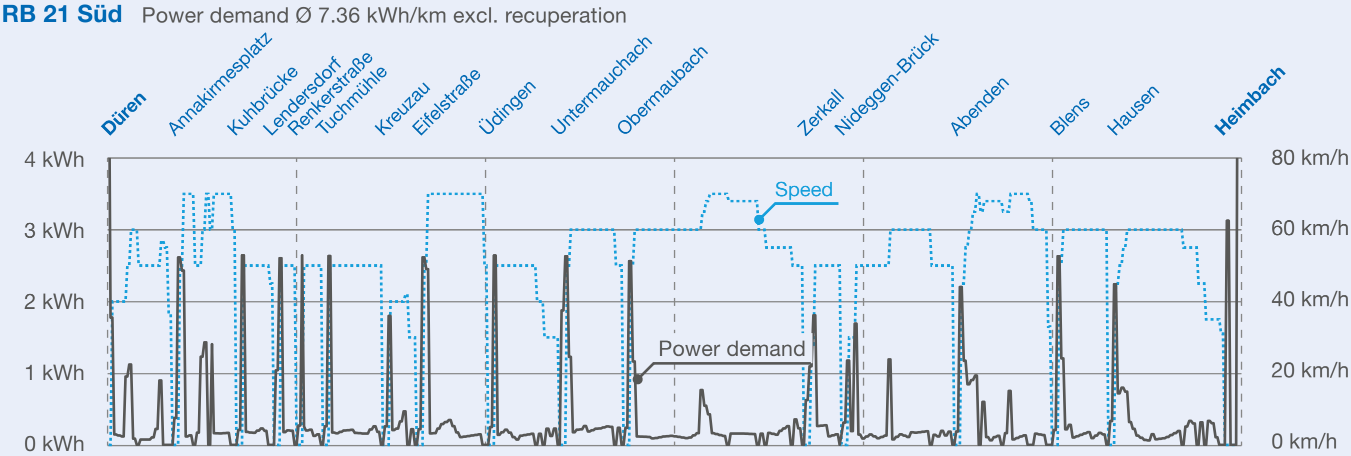


↑ Figure 55: DMU diesel requirement on the ›Düren network‹ railway lines (2026+)

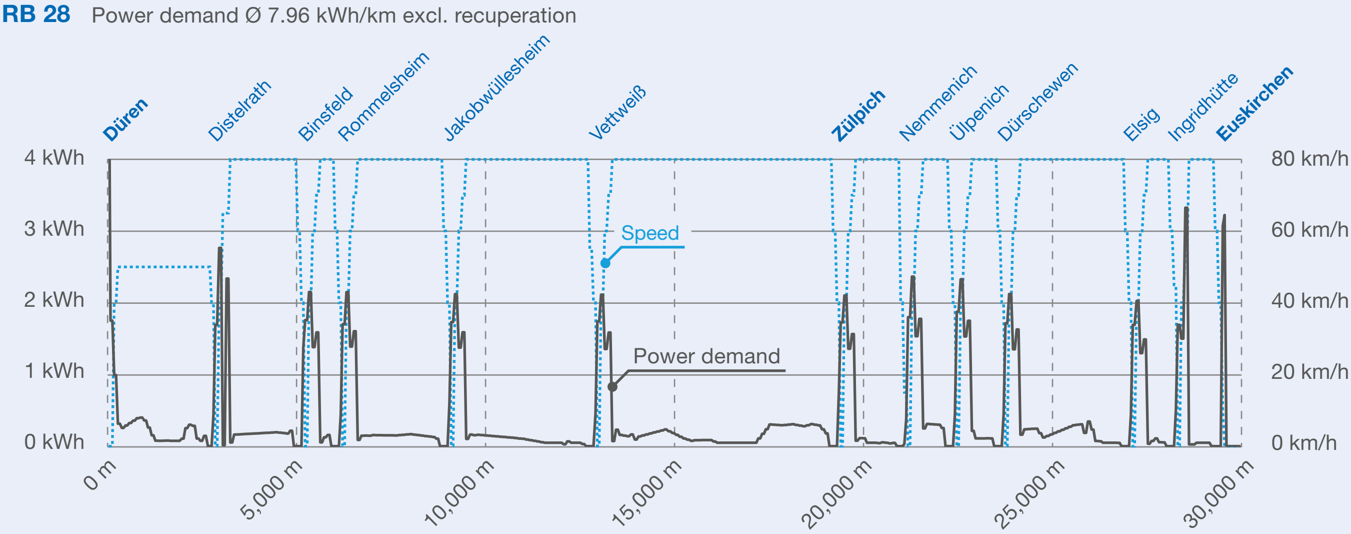
RB 21 Nord Power demand Ø 7.48 kWh/km excl. recuperation



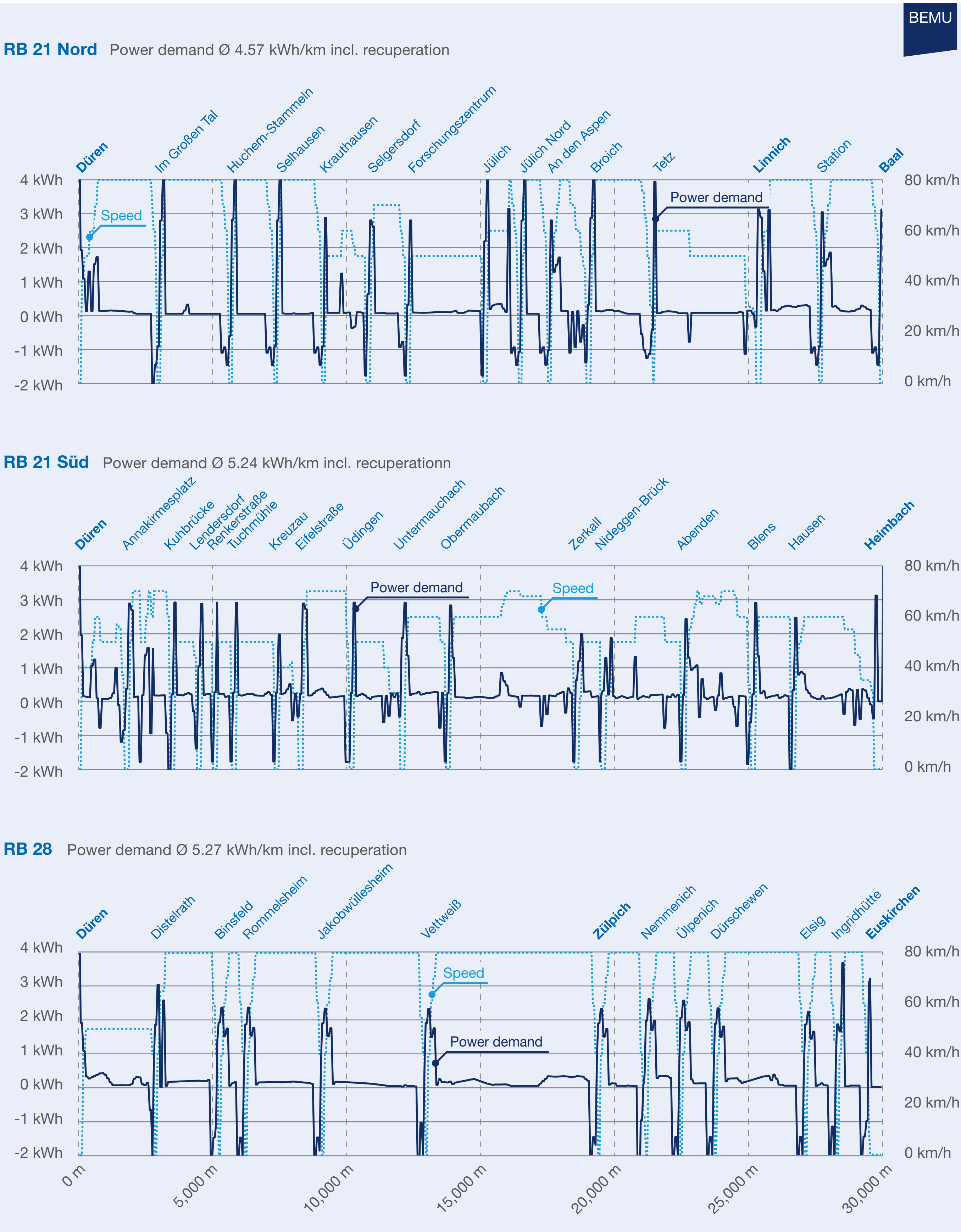
RB 21 Süd Power demand Ø 7.36 kWh/km excl. recuperation



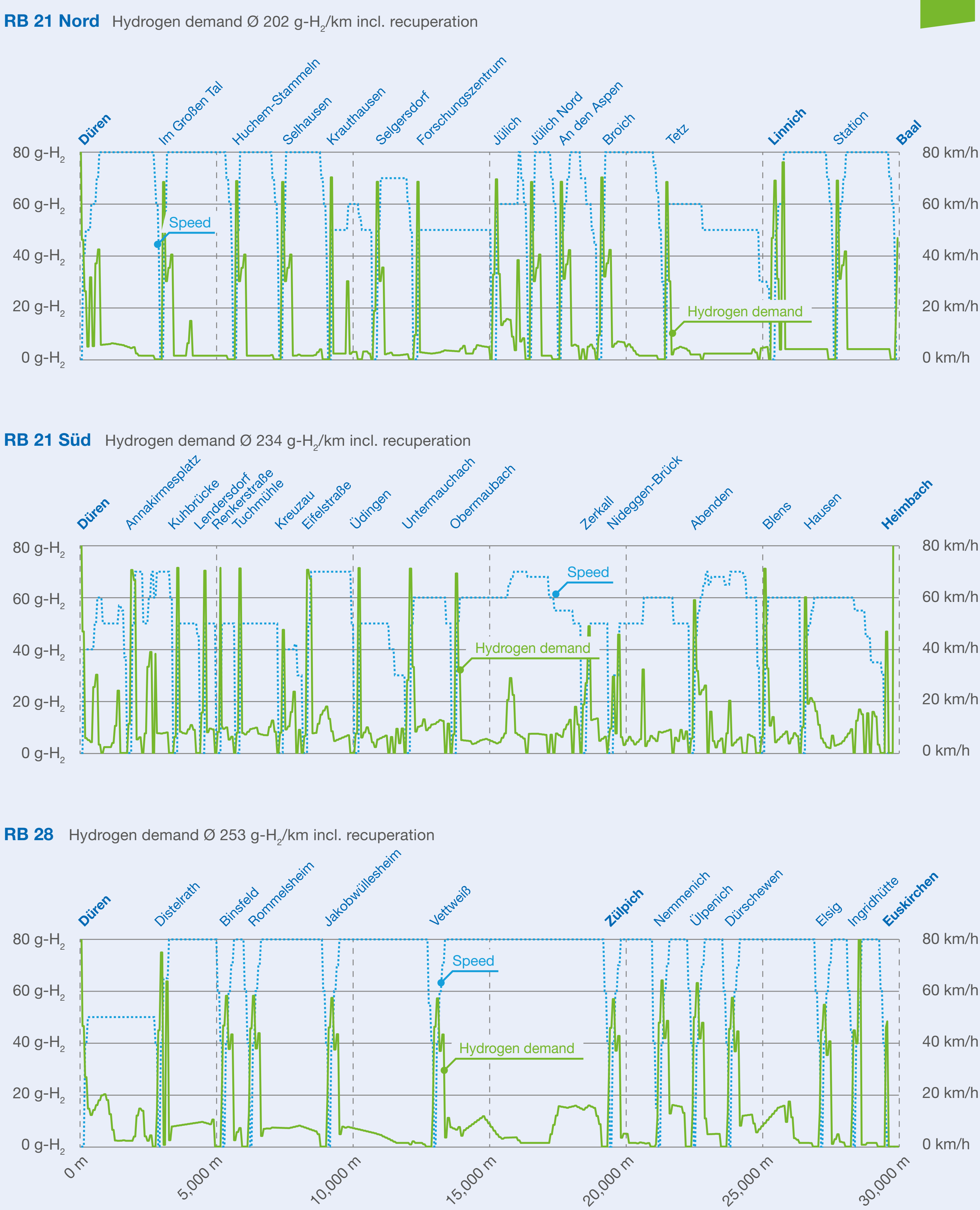
RB 28 Power demand Ø 7.96 kWh/km excl. recuperation



↑ Figure 56: EMU power requirement in the ›Düren network‹ without OL recuperation (2026+)



↑ Figure 57: BEMU power requirement in the ›Düren network‹ with recuperation (battery) (2026+)



↑ Figure 58: HEMU hydrogen requirement in the ›Düren network‹ incl. recuperation (2026+)

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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)
BR	Baureihe (series)
CO2	Carbon dioxide
DB	Deutsche Bahn (German Railways)
DMU	Diesel Multiple Unit
EIU	Eisenbahninfrastrukturunternehmen (railway infrastructure company)
EMU	Electric Multiple Unit
ETA	Elektrotriebwagen mit Akku (electric multiple unit with battery)
EVU	Eisenbahnverkehrsunternehmen (railway undertaking)
HEMU	Hydrogen Electric Multiple Unit
kWh	Kilowatt hour
OL	Overhead line (catenary)
pkm	Passenger kilometres (measure of passenger train transport capacity)
RB	Regionalbahn (regional railway/train)
RE	Regional Express
RTB	Rurtalbahn
SoC	State of Charge
SPNV	Schienenpersonennahverkehr (regional passenger rail transport)
VDE	Verband der Elektrotechnik Elektronik Informationstechnik e. V. (German Association for Electrical, Electronic & Information Technologies)
VT	Triebwagen mit Verbrennungsmotor (multiple unit with combustion engine)
X-EMU	Abbreviation for BEMU or HEMU
tkm	Train kilometres (measure of operational performance of trains)

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