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Project Report

Zero-Emission Rail in Czechia

Techno-economic analysis of lines R14, R21, R22, R25, R26, R27, SP14, U28

Author(s)

Federico Zenith
Andreas D. Landmark
Line Skeidsvoll

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Client(s)

ÚJV Řež

Technology for a better society

SINTEF Digital
Address:
Postboks 4760 Torgard
7465 Trondheim
NORWAY

Telephone: +47 40005100

`info@sintef.no`

Enterprise Number:
NO 919 303 808 MVA

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AUTHOR(S)
Federico Zenith
Andreas D. Landmark
Line Skeidsvoll

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ABSTRACT

This report analyses several representative regional, non-electrified rail lines in Czechia and evaluates different zero-emission technologies for their electrification: hydrogen, batteries, partial and full catenary. Single-train simulations are set up for every line to calculate energy requirements and state-of-charge profiles for batteries; the resulting data is fed into a detailed techno-economic analysis to rank the technologies. The results indicate that some lines are best served by hydrogen, other ones by batteries, which in some cases may be cheaper than diesel operation overall; catenary electrification (predictably, as these are all non-electrified lines) is always far more expensive.

PREPARED BY
Federico Zenith

SIGNATURE
Federico Zenith (25. apr.. 2024 18:15 GMT+2)

CHECKED BY
Raymond A. Stokke

SIGNATURE
Raymond Andreas Stokke
Raymond Andreas Stokke (26. apr.. 2024 08:37 GMT+2)

APPROVED BY
Aksel A. Transeth

SIGNATURE

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Contents

Chapter 1

Introduction

This report analyses eight Czech regional rail lines, all currently operated with diesel-fuelled multiple units, and evaluates the technical and economic feasibility of replacing these with zero-emission alternatives. The lines are indicated in figure 1.1.

Note that all of the selected lines have at least some sections already electrified with Overhead Line Equipment (OLE), at least one and sometimes both termini at electrified stations. The Czech rail network has currently several standards for electrification, mostly 3 kV DC and 25 kV, 50 Hz AC. Most of the electrified segments of the considered regional lines are of the DC type; however, Czech railway authorities are planning to convert the whole network to AC over the next years, which would make new DC trains rapidly obsolete [1].

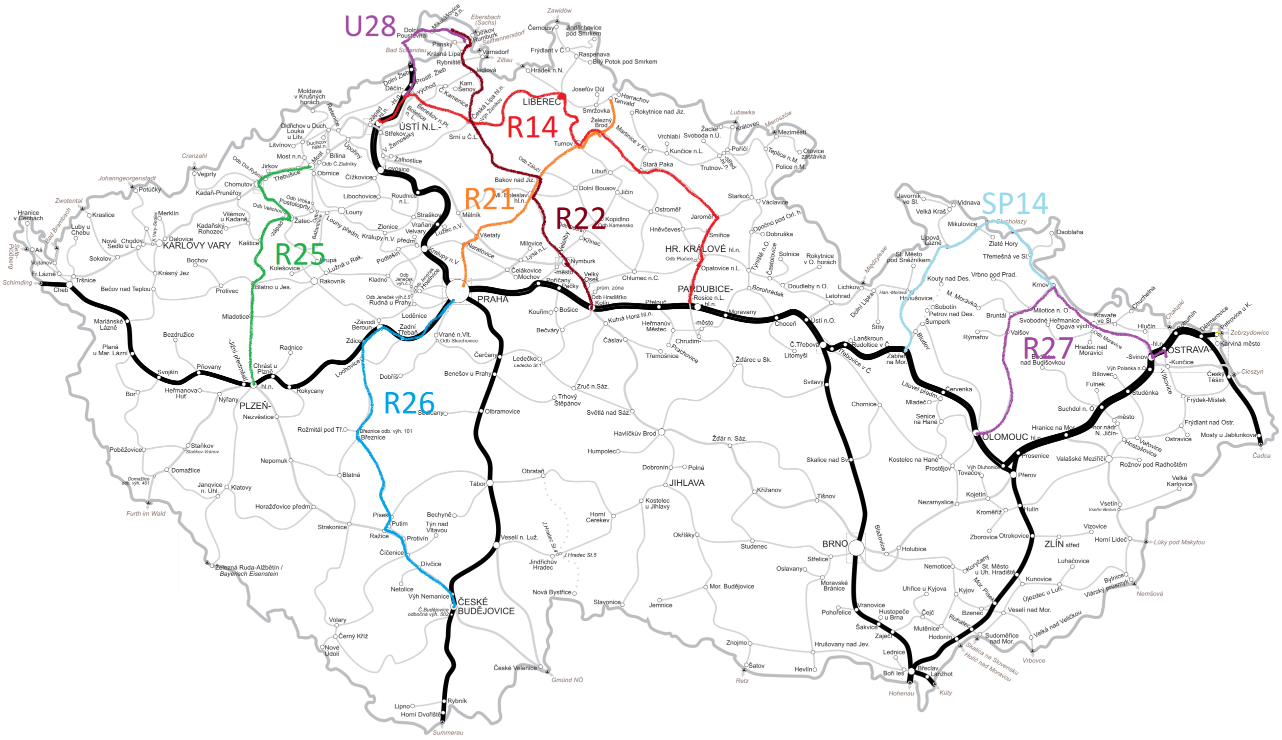

Figure 1.1: The rail lines considered in this report.

1.1 Alternatives for Zero-Emission Operation

All lines are currently operated with Diesel Multiple Units (**DMU**s), and diesel propulsion is therefore assumed as a baseline for economic evaluation. DMU costs are essentially related to fuel and maintenance, which is more expensive than for electric alternatives due to the presence of combustion engines.

EMU Electric Multiple Units make use of Overhead Line Equipment (OLE), also colloquially known as catenary, and are the established zero-emission technology. As it requires large investments per length of track, it is usually limited to high-traffic lines rather than the regional lines analysed in this report. While its investment costs are significant, operation is far cheaper than with diesel, both because of higher energy efficiency and lower maintenance costs.

HMU Hydrogen Multiple Units are essentially electric trains with fuel cells as sources of electricity instead of OLE. Storing energy in hydrogen allows to run the train for a whole day without refuelling, or to refuel rapidly if necessary. Hydrogen trains will be modelled with data from Alstom's iLint, with 400 kW of fuel cells, 260 kg of hydrogen tank capacity and 220 kWh of on-board battery for regenerative braking [2, 3][1]. Starting from water electrolysis, the hydrogen cycle is significantly less efficient than OLE, but has the advantage of not requiring expensive additional infrastructure.

An important source of information on the cost of hydrogen trains is a deal signed in 2019 between the German state of Hesse and Alstom for the operation of 27 iLint hydrogen trains for 25 years against a total sum of 500 million € [4]. According to publicly available data, this contract covers purchase, fuel, maintenance and reserves—essentially covering all relevant costs, and providing a useful benchmark of 740,740 € per train, per year[2].

This report will assume that hydrogen is produced by electrolysis from grid electricity; sourcing zero-emission power or additionality requirements are beyond the scope of this report. Note that hydrogen may also be obtained from other zero-emission sources, such as blue hydrogen or as by-product of some chemical plants.

HEMU There are currently plans to roll out hydrogen trains able to exploit the presence of OLE in sections of the track, called Hydrogen-Electric Multiple Units[3]: this allows to reduce daily hydrogen consumption and use the more efficient OLE energy supply when available. The first commercially available hydrogen train, Alstom's iLint, does however not have this possibility, whereas the Coradia Polyvalent, currently in development, should have it [5].

Both cases will be calculated for hydrogen trains, but it should be noted that HEMUs with the same size as iLints may or may not be produced; the additional pantograph equipment may not find space on the roof of the MUs, and the HEMU option may turn out to be possible only with longer trains.

BEMU Battery-Electric Multiple Units are also electric trains, but in which electricity is stored in Li-ion batteries, most often of the LTO subtype that allows high power rating and durability at the cost of higher price and lower energy density. Due to the high weight and cost of batteries per kWh of capacity, these trains will need to be recharged several times a day; this can occur either at a terminus or by exploiting the already available sections of OLE along the line. Battery trains will be modelled according to a modified parameters set of the 650 RegioPanter series, with some extra weight and the same battery capacity of the Siemens Mireo+B, 580 kWh [3][4].

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[1] Sources can quote slightly different numbers, especially for hydrogen capacity; this is likely due to different configurations of the initial prototypes.

[2] It is assumed the 500 million € will be paid in equal yearly instalments, so that discounting and actualisation are unnecessary.

[3] HMUs are also fully electric, but they cannot source energy from OLE.

[4] We are here considering the 2-wagon version of the Mireo+B, rather than the 3-wagon version with 700 kWh.

Where necessary, fast-charging stations at terminus will be included in the analysis. The state-of-charge (SoC) profile of the battery will also be calculated, under the assumption that it should remain between 80 % and 20 % in order not to wear the battery.

Partial Electrification It is possible to build only some sections of OLE in a non-electrified line to enable the operation of battery trains over a long line; these sections will serve the double purpose of powering the train and recharging the batteries.

The Czech ministry of transportation has produced a report in this sense with cost estimates for both OLE and feeding substations; they call this approach “simple electrification” (*prostá elektrizace*) [6]. In Germany, the approach is often called “electrification islands” (*Elektrifizierungsinsel*).

Chapter 2

Parameters and Assumptions

Where specific sources are not indicated, data shall be understood to have been received from project partners.

2.1 Train Specification

Currently, most of the analysed lines are predominantly served by CZ845 DMUs, except in the east (R27 and SP14) where CZ843 units are in service, and U28 where German Desiro 642D are in service. These diesel units are considered the reference case, and data are available for their Lomonosoff A, B, C parameters for their tractive effort curves.

For EMUs, the 650 RegioPanter will be modelled; the same train will be assumed also for BEMUs, with an additional 8 tons of weight to account for battery pack that will be assumed to be equal to that of the 2-wagon version of the Mireo+B (580 kWh). A regeneration efficiency of 70 % is assumed for both BEMU and EMU[1].

Data is less easy to come by for hydrogen trains and some estimations are necessary. An approximated tractive effort curve for the iLint is constructed considering starting tractive effort, maximum power and speed; as this is an electric train without a gear shift, the approximation should be good enough. It was not possible to obtain the A, B, C parameters from Alstom, but due to the similar weight and shape of the front, the 650 RegioPanter's parameters have been assumed. Regeneration efficiency is set to 65 %, slightly lower than for battery trains, owing to hydrogen trains' smaller batteries and correspondingly higher C-rates for the same regeneration currents.

All trains need auxiliary systems for heating in winter and AC in summer; all electric trains will be assumed to require 1 kWh/min, or 60 kW, to maintain internal temperature. DMUs are usually older trains without AC, with only heating in winter; they will be therefore assumed to use 30 kW as a year-round average. The auxiliary power requirement could be reduced in hydrogen trains assuming that heat is recovered from fuel cells, as it is available in sufficient quantity and temperature; however, the current iLint design does not recover heat from the fuel cells.

Tractive effort curves are plotted in figure 2.1, and numerical parameters are summarised in table 2.1.

2.1.1 Feasibility of Additional Load

As we will consider mostly rural rail lines in this report, the issue may surface of whether new MUs may be too heavy for the present lines [7].

BEMUs are derived from the 2-unit RegioPanter, which has 8 axles (`Bo’2’+2’Bo’`) and is 52.9 m long: its axle load is therefore 14.2 t, its length load 2.16 t/m. ILints have only 6 axles (`B’2’B’`) and are 41.89 m long, giving 17.8 t of axle load and 2.55 t/m of length load.

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[1] Regeneration efficiency through catenary depends on the presence of other trains on the line able to use the energy at the same moment; depending on traffic conditions, efficiency may be much lower. An exact evaluation of the efficiency of regeneration fed to catenary is beyond the scope of this report.

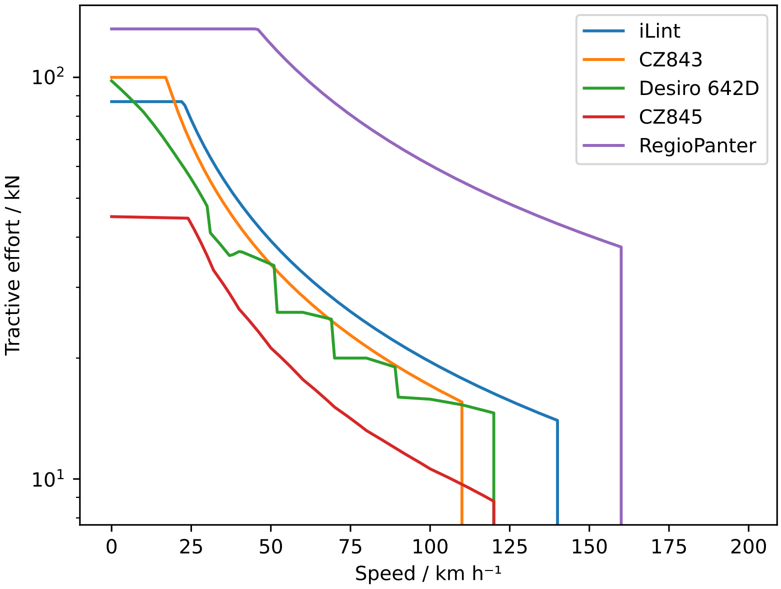

Figure 2.1: Tractive effort curves for the trains modelled in this study. Note how the iLint is roughly equivalent in power to the CZ843, whereas the CZ845 is severely underpowered. The RegioPanter (OLE and battery) is instead far more powerful. Note that the difference in maximum speed has limited influence, as the regional lines being investigated have moderate speed limits.

The lowest line class of loading on the Czech rail network is A1, with a maximum axle load or 16 t or 5 t/m: this means that BEMUs based on the RegioPanter can safely travel on all parts of the Czech rail network, whereas iLints in principle cannot. However, iLints can serve all line classes from the next one, B1, with 18 t per axle and 5 t/m. The amount of A1 lines in Czechia is negligibly small and typically consists of last-mile branches. Almost all sections studied in this report are at least of class C3 (20 t per axle and 7.2 t/m) or higher, with few exceptions:

C2 Liberec–Česka Lípá (R14B), Všetaty–Mladá Boleslav–Bakov nad Jizerou (R21, R22)

B2 Mikulášovice–Dolní Poustevna (U28)

Therefore, all MUs of table 2.1 can traffic the lines studied in this report.

Table 2.1: Modelling parameters of the different trains modelled in this study.

Train	Type	Mass t	A N	B N/km h^{-1}	C N/km^2 h^{-2}	η_{reg} %	P_{aux} kW
CZ845	DMU	79.9	800	6	0.57	0	30
CZ843	DMU	119	800	6	0.42	0	30
Desiro 642	DMU	68.8	1672	0	0.392	0	30
RegioPanter	EMU	106.2	900	6	0.35	70	60
RegioPanter	BEMU	114.2	900	6	0.35	70	60
iLint	HMU/HEMU	107	900	6	0.35	65	60

2.2 Economic Parameters

The following parameters are used in the analysis:

Diesel fuel priced at 1.28 €/L, assumed without VAT. Maintenance of DMUs is 1.6 €/km. Diesel is assumed to contain 9.7 kWh/L and its conversion in ICEs to electricity has an overall efficiency of 25 % [8].

Electricity 135 €/MWh, which includes cost for energy and supply. Maintenance of EMUs is 1.1 €/km; it is assumed that BEMUs, HMUs and HEMUs will have the same maintenance requirements, as there is very little maintenance that can be done on batteries, fuel cells or hydrogen tanks. All electrical locomotives (OLE, Battery, Hydrogen) have an assumed efficiency of 85 % for internal conversion, in addition to any transmission and conversion efficiencies.

OLE CAPEX of 1.07 M€/km, lifetime 30 years, maintenance 7 €/m/year. This price includes feeders, but lines R25 and R26 can do without extra feeders, as there are previous OLEs to piggyback on: for their case, CAPEX will be 770 k€/km. Note that OLE investments may be shared with other traffic using the same tracks, and can be tricky to allocate: for this reason, we will provide a *critical level of allocation* for each studied line against other technologies: if it will be possible to allocate this percentage of the OLE costs (or less) to the specific line, OLE will be competitive against the other technology. Finally, investments can increase sharply in the case of tunnels or bridges that need higher ceiling to allow OLE, which can be a significant cost when the line crosses a relatively populated and hilly area; these costs are not included in the analysis. Transmission efficiency is estimated at 95 %.

Batteries Assumed of LTO technology as common in rail applications, they have an estimated lifetime of 25 000 cycles[2], a cost of 1000 €/kWh for rail applications [9] and a round-trip efficiency of 85 %.

Charging stations According to the Czech Ministry of Transport's report on partial electrification [6], dedicated train charging stations cost from 50 to 250 MCZK. The wide range in size is not due to power rating, but is mostly related to whether the charger is established in an already electrified station, or one that may need feeders, rectifiers, new power lines and possibly a costly upgrade of the local power infrastructure: therefore, chargers in non-electrified stations like Liberec, Tanvald or Rumburk will be priced at 250 MCZK a piece. Instead, chargers in already electrified stations (e.g. a DC charger in Pilsen or an AC charger in Prague) require less equipment and are therefore priced lower, at 50 MCZK a piece. Note that chargers will not be necessary for DC trains in DC-electrified stations (and conversely for AC). Lifetime will be set to 30 years, same as for OLE.

Hydrogen Fuel cells have an investment costs of 262 $/kW, which is a projection to medium-scale production [10]; efficiency is 18 kWh/kg and lifetime is given as 15 000 hours of operation [11]. Electrolysers cost 700 €/kW with an efficiency of 52 kWh/kg and a lifetime of 80 000 hours of operation, given 8000 hours of operation per year; their maintenance is estimated at 7 % their CAPEX a year [11, 12]. Hydrogen tanks are estimated to cost 375 €/kg of stored hydrogen capacity and have a lifetime of 20 years. Compressors are assumed to cost 650 €/kW of equivalent hydrogen flow and yearly maintenance requirements equal to 4% of CAPEX, with a lifetime of 15 years; consumption is 2 kWh/kg of compressed hydrogen [12].

HEMUs will be assumed to have two pantographs, each valued at 300 k€ and with a lifetime of 30 years.

In addition, all trains must pay a yearly fee to access the rail network proportional to their weight, approximately 1 €/kg.

Each line will be analysed singularly, even if in reality electrification by OLE may be shared between some lines: in particular, R21 has small overlaps with R22 (Mladá Boleslav–Bakov nad Jizerou) and with R14 (Turnov–Železný Brod).

For all calculations, an interest rate of 4 % will be assumed throughout.

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[2] This is an estimate from manufacturers, but reliable numbers are difficult to come by, especially since LTO are a less common type and testing such long-lived batteries are expensive and time-consuming to test until end of life.

2.2.1 Lumped-Cost Analysis vs. Differential Approach

In the previous section, the capital cost of trains was not included, since they are not well known due to confidentiality; instead, the cost of batteries, fuel cells and other additional components was added, with the implicit assumption that the base cost for a bare-bones MU would be the same. This we call the *differential* approach.

Alternatively, we will also perform the same techno-economic analysis by ignoring the cost of new technologies onboard the MUs, and instead using estimates gathered on the market by project partners, with lifetimes assumed to be 30 years; these estimates are gathered in table 2.2. This will be called the *lumped* approach.

The differential approach is considered reliable in terms of what is practically feasible, whereas the lumped approach represents better the current marked picture. The result may differ as new technologies currently command a premium that may in a few years be eroded by market competition. As the cost of DMUs in Czechia is usually referred to *used* DMUs bought from e.g. Germany, their cost will be significantly lower than for new units (as would be the case for any H/B/EMUs), boosting the economic performance of diesel in the lumped analyses.

Table 2.2: Estimated CAPEX, in million euros, for 2-wagon MUs using various technologies. These values will be used in the lumped-cost version of the techno-economic analysis only. Note that DMUs, the current technology, refers to the cost of buying used MUs from e.g. Germany, which is significantly cheaper than buying new rolling stock.

Type	Estimated cost / M€
DMU	3.0
EMU	4.2
BEMU	5.5
HMU	6.5
HEMU	7.0

Note that the lumped approach, including the cost of trains, is amenable to comparison with the deal struck between Alstom and the German state of Hesse, which is about 741 k€ per MU per year [4].

2.3 Economic Indicators

When evaluating the economic performance of a specific propulsion technology, after having established the requirements for it to be feasibly deployed, it is necessary to compare both investments *and* operating costs.

Moving from diesel to electric operation usually involves a radical pivoting from low investments and expensive operation to high investments and cheaper operation. When moving to OLE, the main investment is typically in the construction of OLE itself, whereas in the case of battery or hydrogen trains there will be other investment required for batteries, charging stations, fuel cells, hydrogen tanks, electrolysers and so on.

Equivalent Annual Cost The EAC of a technology translates investments and their lifetime into a virtual yearly cost that would result in the same net present value (NPV). For an investment I at year 0 (therefore by definition $I \triangleq NPV$), with lifetime n years and assuming an interest rate r, its EAC is given by:

$$I \triangleq NPV = \sum_{i=1}^{n} \frac{EAC}{(1+r)^i} \tag{2.1}$$

The annuity factor $A_{n|r} = \sum_{i=1}^{n}(1+r)^{-i}$ can be calculated direcly by rearranging and applying the closed form of geometric series:

$$A_{n|r} = \frac{1-(1+r)^{-n}}{r} \tag{2.2}$$

Notable values are $A_{25|4\,\%} \approx 15.6$ years and $A_{30|4\,\%} \approx 17.3$ years. Dividing the investment by $A_{n|r}$ will produce the associated equivalent annual cost, which can then be summed with yearly operating costs.

$$\sum_j \frac{I_j}{A_{n_j|r}} + \sum_k OPEX_k \tag{2.3}$$

Note that the equivalent annual cost produces the same ranking as NPV, but is able to combine investments with different lifetimes without introducing reinvestments and residual values.

Benefit-Cost Ratio The BCR compares two different technologies by taking the ratio of their EACs. As the current technology on all lines is diesel, the *benefit* will be represented by EAC_{Diesel}, which will no longer be paid, divided by the cost of the alternative, i.e.:

$$BCR_i = \frac{EAC_{\text{Diesel}}}{EAC_i} \tag{2.4}$$

An advantageous technology i will have $BCR_i > 1$. BCR is a direct function of EAC, and as such does not provide new information, but is convenient to rank alternatives.

Payback Period The PBP is the time necessary for the discounted cash flows to compensate the initial investment: as such, it is a measure that reintroduces the time dimension that was removed by the approach of using the equivalent annual cost, and is a complementary indicator to BCR.

The PBP says nothing of how the cash flow develops after the investments are recovered. In case of frequent reinvestments, zero may be crossed more than once: in that case, we will report the smaller value. Any option with BCR < 1 will by definition not pay for itself, and will therefore not have a defined PBP[3].

Upfront Investment Whereas this value is not the most sound economically and completely ignores operating costs, it is often the most cited in public discourse, and represents one of the main hurdles for investment decisions. A large investment will usually require longer decision chains, stricter evaluation, and presents a more significant risk in case of calculation errors; alternatives requiring smaller investments are more “forgiving” and can be tried out with less commitment.

Kilometre Cost A parameter commonly used to compare alternative investments in the rail sector, it is calculated by dividing the EAC by the total distance covered by all involved trains in a year.

Critical Allocation of OLE OLE is track-bound infrastructure that can be used by any train on the same track. In this report, we analyse one line at a time, and allocating all infrastructure costs to the single line may not be fair if several other lines are using the same track: e.g. there is significant traffic between Jaroměř and Liberec overlapping with line R14A. Sensibly allocating OLE infrastructure costs would however be a task far beyond the scope of this report, as it will involve analysing almost all non-electrified lines in Czechia.

Instead, we can calculate a *critical allocation* (CA), which is defined to be the percentage of OLE infrastructure costs (both CAPEX for catenary, feeders and their maintenance) that, if allocated to a line, makes OLE costs equal to another technology.

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[3] There can be corner cases where the investment pays for itself temporarily but then requires a significant reinvestment, but none occurred in this report.

$$CA_i = \frac{EAC_i - (EAC_{\textbf{EMU}} - EAC_{\textbf{OLE}})}{EAC_{\textbf{OLE}}} \tag{2.5}$$

where i is the technology EMUs are evaluated against (DMU, HMU, BEMU, etc.), EAC_{EMU} is the total equivalent annual cost of the EMU alternative (which includes OLE infrastructure), and EAC_{OLE} is the equivalent annual cost of OLE-related items in the EMU alternative (feeder and OLE investments and maintenance). *Mutatis mutandis*, this will also be applied to partial electrification.

The values of critical allocation will be typically, but not always, be between 0 % and 100 %, with the following meaning:

$CA_i < 0\,\%$ This means that $EAC_i < (EAC_{\textbf{EMU}} - EAC_{\textbf{OLE}})$, i.e. that even if all costs for OLE were free, the alternative i would *still be cheaper* than EMUs. This is fairly rare as EMUs have very low OPEX, but occurs once for line U28, figure 3.43, since energy expenses on U28 are very low compared to the annualised cost of trains (DMUs being cheaper than EMUs).

$0\,\% < CA_i < 100\,\%$ This is the most common case. If e.g. $CA_i = 60\,\%$, it means that EMU would be competitive against alternative i if other lines could shoulder the remaining 40 %.

$CA_i > 100\,\%$ This is the case in which $EAC_i > EAC_{\textbf{EMU}}$, i.e. EMUs are cheaper than alternative i even when shouldering all OLE costs. Note that this does not happen often *in this report* because we deliberately selected lines that have not been electrified yet exactly because it was not economically favourable. This does occur in a few cases, always for Partial Electrification against BEMUs, in those cases when one partial electrification section is cheaper than multiple chargers, specifically R21 and R22 (figures 3.12 and 3.17).

Chapter 3

Analysis of Rail Lines

3.1 General Observations on Analyses

For the results presented in the upcoming sections it is useful to keep in mind the following clarifying notes.

Availability of OLE Infrastructure In all plots, the availability of OLE will be indicated with a coloured background, yellow for DC and red for AC, mirroring the current situation as of 2023; there is a long-term plan to convert all DC electrification in Czechia to AC.

Speed profiles For each line, multiple speed profiles are calculated for each propulsion technology. The speed profile is determined respecting speed limits and the necessary acceleration and deceleration to respect them, in addition to the line schedule as of 2023. Train schedules are enforced by reducing the train's maximum speed since the previous stop; this has the objective to minimise energy usage, as rolling and air resistance increase with speed. Reducing the maximum speed is a slightly suboptimal solution compared to stragegies based on Pontryagin's maximum principle [13], but is far easier to calculate and "close enough" to be practical.

Usually, speed profiles are quite closely grouped, but lower-powered alternatives (often diesel) may be initially left behind, and compensate with higher speeds later (see e.g. figure 3.2 between Děčin and Benešov). Speed profiles are usually well below the speed limit, but may follow it closely if the train schedule is demanding or unattainable (see e.g. figure 3.2 between Mimoň and Jablonné, and between Turnov and Semily).

Note that current train schedules have been tailored to present diesel MUs, and better-performing electrical units may enable improvements to the schedule that are currently infeasible. An evaluation of possible changes to train schedules is beyond the scope of this work.

Finally, please note that the acceleration performance of the different trains represents the capabilities of these specific trains, and not inherent limitations of the proposed technologies.

Motor Energy and State-of-Charge Plots For each line we show motor energy plots for each technology. The diffences between technologies for the same line are due to the ability of electric trains to regenerate braking energy, and the different weight and dynamic properties of the trains. These plots focus only on the propulsion requirements, and ignore e.g. auxiliary systems.

State-of-Charge (SoC) plots, on the other hand, look specifically to the energy stored in batteries, to judge how the stardard battery sizes of two popular battery and hydrogen alternatives (Mireo+B and Coradia iLint) fare in actual use. The battery levels are netted for a 20 %–80 % SoC window and refer to energy as stored in the batteries, i.e. netted for conversion efficiencies between battery and motor; finally, they also include auxiliary consumption.

This means that motor-energy and SoC plots differ in shape and values, and represent different data.

Start Point for State-of-Charge Plots SoC plots always start at 100 % of usable capacity (i.e. 80 % of total capacity) for BEMUs and at 0 % (i.e. 20 % of total capacity) for H(E)MUs. The SoC in H(E)MUs will never drop below 0 % since fuel cells are assumed to deliver the necessary energy in that case.

The rationale for starting from 0 % for hydrogen trains is to showcase a number of properties, e.g. whether a HEMU is able to fully charge the batteries in an initial section (something possible from Ústí nad Labem, see figure 3.6, but not from Zábřeh, see figure 3.36). In the case of HMUs, the SoC will rarely move from 0 %, with small increases when stopping at a station, and larger ones when a sustained downhill section is encountered (see e.g. figure 3.26 from Přibram towards Prague).

In practice, HMUs and HEMUs could start with full batteries (and often will), but the case of starting from 0 % is more conservative. Partly or fully charged batteries may even be made mandatory as redundancy requirements, especially in the first period of operation of fuel cells when authorities may not be fully confident.

State-of-Charge Plots and Techno-Economic Analyses The information in SoC plots is *not* tranferred directly into techno-economic analyses, since a real BEMU may need larger batteries than a Mireo+B in order to be able to traverse a given line, or may be able to work with significantly smaller ones. Battery sizes are recalculated based on each line’s demand, and this invalidates the original SoC plot, which is based on standard sizes.

When calculating energy consumption, it will be assumed that HEMUs do not use battery to store energy, even though this could be a relevant strategy; the reason is that this would add another degree of freedom for the definition of this strategy, making the analysis much more complicated. In techno-economic analyses, HEMUs will be assumed to operate with OLE energy when available and on hydrogen otherwise; this is a conservative assumption.

Maintenance of Battery and Hydrogen Trains In principle, BEMUs and H(E)MUs are EMUs with an on-board electricity source. As there is limited maintenance to be done on fuel cells or batteries, other than routine inspections and the occasional change of air filters and coolant, the main extra cost will be their replacement at end of life. This is included in the techno-economic analyses as an ad-hoc term rather than included in maintenance, which is therefore the same for EMUs, BEMUs, and H(E)MUs.

3.2 R14, Pardubice–Liberec–Ústí nad Labem

Line R14 from Pardubice to Ústí nad Labem is a mainly passenger-oriented, partially electrified rail line in northern Czechia. The line is often split between the main section from Liberec to Pardubice (R14A) and the secondary section from Liberec to Ústí nad Labem (R14B) [14, 15].

Trains run currently on diesel for the entirety of the line, and typically have continuous operation through the day starting in the early morning (4:00) until midnight, with about two hours between two trains in the same direction. Six trains run the entirety of the line back and forth, with four starting from Liberec (two per direction), one from Ústí nad Labem and one from Pardubice; four more units are added to double capacity for trains between Liberec and Pardubice, so that trains on R14A are always assumed to have two MUs, and trains on R14B a single one[1]. A total of 10 MUs in operation is assumed.

Each of the trains performs 1.5 circuits on regular days (Monday-Saturday), for a total of 9 daily circuits. For an entire year, we assume 3250 full R14 circuits (double MUs on R14A and single MUs on R14B).

R14 starts with an OLE-electrified section from Ústí nad Labem until Děčin, which is followed by a non-electrified section through Liberec until Jaroměř, from which the line is again electrified until Pardubice.

The train schedule foresees stops between half an hour and one hour at Ústí nad Labem and at Liberec. It will be assumed that in normal operation trains have stops in Pardubice of a similar length to those in Ústí and Liberec (at the time of writing, schedules are delayed because of a temporary closure of the line).

3.2.1 Simulation Results

The speed profiles are provided in the following, in figure 3.1 for westbound and figure 3.2 for eastbound. In figure 3.1 it is visible how trains run at full speed between Hradec Králové and Semily; due to lower power, the diesel train accumulates some delay that it recovers between Semily and Železný Brod by keeping a higher speed than other technologies. It would appear that the adoption of electrified solution can improve punctuality of trains from Hradec Králové to Semily.

In R14B, trains run at maximum speed to Jablonné, but in general the timetable seems easier to achieve for the trains. In figure 3.2, the eastbound speed profiles are quite close, with the usual patter of diesel being a bit slower in acceleration and settling to a higher cruise speed to compensate.

Motor energy profiles are presented in figures 3.3 and 3.4 for respectively west- and eastbound journeys. In both figures, it is visible how the sections from Liberec show a marked divergence between diesel and electrified alternatives, highlighting the effect of regenerative braking as these sections are mostly downhill. The length and total energy consumptions (including auxiliaries) of line segments are presented in table 3.1.

Finally, the state-of-charge profiles for battery and hydrogen trains are presented in figures 3.5 and 3.6. It is visible in figure 3.5 how battery trains seem unable to reach Liberec from Pardubice, with about 100 kWh of energy missing; however, as we limited energy usage to between 80 % and 20 %, a train would actually be able to reach Liberec by using an extra 9 % of the available battery capacity; it remains to be evaluated whether the reduction in battery lifetime due to regular usage beyond the allowed envelope would cause a significant reduction of lifetime and thereby increased costs. The eastbound journey, instead, is able to reach Liberec, albeit with small margin.

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[1] Train composition is actually more variable and in some special occasions triple-MU are assembled, but the assumed distribution is considered enough to yield representative results decision can be based upon.

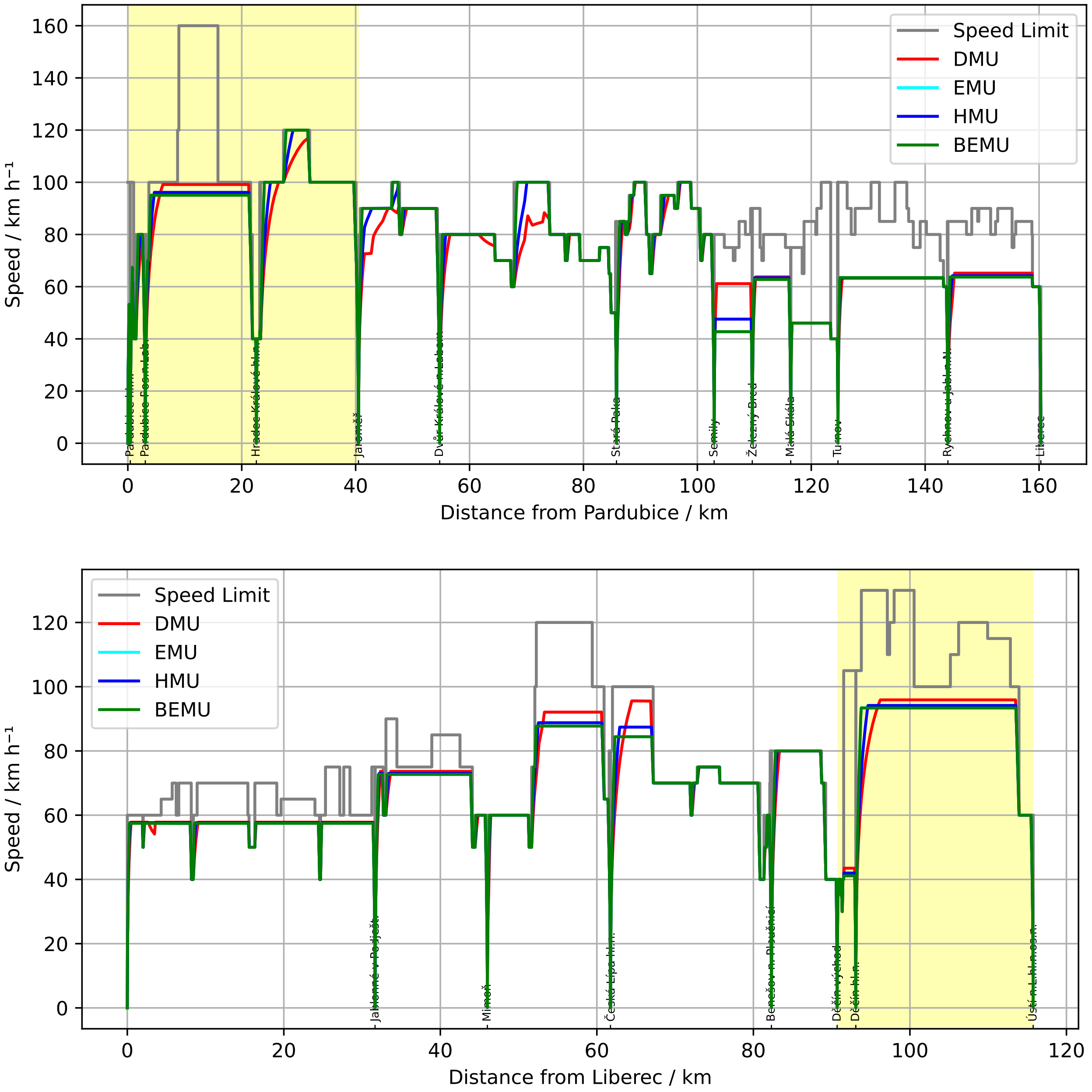


Figure 3.1: Speed profiles in the westbound journey (R14A above, R14B below).

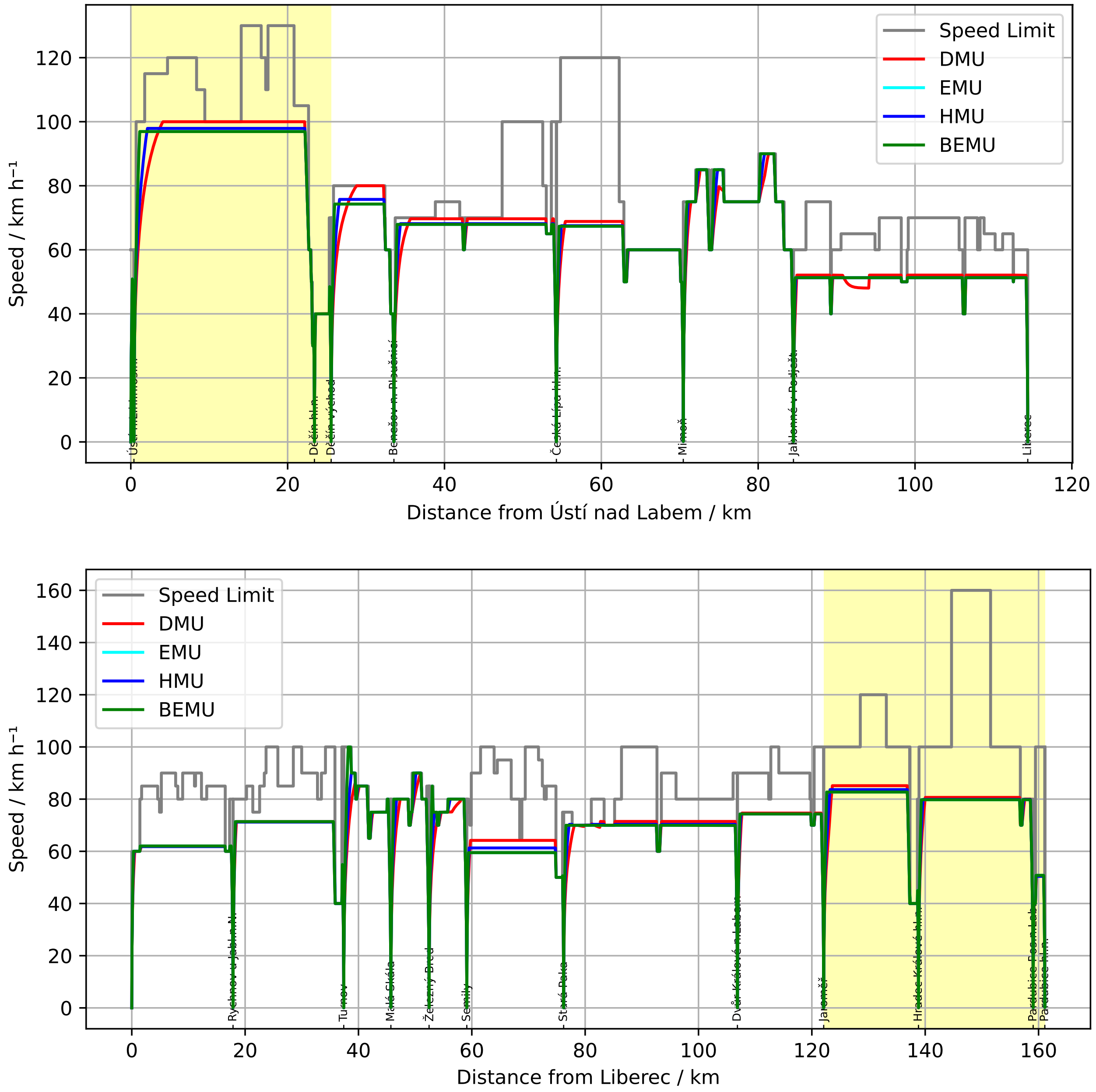


Figure 3.2: Speed profiles in the eastbound journey (R14B above, R14A below).

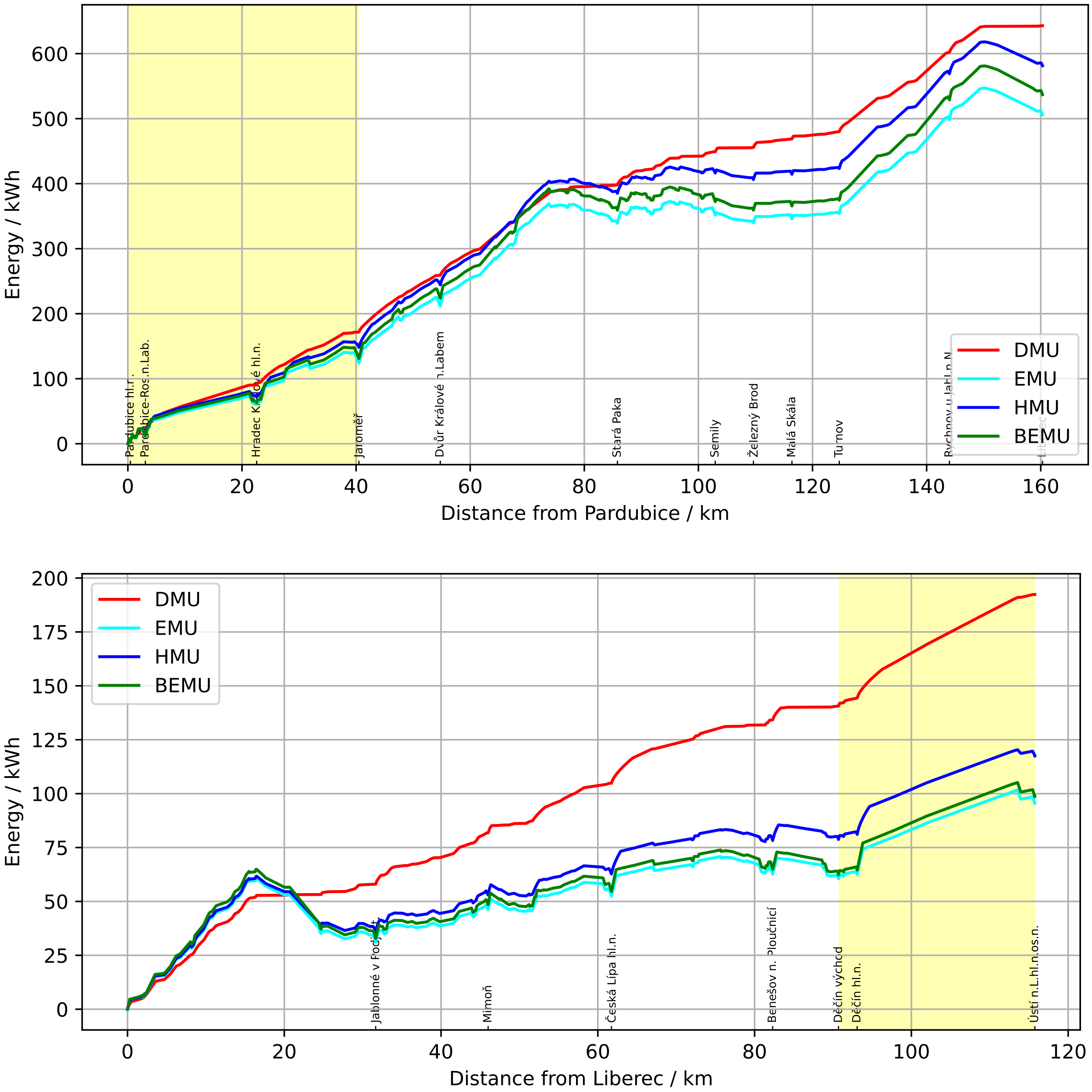


Figure 3.3: Motor energy profiles in the westbound journey. Note that from Pardubice to Liberec there are two MUs instead of a single one. Note that these profiles do not include auxiliary power.

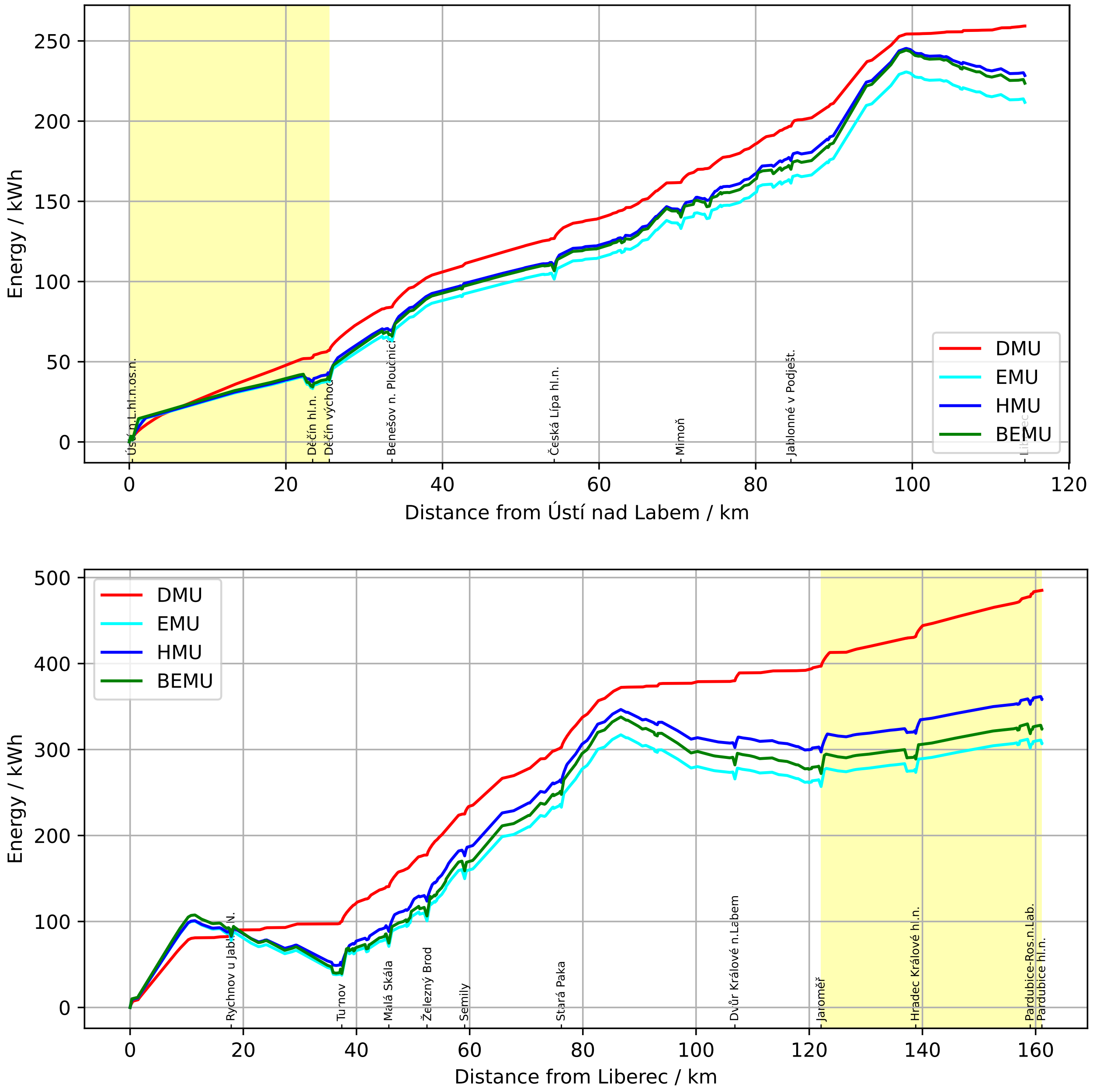


Figure 3.4: Motor energy profiles in the eastbound journey. Note that from Liberec to Pardubice there are two MUs instead of a single one. Note that these profiles do not include auxiliary power.

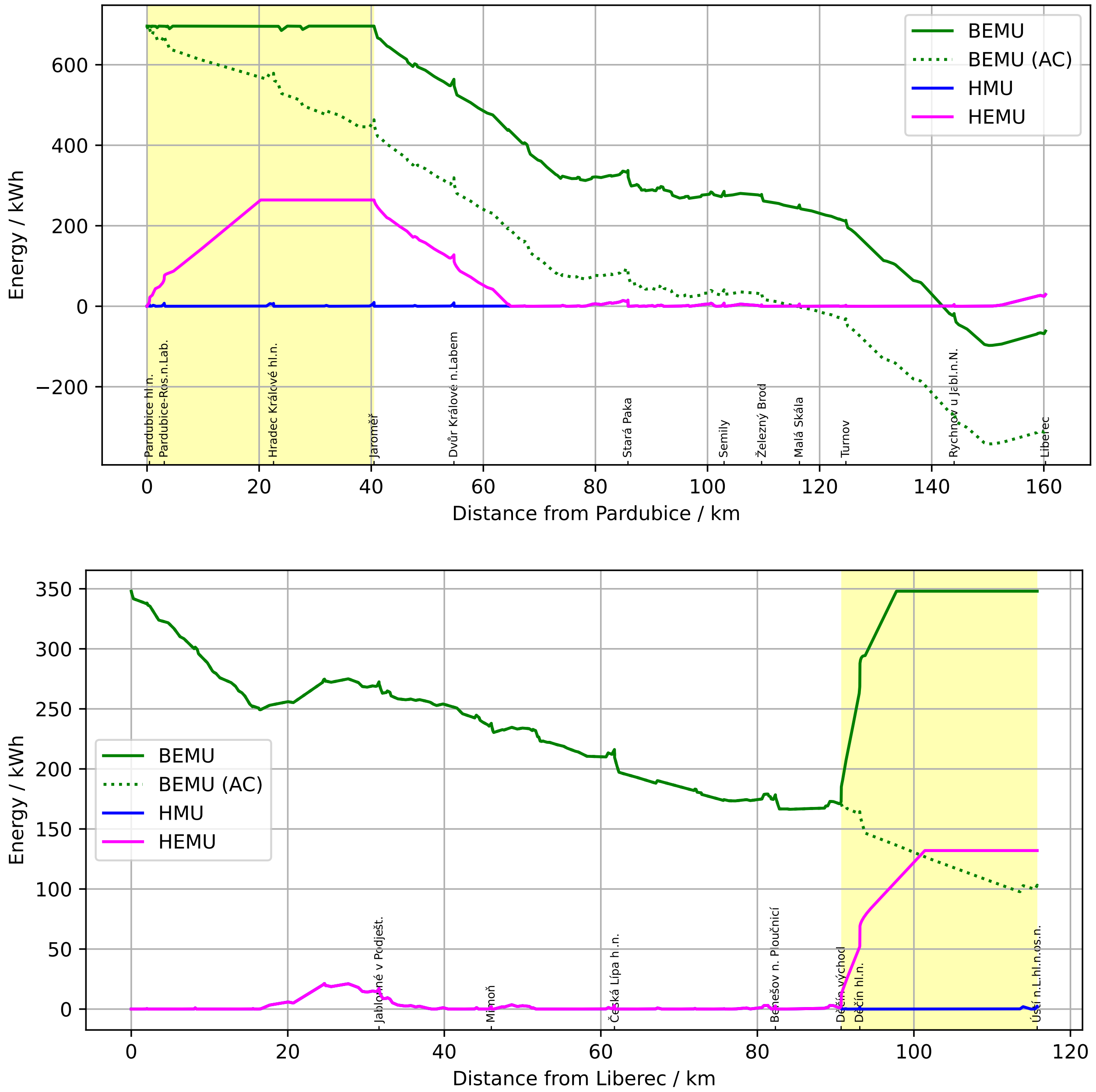


Figure 3.5: SoC profiles in the westbound journey. Note that from Pardubice to Liberec there are two MUs instead of a single one.

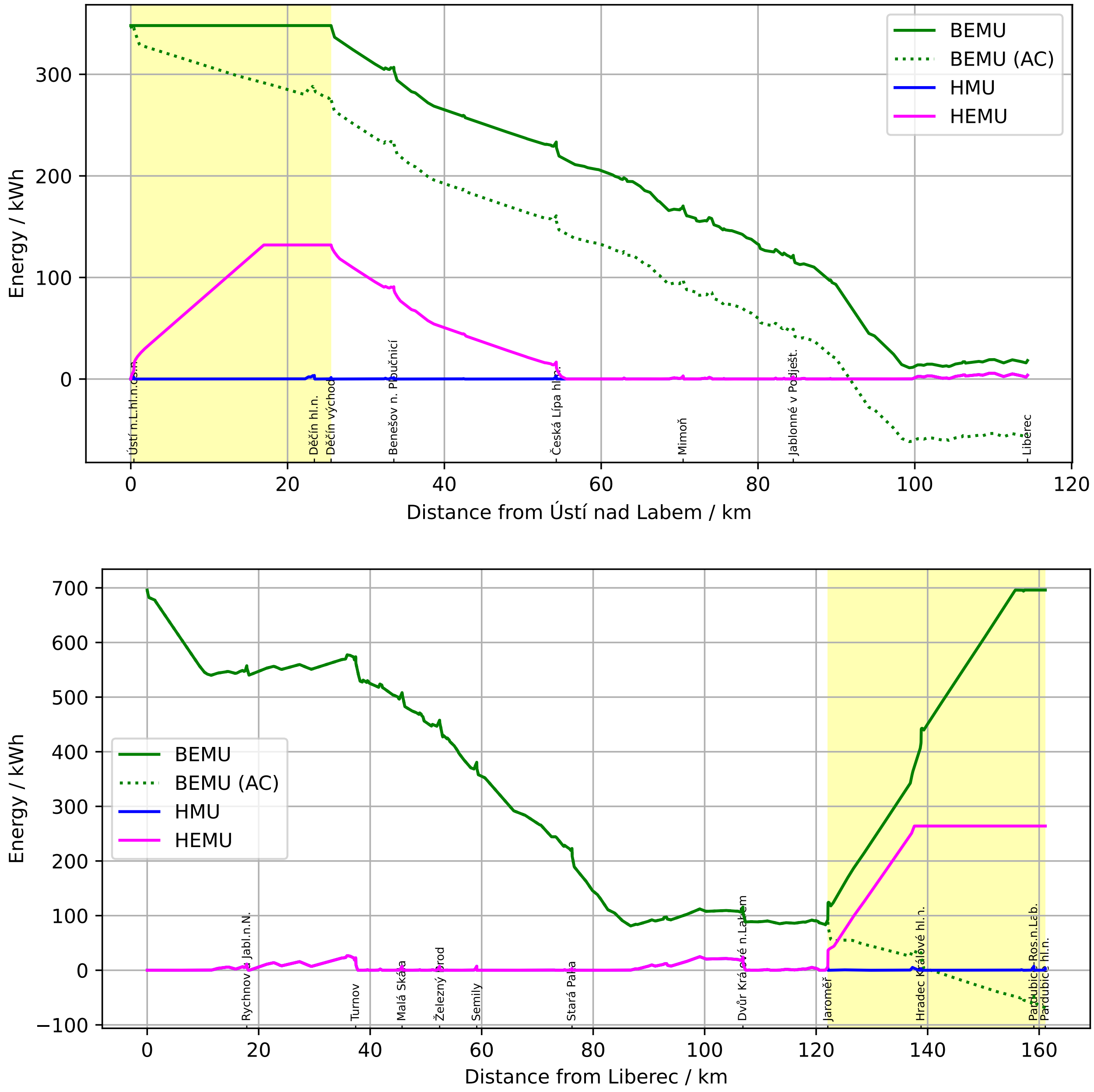
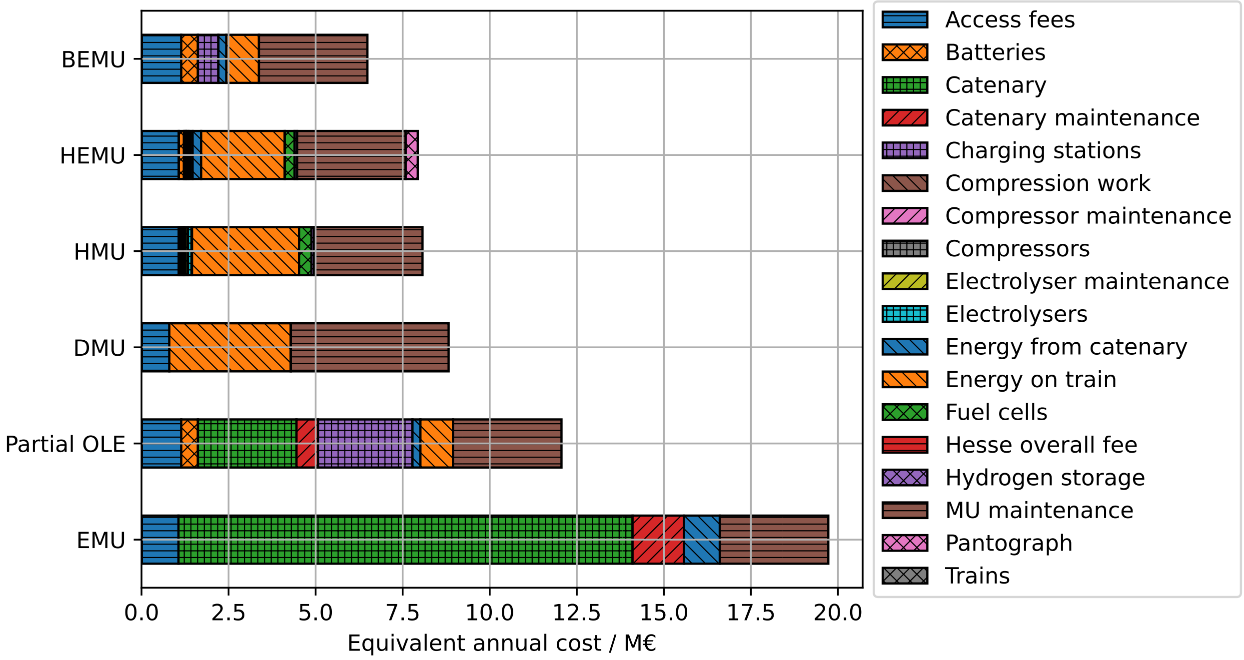


Figure 3.6: SoC profiles in the eastbound journey. Note that from Liberec to Pardubice there are two MUs instead of a single one.

Table 3.1: Total energy consumption for the single sections of line R14. Note that two MUs are used between Liberec, Jaroměř and Pardubice. (E): electrified sectors.

	L		DMU		EMU		BEMU		HMU	
	W	E	W	E	W	E	W	E	W	E
	km		E / kWh							
Děčín-Liberec	91	89	188	251	154	272	156	283	173	285
Děčín-Ústí (E)	25	25	63	66	58	58	59	59	62	62
Jaroměř-Liberec	120	122	604	529	647	521	672	536	699	561
Jaroměř-Pardubice (E)	40	39	203	129	192	132	198	133	215	143
Subtotal electrified	65	64	266	195	250	190	257	192	277	205
Subtotal non-electrified	211	211	792	780	801	793	828	819	872	846
Totals	276	275	1058	975	1051	983	1085	1011	1149	1051



Technology	BCR	PBP a	UFI M€	km cost € / km	CA OLE %	CA POLE %
BEMU	1.36	5.63	16.82	3.62	8.81	9.57
HEMU	1.11	8.33	11.38	4.44	18.81	33.13
HMU	1.09	3.73	3.87	4.51	19.77	35.37
DMU	1.00	N/A	0.00	4.93	24.87	47.40
Partial OLE	0.73	N/A	102.53	6.74	N/A	N/A
EMU	0.45	N/A	225.47	11.02	N/A	N/A

Figure 3.7: Equivalent annual costs for different technologies applied on R14 (differential approach), and their main economic indicators.

3.2.2 Analysis of Alternatives

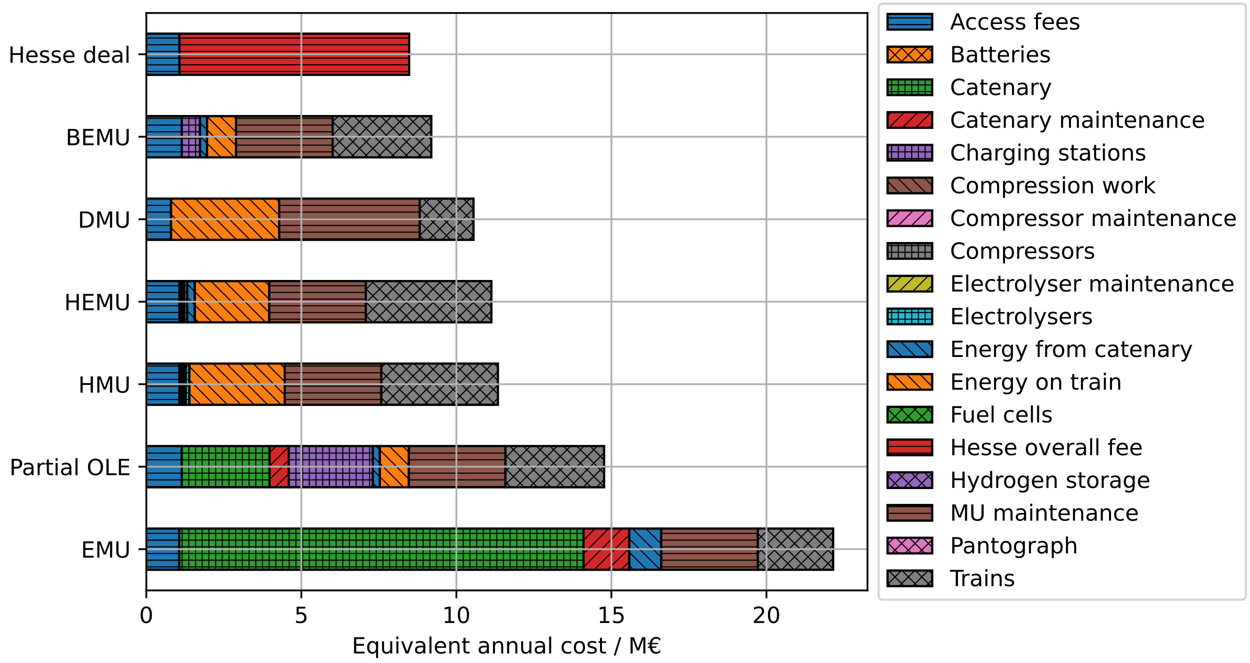
The results of the techno-economic analyses of the alternatives are presented in figures 3.7 (differential approach) and 3.8 (lumped approach).

It is immediately visible that full OLE to enable EMUs is prohibitively expensive; partial OLE is significantly better, but still ranks second most expensive.

With both approaches, batteries and hydrogen are both competitive with diesel, with diesel having a slight advantage in the lumped approach because of the assumption of cheaper, used trains; the most significant advantage of electric alternatives is the cheaper maintenance. Actual battery trains like the Mireo+B, however, have insufficient battery capacity for the Jaroměř–Liberec leg within the 20,%–80 % window, which may lead to increased battery wear and higher costs, which are difficult to estimate.

The Hesse deal ranks first when compared to other alternatives in the lumped approach, which may indicate a preference for hydrogen trains if the conditions applied in Germany can be replicated on R14. A further advantage of the Hesse-style deal is that it does not entail any investment, and has such has instantaneous payback.

In conclusion, both hydrogen and battery trains appear to have an overall similar economy, with costs close



Technology	BCR	PBP a	UFI M€	km cost € / km	CA OLE %	CA POLE %
Hesse deal	1.24	0.00	0.00	4.74	5.79	-2.02
BEMU	1.15	13.65	65.20	5.14	10.71	9.57
DMU	1.00	N/A	30.00	5.90	20.09	31.67
HEMU	0.95	N/A	71.19	6.22	24.06	41.02
HMU	0.93	N/A	66.53	6.34	25.52	44.44
Partial OLE	0.71	N/A	150.92	8.25	N/A	N/A
EMU	0.48	N/A	267.47	12.38	N/A	N/A

Figure 3.8: Equivalent annual costs for different technologies applied on R14 (lumped approach), and their main economic indicators.

to current operation, possibly cheaper; any option with OLE is disadvantaged by the extremely high investment costs. Which should be chosen between batteries and hydrogen depends on the feasibility of actual BEMUs to clear the Jaroměř-Liberec section, and the actual commercial offers received by authorities.

Partial OLE would not be in a too bad situation if it was competing only with diesel: its critical allocation is between 40 % to 50 % depending on the approach, and there are several other lines using the same tracks that could share the remaining half of the costs. However, when batteries and hydrogen are considered, the CA drops rapidly, indicating that new technologies make partial OLE unnecessary.

Table 3.2: Total energy consumption for the sections of line R21. (E): electrified sector.

	L		DMU		EMU		BEMU		HMU	
	N	S	N	S	N	S	N	S	N	S
	km		. . . .	. . . .	. . . . . E / kWh	. . . . .	. . . .	. . . .	. . . .	. . . .
Praha-Skály (E)	12	12	47	18	50	9	53	9	56	13
Skály-Tanvald	125	125	355	282	364	262	377	267	390	291
Totals	137	137	402	300	414	271	430	276	446	304

3.3 R21, Prague–Tanvald

Line R21 from Prague to Tanvald is another passenger-oriented local line serving northern Czechia [16]. It shares some short sections with both line R14A and R22, and is electrified for a very short section between Prague Central Station to the Skály branch just after Prague Vysočany. The altitude profile of R21 is hilly but with limited oscillations until Turnov, after which it rapidly rises to the terminus at Tanvald (470 m). The line's traffic is served by 5 MUs.

3.3.1 Simulation Results

The speed profiles are shown in figure 3.9. The northbound speed profile shows how diesel trains often have to reach higher speed than electric ones to compensate for accumulated delays; this is the case after Skály and Turnov. This indicates that using electric trains may increase reliability and punctuality of the service in the north direction.

Both northbound and southbound speed profiles have sections where trains maintain speeds close to the limit, in particular northwards from Mnichovo Hradiště to Turnov and southwards from Tanvald to Turnov. This may indicate a timetable difficult to achieve with the present speed limits.

Motor energy profiles are presented in figure 3.10. The effect of regenerative braking is especially noticeable on the southward plot, where electric trains briefly achieve a negative profile. The length and energy consumptions of line segments are presented in table 3.2.

The state-of-charge profiles for battery and hydrogen trains are presented in figure 3.11. As visible in the northbound profile, battery trains are unable to reach Tanvald by a measurable margin, which is however small enough to be accommodated by the relaxation of the requirement to remain between 20 % and 80 % of SoC.

It is also remarkable how hydrogen trains, if able to exploit the OLE close to Prague, could accumulate enough energy to run on battery alone until Mnichovo Hradiště, resulting in a significant extension of the calendar lifetime of fuel cells.

3.3.2 Analysis of Alternatives

The results of the techno-economic analyses of the alternatives are presented in figures 3.12 (differential approach) and 3.13 (lumped approach).

While EMUs and their OLE are as expected a prohibitively expensive option, partial OLE performs better and is closer to other option when compared to R14, even though it is still the second most expensive option. Annualised costs for all other technologies are closely packed in both approaches.

The costs estimated by the lumped approach for hydrogen are very close to the ones extrapolated by the Hesse deal, and hydrogen presents a good performance compared to diesel (a little cheaper in differential approach, a little more expensive in the lumped one).

The requirement of a charging station in Tanvald is a major cost item for BEMUs (Prague Central is already DC-electrified). Furthermore, BEMUs cannot run the whole track beyond Jesenny without exiting their 20 %–

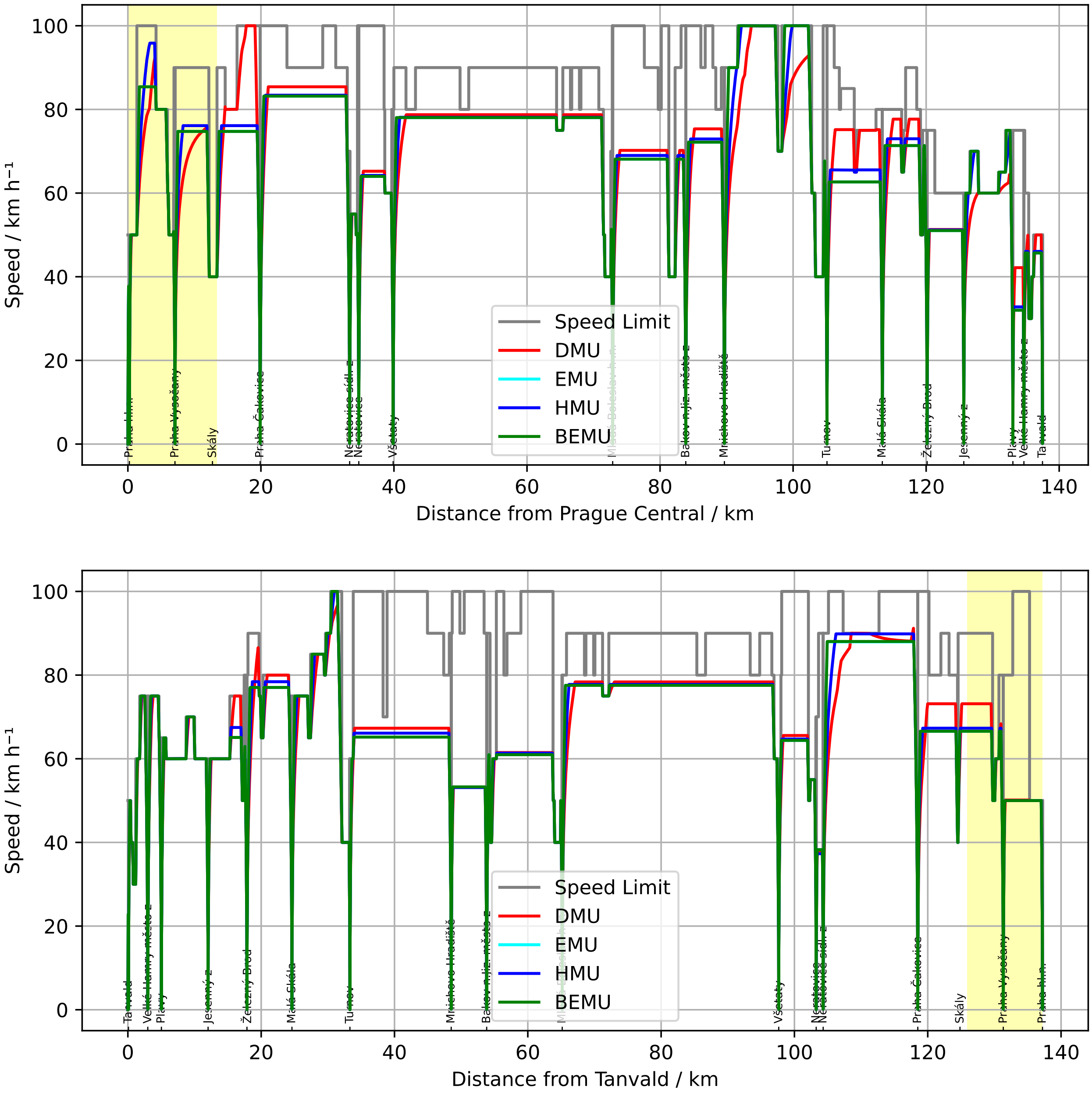


Figure 3.9: Speed profiles in the northbound and southbound journeys of R21.

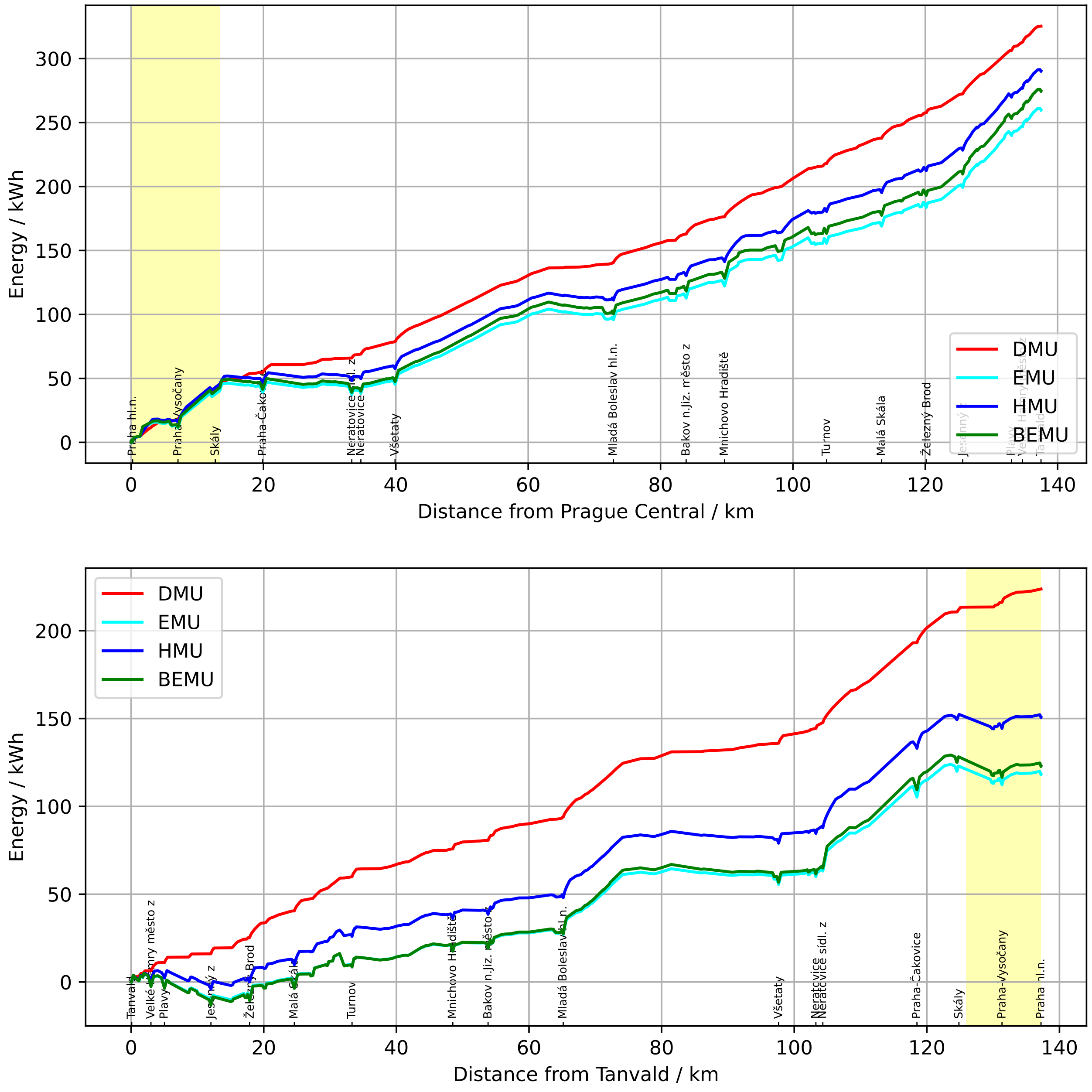


Figure 3.10: Motor energy profiles in the northbound and southbound journeys of R21. Note that these profiles do not include auxiliary power.

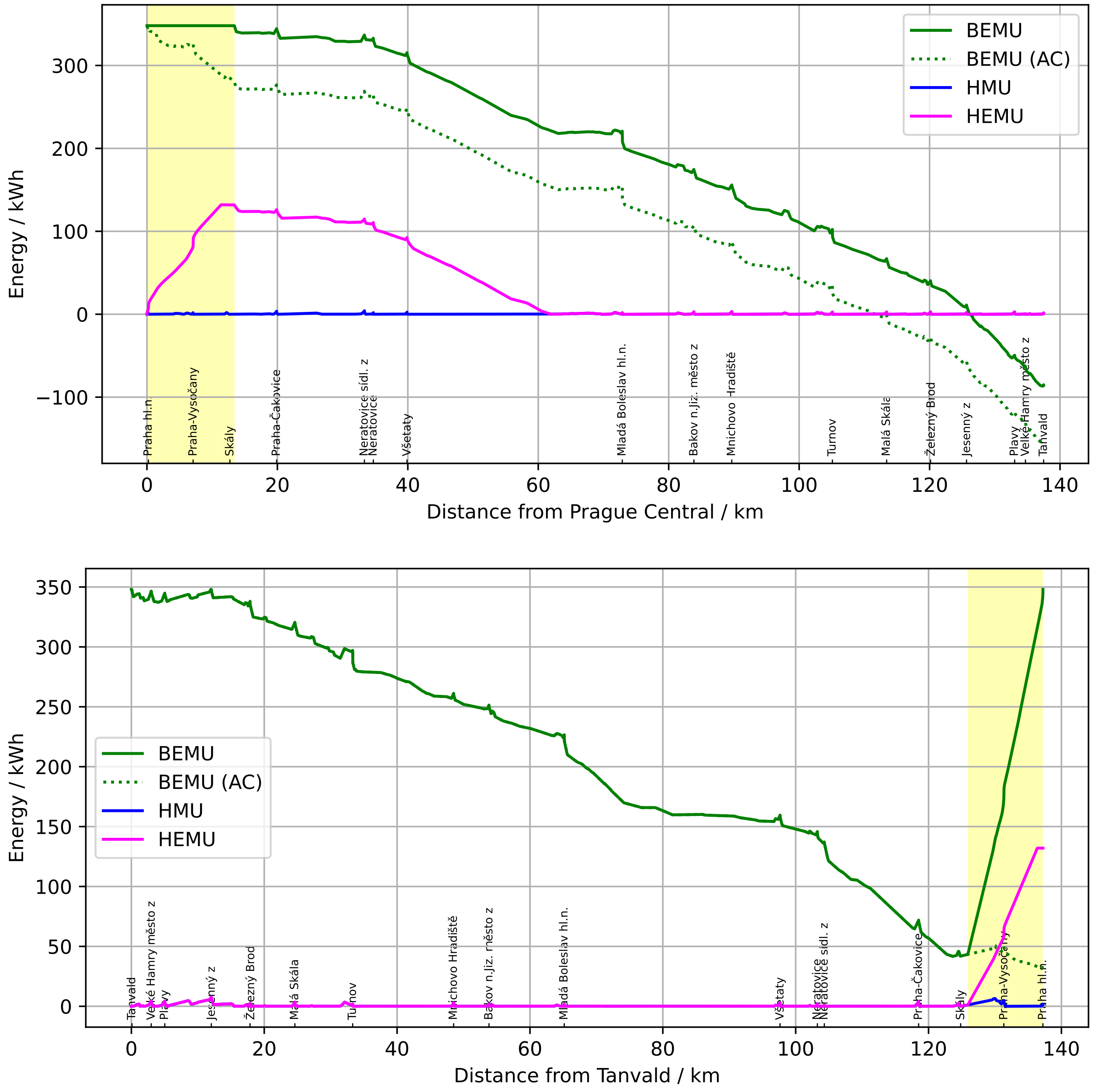
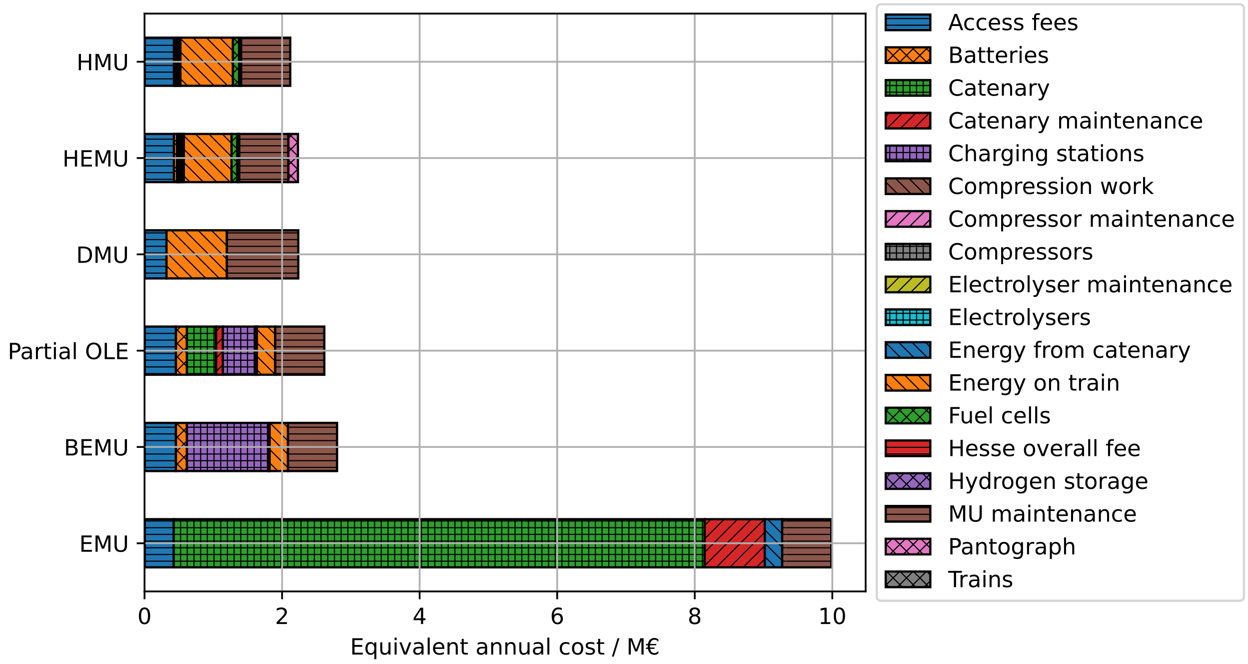
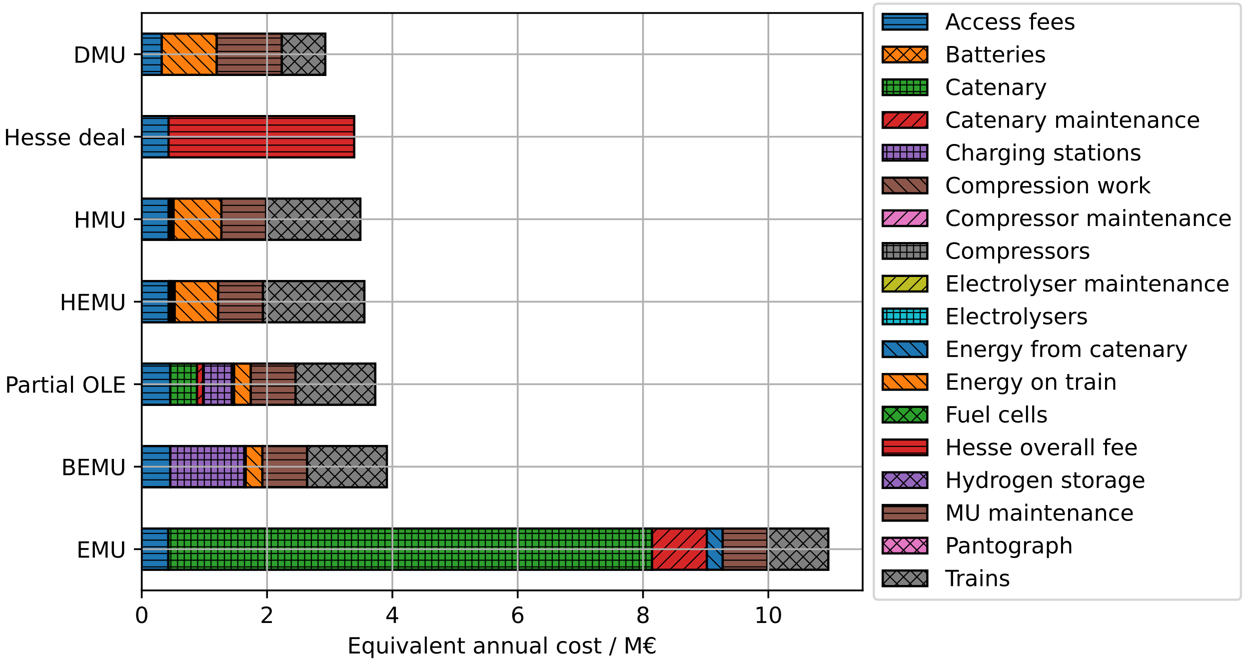


Figure 3.11: SoC profiles in the northbound and southbound journeys of R21.



Technology	BCR	PBP a	UFI M€	km cost € / km	CA OLE %	CA POLE %
HMU	1.05	6.36	1.23	3.27	8.48	50.43
HEMU	1.00	84.50	4.42	3.44	9.78	61.64
DMU	1.00	N/A	0.00	3.44	9.82	61.96
Partial OLE	0.86	N/A	18.41	4.03	N/A	N/A
BEMU	0.80	N/A	23.31	4.31	16.38	118.62
EMU	0.22	N/A	133.49	15.38	N/A	N/A

Figure 3.12: Equivalent annual costs for different technologies applied on R21 (differential approach), and their main economic indicators.



Technology	BCR	PBP a	UFI M€	km cost € / km	CA OLE %	CA POLE %
DMU	1.00	N/A	12.00	4.51	6.59	19.86
BEMU	0.88	N/A	32.20	5.12	11.15	59.31
Hesse deal	0.86	0.00	0.00	5.22	11.95	66.23
HMU	0.84	N/A	26.38	5.37	13.10	76.10
HEMU	0.82	N/A	28.35	5.47	13.84	82.55
Partial OLE	0.79	N/A	37.51	5.74	N/A	N/A
EMU	0.27	N/A	150.29	16.87	N/A	N/A

Figure 3.13: Equivalent annual costs for different technologies applied on R21 (lumped approach), and their main economic indicators.

80 % SoC window: this requires a second charger in Turnov to top up the batteries (current stops in Turnov are scheduled to 7 minutes, sufficient to charge a battery by over 50 % at 5 C rate). A charging station in Turnov is also necessary for the evening train that stops in Turnov and returns directly to Prague the next day. The other train that stops in Mladá Boleslav in the night and returns to Prague, instead, should have enough energy to return on its own power.

The cost of two charging stations is in fact so large that partial electrification is in this case the preferred option for BEMUs, as it is in practice an elongated charging station based around Turnov, allowing enough time to fully charge the batteries rather than just “topping up” to reach Tanvald.

In the case of partial electrification, deploying a short section of catenary around Turnov would be sufficient to enable the use of Mireo+B trains on this line without another charging station in Tanvald, and allow trains taking the partial Prague-Turnov-Prague route to maintain their current schedule.

When considering the lumped-cost approach, DMU remain the cheapest option, again thanks to the assumption of using cheap used MUs. Of the zero-emission technologies, hydrogen is in this case ahead, because of the high cost of chargers in Tanvald and Turnov or of a OLE section in Turnov, either of which is necessary to make BEMU operation possible.

Table 3.3: Total energy consumption for the sections of line R22. (E): electrified sector.

	L		DMU		EMU		BEMU		HMU	
	N	S	N	S	N	S	N	S	N	S
	km		E / kWh							
Kolín-Nymburk (E)	25	24	59	60	50	56	51	57	56	61
Nymburk-Šluknov	140	142	367	339	386	319	398	325	410	347
Totals	165	166	426	399	436	375	449	382	466	408

3.4 R22, Kolín–Šluknov

Line R22 from Kolín to Šluknov is the final one of the three lines of northwestern Bohemia analysed in this report. R22 has a very similar profile to R21: it starts from an electrified area in the plains at Kolín, which soon ends in Nymburk; the no longer electrified line then proceeds to climb up to Šluknov, close to the German border [17]. The line's traffic is served by 4 MUs, shares the section Mladá Boleslav–Bakov nad Jizerou with R21 and crosses R14B at Česká Lípa.

3.4.1 Simulation Results

The speed profiles are shown in figure 3.14. Neither profile indicates significant issues with holding the schedule by diesel trains, though electric variants are as expected better at acceleration. Diesel trains appear to have difficulties in following the schedule only in the section from Šluknov to Rybniště, which is sharply uphill. There is some potential to improve punctuality by introducing electrific trains, but not as much as was the case with lines R14 and R21.

Motor energy profiles are presented in figure 3.15. Electric trains have similar consumptions, and the effect of regeneration is evident in the southward leg, where diesel needs sensibly more energy. The length and energy consumptions of line segments are presented in table 3.3.

The state-of-charge profiles for battery and hydrogen trains are presented in figure 3.16. The northbound profile indicates that battery trains cannot reach Šluknov by a significant margin; this can be in theory accommodated by extending the SoC window, but significant losses in lifetime should be expected. Furthermore, such operation may be limit the operational flexibility of trains in conditions of higher resistance, e.g. snowfall.

The southbound profile also nominally falls under zero just before Nymburk, but by such a small amount to be easily absorbed by the safety margin. Hydrogen trains equipped with pantographs could operate on batteries until Bakov nad Jizerou, reducing wear on fuel cells.

Note that there are plans for the electrification of the section from Nymburk to Mladá Boleslav; while this would significantly improve the feasibility for battery trains, they still would not be able to proceed beyond Svor without exiting their nominal SoC window.

3.4.2 Analysis of Alternatives

The results of the techno-economic analyses of the alternatives are presented in figures 3.17 (differential approach) and 3.18 (lumped approach).

The results are structurally similar to R21's: BEMUs are disadvantaged by the requirement of new charging stations compared to hydrogen. Note however that the situation is more complicated for R22, as there are several journeys covering only part of the track; e.g. only 3 scheduled journeys arrive in Šluknov, whereas 3 stop at Rumburk, 2 at Svor and 1 at Nový Bor: none of these will be able to return to Kolín without additional charging, or even larger batteries. Furthermore, any northward journey beyond Nový Bor will require more than the nominal 20 %–80 % capacity of the batteries, causing additional degradation.

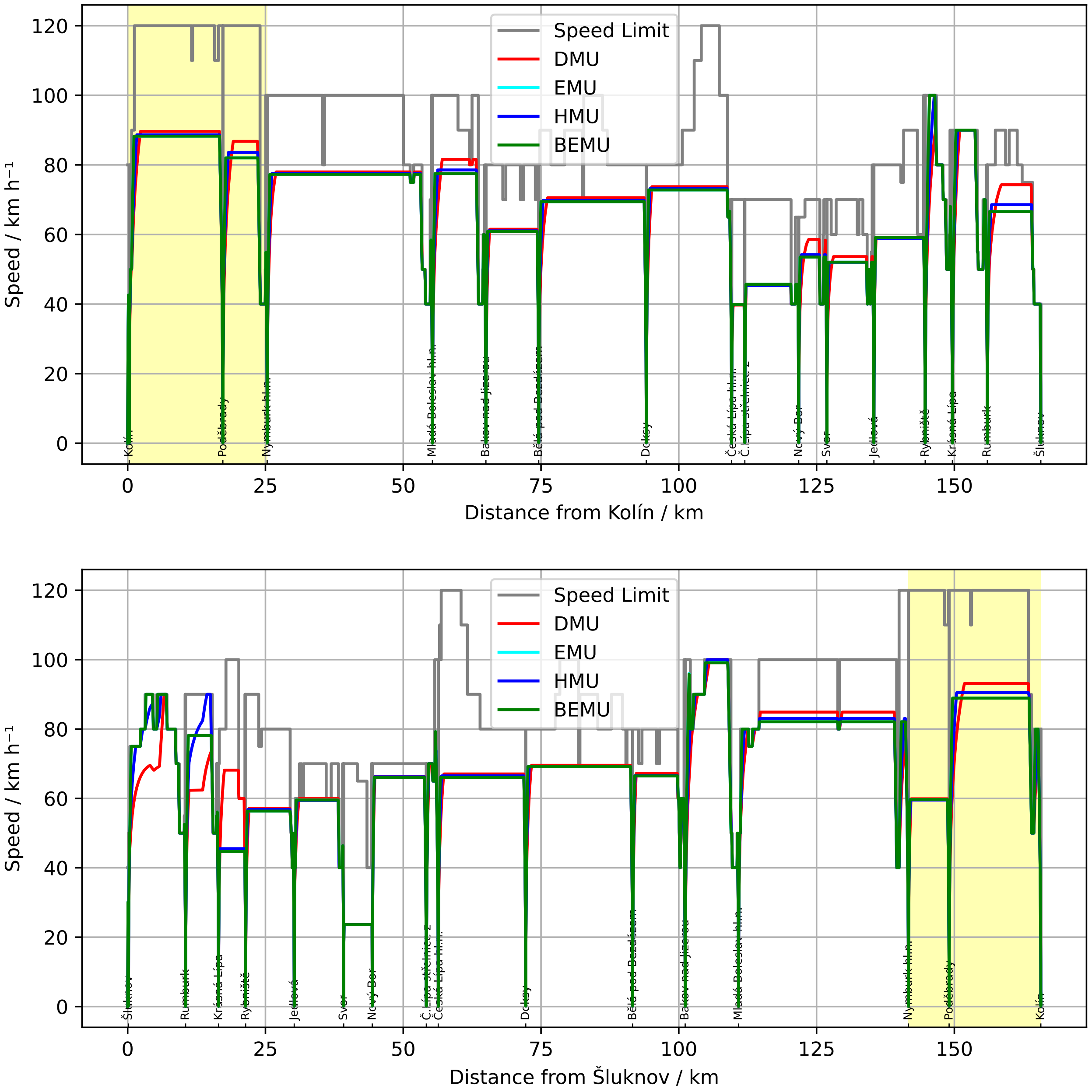


Figure 3.14: Speed profiles in the northbound and southbound journeys of R22.

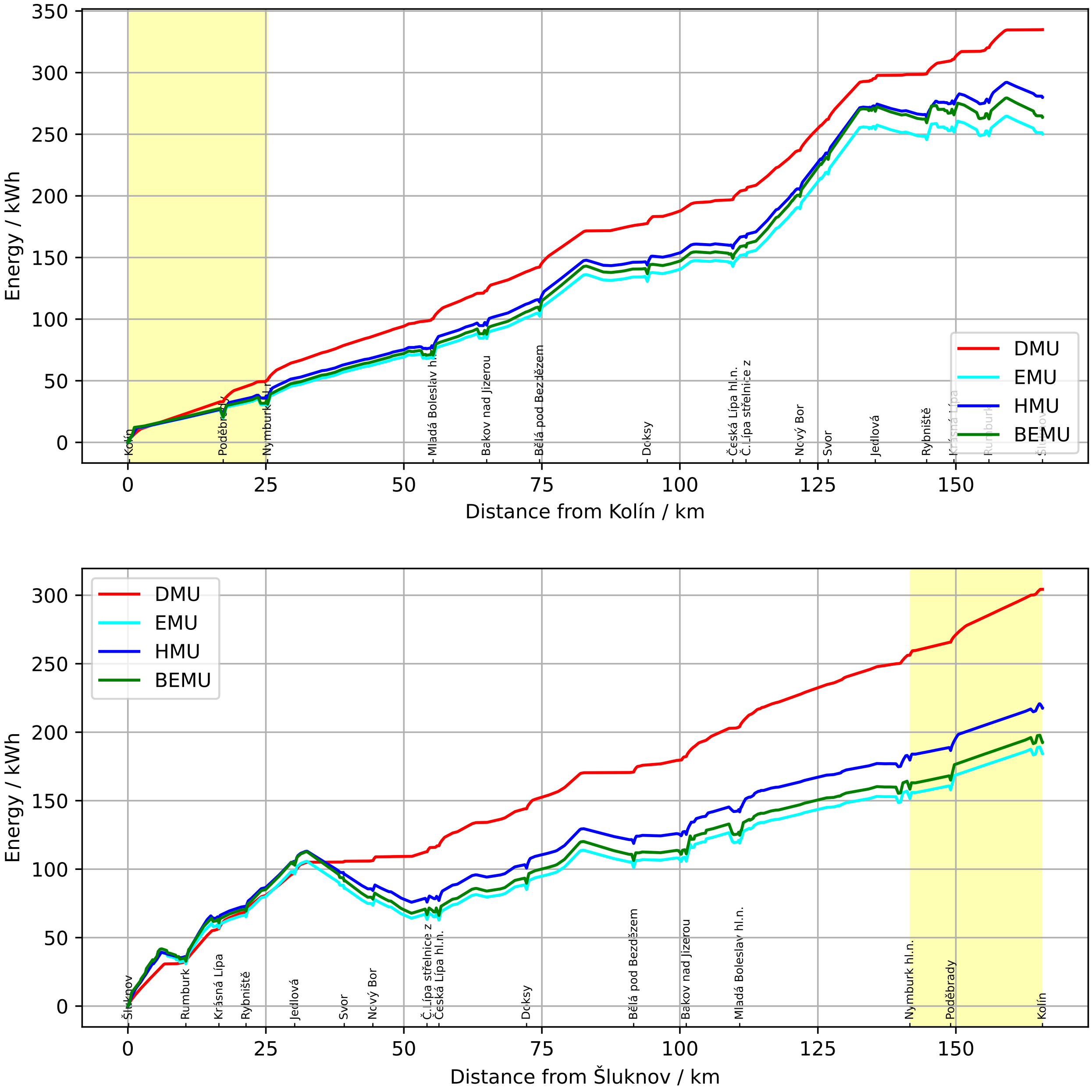


Figure 3.15: Motor energy profiles in the northbound and southbound journeys of R22. Note that these profiles do not include auxiliary power.

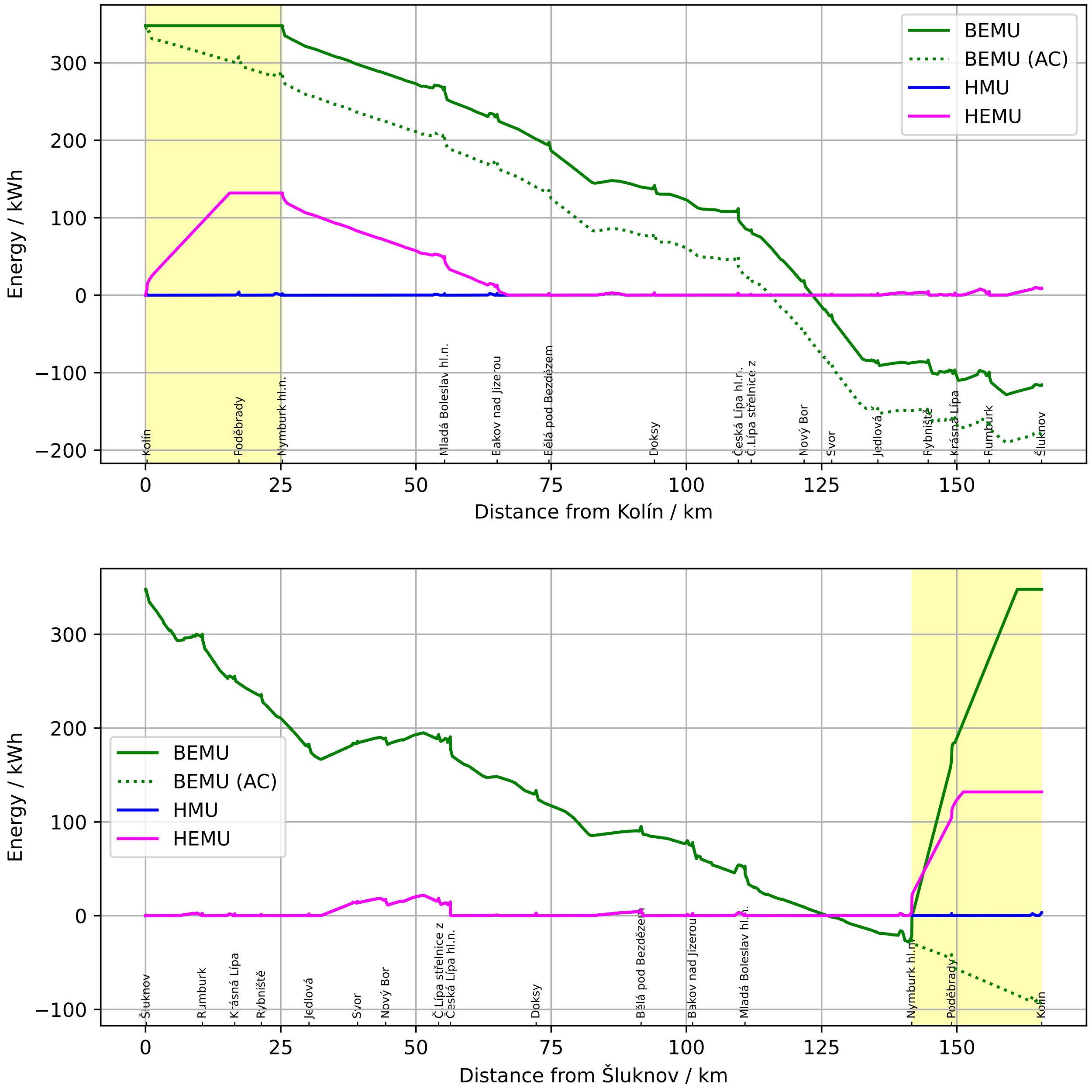
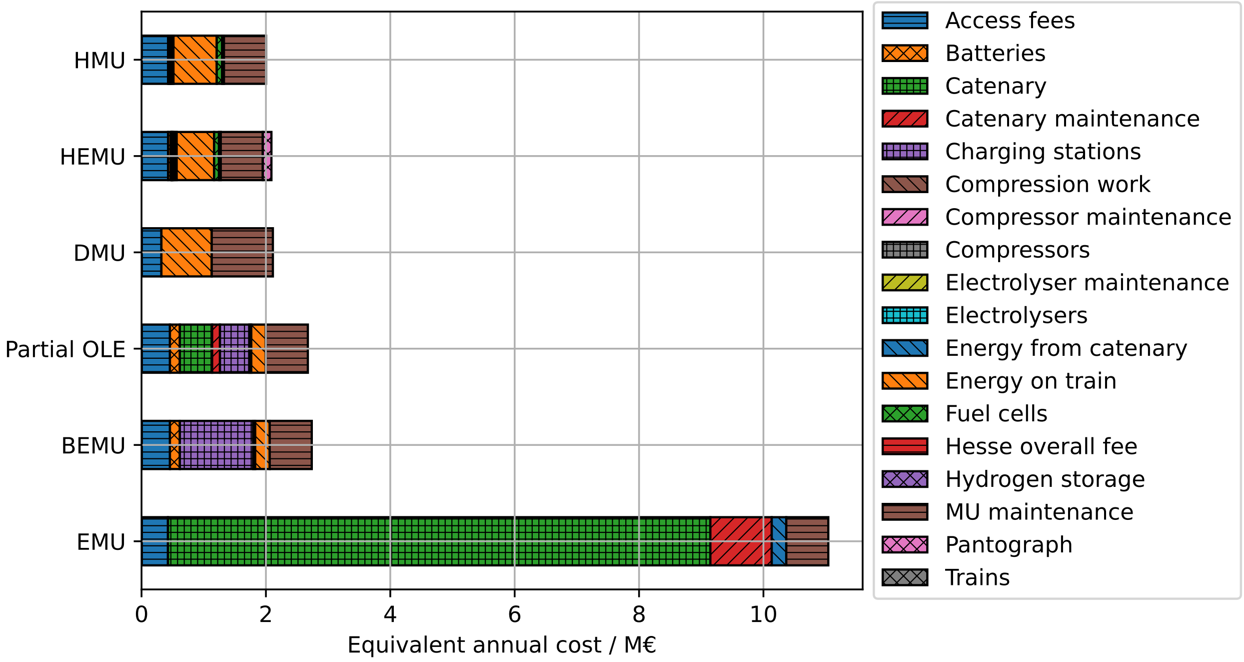
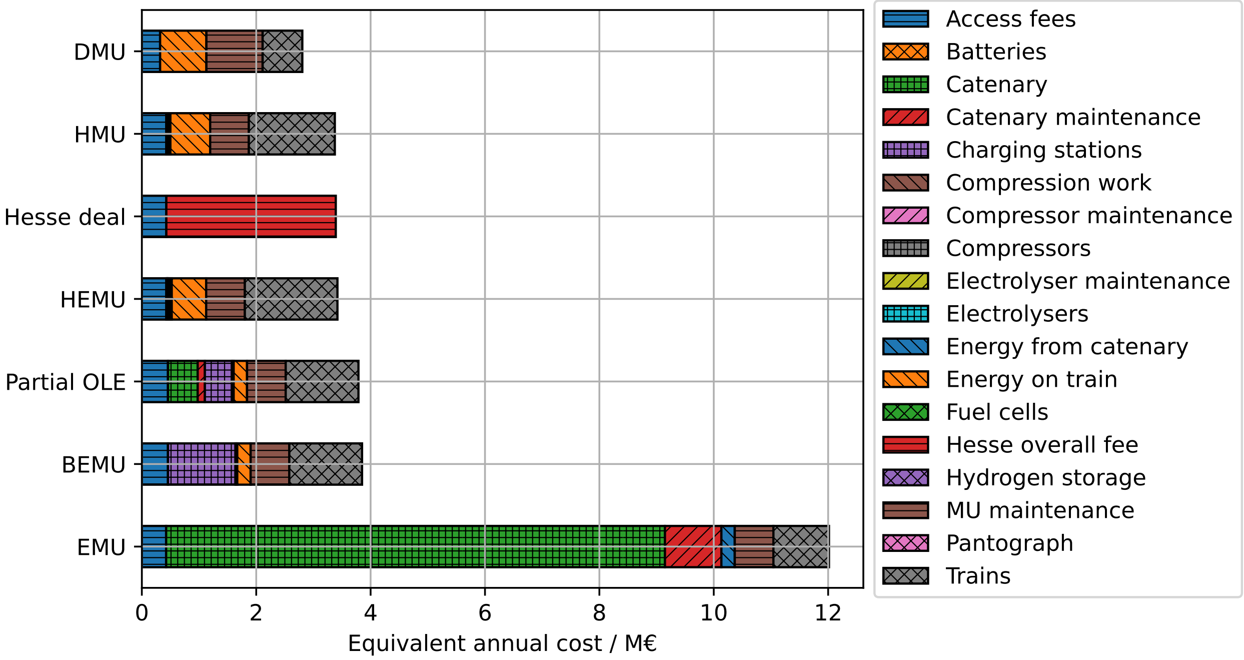


Figure 3.16: SoC profiles in the northbound and southbound journeys of R22.



Technology	BCR	PBP a	UFI M€	km cost € / km	CA OLE %	CA POLE %
HMU	1.05	6.73	1.28	3.26	6.89	39.95
HEMU	1.01	47.53	4.35	3.40	7.79	47.74
DMU	1.00	N/A	0.00	3.44	8.01	49.67
Partial OLE	0.79	N/A	20.30	4.35	N/A	N/A
BEMU	0.77	N/A	23.57	4.45	14.45	105.62
EMU	0.19	N/A	150.82	17.97	N/A	N/A

Figure 3.17: Equivalent annual costs for different technologies applied on R22 (differential approach), and their main economic indicators.



Technology	BCR	PBP a	UFI M€	km cost € / km	CA OLE %	CA POLE %
DMU	1.00	N/A	12.00	4.57	5.15	12.15
HMU	0.83	N/A	26.34	5.49	11.00	63.01
Hesse deal	0.83	0.00	0.00	5.52	11.17	64.50
HEMU	0.82	N/A	28.29	5.57	11.47	67.11
Partial OLE	0.74	N/A	39.14	6.16	N/A	N/A
BEMU	0.73	N/A	42.41	6.27	15.91	105.62
EMU	0.23	N/A	167.62	19.55	N/A	N/A

Figure 3.18: Equivalent annual costs for different technologies applied on R22 (lumped approach), and their main economic indicators.

It would also be economically burdensome to add 4 charging stations, so the most likely solution in order to implement the battery alternative would be significant modifications to the schedule, which may however not be feasible.

We assumed we would have only two stations, one in Šluknov and one in Svor. Trains stopping in Rumburk have long enough turnaround times (at least 35 minutes) to continue to Šluknov (10 minutes each way) and charge the BEMU, even if by the tightest of margins. The train turning in Nový Bor is an unsolved problem as it has such a short turnaround time (6 minutes) it would not be able to charge enough even if it had a charging station available.

Otherwise, as for R21, full OLE is economically infeasible; partial OLE does a lot better, in fact better than having 2 fixed charging stations (which would not be sufficient anyway). Partial OLE foresees a section around Česká Lípa, which would make it possible for BEMUs to operate on the line without separate chargers at the various northern termini. Partial OLE is therefore the only option to implement BEMUs without significant changes in schedule.

As for R21, DMUs are ahead of hydrogen when calculating with lumped costs; if the choice is only between zero-emission options, however, HMUs are clearly the preferable choice, given the expensive infrastructure requirements of BEMUs.

Table 3.4: Total energy consumption for the sections of line R25. (E): electrified sector.

	L		DMU		EMU		BEMU		HMU	
	N	S	N	S	N	S	N	S	N	S
	km		E / kWh							
Plzeň-Žatec	106	105	250	269	237	271	243	280	262	291
Březno-Žatec (E)	15	16	60	30	66	12	69	11	72	20
Březno-Chomutov	12	11	45	25	44	21	46	22	50	24
Chomutov-Most (E)	21	23	42	86	18	90	17	94	25	95
Subtotal electrified	36	39	102	116	84	102	86	105	97	115
Subtotal non-electrified	118	116	295	294	281	292	289	302	312	315
Totals	154	155	397	410	365	394	375	407	409	430

3.5 R25, Pilsen–Most

Line R25 from Pilsen to Most is not connected to any of the ones previously analysed, and has a different profile in several ways. The two termini of the line are at simular altitudes, though the line does rise about 200 m between them [18]. Pilsen is a major national station and electrified with AC; however, the north end of the line, between Žatec and Most (briefly interrupted for the tunnel between Březno and Chomutov), is also electrified, but here with DC. The line's traffic is served by 3 MUs; it is assumed the trains will be DC-electrified, and that a simple charging station with rectifier (50 MCZK) may be installed in Pilsen for BEMUs.

3.5.1 Simulation Results

The speed profiles are shown in figure 3.19. Neither profile indicates significant issues with holding the schedule by diesel trains, though electric variants are as expected better at acceleration. Only in the section between Žatec and Chomutov do diesel trains accumulate a minor delay.

Motor energy profiles are presented in figure 3.20. Electric trains have similar consumption, with regeneration reducing the energy demand compared to diesel somewhat, but not radically. The length and total energy consumption of line segments are presented in table 3.4.

The state-of-charge profiles for battery and hydrogen trains are presented in figure 3.21. Both profiles indicate that Mireo+B trains are able to run the line within their safety margins, so commercially available battery trains are easily applicable to R25.

Thanks to the availability of OLE, hydrogen trains equipped with pantographs could disconnect their fuel cells when entering Žatec in the northbound direction, and would not need them until after passing Vroutek in the southbound leg, possibly almost halving wear on fuel cells.

3.5.2 Analysis of Alternatives

The results of the techno-economic analyses of the alternatives are presented in figures 3.22 (differential approach) and 3.23 (lumped approach).

Almost all train journeys on R25 are the full length of the line; only one evening train stops in Blatno on the way south, and returns to Most the morning after. Looking at figure 3.21, a BEMU arriving in Blatno will have sufficient energy left to return to Žatec without additional charging, since the track back to Žatec is mostly downhill. This means that the current schedule of R25 may be entirely fulfilled by Mireo+B trains.

As traffic on R25 can be operated with current commercial BEMUs like the Mireo+B, partial electrification is a redundant option, unless only AC-fed BEMUs were available on the market; in that case, these trains will have to run on their own power from Plasy to Most (about 300 kWh, feasible), recharge there, and then perform

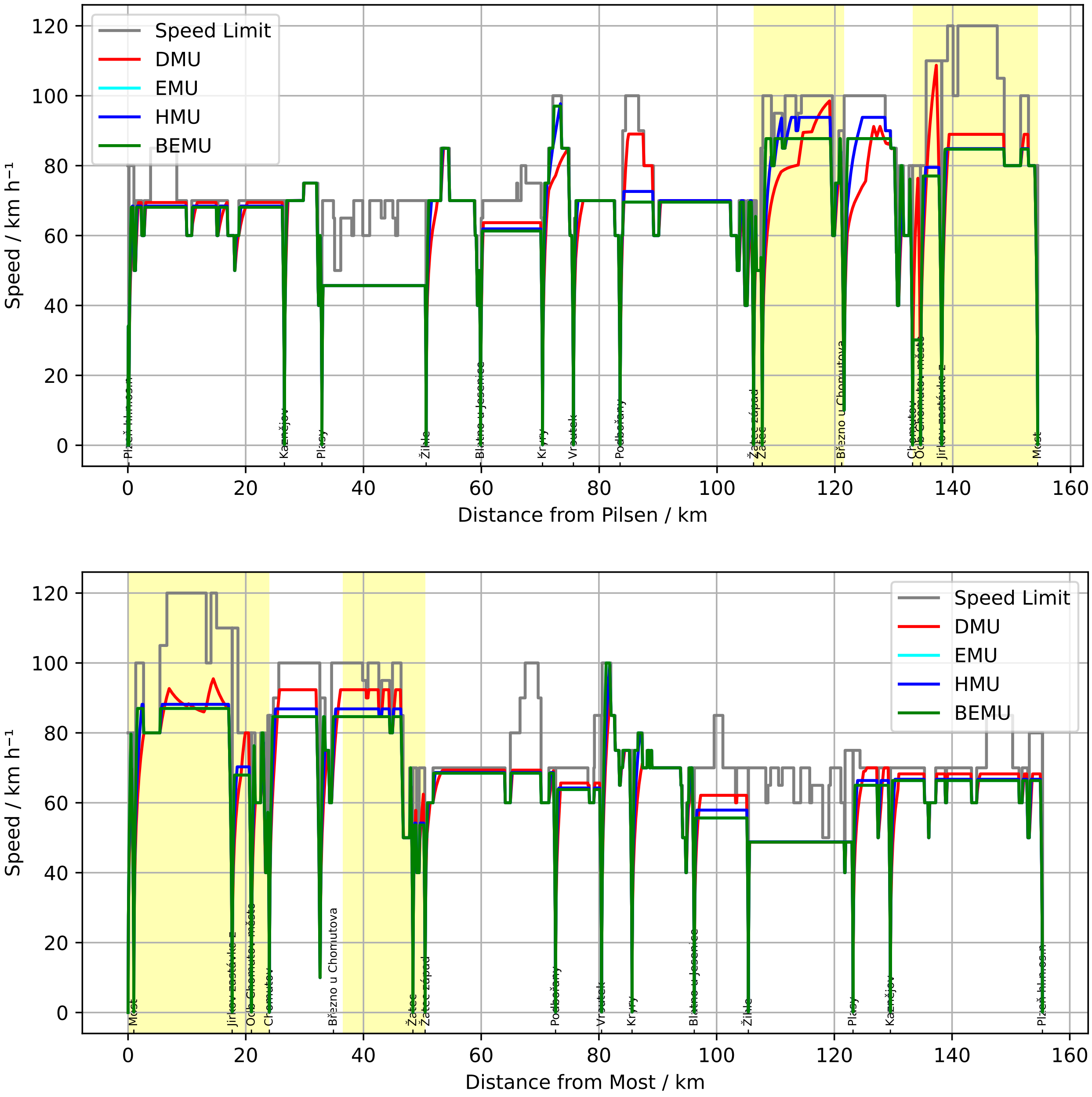


Figure 3.19: Speed profiles in the northbound and southbound journeys of R25.

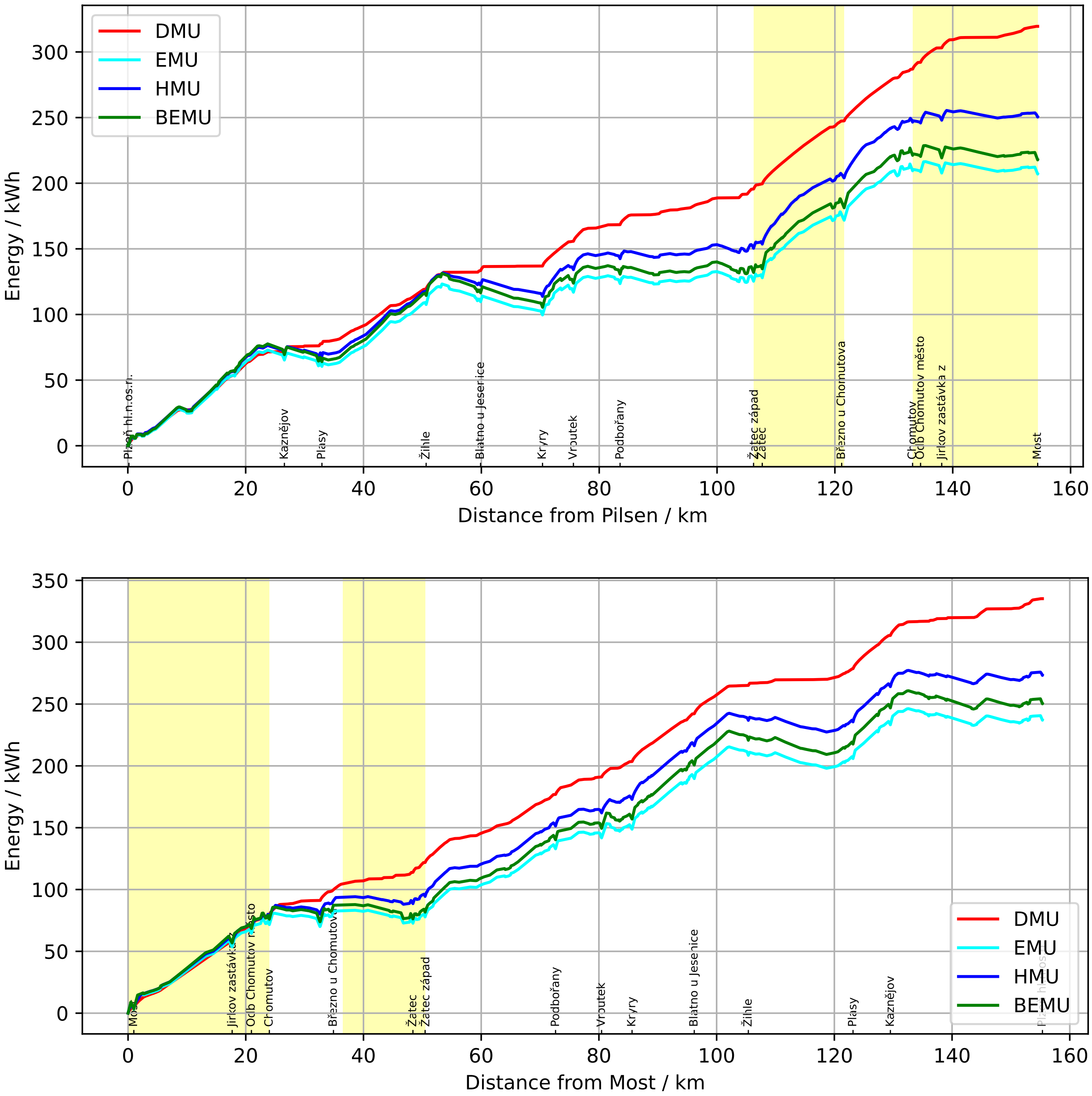


Figure 3.20: Motor energy profiles in the northbound and southbound journeys of R25. Note that these profiles do not include auxiliary power.

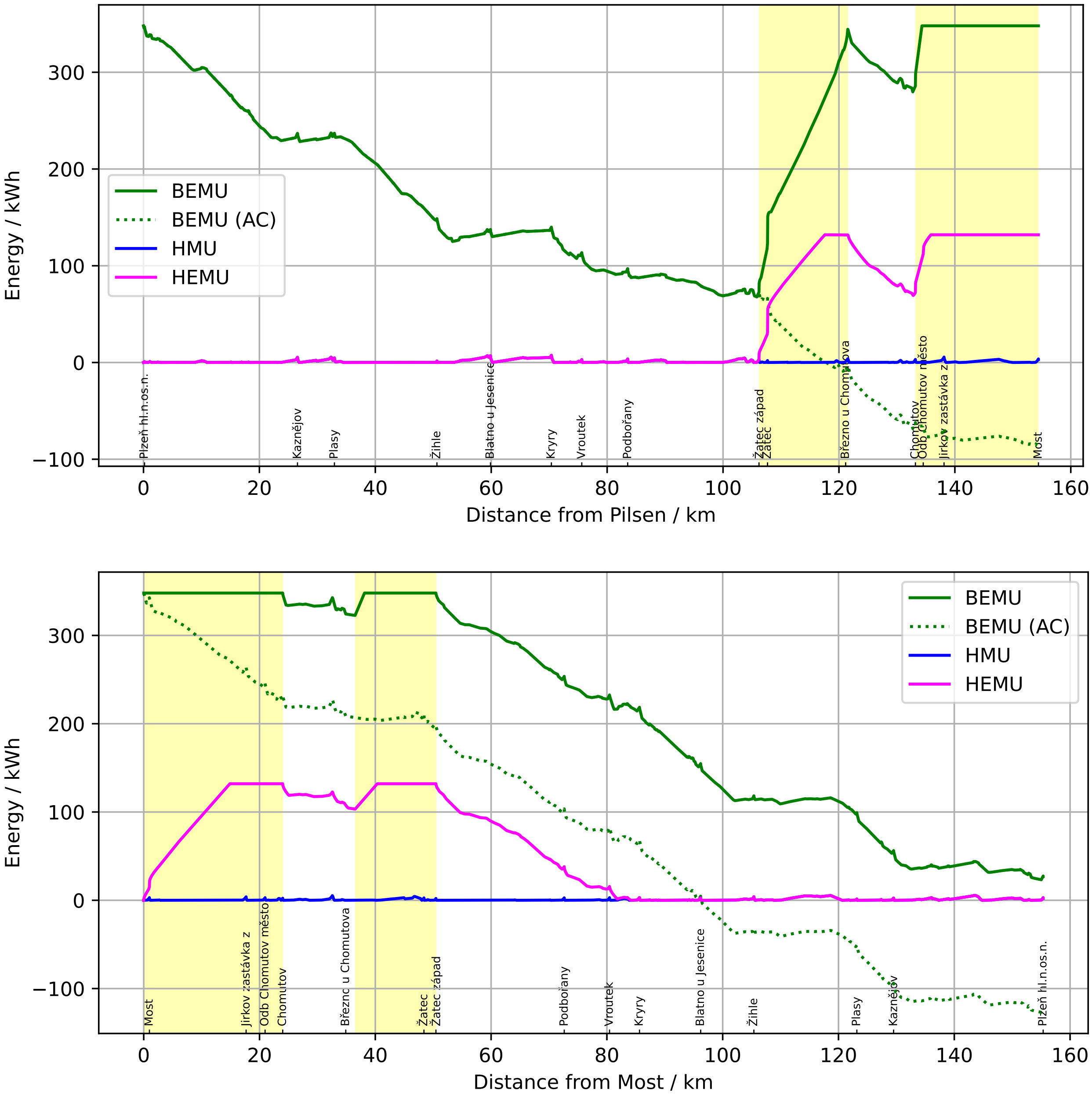
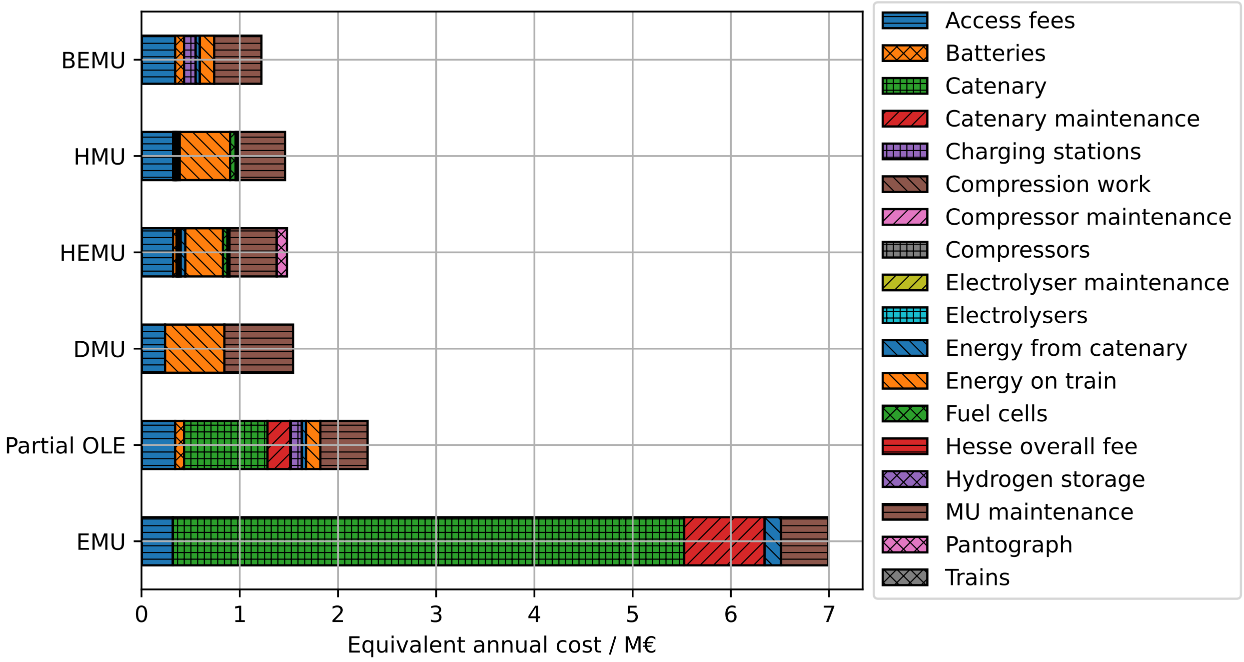
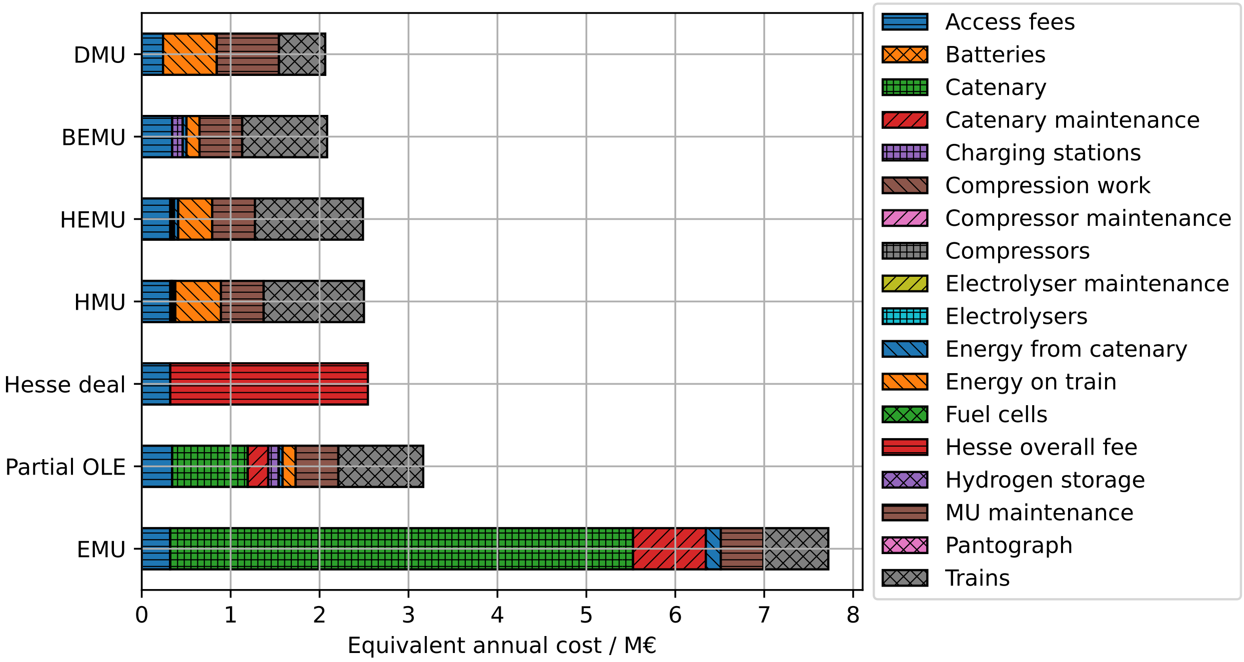


Figure 3.21: SoC profiles in the northbound and southbound journeys of R25.



Technology	BCR	PBP a	UFI M€	km cost € / km	CA OLE %	CA POLE %
BEMU	1.26	8.25	3.66	2.79	4.21	9.85
HMU	1.06	6.98	0.90	3.35	8.21	29.99
HEMU	1.04	18.58	3.25	3.39	8.53	31.59
DMU	1.00	N/A	0.00	3.53	9.55	36.71
Partial OLE	0.67	N/A	18.36	5.27	N/A	N/A
EMU	0.22	N/A	90.03	16.01	N/A	N/A

Figure 3.22: Equivalent annual costs for different technologies applied on R25 (differential approach), and their main economic indicators.



Technology	BCR	PBP a	UFI M€	km cost € / km	CA OLE %	CA POLE %
DMU	1.00	N/A	9.00	4.72	6.10	8.06
BEMU	0.99	N/A	18.54	4.77	6.45	9.85
HEMU	0.83	N/A	21.20	5.70	13.14	43.48
HMU	0.83	N/A	19.77	5.72	13.33	44.41
Hesse deal	0.81	0.00	0.00	5.82	14.06	48.10
Partial OLE	0.65	N/A	33.23	7.25	N/A	N/A
EMU	0.27	N/A	102.63	17.67	N/A	N/A

Figure 3.23: Equivalent annual costs for different technologies applied on R25 (lumped approach), and their main economic indicators.

the return leg from Most to Plasy, which from figure 3.21 is not infeasible but does use more than the design 20 %–80 % SoC window.

Techno-economic results indicate that batteries are ahead of hydrogen, thanks to the higher electrification of the line that reduces costs for charging station; the one required DC charging station in Pilsen is of the cheaper type, as the station is already AC-electrified and the technical requirements are far simpler. On the side of HMUs is that payback times are calculated to be somewhat shorter than BEMUs; on the other hand, BEMUs are significantly simpler to deploy.

While the lumped-cost analysis again places diesel ahead, the advantage is minimal, with BEMUs being essentially tied. Note that BEMUs may further improve their economy if they were able to feed on both AC and DC, making the charging station in Pilsen unnecessary.

Compared to the previous lines in northeastern Bohemia (R14, R21, R22), line R25 is electrified at both ends and does not need an expensive feeder for its charging station, be it a DC charger at Pilsen (AC station) or an AC charger at Most (DC station). The cost of charging stations is therefore much lower, and improves the BEMU economy.

Table 3.5: Total energy consumption for the sections of line R26. (E): electrified sector, DC between Prague and Smíchov, otherwise AC.

	L		DMU		EMU		BEMU		HMU	
	N	S	N	S	N	S	N	S	N	S
	km		E / kWh							
Písek-Č.Budějovice (E)	49	50	129	149	110	129	113	133	126	153
Písek-Zdice	91	90	219	242	189	241	193	250	217	258
Beroun-Zdice (E)	9	10	14	38	13	42	13	43	14	51
Beroun-Praha-Smíchov	33	33	90	104	86	92	88	96	89	99
Praha-Praha-Smíchov (E)	5	5	12	8	16	10	16	10	16	10
Subtotal electrified	63	65	155	195	139	181	142	186	156	214
Subtotal non-electrified	124	123	309	346	275	333	281	346	306	357
Totals	187	188	464	541	414	514	423	532	462	571

3.6 R26, České Budějovice–Prague

Line R26 from Prague to České Budějovice is the line with most OLE coverage of all the ones analysed in this report, but has the particularity of having some sections electrified with AC and some with DC. From Prague, the line is DC-electrified until Prague Smíchov, after which it is non-electrified until it reaches Beroun, from where it is AC-electrified until Zdice, after which the train turns south and leaves the Prague-Pilsen line, entering a non-electrified section [19]. AC OLE is again available from Písek until the terminus in České Budějovice.

Both termini are major stations and electrified, though Prague with DC and České Budějovice with AC. The line's traffic is served by 4 MUs; we will consider the alternatives for trains to be compatible with AC, DC or both OLE systems.

Please note that R26 is currently "temporarily" rerouted between Prague and Beroun via the non-electrified section through Rudná due to traffic congestion; the nominal journey would be the track following the Berounka river, fully DC-electrified from Prague to Beroun. It is unclear how long this situation will persist, but as it is due to persistent congestion rather than temporary works, it may become permanent.

3.6.1 Simulation Results

The speed profiles are shown in figure 3.24. The profiles in both directions show several sections in which all trains proceed at or close to the speed limit, but as there is no significant difference in train speeds after these sections, it appears that the schedule has been optimised carefully for the present rolling stock. An exception is the approach to Prague, far slower than the allowable top speed, possibly because of sub-optimal scheduling due to the temporary nature of the current route from Beroun to Prague.

Motor energy profiles are presented in figure 3.25. Profiles are closer for the leg to České Budějovice, since it arrives at a higher altitude, whereas trains able to regenerate braking energy have almost no net consumption from Příbram to Prague. The length and energy consumption of line segments are presented in table 3.5.

The state-of-charge profiles for battery and hydrogen trains are presented in figure 3.26, in this case with additional cases for trains able to use AC, DC or both available OLE types.

DC-fed Mireo+B trains would not be able to run the line either way, though they may run the leg from České Budějovice if the previous DC-electrified section from Beroun to Prague is made available; in addition, a DC charging station would be needed in České Budějovice. AC-fed Mireo+B trains, instead, are able to run both legs of the line, and do not need an extra AC charging station in Prague, as the remaining charge they have is sufficient to bring them back to Beroun. Of course, combined trains would also be able to run the line, but the cost of the extra power electronics will not bring any further advantage.

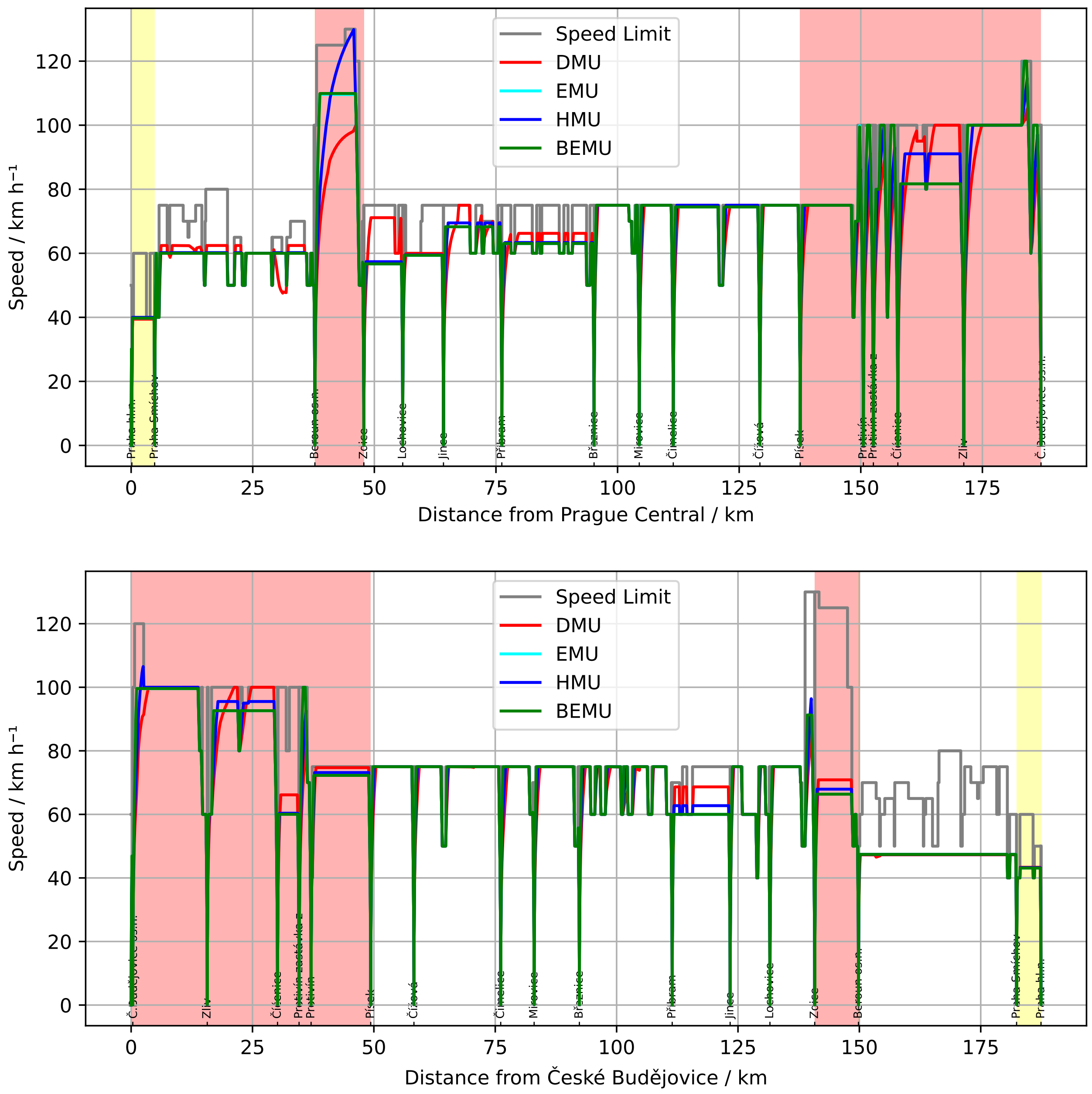


Figure 3.24: Speed profiles in the northbound and southbound journeys of R26.

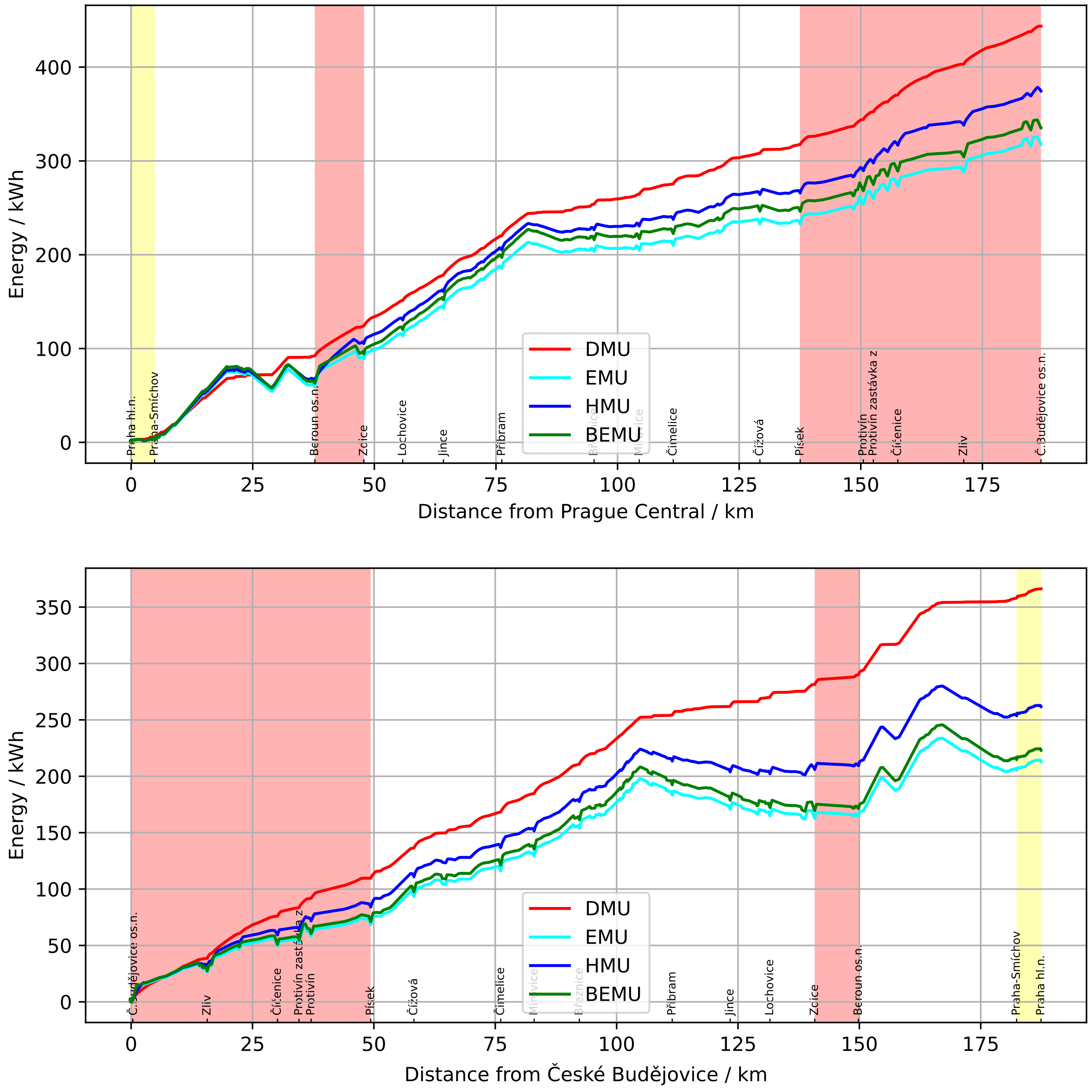


Figure 3.25: Motor energy profiles in the northbound and southbound journeys of R26. Note that these profiles do not include auxiliary power.

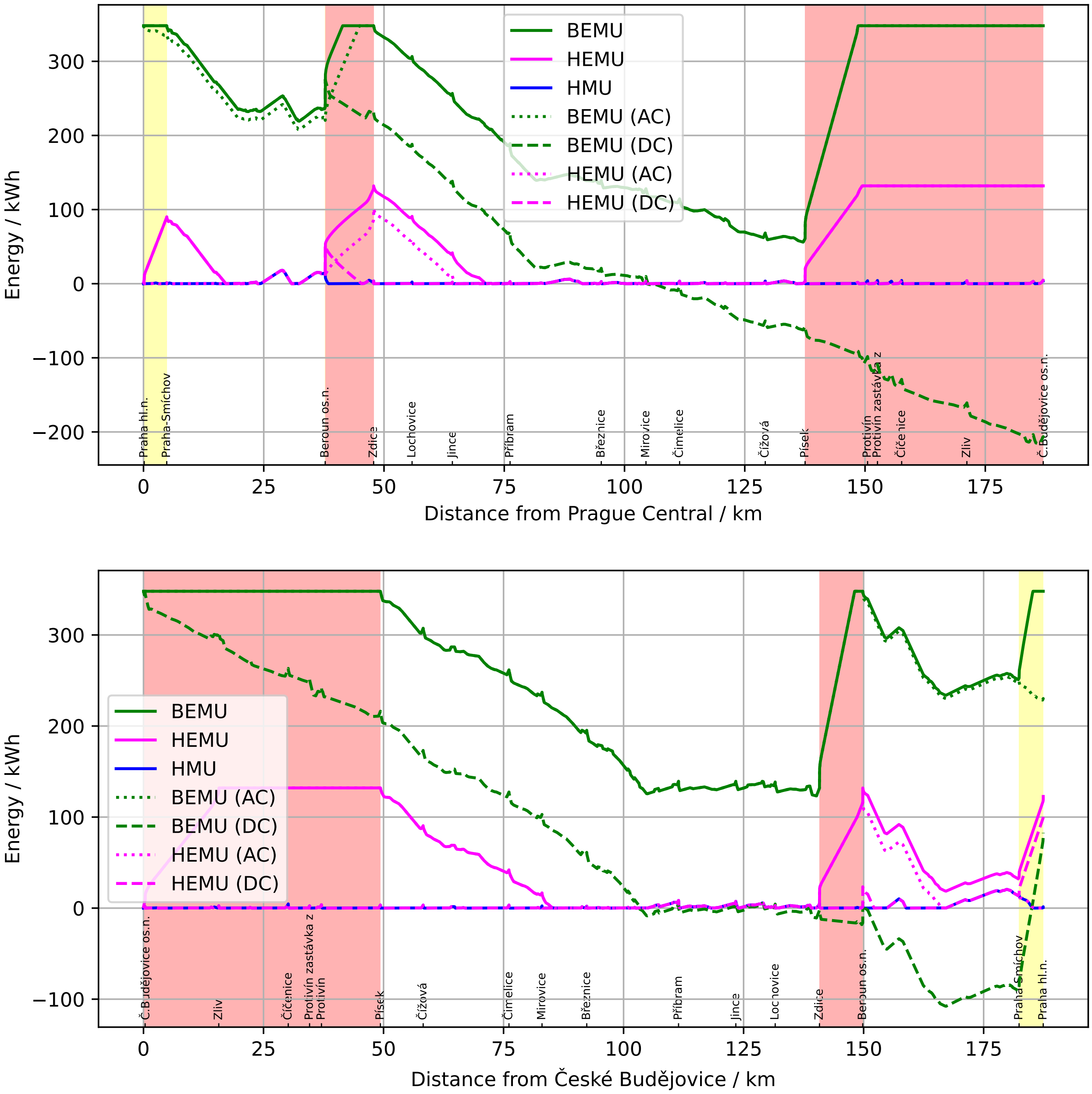


Figure 3.26: SoC profiles in the northbound and southbound journeys of R26.

3.6.2 Analysis of Alternatives

The results of the techno-economic analyses of the alternatives are presented in figures 3.27 (differential approach) and 3.28 (lumped approach).

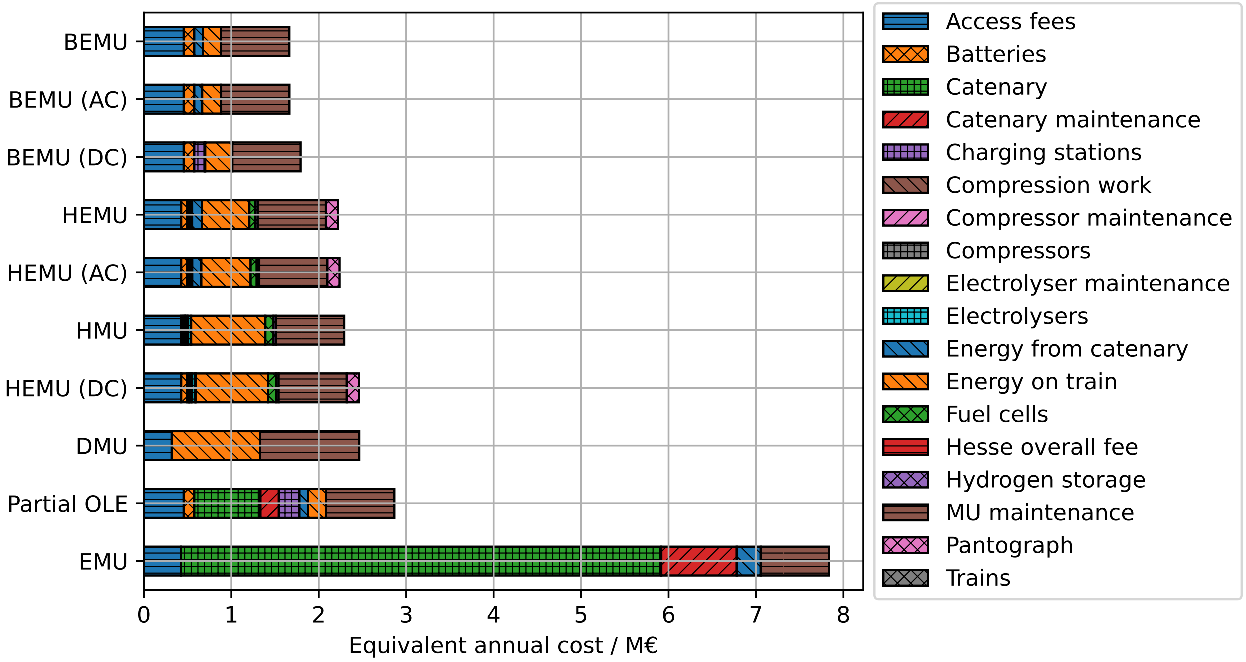
Most train journeys on R26 are the full length of the line, and some more are on the fully electrified section between České Budějovice and Písek. There is in addition a train from Prague stopping in Písek and returning directly to Prague, but as the train stays overnight in Písek it has plenty of time to recharge (assuming it runs on AC). This means that the current schedule of R26 may be entirely fulfilled by AC-fed Mireo+B trains.

An AC-fed BEMU is able to fully recharge in the short AC section between Zdice and Beroun, owing to the much higher power transfer from AC catenary, and will be able to reach Prague and back to Beroun, making an AC charging station in Prague unnecessary.

While the AC+DC method is ahead by the smallest margin (only 0.01 €/km), the AC-only BEMU option is more realistic, as the additional cost of combined AC-DC operation, which we neglected, will likely more than compensate this small advantage; besides, in perspective, all DC lines in Czechia are planned to be converted to AC.

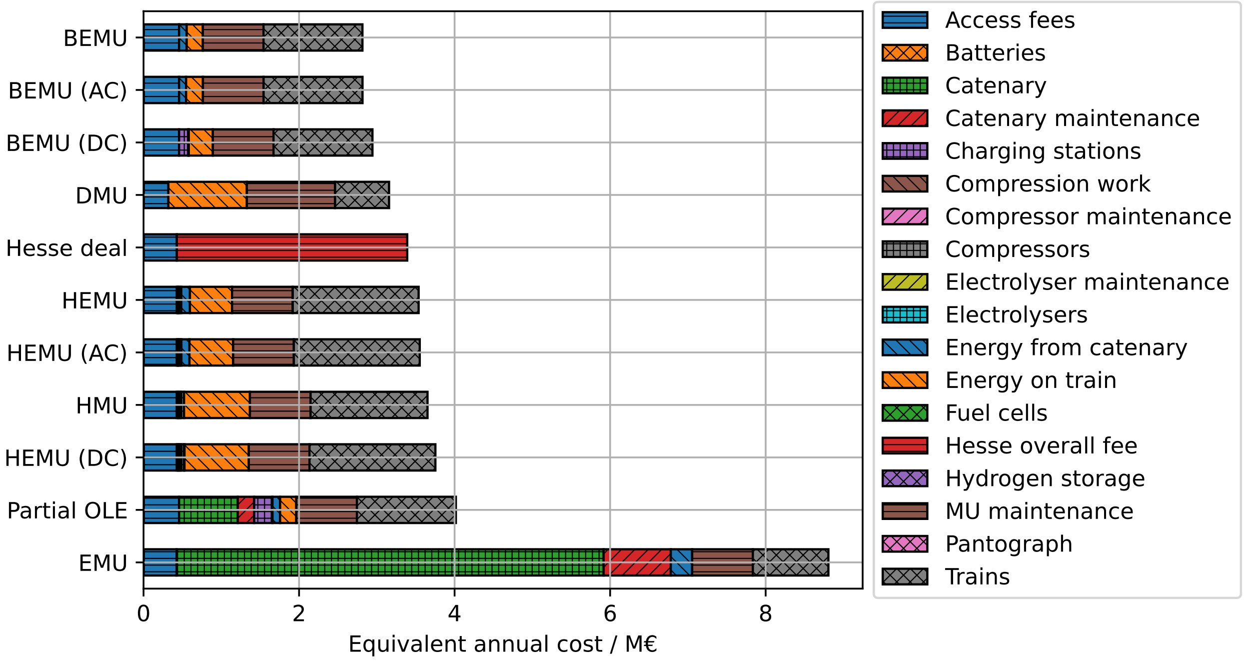
As we established that R26 is a line that can be operated with current commercial battery trains like the Mireo+B, partial electrification is wholly unnecessary as an option. The Czech ministry of transportation, however, prepared some plans for this case (possibly underestimating the battery capacity of prospective MUs).

Line R26 is especially well suited for BEMUs, due to the presence of significant sections of both AC and DC OLE; as such, it is no surprise that AC-fed BEMUs rank highest, with both differential and lumped calculation methods. BEMUs are ahead of both HMUs and HEMUs, due to the possibility of running trains without any additional charging stations. Furthermore, for the same reason, investment for the battery option are relatively low compared to previous cases, and payback times are faster than for HMUs.



Technology	BCR	PBP a	UFI M€	km cost € / km	CA OLE %	CA POLE %
BEMU	1.48	2.26	1.95	2.34	2.88	0.00
BEMU (AC)	1.48	2.26	1.95	2.35	2.90	0.07
BEMU (DC)	1.37	4.92	3.99	2.53	4.91	10.71
HEMU	1.11	10.29	4.35	3.13	11.67	46.46
HEMU (AC)	1.10	10.64	4.36	3.16	11.95	47.94
HMU	1.07	5.33	1.38	3.23	12.80	52.45
HEMU (DC)	1.00	86.90	4.51	3.47	15.44	66.41
DMU	1.00	N/A	0.00	3.47	15.47	66.57
Partial OLE	0.86	N/A	19.09	4.04	N/A	N/A
EMU	0.31	N/A	94.96	11.04	N/A	N/A

Figure 3.27: Equivalent annual costs for different technologies applied on R26 (differential approach), and their main economic indicators.



	BCR	PBP	UFI	km cost	CA OLE	CA POLE
		a	M€	€ / km	%	%
Technology						
BEMU	1.12	14.54	22.00	3.97	5.72	0.00
BEMU (AC)	1.12	14.56	22.00	3.97	5.73	0.07
BEMU (DC)	1.07	19.22	24.04	4.15	7.74	10.71
DMU	1.00	N/A	12.00	4.45	11.10	28.48
Hesse deal	0.93	0.00	0.00	4.78	14.78	47.94
HEMU	0.89	N/A	28.27	4.99	17.08	60.14
HEMU (AC)	0.89	N/A	28.28	5.01	17.31	61.33
HMU	0.86	N/A	26.44	5.15	18.88	69.65
HEMU (DC)	0.84	N/A	28.43	5.29	20.48	78.09
Partial OLE	0.79	N/A	39.14	5.66	N/A	N/A
EMU	0.36	N/A	111.76	12.41	N/A	N/A

Figure 3.28: Equivalent annual costs for different technologies applied on R26 (lumped approach), and their main economic indicators.

Table 3.6: Total energy consumption for the sections of line R27. (E): electrified sector.

	L		DMU		EMU		BEMU		HMU	
	W	E	W	E	W	E	W	E	W	E
	km		E / kWh							
Olomouc-Opava	116	116	265	297	285	327	293	337	302	341
Opava-Ostrava (E)	38	38	90	82	101	95	104	96	108	104
Totals	154	154	355	379	386	422	397	433	410	445

3.7 R27, Olomouc–Ostrava

Line R27 from Olomouc to Ostrava over Krnov is located in Moravia and Silesia. As the two termini are already connected with a mainline intercity service, R27 serves mostly users along the line. Note that most runs of the R27 trains ("Praděd") feature a 15-minute stop in Krnov, which may be used to top up battery SoC if necessary [20, 21]. From Opava to Ostrava, the line is DC-electrified, as it is in Olomouc station itself. The line's traffic is served by 4 MUs.

3.7.1 Simulation Results

The speed profiles are shown in figure 3.29. Trains almost never need to proceed at top speed to keep their schedule, with the possible exception for the electrified section between Opava and Ostrava; however, since in that case all trains are moving at the speed limit, electrification will offer no improvement to punctuality on the R27 line.

Motor energy profiles are presented in figure 3.30. The profiles of all electric alternatives are quite close together, whereas diesel is much higher, also when compared to other lines. This occurs not just because of the significant altitude reached by the track (over 600 m), but also because the diesel unit used on R27 is the CZ843, much heavier than the usual CZ845 considered in previous lines. The length and energy consumptions of line segments are presented in table 3.6.

The state-of-charge profiles for battery and hydrogen trains are presented in figure 3.31. DC-fed Mireo+B trains would almost be able to run the line in nominal conditions, with the only deviation occurring on the eastward leg after Krnov. A charging station in Krnov is considered necessary to avoid battery wear due to regular operation outside the 20 %–80 % window.

3.7.2 Analysis of Alternatives

The results of the techno-economic analyses of the alternatives are presented in figures 3.32 (differential approach) and 3.33 (lumped approach).

For R27, batteries are slightly ahead of HMUs and HEMUs in terms of BCR, but the necessity of a charging station in Krnov makes the investment costs balloon, resulting also in far longer payback time than for HMUs.

Partial electrification is not competitive with BEMUs since a single charging station in Krnov, where the schedule already foresees a sufficiently long stop, is enough to recharge the batteries; the extra cost of several km of catenary is therefore not justified.

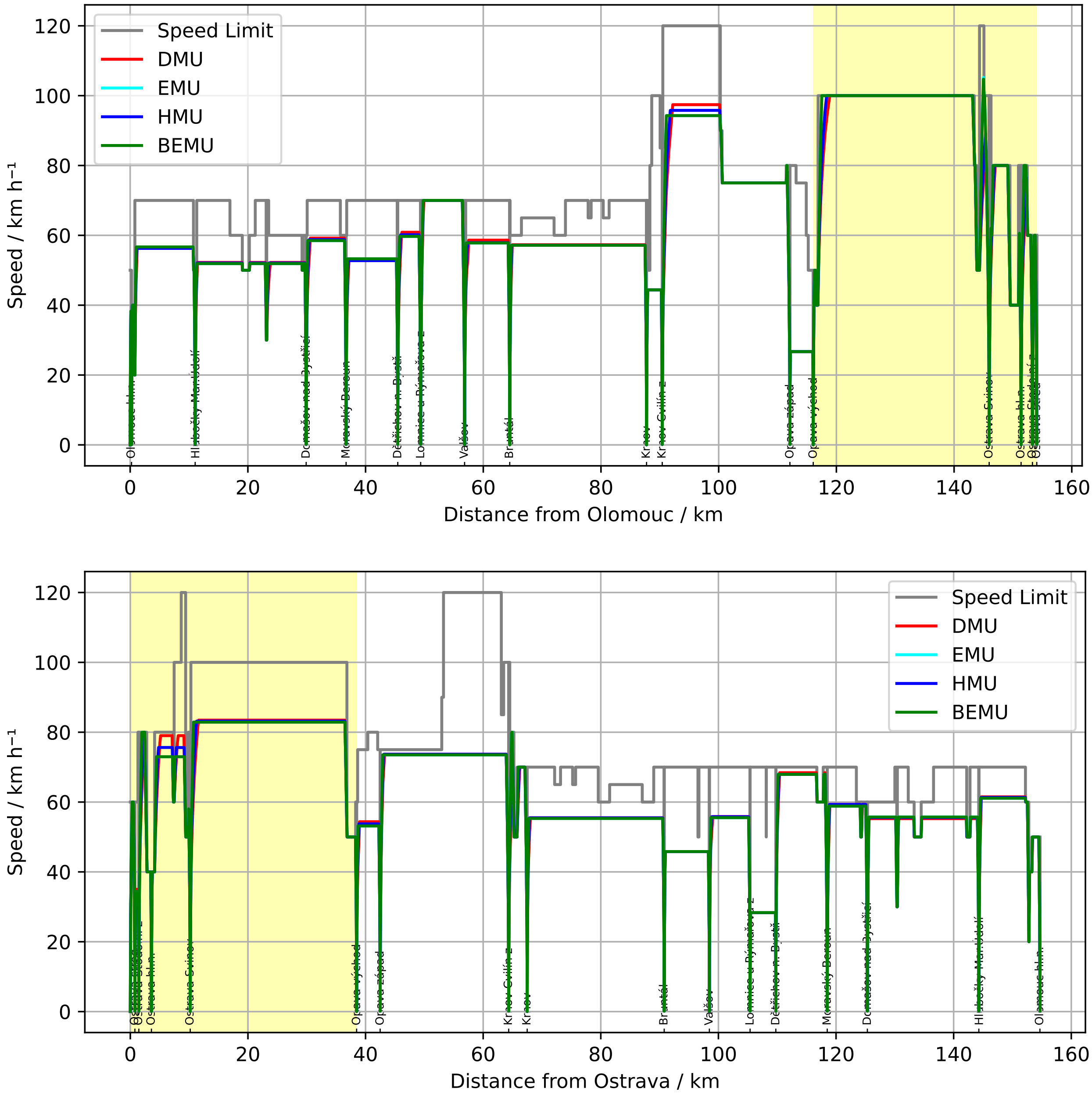


Figure 3.29: Speed profiles in the eastbound and westbound journeys of R27.

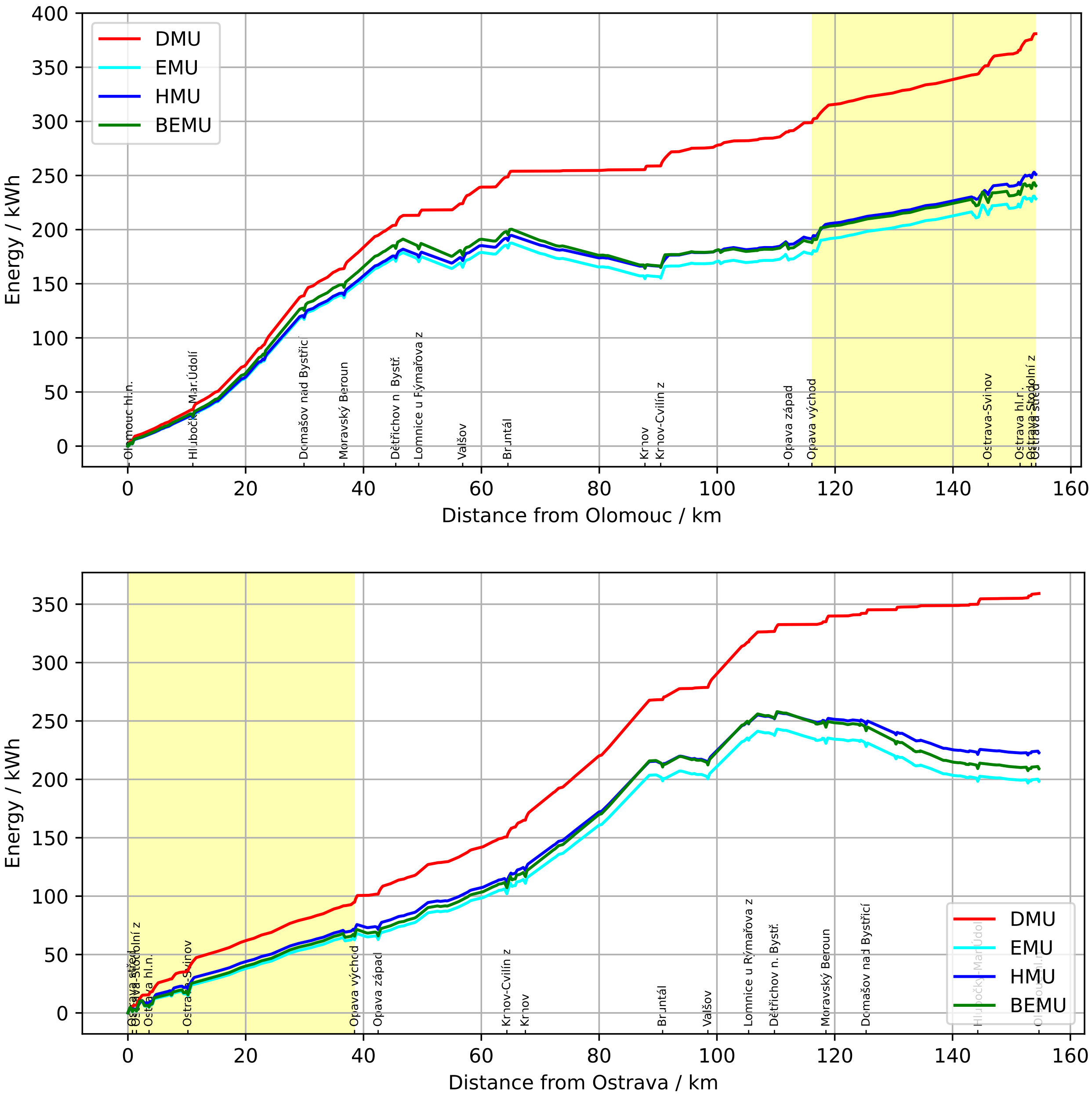


Figure 3.30: Motor energy profiles in the eastbound and westbound journeys of R27. Note that these profiles do not include auxiliary power.

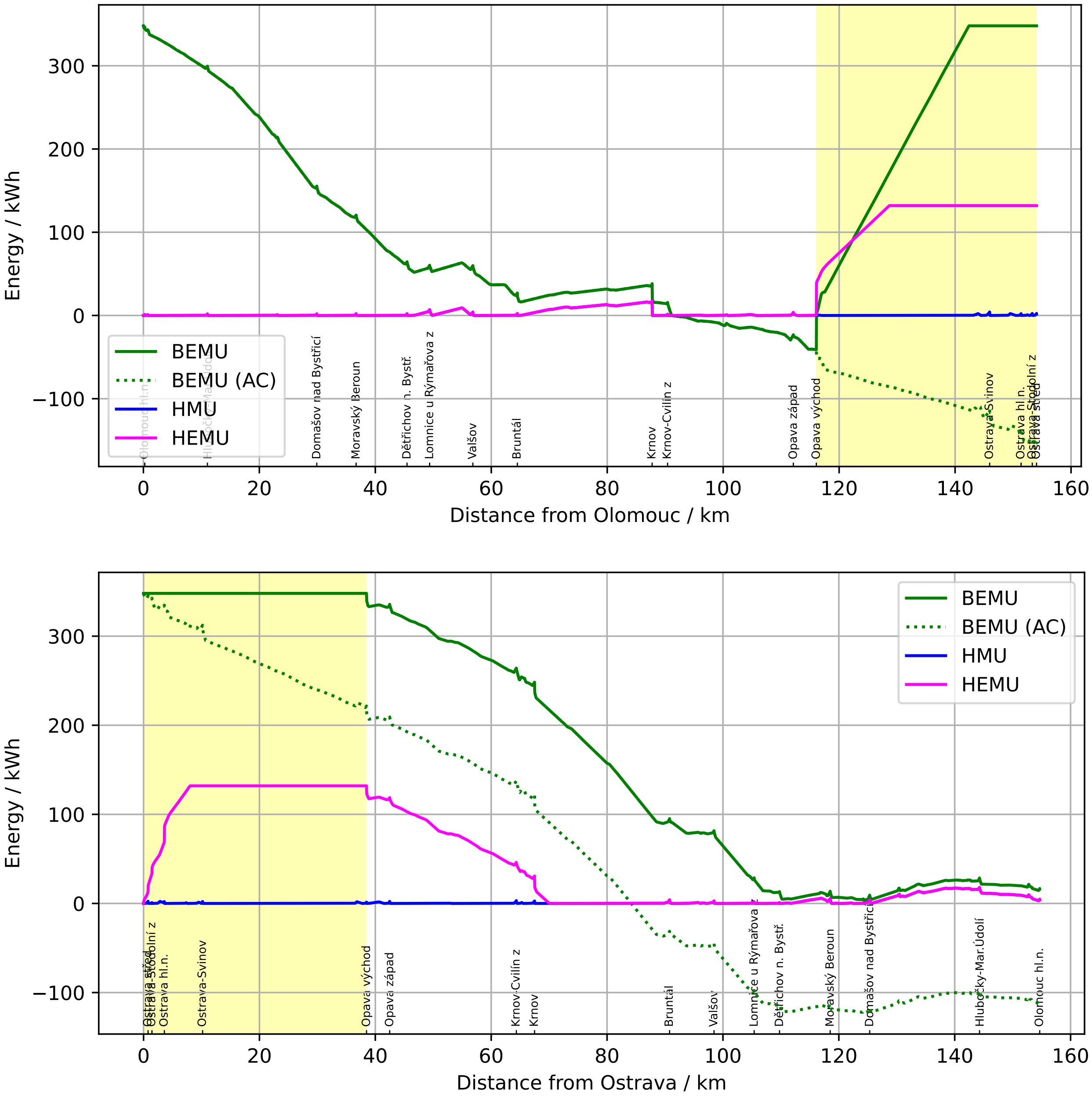
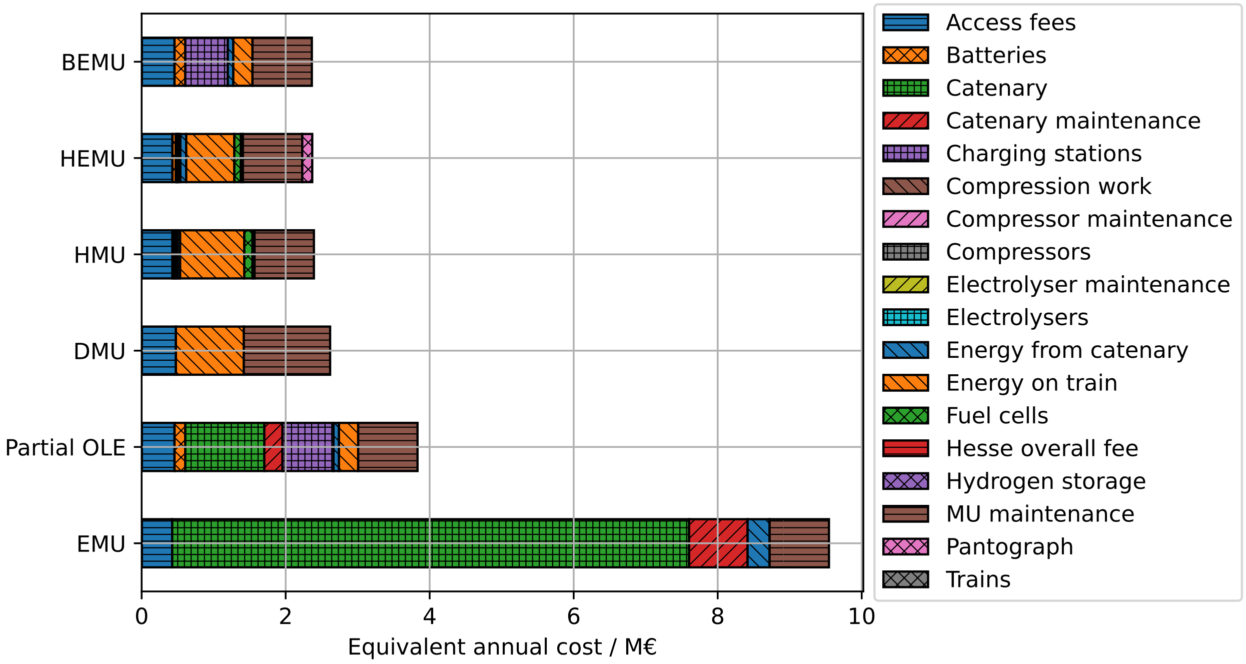
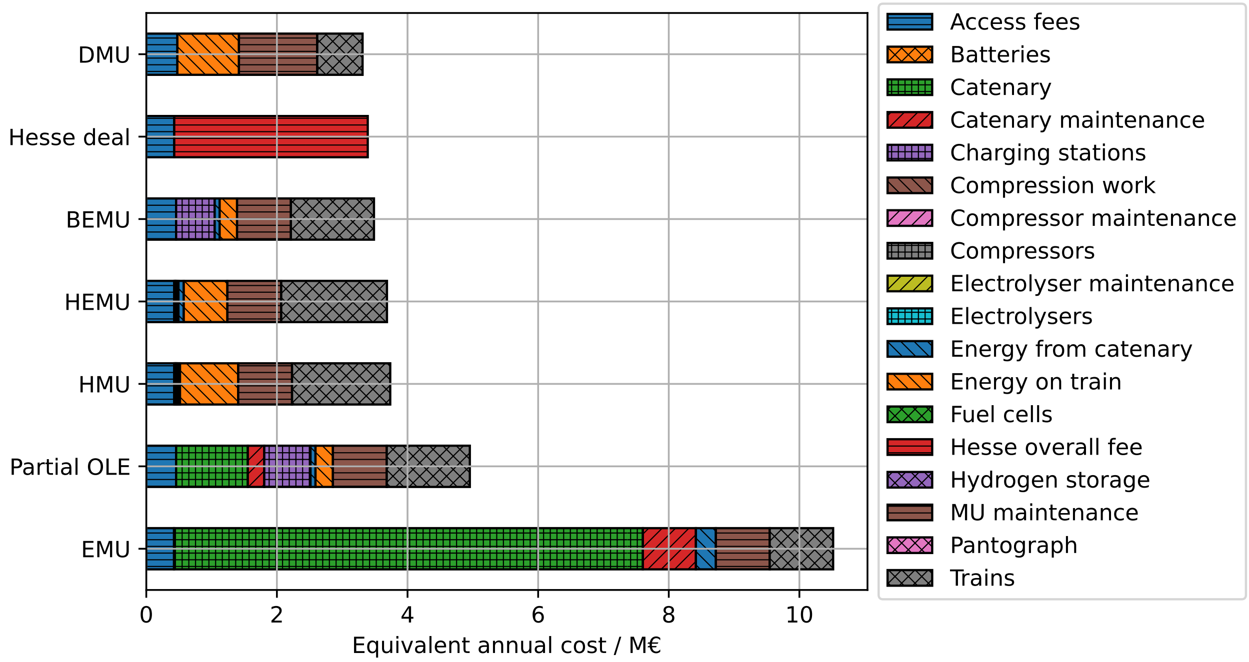


Figure 3.31: SoC profiles in the eastbound and westbound journeys of R27.



Technology	BCR	PBP a	UFI M€	km cost € / km	CA OLE %	CA POLE %
BEMU	1.11	18.44	12.79	3.15	10.13	28.68
HEMU	1.10	10.86	4.33	3.16	10.22	29.05
HMU	1.09	4.33	1.34	3.20	10.52	30.20
DMU	1.00	N/A	0.00	3.49	13.30	41.02
Partial OLE	0.68	N/A	33.81	5.11	N/A	N/A
EMU	0.27	N/A	124.13	12.74	N/A	N/A

Figure 3.32: Equivalent annual costs for different technologies applied on R27 (differential approach), and their main economic indicators.



Technology	BCR	PBP a	UFI M€	km cost € / km	CA OLE %	CA POLE %
DMU	1.00	N/A	12.00	4.42	9.83	20.19
Hesse deal	0.98	0.00	0.00	4.53	10.82	24.04
BEMU	0.95	N/A	32.20	4.65	12.02	28.68
HEMU	0.90	N/A	28.31	4.92	14.50	38.34
HMU	0.89	N/A	26.42	4.98	15.13	40.78
Partial OLE	0.67	N/A	53.22	6.61	N/A	N/A
EMU	0.31	N/A	140.93	14.03	N/A	N/A

Figure 3.33: Equivalent annual costs for different technologies applied on R27 (lumped approach), and their main economic indicators.

Table 3.7: Total energy consumption for the sections of line SP14. (E): electrified sector.

	L		DMU		EMU		BEMU		HMU	
	W	E	W	E	W	E	W	E	W	E
	km		E / kWh							
Bludov-Zábřeh (E)	7	6	10	14	6	20	6	21	10	20
Bludov-Krnov	116	116	329	347	350	366	359	377	375	394
Totals	123	122	339	361	356	386	365	398	385	414

3.8 SP14, Zábřeh na Moravě–Krnov

This line does not formally exist and has been labelled SP14 for convenience. The line is also located in eastern Czechia and is connected at Krnov with R27. Trains start from Zábřeh na Moravě, a DC-electrified station, along a line that is electrified for a few kilometres until the Bludov fork. Trains then continue to Jeseník, where they pause for about half an hour; they then proceed towards Krnov, passing through the station of Głuchołazy in Poland on the way [22]. The line's traffic is served by 2 MUs.

3.8.1 Simulation Results

The speed profiles are shown in figure 3.34. All technologies seem to serve the section adequately, with few sections where it is necessary to proceed at the speed limit. In particular, in the section between Jeseník and Hanušovice, it appears that diesel trains accumulate a delay compared to electric trains, though this is eventually recovered; the potential to improve punctuality with electrification is limited.

Motor energy profiles are presented in figure 3.35. The profiles of all electric alternatives are quite close together, whereas diesel is much higher, also when compared to other lines. This occurs not just because of the significant altitude reached by the track (almost 700 m at Ostružná), but also because the diesel unit used on SP14 is the CZ843, much heavier than the usual CZ845 considered in previous lines. The length and energy consumptions of line segments are presented in table 3.7.

The state-of-charge profiles for battery and hydrogen trains are presented in figure 3.36. Due to the very short distance ran under OLE, battery trains on SP14 will essentially need to run the line's whole length twice (counting the return leg) on a single charge. It is visible from the diagram that Mireo+B trains will not be able to complete either direction without exiting the nominal 20 %–80 % SoC window, resulting in significant degradation over time. In addition, as was the case for R21 and R22, one terminus of the line, Krnov, is not electrified.

However, it is possible to make battery operation feasible by exploiting the long stop (about half an hour) trains have in Jeseník, installing a charger there. This means battery operation will demand two DC chargers and their feeders, one in Jeseník and another in Krnov. Krnov is also a station on R27 and was assumed to have installed a charging station, so there is a possibility to share costs there.

Note also how auxiliary systems demand more energy than propulsion, due to the long stops at several stations, especially Jeseník.

3.8.2 Analysis of Alternatives

The results of the techno-economic analyses of the alternatives are presented in figures 3.37 (differential approach) and 3.38 (lumped approach).

BEMUs have a particularly negative performance on SP14 because of the necessity of chargers in both Jeseník and Krnov increases compounded with such a modest amount of traffic, increasing their cost significantly. Even if the costs for the Krnov charging station were shared with R27, BEMUs would remain behind both

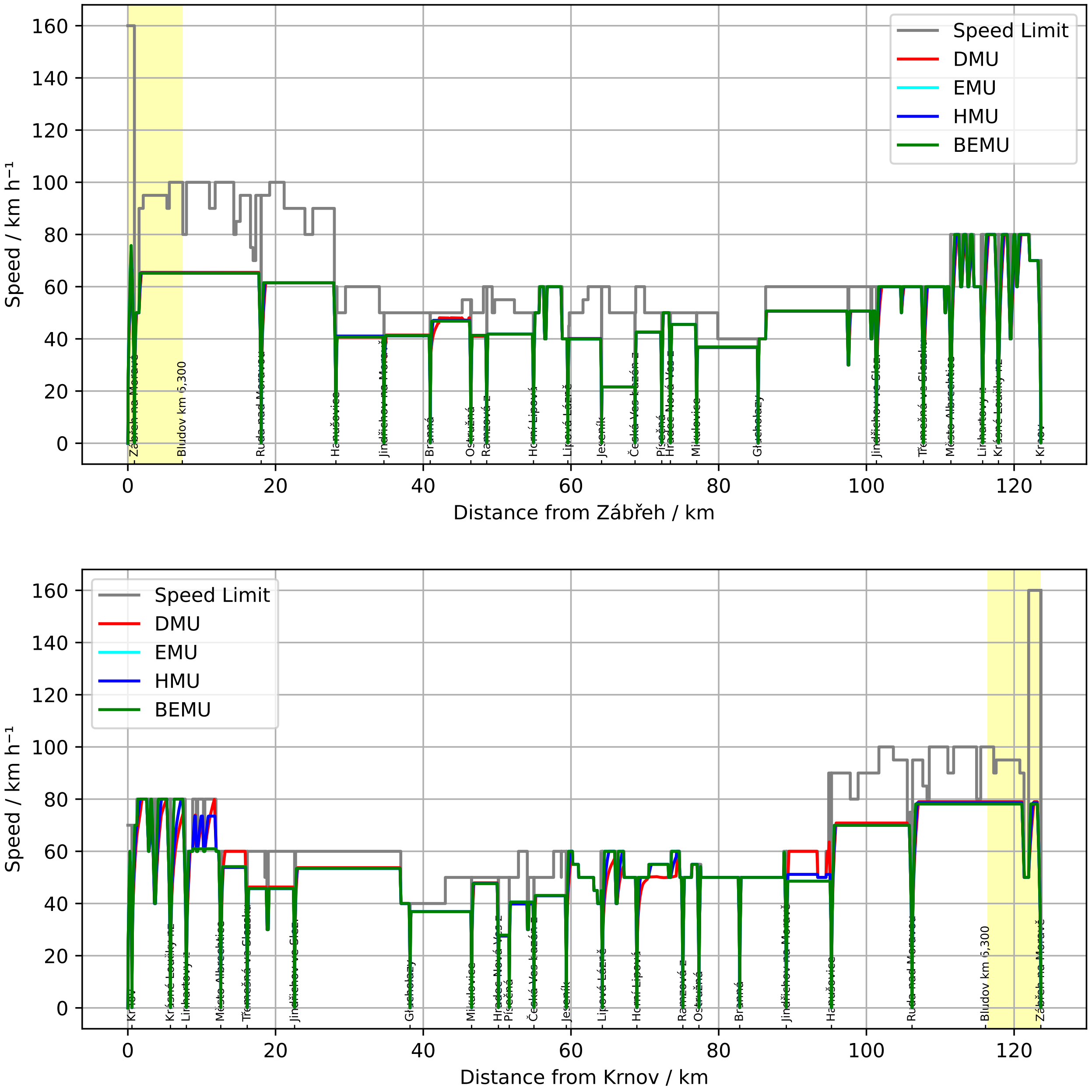


Figure 3.34: Speed profiles in the eastbound and westbound journeys of SP14.

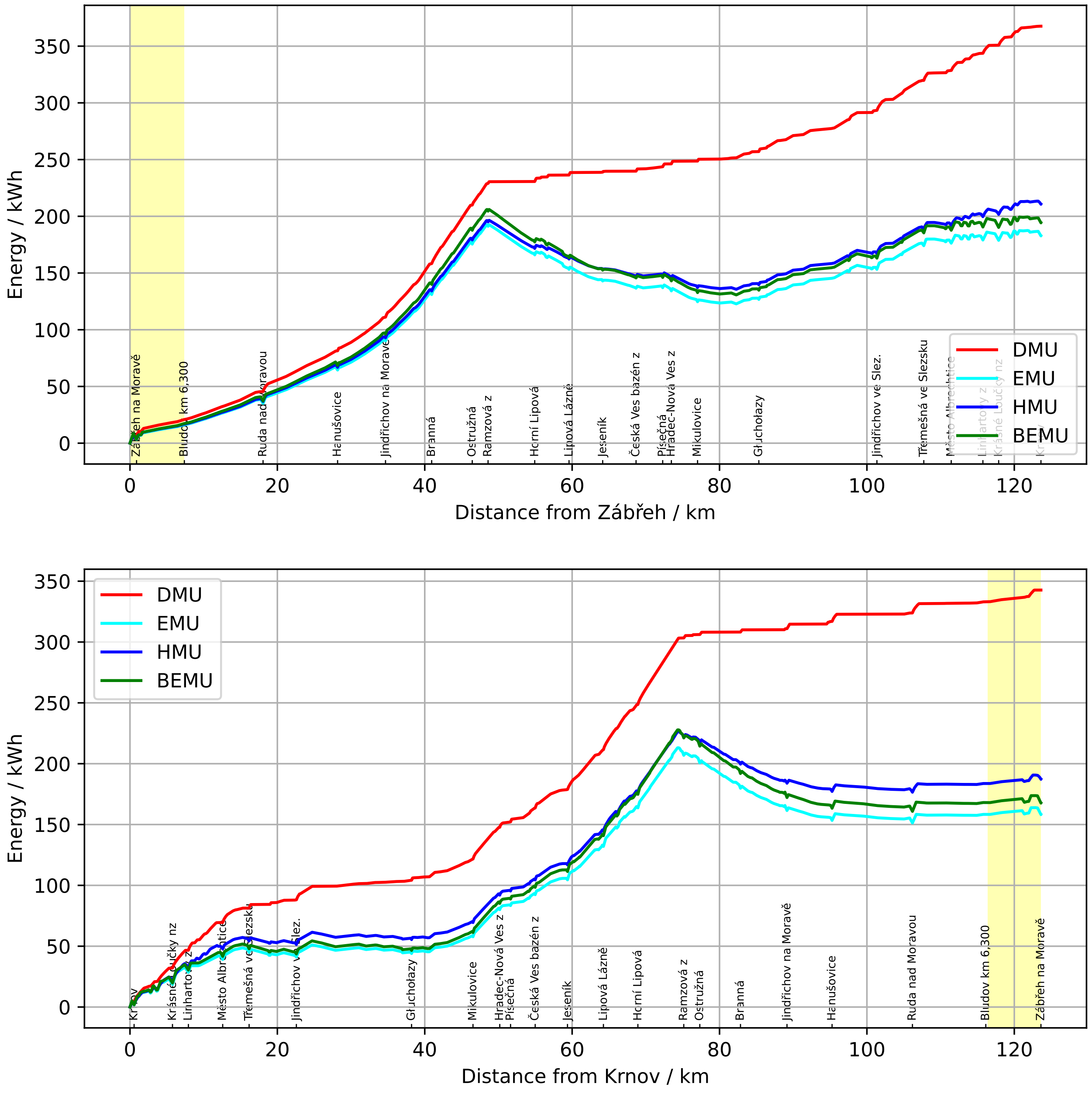


Figure 3.35: Motor energy profiles in the eastbound and westbound journeys of SP14. Note that these profiles do not include auxiliary power.

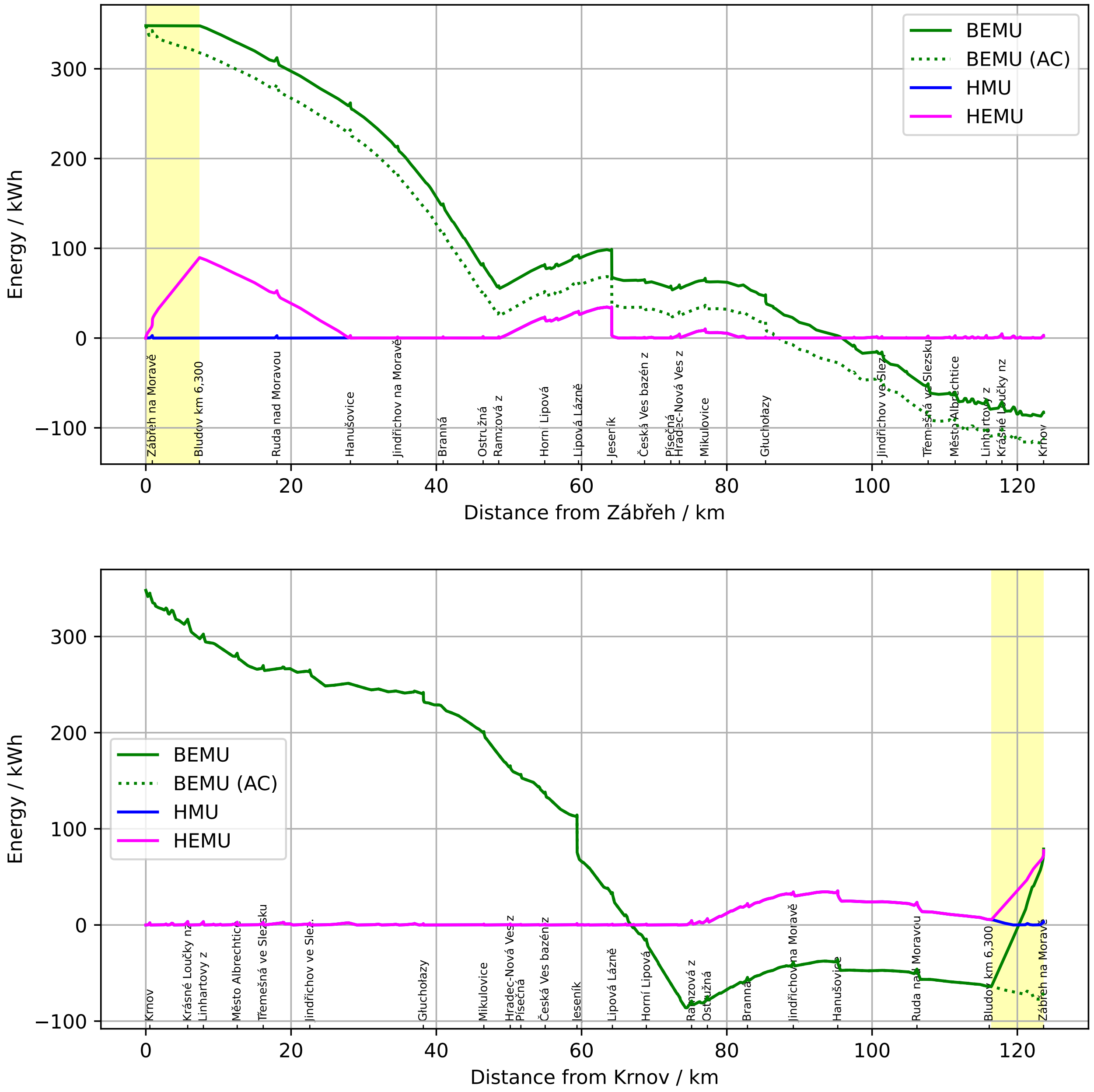
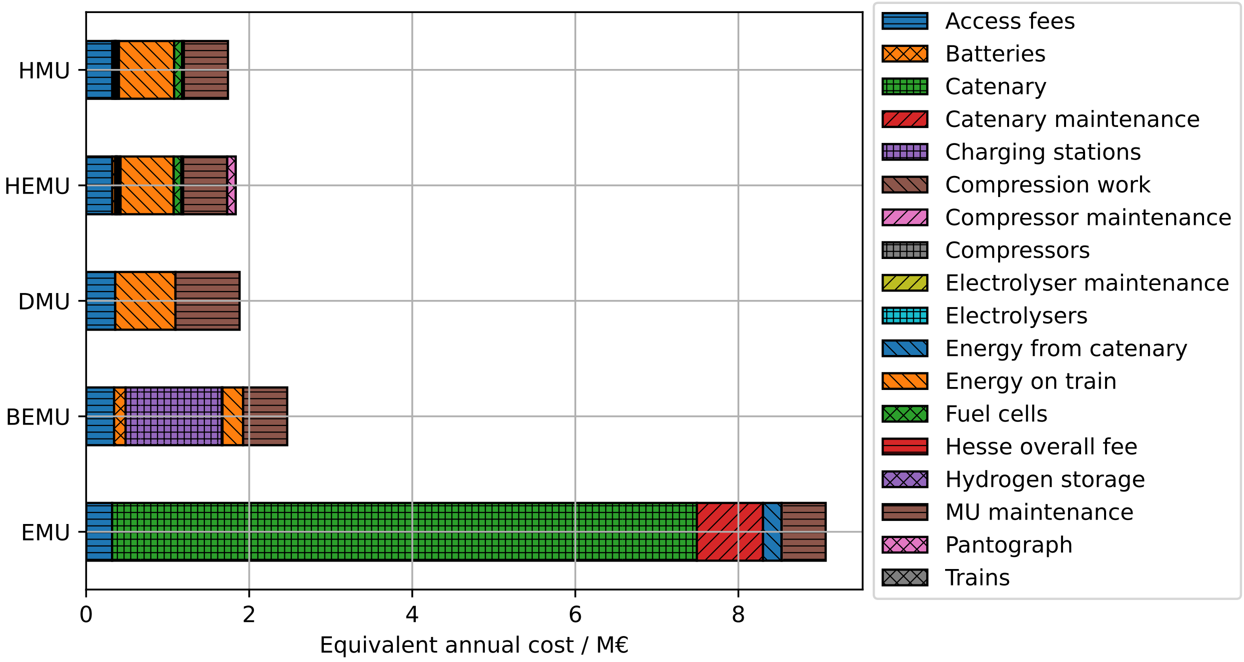
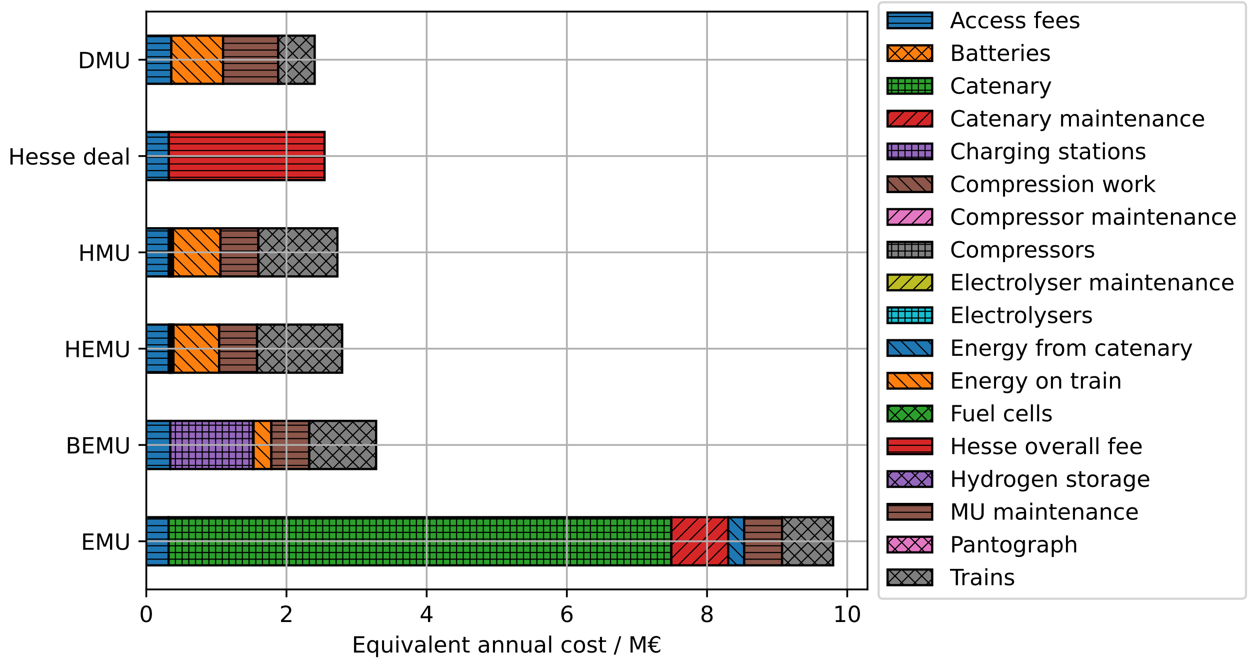


Figure 3.36: SoC profiles in the westbound and eastbound journeys of SP14.



Technology	BCR	PBP a	UFI M€	km cost € / km	CA OLE %
HMU	1.08	4.73	1.06	3.54	8.20
HEMU	1.02	22.67	3.12	3.74	9.39
DMU	1.00	N/A	0.00	3.83	9.96
BEMU	0.76	N/A	22.58	5.02	17.28
EMU	0.21	N/A	124.02	18.45	N/A

Figure 3.37: Equivalent annual costs for different technologies applied on SP14 (differential approach), and their main economic indicators.



Technology	BCR	PBP a	UFI M€	km cost € / km	CA OLE %
DMU	1.00	N/A	9.00	4.89	7.35
Hesse deal	0.94	0.00	0.00	5.17	9.11
HMU	0.88	N/A	19.79	5.55	11.41
HEMU	0.86	N/A	21.28	5.69	12.26
BEMU	0.73	N/A	36.91	6.67	18.33
EMU	0.25	N/A	136.62	19.93	N/A

Figure 3.38: Equivalent annual costs for different technologies applied on SP14 (lumped approach), and their main economic indicators.

hydrogen and diesel trains.

HMUs are a clear favorite for this line, and their estimated costs with the lumped-cost method are well aligned with the estimates of the Hesse deal.

Table 3.8: Total energy consumption for the sections of line U28. (E): electrified sector, 15 kV AC between Bad Schandau and Dolní Žleb, DC from Dolní Žleb to Děčin.

	L		DMU		EMU		BEMU		HMU	
	N	S	N	S	N	S	N	S	N	S
	km		. . . .	. . . .	. . . E / kWh	. . .	. . . .	. . . .		
Rumburk-Sebnitz	27	27	68	48	102	62	106	63	110	72
Bad-Sebnitz	15	15	58	14	99	0	104	-2	102	7
Bad-Dolní (E)	12	12	43	48	39	57	41	59	54	68
Dolní-Děčín (E)	10	10	34	40	35	40	36	41	43	50
Subtotal electrified	22	22	77	88	74	97	77	100	97	118
Subtotal non-electrified	42	42	126	62	201	62	210	61	212	79
Totals	64	64	203	150	275	159	287	161	309	197

3.9 U28, Rumburk–Děčin (over Bad Schandau)

This line is a particular case as it crosses the German-Czech border twice. Used mainly for tourist traffic, U28 overlaps the final leg of R21 and proceeds southwest through a non-electrified track until it crosses the border at Sebnitz [23]. There is a quick descent to lower altitudes, from 320 m in Sebnitz to 120 m in Bad Schandau, where an AC-electrified track begins and continues until re-entering Czechia at Dolní Žleb; note that this is *German* AC, i.e. 15 kV, not the Czech 25 kV. From the border until the terminus in Děčin, the track is then DC-electrified. The line's traffic is served by 3 diesel MUs of the type Desiro 642.

3.9.1 Simulation Results

The speed profiles are shown in figure 3.39. All technologies serve the section adequately in the section between Rumburk and Bad Schandau, but only (B)EMUs can take advantage of the higher speed limit between Bad Schandau and Děčin, with hydrogen and diesel trains showing clearly slower acceleration at high speeds.

While more than half of the stops on U28 is only on demand, no one of the optional stations are between Bad Schandau and the Czech border (whereas all stations between Dolní Žleb and Děčin are on demand). This seems to indicate that Desiro 642s and iLints are underpowered for the Bad Schandau–Dolní Žleb section, and may accumulate some regular delay.

The uphill section from Bad Schandau to Sebnitz, on the other hand, seems not to be an issue for any of the technologies, due to the low speed limit.

Motor energy profiles are presented in figure 3.40. They are significantly different in that motors in the downhill direction can regenerate so much energy that they will produce more of it than use until they pass Bad Schandau; diesel trains, not having the ability to regenerate energy, have therefore about 3 times the motor energy consumption of EMUs.

The returning profiles from Děčin are instead much closer, due to the lower opportunities for energy regeneration. The length and energy consumptions of line segments are presented in table 3.8.

The state-of-charge profiles for battery and hydrogen trains are presented in figure 3.41. Due to the downhill profile of the southbound journey, battery trains have hardly any loss of charge, and reach Bad Schandau in the plains having used less than 70 kWh; as the rest of the track is flat and electrified with *two* systems, battery trains are all but guaranteed to arrive in Děčin almost fully charged.

The northbound journey is more challenging, with a long non-electrified uphill section; however, the short distance and the slow speed result in moderate consumption, making the journey feasible for both AC and DC battery trains.

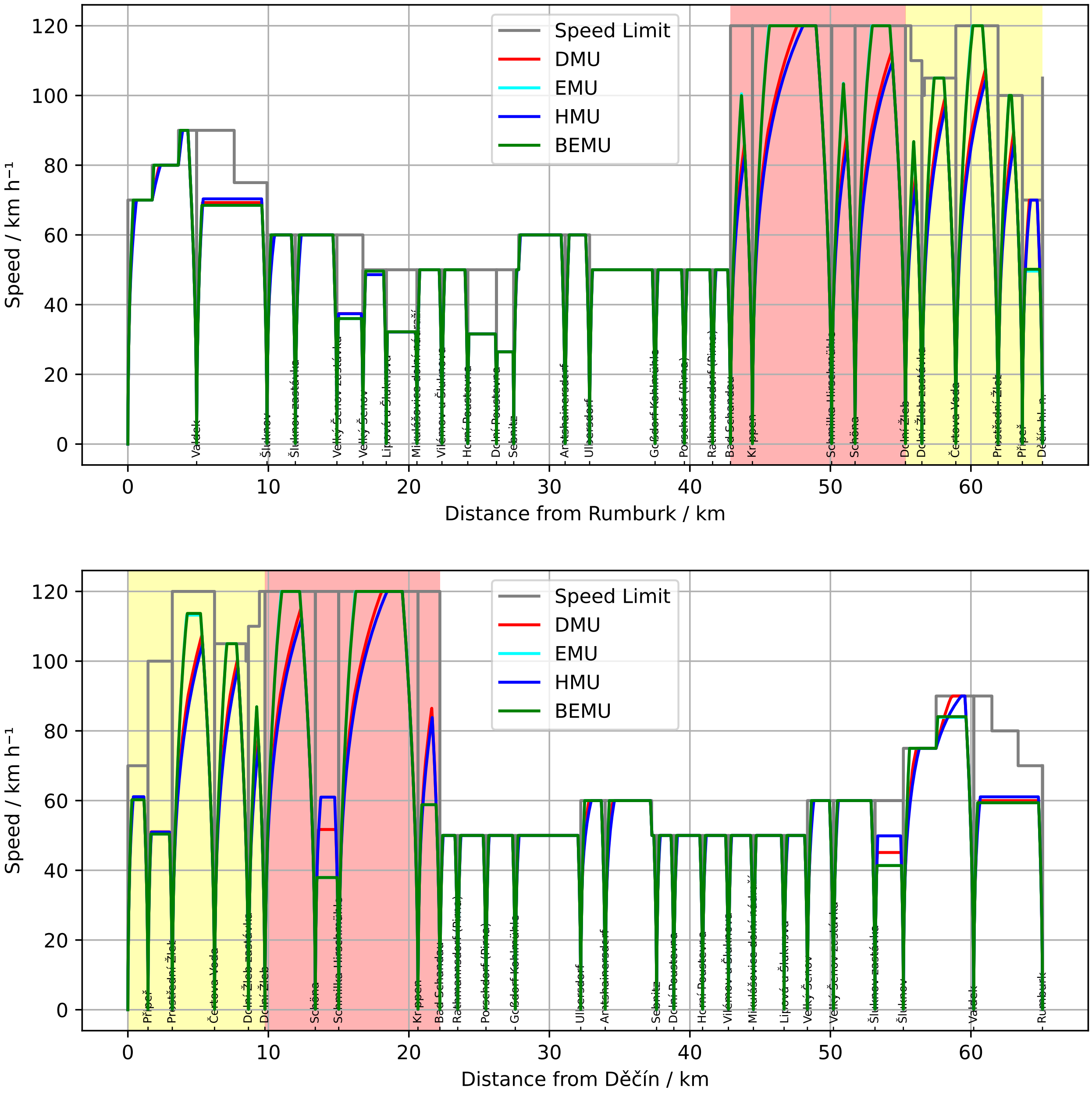


Figure 3.39: Speed profiles in the southbound and northbound journeys of U28.

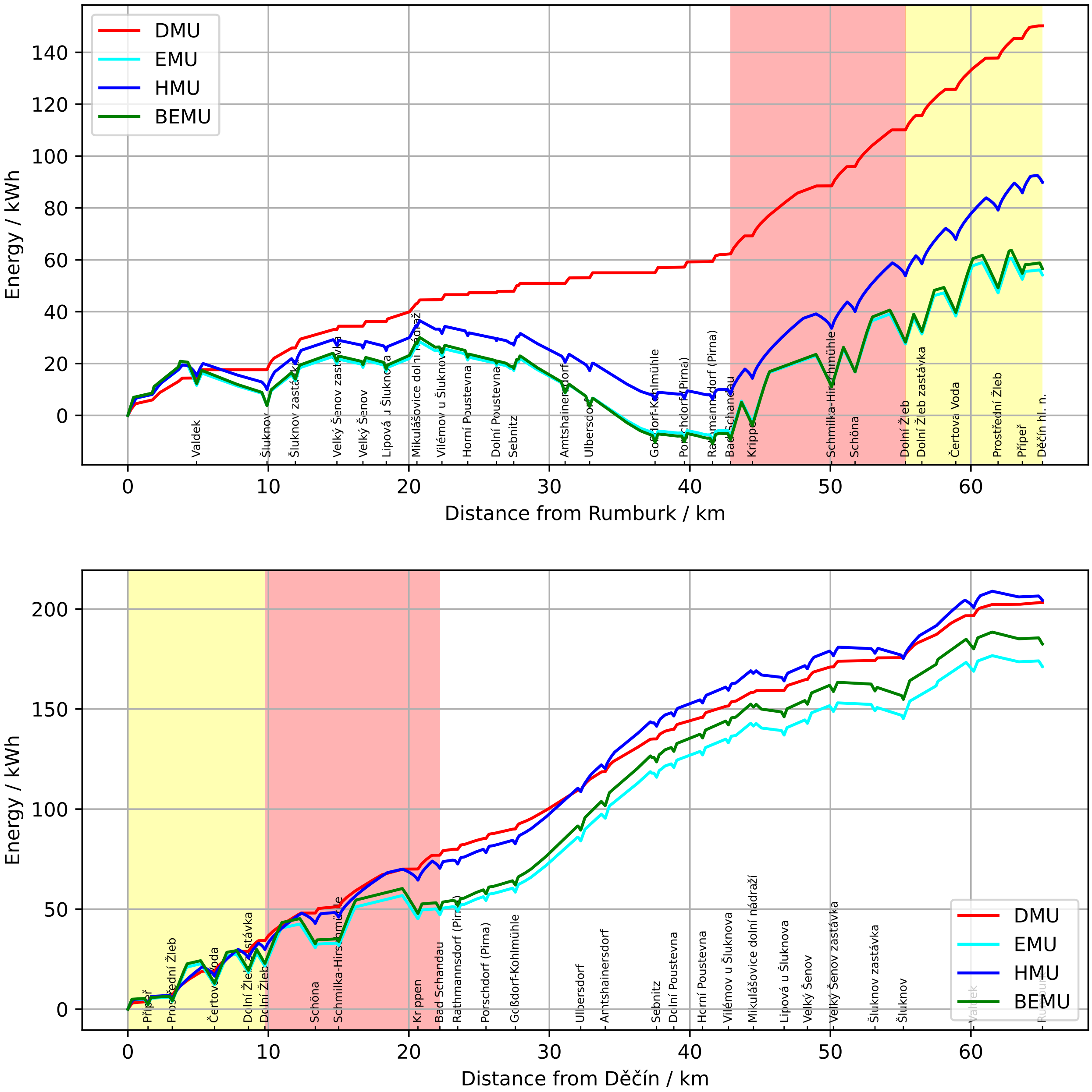


Figure 3.40: Motor energy profiles in the southbound and northbound journeys of U28. Note that these profiles do not include auxiliary power.

Considering the SoC level expected at Rumburk, AC BEMUs will easily be able to return to Bad Schandau, where they will be able to recharge, without the need of an additional charging station in Rumburk (which may be incompatible with other Czech AC BEMUs).

DC BEMUs, instead, must cover a longer section without charging, and their residual charge in Rumburk is insufficient to take them back all the way to Dolní Žleb: for this reason, they will need a charging station in Rumburk, which will negatively affect the feasibility of the option.

3.9.2 Analysis of Alternatives

The results of the techno-economic analyses of the alternatives are presented in figures 3.42 (differential approach) and 3.43 (lumped approach).

AC BEMUs have the best performance among zero-emission options, thanks to the ability to piggyback on the pre-existing catenary in German territory, which is aptly located in the middle of the route. Hydrogen options come in third after diesel, due to higher energy costs, and DC BEMUs come in last of the non-catenary options, because of the heavily distorting effect of the charging station required in Rumburk for just 3 MUs.

Note that DMUs have the additional advantage of operating a light unit, resulting in much lower access fees. These access fees were modelled on the Czech rail network, and the German network may have different rules.

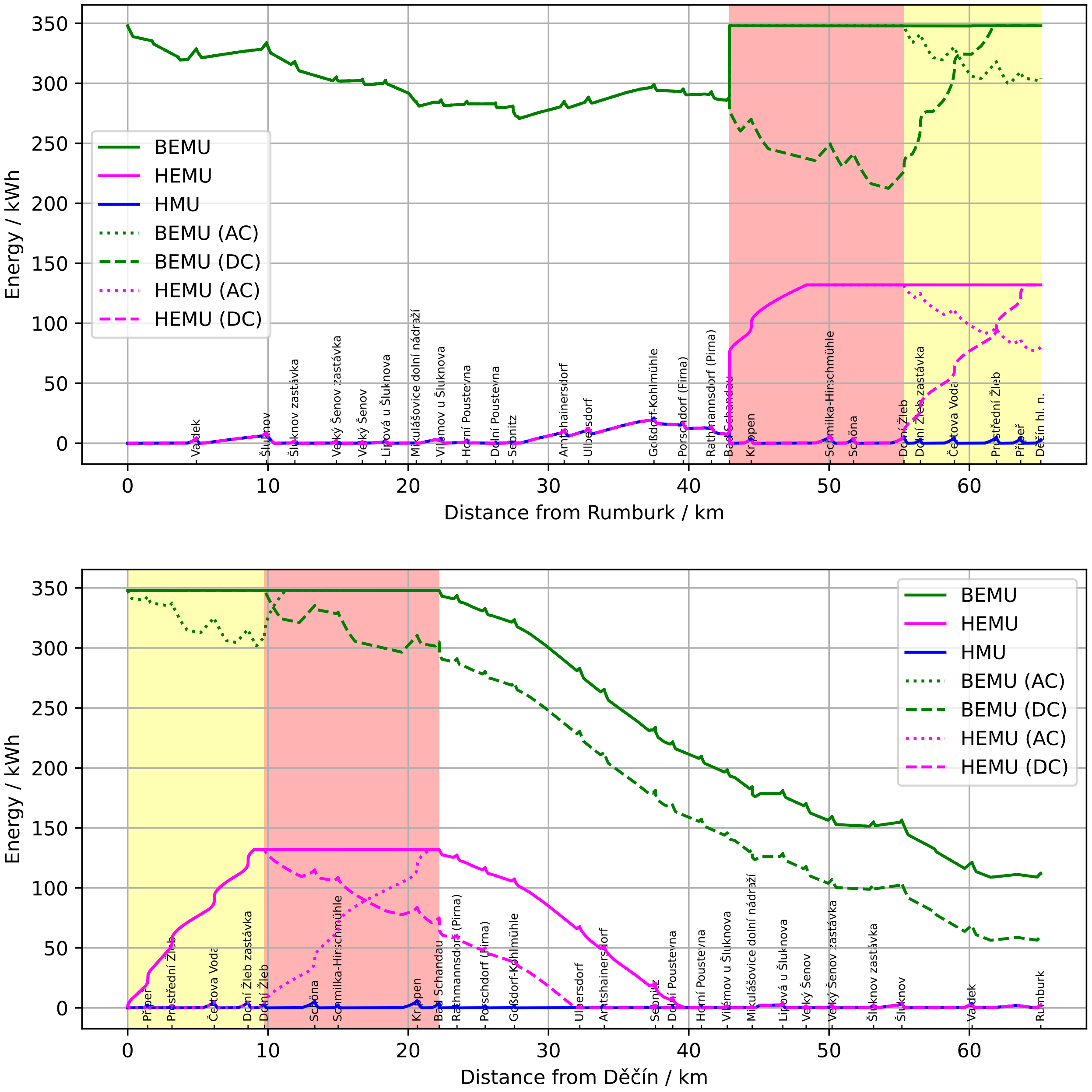
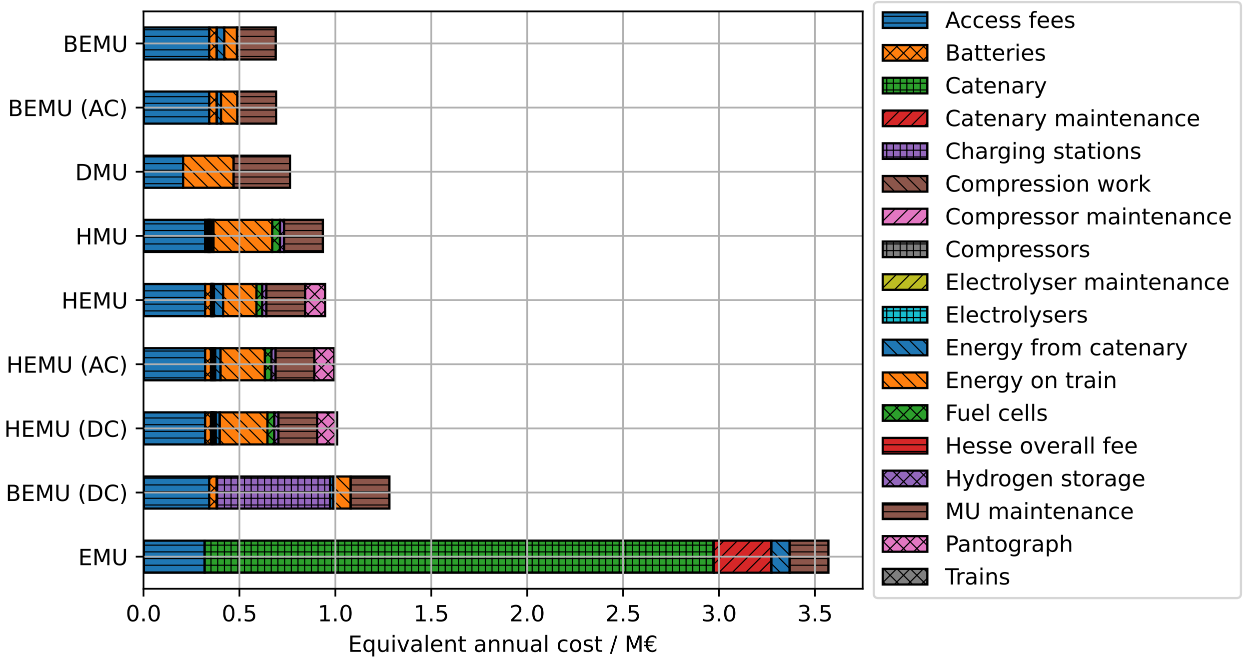
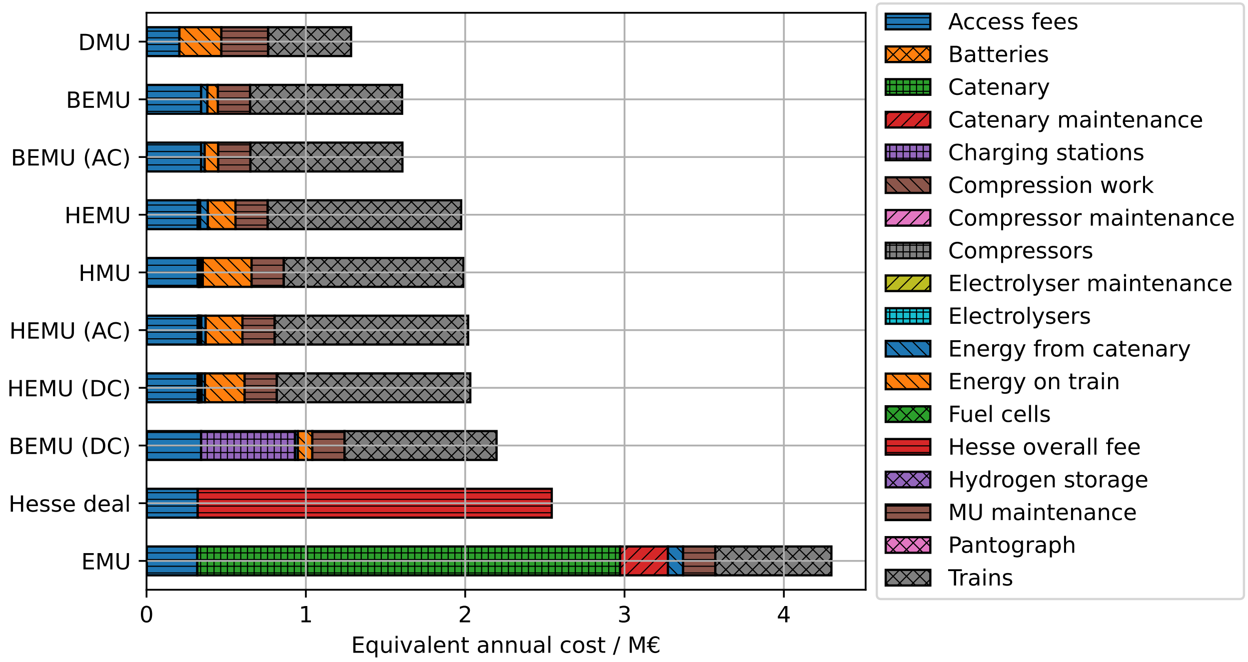


Figure 3.41: SoC profiles in the southbound and northbound journeys of U28.



Technology	BCR	PBP a	UFI M€	km cost € / km	CA OLE %
BEMU	1.11	6.14	0.61	3.75	2.48
BEMU (AC)	1.10	6.27	0.61	3.76	2.55
DMU	1.00	N/A	0.00	4.16	5.00
HMU	0.82	N/A	0.86	5.09	10.82
HEMU	0.81	N/A	3.13	5.16	11.22
HEMU (AC)	0.77	N/A	3.16	5.42	12.85
HEMU (DC)	0.76	N/A	3.17	5.50	13.35
BEMU (DC)	0.60	N/A	10.81	6.98	22.54
EMU	0.21	N/A	45.89	19.44	N/A

Figure 3.42: Equivalent annual costs for different technologies applied on U28 (differential approach), and their main economic indicators.



Technology	BCR	PBP a	UFI M€	km cost € / km	CA OLE %
DMU	1.00	N/A	9.00	6.99	-2.05
BEMU	0.80	N/A	16.50	8.74	8.79
BEMU (AC)	0.80	N/A	16.50	8.75	8.86
HEMU	0.65	N/A	21.07	10.75	21.34
HMU	0.65	N/A	19.65	10.83	21.82
HEMU (AC)	0.64	N/A	21.11	10.99	22.82
HEMU (DC)	0.63	N/A	21.12	11.07	23.28
BEMU (DC)	0.58	N/A	26.70	11.96	28.86
Hesse deal	0.50	0.00	0.00	13.85	40.58
EMU	0.30	N/A	58.49	23.41	N/A

Figure 3.43: Equivalent annual costs for different technologies applied on U28 (lumped approach), and their main economic indicators.

Chapter 4

Conclusions

4.1 General Results

The main conclusion of this report is that there is significant potential for battery and hydrogen trains in Czechia, and that their operation is far cheaper than any plans for full or even partial electrification, in addition to be much simpler and quick to deploy. Furthermore, the overall costs of H(E)MUs or BEMUs are often lower than renewed operation with DMUs.

There is no general answer on which between hydrogen and battery is the best zero-emission electrification technology, as it depends highly on the local conditions: for example, HMUs have a strong advantage on SP14, while BEMUs lead on R26. The most recurring decisive factors in determining the competitiveness of battery vs. hydrogen trains were the length of the line and the necessity of charging stations at non-electrified termini: if the line is short enough, and power is available in some form at both termini, BEMUs are usually favoured.

All techno-economic analyses have been run with the differential and lumped cost approaches, i.e. pricing single technology items (fuel cells, batteries etc.) or using MU market price estimates. The results indicate that market costs for BEMUs and H(E)MUs appear significantly higher than what their technological cost should indicate, which may be due to premiums paid by first movers, risk hedging by manufacturers or increased costs due to still low production volumes. It is however likely that costs for BEMUs and especially H(E)MUs will decrease in the following years.

4.2 Comments on Hydrogen

Hydrogen has been assumed to be produced by electrolysis with electricity sourced from the Czech grid, and its cost has been calculated to be about 8.5 €/kg (see table 4.1), a high price compared to the ambitions of the EU; most of this cost is due to energy. If a sizeable source could be found able to provide hydrogen at a lower cost, for example as by-product of industrial processes, the general economy of hydrogen trains would be improved, as fuel is a significant component of their cost breakdown.

It should be noted that electrolysers and fuel cells are not a major component of the cost breakdown for any line: this means that further CAPEX reductions (as recently revealed for electrolysers after a public auction in China [24]) will have limited impact on the results.

On the other hand, being able to provide hydrogen at a lower cost may be much more effective in promoting H(E)MUs; we assumed in this study that all hydrogen was produced from electrolysis, but there are several options to reduce its cost:

- Import cheaper hydrogen from abroad;
- Run HEMUs with hydrogen as range extender (i.e. only when batteries are insufficient) to reduce its consumption;

Table 4.1: Cost items for the production of hydrogen from electrolysis in Czechia.

Item	Cost / € kg^{-1}
Electrolysers	0.3
El. maintenance	0.17
El. energy	7.74
Compressors	0.13
Comp. maintenance	0.06
Comp. energy	0.16
Total	**8.55**

- Exploit by-product hydrogen that is currently being burned or released to atmosphere by industrial processes;
- Increase the size of the electrolyser, and produce hydrogen only a fraction of the day when power is cheaper;
- Employ cheaper tariffs for disconnectible power (to be evaluated if available in Czechia, now or in the future);
- Increase the size of the electrolyser, and provide reserve services to the grid, i.e. monetising the electrolyser's flexibility, creating a new income stream.

The calculated consumption of hydrogen per km was calculated to be significantly lower than what was claimed by manufacturers for some of the lines; this was tracked down to the low speeds that characterise the rural Czech lines we investigated. When isolating e.g. the Sebnitz–Bad Schandau section, with speed limits over 100 km/h, hydrogen consumption was calculated to be more in line with commercial estimates.

Current hydrogen prices in Czechia are estimated in the range of 10–14€/kg. We consider this price an excessive estimate for any sensible planning, as it is significantly higher than our calculation; while there are some extra costs we did not consider (e.g. area procurement for fuelling stations, personnel training, etc.) these are minor compared to the cost of electrolysers, which in turn are far cheaper than energy in table 4.1. Indeed, the uncertainty alone in the current market prices is *double* the EU's ambition for green hydrogen production cost in 2030.

The reason for so high prices is to be found in the low volumes currently traded, typically to laboratories and workshops, the high relative cost of transport of few gas flasks to many small customers, and generally the immaturity of the market. Trains will require far larger quantities, to be produced regularly through the year, allowing economies of scale and long-term purchase agreements to have an effect on market prices.

4.3 Comments on Batteries

All examined routes are partially electrified, even though SP14 has just a few kilometres outside Zábřeh and R26 more than half its length[1]; with the exception of R26, U28 and one terminus of R25, these segments are all electrified with DC. As there are plans to replace all DC with AC across the Czech network, battery trains would cause a dilemma:

- Buy DC-compatible BEMUs, and have to replace them in a few years;
- Buy DC- and AC-compatible BEMUs, possibly more expensive;

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[1] Assuming its nominal route along the Berounka, rather than the current less-electrified route through Rudná.

- Put off electrification until lines have been converted to AC, and then buy AC-compatible BEMUs.

While battery trains have consistently lower operation cost than hydrogen trains, they also often require charging stations that rapidly increase required investments. As a result, even when their overall equivalent annual cost is competitive or even better than hydrogen alternatives, battery trains often have a significantly longer payback period.

The SoC simulations done with data for Mireo+B 2-car MUs seems to indicate a longer range than what usually claimed by the manufacturer, i.e. over 100 km compared to about 80 km. This may be due to the lower speeds simulated for the lines in this study (similarly to the effect of low hydrogen consumption measured for HMUs), but it may also indicate a more severe limitation of SoC than 20 % to 80 %, possibly accounting for degradation over time.

4.4 Recommendations

Given the analyses of the previous chapters, the recommendations for technology choices are:

Northeastern Bohemia (Lines R14, R21, R22) Hydrogen trains appear to be a better option overall. The required chargers in Liberec, Tanvald, Turnov, Svor and Šluknov make the battery alternative less competitive, and the presence of several partial train routes (especially Jaroměř–Liberec on R14 and trains stopping at Rumburk, Svor and Nový Bor on R22) may demand further ones. Batteries appear to have better economic performance on R14, but the section from Pardubice to Liberec is slightly beyond their range.

Western Bohemia (Lines R25 and R26) Battery trains have here an advantage in that OLE is more available in this area. All termini in this area are electrified, so additional chargers are not needed, and all non-electrified sections can be traversed by commercially available trains with good SoC margin. The only challenge is the mixture of AC and DC in the area: R26 can immediately choose AC, but R25 can only choose DC, which may need to be replaced in a few years.

R27 This line is a “draw” between battery and hydrogen trains, because of a long section of OLE (Opava–Ostrava) and possibility to charge in Olomouc station, but also of the need of a top-up charger in Krnov. Depending on the plans for conversion to AC, hydrogen may be favoured until the switch is completed.

SP14 Hydrogen trains have a significant advantage here, as the line has very little traffic, but requires two charging station in Krnov and Jeseník for battery trains, which significantly hamper their economy.

U28 (German) AC battery trains are a clear choice for this line, both for the ability to exploit the pre-existing AC catenary and the short length of the line.

In almost all cases, both batteries and hydrogen are competitive with diesel, which is due to the high cost of diesel fuel and low efficiency of internal combustion engines, but also to the latter’s higher maintenance costs. In the lumped analyses, DMUs can sometimes outperform clean alternatives as DMUs are assumed to be far cheaper second-hand units.

It is also clear from all analyses that full OLE deployments are not economically viable, as their enormous investments are not worth the savings obtained by moving to electric propulsion. Finally, partial electrification (as designed in the document of the Czech Ministry of Transport) is indeed cheaper than full OLE deployment, and may even have been competitive in some cases if the alternative had been only DMUs, but can as a rule not compete with either BEMUs or HMUs.

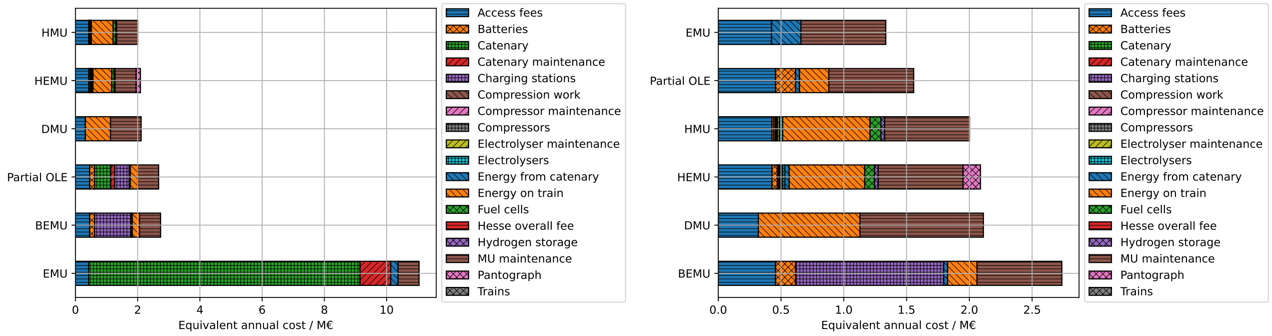

Figure 4.1: The annual costs of various alternatives for R22 from an all-society perspective (left) and one limited to local authorities (right).

4.5 Perspective of Local Authorities

Local authorities have expressed interest in OLE solutions because, from their point of view, they will be responsible for OPEX (which is indeed lowest for EMUs), whereas the central government will be responsible for the much larger CAPEX of the infrastructure.

While such a perspective may be myopic, it shows that local authorities, acting rationally, may push for solutions far more expensive for society as a whole. See for example figure 4.1, referred to R22: when applying the perspective of local authorities, the ranking of solution is almost inverted, placing EMUs in first place.

This indicates that, if the central government in Prague intends to choose hydrogen or battery alternatives, it may have to win local authorities over by sharing its savings with them by transferring funds to compensate for their higher OPEX. Specifically for the example in figure 4.1, the central government could save about 9 million € a year by choosing e.g. HMUs over EMUs: if this amount were to be evenly split with local authorities, the resulting 4.5 million € transfer would far more than compensate for the additional 0.7 million € that local authorities would have to pay for operation, mostly for procurement of hydrogen fuel.

4.6 Basic Sensitivity Analysis

A full sensitivity analysis is beyond the scope of this report, but the following parameters deserve special mention for increased attention when applying this report's conclusion:

Diesel cost Fossil fuels have historically had very variable costs depending on international contingencies, and are the main factor of uncertainty for DMU operation.

Hydrogen cost Ambitious EU targets aim to reduce the price far below the one estimated in this report. Even a limited success of these efforts may significantly improve the economy of HMUs.

Electrical energy cost Electricity is actually a minor cost item for (B)EMUs, but has stronger impact on H(E)MUs through the cost of hydrogen from electrolysis.

Electrical *power* cost As societies strive for decarbonisation, it is easy to predict a shift to electrical power transmission from fossil sources: this may overload the electrical grid, placing limits on power transmission that may translate to higher costs per unit of *power* (kW) rather than *energy* (kWh): as BEMUs often require rapid charging at specific times, this cost may become significant.

Chargers in rural areas It was noted by the Czech Ministry of Transportation's study on partial electrification that chargers in small, rural stations are far more expensive than in large urban stations: this is because the installation of the charger implies an extension of the grid, which may be a far more expensive proposition. This could however be very variable from case to case, and needs to be ascertained before a decision on technology is made.

4.7 Limitations and Caveats

As a techno-economic study on emerging technologies in an opaque market, there are significant uncertainties in the results that readers need to keep in mind.

In this study, we analysed lines one by one, considering the main train journeys that make up most of the traffic. However, it would be advisable to run a full-system study including minor routes in the area to verify feasibility for all selected options: for example, there is a significant number of trains shuttling between Liberec and Jaroměř, and battery trains would need to charge in Jaroměř, increasing turnaround times. Another example is the many local trains and branches of R27.

However, the general pattern seems established enough to predict that hydrogen will dominate on longer non-electrified lines, especially if their terminus is not electrified, whereas batteries will be a better option when trains will traverse OLE sections or stop at an electrified terminus station.

This study has also neglected to verify the availability of hydrogen fuel or grid power capacity, but due to the relatively limited energy demand this is not a major point of concern. It should be noted, however, that battery trains under OLE will consume significantly more power than for propulsion alone, i.e. to charge their batteries; if grid capacity were to limit battery charging, this may invalidate the calculated SoC profiles.

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