AN OPTIMIZATION MODEL FOR COST-MINIMAL CONFIGURATION OF BATTERY TRAINS AND RECHARGING INFRASTRUCTURE

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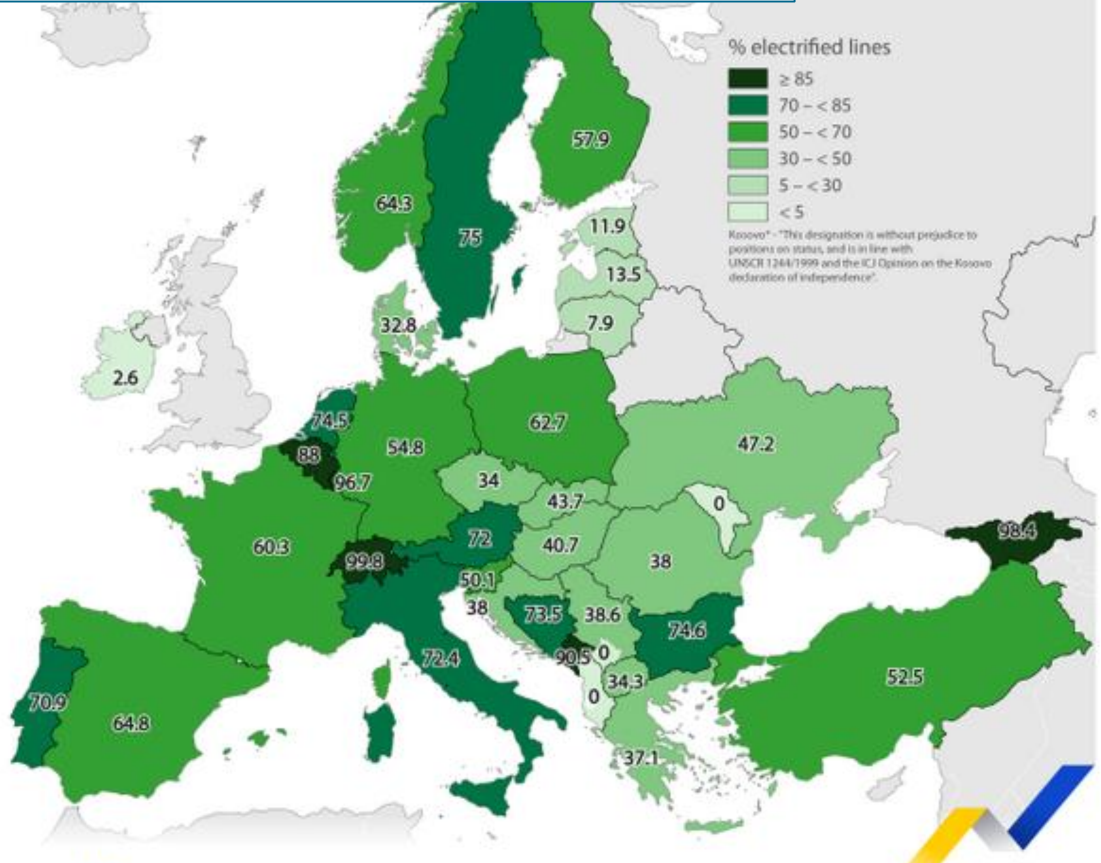
DLR

European railroads without full electrification and country-specific traction supply systems

- In the EU, about 43% of line kilometers had been non-electrified in 2022 (Eurostat [1])
- Substantial share of diesel trains in operation, especially in regional rail passenger transport
- Regional rail passenger transport in Germany: 36.5% (2019, [2]) is operated with diesel train (of operating performance)

Electrification of railway lines for European countries* (Eurostat 2022, [1])
**EU, EFTA and candidate countries*



- Full electrifcation of all lines is economically not viable
- Battery trains as a promising alternative to state of the art diesel trains

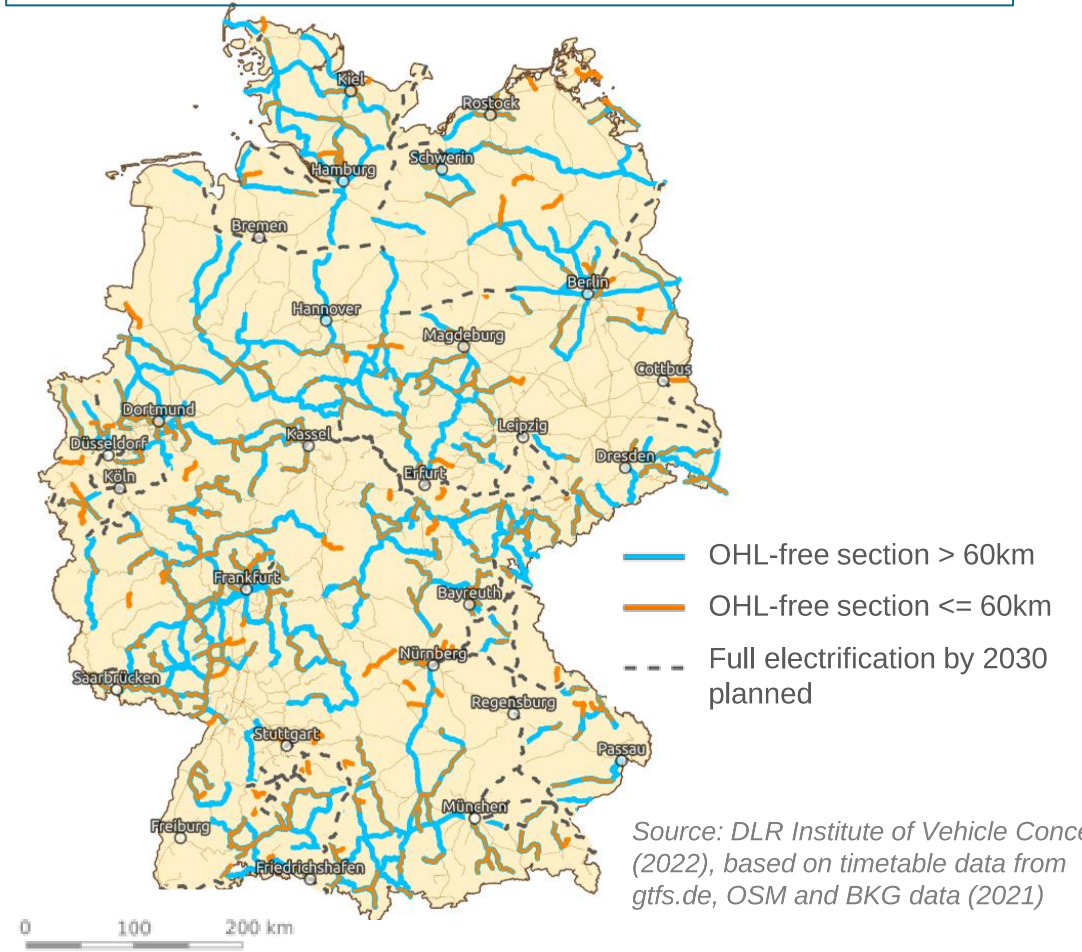
Requirements on Battery Electric Multiple Units (BEMU) autonomy in Germany

- Substantial share of lines with non-electrified sections (regional passenger rail transport)
- BEMU ESS[2] capacity has to be designed according to timetables and line characteristics (length, topography, speed profile, ...)
- Current BEMU usually offer autonomies of 70 to 100 km

[2]*ESS – energy storage system*

- Recharging of BEMU may require additional recharging infrastructure
- Integrated **planning** of **BEMU ESS** and new or extended **recharging infrastructure** needed

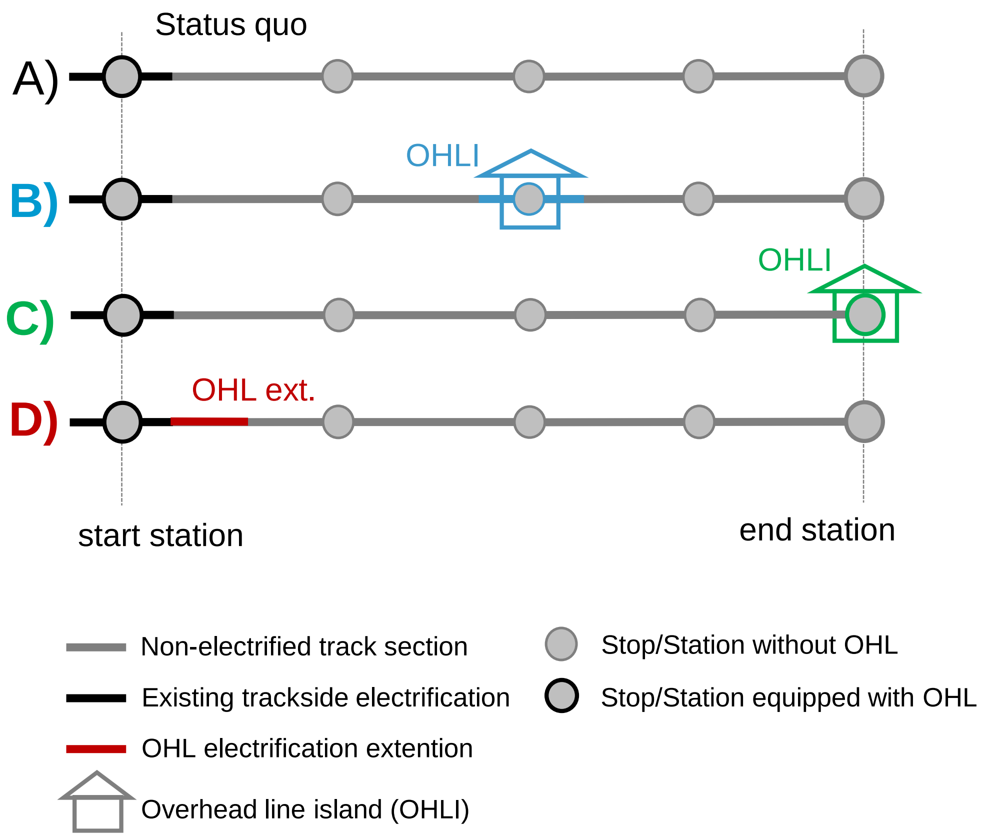
Overhead line (OHL) free sections on German regional rail passenger transport lines



Source: DLR Institute of Vehicle Concepts (2022), based on timetable data from gtfs.de, OSM and BKG data (2021)

Overview on decentralised recharging infrastructure alternatives

Alternatives for German traction power supply system, 15kV / 16.,7 Hz (AC)



A) Using existing Electrification

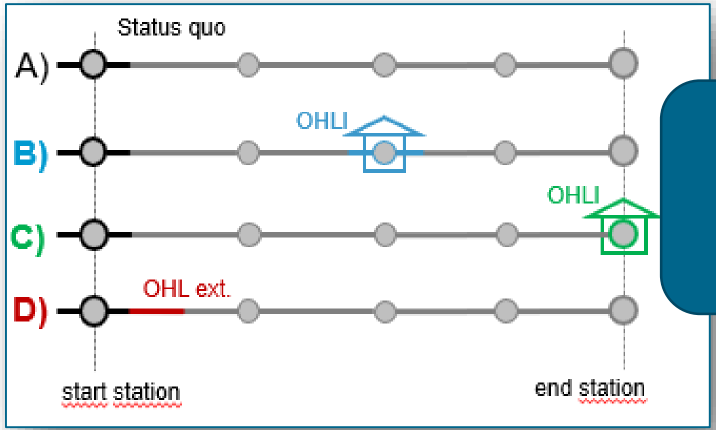
B) Overhead line island (OHLI) with converter substation (OHL with 15 kV 16,7 Hz)

C) Charging Station with Scott-Trafo (OHL 15 kV / 25 kV, 50 Hz, power supply of BEMU only during stand still)

D) Extension of existing OHL (OHL with 15 kV 16,7 Hz)

Source: Furrer+Frey Voltap, Stadtwerke Tübingen

Integrated planning of BEMU ESS and new or extended recharging infrastructure is required



Depending on rail line characteristics different configurations are technically feasible…

A1: OHLI (site B)
+ Small ESS

A2: OHLI (site C)
+ Medium ESS

A3: OHL extension
+ Large ESS

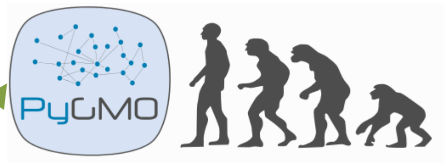
…

Example number of optimal candidates alternatives:
~11 million

(example of a 31 km rail line with a max. of 2 OHLIs and 36 ESS configurations)

- Goal: determination of **optimal system configurations** considering variable **ESS capacity** and **recharging infrastructure positioning**
- Approach: **multiparameter optimization** with metaheuristic algorithms

Toolchain for Pareto Optimisation



Optimization Vector

$$\vec{x} = \begin{pmatrix} \mathrm{perm}_{\mathrm{Batterie}} \\ \mathrm{Locator}_1 \\ \cdots \\ \mathrm{Locator}_M \\ \mathrm{Länge}_1 \\ \cdots \\ \mathrm{Länge}_M \end{pmatrix}$$

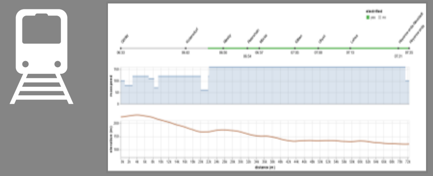
Toolchain

- Positioning of recharging infrastructure
- BEMU BMS[1] model
- SoC[3] feasibility check
- Aggregation to daily load profile
- Evaluation of solutions & KPI analysis

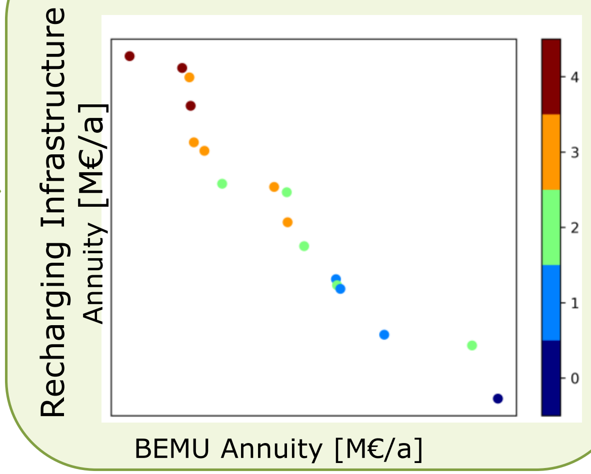
$$Costs^{Recharging\ Infra.} + Costs^{BEMU}$$

Input Parameters
(ESS characteristics, circulation plans, costs, …)

Trajectory Planning Tool (*DLR FK TPT*[2])



Pareto Front



[1]*Battery Management Strategy*
[2]*DLR FK TPT based on [3]*
[3]*SoC: State of Charge*

Optimization – Target function

- Comprises annualized **Capex** and **Opex** of **trains** and **recharging infrastructure** (annuities)
- Annuity calculation based on (VDI 2067)
- Residual values considered

BEMU costs per train

- $\text{Capex}_{\text{base train}} + \text{Capex}_{\text{ESS}} + \text{Capex}_{\text{ESS reinvest}}$
- $\text{Opex}_{\text{base train}} + \text{Opex}_{\text{electricity}}$

Recharging infrastructure per site

- $\text{Capex}_{\text{OHLI}} + \text{Opex}_{\text{OHLI}}$
- $\text{Capex}_{\text{OHL ext.}} + \text{Opex}_{\text{OHL ext.}}$

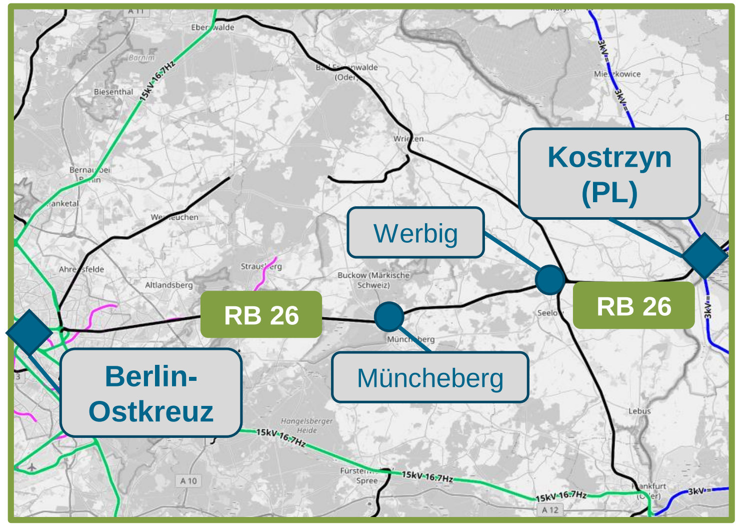
Parameter	Value	Reference
Capex ESS (High Power[1])	1000 €/kWh	Koh et al. [4]
Capex base train (EMU)	5 M€	Educated guess
Maintenance costs	0.8 €/km	StaBW 2016+
Energy costs [€/kWh] (excl. Charges	0.162 €/kWh	Based on DB energy pricing
Capex OHL extension	1 M€/km	/
Capex OHLI	2 M€/MW (substation) + 1 M€/km (OHL)	/
Opex OHLI / OHL ext.	1.4% of Capex /a	StaBW 2016+
Evaluation period	15 a	parameter
Interest rate	1.7 %/a	
Inflation rate	3 %/a	

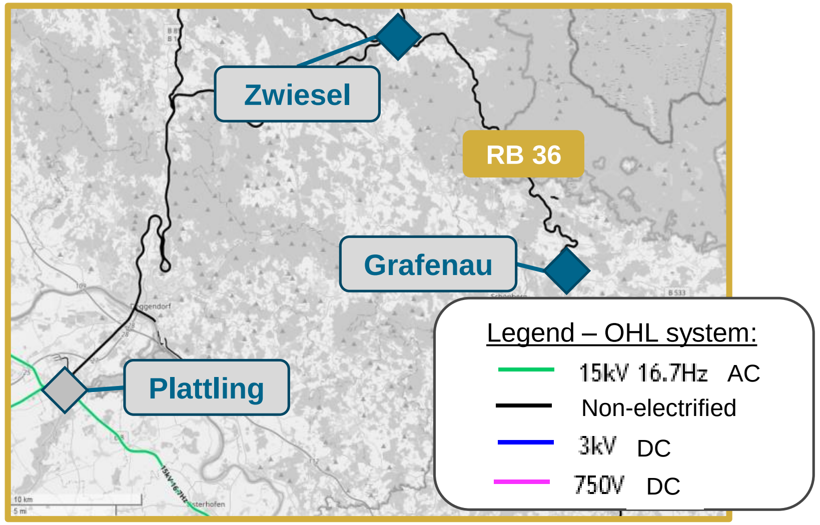
[1]High Power: Lithium Titanate batteries

2 Case studies – Regional passenger rail lines in Germany

	Berlin – Kostrzyn (PL)	Grafenau-Zwiesel
Line characteristic, operator	Connecting Berlin with Kostryn (PL), operated by NEB[1] (RB 26)	Secondary line in Bavarian Forest, operated by DLB[2] (RB 36)
Line length (with existing OHL)	**85 (3.5) km**	**31.5 (0) km**
Cumulated climb (roundtrip)	**143.3 hm**	**360.9 hm**
Number of stops	15	8
Max speed limit	120 km/h	120 km/h
Mean velocity	70.3 km/h	43 km/h
Daily number of trips (in each direction)	19 [5]	15 [6]
Multiple units in operation	**6**	**2**
Traffic performance per day	6,460 km/day[3]	945 km/day

[1]NEB: Niederbarnimer Eisenbahn GmbH
[2]DLB: Die Länderbahn GmbH DLB
[3]assuming operation in double traction

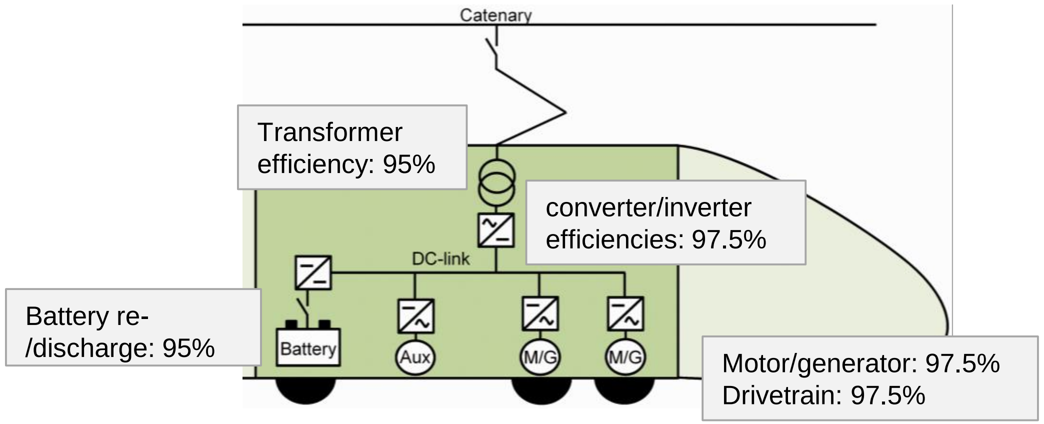




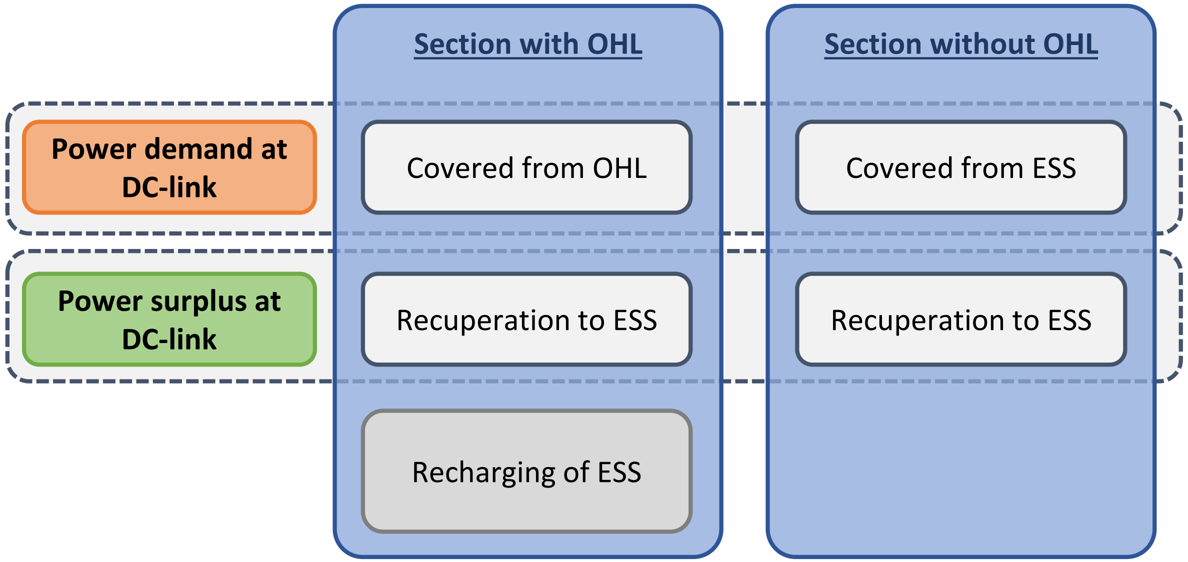
Source: https://www.openrailwaymap.org/

BEMU – Train specifications and battery management strategy (BMS)

Parameter	Generic BEMU (2-car)
Train length	46 m
Occupied mass	112 t
Power at traction motor (accelerating/braking)	1400 kW
Max. power from catenary	1200 kW
ESS type	High power (LTO)
ESS capacity	Variable (stepsize: 10 kWh)
HVAC consumption design / average case	80 kW / 40 kW

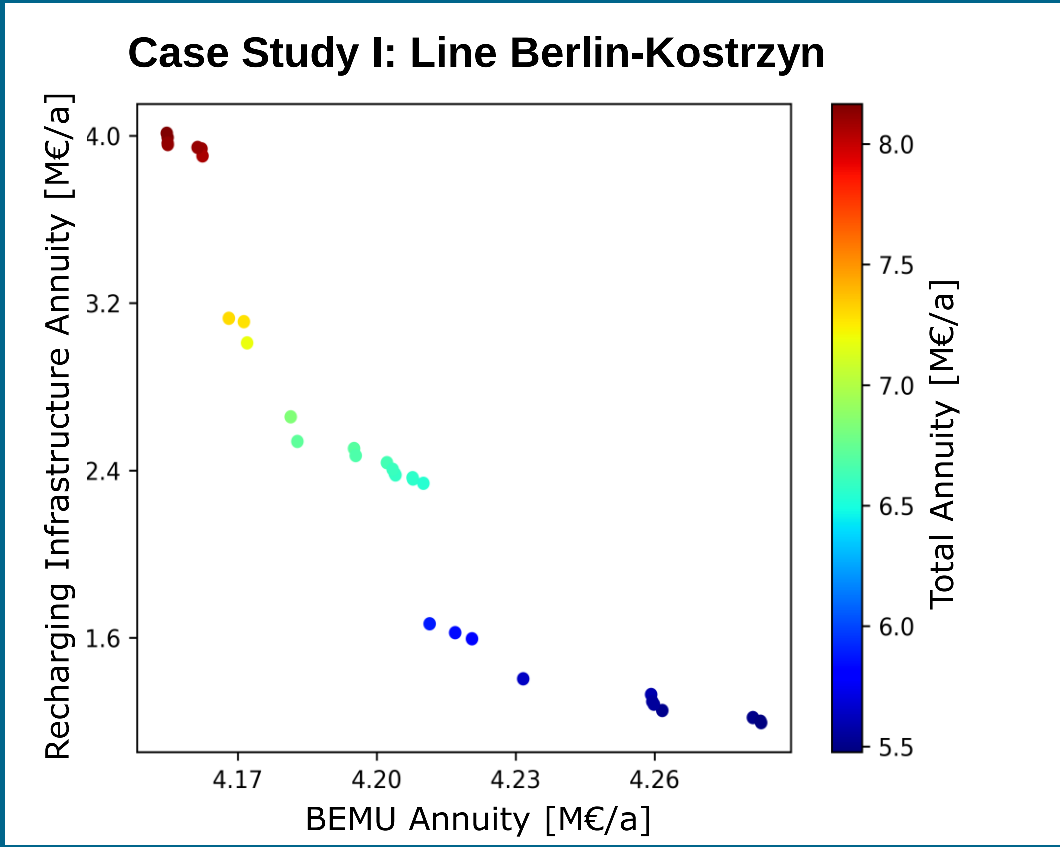


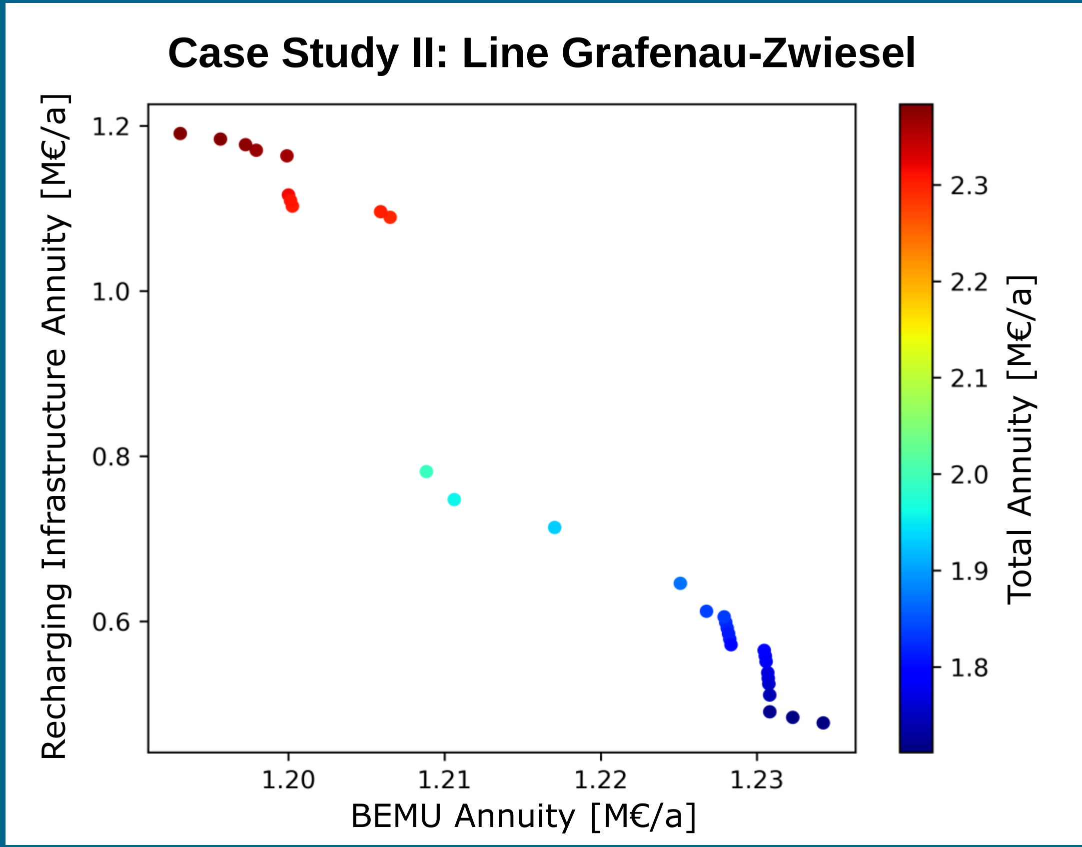
BEMU – BMS model



- Simulated energy demand at wheel (*DLR FK TPT [3]*)
- ESS State-of-Charge characteristic is modelled for given line characteristic considering variable electrification scenarios

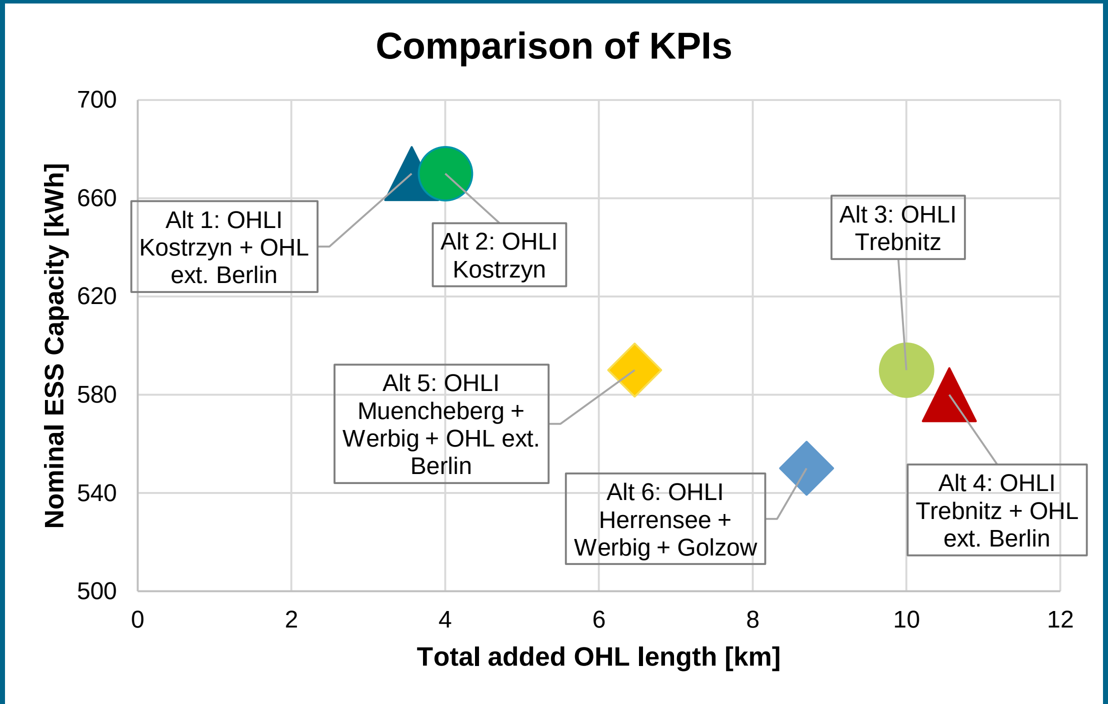
Pareto front – Overview of optimisation results

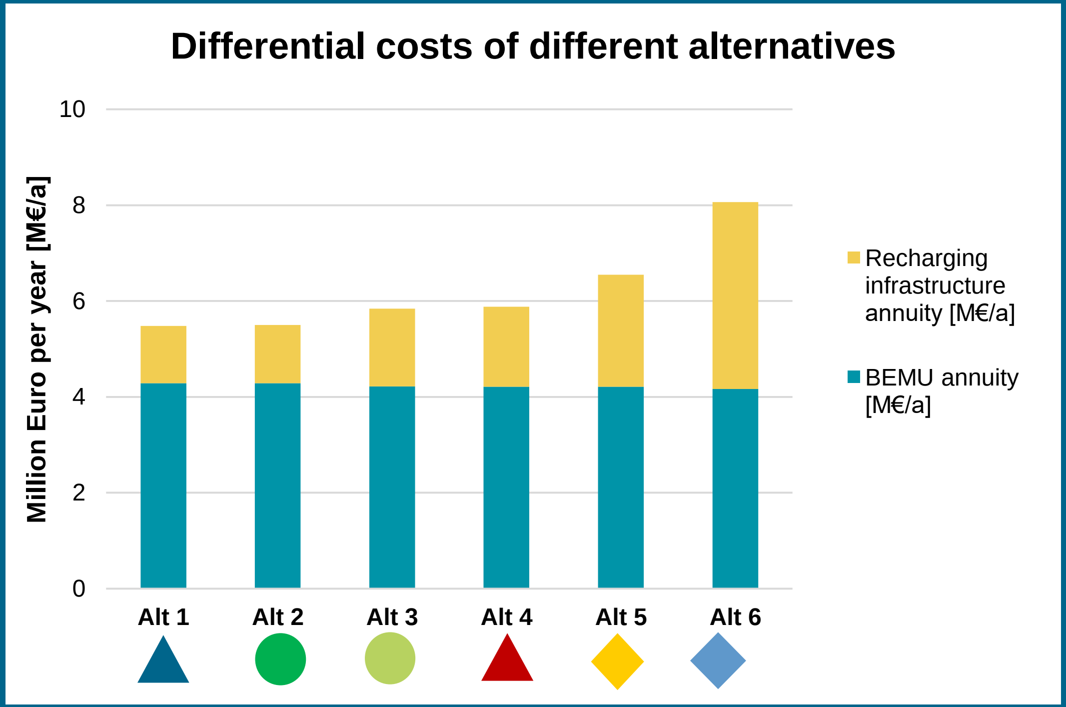




- Larger ESS capacities result in lower overall costs in both scenarios
- Clustering of solutions on pareto front based on number of new OHLIs

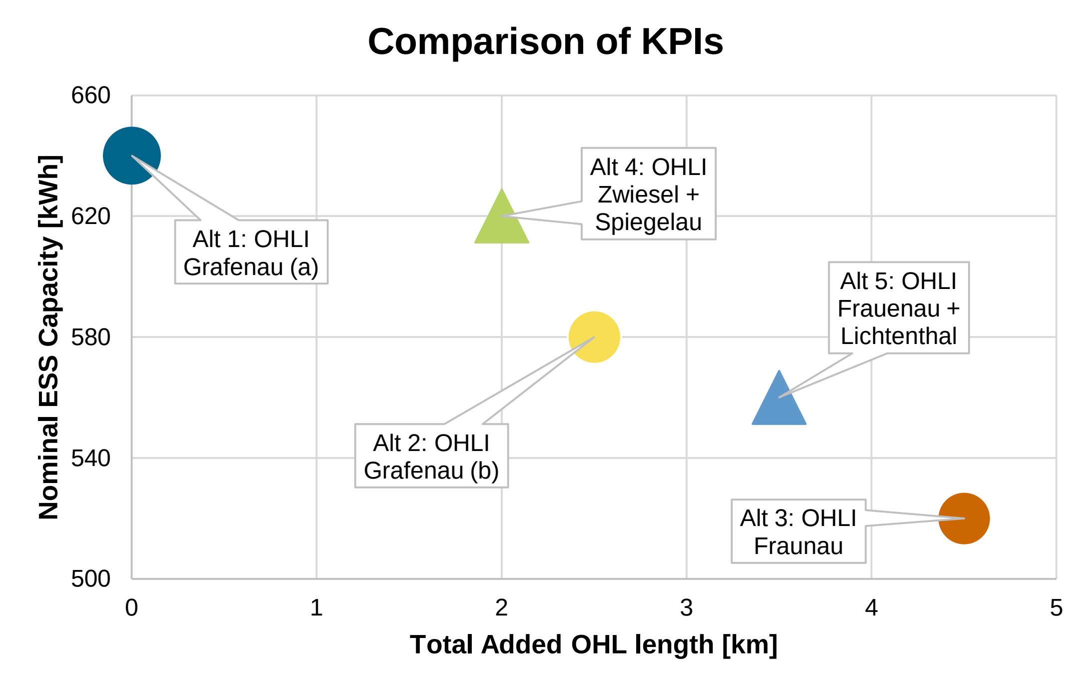
Case Study I – Line Berlin-Kostrzyn
KPIs and differential LCC of electrification alternatives

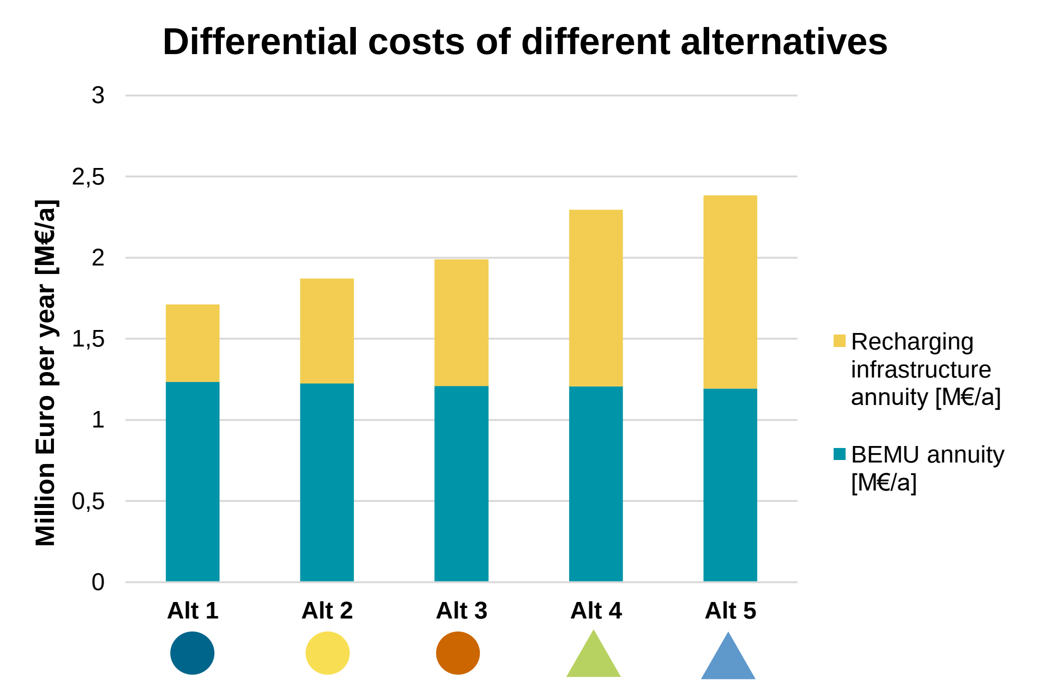




- ESS installed vary from 550 to 670 kWh (nominal)
- BEMU annuities: 4.16 to 4.28 M€/a
- Recharging infrastructure annuities : 1.19 to 3.90 M€/a → **0.014 – 0.046 M€/km*a**

Case Study II – Grafenau-Zwiesel
KPIs and differential LCC of alternatives





- ESS installed vary from 520 to 640 kWh (nominal)
- BEMU annuities: 1.19 to 1.23 M€/a
- Recharging infrastructure costs: 0.47 to 1.19 M€/a → **0.015 – 0.038 M€/km*a**

Conclusion & Outlook

Conclusion

- Optimization tool successfully generates pareto front based on the given target values
- Optimization approach can be applied on rail lines and networks, including different ESS types

Critical Aspects

- Capex for recharging infrastructure vary substantially and effect the overall solution
- Calculation time increases significantly with number of daily trips, vehicles and line length
- Convergence depends on the system complexity

Outlook

- Non-linear battery ageing models allow for a more accurate estimation of replacement intervals and thus BEMU lifetime cost
- ESS costs developments and cell improvements will impact BEMU lifecycle costs

The method has been developed within the **Project Mosenas.**

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