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Comparing options to electrify heavy-duty vehicles. Findings of German pilot projects.

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Summary

While the electrification of passenger vehicles is already in full swing, for the decarbonization of heavy-duty trucks still various challenges exist. Especially the high specific energy consumption in combination with high daily driving ranges makes battery electric operation much more difficult than for passenger cars. Accordingly, a broad set of different drivetrains is discussed, inter alia hydrogen powered trucks, catenary hybrid trucks and synthetic fuels. One main advantage of the direct use of electricity in trucks is the high energy efficiency. Still, for heavy duty trucks different concepts for electric trucks do exist. Here, we compare battery electric trucks with a fast charging option, full electric catenary trucks and battery swap trucks. For a broad perspective, we use seven different comparative dimensions ranging from total cost of ownership to more qualitative but not less important aspects such as necessity of standardization, which would reduce OEM decision-making freedom. We base our comparison on findings from German pilot projects. While battery electric trucks or battery swap are advantageous since they can be operated in niche operations and thus allow a demand driven rollout of charging infrastructure, catenary infrastructure needs high investments upfront which entails financial risks, but allows for lowest cost if utilized to capacity.

Keywords: case-study, electric vehicle (EV), fast charge, heavy-duty, truck

1. Introduction / Motivation

Electric vehicles with electric energy from renewable sources are often discussed as an important instrument to reduce greenhouse gas emissions from the transport sector. However, most studies focus on passenger cars. Nevertheless, heavy road transport is responsible for about one third of CO_2 emissions of all vehicles in Germany and it is expected to grow in emissions beyond the passenger car sector [1]. Electrification seems interesting due to its high energy efficiency. Since heavy-duty vehicles (HDV) typically travel long distances per day, the limited battery range is critical for implementing electric heavy road transport.

Although the driving range of HDV is critical for battery electric operation, a full electric range of 300 km would already allow to electrify 30% of the German semitrailer truck fleet (according to Germany's largest survey for heavy-duty vehicle traffic [2]) (Fig. 1). Still, this would make a battery capacity of more than 300 kWh necessary which would weigh more than 1.4 tons, even as late as in 2030 [3]. For higher daily driving ranges, if not applying even higher battery capacities, a fast charging option would be necessary with at least several hundred kilowatts to allow for a fast charge of the full range within the break times of the driver.

Accordingly, besides battery electric trucks with a fast charging option (BEV), also battery swap trucks (BSV) and catenary trucks (CV) are discussed as options to electrify heavy road transport. While BSV alleviate the time pressure needed for charging, CV allow for charging during the trip and thus, can completely set aside charging time restrictions while also allowing for longer distance trips.

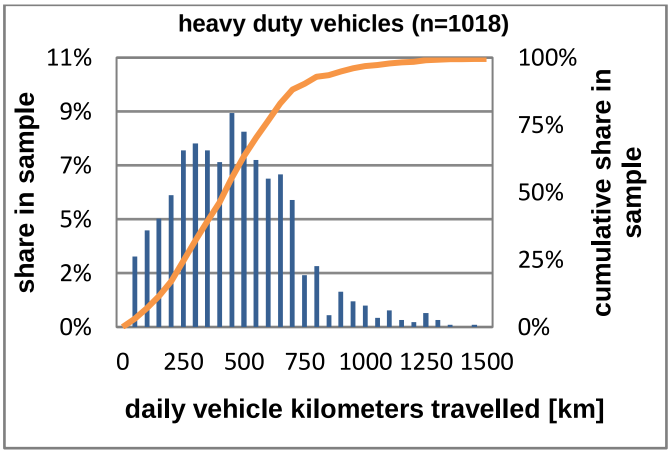

Figure 1: Daily vehicles kilometers travelled by heavy-duty vehicles (semitrailer trucks) in Germany. Data from [2]

In this paper, we will focus on electric trucks with a gross vehicle weight above 12 t. We compare three different types of electric trucks:

1. Battery electric trucks with a fast charging option (BEV). All driving energy is stored in the battery that has to be recharged regularly.
2. Overhead catenary electric trucks (CV). These trucks can be operated via a pantograph to obtain electricity from the overhead lines. If power supply exceeds driving power, the battery can be recharged during driving. For driving off the line, driving energy might stem from an additional internal combustion engine or a battery that allows for electric driving compared to the battery electric vehicle. Here, we only discuss a full electric CV without an internal combustion engine.
3. Electric trucks with a changeable battery (BSV). Operation is similar to battery electric truck, but instead of recharging the battery, the empty battery in the truck is swapped for a fully charged one. Charging of these batteries can thus happen slower during times where no battery swap is demanded.

For the market success of electric trucks, various aspects are necessary. Besides the environmental dimension, mainly technical and economic aspects are of special interest [4]. Surveys among fleet operators show that total cost of ownership (TCO) and reliability are the most important user requirements [5].

This paper aims at contributing to the discussion by giving a comparative overview of the aforementioned electric truck drivetrains with regard to the following seven dimensions:

1) Technical readiness of the vehicle,
2) Necessity of vehicle standardization,
3) Possibility to be operated in niches,
4) Technical readiness of infrastructure,
5) Long-term infrastructure cost (per km),
6) Operational flexibility and
7) Total cost of ownership (TCO), including both vehicle and charging infrastructure cost.

The technical readiness of the vehicle and charging infrastructure are important for a potential near-term testing of the electric trucks and as indicator for the required reliability of the system [4]. In order to ensure interoperability between different manufacturers, standardization of interfaces between the vehicle and its charging environment is necessary. The need for complex interfaces may increase the necessity of standardization and thus hamper the market diffusion of the technology in an early stage [6]. Niche applications tend to be a source of knowledge and experience. As long as niche applications do not result in local lock-ins due to different standards, there is a need for local niche projects to enable market diffusion [6]. The possibility of the trucks to be operated in niches might be interpreted as "soft factor" for the technology to be developed and tested independent from market constraints, e.g. since not being dependent on a nationwide built-up of charging infrastructure. In contrast, long-term infrastructure cost are decisive for the widespread diffusion and success of the technology [7]. Especially when using one vehicle on different routes operational flexibility is of special interest. Most users demand for vehicle ranges above 800 km [5]. Smaller driving ranges might harm their willingness to buy an electric vehicle. Finally, the total cost of ownership is the major criteria to decide for or against a vehicle in transport business [5,7].

2. Pilot projects

Since only prototypes of electric long-haul trucks exist, we base our analysis on pilot projects and literature, which represent the best available data basis for our analysis as described in the following section. Two pilot projects are of particular importance in this context:

- eWayBW: The pilot project consists of 18 km public road (one direction) with 6 km overhead catenary infrastructure in the federal state of Baden-Württemberg in south-west Germany [8]. In the first stage, catenary trucks (CVs) with an additional diesel engine will be tested. Later, CVs with a battery system as hybrid component will be deployed. Additionally, pure BEVs serve as a reference.
- RouteCharge: The pilot project consists of driving on 250 km public road (one direction) from Berlin in the northeast of Germany to Peine in western Germany, following the Autobahn A2 [9]. The test track is equipped with three battery swap stations (start, middle and end). A battery swap vehicle (BSV) will travel circular traffic on this route.

Following the dimensioning of the pilot projects, our analysis focuses on a trip with a total length of 500 km. As the outward and return routes are identical, the distance to be electrified is 250 km. Considering regular breaks and loading operations in circular traffic, 500 km is a good approximation for daily mileage of a vehicle (Figure 1). For BEV, we assume two charging stations, one at the beginning and one at the end of the track. Since a battery swap is still faster, we assume three swap stations. The additional station is positioned after 125 km. In accordance with [7] and [10], we assume a CV infrastructure of 100 km (40% of the total track), starting at one end point (for details please refer to the methods section). Please note, that our results are highly influenced by the infrastructure design inspired by the pilot projects. The feasibility of a widespread diffusion has to be evaluated. However, this is beyond the scope of the current study and left for future research.

We assume seven vehicles travelling along the route. This is based on the experience from the pilot projects, especially the expert opinion of the involved transport company, and seems to be a valid utilization in an early market diffusion when taking one transport company and one route into account [9]. Since currently the main target of alternative trucks is CO_2 reduction, we presume a pure electric drive for all drivetrains. Therefore, the CVs are equipped with batteries too and do not have a diesel engine. The chosen battery range ensures the operation of the vehicle on the given track and considers battery aging.

Figure 2 outlines the assumed infrastructure layout. The overhead catenary system is regularly fed by substations (one station every two kilometers), while the fast charging infrastructure and the battery swap infrastructure are connected to one single grid connection per station. The infrastructure is designed in a way that seven vehicles can be served in 12-minutes intervals and with a maximum idling time of 60 minutes at the end points of the route.

Table 1: Comparison of the different technologies (assumptions)

	Battery electric vehicle (BEV)	**Catenary vehicle (CV)**	**Battery swap vehicle (BSV)**
Daily mileage	500 km (one direction: 250 km)		
Infrastructure description	2 charging points at both end points of the route	One section of 100 km overhead lines starting at one end point	3 swapping stations along the route
Max. capacity of infrastructure	5 vehicles/hour	180 vehicles/hour	5 vehicles/hour
Max. distance to travel without recharging	250 km	300 km	125 km
Battery capacity	525 kWh	650 kWh	275 kWh
Battery range	293 km	342 km	153 km

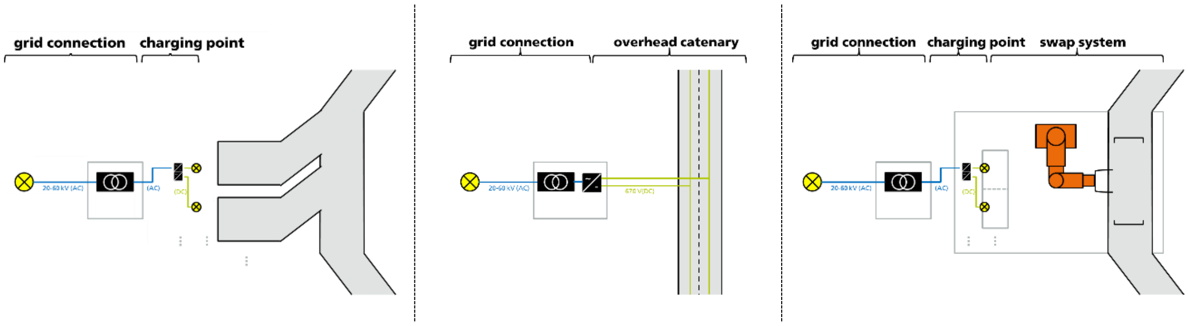

Figure 2: Structure for BEV, CV and BSV charging infrastructure

3. Methods

Using the seven dimensions from chapter 1, we compare the given alternatives for electrification regarding the vehicle, the necessary infrastructure and the system of both. The methodology of each of these dimensions is explained in more detail below.

Vehicle

A comparison in two indicators describes the advantages and disadvantages of the selected vehicle concepts.

1) In accordance with [4], we focus on technological readiness as first indicator. There are nine technology readiness levels (TRL), from basic principles to operational environment.

Table 2: Technology readiness level (TRL) [11]

TRL	Description
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

2) Based on the vehicle design, we evaluate the necessity of standardization to ensure interoperability between different vehicle manufacturers. To enhance compatibility, design standards are necessary. As described in [6], standardization is a struggle of different actors with various interests. Therefore, we identify technical components that have to be harmonized in order to ensure interoperability.

Infrastructure

3) We analyze the possibility of niche operation. Especially during an early market diffusion, highly used sections could be an option to launch the system. While some infrastructure alternatives can be built by individual operators, e.g. logistics companies, others require large infrastructure providers, e.g. governmental agencies. As discussed in [7], the infrastructure investment is a critical aspect in an early market diffusion. To appraise the niche operation possibility, we compare the total investments of the different infrastructures for the given scenario.

4) We compare the technical readiness of fast charging stations (FCS), overhead catenary infrastructure (OC) and battery swap stations (BSS) with regard to technical readiness. To this aim, we gather size, building year and the degree of completion for different pilot projects in Germany and worldwide to determine the technical readiness. Therefore, we use the TRL, as described in Table 2.

5) We calculate long-term per-kilometer cost for users for every infrastructure according to equation (1) and compare the results. Since the operation of a catenary infrastructure in a niche operation of seven vehicles is economically not feasible, we presume a nationwide catenary infrastructure to be in place. For Germany, a network of 2,000 km represents a potential early stage infrastructure setup, as described in [7]. We assume the installation of overhead catenaries on the considered highway being part of German-wide 2,000 km infrastructure diffusion, since the operation of one OC-highway for seven vehicles can't be economically feasible. Therefore, the long-term per-kilometer cost for CV are costs per kilometer actually driven under an OC. The cost for the usage of FCS and BSS are calculated per kilometer.

$$c_{i,s} = \frac{\frac{I_{i,s} * (1+i)^{T_i} * i}{(1+i)^{T} - 1} + c_{opex,i,s}}{VKT_{i,s} * veh_{i,s},} \qquad (1)$$

$I_{i,s}$	investment for infrastructure *i* and drivetrain *s* [EUR]
i	interest rate
T_i	investment horizon [a]
$c_{opex,i,s}$	operative expenditures for infrastructure *i* for vehicles of drivetrain *s* [EUR/a]
$VKT_{i,s}$	annual vehicle kilometers travelled by one vehicle of drivetrain *s* on infrastructure *i* [km]
veh_s	number of vehicles of drivetrain *s* driving on infrastructure *i* [#]

System

6) We distinguish two types of operational flexibility. On the one hand, we use the autonomous range of the vehicles, e.g. the battery range on a single charge, as an indicator for operational flexibility [4]. On the other hand, there are conflicting priorities between high operation flexibility and load flexibility in the electricity grid. Therefore, we evaluate the different drivetrains in terms of their system-related charging flexibility. Additional batteries, which are needed e.g. for the smooth operation of the battery swap system, can buffer peak loads and promote network integration. In general, however, the higher the infrastructure capacity utilization - e.g. battery swap stations serve more vehicles and thus, a lower number of swap batteries are needed-, the lower the flexibility to buffer peak loads.

7) The total cost of ownership (TCO) determine the economic efficiency of the vehicle concept. As stated in [5], costs are the most important factor for buying decisions in transport industry. We use equation (2) and (3) to calculate TCO for the three selected drivetrains (BEV, CV and BSV). The total cost of ownership (TCO) contains cost for the capital expenditure and cost for the operating expenditure. Both are calculated as kilometer-specific cost. In a battery swap station, more than one battery per vehicle is required to ensure the supply with fully charged batteries. Since the batteries in a BSV are interchangeable, the usage time of the battery in battery swap vehicles is independent from vehicle lifetime and thus different from the other vehicles with permanently installed batteries. We assume a longer usage for batteries of BSV than for BEV and CV.

$$a_{capex}^{s} = \left(\frac{I_s * (1+i)^T * i}{(1+i)^T - 1} + \frac{I_{s,B} * bat * (1+i)^{T_B} * i}{(1+i)^{T_B} - 1}\right) * \frac{1}{VKT_s} \tag{2}$$

I_s	investment for vehicles of drivetrain s without battery [EUR]
i	interest rate
T	investment horizon [a]
VKT_s	annual vehicle kilometers travelled by vehicle of drivetrain s [km]
$I_{s,B}$	investment per battery for vehicles of drivetrain s [EUR]
bat	number of batteries per vehicle [#]
T_B	investment horizon for battery [a]

$$a_{opex}^{s} = \left(c_{e,s} * e_s\right) + c_{i,s} * share_{i,s} + c_{OM,s} \tag{3}$$

$c_{e,s}$	cost for electric energy for vehicle of drivetrain s [EUR/kWh]
e_s	energy demand for vehicle of drivetrain s [kWh/km]
$c_{i,s}$	infrastructure usage cost for vehicle of drivetrain s [EUR/km]
$share_{i,s}$	share driven on infrastructure. 1 for BEV and BSV, 0.4 for CV
$c_{OM,s}$	operations and maintenance for vehicle of drivetrain s [EUR/km]

4. Techno-economic assumptions

In general, our assumptions are based on the experience of the pilot projects. Table 3 sums up vehicle parameters. Infrastructure parameters can be found in Table 4, general parameters in Table 5.

Table 3: Vehicle parameters. BEV: Battery electric vehicle, CV: catenary vehicle, BSV: battery swap vehicle.

Attribute	Abbr.	Unit	BEV	CV	BSV	Source
Investment for vehicles of drivetrain s without battery	I_s	EUR	77,590	87,590	77,590	[12,13,7]
Investment horizon	T	a	6	6	6	[7,12]
Investment per battery for vehicles of drivetrain s	$I_{s,B}$	EUR	97,650	120,900	51,150	[7]
Investment horizon for battery	T_B	a	6	6	10	[10]
number of batteries per vehicle	bat	#	1	1	1.86	[9]
annual vehicle kilometers travelled by a vehicle of drivetrain s	VKT_s	km	120,000	120,000	120,000	[12]
energy demand for a vehicle of drivetrain s	e_s	kWh/km	1.42	1.51	1.42	[12]
operations and maintenance for a vehicle of drivetrain s	$c_{OM,s}$	EUR/km	0.0411	0.0411	0.0411	[7]

Table 4: Use case specific infrastructure parameters. BEV: Battery electric vehicle, CV: catenary vehicle, BSV: battery swap vehicle.

Attribute	Abbr.	Unit	BEV	CV	BSV	Source
Investment for infrastructure i, drivetrain s	$I_{i,s}$	kEUR	1,176	3,421,000	1,849	[7,9,10]
Investment horizon	T_i	a	30	30	30	[7]
operative expenditures for infrastructure i, drivetrain s	$c_{opex,i,s}$	EUR/a	24,000	68,420,000	37,000	[7,9,10]
Annual vehicle kilometers travelled by one vehicle of drivetrain s on infrastructure i	$VKT_{i,s}$	km	120,000	61,900	120,000	[7]
Number of vehicles of drivetrain s driving on infrastructure i	veh_s	#	7	61,875	7	[7,9,10]

Table 5: General parameters. BEV: Battery electric vehicle, CV: catenary vehicle, BSV: battery swap vehicle.

Attribute	Abbr.	Unit	BEV	CV	BSV	Source
Interest rate	i	%	5	5	5	[7]
cost for electric energy for vehicle of drivetrain s	$c_{e,s}$	EUR/kWh	0.16	0.16	0.16	[14]

5. Results

Technical readiness of the vehicle and necessity of vehicle standardization

Today, heavy-duty battery electric trucks are tested under real-world conditions, mainly for inner-city logistics with ranges of 200 km (e.g. Daimler eActros [15]). Vehicles with a range of 250 km and recharging times smaller than one hour are not available today. In summary, prototypes with lower performance requirements are demonstrated in the operational environment (TRL 7). For the given scenario, no comparable demonstration projects are known in Germany. Hence, we assume TRL 5 (see also [4]). For CV, there are several demonstration projects in Germany and worldwide (Table 6). The vehicle technology is demonstrated in the relevant environment (TRL 6). For BSV, RouteCharge is the only project known to the authors. From a vehicle perspective, the project demonstrated all requirements in the relevant environment (TRL 6). Please note, that this description is rather indicative.

Table 6: Catenary vehicle projects worldwide

Project	Region	Period	Electrified section
eHighway USA	Los Angeles & Long Beach	2017	1.6 km
eHighway Sweden	Gävle – Sandviken	2016-2018	2 km
eWayBW Germany	Gernsbach – Kuppenheim	2017-2023	6 km
ELISA Germany	Frankfurt - Darmstadt	2017-2022	6 km
FESH Germany	Hamburg-Lübeck	2017-2022	6 km

While all three technologies need standardization of plugs and voltage level, BSV need additional standardization with respect to the swap system. Agreements between manufacturers would be necessary. Hence, the necessity of standardization is more complex for BSV.

Niche operation, long-term infrastructure cost and technical readiness of infrastructure

The following results refer to the systems described in Figure 2.

We assess the niche operation possibility by the number of vehicles that are necessary to bring charging infrastructure cost down to less than 0.2 EUR/km for the given scenario. That corresponds to the infrastructure cost for seven battery swap vehicles. The first three rows of Table 7 sum up the results for an infrastructure as it is described in Table 1. While battery swap stations and fast charging infrastructure might be interesting with a vehicle fleet of seven vehicles, overhead catenary infrastructure cannot be operated within a niche, as indicated by the high number of vehicles that are necessary for low infrastructure cost. Therefore, we assume a German-wide infrastructure ramp-up for CV in the long term. The long-term infrastructure cost in Table 7 are calculated with the data from Table 4. If a German-wide CV infrastructure is highly used, it can be clearly cheaper in terms of per kilometer cost than a BEV or a BSV infrastructure. The CV infrastructure has to be prepared for higher usage due to the construction from the very beginning. Therefore, a higher usage will spread almost the same costs over more vehicles.

Table 7: Infrastructure cost. BEV: Battery electric vehicle, CV: catenary vehicle, BSV: battery swap vehicle.

	Unit	BEV	CV	BSV
Total infrastructure cost for the given scenario	kEUR	1,176	171,050	1,849
infrastructure per-km cost for seven vehicles	EUR/km	0.12	17.32	0.19
Number of vehicles, if $c_{i,s} * share_{i,s} <$ 0.2 EUR/km	#	5	607	7
long term infrastructure cost	EUR/km	0.12	0.03	0.19

Today, battery electric trucks are charged with the technology adapted from the passenger car sector with a maximum of 350 kW. Truck manufacturer currently improve charging power in order to serve use cases as the one given in the scenario. In summary, the BEV infrastructure technology is validated in lab (TRL 4), but up to now, there are no industrial standards and no public demonstration projects. As mentioned in Table 6, overhead catenary infrastructure is demonstrated in the relevant environment (TRL 6) during several demonstration projects. RouteCharge validates BSV infrastructure in the relevant environment (TRL 5). Today the battery swap works manually. However, applications for port vehicles show that automation of battery swap is possible. Also for BSV infrastructure, fast charging needs to be improved if a larger number of vehicles shall be supplied, although additional batteries are an alternative option, which might be used in the meantime.

Operational flexibility and total cost of ownership

The operational flexibility depends on the battery range of the electric truck as well as the idling time of the vehicle for charging. The higher the battery range, the lower the need for a dense charging infrastructure. While charging times must be considered in the operation of a BEV and a BSV truck, catenary trucks allow for charging along the overhead lines while driving. Accordingly, operational flexibility is higher. Since the battery range is higher too, CVs offer the highest flexibility, followed by BEVs and BSVs from a user perspective. From a grid perspective, BSV seem interesting, since the additional batteries in the stations could buffer load peaks. Further investigations within the RouteCharge project show, that grid services are financially interesting, as long as the infrastructure is not highly used.

Finally, Figure 3 provides the TCO calculation for all three alternatives. In total, the CV is potentially 5% cheaper than BEV and BSV in the long term.

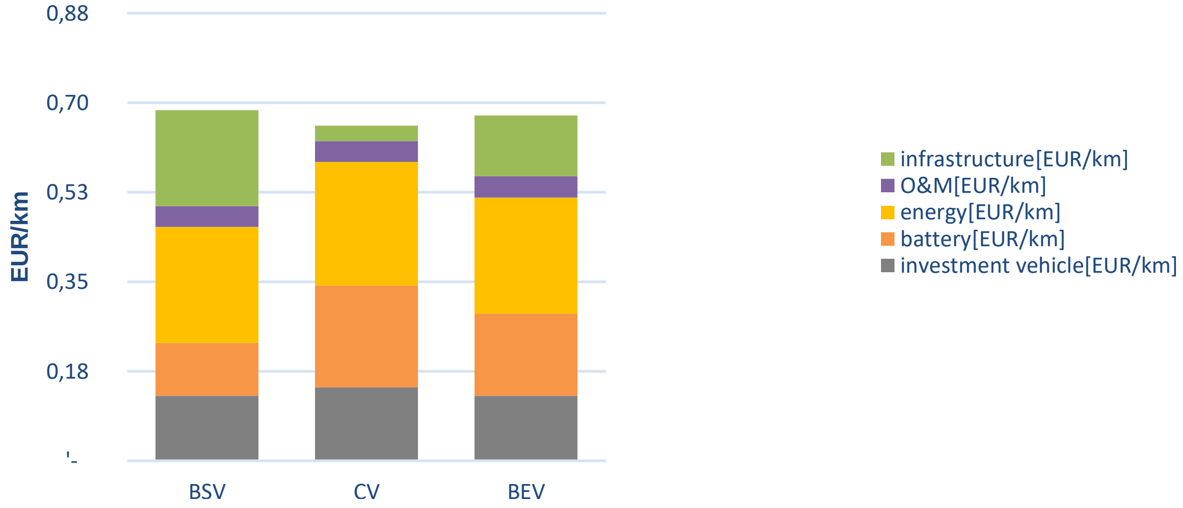

Figure 3: TCO analysis for different drivetrains

6. Summary and conclusion

Table 9 summarizes our findings. The main advantage of the electric truck (BEV) is the possibility of niche operation, while the needed high-power charging infrastructure is still to be developed and tested. In this context, the negative assessment of technical readiness of the vehicle is strongly correlated to the required recharging power in the described scenario. The advantages of the battery swap truck (BSV) are comparable, whereby the BSV benefits from lower required charging power. OEMs do not seem to be interested in this technology, due to the necessity for standardization of the battery swap system, which has large implications on vehicle design. Finally, the built-up of overhead lines for catenary trucks is challenging due to high investments and the need for heavy use to bring down per kilometer cost. Accordingly, niche operation is not possible. However, once high utilization is reached, this technology allows for lowest total cost.

Table 9: Summary assessment in seven dimensions for long-haul trucks. BEV: Battery electric vehicle, CV: catenary vehicle, BSV: battery swap vehicle.

	BEV	**CV**	**BSV**
Technical readiness vehicle	-/o	o	o
Necessity of standardization	o	o	-
Possible niche operation	+	-	+
Technical readiness infrastructure	-	o	-
Long-term infrastructure cost per km	o	+	o
Operational flexibility	o	+	o
Total cost of ownership	o	+	o

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