EVS35 Symposium
Oslo, Norway, June 11 - 15, 2022

What is the right battery size for an electric truck with respect to its charging infrastructure?

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Abstract

The complete reduction of greenhouse gases from the transport sector is a major challenge in the next decades. Here, we focus on electric trucks and determine the optimal battery infrastructure combination of battery and catenary electric tucks with respect to market shares and energy consumption. The analysis is based on the market diffusion model ALADIN with which we run a monte carlo simulation with 1,000 random variable combinations for battery capacities and infrastructure to understand the interdependencies. We find increasing market shares of battery electric and catenary electric trucks with higher battery capacities. The influence of infrastructure on market shares and energy consumption is of secondary order and limited.

1 Motivation

A large reduction of greenhouse gas emissions has to be contributed by the transport sector to reach the goals from the Paris Agreement. While the transport volume of passenger cars is stagnating, it is still increasing for heavy-duty vehicles, which will be the largest emitter of greenhouse gas emissions by 2030 in Europe [1]. One promising solution to reduce these emissions is to largely introduce electric trucks. As for electric passenger cars a decade ago, there is the issue of limited range and missing infrastructure of the battery is not large enough. However, a tall battery increases vehicle weight and reduces load capacity which may detain vehicle buyers from purchasing.

In this paper, we want to examine the optimal roll-out of infrastructure and battery sized for electric trucks with respect to total system cost, maximum number of alternative fuel vehicles and minimum amount of energy consumed. We examine two types of electric trucks: battery electric trucks (BET) that are charged at high power charging stations (HPC) and catenary electric trucks (CET) that are charged at overhead lines. These are considered to contain a diesel engine and tank (CET-D) or a battery (CET-B). Different battery size and infrastructure combinations are analyzed in the market diffusion model ALADIN and varied in a monte carlo simulation with 1,000 calculations for Germany until 2050.

2 Methods and data

In this paper, we use the market simulation model ALADIN (Alternative Automobiles Diffusion and Infrastructure) to determine the market shares of trucks in with different parameter settings. The settings are randomly varied 1,000 times and we analyze the impacts of the parameter variation on market share, energy demand and total cost of the system. In the following, we will describe the model ALADIN, the parameters to be varied and their variation range (see e.g. for a similar approach [2]).

The model ALADIN was used for many publications for the market diffusion of passenger cars and heavy-duty vehicles [3-5]. The core of the model is driving profiles of several thousand vehicles and an individual calculation of utilities for different drive trains. For trucks, the model is slightly simplified as the driving profiles mainly consist of annual mileages and vehicle size information because further data is lacking. For heavy-duty vehicles, the annual mileages from 6,000 trucks are analyzed that stem from truckscout24 and KiD2010 [6, 7] and their representativeness has been shown in [5]. For every vehicle, we first determine whether the vehicle can fulfill all the daily driving with the given drive train and infrastructure and then calculate the drive train specific total cost of ownership (TCO). The lowest TCO for each drive train determines the vehicle choice; the share of users with one drive train result in its market share. By doing so with changing inputs over time, we can calculate the market diffusion of alternative drive trains.

Here, we put special emphasis on the utility of infrastructure for the individual user. The following assumptions are made:

- Daily mileage is calculated as annual vehicle kilometers traveled (VKT) divided by 260 working days.
- The mileage on highways is based on a survey described in [4] as $s_h = 1 - exp(-\frac{dVKT}{L_0})$ with L_0 = 127.3 km.
- We assume that HPC charging infrastructure are rolled out based on their utility with a maximum coverage of 2,258 charging stations [8] with 100 km maximum distance between charging stations and 20% charging in public.
- The user of a BET can charge overnight in a depot and starts his daily trips with a full battery. When the battery is completely discharged, the battery range charged at the highway is based on the infrastructure rollout and the additional range through HPCs is calculated as $r_{HPC} \coloneqq \kappa \cdot \frac{n_{HPC}}{2,258}$. with n_{HPC} being the number of HPCs and κ the battery capacity.
- The infrastructure for CET is constructed based on truck usage. We order the highways sections by the number of truck-km per segment within a highway and thus obtain stretches with very high average utilization. The for individual user, this results in an individual utility of an infrastructure construction of $u_{BAB}(x)=1-\Phi(\Phi_{-1}(1-x)-\sigma^2)$ with σ = 1.19 and x is the share of highway-km traveled. With this formula, we can determine the share of kilometers driven below overhead lines and the amount that has to be fulfilled with a battery.

We calculate the market shares for 2030 and 2050 with the model ALADIN [5]. The basis for our calculations is the scenario "TN-Strom" from [9]. The main assumptions on energy prices, battery capacity and fuel cell prices are shown in Table 1.

Energy carrier price	2030	2050
Gasoline price	0.233	0.293
Diesel prices	0.197	0.261
Hydrigen price	0.285	0.235
LNG price	0.212	0.304
Electricity price industrial	0.101	0.085
Battery price BET	100	80
Battery price PHET	110	88
Fuel cell price	80	55

Table 1: Energy carrier, battery and fuel cell prices in Scenario "TN-Strom" in [9] [€/kWh].

Here, we will vary four main parameters: battery capacity of BET, battery capacity of CET, HPC infrastructure density, overhead line infrastructure. The parameter ranges, evolution over time, and cost assumptions are given in Table 2 and **Fehler! Verweisquelle konnte nicht gefunden werden.**. The random values for 2050 are drawn from an equal distribution.

parameter	Value range 2030	Value range 2050
battery capacity of BET	[100, 500]	[100; 1000] -
battery capacity of CET	[100, 500]	[100; 1000]
HPC infrastructure density [number of HPCs]	[0;677]	[0; 2258]
overhead line infrastructure [total construction in km]	10	[500; 4,500]

Table 2: Overview of variable parameters with parameter ranges in 2050 and start values in 2020.

We will neither vary the maximum number of battery cycles, nor the battery cost although both might have a meaningful impact. Battery ageing through cycles is not considered in the approach and we want to integrate battery ageing because of high power charging (because of high C-rates) in further work.

3 Results

With 1,000 random variations of the parameters in Table 2 and run the simulations. We determine the market shares of the different solutions as well as their amount of electricity and diesel used.

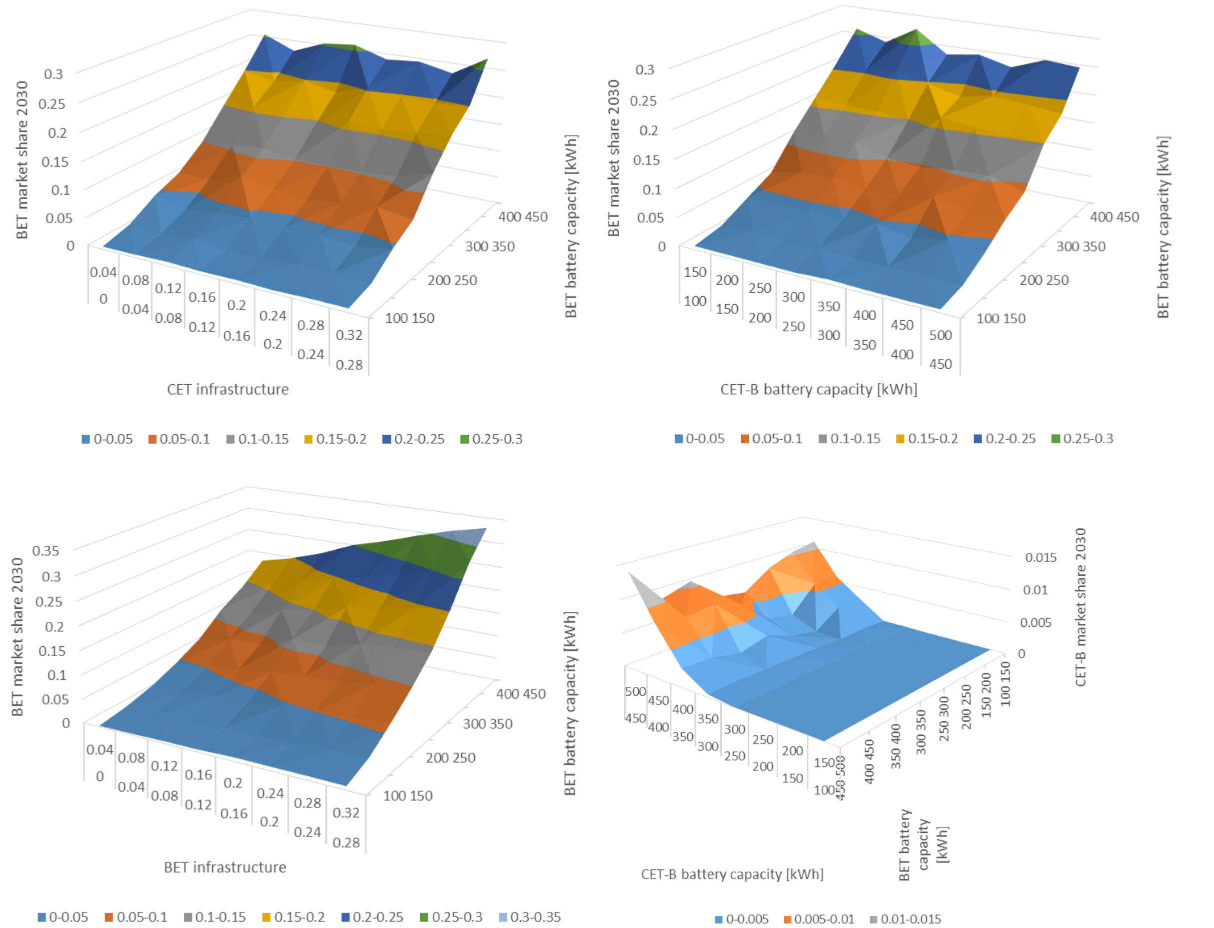

Figure 1: Influence of parameter variation on market shares in 2030. Upper left: *Influence of CET infrastructure and BET battery capacity on BET market share.* Upper right: *Influence of BET battery capacity and CET-B battery capacity on BET market share.* Lower left: *Influence of BET infrastructure and battery capacity on BET market share.* Lower right: *Influence of CET-B battery capacity and BET battery capacity on CET-B market share.*

Figure 1 shows the results for the 2030 market shares in different settings. In the upper left corner of the figure, we find an increasing market share of BET with battery capacity. It is not influenced by CET infrastructure and seems independent of it. The same holds for CET-B battery capacity shown in the upper right corner. Thus, with a battery with a sufficient size, the market share for BET can be increased independent of the CET battery capacity and inrastructure. However, market shares of BETs can be further increased with more HPCs (lower left panel of Figure 1.Then market shares up to 35% are possible. The market shares of CET-B can be increased with additional battery capacity - also independent of BET market shares. Thus, in 2030 the main factor to increase the number of trucks with alternative drive trains is by adding battery capacity. The two options do not have large influence on each other's market shares. The effect of additional infrastructure for CET-B did not show a strong effect. Thus, a pure infrastructure increase is not sufficient for both technologies.

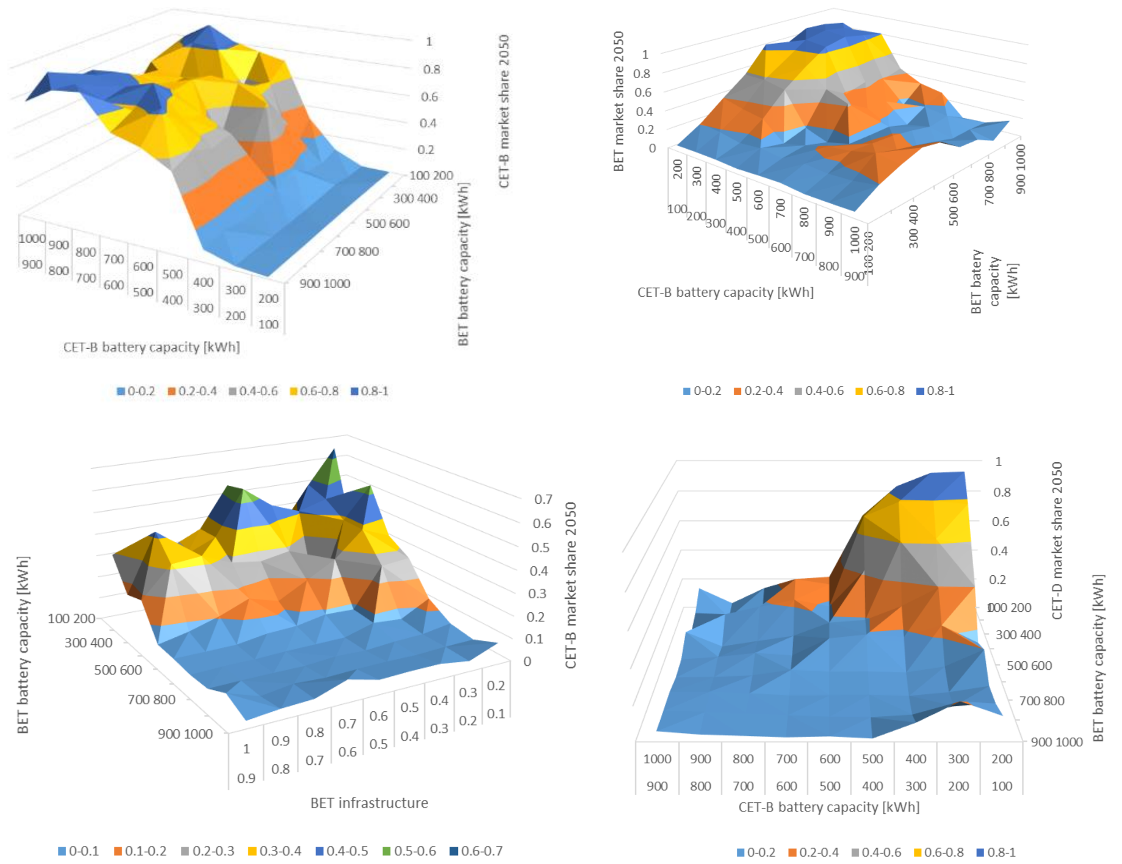

Figure 2: Influence of parameter variation on market shares in 2050. Upper left: *Influence of CET-B battery capacity and BET battery capacity on CET-B market share.* Upper right: *Influence of CET-B battery capacity and BET battery capacity on BET market share.* Lower left: *Influence of BET infrastructure and battery capacity on CET-B market share.* Lower right: *Influence of CET-B battery capacity and BET battery capacity on CET-D market share.*

Figure 2 contains selected market shares for 2050 with different variations. In the upper left panel, we may observe that the market share of CET-B increases with larger battery size independent of the BET battery size. Thus, the effect from 2030 remains stable in 2050. The market shares of BET decreases when CET-B batteries are large or the battery capacity of BETs is low (upper right panel). So, we can now see an impact and changing market shares from BET to CET-B. The market share of CET-B is also dependent on BET battery capacity and infrastructure setup (lower left panel). Finally, if battery capacities for BET and CET-B are low, CET-D gain the highest market shares with the scenario underlying assumptions (lower right panel). Increasing the infrastructure for CET does not show clear effects on market shares.

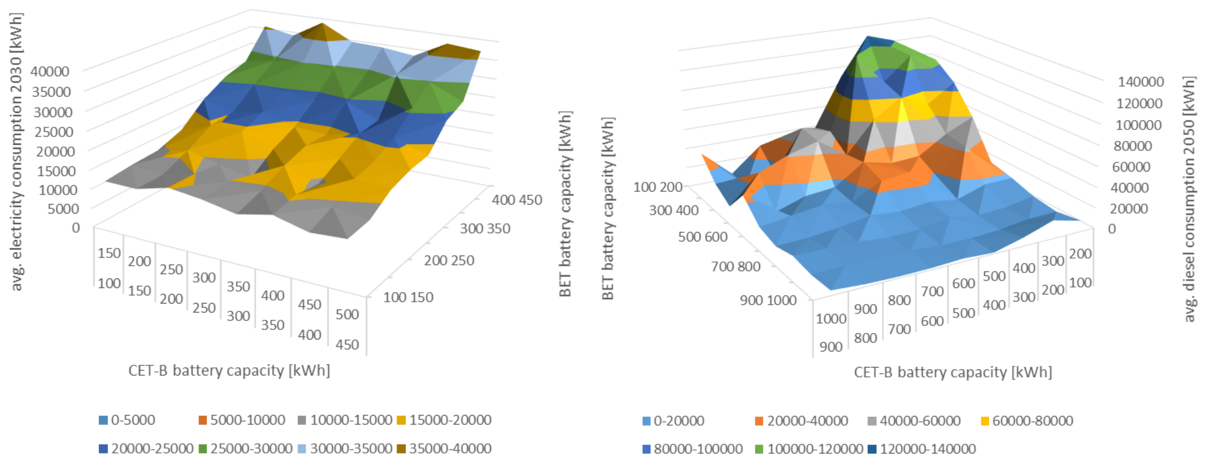

Figure 3: Energy consumption variation. Left panel: *average electricity consumption per truck in 2030 w.r.t. CET-B battery capacity and BET battery capacity.* Right panel: *Average diesel consumption in 2050 w.r.t. CET-B battery capacity and BET battery capacity.*

Figure 3 shows the effect of BET and CET-B battery capacity on electricity consumption in 2030 and diesel consumption in 2050. Both panels show a very clear story. In 2030, we can increase the electricity consumption by increasing BET battery size while CET-B battery capacity has hardly any effect. In 2050, the diesel consumption is highest when BET and CET-B battery capacities are low. This corresponds to CET-D market shares in Figure 3.

Discussion and conclusions

This analysis contains first results on the dependence of battery capacity and infrastructure setup on market shares of battery electric and catenary electric trucks in 2030 and 2050. For this analysis, we used a monte-carlo-simulation and varied battery sizes and infrastructure availability within certain boundaries.

These calculations are subject to a number of assumptions. The approach of using a monte-carlo-simulation is discussible and a regression analysis of results or an analytical approach could be more useful [10]. Yet, the approach is simple and retrieves first insights that can further be analyzed in more depth. The assumptions for the integration of infrastructure is based on earlier publications [5, 8]. Other approaches for a direct utility integration of infrastructure into the user buying decision for a truck have not been published so far to the authors' state of knowledge. The assumptions for parameters stem from a very ambitious scenario for greenhouse gas neutrality in Germany in 2050 and have been discussed in depth in [9]. If goals from the Paris agreement are considered feasible, these assumptions are very reasonable.

From these first calculations, we can retrieve the following insights: (1) Market share for BET and CET-B mainly depend on their battery capacity in 2030 and are only affecting each other in 2050. (2) Additional infrastructure seems to only have a limited effect on market shares for BET and hardly any on CET-B. (3) By increasing battery capacities, the use of electricity can be increased; otherwise diesel remains the dominating fuel in this setup. Further analyses will also comprise the investments for battery capacities and infrastructure.

Acknowledgments

This research was funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMUB) in the project "ewayBW" (FKZ 16EM3167-1).

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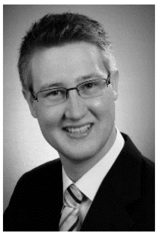

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