

Potential analysis of electric vehicle road sweepers in Germany

Michael Haag¹, Dr. Clemens Fischer²

¹*Fraunhofer IAO, Nobelstrasse 12, 70569 Stuttgart, michael.haag@iao.fraunhofer.de*

²*Alfred Kärcher GmbH & Co. KG*

Abstract

Transportation is often referred to as an early adopter market for plug-in electric vehicles (PEVs) [1]. This paper seeks to analyse driving profiles of conventional road sweepers collected in the German showcase project ‘Umweltfreundliche Kommunalfahrzeuge’ [2]. The analysis aims at determining PEV-potentials and estimating the influence of different factors on the economic and technical potential of electric road sweeper vehicles. We conclude that road sweeper vehicles can economically be electrified in the year 2020. In favorable conditions range extended electric vehicles (REEVs) and battery electric vehicles (BEVs) can substitute every second conventional road sweeper. However it becomes apparent, when varying the input parameters of our estimates, the economic potential is very sensitive to vehicle prices, consumption and maintenance costs.

Keywords: market, cost, EREV (extended range electric vehicle), BEV (battery electric vehicle), modeling

1 Introduction

Motorized transport is nowadays responsible for a large share in greenhouse gas (GHG) emissions. Using renewable energy sources, electric vehicles can achieve a significant decrease in local and global emissions from the transport sector without losing the advantages of motorized individual traffic. However, conventional mobile working machines still account for almost 50% of the urban particle emissions and 20% of NO_x-emissions [3]. Electrified propulsion technologies with little or no (local) emissions can help to solve the problem, if energy from renewable energy sources is used. Plug-in electric vehicles have been subject of research since the 1980's, while research on fuel cell electric vehicles just started in 1990's [4]. How-

ever, research was mainly focused on PEVs for passenger transportation. Commercial vehicles and municipal tool carriers were merely taken into research, though this segment exhibits a huge potential for vehicle electrification. In the municipal area, road sweepers are often used on shorter daily distances, which defuses the range limitations of current electric vehicles. The benefits of lower fuel consumption, reduced noise and exhaust emissions, might also contribute to the improvement of living conditions of citizens in residential areas.

In Figure 1 we show the development of the vehicles for road sweeping in the years 2005 to 2010. We observe that the vehicle stock of mobile machines for street cleaning over the years has steadily grown. In 2010 about 9,000 mobile machines were registered in Germany. In addition, the Figure shows that the vehicle stock of the year 2007 to

2008 strongly declined. This is due to a changed capture methodology by the Kraftfahrtbundesamt, according to which only registered cars without temporary shutdowns will be counted.

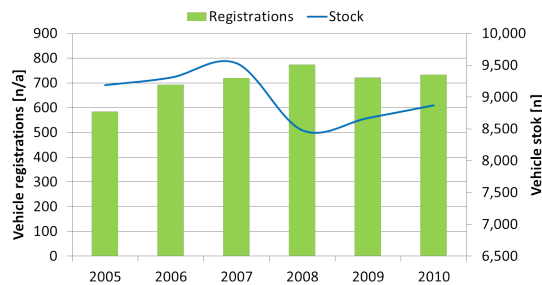


Figure 1: Registrations and vehicle stock of mobile machinery in Germany (Source: [5] and [6]).

In this paper, we use driving profiles of sweeper vehicles for the analysis which is described in section 2. Given this data, we will determine what share of a driving profile of a conventional road sweeper may be operated by a plug-in electric vehicle (technical analysis) and compute its economic efficiency (economical analysis). The applied methodology is described in section 2. Results are shown in section 3 and discussed in section 4.

2 Data and Methodology

2.1 Driving profiles

There are two major data sets for driving profiles in Germany. For a large collection of driving profiles in private transportation, Mobility in Germany (MiD) is the major database, while Motor Traffic in Germany (KiD) is the major database for commercial transportation. However, none of these data sets of driving profiles covers a decent sub sample of road sweepers. Thus, to determine the technical and economic potential of road sweeper vehicles, the German showcase project ‘Umweltfreundliche Kommunalfahrzeuge’ collected driving profiles of road sweeping vehicles in service for municipal utility companies across German cities.

At the outset of the project conventional road sweepers were equipped with ordinary GPS-data trackers to record driving profiles with an associated time stamp, geographic information, speed and distance. The survey was conducted from May 2014 to August 2015. Since every five seconds a data point was generated, we summarized movement profiles to single trips with a start and end time and corresponding geographical location. This reduced the data points to 7,072 trips in total.

Table 1: Driving profiles

Criteria	eKommunalfahrzeuge
Data collection	GPS-tracking
Avg. observation period	238.7 days
Total number of profiles	6
Avg. VKT per day	29.5
Total number of trips	7,072

In Figure 2 we display the cumulative distribution function of the vehicle kilometers travelled (VKT)

per day, displaying the percentage (abscissa) of samples which drive less or equal to the daily driving distance in the ordinate. We observe that around 50 % of the driven daily mileage is less than 30 km, while only 10 % of the driven daily mileage exceeds 50 km per day.

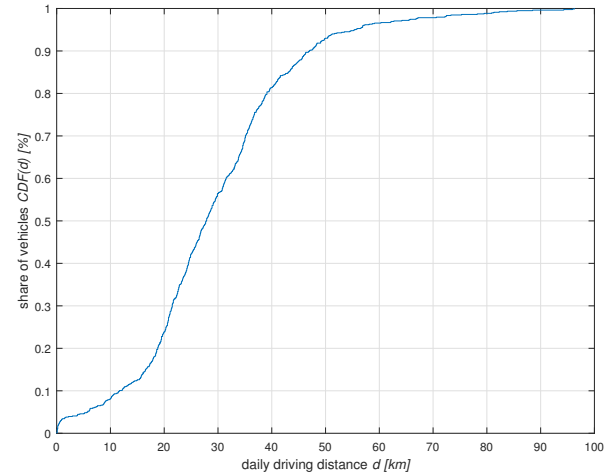


Figure 2: Cumulative distribution function of daily driving distances of road sweeper vehicles. The trips described in section 2 are summed up on a daily basis.

It must be distinguished between a road sweeper vehicle in transportation and working mode. In this paper, it is assumed that when driving at a speed of less or equal to 10 km/h the vehicle is supposed to work and when driving at speeds more than 10 km/h a transportation trip to the place of work or the home base is given. Based on that assumption and on the average speed of a single trip it can be found out whether a vehicle is in work or transport usage.

In Table 2 we show the average daily distance and corresponding average speed of a vehicle as well as the work and transport shares. We observe that the surveyed vehicles have a work share between 38% and 97% (compared to the total driving distance).

Table 2: Analysis of driving profiles

Vehicle	Average daily distance [km]	Average speed [km/h]	Work share [%]	Transport share [%]
1	32	11.1	62.9	37.1
2	37	10.1	74.6	25.4
3	18	5.5	97.3	2.7
4	41	11.8	38.2	61.8
5	19	8.1	78.7	21.3
6	30	8.2	82.9	17.1

2.2 Methodology

For the assessment of the economic potential a Total Cost of Ownership-Analysis (TCO) is undertaken. Analysed propulsion technologies are Diesel (ICE-CI), REEV and BEV. With the driving profiles described above we calculate the battery

state of charge (SOC)

$$SOC_t(t+1) =$$

$$\begin{cases} SOC(t) - d_{\Delta t} * c_{ewt,y} & \text{if } d_{\Delta t} > 0 \text{ and } \\ & \varnothing v_d \leq 10 \text{ km/h} \\ SOC(t) - d_{\Delta t} * c_{et,y} & \text{if } d_{\Delta t} > 0 \text{ and } \\ & \varnothing v_d > 10 \text{ km/h} \\ SOC(t) + \Delta t * P_{loc_t}, C & \text{if } d_{\Delta t} = 0 \end{cases}$$

for the given electric propulsion technologies BEV and REEV [7],[8]. If the average velocity v_d of a trip is less or equal to 10 km/h and the travelled distance $d_{\Delta t}$ is greater than 0 km, the vehicle is considered to be in working mode and hence the work consumption c_{ew} is used. Similarly, if the average velocity is greater than 10 km/h, the vehicle is considered to be in transport with transport consumption c_{et} .

Given the calculation of the SOC, every recorded driving profile is simulated according to its charging and discharging process. Based on the simulation of the battery profile, the electric work and transport (for BEV and REEV) as well as the conventional work and transport (for REEV and ICE-CI) on the total mileage is computed.

For every driving profile the annual total cost of ownership for the examined propulsion technologies are calculated based on the computed technical potential. The annual TCO are given by:

$$TCO_a = a_{capex} + a_{opex}$$

To determine the a_{capex} the equivalent annuity method is used

$$a = \frac{(1+i)^L * i}{(1+i)^L - 1}$$

in which a is the annuity, i denotes the interest rate and L is the holding period. We choose $i = 5\%$ and $L = 7$ years throughout this paper.

$$a_{capex}^y = (((NCP_{t,y} + \kappa_{t,y} * p_{t,y}) * a - RV_{p_{t,y}}) * (1 + VAT)_p)$$

NCP denotes the net price of a vehicle with propulsion technology t in year y . κ denotes the corresponding battery capacity with price p per kWh. RV denotes the residual value, which is modeled using a hedonistic price index according to [9] and [10].

$$a_{opex}^y = (((s_{ewt,y} * c_{ewt,y} + s_{et,y} * c_{et,y}) * d_{et} + (s_{cwt,y} * c_{cwt,y} + s_{ct,y} * c_{ct,y}) * d_{ct}) * AM_{p,y}) * (1 + VAT_y) + d_{t,y} + d_{m,t,y}$$

s_{ew} denotes for electric driving share in work mode, while s_{et} is the share for electric driving in transport mode. Analogously, s_{cw} denotes for conventional driving share in work mode, while s_{ct} is the

share for conventional driving in transport mode. c_e is electric consumption in kWh/h and c_c is conventional consumption in l/h. The cost of driving consists of d_e in €/kWh and d_c in €/l. The cost for driving in electric and conventional mode are multiplied with the travelled annual mileage AM and finally the annual taxes d_t as well as the gross annual maintenance cost d_m are added.

Computing the cost optimal propulsion technology, summing up all the driving profiles for each propulsion technology and dividing them by the amount of vehicles, the economic potential of a propulsion technology is calculated.

2.3 Techno-economical Parameters

The parameters are anticipated values for Germany and the year 2020. The vehicle specific values are given in table 3.¹

Table 3: Techno-economical parameters

Parameter	Diesel	REEV	BEV
Investment excl. battery [Euro]	75,000	85,000	80,000
Battery capacity [kWh]	-	20	45
Electricity cons-work [kWh/h]	-	6	6
Electricity cons. transport [kWh/h]	-	2	2
Fuel cons. work [l/h]	3	3	-
Fuel cons. transport [l/h]	2	2	-
Maintenance [Euro/a] ²	3,000	3,500	4,500

We assume fuel prices at 1.33 Euro/l for diesel fuel and 0.18 Euro/kWh for electricity. VAT of 19 % is added to fuel and electricity prices. The battery price for the year 2020 is estimated at 280 Euro/kWh.

The charging capacity depends on the infrastructure which is given in table 4. Since there are different driving strategies with road sweepers, multiple charging scenarios apply. Depending on the strategy, road sweepers can be charged anywhere, at home location or overnight. Besides that, road sweepers can be charged with different power rates, ranging from 3.7 kW to 50 kW. In total we analyse the impact of 12 different charging scenarios.

¹Please note that the parameters are not deducted from a specific vehicle and were primarily estimated with the purpose to compare the different propulsion technologies.

² incl. replacement battery over vehicle lifetime

Table 4: Charging infrastructure scenarios

	overnight	at home	anywhere
3.7 kW	①	②	③
7.4 kW	④	⑤	⑥
22.2 kW	⑦	⑧	⑨
50 kW	⑩	⑪	⑫

3 Results

3.1 Technical potential

For electric sweeper vehicles we calculate the minimal net battery capacity needed using the above formalized simulation method. Figure 3 shows the electric driving share (abscissa) of REEVs in relation to the net battery capacity.

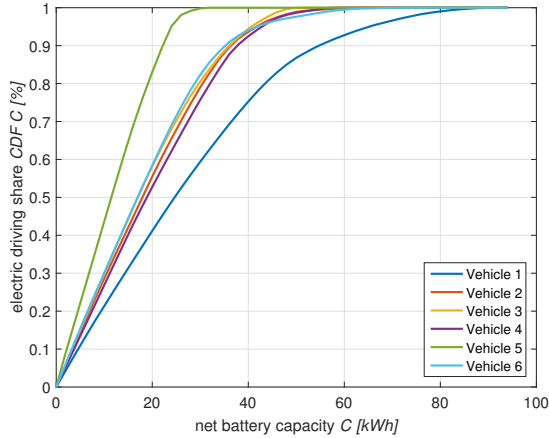


Figure 3: Cumulative distribution function of battery net capacities with corresponding electric driving share for recorded driving profiles.

In Figure 3 we observe that with a given net battery capacity of 10 kWh, half of the vehicles show an electric driving share of about 30 %. If net battery capacity is doubled to 20 kWh, 80 % of the analysed vehicles can obtain electric driving shares around 50 %. Furthermore, a net battery capacity of about 40 kWh is adequate to exceed electric driving shares of 90 %.

Figure 4 shows the technical potential for BEVs and reveals what share of vehicles in the given driving profiles can be a BEV considering the individual technical potential. With regard to location we

analyse three scenarios (charge overnight, at home and anywhere) with four different power rates (3.7 kW, 7.4 kW, 22 kW and 50 kW).

We observe that with a charging capacity of 3.7 kW there is no technical potential for BEVs if they are charged at home or overnight. However, if charging capacity is doubled to 7.4 kW already 50 % of the driving profiles show technical potential for BEV. If the vehicles can be charged at every stop, the technical potential rises from 50 % with 3.7 kW to 100 % with 50 kW.

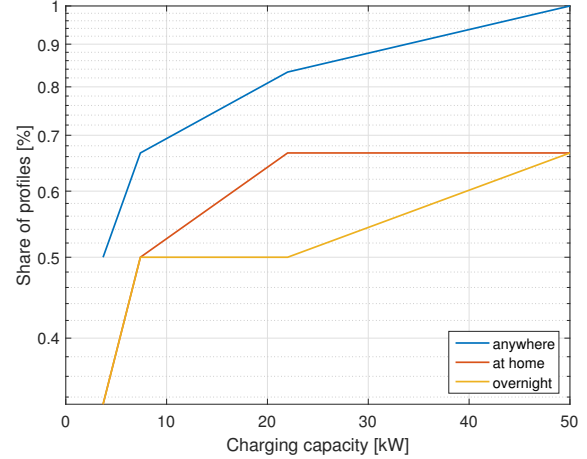


Figure 4: Technical potential for BEVs of driving profiles.

In Figure 5 the simulation of an exemplary driving profile of a REEV and an observation period of seven days is given. In this example the scenario ‘Charging at home’ with 7.4 kW is simulated. In the top panel the simulated vehicle status is displayed. For work and transport a road sweeper can have one of the following states: work electric, work ice and transport ice. For parking a road sweeper can have one of the following states: stand somewhere, stand at home and stand at home & charge. While in the middle panel the travelled distance is displayed, the bottom panel shows the corresponding battery state of charge.

In the analysed observation period a distance of 202.5 kilometers in total was travelled. 44.8 km of the travelled distance were covered for transport purposes. 157.7 were covered in work mode, from which 97.1 km were operated in electric work mode. This corresponds to a electric work driving share of 61.5 % and to a total electric driving share of about 48.0 % for the observed period. In addition, the average mileage per day was 35.62 km and the average working hour came up to 5.94 hrs per day.

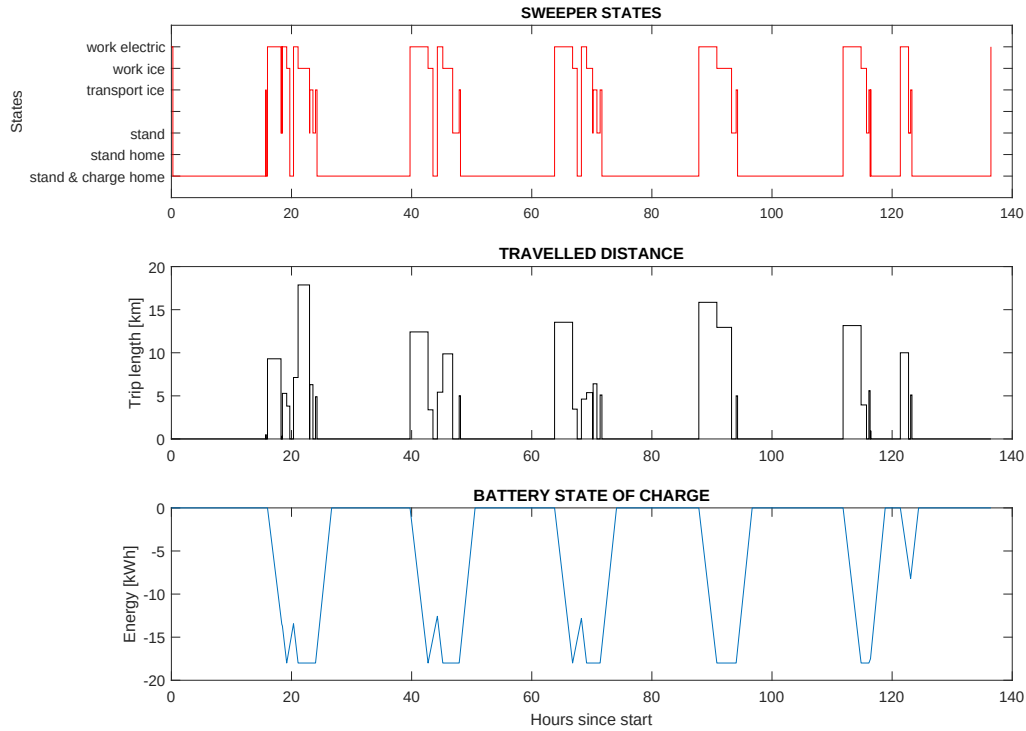


Figure 5: REEV-simulation of a driving profile for the observation period of one week. The top panel shows the states of the simulated electric road sweeper. The middle panel displays the travelled distance, while the bottom panel shows the corresponding SOC.

3.2 Economic potential

Figure 7 shows the economic potential of the three propulsion technologies BEV, REEV and ICE-CI for different charging scenarios and charging capacities in 2020. An observation period of seven years is being used. The costs for the charging infrastructure are not included in this analysis. The left panel shows the scenario for charging overnight. The middle panel shows the charging scenario at home, while the right panel displays the scenario for charging anywhere (at every stop).

In the overnight charging scenario, there is only very little economic potential for REEVs. Similarly, for little charging capacities in the home charging scenario, the analysis is largely dominated by ICE-CI. With a charging capacities equal to 22

kW, the share of REEVs rises to 50 %. Higher charging capacities like 50 kW show no further increase in economic potential for PEVs. For the charging anywhere scenario, already 50 % of the driving profiles could economically be electrified with a relatively little charging capacity of 3.7 kW. We can see that BEVs get economically feasible and with charging capacities of 50 kW two third of the driving profiles can be electrified in an economic manner.

Summing up, it becomes evident that REEVs play an important role to electrify road sweeper fleets in an economic manner. However, from an economic point of view, BEVs play a minor role. With favorable operating strategies, REEVs are an economical alternative to ICE-CI in 2020.

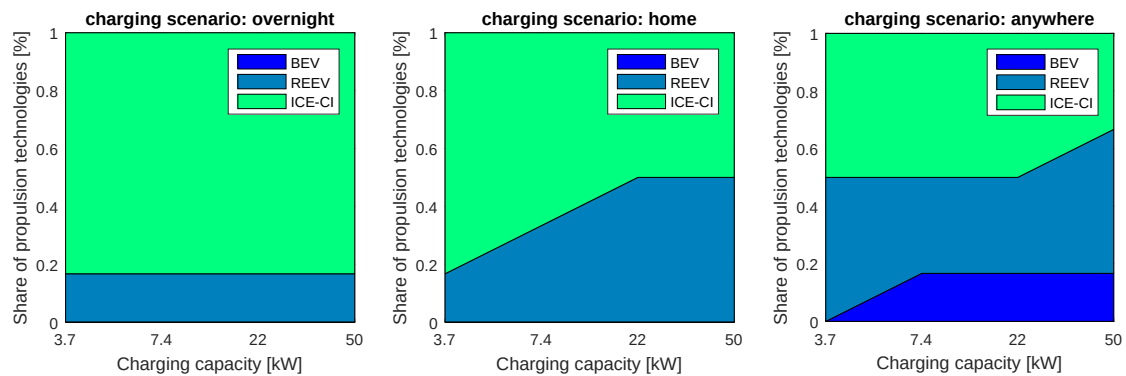


Figure 6: Economic potential for propulsion technologies in 2020 with an observation period of seven years. The figure shows the computed shares of propulsion technologies in the fleet if vehicles are charged overnight (left panel), only at home location (middle panel) or if charging occurs at every stop (right panel).

3.3 Sensitivity Analysis

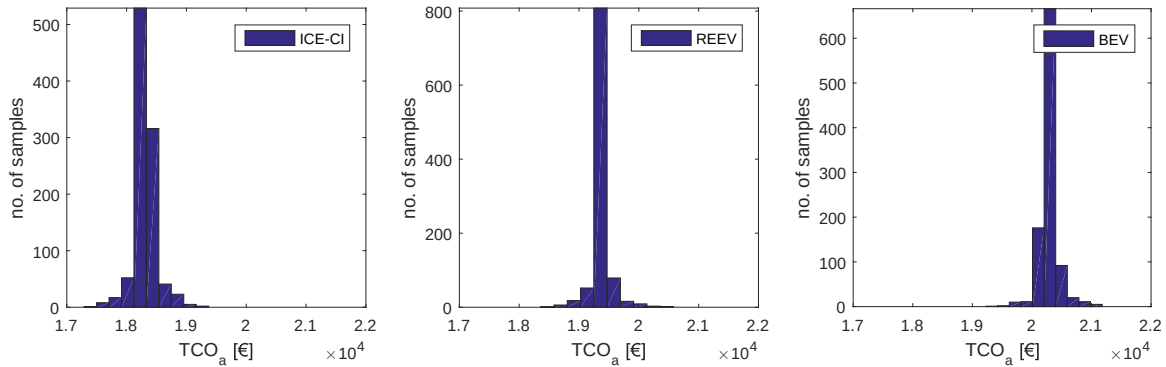


Figure 7: Distribution of TCO for propulsion technologies ICE-CI (left panel), REEV (middle panel) and BEV (right panel) in year 2020.

Since our analysis is based on several assumptions it can be afflicted with uncertainty. Changing parameters may cause different results and different shares for the given propulsion technologies. Therefore, a Monte Carlo simulation with 1,000 runs is performed to estimate the sensitivity of our results based on one exemplary driving profile. We change the parameters net vehicle price (excl. battery costs), battery price per kWh, vehicle consumption, maintenance, power price as well as fuel price. The Monte Carlo simulation is using a normal, PERT and gamma distribution for the changed parameters (see [11] for details on the distribution).

Figure 7 shows the results of the Monte Carlo simulation with the distribution for all simulated TCO cases. Due to the given uncertainty of the input parameters, the annual TCO-results vary across the 1,000 simulations. With the varying parameters the ICE-CI vehicle has the lowest overall costs. The REEV has slightly higher costs, while the BEV is more likely to have greater TCO.

To analyse the impact of each input parameter we conducted a sensitivity analysis for the year 2020 which is based on the Monte Carlo simulation. Therefore, we analysed the resulting variance of each parameter in relation to its initial value which is given in TCO/km. Figure 8 presents the sensitivity analysis of one exemplary driving profile for a REEV.

From Figure 8 we can observe that the greatest impact for the TCO is given by the variance of the net vehicle price. Considering a REEV, TCO can vary about 0.22 Euro per km. The second highest impact is given by maintenance costs, which can vary about 0.07 Euro per km. While fuel or electricity prices play a minor role, consumption can vary about 0.08 Euro per km.

In general, the parameters discussed above can explain a high share of the TCO variance for the analysed electric road sweepers. In comparison to passenger cars the higher investment costs and lower annual mileage leads to a greater influence of the discounted investment.

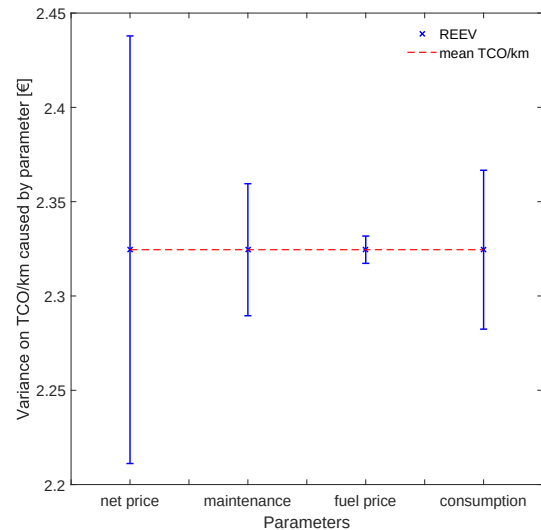


Figure 8: Sensitivity analysis for a REEV with variance on TCO/km caused by several parameters.

4 Conclusions and discussion

This paper provides an analysis for the future market potential of electric road sweeper vehicles in Germany. We use driving profiles for our analysis and can conclude the following results:

- Assuming frequent charging and high charging capacities (≥ 22 kW) more than 50 % of the analysed vehicles could be technically operated as BEVs.
- REEVs can reach a significant share in road sweeper fleets in 2020. Under favorable conditions, 50 % of the the vehicles could economically be operated as range extended electric vehicles. However, with only 16 % of the analysed vehicles, BEVs play a minor role for electrification of road sweeper fleets.
- The economic potential of a propulsion technology depends on the actual usage. With

shorter holding periods or low utilization, diesel vehicle are predominant while with longer holding periods or high utilization PEVs exhibit economic potential.

- However, the analysis is afflicted with uncertainty. A Monte Carlo simulation shows, that a varying net vehicle price has the greatest impact on the total cost of ownership.

This paper is based on multiple assumptions as described in section 2. Moreover, a buying decision solely focusing on the total cost of ownership was considered, excluding other purchasing factors such as emissions, service, brand image, safety (and others) [12].

Future analysis could assess how the recorded conventional driving profiles distinguish from actual driving profiles of electrified road sweepers. Furthermore, the use case of different kinds of cleaning assignments as well as the type of city and its effect on the type of propulsion technology should be covered by further research.

Within the project ‘Umweltfreundliche Kommunalfahrzeuge’ we will use electrified prototypes in different German cities to assess the potential of electrified road sweepers. In addition, we will continue to record driving profiles for further analyses of electric road sweepers.

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References

- [1] T. Gnann et al. “Market potential for electric vehicles in the German commercial passenger transport sector”. In: *Accepted Paper*. Barcelona, Spain, Nov. 2013.
- [2] e-mobil BW. *Umweltfreundliche Kommunalfahrzeuge im LivingLab BWe mobil*. 2013.
- [3] H. Helms and C. Heidt. *Erarbeitung eines Konzepts zur Minderung der Umweltbelastung aus NRMM*. Tech. rep. Ifeu – Institut für Energie- und Umweltforschung, Mar. 2014.
- [4] T. Gnann. “Market diffusion of plug-in electric vehicles and their charging infrastructure”. PhD thesis. :Karlsruhe Inst. für Technologie (KIT), 2015.
- [5] Kraftfahrt-Bundesamt. *Jahresbilanz der Neuzulassungen 2014*. 2015.
- [6] Kraftfahrt-Bundesamt. *Bestand an Nutzfahrzeugen, Kraftfahrzeugen insgesamt und Kraftfahrzeuganhängern nach technischen Daten (FZ 25)*. Tech. rep. Flensburg: Kraftfahrt-Bundesamt (KBA), Jan. 2014.
- [7] M. Haag and L. Ade. “Elektromobilität in kommunalen Reinigungsflotten”. In: (2015).
- [8] T. Gnann, P. Plötz, and F. Kley. “Vehicle charging infrastructure demand for the introduction of plug-in electric vehicles in Germany and the US”. In: *Electric Vehicle Symposium 26 (EVS26)*. Los Angeles, May 2012.
- [9] V. Dexheimer. “Hedonic methods of price measurement for used cars”. In: *Statistisches Bundesamt (Destatis)* (2003).
- [10] P. Plötz et al. *Markthochlaufszszenarien für Elektrofahrzeuge - Langfassung*. Tech. rep. Karlsruhe: Fraunhofer ISI, 2013.
- [11] G. Wu, A. Inderbitzin, and C. Bening. “Total cost of ownership of electric vehicles compared to conventional vehicles: A probabilistic analysis and projection across market segments”. In: *Energy Policy* 80 (2015).
- [12] Deutsche Automobil Treuhand (DAT). *DAT Report 2011*. Tech. rep. Ostfildern: Deutsche Automobil Treuhand (DAT), Apr. 2011.

Authors



Michael Haag studied Business Engineering at the Karlsruhe Institute of Technology (KIT). He works as a scientist in the Competence Center Mobility Innovation at the Fraunhofer Institute for Industrial Engineering IAO. His current research focuses on electric vehicles.



Clemens Fischer studied at the Johannes Kepler Universität Linz technical mathematics and did his PhD at the Johan Radon Institute for Computational and Applied Mathematics. He is now working in the development of municipal cleaners for the Alfred Kärcher GmbH Co. KG.