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Showing the Feasibility of Electric Waste Collection Vehicles in Rural Areas: A Case Study in the Vulkaneifel District, Germany

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Abstract

This study evaluates the feasibility and environmental impact of transitioning to electric waste collection vehicles in the Vulkaneifel district, a rural region in Germany. Using the multi-agent transport simulation (MATSim) and the integrated vehicle routing problem solver Jsprit, we analyze fleet operations, total cost of ownership (TCO), and well-to-wheel (WTW) greenhouse gas emissions. Results indicate that EVs can meet operational demands with a cost increase of 9% compared to internal combustion engine vehicles (ICEVs) while achieving significant GHG reductions of up to 70%. These findings suggest that electrifying waste collection in rural areas is both technically and environmentally viable, offering a critical pathway for sustainable development in transportation.

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1. Introduction

A greenhouse gas (GHG) is a gas that traps heat in the atmosphere of a planet, leading to global warming and climate change [24]. Rising temperatures can cause more severe weather events [24], such as flooding due to heavy rain in the Ahrtal region in Germany in 2021 [14]. The most significant contributor of GHG emissions, for example, carbon dioxide (CO₂), is burning fossil fuels such as coal, oil, and gas. They account for 75% of global GHG emissions and 90% of global CO₂ emissions [24]. To reduce the negative effects of climate change, the European Union (EU) and the German government have set goals that require to reduce at least 55% of GHG emissions by 2030 compared to 1990 levels [2, 6]. The transportation sector is an important contributor to GHG in Germany, which is responsible for a share of 22% of the total emitted CO₂ in 2023 [23]. One solution to reduce GHG emissions by transportation is to switch from fossil fuel-burning internal combustion engine vehicles (ICEVs) to, for example, battery-powered electric vehicles (BEVs) [10]. These BEVs have already been adopted in Germany's transportation sector, e.g., private

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cars and public buses [3]. Additionally, many parcel service providers, such as DHL, have opted to transform their fleet to electric ones [18].

In our research, we investigate the waste collection as a specific segment of commercial transportation. BEVs have been introduced to urban waste collection in large metropolitan areas like London, and Copenhagen [17, 25]. Also from the Manufacturers side, many available vehicles have been launched, e.g., Mercedes-Benz[15], and Volvo [26]. Currently, these new electric waste collection trucks are mainly for urban waste collection. Many studies, such as Ewert et al.[7, 20], have previously explored the feasibility of EVs in waste collection and its potential benefits. However, these studies have mainly addressed BEVs in urban areas.

This paper aims to address this gap in both research and application, and will evaluate the potential of electric waste collection vehicles in rural areas. The case study focuses on the rural German district Vulkaneifel, and it will follow the methodology introduced by Ewert et al. [7]. This involves tour generation and simulation of waste collection vehicles using the open-source multi-agent transport simulation Multi-Agent Transport Simulation (MATSim) [11] and the in MATSim integrated solver for vehicle routing problems (VRPs) Jsprit [13]. This research compares the Total Cost of Ownership (TCO) and the Well-To-Wheel analysis (WTW) for the different scenarios and evaluates the feasibility of using BEVs to reduce carbon emissions.

Analyzing the feasibility of BEVs in rural waste collection is vital, since variables such as demand and travel distance may differ from an urban scenario such as Berlin. Therefore, this study plans to determine whether BEVs could also satisfy the demands of a rural area while being an economically viable solution. The results will provide a first impression of the feasibility and potential environmental impact of switching to BEVs.

2. Methodology

Our approach consists of a transport simulation, a TCO, and a WTW analysis. The transport simulation in combination with a tour planning algorithm is used to generate a possible solution for waste collection in a given geographical region. The required fleet size, distances traveled, and energy consumption are provided. We investigate the economic and environmental implications by comparing different propulsion systems using the TCO and WTW methods.

2.1. Transport Simulation: From Demand Generation to Vehicle Trajectories

The approach of using the Multi-Agent Transport Simulation (MATSim) is used to build a microscopic model of this specific segment of the transportation system. "Microscopic" means that each part of the system can be resolved individually. The methodology for economic assessment involves building a base case model (ICEV), creating policy case models (EV), and comparing their costs and benefits.

The base case model represents the waste collection in the rural area using ICEVs. It involves (a) generating daily demand for waste collection and (b) planning plausible vehicle tours to handle this demand. The demand specifies the quantity of waste to be moved between locations and is generated synthetically using average waste collection data, spatial information (e.g., vehicle depots, dumps, and the street network), and plausible assumptions. The detailed steps and related parameters for the demand generation of our case study are presented in Section 3.2.

Each vehicle tour starts at a depot, proceeds through collection points to a dump, and returns to the depot. If the capacity of the vehicle is exceeded, the vehicle can unload the waste at the dump and continue the tour. This is modeled as a pickup-and-delivery VRP, where vehicles, constrained by payload capacity and time, may require multiple trips. To solve this VRP, the in MATSim integrated software Jsprit [13] is used to find heuristic solutions by minimizing the total costs. The policy case is similar but assumes EVs with different payloads and range constraints, resulting in potentially different tours. The process of building the synthetic tours for the collection vehicles can be summarized with the following steps:

1. Generate a plausible demand from data and based on assumptions about the system (see Section 3.2).
2. Define the possible vehicle options to serve the demand (see Table 1).
3. Run the tour planning and fleet assignment algorithm of Jsprit to create trajectories that handle the demand.
4. Use MATSim for traffic assignment and for analyzing the results.

The result is a set of vehicle tours that serve the demand under the given constraints of the possible vehicle fleet (e.g., vehicle capacity, range, etc.). By analyzing the tours, one can determine the total cost of ownership and the well-to-wheel analysis of the environmental impacts for the different scenarios. To allow for a comparison of the scenarios, the same demand is used for all scenarios.

2.2. Total Cost of Ownership

The Total Cost of Ownership (TCO) is an economic model that calculates all the costs associated with owning and operating a product, e.g., a vehicle, over its entire lifespan or usage [9, 8]. In the context of waste collection, TCO accounts for direct and indirect costs, including purchase price, fuel or electricity consumption, maintenance, operational costs, and infrastructure costs, such as charging stations for electric vehicles. The TCO analysis can support the purchase decision of which vehicle type to decide on and is ideal for this assessment.

For this study, we assume a product lifetime of 10 years for vehicles and 20 years for charging infrastructure, and annualize the investment using an average interest rate of 4% according to [12]. The operational costs are calculated for each scenario based on simulation results. An overview of all relevant cost parameters is presented in Section 3.3.

2.3. Well-to-Wheel Analysis

The Well-To-Wheel Analysis (WTW) is a method that analyzes the GHG emissions emitted from production, Well-to-Tank (WTT), to usage, Tank-to-Wheel (TTW), of an energy source [5]. For example, for diesel, the WTT entails aspects such as crude oil production, crude oil transportation to the refinery, refining it to diesel, and distributing and dispensing the diesel at a gas station. TTW describes the emissions produced from running a vehicle. For EVs, only emissions from the production of electricity need to be accounted for, since driving EVs is emission-free.

For the WTW calculation, we used the following factors for the *electricity* production [21]: 490 g *CO_{2eq}*/kWh in 2021, 251 g *CO_{2eq}*/kWh in 2030, and 94 g *CO_{2eq}*/kWh in 2050. For *diesel* 3 170 g *CO_{2eq}*/l diesel is assumed [4].

3. Case Study

The case study uses the Vulkaneifel district in Germany as a test bed to simulate the household waste collection in a rural area. Household waste means the waste produced by households and is also known as municipal solid waste. This means that other waste types, such as commercial waste, recycling waste, or paper, are not considered in this study. Vulkaneifel is a district in the German state of Rhineland-Palatinate with a population of 60,000 and an area of 912 km² and is one of the least densely populated areas in Germany. It consists of 109 municipalities and smaller towns, which are grouped into three municipal associations: Daun, Gerolstein and Kelberg.

3.1. Population and Road Network

To generate the demand and to simulate the waste collection, the population and the road network of the Vulkaneifel district are needed. The population data for the Vulkaneifel region is extracted from the open-source agent-based transport model for the Vulkaneifel and its surroundings.¹ In the context of this study, the population data is used to locate the households which are the locations for the synthetic demand for waste collection.² By using this synthetic population data it has to be observed that the population is a 25% sample of the real population. To create a 100% demand for the waste collection, each person of the population represents a demand for 4 persons and can be interpreted as a household. This is an important difference to the approach used by Ewert et al.[7], where demand is distributed evenly across all roads in the city of Berlin based on their length. The road network is generated from OpenStreetMap[19] data and includes all roads in and around the area of interest.

3.2. Generating a Synthetic Demand for Waste Collection

The waste demand generation of this study is based on the synthetic population data of the Vulkaneifel district. Therefore, we assume that each person in the synthetic population represents a household and each household produces the same average amount of waste. As the average household waste per person in Vulkaneifel, we assume 168.8 kg per year, which is the average amount for the related collection area of the ZV A.R.T. ("Zweckverband Abfallwirtschaft Region Trier") in 2022 [16]. For this study, it is necessary to convert the annual waste amount to waste per single collection. For this calculation, we assumed 13 collections per household per year (number of annual collections being free of charge) [30], and the assumption that every agent in the synthetic population represents a 4-person household. This results in an amount of round 52 kg waste per collection per household.

¹ <https://github.com/matsim-scenarios/matsim-vulkaneifel>

² <https://svn.vsp.tu-berlin.de/repos/public-svn/matsim/scenarios/countries/de/vulkaneifel/v1.1/input/>

Another important aspect is the published collection calendar that sets for each municipality the collection day in a 2-week cycle [29]. Integrating this information into the demand generation, we can assign a collection day to each household. So it is possible to create a demand for waste collection for each day of the week. The result of the assignment to collection days is shown in Figure 1. Because in reality, not every household orders a collection on every collection day, the demand should be interpreted as a collection scenario with a high demand. The rest of the demand generation process is similar to the approach of Ewert et al. [7] and can be summarized for this case study as follows:

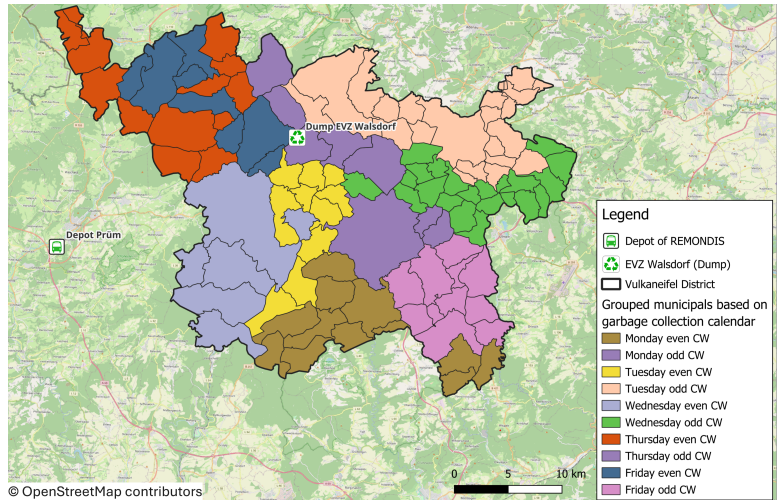


Fig. 1: Visualization of the collection calendar. Own illustration based on data from [29]

- The unloading duration for a fully loaded vehicle at the dump is set to 45 minutes, which is the break time for the vehicle crew.
- Pickup Time Window and Delivery Time Window will be set from 6:00 to 15:00.
- The location of the collection is the nearest network link to the household.
- The pickup duration is 19 seconds per bin, which is the average time for collecting a 240-liter waste bin in a rural area [27].
- If on one link more than one household is located, the number of bins is aggregated and an additional travel time of 15 seconds per bin is added [27].
- Due to its proximity to the district, the collection company location in Prüm will be assumed as the start depot for the waste collection in the Vulkaneifel. The vehicles will begin and end their tours at this depot.
- The collected waste is dumped in the collection facility in Walsdorf, Vulkaneifel (see Figure 1).

3.3. Vehicle Parameters and Charging Infrastructure

Since vehicle parameters, such as cost, range, fuel economy, and other factors often vary between manufacturers, the vehicle parameters introduced by Ewert et al. [7] will be used. This leads to the same vehicle types, which are ICEV, EV1 (higher range and lower payload), and EV2 (shorter range but same payload as ICEV). The only difference is that the maintenance and insurance costs are updated because [20] provides more recent data. All parameters for these vehicle types are presented in the supplementary material, see Section 6. The important parameters are summarized in Table 1.

Table 1: Vehicle type specifications for ICEV and EVs.

| Parameter | ICEV | EV 1 (large battery) | EV 2 (small battery) | Reference |
|--|--------|----------------------|----------------------|-----------|
| Payload [kg] | 11,500 | 10,500 | 11,500 | [7] |
| Battery Capacity (usable) [kWh] | - | 310 | 155 | [7] |
| Diesel Price per liter in 2024 (January-June) [€ per L] | 1.7203 | - | - | [28] |
| Electricity price per kWh in 2024 (January-June) [€ per kWh] | — | 0.1665 | 0.1665 | [1] |

4. Results

The results of this study are the tours required to handle the demand under the given conditions. These tours are simulated on the network so that every tour can be analyzed by all relevant parameters, e.g., the driven distance, tour duration, or the handled demand. Also, a vehicle type is related to every tour. The results are presented in three parts: the base case with ICEVs, the policy case with EVs, and the comparison of the Total Cost of Ownership (TCO) and the Well-to-Wheel analysis (WTW) for the different scenarios. The scenarios only differ in the vehicle type which are possible for the waste collection.

Because the collection areas for each day of the week are different, we simulated the waste collection for each scenario for each day of the 2-week cycle. So it can prevent the results being biased by the collection areas of the different days. The resulting tours for one day are visualized in Figure 2. Here one also can observe that the collection locations are located only in residential areas, which is an advantage of using the synthetic population data. This is the main difference to Ewert et al. [7], where the demand is distributed evenly across all roads in the area of interest.

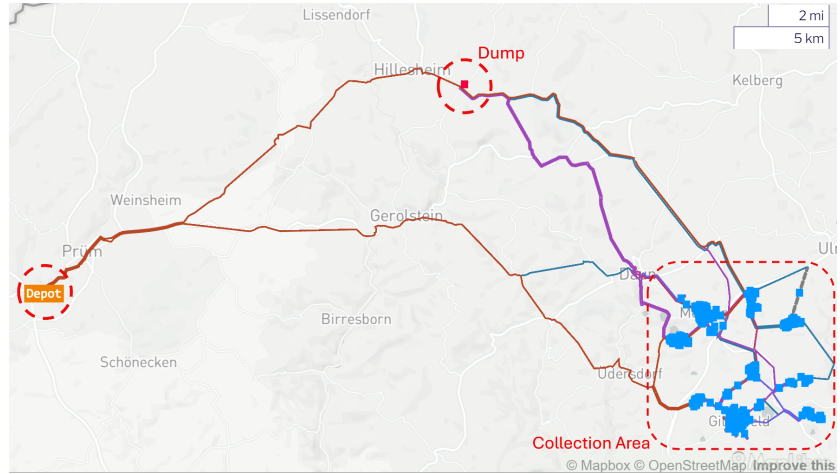


Fig. 2: Visualization of all tours for waste collection in the Vulkaneifel district on one-day (Friday, odd week). All tours have the same depot, unload the waste in the same dump, and are collecting the waste in the area for this weekday.

Table 2: Simulation results for the waste collection in the Vulkaneifel district. The values are given as an average daily value and as the range

| Values per day | ICEV (Base Case) | EV 1 (large battery) | EV 2 (small battery) |
|---------------------------|------------------------------|-------------------------------|-----------------------------|
| Avg. Number of vehicles | 5.3 (3–8) | 5.5 (2–9) | 8.4 (3–11) |
| Avg. Driven Distance [km] | 143.5 (74–213) | 154.1 (64.2–222.5) | 110.9 (69.2–125) |
| Avg. Collected Waste [kg] | 77,953.2 (38,896–127,192) | | |
| Avg. Waste per Tour [kg] | 14,708.2 (4,056–21,996) | 14,173.3 (1,872–20,904) | 9,280.1 (1,248–21,580) |
| Avg. Tour Duration [h] | 7.6 (3.2–9.3) | 7.7 (2.2–9.2) | 5.3 (3.2–8.7) |
| Avg. Costs [€] | 5,619.5 (3,027.9–8,505.3) | 6,121.6 (2,208.1–10,049.3) | 8,869.7 (3,160–11,667.7) |

4.1. Base Case: Collection with ICEVs

The base case scenario is the waste collection, where only ICEVs are possible to solve the VRP. Because the demand and their location for the days are different, the results for each day of the week are different. In total, we analyzed the results for 10 different days of the 2-week cycle because the given collection calendar is a 2-week cycle. The results are presented in Table 2. Because the daily amount of waste within the 10 days differs between 38,896 and

127,192 kg per day, we decided to present the results as an average value over the 10 days. To identify the differences of the results, the range of the daily values is also presented in Table 2. For the base case, the average number of vehicles is 5.3 per day and differs between 3 and 8 vehicles. This results in an average-driven distance of 142.5 km per day, which differs between 74 and 213 km per vehicle. The average collected waste per tour is 14,708.2 kg (max. payload is 11,500 kg), which shows a typical tour has two periods of collecting and unloading it at the dump. Analyzing these results shows that our approach creates plausible tours for the waste collection in this rural area.

4.2. Policy Case: Collection with EVs

In comparison to the base case, the policy case uses only EVs to solve the VRP. Therefore, two different EVs are possible, EV1 with a large battery and EV2 with a small battery. The EV1 has a usable battery capacity of 310 kWh and the EV2 has a battery capacity of 155 kWh. Because the collection of the waste is also consuming energy, the usable capacity for driving has been reduced under the given consumption factor for collecting to 280 kWh for EV1 and 125 kWh for EV2. For all tours, we assumed that the battery is charged to 100% at the beginning of the tour and the battery is not rechargeable during the tour.

Based on these assumptions, the results for the policy cases are presented in Table 2. As expected, the results show that the number of vehicles is higher for the EVs than for the ICEVs (5.5 for EV1 and 8.4 for EV2) although the difference between the EV1 and the ICEV is not significant. The reason for this little difference can be the lower payload of the EV1 compared to the ICEVs which can be observed in the reduction of the collected waste per tour. On the other hand, the number of vehicles for EV2 is around 3 vehicles higher than for the ICEVs. The driven distance for the EV2 is around 110.9 km per day, which is 32.6 km less than for the ICEVs. This is caused by the smaller battery capacity of the EV2, which results in a lower range and therefore more vehicles are needed to handle the demand. As a consequence, the handled demand per vehicle is significantly lower for the EV2 compared to ICEVs and the EV1.

4.3. Total Cost of Ownership

The Total Cost of Ownership (TCO) is calculated for all scenarios to compare the costs of the different vehicle types. The total daily costs for the scenarios are presented in Table 2 and the detailed comparison of the costs is shown in Figure 3. Here you can observe that the fixed costs are the main factor for the increase in the costs from ICEV to EV1. From EV1 to EV2, also the labor costs increase strongly, since more drivers are needed to drive the larger fleet of vehicles. Currently, the lower fuel costs for the EVs can not compensate for the higher fixed costs. But it is expected that the costs for the EVs will decrease in the future because the battery prices are expected to decrease and the electricity prices are expected to be stable or decrease. The total increase in the costs for the EVs compared to the ICEVs is around 500 € per day (+9%) for the EV1 and 3,250 € per day (+58%) for the EV2. This relatively low increase in the total costs is caused by the high share of the labor costs, which are the same for all vehicle types.

4.4. Well-to-Wheel Analysis

The results of the Well-to-Wheel analysis are presented in Figure 4. It can be seen that the CO_{2eq} emissions for the EVs are significantly lower than for the ICEVs. For 2021, this is because 59% of electricity was carbon-free [21]; additionally, EVs are more efficient than ICEVs for the start-stop driving cycles which are typical for waste collection. For the future years, an even larger carbon-free share of electricity is projected. In total, using EVs can save around 1.1 t CO_{2eq} per day (286 t per year with 260 working days) compared to the ICEVs by comparing the values of 2021. In relation to the cost increase of the EV1 of 502€ per day, this results in decarbonization costs of around 456€ per t CO_{2eq} . This can be compared with CO2 damage costs provided by the German environmental protection agency [22]. They show 300€ and 880€ per t CO_{2eq} for 2024, 335€ and 940€ per t CO_{2eq} for 2030 and 435€ and 1080€ per t CO_{2eq} for 2050. The lower values correspond to a 1% pure time preference rate, which discounts the interests of future generation, while the larger values, corresponding to a 0% pure time preference rate, set the interests of future generations equal to those of the current generation. Overall, the decarbonization costs for the rural waste collection case study are within the ranges given by currently discussed damage costs.

5. Conclusion and Outlook

As shown, the EV with large size battery can easily manage the simulated demand. Although the fleet's operational cost for this vehicle type would increase by 9% when compared to an ICEV fleet, market developments could offer vehicles at a lower price than estimated. Additionally, there is the potential to save 68–70% GHG emissions, which

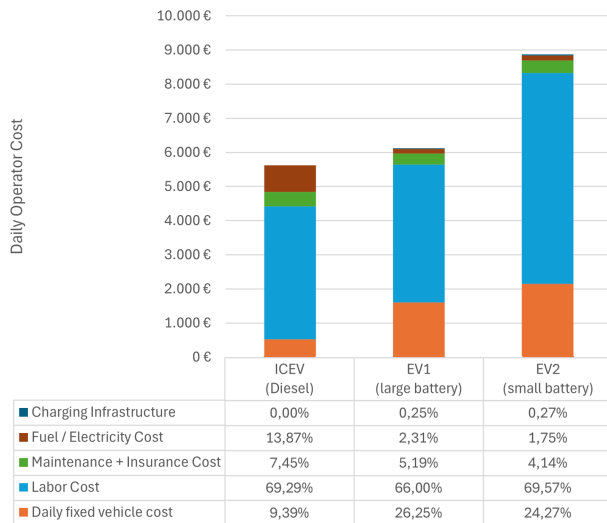


Fig. 3: Comparison of the average daily operator costs for the scenarios. The percentage gives the share of this cost group of the total costs.

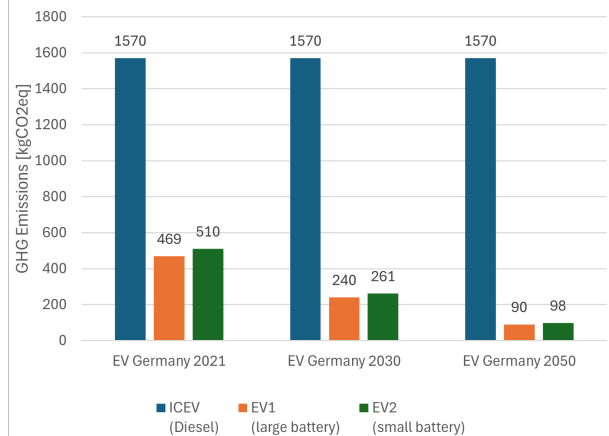


Fig. 4: Comparison of the average daily CO₂eq emissions for the scenarios.

would be around 1,100 kg of CO₂eq per day. The deployment of a fleet of EVs with a small battery would also bring similar GHG savings. However, due to their limited battery capacity, a larger fleet size of that vehicle type would be necessary to complete the same waste collection. This would lead to a much higher operation costs. In addition, a fleet of EVs with a small battery would generally struggle in a rural waste collection, as the longer distances in rural areas require high energy consumption compared to the urban setting.

It can be concluded that, similar to Ewert et al.'s urban scenario[7], replacing an ICEV waste collection fleet in a rural environment with an EV fleet is technically feasible. There is no need to recharge during the tour as the range of the EVs is sufficient. Because the vehicles are recharged over the night at the depot and high power charging infrastructure is not necessary, the charging infrastructure costs are relatively low.

On the way to decarbonizing transport in a rural area, electric waste collection could be a good starting point because everyone will recognize the waste collection and the switch to electric vehicles. If the cost increase based on the current EV prices is acceptable to get this additional benefit should be discussed on the political level and can not be solved by scientific research.

6. Supplementary Material

Supplementary material can be found under: <https://doi.org/10.14279/depositonce-22428>.

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