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Article

Method for a multi-vehicle, simulation-based Life Cycle Assessment and Application to Berlin's Motorized Individual Transport

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Abstract: The transport sector in Germany causes one-quarter of energy-related greenhouse gas emissions. One potential solution to reduce these emissions is the use of battery electric vehicles. Although a number of life cycle assessments have been conducted for these vehicles, the influence of a transport system wide transition has not been researched sufficiently. Therefore, we developed a method which combines life cycle assessment with an agent-based transport simulation and synthetic electric, diesel and gasoline powered vehicle models. We use the transport simulation to obtain the number of vehicles, their lifetime mileage and road-specific consumption. Subsequently we analyze the product systems' vehicle production, use phase and End-of-Life. The results are scaled depending on the covered distance, the vehicle weight and the consumption for the whole life cycle. The results indicate that the sole transition of drive trains is insufficient to significantly lower the greenhouse gas emissions. However, sensitivity analyses demonstrate that there is a considerable potential to reduce greenhouse gas emissions with higher shares of renewable energies, a different vehicle distribution and a higher lifetime mileage. The method facilitates the assessment of the ecological impacts of the complete car based transportation in urban agglomerations and is able to analyze different transport sectors.

Keywords: life cycle assessment, agent-based traffic simulation, battery electric vehicles, sustainability, urban transportation, urban mobility, environmental engineering

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1. Introduction

Life Cycle Assessment (LCA) is a standardized method to assess environmental impacts [1]. In the past years, many LCAs have focused on the comparison of battery electric and internal combustion engine vehicles (BEV and ICEV) [2–6]. Kawamoto et al. studied the influence of different regions and their implications on the life cycle emissions of ICEVs and BEVs [7]. Plenty studies have solely assessed the battery of electric vehicles [8, 9], as it is one of the major contributor to the emissions from BEVs' production [10]. Almeida et al. investigated new Li-Ion batteries and if dependencies on vehicles segments exist [11]. Recently, a considerable number of LCAs have addressed transport system strategic-specific scopes: Dér et al. investigated EVs in fleets [12]. They analyzed the influence of the grid mix, ambient temperatures and driving parameters. Another study investigated different drive train technologies for Brazil's transportation system [13]. Lajunen et al. analyzed the influence of increasing electrification of the passenger vehicle fleet in Finland and found that the high average age of the fleet is one main obstacle to lower greenhouse gas emissions in the next years [14]. Torzynski et al. tested battery electric buses in Berlin and conducted a comparative life cycle assessment on the battery electric and the diesel-fueled bus [15]. Ding et al. focused on the comparison of different car sharing concepts in Beijing [16]. Jaeger et al. developed a LCA method for strategic decision making in urban transportation [17]. Therefore, they focused on direct emissions. Others focused on reviews and comparisons of the conducted studies [9, 18, 19].

Some researchers focus on new strategies and challenges, which arise due to the use of BEVs. Jahn et al. developed a methodology to determine charging strategies for a complete electrified

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individual transport system in Berlin [20]. Gong et al. research realistic driving cycles for battery electric vehicles [21]. Another field gaining attention in connection with BEVs are autonomous shuttles. Grahle et al. developed an approach to define initial requirements for the vehicle concepts. Using this approach, theoretical LCAs on future concepts become a possibility [22]. Kohl et al. developed a guideline to investigate the social sustainability of automation technology [23]. Onat et al. analyzed not only environmental, but also social and economic impacts of alternative vehicle technologies and found that BEVs perform best in most sustainability metrics (ICEVs were only more promising for the water-energy ratio) [24].

One major issue for LCA's of passenger cars is the lack of current data. Most studies used the data sets from Ecoinvent [25] or Gabi [26]. Del Pero et al. adjusted the vehicle parameters with the help of specific questionnaires on materials, masses and manufacturing technologies [3]. Tagliaferri et al. adopted parameters from existing vehicles [27]. Messagie et al. presented an approach with different vehicle sizes, weights and consumptions [6]. Helmers et al. performed sensitivity analysis for attributes like car size, emission profile, fossil fuel and electricity choice, and lifetime mileage [28].

The main focus of most studies was the investigation of the global warming potential (GWP) (like in [29]) accompanied by acidification potential (AP), eutrophication potential (EP), photochemical ozone formation potential (POFP), particulate matter formation potential (PMFP) and others. Figure 1 displays the results for the GWP from several studies. The data offers a validation of our own results. Dolganova et al. summarized that most studies concentrated on a variety of impacts but neglected detailed analyses of resource use [18]. Additionally, they state that only few studies addressed resource-related impact categories and that even fewer provided criticality assessments. They emphasized the use of current literature [30, 31] to choose impact categories [18].

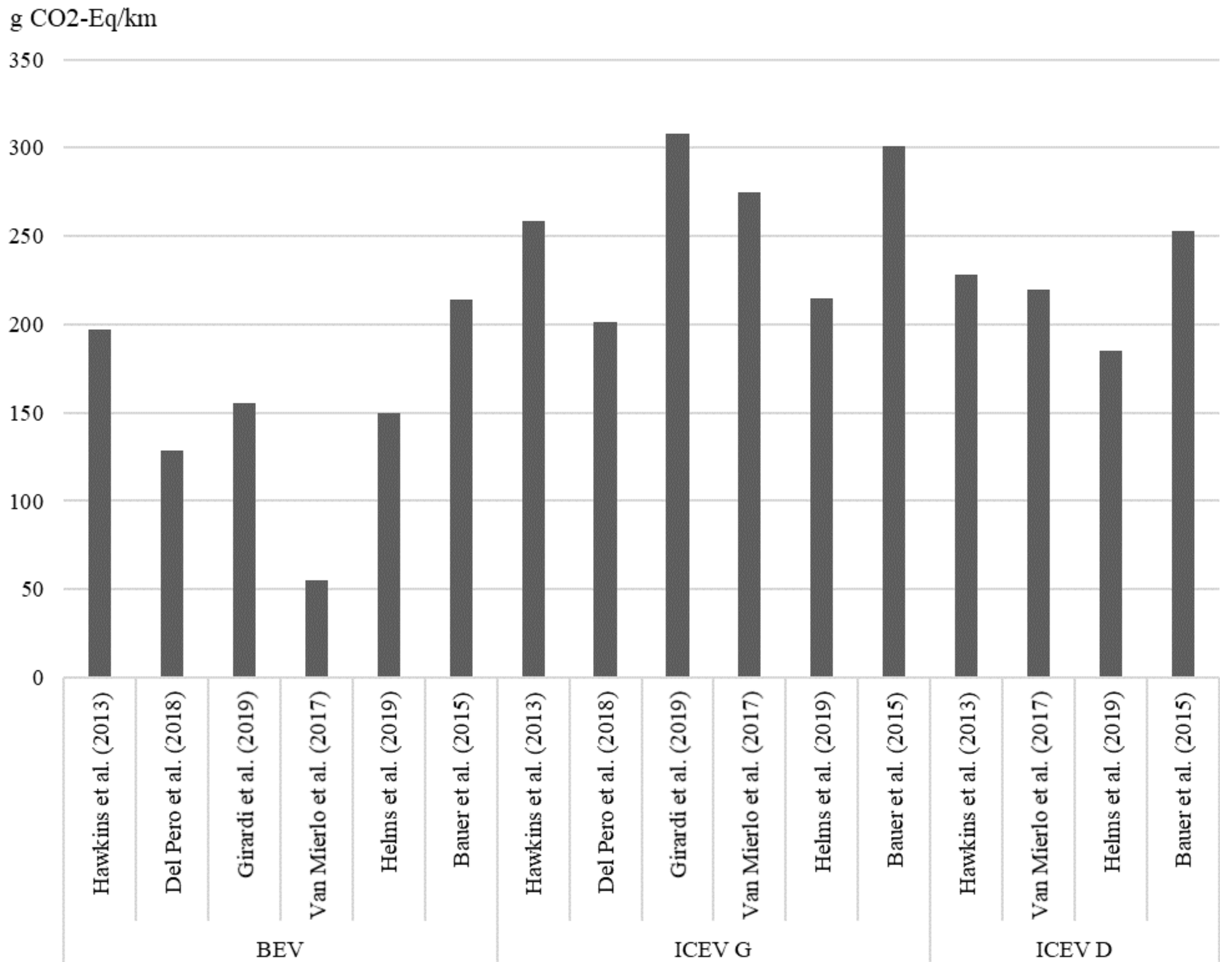

Figure 1. Global Warming Potential from several studies; BEV – battery electric vehicle, ICEV G – internal combustion engine vehicle gasoline, ICEV D – internal combustion engine vehicle diesel [3–5, 19, 32, 33]

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We present a method, that serves two purposes: Primarily, we developed a methodological approach to combine agent-based transport simulation and life cycle assessments. The approach is adjustable in terms of different input data (like LCA data bases and simulation data) and the design of the LCA study (like the choice of system boundaries or impact categories). Additionally, we present the results for a conventional and a completely electrified transport system. Therefore, we used the metropolitan region Berlin-Brandenburg as a case study.

2. Materials and Methods

2.1 Case Study: Berlin's Motorized Individual Transport

The total length of Berlin's urban road network is around 5,400 km [34]. It consists of a city highway, four additional highways, eight federal highways and other roads. The road network of Brandenburg has a total length of 12,190 km with 805 km highway and 2,740 km federal highway.

2.1.1 Vehicles and Vehicle Distribution

The road transport sector of the metropolitan region Berlin-Brandenburg consists of 82.48 % passenger cars, the rest are motorcycles, trucks, busses and others [35]. 2.63 million cars are registered in the region, 1.21 million are registered in the City of Berlin. Most (97.52 %) passenger cars are internal combustion engine vehicles (ICEV), with 71.14 % gasoline and 26.38 % diesel fuelled vehicles [35].

Figure 2 shows the vehicle distribution for conventional and electric cars in Germany in 2018 and the new battery-electric vehicle (BEV) registrations for 2017 [36, 37]. In 2018, most vehicles were either compact cars (25.9 %), small cars (19.2 %) or mid-range cars (14.5 %). In contrast, the new BEV registrations describe possible trends of a future vehicle distribution. They consist of 31.6 % small cars and only 20.0 % compact cars. The mini car has a share of 18.1 % and therefore accounts for twice as high share of vehicles compared to ICEV.

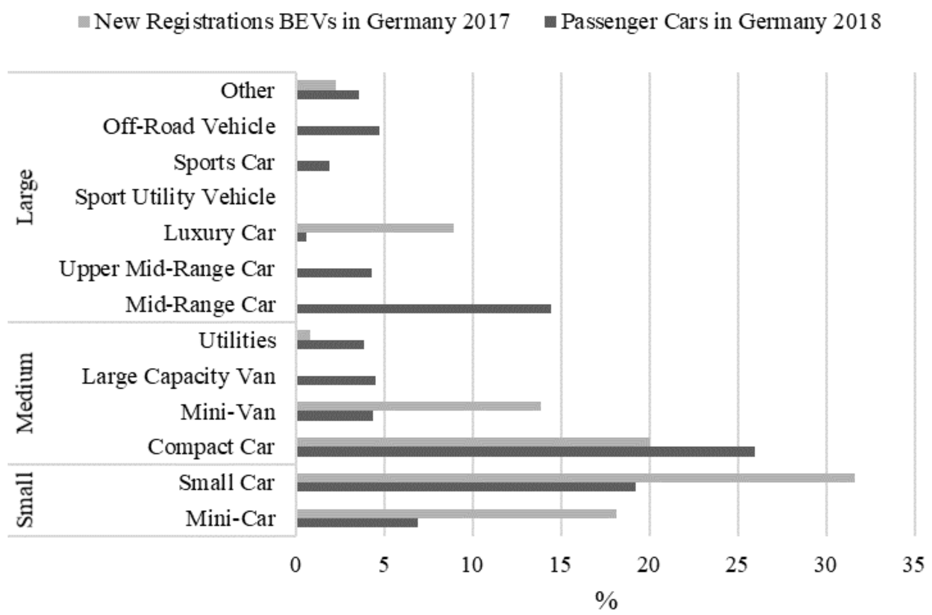

Figure 2. Vehicle Distributions in Germany in percent [35–37]

2.1.2 Agent-based Transport Simulation

MATSim is an agent-based traffic simulation in which individual agents optimize their daily plans (e.g. work and leisure activities) with respect to travel time and distances. This results in traffic flows over the duration of one day, whereby the routes can be covered by car (as driver or passenger), bicycle, public transport or on foot. Furthermore, road-dependent speeds and capacities as well as

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traffic light changes are taken into account. The traffic network consists of nodes, which are connected by links. The latter have the attributes length in meters, capacity in vehicles per hour, free speed in meters per second, number of lanes and the type of means of transport allowed on them (e.g. car and bicycle) [38]. We use the MATSim Open Berlin Scenario version 5.3 10% [39] for the evaluation of the LCA method. The network for Berlin corresponds to the entire Berlin road network, while for Brandenburg all main roads are mapped. The underlying map data is taken from OpenStreetMap [40]. The agent-population consists of all persons over 18 who live in Berlin and Brandenburg according to the 2011 census. The agents' daily schedules are based on commuter statistics. The traffic flows were calibrated with 346 traffic counting stations in Berlin and Brandenburg. In addition, agents representing freight traffic were implemented, but in this study neglected. The simulation results can realistically reproduce the traffic in Berlin and Brandenburg [39]. Both the travel distances and times as well as the shares of the activity types (leisure, work, shopping, home, others) are well represented.

2.2 Life Cycke Assessment of Transport Systems

The goal of this study is to demonstrate the influences of different technologies and strategies for transport systems on several impact categories. Therefore, we present a method which combines a LCA with an agent-based transport simulation. For the presented case study (compare Case Study: Berlin's Motorized Individual Transport) the method focuses on two vehicles' drive train options (ICEVs and BEVs). The study compares today's transport system (high share of ICEVs) and a complete electrified transport system (only BEVs). Today's transport system mainly consists of diesel- and gasoline-fuelled vehicles.

The considered cradle-to-gate life cycle of the vehicle includes production, use phase and End-of-Life (EoL). We display the results on vehicle level and on transport system level to enable comparisons within both. On vehicle level, the functional unit represents one kilometre driven by the respective vehicle to match the results with other publications. On transport system level, the functional unit displays one kilometre driven within the transport system. Consequently, all vehicles (with different sizes) are factored within one coefficient.

Further specifications are explained in detail in the following.

2.2.1 Inventory Analysis

The MATSim simulation results contain the road network of the transport system, including the coordinates of the nodes of the network and the resulting links with the corresponding attributes. Additionally, all events of agents or vehicles are listed with time information [39]. The vehicle identifier (ID) can be deduced directly by the results of the agent-based simulation. We prepare a vehicle object, which contains several attributes to calculate the ecological impact for an agent-based transport simulation: the vehicle ID, the lifetime mileage, the shares of road categories, the drive train type, the consumption, and as dummies for the final results the total LCA results, the kilometer-specific LCA results und the proportional LCA results.

The Open Berlin Scenario covers one average, synthetic day (compare 2.2 Agent-based Traffic Simulation). However, the entire lifetime mileage needs to be calculated for the assessment of the use phase in a LCA. Therefore, we extrapolate the single simulation day to a whole vehicle lifetime. On weekends, vehicles cover only 82 % of their daily routes [41]. Consequently, we assume five unmodified simulation days within one week und two modified simulation days with 82 % of the daily mileage. Then, we scale this week to the average use phase duration of passenger cars in Germany. The average use phase duration is 12.6 years according to Helms et al. [10]. This way, we obtain the vehicles' average lifetime mileage: 206,396 km. We perform 100 additional calculations in which we scale the lifetime mileage between 0 to 300 %. This results in an interval from 0 to 619,188 km.

Types of roads are urban- and suburban roads as well as highways, which each differ in their respective free speeds, which are considered to calculate the respective consumption (Table 1). The

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link-specific free speed is given by the simulation results (compare 2.1.2 Agent-based Transport Simulation).

Table 1. Road Categories

Road Category	Free Speed [km/h]
Urban	$v \leq 50$
Sub-urban	$50 < v \leq 100$
Highway	$v > 100$

We define three vehicle classes in account of the variability of different vehicle segments and simultaneously limit the level of detail (like in [42] and [6], compare Table 2). We use the data sets from Ecoinvent version 3.6 [25].

Table 2. Vehicle Classes

Small	Medium	Large
Mini-Car	Compact Car	Mid-Range Car
Small Car	Mini-Van	Upper Mid-Range Car
	Large Capacity Van	Luxury Car
	Utilities	Sport Utility Vehicle
		Sports Car
		Off Road Vehicle

Both ICEVs and BEVs consist of the same vehicle body for the respective vehicle class to maintain comparability (like in [10]). The according Ecoinvent process "glider production, passenger car" is based on the inventory analysis of a Golf A4. According to Del Duce et al., the gasoline-fueled vehicle body has a share of 74 % of the whole vehicle mass, the diesel-fueled of 69 % and BEV body without the battery has a share of 91 % [43]. With the vehicle weights (from [42]) and the vehicle body and drive train shares, we calculate the mass for the respective vehicle size (Table 3). The material composition of the vehicle classes mainly differs for the lightweight components [44]. Therefore, we adapt aluminum and steel shares according to [10].

Table 3. Vehicle Specifications

	Vehicle Body Share [%]		Vehicle Mass [kg]	Battery Capacity [kWh]	Battery Weight [kg]
battery electric	91 (w/o battery)	small	1199	25	333
		medium	1677	40	533
		large	2329	75	1000
gasoline-fueled	74	small	1068	-	-
		medium	1411	-	-
		large	1639	-	-
diesel-fueled	69	small	1137	-	-
		medium	1503	-	-
		large	1745	-	-

We adopt the respective Ecoinvent processes for the EoL of the vehicle bodies and drives. We adjust the material composition according to the production of the products. Parts of aluminum, iron, copper, plastics and electric components are recyclable according to [43]. The materials for production consist of secondary material [10], the respective share is presented in Table 4. We use the cut-off approach for allocation.

Table 4. Share of Secondary Materials

Aluminum	Copper	Lead	Platinum

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32 %	44 %	75 %	5 %

We use the Ecoinvent process "internal combustion engine production, passenger car" as a basis for the drive train of the ICEV and scale it pursuant to the shares of the diesel- and gasoline-fueled drive trains. This process includes the engines, the gears, the tanks, the air conditionings, and exhaust systems. As stated in [10], the platinum and palladium content in the ICEVs' exhaust systems are considerably relevant in comparison to the BEV drive train. Thus, we adapted the values for the respective vehicle classes and types (Table 5).

Table 5. Platinum and Palladium Contents

	Diesel			Gasoline		
	small	medium	large	small	medium	large
Platinum [g]	2	4	7.5	0.5	0.5	0.5
Palladium [g]	0	0	0	1	2.5	5

The fuel consumption of the ICEVs is adopted by [45] and categorized by urban roads, suburban roads and highways (Table 1).

In Germany, fossil fuels contain biofuel components [10]. We assumed that diesel consists of 8.7 % rape seed oil and that petrol consists of bioethanol from wheat with a 5 % share. Those fuels are supplied on the markets for fuel supply in Europe, which is deposited in Ecoinvent.

For the BEV drive train, we apply the process "powertrain, for electric passenger car". It includes the motor, the charger, the power electronics, converter and inverter [43]. We choose the battery capacities for the vehicles sizes small and medium according to [44]. These capacities correspond to current vehicle models in the respective segments [10]. We model the production of the battery with the Ecoinvent process "battery production, Li-ion, rechargeable, prismatic". The data is provided by [46]. According to them, the cathode material production has the greatest influence on ecological impacts. Simultaneously, Helms et al. reported that the results for the production of different cathode materials vary more than 20 % depending on the chosen impact category [10]. However, Notter et al. argues, that the difference varies less than 2 % regarding a vehicle cradle-to-gate [46]. We add a transport per ship from Peking to Amsterdam and transport per truck of 1000 km within Europe for the batteries. Most electric vehicles in the vehicle class large are luxury cars. Consequently, we adjust this vehicle class with the specification of a Tesla Model S. The basic version has battery with 75 kWh capacity [47]. The calculated vehicle mass is 100 kg heavier compared to the real vehicle, caused by the battery's energy density and assuming same vehicle bodies for all drive train types (Table 3). We adopt the electricity consumption from [44], for the vehicle classes small and medium (Table 6). These include charging losses. For the vehicle class large, we use the consumption values based on [47]. We assume a charging efficiency of 84 % [48] to reflect charging losses (Table 6).

Table 6. Vehicle- and Road-Specific Consumption

		Urban Consumption [l or kWh/100 km]	**Suburban Consumption [l or kWh/100 km]**	**Highway Consumption [l or kWh/100 km]**
battery electric	small	15	14	24
	medium	20	17	28
	large	25.9	25.2	37.8
gasoline-fueled	small	7.3	4.9	6.3
	medium	8.7	5.8	7.5
	large	10.5	7.2	9.2
diesel-fueled	small	5.7	3.8	4.5
	medium	6.7	4.5	5.3
	large	8.4	5.8	6.7

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We use the German grid mix of the year 2018 to calculate the emissions of the BEV's use phase. For this purpose, we adjust the Ecoinvent process "market for electricity, low voltage for Germany" (which in the current version v3.5 is based on the electricity mix of 2014) to the composition of gross electricity generation for 2018 estimated in [49]. The above process is composed of electricity production at medium and high voltage level, the transformation to the low voltage level (relevant for charging), transmission losses, and other emissions within the transformation. The construction of the power plant and electricity grid infrastructure is included in the process as well. We deduct electricity exports from the distribution of gross electricity generation to calculate the shares of the individual energy sources in the electricity available in Germany. As reported in [49], the exported electricity is based on the same electricity mix as the gross electricity generation. We include electricity imports, assuming the composition of the countries according to [50]. The resulting electricity mix for 2018 is shown in Table 7.

Table 7. Shares Grid Mix Germany 2018 [50]

Lignite	20.95%	**Nuclear Energy**	10.95%	**Others**	3.81%
Wind	16.03%	**Photovoltaics**	6.67%	**Water**	3.65%
Hard Cole	11.90%	**Biomass**	6.51%	**Waste**	0.95%
Natural Gas	11.90%	**Imports**	5.88%	**Oil**	0.79%

All energy sources except waste and photovoltaics (PV) are entered at high-voltage level, waste at medium-voltage level and PV at low-voltage level. If there are several processes for one energy source (e.g. onshore and offshore for wind energy), we modify corresponding Ecoinvent processes with the respective shares.

We perform additional calculations assuming a share of 100 % renewable energies in the German grid mix. A 100 % renewable grid mix in Germany for the year 2050 is presented in [51]. Accordingly, the adjusted grid mix contains of 30.4 % PV, 46.0 % wind onshore and 23.6 % wind offshore.

We perform a LCA for the generic vehicles, to compare the results with current research. Therefore, we apply the lifetime mileage and the road shares proposed by [10]: 168.000 km and 30 % urban road, 40 % suburban road and 30 % highway. The road shares with the respective consumption result in average consumption for the vehicles (Table 8). A brought spectrum of impact categories' methods reduces the comparability. Therefore, we conducted studies which used similar methods (ReCiPe Midpoint). Nonetheless, this comparison is limited by different method versions (e.g. different year of publication).

Table 8. Average Consumption with Respective Road Shares

diesel-fuelled [l/100km]			**gasoline-fuelled [l/100km]**			**battery electric [kWh/100km]**		
small	medium	large	small	medium	large	small	medium	large
6.04	7.18	8.79	4.58	5.4	6.85	17.3	21.2	29.19

On an average day in Berlin or Brandenburg, 40 % or 23 % of the passenger cars are idle [52]. This results in a standstill of 29 % for the region Berlin-Brandenburg, weighted according to the registered passenger cars (compare Case Study: Berlin's Motorized Individual Transport). As these vehicles aren't represented in the MATSim simulation, we assume 29 % additional vehicles with zero covered distance. Moreover, we prepare the results without the additional vehicles to demonstrate the influence of standstill.

The simulation does not differentiate vehicle segments or size categories. Hence, the defined vehicle classes must be assigned to the vehicles in the simulation. We convert the registered vehicles per vehicle segments [36] to the vehicle classes small, middle and large (Table 9). For the ICEVs we differentiate diesel- and gasoline-fueled vehicles. For further investigation of the vehicle distribution, we adjust the vehicle classes with the registration numbers of BEVs from 2017 (compare 2.1.1 Vehicles and Vehicle Distribution, Table 9). We modify the BEV and ICEV distribution to display possible potentials of both technologies.

Table 9. Distribution Vehicle Classes

Vehicle Class	Distribution Base Case	Distribution BEV 2017
Small	27.10 % (93.23 % gasoline- and 7.77 % diesel-fueled)	50.90 %
Medium	40.10 % (65.05 % gasoline- and 34.98 % diesel-fueled)	35.50 %
Large	32.80 % (49.30 % gasoline- and 50.70 % diesel-fueled)	13.60 %

We modeled the direct emissions from the combustion (ICEV) based on the emissions from the corresponding processes (e.g. "transport, passenger car, medium size, diesel, EURO 5") in Ecoinvent. The Ecoinvent data sets distinguish between consumption dependent and independent emissions. The independent emissions rest on the EURO 5 standard, but as the modeled vehicles in Ecoinvent are from 2010 and the consumption is based on a realistic drive cycle (EURO standards are based on analytic test cycles), the standards are exceeded [53]. Therefore, we parameterize the independent and dependent emissions according to the consumption of the ICEV and the emission factors for biofuels as defined by [54].

The abrasion of tires, brakes, and road is included using the Ecoinvent transport processes. The emissions are parameterized according to the vehicle weight. For the abrasion of BEV's brakes, we assumed only 20 % of the abrasion of ICEV's brakes because of recuperation [43].

The maintenance of the vehicles is included in the Ecoinvent maintenance processes for the respective drive trains, parameterized for the lifetime mileage and the vehicle weight. The maintenance process for BEVs relies on the process for ICEV. All ICEV-specific tasks (e.g. oil change) are deleted (like in [43]). We discovered an unexplainable large amount of ethene as an output of the BEV process, which doesn't occur for the ICEV process. According to [43] (and additional E-Mail correspondence), the amount of ethene should be equal for the maintenance of BEV and ICEV. Therefore, we adjusted the corresponding processes.

Additionally, the construction of road infrastructure and production facilities is included depending on the vehicle weight.

2.2.2 Impact Assessment

We perform the impact assessment using Ecoinvent data sets [25] and the included impact assessment methods. Like most studies, we include the GWP in our study, accompanied by the AP, EP, POFP, PMFP and metal depletion potential (MDP) (compare Table 9).

Table 10. Impact Categories and Methods

Category	Name (Method (Version))	Unit
GWP	Climate change (ReCiPe Midpoint (Iv1.13))	kg CO2-Eq
AP	Terrestrial acidification (ReCiPe Midpoint (Iv1.13))	kg SO2-Eq
EP	Freshwater eutrophication (ReCiPe Midpoint (Iv1.13))	kg P-Eq
POFP	Photochemical oxidant formation (ReCiPe Midpoint (Iv1.13))	kg NMVOC-Eq
PMFP	Particulate matter formation (ReCiPe Midpoint (Iv1.13))	kg PM10-Eq
MDP	Metal depletion (ReCiPe Midpoint (Iv1.13))	kg Fe-Eq

2.2.3 Implementation

We create three product systems for every vehicle type: vehicle production and EoL; vehicle operation and fuel or electricity consumption. It would also be possible to create one product system for all processes and calculate the impacts for each vehicle. However, as the program needs several minutes to calculate just one vehicle, this approach is inefficient for transport systems with a great number of vehicles. Therefore, we scale the results of the separated product systems depending on the covered distance, the vehicle weight and the fuel/electricity consumption for the whole life cycle within the program. This provides the vehicle results for the inventory analysis and the impact indicators differentiated according to the product systems: vehicle production and EoL depending on the vehicle weight in kg; vehicle operation depending on the covered distance in km and fuel or electricity consumption in kg or kWh. We included the battery size as an optional parameter, so it is adjustable. Simultaneously, the shares of the considered product systems in the respective impact categories are visible. Last, we sum up the vehicle results to get the results for the simulated transport system.

The LCA results need to be scaled to a 100 % scenario, as the Open Berlin Scenario v5.3 represents only 10 % of traffic flow (compare 2.1.2 Agent-based Transport Simulation). Therefore, we duplicate the existing vehicles with their respective LCA results. The results of the 100 % scenario are then related to the functional unit (total kilometers driven within the transport system). Additionally, we calculate the average lifetime mileage, consumption, road shares, and vehicle weights.

3. Results

This chapter displays the results on the synthetic vehicles' LCA (including an interim discussion) and the transport systems' LCA. The diagrams serve as an overview; detailed results are prepared in the supplementary materials.

3.1 Validation Synthetic Vehicles

The results vary for the vehicle classes and types, and for the impact category (Figure 3 to Figure 9):

The electric vehicle has the lowest GWP for all vehicle classes except large, although it has the highest share in production and EoL compared to the diesel- and gasoline fueled vehicles. Especially for the large electric vehicles, the battery causes marginally higher GWP, compared to the large diesel-fueled vehicle (Figure 3, Figure 4).

The results for GWP are consistent with other studies [5, 19]. Others present even lower GHG emissions for BEV [3, 33]. Helms et al. summarized the GWP of vehicles from different studies and conducted seven main influencing factors: lifetime mileage, energy consumption in use phase, grid mix, battery capacity, battery density, battery chemistry and GHG emissions from battery production [19]. The results of different studies vary widely due to a great variation in these factors (compare Figure 1).

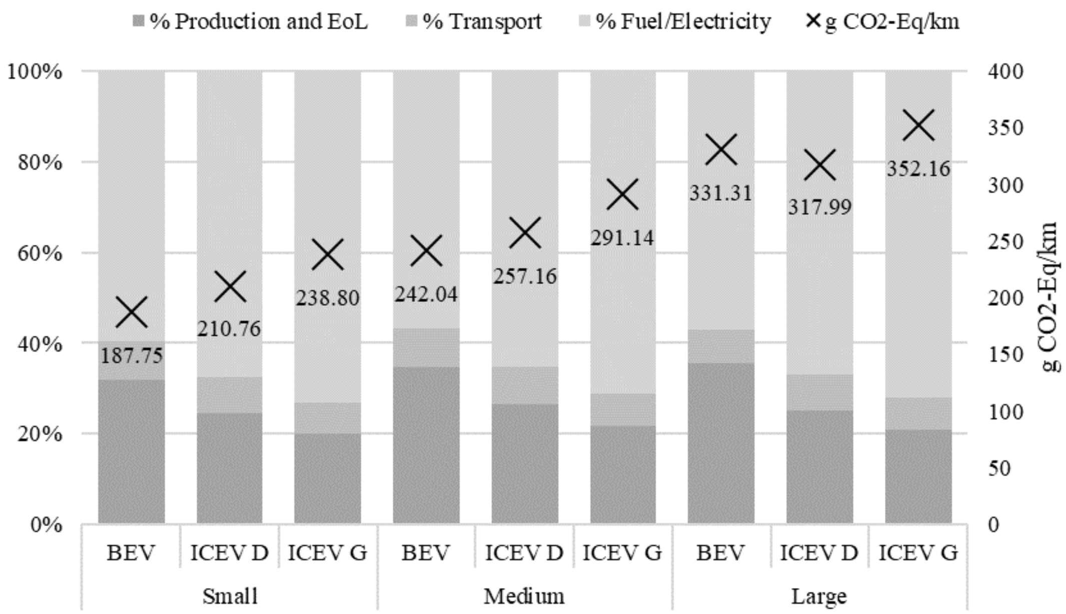

Figure 3. GWP Synthetic Vehicles at 168,000 km Lifetime Mileage

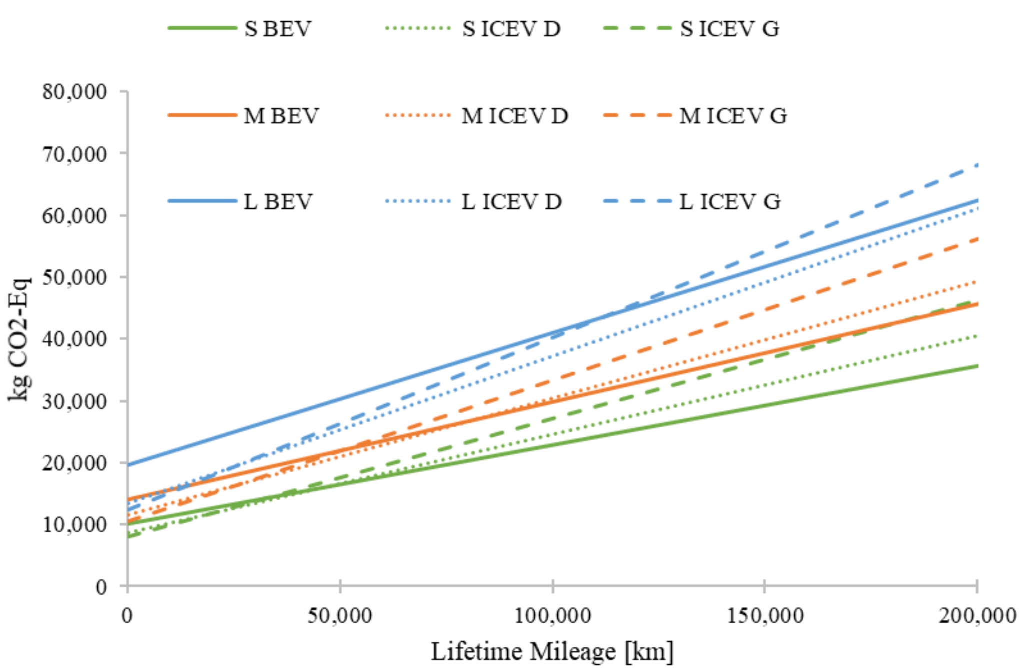

Figure 4. GWP Vehicles over Lifetime Mileage

The gasoline-fueled vehicle shows the fewest AP for all vehicle classes, followed by the diesel-fueled car. The BEV has the highest impact in AP. Major contributors are the production and EoL (especially the battery production) and the electricity consumption (main contributors: electricity from hard coal, lignite and biomass) during driving (Figure 5). For the ICEV, the fuel consumption is the main cause for Sulphur dioxide equivalent emissions.

The results of the vehicles' AP lie within the same bandwidth (0.92 to 0.94 g SO2-Eq/km) like the results presented by [32] and [5]. Other studies like [3] or [4] used different impact methods (CML2001 air acidification and Acidification midpoint [Mole of H+ eq.]). Therefore, a comparison of the total values is not recommended. Nonetheless, the results by Del Pero et al. show higher values for BEV than for ICEV, like the results presented here [3]. Only Girardi et al. show fewer impact by BEV than ICEV [4].

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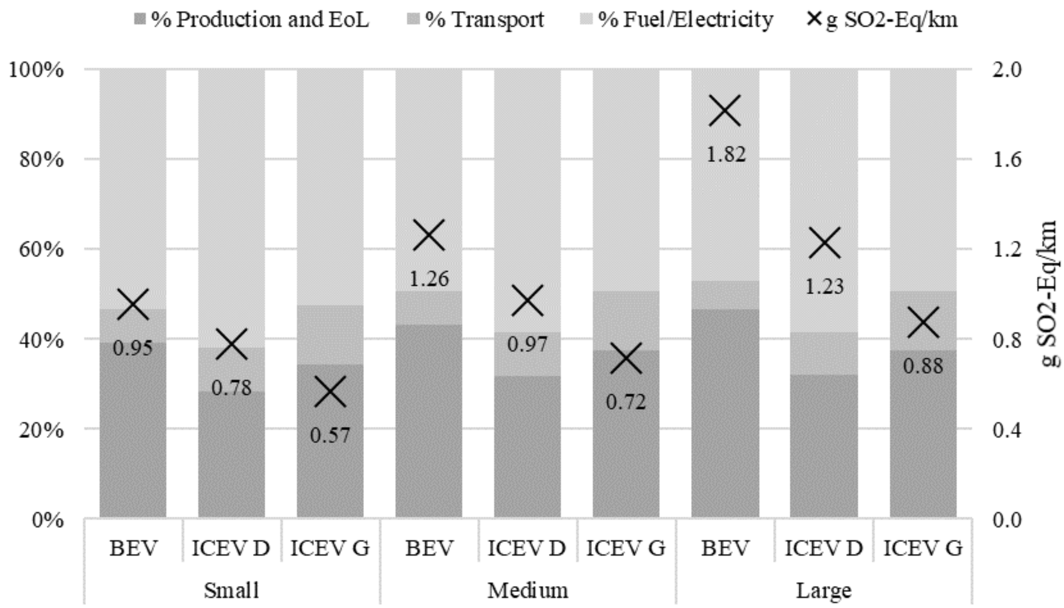

Figure 5. AP Synthetic Vehicles at 168,000 km Lifetime Mileage

Additionally, for EP, the BEV has the highest impact for all vehicle classes. In comparison to the ICEVs' fuel consumption, the electricity consumption has a dominant share in BEV's EP. Within the grid mix, the electricity produced with lignite causes high phosphor equivalent emissions (Figure 6).

For EP, the results show a sufficient compliance (deviation of around 15 to 25 %) with the results presented by [32] and [5]. Other studies used different impact methods, therefore we waive further comparisons.

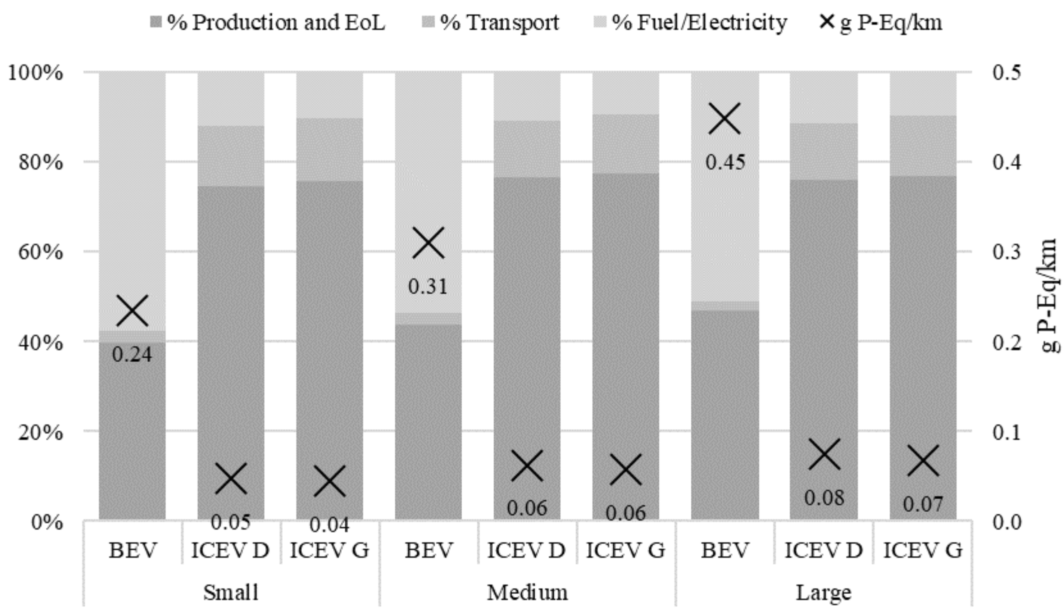

Figure 6. EP Synthetic Vehicles at 168,000 km Lifetime Mileage

The diesel-fueled vehicle has the greatest impact in POFP, with a major share of diesel consumption. The small diesel-fueled vehicle shows higher emissions than the medium and large BEV and gasoline-fueled vehicle. For the BEV, the production and EoL has a comparatively high share in POFP (Figure 7).

The results for the BEV for the POFP are reflected by the results presented in [3–5, 32]. All show a comparable bandwidth (0.35 to 0.64 g NMVOC-Eq/km for small to medium size vehicles) for the

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respective results. Del Pero et al. and Bauer et al. compute lowest NMVOC emissions for the gasoline-fueled vehicle [3, 32]; Hawkins et al. and Girardi et al. for the BEV, but the latter didn't assess any diesel-fueled vehicles [4, 5].

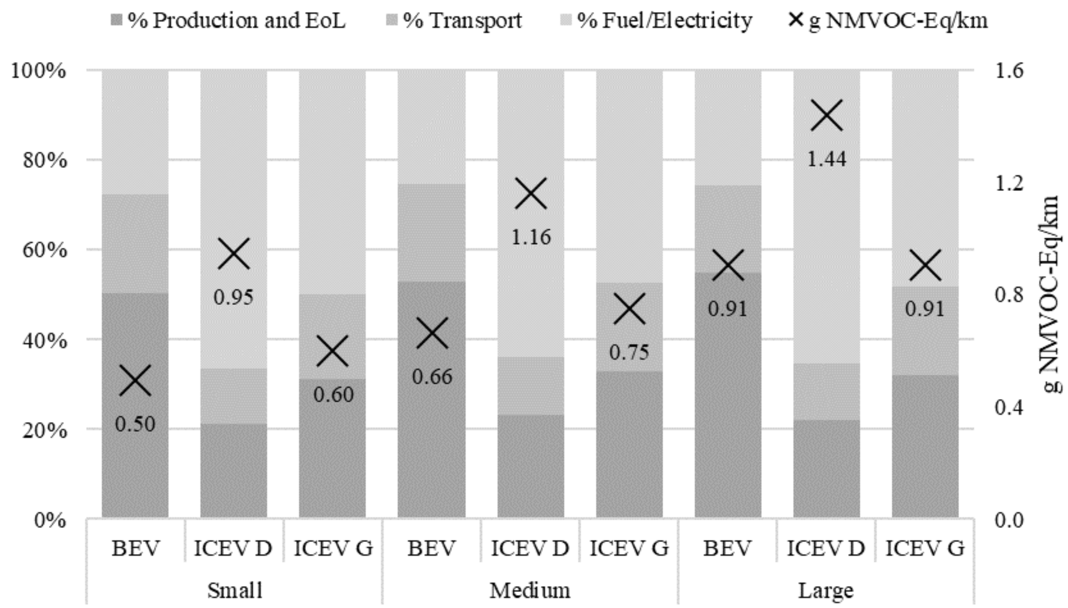

Figure 7. POFP Synthetic Vehicles at 168,000 km Lifetime Mileage

For the small vehicle class, the diesel-fueled vehicles show the highest impact in PMFP, around 40 – 50 % of the emissions are caused by diesel consumption. In the medium class, the BEV pass the diesel-fueled vehicle slightly and in the large class, the difference is substantial. The battery production of the EV is a major contributor to the PMFP. Abrasion by tire, brakes and roads contributes around 2 % for ICEVs. For BEVs the share is significantly smaller (Figure 8).

For PMFP, Hawkins et al., Girardi et al. and Bauer et al. present values in the same bandwidth like the here presented results [4, 5, 32]. In [5] and [32] the ICEVs have fewer PM10 emissions than BEV. In [4] the gasoline-fueled vehicle emits fewer PM10 emissions. Del Pero et al. used the impact method Part. matter / Resp. inorganics midpoint in kg PM2.5 eq. [3]. Therefore, we waive comparisons.

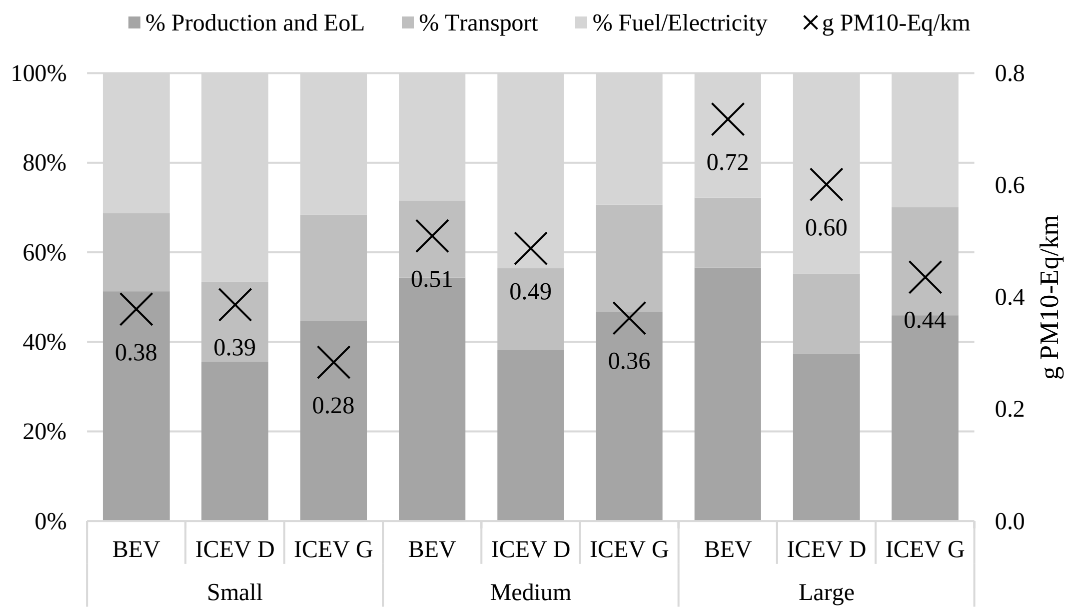

Figure 8. PMFP Synthetic Vehicles at 168,000 km Lifetime Mileage

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The BEV has the highest values for MDP. For all vehicles, the production and EoL is the major contributor to MDP. The fuel and electricity consumption as well as the transport (including e.g. maintenance) have less than 10 % share in MDP (Figure 9).

The results for MDP have the same ratio like in [5]. There is a great lack of knowledge in metal depletion and other resource use-related potentials (compare [18]).

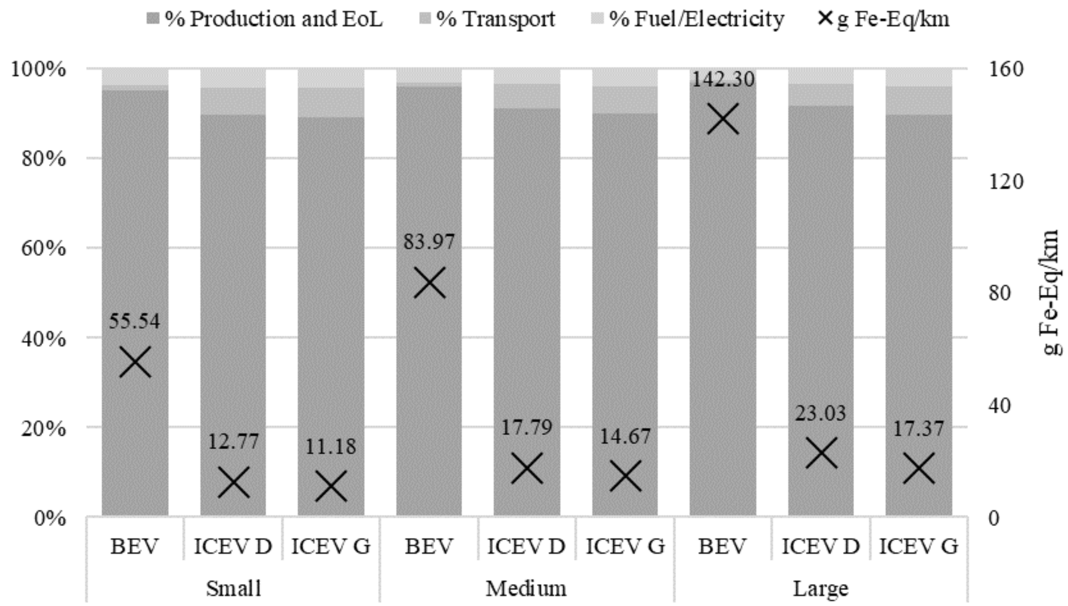

Figure 9. MDP Synthetic Vehicles at 168,000 km Lifetime Mileage

3.2 Case Study: Results for Berlin's Motorized Individual Transport

The GWP for the ICEV and BEV base case is between the values for small and medium sized vehicles (compare Figure 3 and Figure 10). The BEV base case emits around 20 % less CO2-Eq. emissions per kilometer. The standstill case (we assume 29 % standstill for the base case, compare Vehicle Distribution) results in smaller values. The share of production and EoL decreases for both, the ICEV and BEV standstill case. The difference for the ICEV standstill case is 5.60 %, for the BEV standstill case is 9.70 % compared to the respective base case. The gap between the base case and the distribution case (we assume the vehicle distribution from the new registrations of BEVs in 2017, compare Vehicle Distribution) is slightly higher: 7.38 % less GHG emissions for the ICEV distribution case and 10.08 % for the BEV distribution case. Although, the share of production and EoL decreases. The only renewable energy case (only renewable energies, compare Synthetic Vehicles) shows more substantial differences: the kilometer-specific GHG emissions are 52.76 % smaller than in the base case (regarding BEV) and the share of production and EoL increases significantly.

The investigation of the lifetime mileage (compare Lifetime Mileage) shows that the breakeven point for the GWP is at about 55,000 km (Figure 11). The ICEV base case has smaller GHG emissions for production (see Figure 11 at Lifetime Mileage = 0) for production and EoL, but deteriorates with increasing lifetime mileage.

The results for the AP show higher values for the BEV base case than for the ICEV base case. These values decrease for all cases. A substantial decrease is visible for the BEV renewable case: The Sulphur dioxide equivalents reduce by 44.76 %. Simultaneously, the share of production and EoL rises over 75 %. For the AP, the ICEV base case starts with a burden half as high as the BEV base case. The gap stays nearly constant for rising lifetime mileage (Figure 13). The BEVs reach lower values only for the renewable case (Figure 13).

The base case reveals a noticeable advantage of the ICEVs regarding phosphor equivalent emissions, comparable with the synthetic vehicles results. Even the renewable case accounts for more than 250 % of the ICEV base case emissions (Figure 15).

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For POFP, the BEV base case generates smaller values compared to the ICEV base case. This advantage increases with the use of renewable energies (Figure 16). Although the values for production and EoL are higher for the BEVs, after 30,000 to 100,000 km (depending on the respective case) the investigation cases reach the breakeven points (Figure 17).

For PMFP, the ICEVs have lower emissions compared to the BEVs. Only the BEV renewable case shows lower emissions than the ICEV base case (Figure 18). As the BEVs' production and EoL values are noticeably higher, the BEV cases only demonstrate lower values for high lifetime mileage (Figure 19).

For MDP, the advantages of the ICEV cases are tremendous (Figure 20). The production has a share of over 80 % for all cases. Subsequently, the BEV renewable case shows only slight differences. Whereas, the standstill and distribution case demonstrate higher gains. In addition, the consideration of MDP over lifetime mileage illustrates only slight gains. In contrast to all other investigated impact categories, covering the energy demand with renewables sources even increases the MDP (Figure 21).

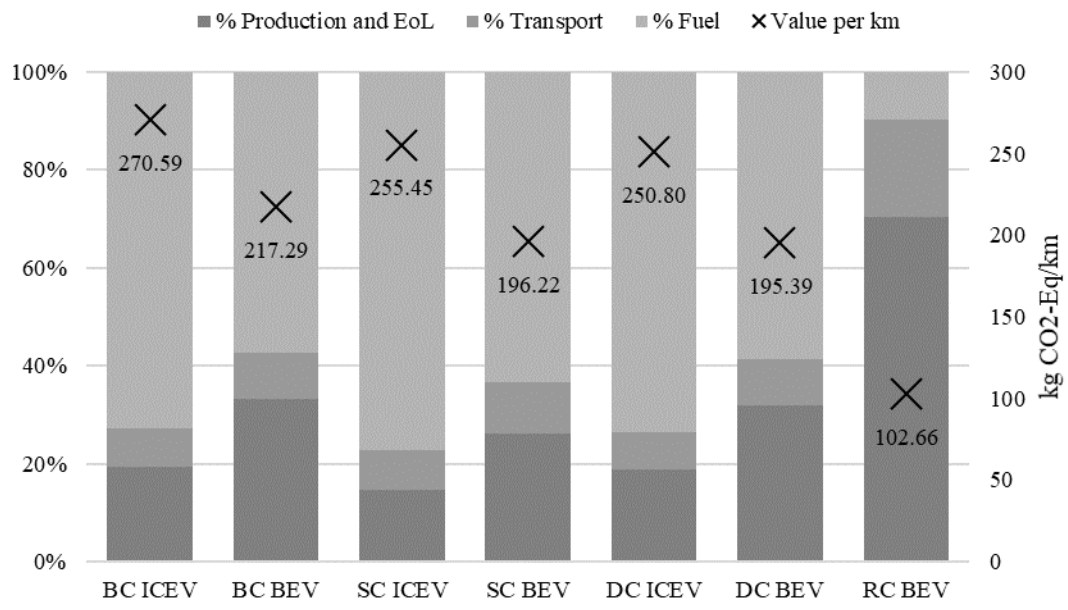

Figure 10. GWP Transport System; BC - base case, SC – standstill case, DC – distribution case, RC – renewable energies case

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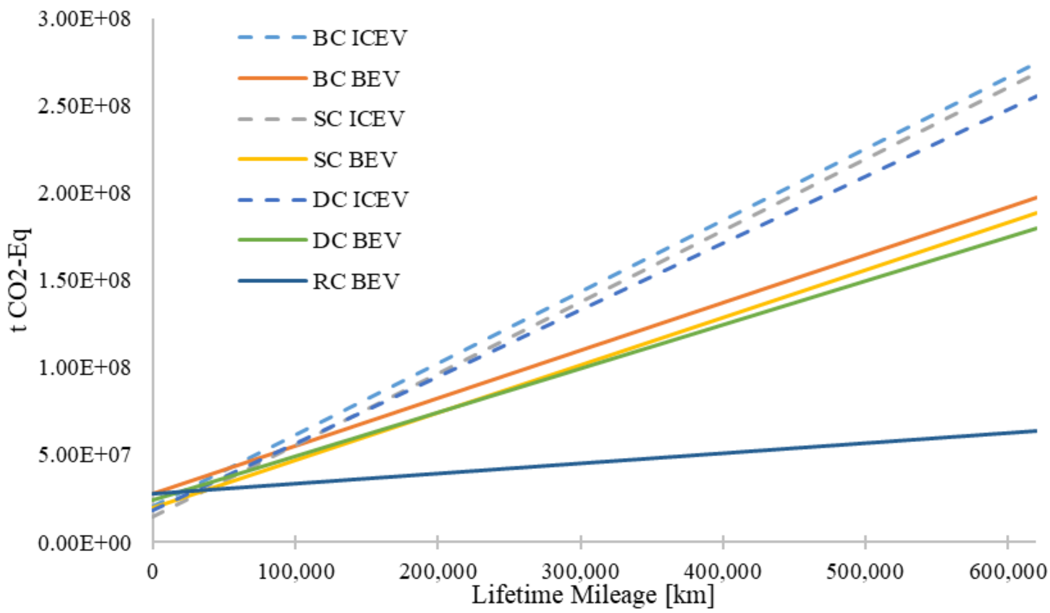

Figure 11. Total GWP vs. Lifetime Mileage; BC - base case, SC – standstill case, DC – distribution case, RC – renewable energies case

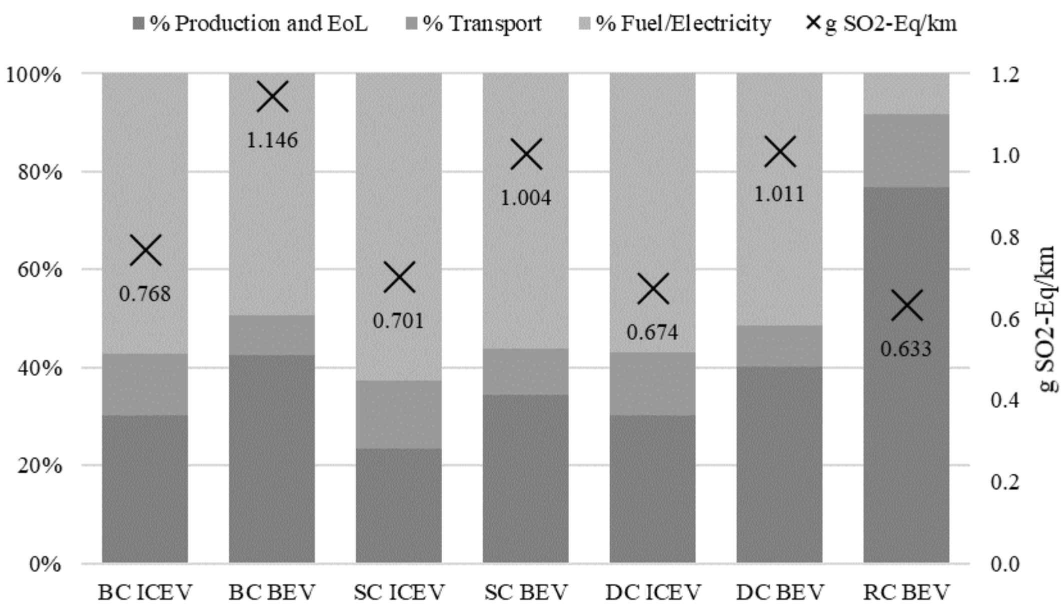

Figure 12. AP Transport System; BC - base case, SC – standstill case, DC – distribution case, RC – renewable energies case

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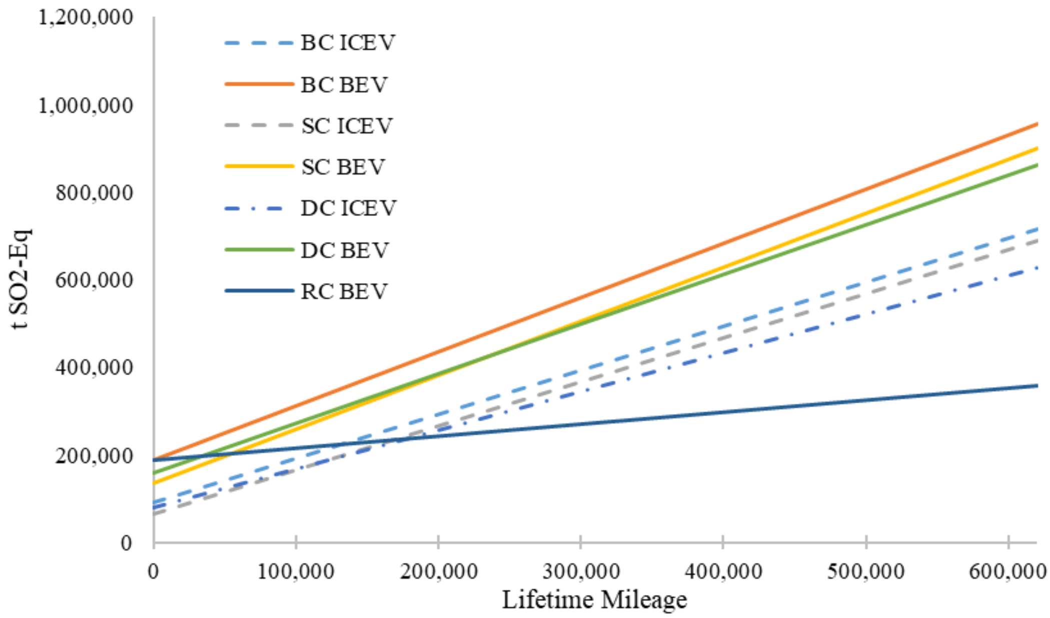

Figure 13. Total AP vs. Lifetime Mileage; BC - base case, SC – standstill case, DC – distribution case, RC – renewable energies case

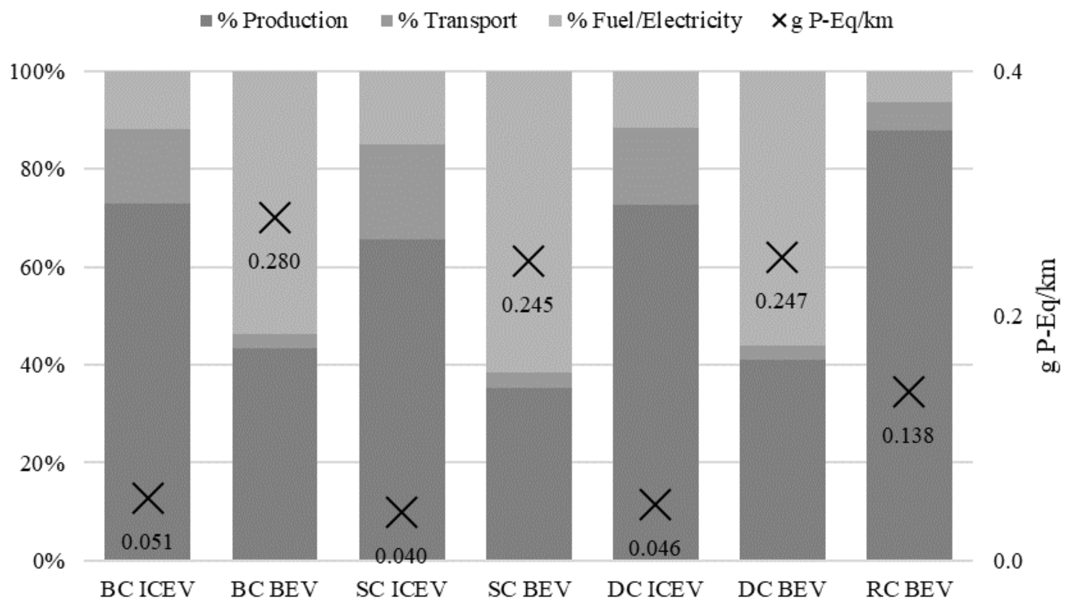

Figure 14. EP Transport System; BC - base case, SC – standstill case, DC – distribution case, RC – renewable energies case

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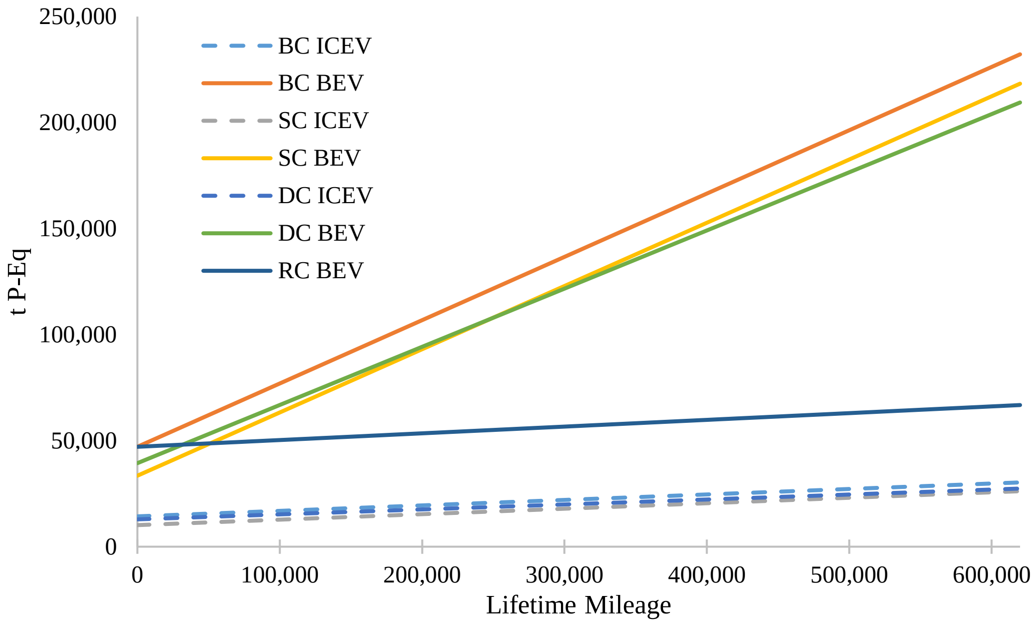

Figure 15. Total EP vs. Lifetime Mileage; BC - base case, SC – standstill case, DC – distribution case, RC – renewable energies case

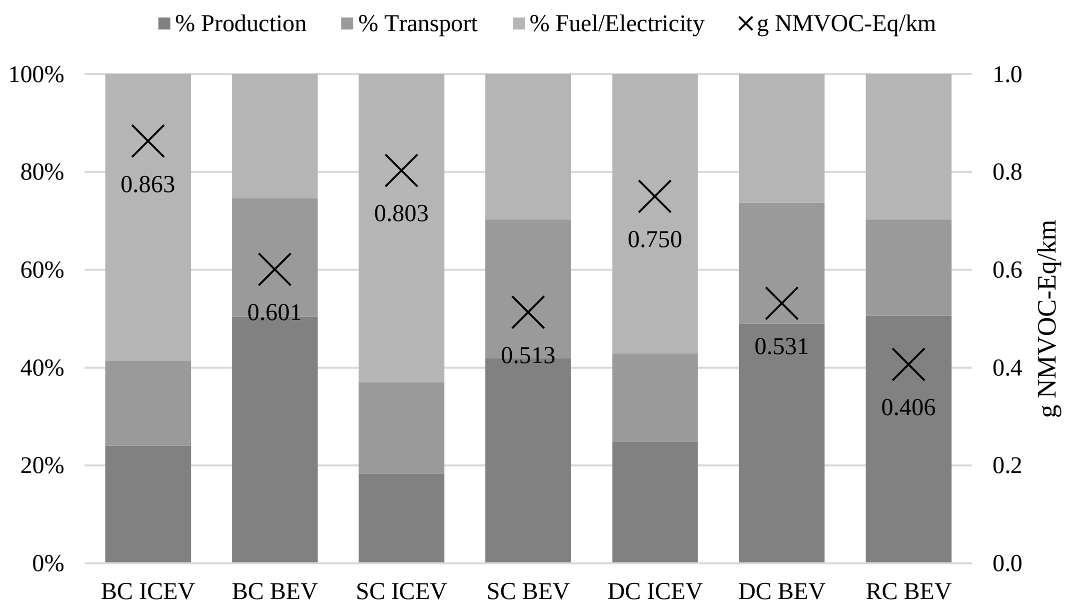

Figure 16. POFP Transport System; BC - base case, SC – standstill case, DC – distribution case, RC – renewable energies case

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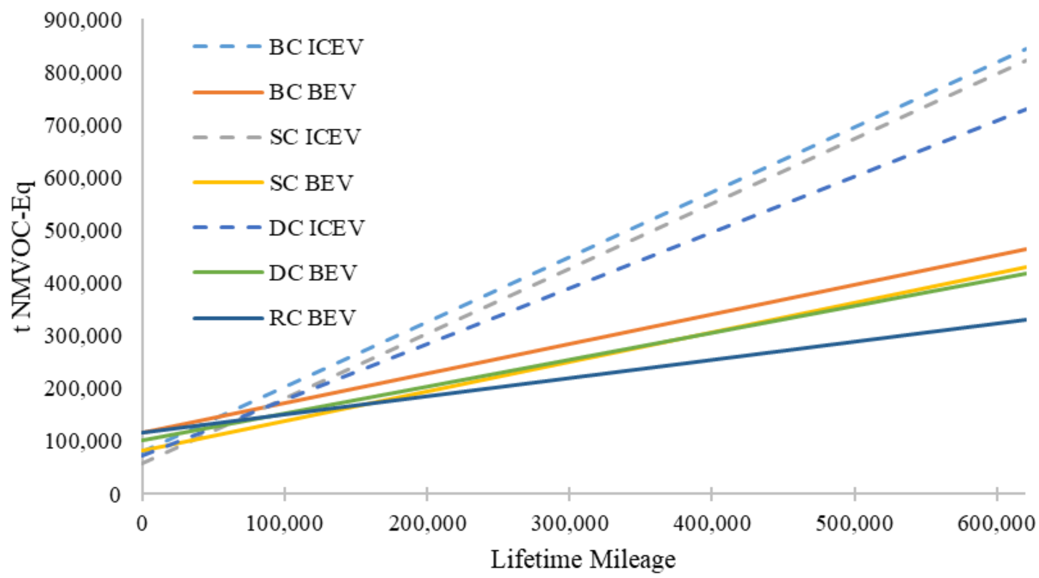

Figure 17. Total POFP vs. Lifetime Mileage; BC - base case, SC – standstill case, DC – distribution case, RC – renewable energies case

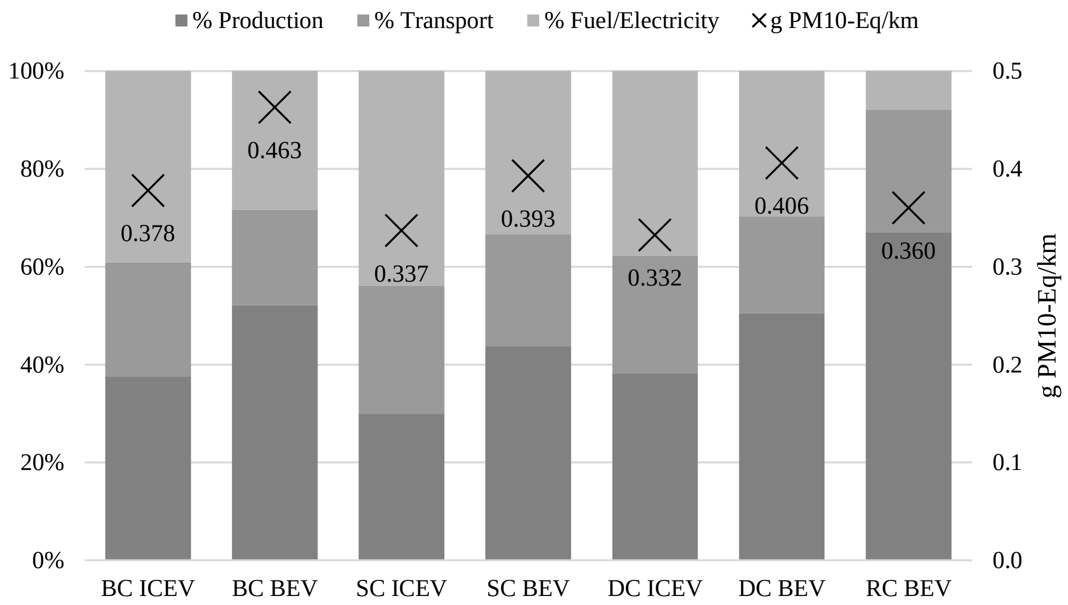

Figure 18. PMFP Transport System; BC - base case, SC – standstill case, DC – distribution case, RC – renewable energies case

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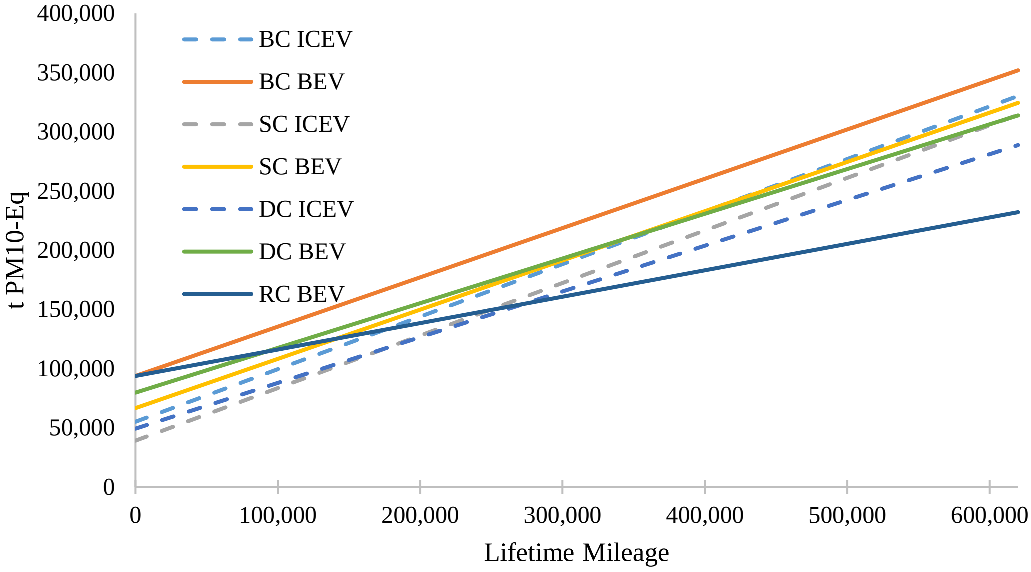

Figure 19. Total PMFP vs. Lifetime Mileage; BC - base case, SC – standstill case, DC – distribution case, RC – renewable energies case

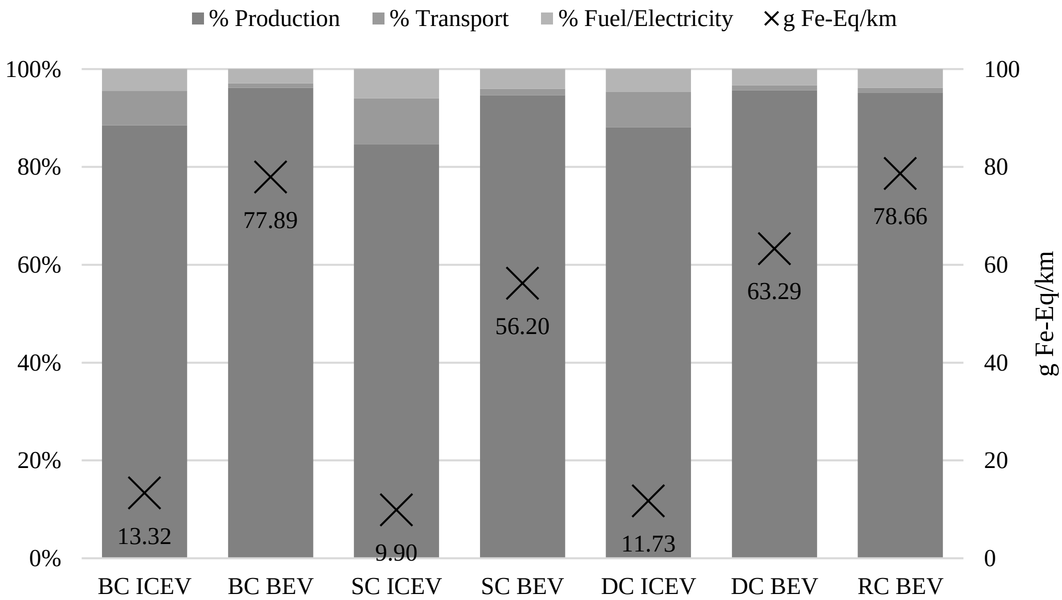

Figure 20. MDP Transport System; BC - base case, SC – standstill case, DC – distribution case, RC – renewable energies case

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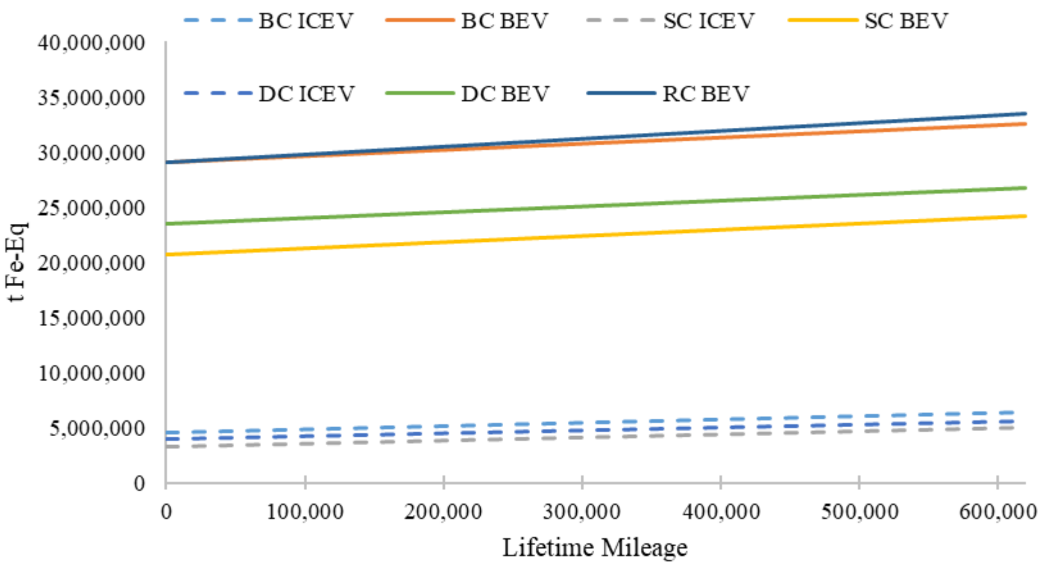

Figure 21. Total MDP vs. Lifetime Mileage; BC - base case, SC – standstill case, DC – distribution case, RC – renewable energies case

4. Discussion

The BEV base case shows advantages for the GWP and POFP compared to the ICEV base case. With renewable energy as electricity source it gains additional advantages in the AP and comparable results to the ICEV base case in the PMFP. The ICEV base case has smaller emissions in the EP and MDP for all cases. The standstill case results in smaller values compared to the base case for both transport systems. This is a logical consequence of assuming 0 % standstill and therefore less vehicles with no mileage, especially for the production and EoL intensive categories like MDP. There are only slight differences for the fuel- or electricity dependent categories (e.g. GWP, AP and POFP). The standstill case implies inspirations for mobility on demand (MOD) or car sharing services, like Ding et al. investigated [16]. A reduction of the total number of vehicles which are used to cover the same ways leads to smaller life cycle emissions. Advantages are conceivable, even with an increase of mileage for the transport system. The here developed method allows to investigate possible effects of MOD or even autonomous MOD services with vehicle concepts introduced in [22]. The distribution case demonstrates the advantages of a vehicle distribution consisting of a high small vehicle share. The ICEV distribution case improves in all categories compared to the base case, slightly more in categories with high fuel dependence. On the contrary, the BEV distribution case shows similar improvements for production intensive categories because of the battery sizes of the respective vehicle classes. The renewable case considers renewable energies only for the driving consumption and even gains advantages in all investigated impact categories. Helmers et al. imply major advantages from battery cell production with renewable energies [28]. Additionally, the results by Almeida et al. demonstrate great savings of greenhouse gas emissions for newer Li-ion batteries compared to older ones [11].

Jaeger et al. underline the spatial and temporal dependence of air pollutants [17]. This study represents POFP and PMFP for the whole life cycle, including production and EoL (which often do not happen at the place of use). The results imply a slight advantage of the BEV base case in PMFP considering only the use phase. However, this still includes the emissions that are not emitted and effective locally. Moreover, the Open Berlin Scenario covers among others suburban roads, which often don't suffer from air pollution. First approaches emphasize to combine a detailed air pollutant investigation in the use phase with the road network from the Open Berlin Scenario.

Dér et al. point out that the ambient temperature has a remarkable effect on the energy consumption of BEV [12]. Their field test has shown that cooling and heating systems account for an increase of 24 or 38 % in energy demand in summer and winter conditions. The here presented consumption values are averages for the respective vehicle class and drive train.

We assign the vehicle distribution randomly to the vehicles of the Open Berlin Scenario. This results in a similar resolution for the lifetime mileage of the respective vehicles. Caused by the standstill restriction the share of vehicles with a modest lifetime mileage is higher than in [52]. Additionally, we compared the shares of the vehicle classes lifetime mileage resulting in noticeable differences. Nonetheless, the referred study displays a picture of Germany. Whereas, Berlin-Brandenburg is an urban region with different conditions. We provided the distribution case to show the potential of different vehicle distributions.

The data provided by Ecoinvent was conducted several years ago. We adjusted certain parameters and the results of the synthetic vehicles are comparable to current studies. Still, further changes with the latest date are pending. The transport system depends on the MATSim results. Other versions of the Open Berlin Scenario or other locations can be easily added within this method. Extensions to other transport sectors like waste collection or freight traffic are possible with the respective vehicle data and traffic simulation. The usage of other data bases and/or traffic simulations is possible with a certain effort.

The results display midpoint results of the conducted ReCiPe methods. This prohibits assertion on the environmental impact as a whole. However, impacts in the respective impact categories are displayed.

The study investigated environmental impacts of battery electric passenger cars, which solely replace ICEVs. Nonetheless, investigations on areas like vehicle ownership, autonomous vehicles and others are possible with the respective transport simulations.

5. Conclusions

We presented a method that combines agent-based transport simulation and LCAs. Therefore, we provided a literature review on the latest LCA studies and introduced the case study (Berlin's Motorized Transport Sector). We developed synthetic vehicles and compared their impacts to current research. Furthermore, we established approaches to investigate the influence of lifetime mileage, vehicle distribution, energy supply, and standstill. Sole vehicle LCAs enable the comparison of the conducted vehicles, but neglect influences and opportunities of whole transport systems. The developed method demonstrates that the effects of new strategies in transportation can be analyzed by transport system LCAs. We showed the influence of different vehicle distributions and a reduction of vehicles, but further analyses (e.g. city-wide autonomous driving) are possible. The BEV base case has smaller impacts regarding the GWP and POFP compared to the ICEV base case. This implies that today's transport system gains advantages regarding climate change if operating with electric vehicles. In the renewable case, it gains additional advantages regarding the AP and similar results to the ICEV base case in the PMFP. Additionally, GHG emissions are reduced by over 60 %. The ICEVs have smaller emissions in the EP and MDP for all cases. The standstill case and distribution case demonstrate reduced emission in all categories. The standstill case allows imagination of mobility on-demand services: the total number of vehicles is reduced as multiple users have access to the vehicles. Especially for BEVs (with high production emissions), the standstill case shows fewer emissions than the base case. For ICEV the gap is much smaller. Nonetheless, influences of a real mobility on-demand scenarios (e.g. additional routes and therefore increased number of driven kilometers) need further research. The distribution case exhibits the benefits of a shift to smaller vehicles. The new distribution reduced the GHG emissions for BEVs by 10.1 % and for ICEVs by 7.4 %. The use of BEVs with renewable energies accompanied by a vehicle distribution consisting of mostly small vehicles and mobility a demand services provides a chance to achieve the German climate goals for transport in the future.

Future approaches will focus on different levels: time-dependent LCA data for vehicles and batteries to develop a vehicle segment and time-dependent vehicle distribution; the implementation of further transport simulation results to investigate other transport sectors like freight or waste collection and strategy options like mobility on-demand or autonomous driving; the comparison to

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other technologies like fuel-cell vehicles; the deployment of Endpoint results to enable assertions on the ecological impact; a detailed consumption model including ambient temperatures that allows locally and temporal investigation of air pollutant emissions and displays the use phase emissions more detailed.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Table S1: LCIA Small Vehicle; Table S2: LCIA Medium Vehicle; Table S3: LCIA Large Vehicle; Table S4: LCIA Transport System – Base Case; Table S5: LCIA Transport System - Standstill Case; Table S6: LCIA Transport System – Distribution Case; Table S7: LCIA Transport System Renewable Case

Author Contributions: Conceptualization, A.S. and F.H.; methodology, A.S. and F.H.; software, A.S. and F.H..; validation, A.S., F.H. and G.D..; formal analysis, A.S. and F.H..; investigation, A.S. and F.H..; resources, A.S. and G.D..; data curation, A.S..; writing—original draft preparation, A.S..; writing—review and editing, A.S..; visualization, A.S..; supervision, D.G..; project administration, D.G. and A.S..; funding acquisition, D.G. All authors have read and agreed to the published version of the manuscript.

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