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In-Life Range Modularity for Electric Vehicles: The Environmental Impact of a Range-Extender Trailer System

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Abstract: *Purpose*: In the light of decarbonizing the passenger car sector, several technologies are available today. In this paper, we distinguish plug-in hybrid electric vehicles (PHEV), electric vehicles (EV) with a modest battery capacity of 40 kWh, and long-range EVs with 90 kWh installed. Given that the average motorist only rarely performs long-distance trips, both the PHEV and the 90 kWh EV are considered to be over-dimensioned for their purpose, although consumers tend to perceive the 40 kWh EV's range as too limiting. Therefore, in-life range modularity by means of occasionally using a range-extender trailer for a 40 kWh EV is proposed, based on either a petrol generator as a short-term solution or a 50 kWh battery pack. *Method*: A life cycle assessment (LCA) is presented for comparing the different powertrains for their environmental impact, with the emphasis on local air quality and climate change. Therefore, the combination of a 40 kWh EV and the trailer options is benchmarked with a range of conventional cars and EVs, differentiated per battery capacity. Next, the local impact per technology is discussed on a well-to-wheel base for the specific situation in Belgium, with specific attention given to the contribution of non-exhaust emissions of PM due to brake, tyre, and road wear. *Results*: From a life cycle point of view, the trailer concepts outperform the 90 kWh EV for the discussed midpoint indicators as the latter is characterized by a high manufacturing impact and by a mass penalty resulting in higher contributions to non-exhaust PM formation. Compared to a petrol PHEV, both trailers are found to have higher contributions to diminished local air quality, given the relatively low use phase impact of petrol combustion. Concerning human toxicity, the impact is proportional to battery size, although the battery trailer performs better than the 90 kWh EV due to its occasional application rather than carrying along such high capacity all the time. For climate change, we see a clear advantage of both the petrol and the battery trailer, with reductions ranging from one-third to nearly sixty percent, respectively. *Conclusion*: Whereas electrified powertrains have the potential to add to better urban air quality, their life cycle impact cannot be neglected as battery manufacturing remains a substantial contributor to the EV's overall impact. Therefore, in-life range modularity helps to reduce this burden by offering an extended range only when it is needed. This is relevant to bridge the years up until cleaner battery chemistries break through, while the energy production sector increases the implementation of renewables. Petrol generator trailers are no long-term solution but should be seen as an intermediate means until battery technology costs have further dropped to make it economically feasible to commercialize battery trailer range-extenders. Next, active regulation is required for non-exhaust PM emissions as they could dominate locally in the future if more renewables would be applied in the electricity production process.

Keywords: range-extender; CO_2; air quality; mobility needs; LCA; Paris Agreement

1. Introduction

Air quality levels across Europe remain problematic, especially in urban regions [1]. These are found to be hotspots for nitrogen oxides (NO_x) and particulate matter (PM), for which road transport has a substantial contribution [2]. In the light of mitigating local air quality levels, pollutant emissions from both passenger cars, light-commercial, and heavy-duty vehicles have been regulated by the so-called Euro emission standards [3]. For cars, these progressive reduction targets have proven their efficacy for bringing down the emissions of exhausted PM, carbon monoxide (CO), unburned hydrocarbons (HC), and petrol NO_x. For diesel cars, however, substantial exceedances with the imposed NO_x limits are found. Evidence results from both rigorous chassis dynamometer testing [4,5], real-world driving tests using portable emissions measurement systems (PEMS) [6,7], and roadside remote sensing campaigns [8,9]. For heavy-duty vehicles, which are no further discussed in the presented paper, substantial NO_x reductions for heavy-duty vehicles have been realized since Euro VI. As such, they produce only half the NO_x emissions compared to the average Euro 6 diesel car, when compared on a kilometer basis [10].

Concerning transport's impact on climate change, the European light-duty vehicle sector is imposed to a target for carbon dioxide (CO_2) emissions. Therefore, each car manufacturer is required to obtain a corporate average fleet fuel economy of 95 g of CO_2 per kilometer by 2021, as described in Regulation (EC) 2009/443 [11]. Electric vehicles (EVs) are key assets in reaching this target, as they are given extra weight in the balance using so-called *super-credit factors* [12]. These allow EVs to count for more than one car in the fleet average calculation. An indirect effect of Regulation 443 is that EV-producing car manufacturers are less incentivized to lower the CO_2 emissions of their remaining conventional models, as electric vehicles bring down their fleet's average [13]. The importance of the 2021 and future CO_2 targets in Europe is strengthened by the 2015 Paris Agreement, in which the majority of the world's nations agreed to strictly reduce greenhouse gas emissions (GHG, represented by CO_2-equivalent gasses), in order to keep the global temperature increase well below 2 °C, relative to pre-industrial levels [14]. Despite the current lack of a well-defined roadmap towards this goal, a net-zero GHG economy is required by 2050 or shortly after that [15]. For this reason, the European Union strives to a minimum GHG reduction by 60 percent for its transport sector by 2050, while its entire economy is bound to reduce its GHG contribution by 80 to 95 percent [16]. In the light of decarbonizing the light-duty fleet, electrification is believed to play a major role if the electricity production sector follows the same decarbonization trend. Notwithstanding, we see that EVs applied in Europe already produce less CO_2 than a diesel car of the same segment on a well-to-wheel basis, even when applying electricity from a coal-intensive production like in Poland [17]. Besides the CO_2 reduction potential, however, current battery technologies have a significant environmental impact when their manufacturing process is considered, and this is primarily due to mining practices [18]. This indicates the need for cleaner technologies and a ramping-up of recycling used batteries. Given an average lifetime of a battery applied in an automobile of ten years, a substantial stream of used batteries is yet to come. Moreover, second-life application in stationary power storage can extend the useful life of batteries significantly, indicating a further shift in time before recycling the current generation of batteries becomes economically viable. Disregard this fact, precious metals like cobalt are already being recovered from battery waste, whereas the increase of prices raw lithium has led to the start of industrializing its recovery as well [19]. Large-scale recycling is nonetheless to be expected beyond 2025 [20].

Widespread adoption of EVs requires a paradigm shift in the mind of consumers, as the technology is characterized by limited onboard energy storage. Despite substantially lower operational expenses (OPEX), both fiscal and financial incentives remain a necessity to bring down the capital expenditure

(CAPEX). Next, there is the need for a widely available network of public charging infrastructure. Incentivization will, therefore, be required (at least) up until the point where cost parity is reached with a conventional car of the same segment. This moment is forecast to arrive between 2022 and 2026 [21]. Whereas the electric range is repeatedly indicated as one of the significant hurdles for EV breakthrough, it is a fact that the technology cannot cover the mobility needs of every consumer. Travel surveys are an essential source for estimating real-world needs for the daily range for passenger car users. Examples of such studies can be found in Pearre et al. [22] and Needell et al. for North-American statistics [23]; and Pasaoglu et al. [24] and Corchero et al. [25] for European variants. These different sources confirm that most of the daily range needs are in the 0 to 80 km range, while ranges exceeding 150 km/day are found to occur only on a limited number of days per year, i.e., for only 5 percent of the daily trips [26,27]. An exemplary distribution of the daily driven distances is given in Figure 1. These examples show the potential for substituting conventional cars with EVs for a substantial part of the year while relying on alternatives for the days when more considerable distances are traveled. In the absence of a sufficiently deployed charging infrastructure, this statement firstly targets consumers that have private parking places and/or a garage that can be equipped with a charger, i.e., the early adopters.

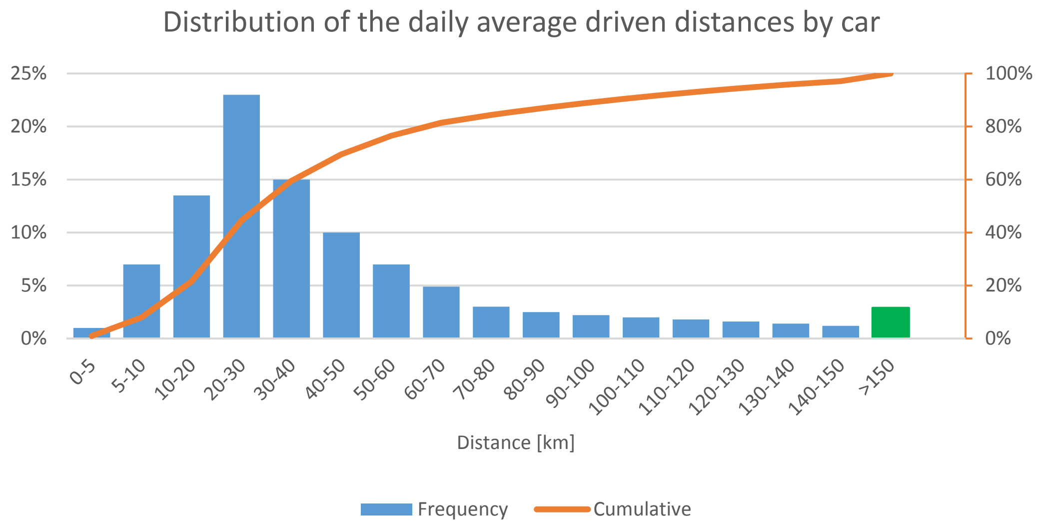

Figure 1. Example of an average daily driven distance distribution (based on Redelbach et al. [28]).

Options for covering these few percent of long daily distances could either be a conventional car, a plug-in hybrid electric vehicle (PHEV), or an EV with a high-capacity battery pack. PHEVs have the potential to mitigate both greenhouse gas and pollutant emissions as they typically allow an all-electric distance of 30–50 km. This nonetheless implies PHEV users must recharge on a daily basis, which is not always the case, as Ligterink et al. indicated by concluding only 30 percent of the Dutch PHEV company cars' kilometers were covered electrically [29]. The Dutch example shows how a large-scale market adoption of PHEVs was rather a consequence of a favorable tax regime than of an environmental motivation. Due to the incentives for car manufacturers to market PHEVs, European variants typically combine powerful engines with modest battery packs, which allow unrealistically low type-approval CO_2 emissions [30]. Nonetheless, a significant amount of attention has been given to PHEVs in the scientific literature. Popular topics are the optimization of battery capacity [28,31–33], the environmental impact of the dual technology [34,35], and total cost of ownership [36–39]. Whereas the automotive industry regards PHEVs as an important asset for reaching future GHG and pollutant emission targets [40], the question remains which future market share this expensive dual technology is destined for, as EVs are gaining momentum and battery innovation aims for driving ranges equaling those of conventional petrol cars, while the cost difference decreases as well. Despite current EV autonomies ranging from 250 to 400 *real* kilometers, manufacturers claim ranges up to 600 km and more for models that will be introduced in short-term. Given the limited adoption of EVs to date, we can assume those consumers that are buying such cars are early adopters with the possibility to recharge on a daily basis. In this case, however, the full potential of such batteries will potentially only be addressed in rare cases. Thus, the respective EV will have to move a 'dead mass' for most of the time, diminishing its inherent environmental impact due to high energy consumption, a higher manufacturing impact and higher tyre and road wear [41].

Another solution might be a roll-out of fast-chargers and, parallel to this, the development of battery chemistries that can be charged at higher currents. Although this option creates a lesser burden for the EV user in terms of charging time, the challenge remains to limit the impact of charging rates >50 kW have on the cycle-life of the respective battery packs. Moreover, fast-chargers put a substantial strain on the available power grid [42,43] , if they are not coupled to a local storage system, consisting of second-life batteries or supercapacitors that are charged when power demand is low. For these reasons, a concept of in-life modularity is proposed in this paper, consisting of a range-extender trailer that can be connected to an EV. Both a petrol generator and a battery pack trailer are shown in Figure 2.

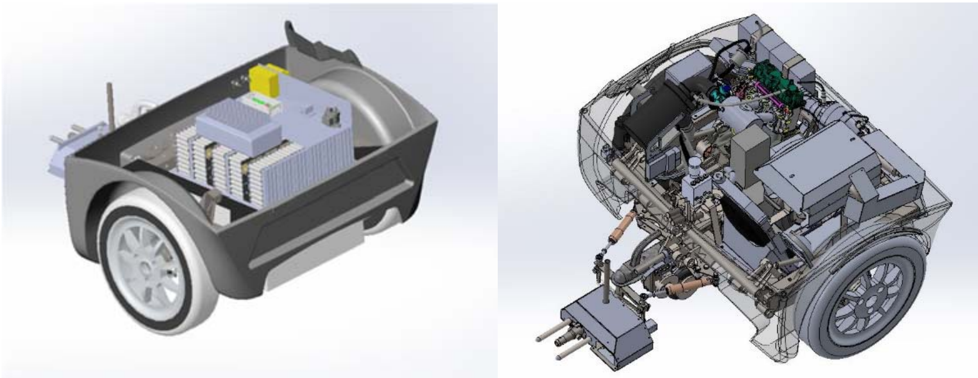

Figure 2. Graphical representation of the generator trailer (**left**) and the battery trailer (**right**).

Ideally, this concept consists of a trailer fitted with an extra battery pack, allowing the EV's battery to be used in a charge-sustaining mode for an additional 300 km. Whereas extra range is typically required to cover long distances over highways, this range-extender concept (from now on abbreviated to 'ReX') could complement fast-charging stations located near highways and would be offered on a rental basis, to avoid a high upfront cost for its sporadic use. As an intermediate towards the ideal situation, a petrol generator could serve as a power source for a generator to supply energy to the EV. As battery costs continue to decrease with increased production and a further fine-tuning of the production process, the petrol generator could be phased-out on the short to mid-term to maximize the environmental potential of in-life range modularity. Therefore, the objective of the presented paper is first to assess the environmental impact of this setup considering both climate change and air quality, by comparing a 40 kWh EV + ReX trailer combination to a range of mid-sized family cars. These are based on either petrol, diesel, petrol hybrid, or petrol PHEV powertrains. Also, the comparison is made with four existing EV models, characterized by battery capacities of 30, 60, and 90 kWh, respectively. The main focus is on the results for a petrol generator and a 50 kWh battery trailer, which are discussed in relation to the PHEV and the 90 kWh EV, as these are the technologies we expect to compete in the coming decade.

2. Methodology

2.1. Life Cycle Assessment

An environmental Life Cycle Assessment (LCA) is applied to compare the impacts, damages, and benefits of the combination of an EV + ReX trailer while considering all the associated emissions, both direct and indirect. An LCA consists a four-step approach, including a definition of a goal and scope, a life cycle inventory, an impact assessment, and the interpretation of the results, following the methodology according to ISO 14040 [44] and ISO 14044 [45].

2.1.1. Goal and Scope

For the presented paper, different powertrain technologies are compared to the combination of a 40 kWh EV and a range-extender trailer for their impact on both climate change and human health. Despite the technological differences between the discussed powertrains regarding, for instance, their nominal driving range, they all provide the same function of mobility. Therefore, the functional unit for comparing the different powertrains is their respective impact per kilometer driven. The entire life cycle impact is calculated by considering a lifespan of 210,000 km, which represents the European average end-of-life age for passenger cars of 15 years and an assumed annually driven distance of 14,000 km. For the discussed EVs, we assume a battery pack replacement after 150,000 km.

Whereas the scope of this assessment concerns the global impact of the different technologies, seen over their entire life cycle, we also zoom in on the specific case for Belgium to assess the impact on human health locally. Therefore, a full-scale LCA for both the impacts on climate change and human health is complemented with a well-to-wheel emissions analysis for which all emissions produced outside of Belgium's national borders are excluded from the scope. Therefore, refinery-to-tank (RTT) emissions are applied instead of the conventional well-to-tank (WTT) emissions, as discussed earlier in Hooftman et al. [41]. For a graphical overview of the methodology, please refer to Figure 3. Addressing local impacts is relevant in the light of improving air quality levels in European cities, as virtually every city dweller is deemed to breathe air that is found harmful to human health.

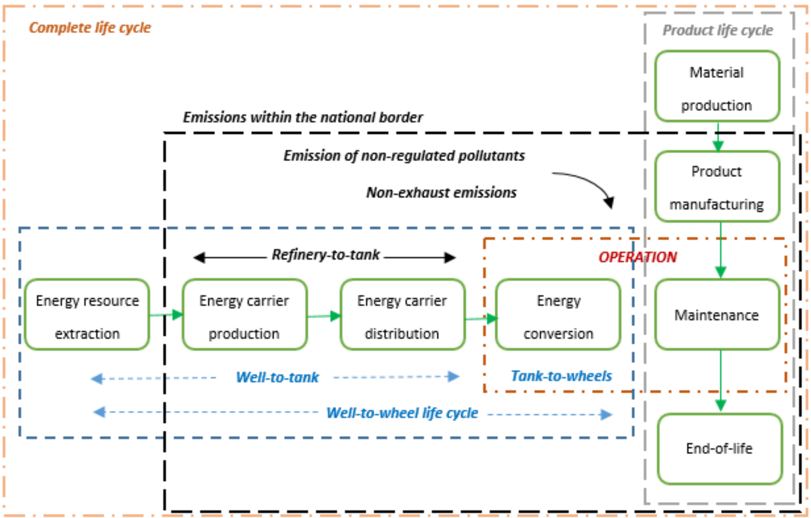

Figure 3. Flowchart of the LCA approach (based on [36,41]).

2.1.2. Lifecycle Inventory

For the different powertrains, life cycle inventories (LCI) were produced based on Messagie et al. in [46], and cover both emissions related to the well-to-tank and tank-to-wheel phase, as well as those related to the manufacturing of the bodywork and powertrain. Concerning end-of-life recycling, we accredit the benefit of recovering materials from the recycling processes to the manufacturing phase, avoiding the material production from virgin ores. The advantage of separating the different product life stages enables the identification of the causes of specific impacts and emissions per stage in the product's value-chain. The original inventories have been updated to reflect the real-world fuel consumption and regulated emission data based on the discrepancies found in literature, and have been supplemented with emission factors for the most important non-regulated pollutants based on Hooftman et al. in [41]. A deliberate divergence from the official emission factors was chosen to allow a fair comparison between the different technologies. For the EVs, the energy consumption data published by the U.S. Department of Energy (DOE) was used [47]. The specifications of the assessed EVs are given in Table 1, while the assumed energy consumption factors for the discussed ICE cars are given in Table 2. The energy consumption of the 40 kWh EV combined with a trailer is assumed to increase by five percent, Finally, whereas the original powertrains database only described a 24 kWh EV, the LCI for the 30, 40, 60, and 90 kWh EVs discussed in this paper result from a parametrization exercise for which vehicle mass, battery mass, and electric consumption served as determinants.

Table 1. Specifications of the discussed electric vehicles (based upon [47]).

Parameter [Unit]	30 kWh EV (Nissan Leaf)	40 kWh EV (Renault Zoe)	60 kWh EV (Chevrolet Bolt)	90 kWh EV (Tesla Model S90)
Capacity [kWh]	30	40	60	90
Mass in Running Order [kg]	1591	1450	1624	2200
Weight battery [kg]	272	305	435	540
Average consumption [kWh/km]	0.15	0.15	0.15	0.25
Highway consumption [kWh/km]	0.20	0.20	0.20	0.26
Highway consumption with ReX trailer [kWh/km]		0.21		
EU electricity mix in g/kWh			*276*	

Table 2. Overview of the real-world tank-to-wheel fuel consumption indicators per technology (based upon [29,30]).

Unit	Petrol	Petrol Hybrid	Diesel	Petrol Plug-in Electric Vehicle
[l/100 km]	6.8	5.6	5.3	3.4
gCO_2/km	162.7	134.0	140.0	81.3

3. Life Cycle Inventory

3.1. Impact Assessment

The selected impact assessment methodology that was applied in the SimaPro 8.3 software is ReCiPe midpoint (H) [48]. Out of a set of eighteen midpoint impact categories, four are discussed in this paper as they represent both GHG emissions and air quality in urban environments. These are Climate Change (CC), Photochemical Oxidant Formation (POF), Human Toxicity (HT), and Particulate Matter Formation (PMF). These midpoint indicators serve as an intermediate between the emission source and the 'endpoint', representing the recipients of the environmental effects caused by anthropogenic activities; these are Human Health, Ecosystem Quality, and Natural Resources [39]. No endpoint indicators are discussed in this paper.

Concerning the midpoint indicator for climate change, CO_2-equivalents represent the group of greenhouse gasses. Primary drivers of POF are elements from the family of benzenes, nitrogen oxide(s), and other non-methane organic compounds, which are precursor gasses for ground-level ozone (O_3) formation. POFs are in this paper represented by the group of non-methane volatile organic compounds (NMVOC). As for HT, copper, dioxins, cadmium, silver, and zinc among others contribute to the impacts in this category, grouped as 1,4-dichlorobenzene equivalents (1,4-DB). Particulate Matter Formation highlights the impacts of primarily formed particulates as well as particulates formed by the condensation of nitrogen oxides, sulphur oxides, ammonia, and non-methane volatile organic compounds (secondary PM). PMF is represented by the emission of PM10-equivalents, i.e., particles with an aerodynamic diameter smaller or equal to 10 micrometers. Both PMF from combustion and from tyre, brake, and road wear are considered to offer a maximal scope on the most relevant pollutants.

3.2. Assumptions

The discussed EVs are assumed to be charged with the average European energy mix, characterized by an average CO_2 emission intensity of 276 g per kWh of electricity produced [49].

The authors of this paper deliberately chose not to address marginal energy production for generating the electricity for EVs, as EVs are thought to be part of the total load system, confirming the viewpoints found in Refs. [35,50–52].

For the comparison of the different powertrain technologies, the 40 kWh EV is chosen as the reference to be combined with the range-extender. Also, the marginal application of the trailer is assumed to be 5 percent of the vehicle's lifetime driven distance, reflecting the outcome of the aforementioned travel surveys and the fact that long distances are in general only seldom performed. Next, one trailer is assumed to be shared by a maximum of 15 users on a rental basis, resulting in the fact that its manufacturing impact is subsequently shared over these 15 users. In the sensitivity analysis in Section 5, we assess the impact of a higher trailer uptake and thus a lower number of users per unit. For the remaining 95 percent of the EV's lifetime, it is assumed to drive purely electric. Equation (2) represents how well-to-tank emissions are based on both the EV's average consumption (kWh/km) and the increased consumption while towing the trailer. This increase is assumed to be capped at 5 percent as the trailer is closely coupled behind the EV and therefore has a minimal influence on its aerodynamics. In case of towing the battery trailer, an extra consumption of 10 percent is considered. The specifications for the trailers per power source concept are given in Table 3, while Table 4 presents the use stage emissions for a suitable generator.

$$WTT_{EV40+ReX} = \left(0.95 \times WTT_{EV40,\,avg}\right) + \left(0.05 \times \left(WTT_{EV40,\,highway} + WTT_{ReX}\right)\right) \tag{1}$$

Table 3. Overview of the trailer characteristics for a petrol generator and an additional battery pack.

Parameter	Petrol Generator	Battery Pack
Rated power [kW]	25	50
Mass [kg]	265	480
Fuel tank [L]	35	/
Fuel type	Petrol	Electric
Range [km]	300	300
Average consumption [L/kWh]	0.44	/
Average consumption [L/100 km]	7.5	/

Table 4. Emission factors for the generator ReX trailer [53].

Unit	Average Generator Emissions				
	HC	CO	NO_x	CO_2	HC + NO_x
[g/kWh]	2.5	40.5	1.1	999.4	3.6

Based on a life cycle inventory (LCI), the elementary flows which are linked to the various vehicle technologies need to be converted to the different impact categories. These allow quantification and a comparison between the potential impacts. This step is referred to as the life cycle impact assessment (LCIA). An exemplary full LCIA of a 30 kWh EV is given in Table A1 in the Appendix A. Concerning the environmental performance of both the generator and the battery ReX trailer concepts, please refer to Tables 5 and 6, respectively. These tables show a deliberate distinction between the production of the 'trailer body' and the production of the power source, while the operation of the latter was analyzed during its use phase. This choice was made to allow better insight into the allocation of their respective contribution to the midpoint indicators. The total lifetime of the trailer was chosen to be identical to that of a passenger car itself, namely 210,000 km. The European electricity mix is included, representing the 95 percent of the time during which the generator trailer is decoupled from the EV. For all four midpoint indicators discussed in Table 5, it is this 'EV part' which is responsible for approximately three-quarters of the respective impact. The fact that the generator ReX trailer has a significant impact for being active only 5 percent of the time emphasizes the potential environmental improvements if the generator would be substituted by a battery pack, as indicated in Table 6. Keep in mind that in the remainder of this paper, the impacts of the trailer's assembly for both the bodyworks and the generator are divided by 15, as the product is developed to be shared by the same number of users.

Table 5. LCIA of the 40 kWh EV + generator ReX for the various impact categories

Impact Category	Unit	Total	Trailer Assembly Excl. Generator	Generator Manufacturing	Generator Operation	EV Electricity (EU Mix)
Climate change	gCO_2-eq./km	109.31	2.12	3.67	12.66	90.85
Human toxicity	g1,4-DB-eq./km	63.44	2.33	9.94	0.45	50.72
Photochemical oxidant formation	gNMVOC/km	0.26	0.01	0.01	0.04	0.19
Particulate matter formation	gPM_{10}-eq./km	0.16	0.01	0.01	0.01	0.13

Table 6. LCIA of the 40 kWh EV + battery trailer.

Impact Category	Unit	Total	Trailer Assembly Excl. Battery	Battery Manufacturing	Battery Operation	EV (EU Mix)
Climate change	gCO_2-eq./km	102.5	3.2	18.0	0	81.3
Human toxicity	g1,4-DB-eq./km	36.3	3.5	31.5	0	1.27
Photochemical oxidant formation	gNMVOC/km	0.62	0.02	0.05	0	0.10
Particulate matter formation	gPM_{10}-eq./km	1.16	0.02	0.07	0	0.02

4. Results and Discussion

4.1. Climate Change

Figure 4 presents the life cycle impact on climate change for the different powertrain technologies. Starting from the left-hand side, the impact of the use phase is emphasized for the ICE-based powertrains. For the plug-in hybrid, we report a similar impact than for diesel, and this is primarily due to the high real-world tank-to-wheel emissions of the former. Moving over to the EVs, an unmistakable difference gap is caused by the absence of tank-to-wheel emissions for the electric models, resulting in a lesser overall CO_2 impact, while well-to-tank emissions result from the average energy consumption and the characteristic CO_2-intensity of the European energy mix. The fact that battery size is proportional to energy consumption is highlighted for the 90 kWh EV. Thus, it represents nearly twice the climate change impact of the 30 kWh variants. Regarding the impact of the EV + trailer combinations, the battery and the generator trailer prove to have a favorable effect when compared to the 90 kWh EV. While offering the same range as the latter, the generator trailer combination allows a 33 percent lower CO_2 emission. In the case of the battery-equipped trailer, this gap widens to over 40 percent. When comparing the trailer combinations to the 60 kWh EV, only a small difference is reported for both concepts. Regarding the potential for carbon savings by substituting PHEVs by a range-extender trailer that is only occasionally coupled to a 40 kWh EV, a reduction exceeding 50 percent is offered by the petrol trailer and over 58 percent in the case of the battery trailer.

The results shown in Figure 4 confirm both the benefits of electric vehicles over internal combustion engine vehicles when climate change is concerned, and the energy mix as a strong determinant of the EV's well-to-tank emission profile. This energy mix could be managed intelligently if smart charging mechanisms would allow EVs to recharge only when solar and wind energy is abundant. Thus, EVs could be the intermediary solution until battery storage of renewables becomes economically viable. In the absence of smart meters, an uncontrolled grid connection of a significant EV fleet could nonetheless result in additional peak loads. Responding to this power demand using coal-fired power plants results in high CO_2 emissions and adversely impacts air quality. Merely allocating these excess emissions to EVs alone should be avoided as they are deemed to be part of the total load system. These factors indicate that the environmental potential of EVs goes hand in hand with how one produces the electricity they charge with.

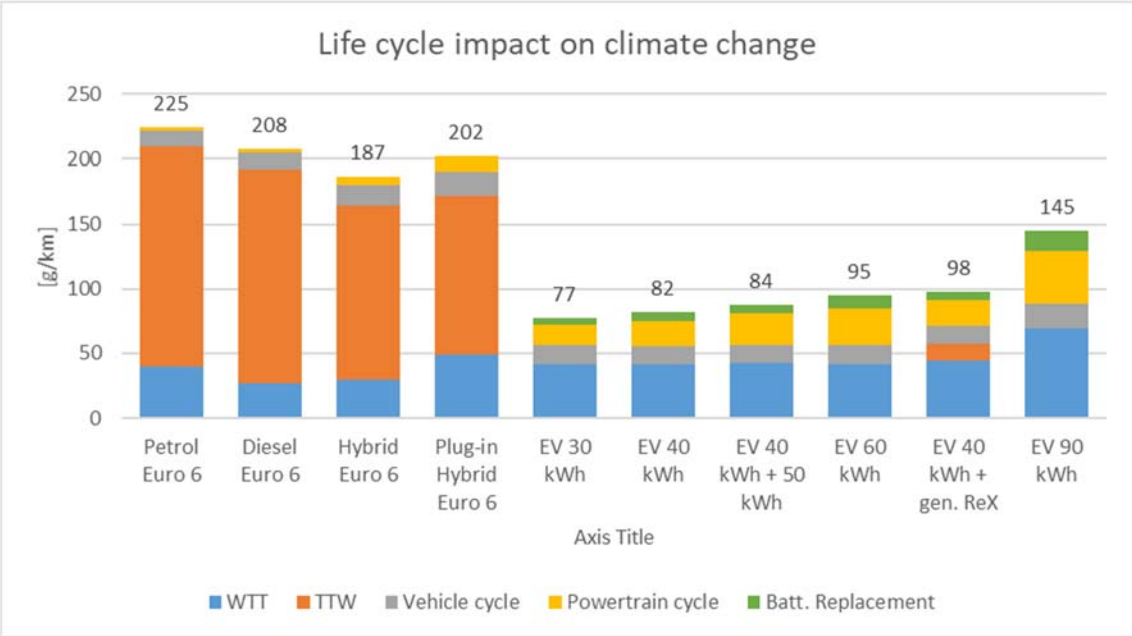

Figure 4. Impact per kilometer on climate change considering the entire LCA.

4.2. Photochemical Oxidant Formation

Concerning photochemical oxidant formation (POF) seen over the vehicle's lifetime, Figure 5 shows the significant impact of diesel technology originating from the tank-to-wheel phase, as its combustion inherently causes high emissions of NO_x. By including real-world driving emissions (RDE), the 'struggle' for European car manufacturers to control NOx emissions is emphasized. Disregarding the dominance of diesel powertrains for POF, we see that the higher the battery capacity becomes, the higher the impact on POF gets. Thus, the petrol-fueled plug-in hybrid performs worse than the conventional petrol car, although the latter's impact would be far higher if it were diesel-fueled. Linked to the battery size are the vehicle weight and the electric consumption, which is reflected in the well-to-tank emissions for the electrified powertrains. Thus, the 90 kWh EV once more presents a POF contribution that is nearly twice what is reported for the 30 kWh model. Principal sources for POF among the feedstocks for electricity production are coal, gas, and oil, indicating the potential reductions if the more renewable energy sources would be applied. Considering the trailer combinations, we report a very similar POF contribution when compared to the 60 kWh EV, while representing about 35 percent lower POF emissions when compared to the 90 kWh EV. Compared to the PHEV, the occasional application of a generator or a battery trailer generates 9 to 14 percent higher POF contributions, respectively.

If we were to assess only the POF emissions caused locally, the scope narrows down to a well-to-wheel analysis for Belgium, for which we consider the earlier mentioned refinery-to-tank (RTT) emissions for the contributions occurring upstream the use phase. Figure 6 represents the results of this exercise and shows the potential for EVs in strategies to bring down local emissions without ignoring the impact of manufacturing their powertrains. Locally, the TTW phase of the generator trailer makes it perform like the PHEV while contributing roughly 60 percent more to photochemical oxidant formation when compared to the 90 kWh EV. Substituting the generator with an additional battery pack would level its impact with that of the 60 kWh EV, or about 40 percent less than what is reported for the 90 kWh EV. If we compare the battery trailer combination to the PHEV, local POF contributions for the former end up to be two-thirds less. No POF originates from tyre, brake or road abrasion.

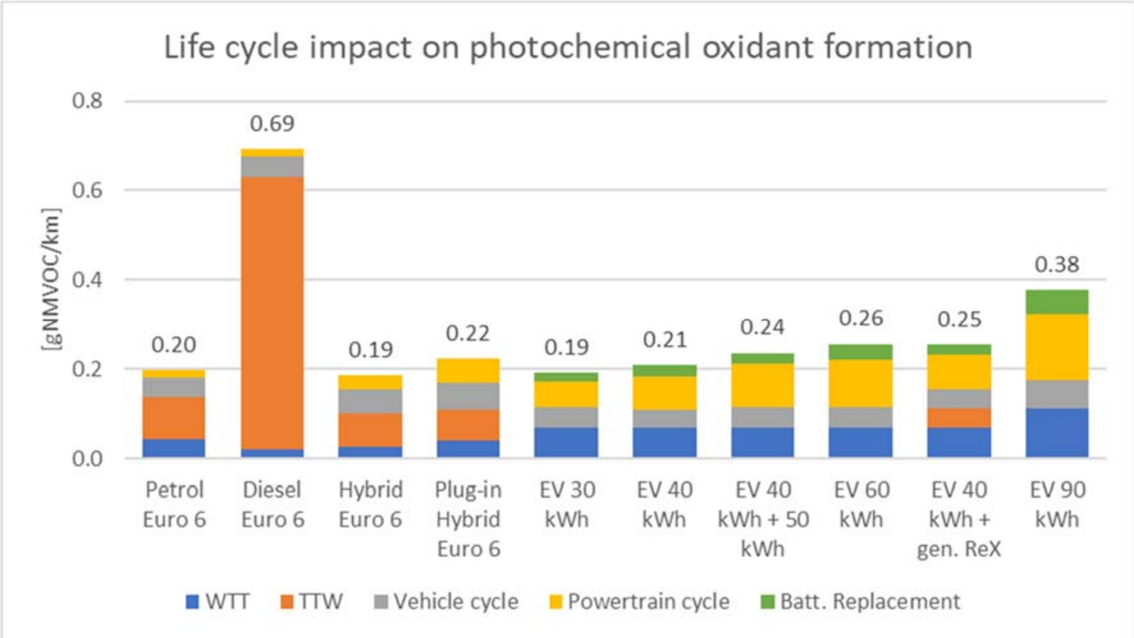

Figure 5. Impact per kilometer on photochemical oxidant formation.

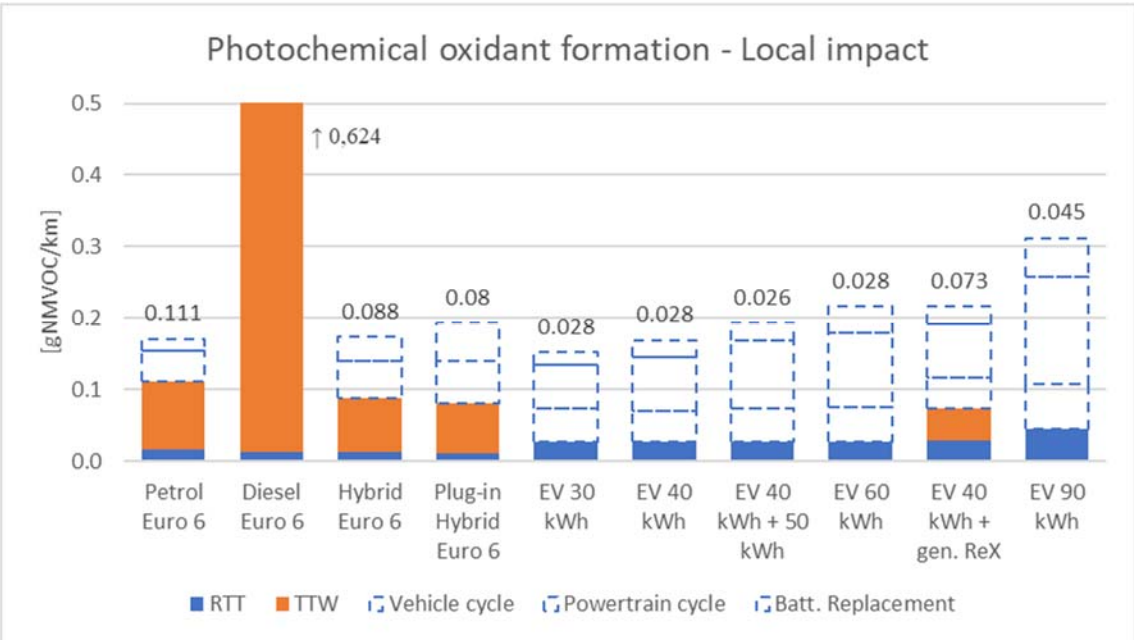

Figure 6. Photochemical oxidant formation at a local level per powertrain technology.

4.3. Particulate Matter Formation

For particulate matter formation (PMF), Figure 7 shows the contribution of the different powertrain technologies per kilometer driven. For this impact category, non-exhaust emissions are distinguished from the total TTW emissions, to highlight their significance relating to battery size. The specific impact regarding PMF from non-exhaust sources ranges from roughly one-fifth of the total PM emissions (petrol) to about one-tenth in case of the 90 kWh EV and the diesel car. Keep in mind that the non-exhaust fraction originates from brake, tyre, and road wear and currently is not regulated within Europe. Again, we see the inherently high contribution of PM emissions during the use phase for diesel cars, while for the other ICEVs and EVs this impact increases with the applied battery capacity. What catches the eye is that for the entire life cycle, the 90 kWh EV's PM emissions actually exceed those of a diesel car, particularly if a battery replacement is considered.

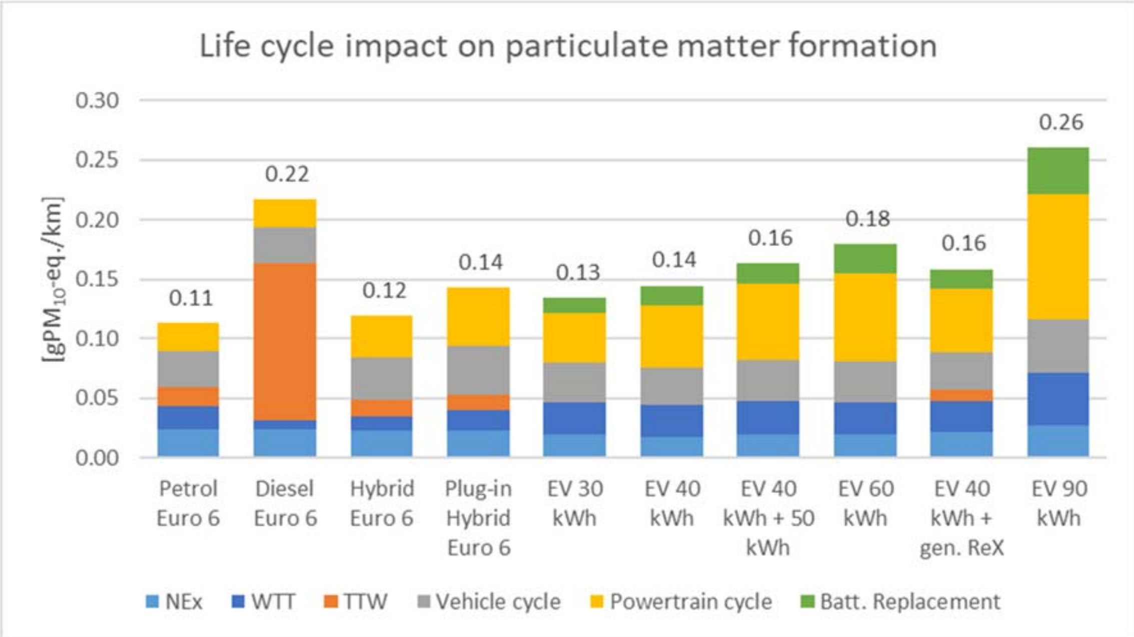

Figure 7. The contribution of particulate matter per technology.

For the range-extender trailer combinations, brake wear is excluded as the trailer is assumed not to be provided with a braking system. The effect of towing a trailer—and thus an extra weight—on the non-exhaust sources is nonetheless encompassed, albeit that due to the occasional nature of using the trailer, these impacts are negligible. Notice how both the trailer combinations and the 60 kWh EV have a similar impact over the full life cycle, which is about 40 percent lower than for the 90 kWh EV. Compared to a PHEV, the trailers have a 14 percent higher contribution to PMF, although one must keep in mind that the discussed PHEV is based on petrol technology. In case of a diesel PHEV, the tank-to-wheel contribution would be significantly higher.

If we look at the local emissions considering a refinery-to-wheel analysis, Figure 8 stresses the importance of regulation of non-exhaust emissions as they now have relative shares ranging up to 75 percent in case of the 40 kWh EV. Locally, the battery trailer performs about 30 percent better than the generator trailer and the 90 kWh EV, which have an equal contribution. Compared to the other EVs, the 90 kWh EV does represent a substantially higher local impact, which is mostly because of the higher vehicle mass' influence on non-exhaust emissions. Thus, we can confirm that the extra weight of the 90 kWh EV's battery has a negative effect seen for both its lifetime and local impact, although for the latter this effect is similar to the contribution of a hybrid powertrain. Whereas the trailer concept is designed in the light of a sharing economy and for covering longer distances, it is likely the trailer will be dropped off and picked up near highways. Therefore, the impact of the trailer combination is less relevant concerning local air quality levels.

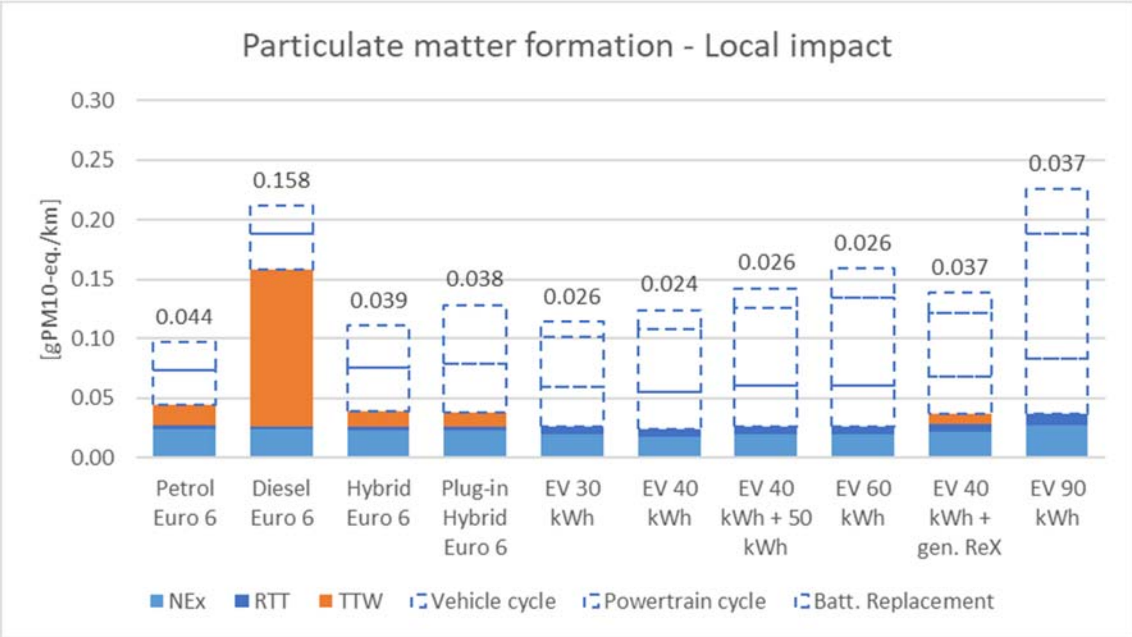

Figure 8. Impact per kilometer on particulate matter formation during use of the vehicle (including the refinery-to-tank (RTT) emissions upstream). Tank-to-wheel (TTW) emissions are further disaggregated to exhaust TTW and non-exhaust PMF (NEx).

4.4. The Impact on Human Toxicity

Figure 9 presents the impact of the different powertrains on human toxicity. As can be seen, the contribution of the well-to-wheel phase (i.e., non-exhaust, WTT, and TTW) is only marginal for the conventional powertrains, while it increases with battery capacity. Also, the contribution by the electricity production is emphasized in this exercise, indicating the reduction margin for changing the feedstock with renewable sources. What must be noted here is that the HT impact of EVs is far more researched than for the ICE-based technologies. For conventional petrol and diesel cars, for instance, an update of the current situation is needed as the substantial increase in sensor applications over the last decade resulted in more copper use, the 90 kWh performs worst of the given options, followed by the battery trailer combination due to the high impact of the battery production process. Locally, the impact of the manufacturing phase is filtered out of scope in Figure 10. Thus, the impact of non-exhaust PM emissions is emphasized, for which EVs have the benefit of relying less on the conventional brakes. Notice the little difference between the presented powertrains based on internal combustion engines, the generator trailer combination, and the 90 kWh EV.

What can be concluded from these figures is that the manufacturing phase of EVs should not be neglected in the debate on which powertrain causes the least environmental impact. If we use the petrol car's powertrain as a reference, the impact of EVs on human toxicity ranges from double to nearly four times, although this difference would reduce if more recent LCI data on conventional cars were available. Next, we highlight the need for both more sustainable mining techniques, battery chemistries that rely on more locally and abundantly available feedstocks and an increased uptake of recycled materials in the battery manufacturing process. Nonetheless, if local policy is concerned, attention should primarily go to the impact different technologies have locally. In this regard, neither the PHEV nor the 90 kWh EV prove to be the optimal solution. Instead, a reduced impact on human toxicity is reached by addressing a battery trailer on those occasions when the nominal range of a 40 kWh EV is not sufficient.

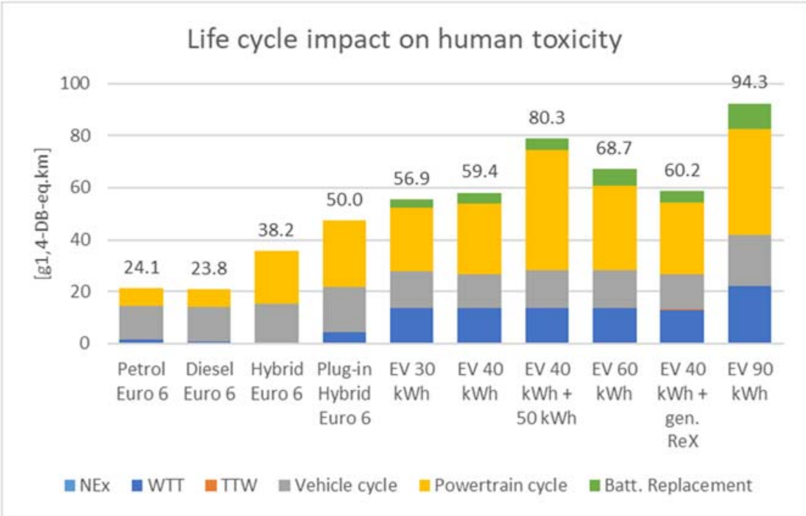

Figure 9. An overview of the well-to-wheel impact on human toxicity per powertrain.

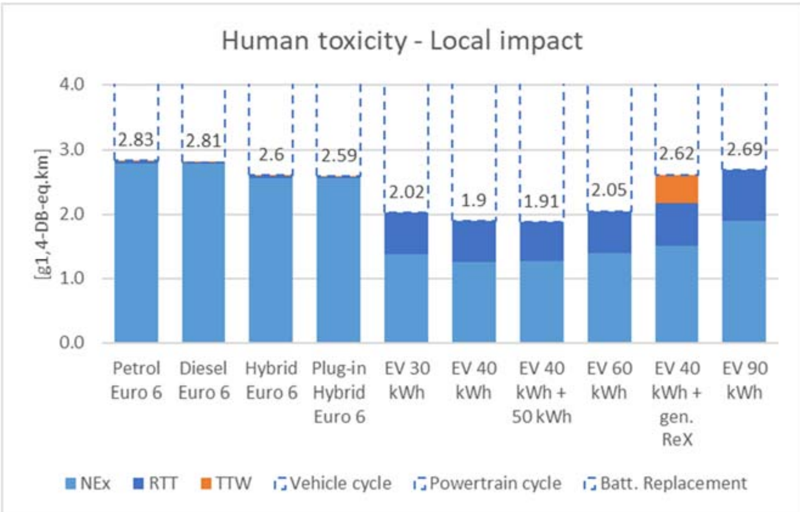

Figure 10. The impact on human toxicity at a local level per powertrain technology, considering refinery-to-tank (RTT) instead of well-to-tank emissions.

4.5. Sensitivity Analysis

Whereas the results presented in this paper are based on certain assumptions, a sensitivity analysis is recommendable to highlight possible weaknesses and/or potentials for the trailer combinations, combined to an EV. An overview is given of examples which are thought to influence the results of this exercise.

4.5.1. The Electricity Production Mix

For the comparisons made in this paper, the European electricity mix was applied, representing 276 g of CO_2 produced per kWh. As EVs are only exploited to their full environmental potential when its electricity originates from renewable sources, this is where the focus of European policy concerning energy production should be. Thus, we emphasize the agreed commitments towards carbon-neutral economy by 2050. As indicated by Messagie et al., the climate change impact of EVs powered by energy from renewable sources could be reduced to approx. 40 g of CO_2-equivalents per kilometer driven. The other way around; if energy production would shift to fossil fuels such as oil or coal, the impact per kilometer would significantly exceed the impact of conventional cars. This is shown in Figure 11, for which the 40 kWh EV's impact is distinguished per energy production source (based on [42]). A drastic shift to renewable sources would thus mean the well-to-tank emissions for EVs could be marginalized, which will also have a substantial impact on the other three discussed midpoint indicators.

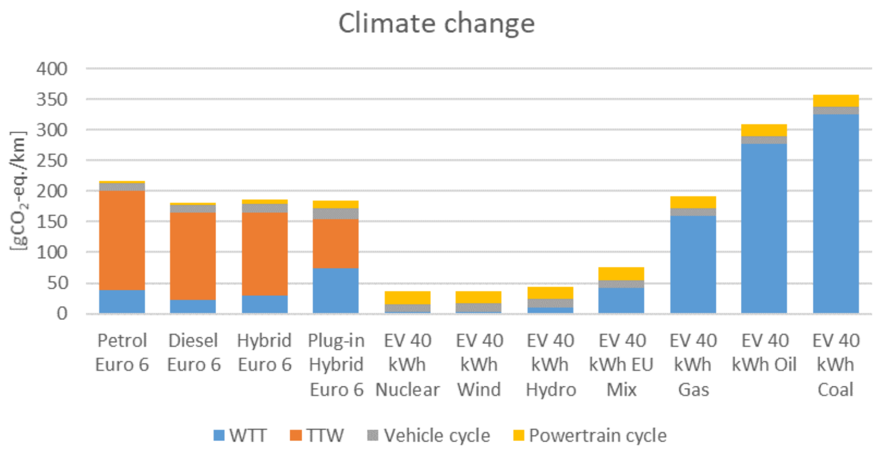

Figure 11. Impact of the energy production mix in grams per kilometer (based on 46).

In the current absence of large-scale power storage facilities for renewable sources such as wind and solar power, EVs might prove to be a solution as well. Slow-charging facilities could, therefore, be maximally provided with green power, although this is far less likely for fast-charging facilities unless ultracapacitors are applied. In the case of fast-chargers, energy is needed immediately at high power rates, which is why the share of renewable energy is likely to be on the low side.

4.5.2. The Use Pattern for the ReX Trailer

An important aspect of this sensitivity analysis is the marginal application factor of the ReX trailer. If one would apply the ReX trailer for one-tenth of the driven distance rather than one-twentieth, this could have a significant influence on the comparison of the different midpoint indicators. For climate change, applying the ReX trailer for 10 percent of the time would result in a relative increase by 17 percent.

Another aspect of the use pattern is the central issue of people tending to cover longer trips during weekends, e.g., to visit relatives. This can result in distorted availability for the ReX concept and thus, at peak demand in a lower number of users for one trailer. This sensitivity has been calculated for five users and ten users concerning the impact on climate change. Results showed no significant impact on either the vehicle cycle or the powertrain cycle, as the increase was found to remain below 2.5 percent in the worst case of 5 users.

5. Conclusions

In the light of decarbonizing society by mid-century, electrification of passenger cars is imminent. Therefore, several alternatives for the conventional ICE-based passenger car are available today, although their sustainability varies. Whereas the average motorist mostly covers short distances on a daily basis, one can either opt for a plug-in hybrid electric vehicle, an EV with a large battery pack, or a small (40 kWh) EV and the option of fast-charging. A fourth alternative is proposed in this paper by means of occasionally coupling the 40 kWh to a range-extender trailer that is shared with other EV users. Here, we discussed a petrol generator trailer for application in the short-term, while substituting the generator on the mid-term with a 50 kWh battery pack as battery prices further decrease. While the impact of fast-charging exceeds the scope of the presented paper, we did compare the environmental impact for the PHEV, 90 kWh EV, and the 40 kWh EV + range-extender for their contribution to climate change, photochemical oxidant formation, particulate matter formation, and human toxicity. The European electricity mix was considered for charging the electrified powertrains, characterized by a carbon-intensity of 276 g CO_2/kWh, while an end-of-life range of 210,000 km was assumed for each technology. Finally, we included an EV battery replacement after 150,000 km.

Results show that seen over the different life stages of a passenger car, the trailer concepts outperform the 90 kWh EV's contributions for the discussed midpoint indicators. Compared to the petrol-fueled PHEV, both trailers are found to exceed the impact on POF and PMF by up to 15 percent, whereas this situation would be different if the PHEV would be based on diesel technology, given the impact during the latter's use phase. Concerning HT, results show that the higher the larger the batteries are dimensioned, the bigger the impact gets. Thus, the 40 kWh EV with a battery trailer performs significantly worse than the PHEV, while remaining a less toxic solution compared to the 90 kWh for offering the same range. For climate change, we see a clear benefit of driving all-electric most of the time with a modest battery capacity of 40 kWh, even when addressing a petrol-based range-extender. These life cycle results indicate the potential for substituting the internal combustion engine with an electrified powertrain, although there are limits to the sustainability of the selected battery pack size. Nonetheless, the results also indicate the need for cleaner battery technologies, as significant contributions to the discussed impact factors can be linked to the battery manufacturing process. In most cases, it is the impact of mining for specific metals that is expressed the most.

Next to the life cycle impact, we also addressed to the potential of electrifying powertrains on local air quality levels, which remain poor throughout Europe's cities. Therefore, a well-to-tank assessment for all emissions occurring within Belgium was presented. Thus, the significance of non-exhaust PM emissions are highlighted, as the mass penalty for large battery packs translates to a substantial impact on both PMF and HT. The petrol trailer was found to have a slightly worse impact locally, compared to the petrol PHEV, while performing significantly worse on POF when compared to the 90 kWh EV. This indicates the potential effect the substitution of combustion-based technologies in cities can have on local air quality.

The comparison of the PHEV, an EV with a large battery pack and an EV relying on in-range range modularity is relevant as our personal transportation system drastically needs to shift away from the monopoly of conventional internal combustion engine vehicles. This shift should be as durable as possible, which is why different midpoint indicators have been compared for the mentioned technologies. The specific impact of fast-chargers on the electricity grid has not been modeled for this exercise, although its potential cannot be neglected in case the recharging power is sourced from a durable source through energy storage locally. In the light of improving the presented model, more insights into the human toxicity impact of both the most recent conventional cars as in upcoming battery chemistries are important. Next, the inclusion of a diesel PHEV into the benchmark could indicate to what extent the 40 kWh EV + range-extender could be beneficial in terms of the impact on air quality, both locally and seen over the entire life cycle. Finally, this work could be complemented with a one-on-one comparison of the EV + trailer combination and the same EV relying on fast-chargers. For the latter, the focus should be expanded to the environmental impact of the uncontrolled demand for high-power during the charging session, while solutions must be sought to maximize the implementation of renewable energy, for instance by locating fast-chargers next to renewable power facilities. The presented paper aims to add to the potential of electric vehicles, by offering a solution bridging current technologies to future generations.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. LCI of a 30 kWh EV for the European electricity mix (276 g CO_2/kWh) (based on 46).

Midpoint Indicator	WTT		TTW				Vehicle Cycle			Powertrain Cycle							
	WTT	Public Charging Station	Tire Abrasion	Road Abrasion	Brake Abrasion	TTW	Body Shell	Lead Battery	Maintenance	Li Battery	Electric Motor	AC/DC Converter	DC/DC Converter	Onboard Charger	Catalytic Converter	Starter and Generator	Engine Control Unit
CC [kgCO_2/km]	4.14×10^{-2}	2.95×10^{-4}	0.00	0.00	0.00	0.00	1.30×10^{-2}	6.29×10^{-5}	1.52×10^{-3}	1.24×10^{-2}	1.19×10^{-3}	1.35×10^{-3}	5.08×10^{-4}	4.14×10^{-4}	0.00	0.00	0.00
POF [kgNMVOC/km]	2.68×10^{-5}	7.42×10^{-7}	0.00	0.00	0.00	0.00	4.08×10^{-5}	2.56×10^{-7}	4.94×10^{-6}	4.54×10^{-5}	4.68×10^{-6}	5.66×10^{-6}	1.99×10^{-6}	1.98×10^{-6}	0.00	0.00	0.00
PMF [kgPM_{10}/km]	5.83×10^{-6}	4.51×10^{-7}	7.05×10^{-6}	1.00×10^{-5}	2.46×10^{-6}	0.00	3.12×10^{-5}	1.91×10^{-7}	2.46×10^{-6}	3.16×10^{-5}	4.77×10^{-6}	3.21×10^{-6}	1.19×10^{-6}	1.07×10^{-6}	0.00	0.00	0.00
HT [kg1,4-DB/km]	2.03×10^{-4}	4.43×10^{-4}	6.37×10^{-4}	4.01×10^{-6}	7.35×10^{-4}	0.00	1.34×10^{-2}	3.03×10^{-4}	5.86×10^{-4}	8.22×10^{-3}	5.72×10^{-3}	6.12×10^{-3}	2.31×10^{-3}	1.97×10^{-3}	0.00	0.00	0.00

References

1. European Environment Agency (EEA). *Air Quality in Europe—2017 Report*; European Environment Agency: Copenhagen, Denmark, 2017.
2. European Environment Agency (EEA). National Emission Ceilings Directive Emissions Data Viewer—European Environment Agency. 2017. Available online: https://www.eea.europa.eu/data-and-maps/dashboards/necd-directive-data-viewer#tab-related-briefings (accessed on 31 October 2017).
3. Dieselnet. EU: Cars and Light Truck. 2016. Available online: https://www.dieselnet.com/standards/eu/ld.php (accessed on 6 May 2017).
4. Fontaras, G.; Franco, V.; Dilara, P.; Martini, G.; Manfredi, U. Development and review of Euro 5 passenger car emission factors based on experimental results over various driving cycles. *Sci. Total Environ.* **2014**, *468–469*, 1034–1042. [CrossRef] [PubMed]
5. Yang, L.; Franco, V.; Mock, P.; Kolke, R.; Zhang, S.; Wu, Y.; German, J. Experimental Assessment of NOx Emissions from 73 Euro 6 Diesel Passenger Cars. *Environ. Sci. Technol.* **2015**, *49*, 14409–14415. [CrossRef] [PubMed]
6. Weiss, M.; Bonnel, P.; Hummel, R.; Manfredi, U.; Colombo, R.; Lanappe, G.; Le Lijour, P.; Sculati, M. Analyzing on-road emissions of light-duty vehicles with Portable Emission Measurement Systems (PEMS). *Environ. Sci. Technol.* **2011**, *45*, 8575–8581. [CrossRef] [PubMed]
7. Demuynck, J. Real-driving emission results from GDI vehicles with and without a GPF Association for Emissions Control by Catalyst (AECC). In Proceedings of the IQPC 4th International Conference Advanced Emission Control Concepts for Gasoline Engines, Bonn, Germany, 10–12 May 2016; pp. 1–26.
8. Rhys-Tyler, G.; Legassick, W.; Bell, M. The significance of vehicle emissions standards for levels of exhaust pollution from light vehicles in an urban area. *Atmos. Environ.* **2011**, *45*, 3286–3293. [CrossRef]
9. Chen, Y.; Borken-Kleefeld, J. Real-driving emissions from cars and light commercial vehicles – Results from 13 years remote sensing at Zurich/CH. *Atmos. Environ.* **2014**, *88*, 157–164. [CrossRef]
10. Muncrief, R. *NOx Emissions from Heavy-Duty and Light-Duty Diesel Vehicles in the EU: Comparison of Real-World Performance and Current Type-Approval Requirements*; International Council on Clean Transportation: Washington, DC, USA, 2016.
11. Clima, D.G. *Revision of Regulation (EU) No 443/2009 and Regulation (EU) No 510/2011 Regulating CO2 Emissions from Light Duty Vehicles*; Brussels, Belgium, 2016. Available online: https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/docs/evaluation_ldv_co2_regs_en.pdf (accessed on 21 June 2018).
12. Díaz, S.; Tietge, U.; Mock, P. *CO_2 Emissions from New Passenger Cars in the EU: Car Manufacturers' Performance in 2015*; International Council on Clean Transportation: Berlin, Germany, 2015.
13. Massiani, J. Cost-Benefit Analysis of policies for the development of electric vehicles in Germany: Methods and results. *Transp. Policy* **2015**, *38*, 19–26. [CrossRef]
14. Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015 Addendum Part two: Action taken by the Conference of the Parties at its twenty-first session. In Proceedings of the 2015 United Nations Climate Change Conference, Paris, France, 30 November–12 December 2015.
15. Rockström, J.; Schellnhuber, H.J.; Hoskins, B.; Ramanathan, V.; Schlosser, P.; Brasseur, G.P.; Gaffney, O.; Nobre, C.; Meinshausen, M.; Rogelj, J.; et al. The world's biggest gamble. *Earth's Future* **2016**, *4*, 465–470. [CrossRef]
16. European Commission. *Roadmap to a Single European Transport Area—Towards a Competitive and Resource Efficient Transport System*; European Commission: Brussels, Belgium, 2011.
17. Messagie, M. *Life Cycle Analysis of the Climate Impact of Electric Vehicles*; Brussels, Belgium, 2017. Available online: https://evobservatory.iit.comillas.edu/publicaciones/life-cycle-analysis-of-the-climate-impact-of-electric-vehicles (accessed on 21 June 2018).
18. Sanfélix, J.; de la Rúa, C.; Schmidt, J.; Messagie, M.; van Mierlo, J. Environmental and economic performance of an Li-Ion battery pack: A multiregional input-output approach. *Energies* **2016**, *9*, 584. [CrossRef]
19. Umicore raises $1.1 bn to invest in cathode business. *Focus Catal.* **2018**, *2018*, 4.
20. European Commission. *Report on Raw Materials for Battery Applications*; SWD (2018) 245 Final; European Commission: Brussels, Belgium, 2018.

21. Witkamp, B.; van Gijlswijk, R.; Bolech, M.; Coosemans, T.; Hooftman, N. The Transition to a Zero Emission Vehicles Fleet for Cars in the EU by 2050; Brussels, Belgium, 2017. Available online: https://cris.vub.be/files/35220288/The_Transition_to_a_ZEV_car_fleet_EU_2050_an_EAFO_study.pdf (accessed on 21 June 2018).
22. Pearre, N.S.; Kempton, W.; Guensler, R.L.; Elango, V.V. Electric vehicles: How much range is required for a day's driving? *Transp. Res. Part C Emerg. Technol.* **2011**, *19*, 1171–1184. [CrossRef]
23. Needell, Z.A.; McNerney, J.; Chang, M.T.; Trancik, J.E. Potential for widespread electrification of personal vehicle travel in the United States. *Nat. Energy* **2016**, *1*, 16112. [CrossRef]
24. Pasaoglu, G.; Fiorello, D.; Martino, A.; Scarcella, G.; Alemanno, A.; Zubaryeva, A.; Thiel, C. *Driving and Parking Patterns of European Car Drivers: A Mobility Survey*; European Commission: Sevilla, Spain, 2012.
25. Corchero, C.; Gonzalez-Villafranca, S.; Sanmarti, M. European electric vehicle fleet: Driving and charging data analysis. In Proceedings of the 2014 IEEE International Electric Vehicle Conference (IEVC), Florence, Italy, 17–19 December 2014; pp. 1–6.
26. Khan, M.; Kockelman, K.M. Predicting the market potential of plug-in electric vehicles using multiday GPS data. *Energy Policy* **2012**, *46*, 225–233. [CrossRef]
27. Gonder, J.; Markel, T.; Thornton, M.; Simpson, A. Using Global Positioning System Travel Data to Assess Real-World Energy Use of Plug-In Hybrid Electric Vehicles. *Transp. Res. Rec. J. Transp. Res. Board* **2007**, *2017*, 26–32. [CrossRef]
28. Redelbach, M.; Özdemir, E.D.; Friedrich, H.E. Optimizing battery sizes of plug-in hybrid and extended range electric vehicles for different user types. *Energy Policy* **2014**, *73*, 158–168. [CrossRef]
29. Ligterink, N.; Smokers, R. *Monitoring Van Plug-In Hybride Voertuigen (PHEVs) April 2012 t/m Maart 2016*; TNO: Den Haag, The Netherlands, 2016.
30. Tietge, U.; Díaz, S.; Yang, Z.; Mock, P. *From Laboratory to Road International: A Comparison of Official and Real-World Fuel Consumption and CO2 Values for Passenger Cars in Europe, the United States, China, and Japan*; International Council on Clean Transportation: Berlin, Germany, 2017.
31. Björnsson, L.H.; Karlsson, S. Plug-in hybrid electric vehicles: How individual movement patterns affect battery requirements, the potential to replace conventional fuels, and economic viability. *Appl. Energy* **2015**, *143*, 336–347. [CrossRef]
32. Neubauer, J.; Brooker, A.; Wood, E. Sensitivity of plug-in hybrid electric vehicle economics to drive patterns, electric range, energy management, and charge strategies. *J. Power Sources* **2013**, *236*, 357–364. [CrossRef]
33. Norman Shiau, C.-S.; Samaras, C.; Hauffe, R.; Michalek, J.J. Impact of battery weight and charging patterns on the economic and environmental benefits of plug-in hybrid vehicles. *Energy Policy* **2009**, *37*, 2653–2663. [CrossRef]
34. Michalek, J.J.; Chester, M.; Jaramillo, P.; Samaras, C.; Shiau, C.-S.N.; Lave, L.B. Valuation of plug-in vehicle life-cycle air emissions and oil displacement benefits. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 16554–16558. [CrossRef] [PubMed]
35. Nordelöf, A.; Messagie, M.; Tillman, A.-M.; Söderman, M.L.; van Mierlo, J. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—What can we learn from life cycle assessment? *Int. J. Life Cycle Assess.* **2014**, *19*, 1866–1890. [CrossRef]
36. Rusich, A.; Danielis, R. Total cost of ownership, social lifecycle cost and energy consumption of various automotive technologies in Italy. *Res. Transp. Econ.* **2015**, *50*, 3–16. [CrossRef]
37. Al-Alawi, B.; Bradley, T. Total cost of ownership, payback, and consumer preference modeling of plug-in hybrid electric vehicles. *Appl. Energy* **2013**, *103*, 488–506. [CrossRef]
38. Propfe, B.; Redelbach, M.; Santini, D.J.; Friedrich, H. Cost analysis of Plug-in Hybrid Electric Vehicles including Maintenance & Repair Costs and Resale Values. In Proceedings of the EVS26 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, Los Angeles, CA, USA, 6–9 May 2012.
39. Wu, G.; Inderbitzin, A.; Bening, C. Total cost of ownership of electric vehicles compared to conventional vehicles: A probabilistic analysis and projection across market segments. *Energy Policy* **2015**, *80*, 196–214. [CrossRef]
40. ERTRAC. *Future Light and Heavy Duty ICE Powertrain Technologies*; ERTRAC: Brussels, Belgium, 2016.
41. Hooftman, N.; Oliveira, L.; Messagie, M.; Coosemans, T.; Van Mierlo, J. Environmental analysis of petrol, diesel and electric passenger cars in a Belgian urban setting. *Energies* **2016**, *9*, 84. [CrossRef]
42. Deb, S.; Tammi, K.; Kalita, K.; Mahanta, P. Impact of Electric Vehicle Charging Station Load on Distribution Network. *Energies* **2018**, *11*, 178. [CrossRef]

43. Meyer, D.; Wang, J. Integrating Ultra-Fast Charging Stations within the Power Grids of Smart Cities: A Review. *IET Smart Grid* **2018**, *1*, 3–10. [CrossRef]
44. European Comission for Standardization. *ISO 14040:2009—Environmental Management—Life Cycle Assessment—Principles and Framework*; European Comission for Standardization: Geneva, Switzerland, 2009.
45. International Organization for Standardization. *ISO 14044:2006 Environmental Management—Life Cycle Assessment—Requirements and Guidelines; International Organization for Standardization: Gevena, Switzerland, 2006.*
46. Messagie, M. *Environmental Performance of Electric Vehicles, a Life Cycle System Approach*; Vrije Universiteit Brussel: Brussels, Belgium, 2013.
47. US Department of Energy. Fuel Economy of New All-Electric Vehicles. Available online: http://www.fueleconomy.gov/feg/PowerSearch.do?action=alts&path=3&year1=2016&year2=2017&vtype=Electric&srchtyp=newAfv (accessed on 14 June 2017).
48. Goedkoop, M.; Heijungs, R.; Huijbregts, M.; de Schryver, A.; Struijs, J.; van Zelm, R. *A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level*; Amersfoort, The Netherlands, 2013. Available online: https://www.researchgate.net/publication/302559709_ReCiPE_2008_A_life_cycle_impact_assessment_method_which_comprises_harmonised_category_indicators_at_the_midpoint_and_the_endpoint_level (accessed on 21 June 2018).
49. Moro, A.; Lonza, L. Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles. *Transport. Res. Part D Transp. Environ.* **2017**. [CrossRef]
50. Oliveira, L.; Messagie, M.; Rangaraju, S.; Sanfelix, J.; Rivas, M.H.; van Mierlo, J. Key issues of lithium-ion batteries—From resource depletion to environmental performance indicators. *J. Clean. Prod.* **2015**, *108*, 354–362. [CrossRef]
51. Messagie, M.; Boureima, F.-S.; Coosemans, T.; Macharis, C.; Mierlo, J. A Range-Based Vehicle Life Cycle Assessment Incorporating Variability in the Environmental Assessment of Different Vehicle Technologies and Fuels. *Energies* **2014**, *7*, 1467–1482. [CrossRef]
52. Rangaraju, S.; de Vroey, L.; Messagie, M.; Mertens, J.; van Mierlo, J. Impacts of electricity mix, charging profile, and driving behavior on the emissions performance of battery electric vehicles: A Belgian case study. *Appl. Energy* **2015**, *148*, 496–505. [CrossRef]
53. CERAM. *Test Report N°16/10681*; CERAM: Montlhéry, France, 2017.