FABRIC

Feasibility analysis and development of on-road charging solutions for future electric vehicles

# Environmental life-cycle assessment and scenario analyses for achieving environmental targets

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|---|---|---|---|
| Deliverable No. | | D5.5.3 | |
| Workpackage No. | WP55 | Workpackage Title | Assessment of Business and Societal Consequences |
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| Status | | Final | |
| Dissemination level | | Public | |
| Project start date and duration | | 01 January 2014, 54 Months | |
| Revision date | | 18 December 2018 | |
| Submission date | | 21 December 2018 | |

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 605405

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

## LIST OF ABBREVIATIONS

| ABBREVIATION | DESCRIPTION |
|---|---|
| BEV | Battery Electric Vehicle |
| BS | Battery Shrinking |
| CED | Cumulative Energy Demand |
| DPT | Dynamic Power Transfer (conductive or wireless) |
| DWPT | Dynamic Wireless Power Transfer |
| DWPT-BS | Dynamic Wireless Power Transfer – Battery Shrink |
| DWPT-RE | Dynamic Wireless Power Transfer – Range Extend |
| Dx.x.x | Deliverable x.x.x |
| EER | Effective E-Range |
| EoL | End of Life |
| EV | Electric Vehicle |
| ICT | Information and Communication Technologies |
| LCA | Life Cycle Assessment |
| LCC | Life Cycle Costing |
| PEF | Primary Energy Factor |
| RE | Range Extend |
| TENT-T | Trans-European Networks - Transport |
| TTW | Tank-to-Wheel |
| UB | Urban Bus |
| WP | Work Package |
| WTT | Well-to-Tank |
| WTW | Well-to-Wheel |

# REVISION CHART AND HISTORY LOG

| REV | DATE | REASON |
|---|---|---|
| 0.1 | 1 May 2018 | Structure |
| 0.2 | 1 June 2018 | Complete draft |
| 1.0 | 20 June 2018 | Final version |
| 2.0 | 21 December 2018 | Revised according to EC reviewers' comments |

# EXECUTIVE SUMMARY

FABRIC project assessed the feasibility of Dynamic Wireless Power Transfer (DWPT) solutions for electric vehicles. The aim of the work presented in the deliverable at hand was to conduct a comprehensive environmental Life Cycle Assessment (LCA) of DWPT for EVs, in order to analyse the possible effects on Global Warming and Cumulative Energy Demand due to the introduction of DWPT.

Three scenarios have been selected as the most appropriate for the introduction of such technology. The motorway scenario consists of an e-Corridor exploited both by passenger cars and Heavy-duty vehicles, while the urban and periurban scenarios are meant for bus exploitation and HDV exploitation respectively. For each scenario, the effects by a Battery Electric Vehicle and a vehicle using DWPT recharging technology, in two options – battery shrink (BS) option and range extend (RE) – have been calculated.

Based on the assumptions and the results obtained as regards the system sublevels (vehicle side, grid, e-Road infrastructure) in previous FABRIC deliverables, this complete LCA synthesises all previous results in a complete system level analysis. As impact categories, Energy Demand and Global Warming are assessed, and the results are expressed in MJ/km and $CO_2$-eq/km.

Results show that for every scenario the three recharging options (BEV, DWPT – battery shrink, DWPT – range extended) present similar environmental impacts at system level. Considering the expected evolution of the European energy mix towards more renewable sources, the improvements in the lightweight materials used in the production of the vehicles and the increased energy density of the batteries, these impacts reduce with time.

# 1 INTRODUCTION

FABRIC project assessed the feasibility of Dynamic Wireless Power Transfer (DWPT) solutions for electric vehicles. Among others, the project has performed a series of analyses to assess the impact of such technologies on the road and grid infrastructure and the environment.

The aim of the work presented in the deliverable at hand was to conduct a comprehensive environmental Life Cycle Assessment (LCA) of DWPT for EVs specifically for vehicles, electricity production and e-Roads. It was difficult to obtain several detailed elements of the LCA needed for such a holistic assessment for a future technology, hence the analysis took into account the uncertainties behind the input assumptions.

This deliverable obtains the inputs from previous work packages and tasks, above all from D5.4.1 “Report on effect of upscaling to vehicle fleet and energy grids”, D5.5.2 “Cost benefit analysis and business models of large-scale deployment of on road charging” and D5.3.4 “Detailed LCA/LCC assessment of environment and cost impact of E-roads”.

Section 2 presents the methodology to conduct a complete LCA.

In section 3, the scenarios that have been identified by FABRIC as the most probable for the deployment of DWPT technology are presented and discussed. The main parameters and values useful for the environmental analysis are summarized in tables.

Sections 4, 5 and 6 report the assumptions and results as regards the vehicle impacts, the energy grid assumptions and the impacts of different e-Road structures for two FABRIC DWPT solutions respectively.

Section 7 synthesises all data in a complete system level analysis based on the assumptions and the results obtained as regards the sublevels (vehicle side, grid, e-Road infrastructure).

The results of the system level analysis are discussed in section 8.

# 2 COMPLETE LCA METHODOLOGY

LCA is a systemic tool to evaluate the environmental impact related to goods and services. It includes technical surveys of all product life cycle stages, from material acquisition and manufacturing to use and End-of-Life (EoL). Data are gathered for inflows and outflows at each stage. By linking processes within the system from cradle to grave, a model is made of how the flows are connected and influence each other. This results in an inventory of inflows to the system in terms of natural resources and outflows in terms of emissions to the surrounding natural system. The inventory is then analysed to indicate potential for environmental impacts in various categories, such as global warming, human toxicity, and acidification. (Nordelöf, Messagie et al. 2014).

The described system serves a specific function, and all the inflows and outflows are referred to the functional unit. A functional unit makes explicit the function of the system and it answers the questions what, how much, how well, and for how long the object of the study performs the function (Del Duce, Egede et al. 2013).

An example from (Klöpffer, Grahl 2014) explains the function and the functional unit of a beverage packaging:

> *“The function of a beverage packaging, for example, is – besides shielding of the liquid – above all, transportability and storability. The functional unit is most frequently defined as the provision of 1000 l liquid in a way to fulfil the technical aspects of the performance.”*

In the transport sector, the main service is to deliver persons or goods from one place to another. The functional unit is usually the distance travelled by the vehicle under certain driving conditions (driving cycle, number of passengers, auxiliary, climate...). The reference flow is typically 1 km travelled under specified conditions.

## 2.1 LCA in the transport sector

In LCAs of vehicles, the system can be structured in stages and subsystems. A simple and clear representation can be found in (Nordelöf, Messagie et al. 2014) (see Figure 1).

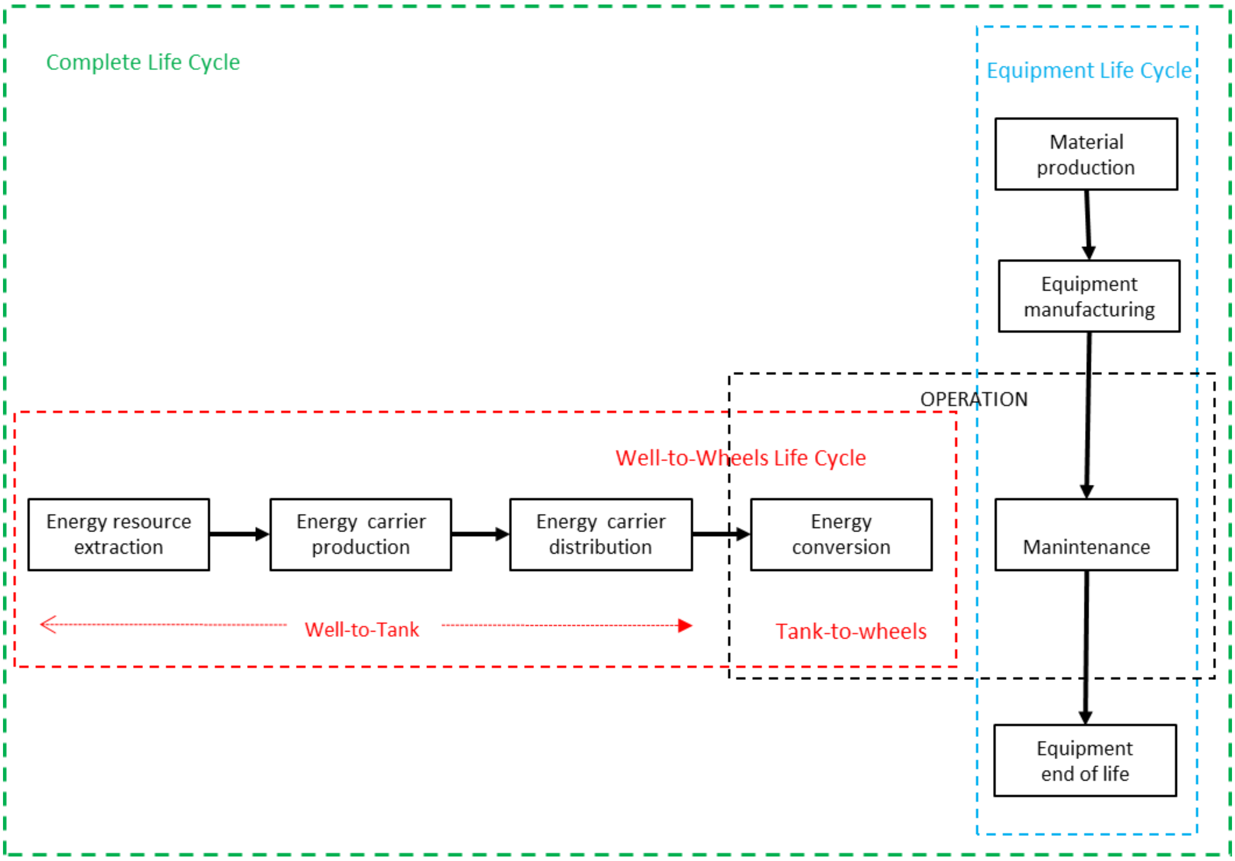


**Figure 1: Simplified view of the well-to-wheels and equipment flows (Nordelöf, Messagie et al. 2014).**

Well-to-Wheel (WTW) analyses consider consumption and emissions of the vehicle during its use and impacts related to the production/supply of the energy carrier used to propel them.

Well-to-Wheel (WTW) analyses are composed of two subparts: the Tank-to-Wheel (TTW) subsection which includes all the path of the energy carrier (electricity or fuel) from the tank (or the plug) to the wheels, and the Well-to-Tank (WTT) which includes the path of the energy carrier from its production to the tank (or plug) passing through the distribution.

The first Life Cycle Analyses were mostly WTW analyses, because of the alleged predominance of the use phase on the total life cycle of the vehicle.

With the introduction of electric vehicles and the impacting production of their batteries and the growing interest on impacts categories other than Global Warming, vehicle LCAs started to include also the Equipment Life Cycle (Production of the vehicle and its components, Maintenance and End of Life) leading to the so called Complete LCAs.

WTW studies are useful to present how efficiently energy carriers are converted to transportation work within different vehicle types. However, disregarding other phases of the vehicle life cycle, WTW analyses can lead to partial and misleading results: complete LCAs are more appropriate (Nordelöf, Messagie et al. 2014).

In this deliverable the structure of a classic Vehicle LCA (Figure 1) is kept, but a third subsystem is added, due to the specificity of the DWPT technology: the infrastructure (see Figure 2).

## 2.2 System boundary and functional unit

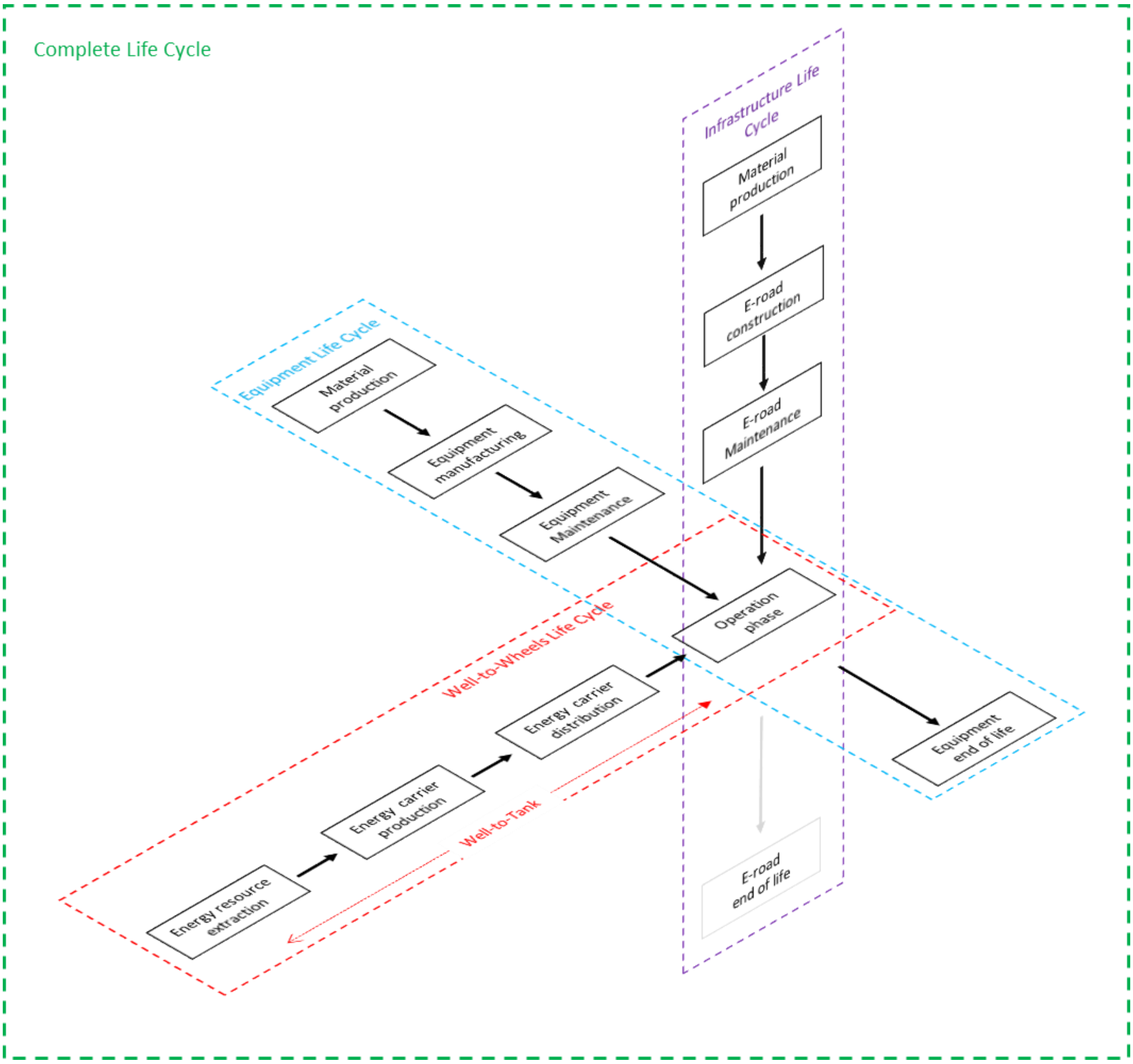


**Figure 2: System boundary.**

Figure 2 presents the system boundary applied in this deliverable. Infrastructure LCA has been described in detail in D5.4.3, while WTW and Equipment Life Cycle have been performed in this deliverable using input from D5.5.2.

Figure 2 shows that all the aspects of the transport sector contribute to the impacts of travelling from one place to another: in addition to emissions from the use of the vehicle, also the

manufacturing of the vehicle and the construction of the infrastructure contributes to the overall impacts.

The allocation of the impacts of vehicle manufacturing and infrastructure construction to the operation phase is a function of their lifetime and exploitation rate.

As discussed in D5.3.4, the End-of-Life of the e-Road has been disregarded in the analysis.

The functional unit used to express the impacts is the km travelled by the vehicle under certain driving conditions. The driving conditions are determined by the scenario and the type of vehicle.

## 2.3 Impact categories

According to the ISO standard definition, an impact category is:

> *"[a] class representing environmental issues of concern to which life cycle inventory analysis results may be assigned."*

Examples of impact categories are Global Warming, eutrophication, and human toxicity (the terms impact categories comprehend also resource use, e.g., land use and resource depletion).

Emissions contributing to the same type of environmental effect are aggregated into one indicator per each impact category. An example of indicator is "kg of $CO_2$-eq per functional unit" for the impact category Global Warming.

In this deliverable the assessed impact categories are:

- Global Warming (indicator kg of $CO_2$-eq per functional unit);
- Cumulative Energy Demand (indicator MJ per functional unit).

# 3 SCENARIOS CONSIDERED

D5.3.4 identified three scenarios as most likely to occur in the near future in relation to DWPT. The assumptions in D5.3.4 and D5.5.2 are used in the present deliverable, to reach a rough vision of the required needs in case the expected deployment process occurs. The selected scenarios are the following:

1. **Motorway Scenario**. In 2030, are expected dedicated external lanes (**e-Corridors**) of 25 km length (in both directions) for light and heavy electric-vehicles dynamic charging in the most congested motorways between two spots at about 400 to 600 km and providing a range extension of 10% to 20%. The TEN-T infrastructure (larger motorways with 3 to 4 lanes per direction) will be the most appropriate for the e-Corridors set up. In 2050, the expertise gained along 20 years will lead to use one of the motorway lanes instead of one constructed externally, thus reducing costs.
2. **Periurban Scenario**. Dynamic charging of heavy vehicles in areas with high density of traffic, from periurban logistic centres, ports, etc. to the city centre or among close cities, travelling a daily distance of around 250 km with e-Corridors of 10 km length (named here as **e-Launchers** due to its short extension).
3. **Urban Scenario**. This will likely be the first entry point in 2030 using bus stops as static charging points and some trenches ahead summing up 25 m for dynamic charging (**e-Trenches**). Cities with trolley lanes will be easily adaptable for dynamic charging if the number of e-buses is sufficient to justify the infrastructure investment.

According to D5.5.2, the deployment process will be as follows for a given very congested motorway with a daily traffic (AADT) per lane of 18.000 vehicles.

**Table 1: Main assumptions for a given congested motorway where an e-Corridor will be placed (D5.5.2).**

| ASSUMPTIONS FOR THE MOTORWAY TRAFFIC | No. | Unit |
|---|---|---|
| Length e-corridors | 25 | km |
| Daily Traffic per lane in selected motorways (ADDT) | 18,000 | units |
| Number of lanes | 3 | units |
| Total number of daily traffic | 54,000 | units |
| Light vehicles | 88 | % |
| Total number of daily light vehicles | 47,520 | units |
| Total number of daily light vehicles/lane | 15,840 | units |
| Heavy vehicles | 12 | % |
| Total number of daily heavy vehicles | 6,480 | units |
| Total number of daily heavy vehicles/lane | 2,160 | units |

In Table 2, the expected number of EVs (light and heavy) crossing and charging at the e-Corridors in 2030, 2040 and 2050 are shown. Note that the number of e-Corridors in motorways in the last line of the table refers to number of units installed in each decade (2020-2030, 2030-2040 and 2040-2050), summing up to a total of 32 e-Corridors by 2050.

**Table 2: Deployment forecast in motorway scenario (e-Corridors) (D5.5.2).**

| | | BASIC SCENARIO (without e-Corridors) | | | | | | FABRIC SCENARIO (with e-Corridors) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **LIGHT VEHICLES IN MOTORWAYS** | **2,030** | | **2,040** | | **2,050** | | **2,030** | | **2,040** | | **2,050** | |
| 1 | Percentage of fleet that it is electric | 25 | % | 44 | % | 58 | % | 25 | % | 44 | % | 58 | % |
| | *Light EVs* | 11,880 | units | 20,909 | units | 27,372 | units | 11,880 | units | 20,909 | units | 27,372 | units/day |
| 2 | Nº electric vehicles that use motorways | 50 | % | 60 | % | 70 | % | 70 | % | 80 | % | 100 | % |
| | *Light EVs in motorways* | 5,940 | units | 12,545 | units | 19,160 | units | 8,316 | units | 16,727 | units | 27,372 | units/day |
| 3. | No. Of light EVs equiped with WPT (dynamic charging) | 0 | % | 0 | % | 0 | % | 60 | % | 75 | % | 100 | % |
| | *Light EVs-WPT in motorways* | 0 | units | 0 | units | 0 | units | 4,990 | units | 12,545 | units | 27,372 | units/day |
| 3 | Users that recharge in motorway superchargers | 20 | % | 20 | % | 20 | % | 20 | % | 30 | % | 40 | % |
| | *Light EVs charging in supercharger in motorways* | 1,188 | units | 2,509 | units | 3,832 | units | 1,663 | units | 5,018 | units | 10,949 | units/day |
| 4 | Users that recharge in motorway e-corridors | | | | | | | 10 | % | 20 | % | 30 | % |
| | *Light Evs-WPT charging in e-corridors in motorways* | | | | | | | 832 | units | 3,345 | units | 8,211 | units/day |
| | % of users charging in e-corridors/EVs equiped with WPT | | | | | | | 17 | % | 27 | % | 30 | % |
| | **HEAVY VEHICLES IN MOTORWAYS** | **2,030** | | **2,040** | | **2,050** | | **2,030** | | **2,040** | | **2,050** | |
| 5 | Percentage of fleet that it is electric | 25 | % | 44 | % | 58 | % | 25 | % | 44 | % | 58 | % |
| | *e-HDVs* | 1,620 | units | 2,851 | units | 3,732 | units | 1,620 | units | 2,851 | units | 3,732 | units/day |
| 6 | Nº electric heavy vehicles that use motorways | 10 | % | 20 | % | 30 | % | 30 | % | 60 | % | 100 | % |
| | *e-HDVs in motorways* | 162 | units | 570 | units | 1,120 | units | 486 | units | 1,711 | units | 3,732 | units/day |
| 7 | No. Of e-HDV equiped with WPT (dynamic charging) | 0 | % | 0 | % | 0 | % | 60 | % | 75 | % | 100 | % |
| | *e-HDVs-WPT in motorways* | 0 | units | 0 | units | 0 | units | 292 | units | 1,283 | units | 3,732 | units/day |
| 8 | Users that recharge in motorway superchargers | 20 | % | 20 | % | 20 | % | 20 | % | 30 | % | 40 | % |
| | *e-HDV charging in supercharger in motorways* | 32 | units | 114 | units | 224 | units | 97 | units | 513 | units | 1,493 | units/day |
| 9 | Users that recharge in motorway e-corridors | | | | | | | 10 | % | 20 | % | 30 | % |
| | *e-HDV charging in e-corridors in motorways* | | | | | | | 49 | units | 342 | units | 1,120 | units/day |
| | % of users charging in e-corridors/EVs equiped with WPT | | | | | | | 17 | % | 27 | % | 30 | % |
| 10 | Nº of e-corridors in motorways | 0 | units | 0 | units | 0 | units | 10 | units | 10 | units | 12 | units |

The assumptions done in D5.5.2 are that all EVs in 2030 will have the possibility of static/stationary wireless charging and will have autonomous driving features which will help avoiding misaligning. As a result, an average 80% of DWPT efficiency will be achieved (D5.5.2).

The same exercise was done in D5.5.2 for the periurban scenario. It applies only to heavy vehicles in motorways close to cities with a reduced e-Corridor length of 10 km (e-Launcher). The assumption here is that the drivers of such vehicles will be mostly professionals (service companies) and the price of electricity will be cheaper (no taxes and VAT). Therefore, the business model is more positive, and the number of e-Launchers will be higher (400). In Table 3 the deployment forecast for the periurban case (e-Launchers) is shown. Similar to the motorway case, the number of e-Launchers (last line of the table) refers to the number of units installed in each decade, summing up to 400 e-Launchers by 2050.

**Table 3: Deployment forecast in periurban scenario (e-Launchers) (D5.5.2).**

| | BASIC SCENARIO (without e-Launchers) | | | | | | FABRIC SCENARIO (with e-Launchers) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **PERIURBAN HEAVY VEHICLES** | **2,030** | | **2,040** | | **2,050** | | **2,030** | | **2,040** | | **2,050** | |
| Percentage of fleet that it is electric | 25 | % | 44 | % | 58 | % | 25 | % | 44 | % | 58 | % |
| *e-HDVs* | 1,620 | units | 2,851 | units | 3,732 | units | 1,620 | units | 2,851 | units | 3,732 | units/day |
| Nº e-HDV that moves in urban and periurban areas | 100 | % | 100 | % | 100 | % | 100 | % | 100 | % | 100 | % |
| *e-HDVs in periurban areas* | 1,620 | units | 2,851 | units | 3,732 | units | 1,620 | units | 2,851 | units | 3,732 | units/day |
| No. Of light EVs equiped with DWPT (dynamic charging) | 0 | % | 0 | % | 0 | % | 60 | % | 75 | % | 100 | % |
| *e-HDVs-DWPT in periurban areas* | 0 | units | 0 | units | 0 | units | 972 | units | 2,138 | units | 3,732 | units/day |
| e-HDV Users recharging in headquarters or urban static c | 100 | % | 100 | % | 100 | % | 100 | % | 100 | % | 100 | % |
| *e-HDV charging in supercharger in headquarters* | 1,620 | units | 2,851 | units | 3,732 | units | 1,620 | units | 2,851 | units | 3,732 | units/day |
| e-HDVs users that recharge in periurban e-launchers | | | | | | | 50 | % | 62 | % | 83 | % |
| *e-HDV charging in e-launchers in periurban* | | | | | | | 810 | units | 1,768 | units | 3,098 | units/day |
| % of users charging in e-launchers/e-HDV equiped with WPT | | | | | | | 83 | % | 83 | % | 83 | % |
| Nº of e-Launchers in periurban areas | 0 | units | 0 | units | 0 | units | 80 | units | 120 | units | 200 | units |

Regarding the urban scenario, applied to public bus fleets, the conclusions in D5.5.2 point out that it is the most positive, if the considered assumptions are fulfilled. The figures show that converting the whole fleet to DWPT e-buses, considering 25 m of static and dynamic charging at each bus stop, 18 round trips and 972 bus stops in total, the system shall be sustainable at a cost equivalent to using a conventional bus fleet. In Table 4 the deployment forecast for the urban scenario is shown. As in the two scenarios above, the number of cities with DWPT bus systems (last line of the table) refers to the number of systems installed in each decade, summing up to 200 cities in 2050.

**Table 4: Deployment forecast in urban scenario (e-trenches) (D5.5.2).**

| URBAN SCENARIO (CITY BUSES) | BASIC SCENARIO (without e-trenches) | | | | | | FABRIC SCENARIO (with e-trenches) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2,030 | | 2,040 | | 2,050 | | 2,030 | | 2,040 | | 2,050 | |
| Case study (200,000 inhabitants city). Nº buses | 400 | units | 400 | units | 400 | units | 400 | units | 400 | units | 400 | units |
| Conventional urban buses | 200 | units | 100 | units | 0 | units | 100 | units | 50 | units | 0 | units |
| No e-buses | 200 | units | 300 | units | 400 | units | 300 | units | 350 | units | 400 | units |
| Nº e-buses equipped with DWPT | | | | | | | 300 | units | 350 | units | 400 | units |
| Nº km of static/dynamic charging (25 m per bus stop * 1.080 stops) | | | | | | | 27.0 | km | 27.0 | km | 27.0 | km |
| Nº of e-buses charging in one e-trench per day (40 routes) | | | | | | | 135 | units | 158 | units | 180 | units |
| Nº of cities with dynamic/static charging at bus stops. | | | | | | | 40 | units | 60 | units | 100 | units |

The urban scenario will have its best application in those cities with tramways or trolley buses in operation, as electricity at suitable power levels will be available close to the bus stops. In 2017 the number of EU cities with tramways reached 280, according to a recent press release from “Ecologistas en acción” (Ecologistas en Acción 2010). We consider 200 of those cities as a possible scenario for the penetration of DWPT e-buses, with 40 in 2030, additional 60 in 2040 and finally, 100 more in 2040.

D5.5.2 concludes that only in 2050, with a critical mass of EVs on the road, the dynamic charging framework will be economically sustainable. Before that, some incentives from governments will be required. It is considered that end-users will be willing to pay for DWPT for the purpose of calculating the electricity requirements in the best case. The next tables summarise the main assumptions presented above.

Table 5: Total daily DWPT EVs using e-Corridors, e-Launchers and e-Trenches in Europe (D5.5.2).

| Daily Vehicles (AADT*Nº E-Roads) | 2,030 | 2,040 | 2,050 |
|---|---|---|---|
| **MOTORWAYS** | | | |
| Nº. E-Corridors | 10 | 10 | 12 |
| DWPT-Light Vehicles (AADT) | 832 | 3,345 | 8,211 |
| DWPT-Heavy vehicles (AADT) | 49 | 342 | 1,120 |
| **TOTAL MOTORWAYS IN EUROPE** | **8,802** | **36,876** | **111,974** |
| | | | |
| **PERIURBAN** | | | |
| Nº. E-Launchers | 80 | 120 | 200 |
| DWPT-Heavy vehicles (AADT) | 810 | 1,768 | 3,098 |
| **TOTAL PERIURBAN IN EUROPE** | **64,800** | **212,129** | **619,592** |

AADT. Annual Average Daily vehicles per lane

| URBAN (Cumulative) | 2,030 | 2,040 | 2,050 |
|---|---|---|---|
| No. Cities with E-Trenches | 40 | 60 | 100 |
| Daily DWPT e-Buses in operation per city | 300 | 350 | 400 |
| **TOTAL URBAN Daily e-buses** | **12,000** | **21,000** | **40,000** |

Table 6: Total forecast for e-Roads (e-Corridors, e-Launchers and e-Trenches) (D5.5.2).

| E-Roads | 2,030 | 2,040 | 2,050 | TOTAL |
|---|---|---|---|---|
| **MOTORWAYS** | 10 | 10 | 12 | 32 |
| **PERIURBAN** | 80 | 120 | 200 | 400 |
| **URBAN** | 40 | 60 | 100 | 200 |
| TOTAL | 130 | 190 | 312 | 632 |

# 4 VEHICLES IMPACT CALCULATIONS

Similar to D5.4.1 three vehicle typologies have been considered in the analysis: an individual passenger car (SUV), an urban bus (Bus) and a Heavy-Duty Vehicle (HDV) used for freight logistics.

Two charging technologies are compared for each vehicle class: the traditional Battery Electric Vehicle (BEV) and the Dynamic Wireless Power Transfer Electric Vehicle (DWPT-EV or, shortly, DWPT). The DWPT-EV solution is equipped with a Wireless Power Transfer (WPT) system that allows the vehicle to receive energy from a dedicated electrified road (e-Road). The DWPT-EV can receive additional energy from the infrastructure while driving. There are two options to manage this energy content:

1. Range Extend: the received energy increases the EER (effective e-range), i.e., the distance that the EV can cover between two consecutive static charging sessions, in a proportional way to the actual Vehicle Energy Consumption. This solution is referred to as DWPT-RE.
2. Battery Shrink: the received energy reduces the need for a big battery, so a smaller battery can be used while maintaining a given EER. This solution is referred to as DWPT-BS.

The analysis in this deliverable conducts a system-level environmental LCA for DWPT-EV with respect to the BEV solution.

## 4.1 Vehicle production impacts

Due to the relevance of the battery production, in the following section is described only the impact of the vehicle production, (without the battery); impacts related to the battery production are presented in section 4.2.

For the impacts due to the vehicles' production, the datasets from the EcoInvent database have been used as starting point. The datasets have then been scaled to the weight of the vehicle considered for the simulation during the use phase.

The vehicle structure and the mass are expected to change significantly in the next decades: light-weighting is considered a means of improving vehicles' energy efficiency and overall $CO_2$-

eq emissions. These aspects have been considered in the simulation as well, where the average weight of the various vehicles is decreased according to the scenario year (2030, 2050). Weights are listed in Table 13. The expected reduction has been derived from (Federation Internationale de l'automobile ) and (Ricardo-AEA 2015).

Along with the weights of the vehicles, also the material composition is expected to change. To consider this aspect, the datasets from the EcoInvent database have been updated to better reflect the share between composite materials and metals in the vehicles in the future scenarios.

In the following paragraphs, the evaluation of the impact for the production of the vehicles has been analysed for each vehicle typology (passenger cars – SUVs –, heavy duty trucks – HDVs –, buses).

### 4.1.1 Passenger cars

In D5.4.1 a Sport Utility Vehicle (SUV) has been selected to represent an individual passenger car. For the passenger cars the following dataset has been used as a starting point of the analysis:

- Passenger car, electric, without battery {GLO}| production | Cut-off, U (of project EcoInvent 3 - allocation, cut-off by classification - unit) for models BEV, DWPT-BS, DWPT-RE.

As mentioned, the impacts, expressed in g $CO_2$-eq per kg of vehicle, are multiplied by the mass of the vehicles which is decreasing in the future years as shown in Table 13.

For the vehicle composition in future scenarios, some literature review has been done. VTO 2016 (Vehicle Technology Office 2016) showed the potential of materials as advanced high strength steel, aluminium, carbon fibre reinforced plastic (CFRP) and magnesium for weight reduction in automotive applications. High strength steel (HSS) and aluminium have seen a constant increase in light duty vehicles, and their use is expected to increase even faster in future generation vehicles. Meanwhile, the content of magnesium and CFRP in LDV is expected to increase in the next decades. A study by Dai, Kelly and Elgowainy (Dai, Kelly et al. 2016)

analysed the evolution in LDV material composition during the years and presented some projections at 2025 (EPA studied models for 2017-2020, NHTSA 2017-2025) and 2030.

The expected reduction of the LDV in the FABRIC project is 11% in 2030 compared to the average weight in 2018 (average weights in 2018 are listed in Table 13) and 28% in 2050.

The new composition has derived from the lightweight design developed by Vehma International and Ford motor Company.

The total weights and material compositions of all the aforementioned lightweight designs, together with those of the corresponding baseline vehicles, are shown in Figure 3.

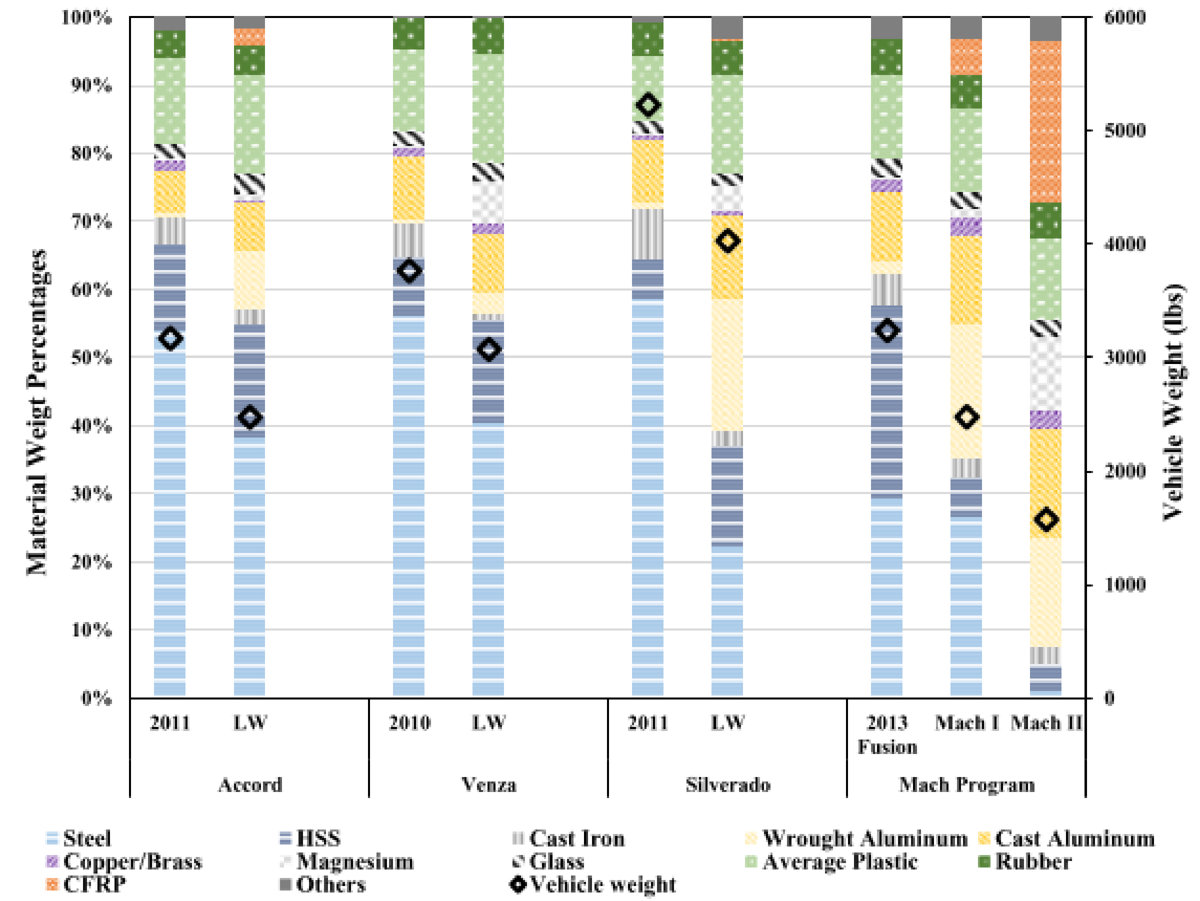


**Figure 3: Weights and material compositions of lightweight designs and their baseline vehicles (Dai et al. 2016).**

The case Venza by EPA (see Figure 3) achieves almost the same weight reduction in percentage as the reduction between reference 2018 case and 2030. The reduction is achieved

mainly by reducing the amount of steel and cast iron and increasing HSS, plastic and Magnesium. Following these indications, the material composition of the glider in the EcoInvent dataset (Glider, passenger car {GLO}| market for | Cut-off, U) has been modified.

Table 7: Material Composition of the glider in 2030 and 2050.

| Material Composition of the vehicle in 2030 and 2050 | Percentage |
|---|---|
| **Steel and HSS** | 55% |
| **Cast Iron** | 2% |
| **Wrought Aluminium** | 3% |
| **Cast Aluminium** | 8% |
| **Copper Brass** | 2% |
| **Magnesium** | 6% |
| **Glass** | 3% |
| **Average Plastic** | 15% |
| **Rubber** | 6% |

Since the materials and manufacturing processes of the EcoInvent dataset are more detailed than the classification in Dai, Kelly and Elgowainy (Dai, Kelly et al. 2016), the shares within the same category has been kept the same as the original EcoInvent dataset, as well as information regarding manufacturing and processing wastes.

No reliable projection on composition at 2050 are available, thus the composition has been kept constant as the one in 2030, while the overall weight of the vehicle is decreased.

As illustrated in section 4.3, the way in which electricity is produced in Europe is expected to change through a more decarbonised scenario. This aspect will affect every manufacturing process in Europe, and also car manufacturing. The electricity mix used for the manufacturing processes of the vehicles in Europe has been changed. However, since the production occurs at a global level, the change in the electricity mix has negligible effect on a global production.

In Table 8 is reported the characteristic of the vehicle and the impact due to its production in 2030 and 2050.

Table 8: Impacts of the production of a passenger car (SUV).

| Vehicle | Charging Technology | Vehicle weight (without Battery) [kg] | Global Warming IPCC 100 y [kg CO2-eq/SUV] | Cumulative Energy Demand [MJ/SUV] |
|---|---|---|---|---|
| **$SUV_{2030}$** | BEV | 1,680 | 18,444,048 | 207,633 |
| | DWPT-RE | 1,740 | 19,102,835 | 215,050 |

| | | | | |
|---|---|---|---|---|
| | DWPT-BS | 1,740 | 19,102,835 | 215,050 |
| **$SUV_{2050}$** | BEV | 1,680 | 15,693,780 | 176,721 |
| | DWPT-RE | 1,740 | 16,350,735 | 184,118 |
| | DWPT-BS | 1,740 | 16,350,735 | 184,118 |

The difference in the three configurations is only due to the different weight, since the glider has the same material composition for the three configurations. The impacts due to vehicle production are the same in 2030 and 2050 (at least in the first decimal digit), since the different European energy mix considered in the manufacturing process has negligible influence at the global production level.

### 4.1.2 Heavy duty vehicles

The considered HDV features a weight of about 15 t. The counterpart in the EcoInvent Database is 'lorry size class 16t-22t' (which is based on the Volvo FH Environmental Product Declaration for the material composition), thus the dataset used is the following:

- Lorry, 16 metric ton {RER}| production | Cut-off, U (of project EcoInvent 3 - allocation, cut-off by classification - unit).

This dataset expresses the impacts of production of one lorry 16 t weight. The results are scaled to the weight used in the use phase simulations.

Since the only type of lorry in EcoInvent is the diesel, for the electric one it is assumed the same glider as the diesel, the value is so scaled to the weight of the electric HDV without battery and engine. To this, the impacts from the production of the electric motor and the batteries will be added.

For the composition expected at 2030 and 2050 the study by Ricardo-AEA 2015 (Ricardo-AEA 2015) has been considered. Among the strategy to reduce the vehicle weight at 2030 it suggests:

> *"Technologies that could be applied for mass-deployment in the medium-term (up to 2030): The options available here include stronger light weighting, mainly through material substitution of iron and steel by advanced high-strength steel and aluminium/magnesium for various components, as well as additional use of some composite materials. This scenario reflects a*

*combination of (i) state-of-the-art measures which currently have seen some uptake on specialist vehicles such as lightweight city buses and lightweight tipper/tanker trucks, and (ii) those that are not yet applied but are expected to be ready for mass-deployment before 2030."*

The composition of the EcoInvent dataset has been modified in order to reach the mass reduction from 16,097 kg in 2018 to 12,940 kg in 2030, shifting from iron and steel to aluminium (see Table 9).

For the production in 2050 the suggested technologies are:

*"Technologies that could be applied for mass-deployment in the long-term (up to 2050): The options available here primarily include much greater levels of material substitution with fibre composites replacing metals for structural elements, the body and smaller components. At present, the measures presented in this scenario have only been applied to HDVs at a prototype stage."*

The share of materials has been then modified in favour of composites materials in order to reach an additional weight reduction of 7% (from 12,940 to 12,065 kg) in Table 13.

**Table 9: Material Composition of HDVs in EcoInvent Dataset and in projection at 2030 and 2050.**

| | EcoInvent dataset | 2030 | 2050 |
|---|---|---|---|
| Steel and HSS | 35% | 28% | 27% |
| Cast Iron | 22% | 18% | 17% |
| Wrought Aluminium | 2% | 11% | 11% |
| Cast Aluminium | 1% | 5% | 5% |
| Copper Brass | 1% | 1% | 1% |
| Iron | 25% | 20% | 19% |
| Glass | 1% | 1% | 1% |
| Average Plastic | 4% | 4% | 6% |
| Rubber | 6% | 7% | 8% |
| Others | 4% | 5% | 5% |

In Table 10 are reported the characteristic of the HDVs and the impact due to their production in 2030 and 2050.

Table 10: Impacts of the production of a HDV in 2030 and 2050.

| Vehicle | Charging Technology | Vehicle weight (without Battery) [kg] | Global Warming IPCC 100 y [kg CO2-eq/HDV] | Cumulative Energy Demand [MJ/HDV] |
|---|---|---|---|---|
| **$HDV_{2030}$** | BEV | 12,940 | 66,310,947 | 782,884 |
| | DWPT-RE | 13,144 | 67,352,212 | 795,177 |
| | DWPT-BS | 13,144 | 67,352,212 | 795,177 |
| **$HDV_{2050}$** | BEV | 12,065 | 60,213,185 | 729,147 |
| | DWPT-RE | 12,269 | 61,227,268 | 741,427 |
| | DWPT-BS | 12,269 | 61,227,268 | 741,427 |

The difference in the three configurations is only due to the different weight, since the glider has the same material composition for the three configurations. The vehicle production reduces slightly through the years, both for the effect of a decreased vehicle weight, but also because in 2050 a higher contribution of polymers is expected at the expense of steel and iron, whose production per kg is significantly higher in terms of $CO_2$-equivalent emissions and energy consumption compared to polymers.

### 4.1.3 Buses

The buses analysed have been modelled using the following EcoInvent dataset:

- "Bus {RER}| production | Cut-off, U" (of project EcoInvent 3 - allocation, cut-off by classification - unit).

Since no information is available on the changings in material composition of buses in the next decades, the same changes in percentage of the heavy-duty vehicle have been applied (see Table 9), and the electricity used for the manufacturing has been updated with the data for 2030 and 2050.

In Table 11 are reported the characteristic of the buses and the impact due to their production in 2030 and 2050.

Table 11: Impacts of the production of a bus in 2030 and 2050.

| Vehicle | Charging Technology | Vehicle weight (without Battery) | Global Warming IPCC 100 y | Cumulative Energy Demand |
|---|---|---|---|---|

| | | [kg] | [kg CO2-eq/Bus] | [MJ/Bus] |
|---|---|---|---|---|
| **$Bus_{2030}$** | BEV | 13,152 | 57,974,056 | 670,924 |
| | DWPT-BS | 13,352 | 58,854,789 | 681,116 |
| **$Bus_{2050}$** | BEV | 11,654 | 50,029,758 | 593,854 |
| | DWPT-BS | 11,854 | 50,887,499 | 604,035 |

The difference in the three configurations is only due to the different weight, since the glider has the same material composition for the two configurations. Since the materials composition has been modelled following the composition changes made for the HDV, the same considerations apply: the production reduces slightly through the years, not only because of the effect of the decreased weight, but also because of the higher contribution of polymers at the expense of steel and iron.

## 4.2 Battery production impacts

Due to the relevance of the battery production, the weights of the vehicles have been disaggregated into "Vehicle without battery" and "battery", in order to model the battery production as a separate component and show its share of impact in the final results. Impacts from battery production are reported as a separate entry contributing to the final overall impact of the vehicle.

The batteries considered during the simulation of the use phase are lithium-ion batteries. To be coherent with the simulations, the dataset used to model the impacts from battery productions is:

- "Battery, Li-ion, rechargeable, prismatic {GLO}| production | Cut-off, U" (of project EcoInvent 3 - allocation, cut-off by classification - unit).

In Table 13 are reported the battery masses estimated at 2030 and 2050 for the different vehicle typology and charging configuration. To estimate the battery masses the simulation model described in D5.4.1 has been used. Among various outputs, the model defines the Battery Energy Storage required at the battery in order to satisfy the range required.

The battery masses calculated in D5.4.1 are reported in Table 13. They represent the masses in the reference year 2018. In 2030 and 2050 the battery mass is expected to decrease because of the reduced vehicles weight (as mentioned in section 4.1) and the increased energy density of the batteries. The vehicle weight of the reference year and the ones expected in 2030

and 2050 are listed in Table 13. The battery energy density used in the reference year presented in D5.4.1 was 240 Wh/kg; for 2030 and 2050 the energy density is assumed to be 450 Wh/kg and 600 Wh/kg respectively, in line with the expectation from the fourth generation of li-ion batteries expected at 2030 ((Meeus 2018) and private communication). These assumptions lead to a battery weight reduction of 37%, in 2030 compared to the reference year and of the 61% in 2050.

For details on the simulation model refer to D5.4.1.

In Table 12 are listed the weights of the batteries calculated with the simulation model and the impacts due to their production.

**Table 12: Impacts of the production of Lithium-ion batteries.**

| | 2030 | | | 2050 | | |
|---|---|---|---|---|---|---|
| | battery weight | g $CO_2$-eq | MJ | battery weight [kg] | g $CO_2$-eq | MJ |
| **Battery production of the SUV BEV** | 198 | 1,711,710 | 18,012 | 149 | 1,711,710 | 18,012 |
| **Battery production of the SUV DWPT-RE** | 169 | 1,461,005 | 15,373 | 128 | 1,461,005 | 15,373 |
| **Battery production of the SUV DWPT-BS** | 198 | 1,711,710 | 18,012 | 149 | 1,711,710 | 18,012 |
| **Battery production of the HDV BEV** | 1,358 | 11,744,018 | 123,580 | 863 | 7,460,635 | 78,507 |
| **Battery production of the HDV-RE** | 1,314 | 11,363,155 | 119,572 | 835 | 7,218,575 | 75,959 |
| **Battery production of the HDV-BS** | 1,358 | 11,745,979 | 123,601 | 863 | 7,460,635 | 78,507 |
| **Battery production of the BUS BEV** | 1,145 | 1,430,747 | 15,055 | 727 | 6,284,915 | 66,135 |
| **Battery production of the BUS DWPT-BS** | 118 | 608,398 | 6,402 | 75 | 648,375 | 6,822 |

The impact of the production of the batteries is linear with the reduction of its mass in the different charging technology and years. As for the vehicle production the battery production is assumed to happen worldwide, thus also in this case the European energy mix modelled for 2030 and 2050 plays a negligible role in the battery production; then, the effect is not even visible in the impact of the battery production.

Table 13: Vehicles' and batteries' weights in 2030, 2050 and 2018 (reference year).

| Vehicle | Charging technology | Vehicle mass 2030 [kg] | Battery mass 2030 [kg] | Vehicle mass without battery 2030 [kg] | Vehicle mass 2050 [kg] | Battery mass 2050 [kg] | Vehicle mass without battery 2050 [kg] | Vehicle mass 2018 (reference Year) [kg] | Vehicle mass without battery 2018 (reference Year) [kg] | Battery mass 2018 (reference year) [kg] |
|---|---|---|---|---|---|---|---|---|---|---|
| SUV | BEV | 1,915 | 235 | 1'680 | 1,582.61 | 149.29 | 1,433.32 | 2,212 | 1,839 | 373 |
| | DWPT-RE | 1,975 | 235 | 1,740 | 1,642.61 | 149.29 | 1,493.32 | | | |
| | DWPT-BS | 1,941 | 201 | 1,740 | 1,621.16 | 127.84 | 1,493.32 | | | |
| HDV | BEV | 14,299 | 1,358 | 12,940 | 12,927.92 | 862.52 | 12,065.40 | 16,097 | 13,941 | 2,156 |
| | DWPT-RE | 14,502 | 1,359 | 13,144 | 13,131.27 | 862.67 | 12,268.60 | | | |
| | DWPT-BS | 14,458 | 1,314 | 13,144 | 13,103.15 | 834.55 | 12,268.60 | | | |
| BUS | BEV | 14,297 | 1,146 | 13,152 | 12,381.11 | 727.31 | 11,653.80 | 16,682 | 14,864 | 1,818 |
| | DWPT-RE | 14,497 | 1,146 | 13,352 | 12,581.12 | 727.52 | 11,853.60 | | | |
| | DWPT-BS | 13,470 | 119 | 13,352 | 11,928.84 | 75.24 | 11,853.60 | | | |

### 4.3 Vehicle operation impacts

To calculate the energy required at the three typologies of vehicles, in the three different charging configurations (BEV, DWPT – BS, DWPT-RE), the simulation model described in D5.4.1 has been applied. The energy model uses a kinematic vehicle approach; this methodology allows to compare different vehicle typologies equipped with several powertrains in terms of energy consumption and $CO_2$ emissions.

The power demand to the powertrain is calculated from the vehicle velocity patterns, which is an input to the kinematic model, considering the driveline efficiency chain and the efficiency of each machine (engine, e-machine and battery) as a function of the operating points. The total power required at the powertrain level, which is the engine for the conventional vehicles and the e-machine for the electric vehicles, is the sum of several components: rolling resistance, grade resistance and drag resistance. The vehicle data used in the analysis come from D5.4.1 and are summarized in Table 14.

**Table 14: Main vehicle specifications per each vehicle typology (D5.4.1).**

| Vehicle typology | SUV | BUS | HDV | Units |
|---|---|---|---|---|
| **Drag coefficient** | 0.24 | 0.7 | 0.96 | - |
| **Front area** | 2.59 | 8.15 | 9.96 | $m^2$ |
| **Rolling resistance** | 0.008 | 0.008 | 0.008 | - |
| **Wheel radius** | 0.32 | 0.48 | 0.52 | m |
| **Wheel inertia** | 1.16 | 2.3 | 2.5 | kg $m^2$ |
| **# of wheels** | 4 | 6 | 12 | - |
| **Vehicle length** | 4.5 | 11 | 13 | m |

The reference driving cycles used to compare the different technologies (BEV, DWPT-BS and DWPT-RE) are:

- the AMDC (Artemis Motorway Driving Cycle) for passenger cars in the motorway scenario.
- The HWM (Highway Mission) for Heavy-Duty trucks in the motorway scenario
- A suitable mix of rural, urban and motorway driving missions for Heavy-Duty trucks in the periurban scenario (see D5.4.1)

- A specific mission based on SORT driving cycle for the urban bus (see D5.4.1)

In Table 15 are reported the results of the simulation model at 2030 and 2050. The reduced energy consumption in 2050 is the result of reduced battery and vehicle weights (see Table 13).

**Table 15: Energy consumption per km in 2030 and 2050.**

| Vehicle | Charging technology | Scenario | Driving Cycle | Energy Consumption TTW [Wh/km] | |
|---|---|---|---|---|---|
| | | | | 2030 | 2050 |
| **suv** | BEV | motorway | amdc | 232.78 | 215.23 |
| **suv** | DWPT-RE | motorway | amdc | 243.96 | 226.63 |
| **suv** | DWPT-BS | motorway | amdc | 242.17 | 225.53 |
| **hdv** | BEV | motorway | hwm | 1,798.99 | 1751.81 |
| **hdv** | DWPT-RE | motorway | hwm | 1,779.08 | 1734.48 |
| **hdv** | DWPT-BS | motorway | hwm | 1,777.64 | 1733.57 |
| **bus** | BEV | urban | sort3 | 991.89 | 863.47 |
| **bus** | DWPT-RE | urban | sort3 | 1,727.28 | 1540.59 |
| **bus** | DWPT-BS | urban | sort3 | 1,627.52 | 1477.58 |
| **hdv** | BEV | periurban | cbd, csc, etc, hdudds, hmw, whvc | 1,458.47 | 1407.93 |
| **hdv** | DWPT-RE | periurban | cbd, csc, etc, hdudds, hmw, whvc | 1,456.02 | 1408.34 |
| **hdv** | DWPT-BS | periurban | cbd, csc, etc, hdudds, hmw, whvc | 1,454.47 | 1407.20 |

All the details of the calculation model applied are reported in D5.4.1.

# 5 ENERGY GRID ASSUMPTIONS

A widespread introduction of electric vehicles in the European transport system will affect the energy system. On the other hand, the way electricity is produced, will be a major factor influencing the environmental viability of shifting to the electric mobility.

D5.4.1 dealt with the mutual impact between electric mobility and energy system. It approached this topic from a national and EU-wide point of view, which is the one of interest for the system level analysis. Figure 4 shows the grid connection design assumed for FABRIC.

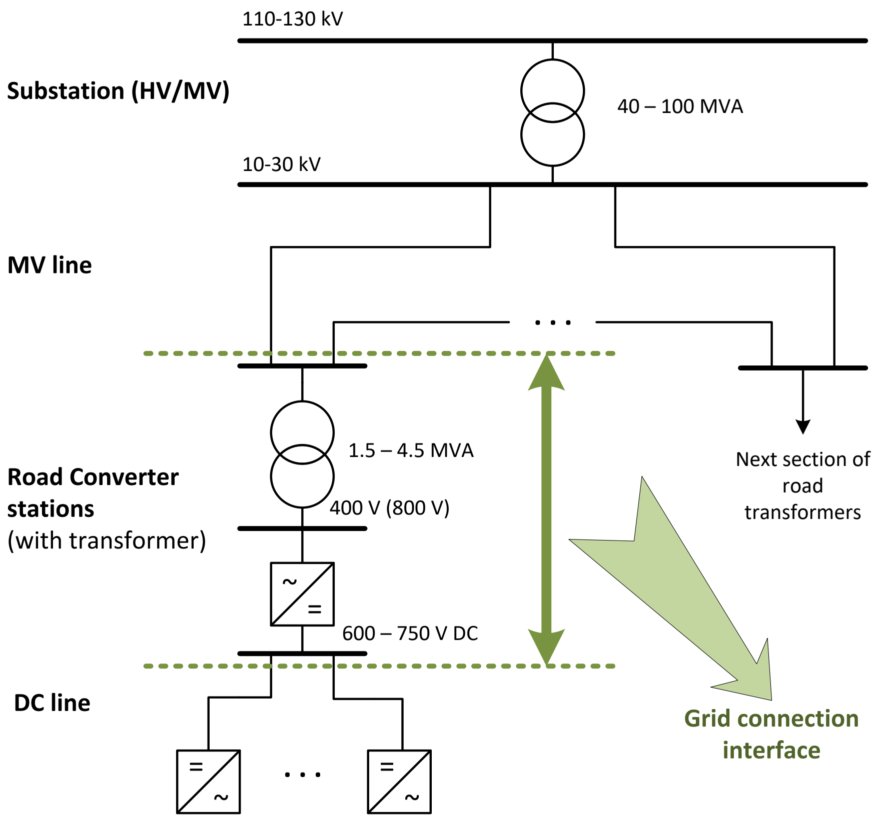


Figure 4: Generic grid connection design from HV down to the 750-V DC line (D5.4.1).

The first aspect to determine the interaction with the grid was the required power level from the infrastructure. To obtain it, the number of vehicles and charging power required by each vehicle has been investigated.

The second aspect considered was the load curve that DWPT technology could determine, according to different temporal span (daily, weekly and seasonal).

Considering that the load curves and power requirements are compatible, the system level analysis results in the system electricity demand and how it is expected to be provided.

In European context, the demand is expected to have negative growth rates in many countries.

In addition to this demand forecast, the uptake of electric transport has been analysed.

FABRIC estimations for the fleet of electric vehicles were presented in D5.4.1: it is assuming a fleet of 1.32 billion cars by 2040, which leads to 2970 TWh/a or 14.7% of global electricity demand compared to 2015. The consumption was calculated assuming an average consumption of 1.5 kWh/km and 15,000 km/year.

This may seem an important extra demand, but the annual growth rates are very small. The horizon is approximately 25 years, which would lead to an average annual growth of demand of 0.4%.

As a conclusion, it can be stated that at national and European level, the additional consumption due to the uptake of electric transport is very small, compared to overall demand. If in addition a tendency of reduced demand is considered, the question would rather be if the new demand from transportation might be able to compensate demand reduction from other sectors (D5.4.1).

These conclusions define that the use of an average European energy mix is appropriate to define the impact of the recharging of the electric vehicle, since the introduction of electric mobility is not going to alter substantially the power generation sector.

Thus the forecast of an average European mix can be used in this study. Relevant parameters to calculate the cumulative energy demand and the Global Warming due to the implementation of DWPT technology are the g $CO_2$-eq/kWh and the Primary Energy Factor (PEF) at 2030 and at 2050.

The Primary Energy Factor (PEF) connects primary and final energy. It indicates how much primary energy is used to generate a unit of electricity or a unit of useable thermal energy.

The European roadmap suggests that, by 2050, the EU should cut its emissions to 80% below 1990 levels through domestic reductions alone (i.e. rather than relying on international credits).

Most relevant for this consideration is the statement that "The power sector [...] can almost totally eliminate $CO_2$ emissions by 2050."

According to the European roadmap (European Commission 2011), the following $CO_2$-reduction targets (compared to 1990 levels) can be assumed for FABRIC scenarios regarding the power sector, which would feed the dynamic charging system:

- 2030: 50% reduction
- 2040: 80% reduction
- 2050: 99% reduction

For the energy efficiency of the electricity production the data from D5.4.1 have been considered.

According to the JRC WTT Report (Edwards, Larivé et al. 2014), the current factor of energy expended per unit of final fuel (electricity in this case), is 1.95 MJ/MJ. In other words, the assumed fuel efficiency of the EU-28 electricity mix is approximately 34%. This is in line with the standard thermal power plant efficiency in the range of 30-40%.

This factor is expecting to evolve from here to 2050. In Figure 5 a possible projection is given for energy expended to deliver final fuel for EU-28 electricity mix. Data has been elaborated based on JRC values (1.95 MJ/MJ for EU-28 mix in 2010) and projections on the EU-28 electricity mix given by the EU reference scenario.

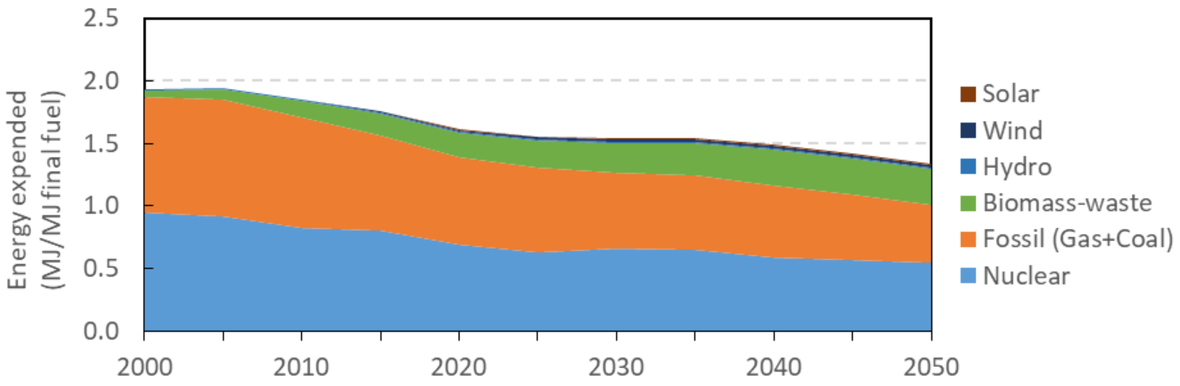


**Figure 5: Projection of energy expended to deliver final fuel for EU-28 electricity mix.**

In line with the $CO_2$-eq reduction, a value of 1.5 MJ/MJ has been used for the 2030 scenario and a 1.4 MJ/MJ has been used for the 2050 scenario.

# 6 COMPLETE LCA FOR E-ROADS

Deliverable D5.3.4 evaluated the LCA of e-Road in terms of energy usage, fuel usage and emissions. The design of the e-Road considered and the LCA of the e-Road construction is summarised below.

The structure of the e-Road was developed for highway applications and adapted for urban and periurban roads. Two WPT technologies have been considered, those developed in FABRIC by Polytechnic University of Turin (**POLITO**) and SAET Industrial Automation Systems (**SAET**). In an on-road power transfer solution, the grid provides three phases 400 V AC to a number of rectifiers and inverters, which convert AC to DC voltage and back to high frequency AC. The converters and control electronics are located at the roadside. The in-road equipment consists of coils that are connected to a roadside cabinet, sensors and switches; when the technology is enabled, one or more coils per segment can be switched on at the same time, depending on the solution design, power rating of the inverters and supply from the grid.

## 6.1 E-road structure

The installation of DWPT into the road structure requires substantial changes to the structure of the road. The equipment installation normally requires installation below the surface layer into the sub-layers of the road structure. Figure 6 shows a typical installation. Depending on the road structure and the characteristics of the DWPT equipment, the concrete structure may intrude into the sub-base, or even into the lower part of the surface layer.

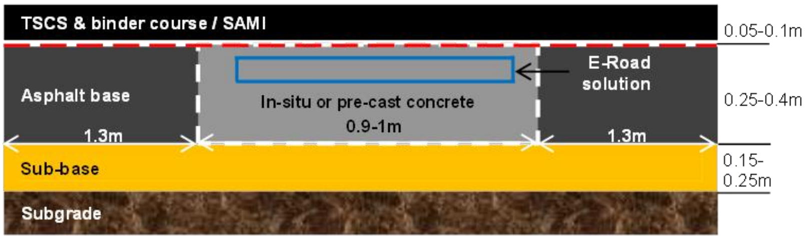


Figure 6: Typical in-road DWPT installation (D5.3.4).

### 6.1.1 POLITO e-Road geometry and construction

The optimal configuration for the POLITO technology requires the installation of the coils 4 cm beneath the road surface. It, however, permits some allowance in depth positioning, thus permitting the placement of the coils in the bitumen layer, even if the overhead wear layer can be higher than 4 cm (in the analysed case is 6 cm, see Figure 7).

At the test site, the construction involved the excavation of narrow micro-trenches (80 mm depth circa) within the pavement and the coil or E-Road system was placed in within a filling material and covered with asphalt.

The filling materials are to be further studied, since capacitive coupling between the E-Road coils and conventional road materials can appear.

Experiment confirms that some unexpected phenomena appear when the coil is embedded into the concrete, evidencing a parallel capacitance with concrete. This phenomenon can be effectively reduced coating the coils with proprietary bitumen, before embedding them into concrete.

Many other options have been investigated and the conclusion from the testing suggested that the best approach was to excavate thin trenches in the asphalt layer, approximately 80mm deep, then to cover the system in proprietary bitumen and pave the holes with cold mix asphalt, as described in D4.5.2.

This type of construction may be suitable for testing the technologies temporally in a test-track environment. It may not be appropriate for the actual in-service highway implementation, from the practical construction and maintenance perspectives.

From interviews with experts, the installation method in motorway will require the dismantling of both the wear and binder layer, the placement of the coils coated with bitumen embedded in a low stiffness concrete and covering the system with asphalt. In Figure 7 a section of the actual design of the adaptation of POLITO solution for real road is reported.

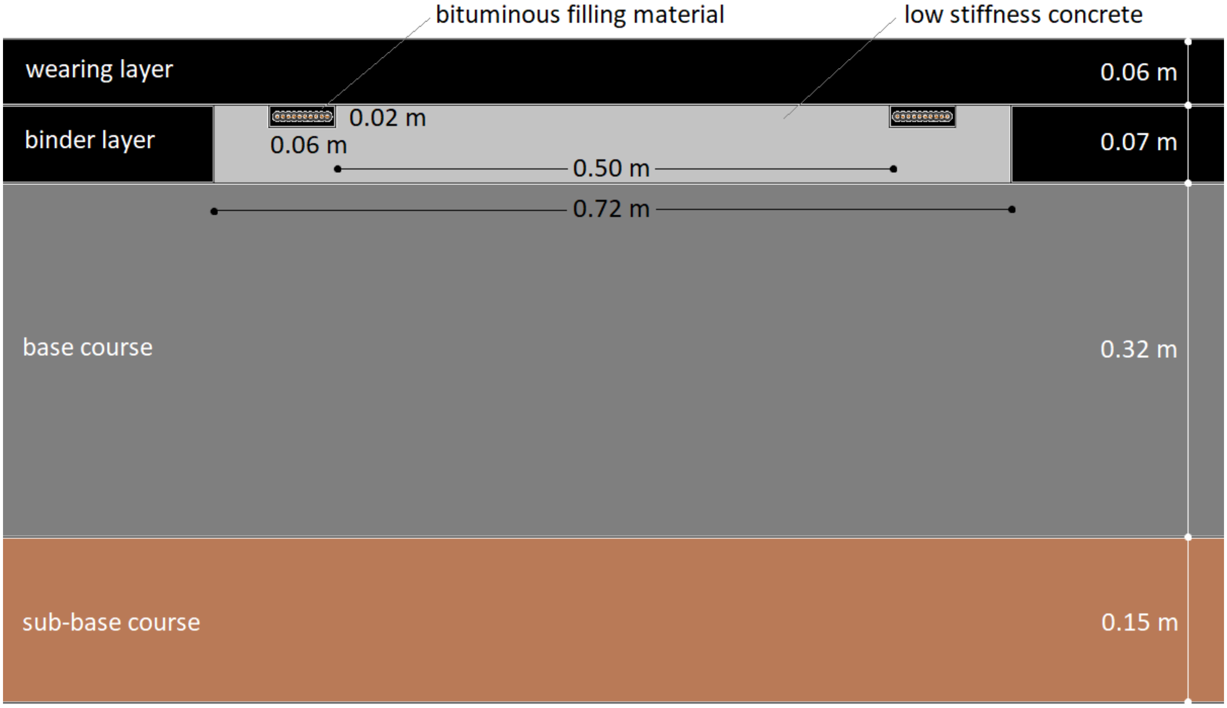


**Figure 7: Section of actual configuration of POLITO solution for real road adaptation (D5.3.4).**

### 6.1.2 SAET e-Road geometry and construction

The optimal configuration for the SAET technology requires the installation of the coils 5 cm beneath the road surface. It, however, permits some allowance in depth positioning, thus permitting the placement of the coils in the bitumen layer, even if the overhead wear layer can be higher than 5 cm.

At the test site the construction involves the excavation of narrow micro-trenches (80 mm depth circa) within the pavement; the coil or e-Road system was placed in within a filling material and covered with asphalt.

The SAET solution does not show capacitive coupling between the E-road coils and the filling material, thus the choice of the filling materials, is not so restrictive. Since the final configuration

is not known, we will assume the simplest configuration experimented in the test site will be kept i.e. the embedment of the coils in concrete. This solution is also the most appropriate for the real-world implementation: rather than a micro trench with 2 cm width and 5 cm depth for each coil, it is supposed, as for the POLITO solution, that the surface layers are completely removed and the pre cast coils are set and then covered with asphalt.

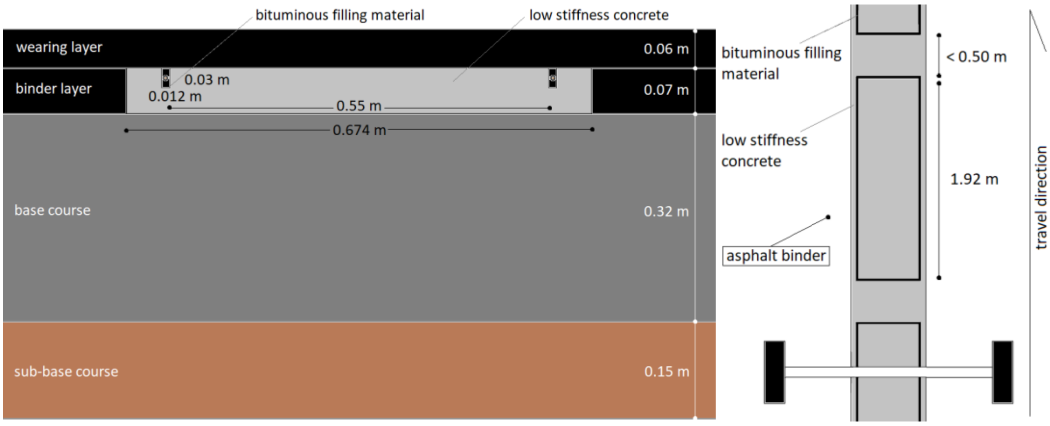


Figure 8: SAET technology: cross section (left) and top view (right).

## 6.2 Relevant assumptions on e-Roads

From D5.3.4 the expected lifetime of an e-Road and the maintenance operations are derived. The expected lifetime of e-Roads lifetime is 20 years; eight rehabilitations of the wear layer are considered during the lifetime of the e-road and one rehabilitation of both the wear and binder layers.

## 6.3 Results of LCA of e-Roads infrastructure

Life Cycle Assessment of e-Roads was developed including the phases presented in the system boundary illustrated in Figure 9.

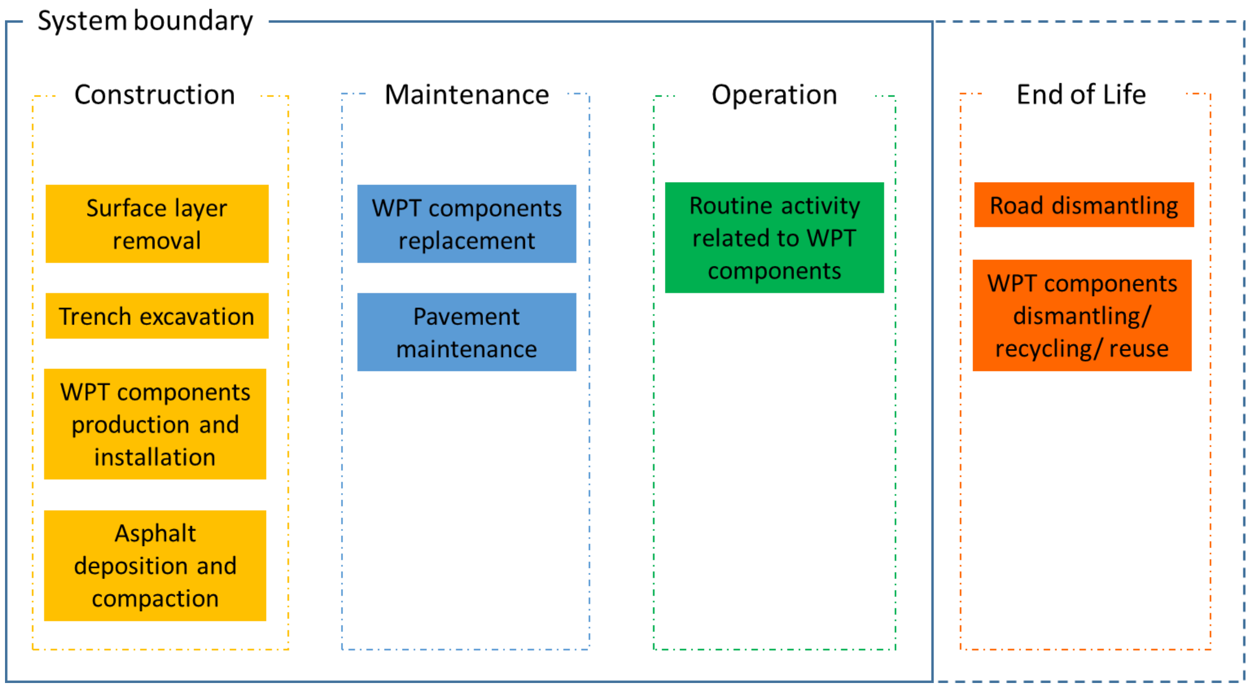


**Figure 9: Phases and sub phases included in the e-Road system boundary (D5.3.4).**

The results are reported following the same structure.

The impact categories considered in this analysis are the CED and Global Warming: CED designates the overall primary energy per functional unit of a product system; it is merely an aggregation of inventory results, since it expresses the total energy required to produce and maintain the e-Road.

Global Warming: In this impact category, substances emitted into the atmosphere for the production of the functional unit are evaluated according to their contribution to heat absorption over time due to their infrared radiative forcing and their persistence in atmosphere. In this analysis the Global Warming is evaluated using the Baseline model of 100y by ICCP (IPCC 2013 GWP 100a V1.03); results are expressed in kilograms of $CO_2$-eq per functional unit. The conversion of substances emitted into atmosphere to a reference unit is made through the characterisation factor “global warming potential (GWP100)”.

In Table 16 and Table 17 synoptic views of the results of the two configurations are proposed, showing the impact of construction, wear rehabilitation and binder & wear layers rehabilitation, sorted by their sub-phases, and their relative importance to the overall impact.

**Table 16: Impact assessment of the e-Road for POLITO solution (D5.3.4).**

| Phase | Sub-Phase | CED [MJ/km] | Global Warming [kg $CO_{2,eq}$/km] |
|---|---|---|---|
| **Construction Phase** | Dismantling | 6,534 | 423 |
| | Installation and paving | 57,693 | 3,739 |
| | Transport (construction materials and WPT comp.) | 134,406 | 8,404 |
| | Transport (machineries) | 10,191 | 636 |
| | HMA | 3,149,172 | 44,484 |
| | WPT production | 1,470,084 | 99,834 |
| | Bituminous emulsion | 61,226 | 480 |
| | Concrete | 72,386 | 10,316 |
| | Total | 4,961,692 | 168,317 |
| | | 22% | 36% |
| **Wear layer rehabilitation (every 25 months)** | Transports (asphalt and bituminous emulsion) | 473,038 | 29,539 |
| | Wear layer dismantling | 36,263 | 2,350 |
| | Wear layer repaving - machineries | 384,627 | 24,925 |
| | HMA | 13,009,548 | 183,768 |
| | Bituminous emulsion | 489,812 | 3,842 |
| | Transports (machinery) | 66,088 | 4,127 |
| | Total | 14,459,377 | 248,551 |
| | | 64% | 52% |
| **Wear and binder layer rehabilitation** | Transports (asphalt and bituminous emulsion) | 113,046 | 7,136 |
| | Wear&binder layer dismantling | 7,650 | 498 |
| | Wear&binder layer repaving - machineries | 57,421 | 3,738 |
| | HMA | 3,003,115 | 44,484 |
| | Bituminous emulsion | 59,178 | 480 |
| | Transports (machinery) | 10,752 | 679 |
| | Total | 3,251,162 | 57,014 |
| | | 14% | 12% |
| **Total** | | 22'672'230 | 473,882 |

Table 17: Impact assessment of the e-Road for SAET solution (D5.3.4).

| Phase | Sub-Phase | CED [MJ/km] | Global Warming [kg $CO_{2,eq}$/km] |
|---|---|---|---|
| **Construction Phase** | Dismantling | 6,534 | 423 |
| | Installation and paving | 57,693 | 3,739 |
| | Transport (construction materials and WPT comp.) | 134,161 | 8,388 |
| | Transport (machineries) | 10,191 | 636 |
| | HMA | 3,173,054 | 44,821 |
| | WPT production | 1,375,935 | 90,653 |
| | Bituminous emulsion | 61,226 | 480 |
| | Concrete | 70,063 | 9,985 |
| | Total | 4,888,858 | 159,126 |
| | | 22% | 34% |
| **Wear layer rehabilitation (every 25 months)** | Transports (asphalt and bituminous emulsion) | 473,038 | 29,539 |
| | Wear layer dismantling | 36,263 | 2,350 |
| | Wear layer repaving - machineries | 384,627 | 24,925 |
| | HMA | 13,009,548 | 183,768 |
| | Bituminous emulsion | 489,812 | 3,842 |
| | Transports (machinery) | 66,088 | 4,127 |
| | Total | 14,459,377 | 248,551 |
| | | 64% | 52% |
| **Wear and binder layer rehabilitation** | Transports (asphalt and bituminous emulsion) | 113,903 | 7,190 |
| | Wear&binder layer dismantling | 7,650 | 498 |
| | Wear&binder layer repaving - machineries | 57,421 | 3,738 |
| | HMA | 3,025,914 | 44,822 |
| | Bituminous emulsion | 59,178 | 480 |
| | Transports (machinery) | 10,752 | 679 |
| | Total | 3,274,817 | 57,406 |
| | | 14% | 12% |
| **Total** | | 22,623,051 | 465,083 |

Comparing the results in Table 16 and Table 17, the two solutions do not show significant differences in the relative shares of each phase. Thus from now on when referring to the impact of the e-road, the values obtained for the Polito solution are considered, if not otherwise specified. For a detailed description of each phase see deliverable D5.3.4

## 6.4 Allocation of e-Road infrastructure to DWPT vehicles

### 6.4.1 Motorway scenario

The environmental burden of the infrastructure is distributed on the fleet which is expected to exploit it. D5.5.2 made some assumptions on the deployment of the infrastructure by the users (see Table 2).

The number of vehicles crossing the e-Corridor and recharging on it during its lifetime is reported in Table 1 and it is expressed in vehicle per day.

In order to allocate the impact of the infrastructure to the vehicles that use it, the number of passenger cars and the number of HDV is summed up, obtaining 881 vehicle recharging on a motorway equipped with e-corridor per day in 2030 and 9341 vehicles per day in 2050.

The impact of the production of the e-corridor has been obtained multiplying the impacts per km of e-road obtained in D5.3.4 per the length of the e-corridor. This value is then divided for the exploitation rate of the e-corridor during its lifetime (multiplying the daily traffic recharging on it per 365 d/y and per 20y of e-corridor lifetime).

To express the impact in term of km travelled the impact of a single trip on the e-corridor has to be divided for the length of the motorway equipped with DWPT (400 km).

The formulas used to allocate this impact is the following

$$Global\ Warming\ of\ eCorridor\ attributed\ to\ the\ km\ travelled\ by\ the\ vehicle\ \left[\frac{kg\ CO_2eq_{eCorridor}}{km\ travelled}\right]$$
$$= \frac{\frac{impact\ eRoad}{km}\ \left[\frac{kg\ CO_2eq}{km}\right] \cdot lenght\ eCorridor\ [km]}{number\ of\ vehicles\ recharging\ on\ the\ eCorridor\ daily\ \left[\frac{\#\ vehicles}{day}\right] \cdot infrastructure\ lifetime\ [day]}$$
$$\cdot \frac{1}{lenght\ of\ the\ motorway\ [km]}$$

$$CED\ of\ eCorridor\ attributed\ to\ the\ km\ driven\ by\ the\ vehicle\ \left[\frac{MJ_{eCorridor}}{km\ driven}\right]$$
$$= \frac{\frac{impact\ eRoad}{km}\left[\frac{MJ}{km}\right] \cdot lenght\ eCorridor\ [km]}{number\ of\ vehicles\ recharging\ on\ the\ eCorridor\ daily\left[\frac{\#\ vehicles}{day}\right] \cdot infrastructure\ lifetime\ [day]}$$
$$\cdot \frac{1}{lenght\ of\ the\ motorway\ [km]}$$

The data used for the calculation derive from other deliverables and have been summarized in Table 18.

**Table 18: Input for the calculation of the allocation of e-corridor impacts.**

| | 2030 | 2050 | Source |
|---|---|---|---|
| **Length e-Corridor [km]** | 25 | 25 | D5.5.2 |
| **Length motorway [km]** | 400 | 400 | D5.5.2 |
| **N° of vehicles recharging on e-Launcher daily [#HDV/day]** | 881 | 9341 | D5.5.2 |
| **Infrastructure lifetime [y]** | 20 | 20 | D5.3.1 |
| **Impact e-road Global Warming /km [kg $CO_2$-eq/km]** | 473882 | 473,882 | D5.3.4 |
| **Impact e-road CED/km [MJ/km]** | 22,672,230 | 22,672,230 | D5.3.4 |

Applying the aforementioned formulas to these data, the following results are obtained (Table 19):

**Table 19: Infrastructure environmental impacts allocated to the DWPT vehicles.**

| Impact | 2030 | 2050 |
|---|---|---|
| **Global Warming per km drive by the vehicle in motorway scenario [kg $CO_2$-eq$_{e\text{-}corridor}$/km travelled by the vehicle]** | 0.0046 | 0.0004 |
| **CED per km drive by the vehicle in motorway scenario [MJ$_{e\text{-}corridor}$/ km drive by the vehicle]** | 0.2203 | 0.0208 |

The allocation results apply both for SUVs and HDVs.

### 6.4.2 Periurban scenario

The periurban scenario applies only to heavy vehicles in motorways close to cities with a reduced e-road length of 10 km (e-Launcher), distributed on a periurban road of 250 km (D5.5.2).

The impacts of the construction of e-launcher has been allocated to the vehicles that uses it to recharge. In D5.5.2 the exploitation of the e-launchers has been predicted (see Table 3). The infrastructure is allocated only to the number of passages that exploit the infrastructure for recharging the vehicle (not to every DWPT vehicle passing on it).

In the same way as for the e-corridor, the impact of the production of the e-launcher has been obtained multiplying the impacts per km of e-road obtained in D5.3.4 per the length of the e-corridor. This value is then divided for the exploitation rate of the e-corridor during its lifetime (multiplying the AADD per 365 d/y and per 20y of e-corridor lifetime).

To express the impact in term of km travelled the impact of a single trip on the e-corridor has to be divided for the length of the periurban road equipped with DWPT (in this case 250 km, since in the periurban scenario the 10 km e-launchers are distributed on a road of 250 km).

The formulas used to allocate this impact is the following

$$Global\ Warming\ of\ eLauncher\ attributed\ to\ the\ km\ driven\ by\ the\ HDV\ \left[\frac{kg\ CO_2eq_{eLauncher}}{km\ driven}\right] = \frac{\frac{impact\ eRoad}{km}\left[\frac{kg\ CO_2eq}{km}\right]\cdot lenght\ eLauncher\ [km]}{number\ of\ HDV\ recharging\ on\ the\ eLauncher\ daily\left[\frac{\#\ HDV}{day}\right]\cdot infrastructure\ lifetime\ [day]} \cdot \frac{1}{lenght\ of\ the\ periurban\ road\ [km]}$$

$$CED\ of\ eLauncher\ attributed\ to\ the\ km\ driven\ by\ the\ HDV\ \left[\frac{MJ_{eLauncher}}{km\ driven}\right] = \frac{\frac{impact\ eRoad}{km}\left[\frac{MJ}{km}\right]\cdot lenght\ eLauncher\ [km]}{number\ of\ HDV\ recharging\ on\ the\ eLauncher\ daily\left[\frac{\#\ HDV}{day}\right]\cdot infrastructure\ lifetime\ [day]} \cdot \frac{1}{lenght\ of\ the\ periurban\ road\ [km]}$$

In Table 3 the deployment forecast for the periurban case (e-Launchers) is shown.

The data used for the calculations derive from other deliverables and have been summarized in Table 20

**Table 20: Input for the calculation of the allocation of e-Launcher impacts.**

| | 2030 | 2050 | Source |
|---|---|---|---|
| **Length e-Launcher [km]** | 10 | 10 | D5.5.2 |
| **Length periurban road [km]** | 250 | 250 | D5.5.2 |
| **N° of HDV recharging on e-Launcher daily [#HDV/day]** | 810 | 3098 | D5.5.2 |
| **Infrastructure lifetime [y]** | 20 | 20 | D5.3.1 |
| **Impact e-road Global Warming /km [kg $CO_2$-eq/km]** | 473882 | 473,882 | D5.3.4 |
| **Impact e-road CED/km [MJ/km]** | 22,672,230 | 22,672,230 | D5.3.4 |

Applying the aforementioned formulas to these data, the following results are obtained (Table 21):

**Table 21: Infrastructure environmental impacts allocated to the DWPT vehicles.**

| Impact | 2030 | 2050 |
|---|---|---|
| **Global Warming per km drive by the HDV in the periurban scenario [kg $CO_2$-eq$_{e\text{-}Launcher}$/km travelled by HDV]** | 0.0032 | 0.0008 |
| **CED per km drive by the HDV in the periurban scenario [MJ$_{e\text{-}Launcher}$/ km drive by HDV]** | 0.15 | 0.04 |

### 6.4.3 Urban scenario

The DWPT technology implemented in the road and the construction method remain the same as in the motorway scenario, while the frequencies of the e-Trenches are different. In Table 4 the deployment forecast for the urban case (City Buses) is shown. The total length of electrified trenches is 27 km.

In order to express the results in the same functional unit as the other scenarios, the infrastructure is allocated on the km travelled by the entire bus fleet: the average daily travel is 313 km for each bus. This value is multiplied for the lifetime of the e-tranches (365*20 y) resulting in the total km travelled by the public buses in 20 years. The impact of the infrastructure is reported in terms of km travelled by the bus both on an e-trench and on a regular road.

$$Impact\ of\ eTrenches\ attributed\ to\ the\ km\ travelled\ by\ the\ bus\ \left[\frac{kg\ CO_2eq_{eTrenche}}{km\ driven}\right]$$

$$= \frac{\frac{impact\ eTrench}{km}\left[\frac{kg\ CO_2eq}{km}\right]\cdot lenght\ eTrench\ [km]}{daily\ km\ travelled\ by\ a\ bus\cdot number\ of\ DWPT\ buses\cdot infrastructure\ lifetime}$$

**Table 22: Input for the calculation of the allocation of e-Trench impacts.**

| | 2030 | 2050 | Source |
|---|---|---|---|
| **Length e-Trench [km]** | 27 | 27 | D5.5.2 |
| **N° DWPT-buses** | 300 | 400 | D5.5.2 |
| **Average daily km of a bus [km]** | 313 | 313 | |
| **Infrastructure Lifetime [y]** | 20 | 20 | D5.3.4 |
| **Impact e-road Global Warming /km [kg $CO_2$-eq/km]** | 473882 | 473,882 | D5.3.4 |
| **Impact e-road CED/km [MJ/km]** | 22,672,230 | 22,672,230 | D5.3.4 |

Applying the aforementioned formulas to these data, the following results are obtained (Table 23):

**Table 23: Infrastructure environmental burdens allocated to the km travelled by the DWPT bus.**

| | 2030 | 2050 |
|---|---|---|
| **Global Warming per km travelled by a DWPT bus [kg $CO_2$-eq$_{e\text{-}trenchess}$/km drive by the DWPT bus]** | 0.018 | 0.014 |
| **CED per km travelled by a DWPT bus [MJ$_{e\text{-}trenches}$/km drive by the DWPT bus]** | 0.892 | 0.669 |

It has to be considered that the function of an urban bus is to transport persons from one place to another. A fair comparison with a car will be expressed in terms of persons*km.

# 7 SYSTEM LEVEL COMPLETE LCA

The data and assumptions listed in sections 4, 5 and 6 for the three levels (vehicle, energy grid, e-Road) have been integrated to obtain a system level analysis for the scenarios depicted in Section 3.

The vehicle and battery production impacts were derived from databases and other research projects and literature and were updated with projection on material composition at 2030 and 2050.

The energy required at the vehicle during motion (TTW Energy consumption) has been calculated with the simulation model explained in D5.4., considering lighter vehicles and lighter batteries.

From the Tank-to-Wheel results, the Well-to-Wheel $CO_2$-eq emissions at 2030 and 2050 have been calculated, including predictions on European electricity production provided in D5.4.1 and discussed in section 5. The formula applied to obtain the WTW impact per km travelled by the vehicle is the following:

$$Global\ Warming\ of\ the\ WTW\ per\ km\ travelled\ by\ the\ vehicle\ \left[\frac{g\ CO_2eq_{WTW}}{km\ travelled}\right]$$
$$= TTW\left[\frac{Wh}{km\ travelled}\right]\cdot impact\ of\ electricity\ produciton\left[\frac{\not{k}g\ CO_2eq}{\not{k}Wh}\right]$$

$$CED\ of\ the\ WTW\ per\ km\ travelled\ by\ the\ vehicle\ \left[\frac{MJ_{WTW}}{km\ driven}\right]$$
$$= TTW\left[\frac{Wh}{km\ travelled}\right]\cdot CED\ of\ electricity\ produciton\left[\frac{MJ}{MJ_e}\right]\cdot 0.0036\ \left[\frac{MJ}{Wh}\right]$$

**Table 24: $CO_2$-eq emission and energy efficiency for electricity production in Europe in 2030 and 2050.**

| Impact of electricity production | 2030 | 2050 |
|---|---|---|
| **g $CO_2$-eq/kWh** | 165.5 | 3.31 |
| **MJ/$MJ_e$** | 1.5 | 1.4 |

The functional unit used to compare the three EV technology (classical BEV, DWPT-BS, DWPT-RE) is the km travelled, as explained in section 2.1; so the impact from every subsystem (vehicle production, electricity generation and infrastructure) illustrated in Figure 2: System

boundary, has to be referred to the functional unit of the system: all the impacts are going to be expressed in term of km travelled in the next sections.

Impacts deriving from the production of the vehicle are expressed in terms of km travelled, distributing the impacts of the vehicle on the expected mileage of the vehicle. The expected lifetime of a SUV is 10 years, with an average yearly mileage of 20,000 km, while for HDV and BUS the lifetime has been considered 10 years and the yearly average mileage 65,000 km, in line with D5.5.2.

The impacts from vehicle production calculated in section 4.1 is then distributed on the km travelled by the vehicle, using the following formula:

$$vehicle\ production\ impact_{km}\ \left[\frac{g\ CO_2eq_{vehicle\ production}}{km\ travelled}\right] = \frac{vehicle\ production\ impact}{average\ vehicle\ mileage}$$

The same concept applies to battery production; whose impacts need to be allocated on the km travelled. For the SUV only one battery is required during its use, so the battery is supposed to cover the 200,000 km travelled by the car during its lifetime; while for BUS and HDV one substitution is considered during the lifetime of the vehicles (D5.5.2). Thus, the production of two batteries need to be allocated. The allocation of the impacts deriving from the production of the battery is calculated using the following formula:

$$battery\ production\ impact_{km} = \frac{battery\ production\ impact}{average\ vehicle\ mileage} \cdot (1 + number\ of\ battery\ substitution)$$

The following paragraphs present the results for each of the three scenarios.

## 7.1 Motorway scenario

The motorway scenario has been foreseen for passenger cars (here represented by a SUV) and heavy-duty commercial vehicles (HDVs) in very dense highways with a critical mass of electric vehicles in the roads and a percentage of those equipped with DWPT systems. The e-Corridors will be built initially in a dedicated external lane to avoid user costs during the assembly process and later using one of the conventional lanes when prefabricated modules will be available and construction times will be significantly reduced. The e-Corridors will be established in the middle of trenches of 400 km where we set the average autonomy of a light

electric vehicle in 2030. The intermediate e-Corridors will reduce the anxiety effect in drivers enhancing them to recover such distance with the assurance that they can recharge between 10% to 35% extra autonomy without wasting time (in opposition to the competing conductive or inductive static stations). A second option (battery shrinking) is instead intended to reduce the size of the battery, keeping the range the same as the classic electric vehicles, allowing for saving during the use phase due to a lighter vehicle.

Data regarding vehicle production are derived from the database EcoInvent 3.4, using the following datasets:

- Passenger car, electric, without battery {GLO}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit) for models BEV, DWPT-BS, DWPT-RE.

The dataset has been updated with the SUV composition expected in 2030 and 2050 and the European energy mix expected in 2030 and 2050 has been replaced with the one used in the original dataset, for what concern the manufacturing processes that occur in Europe. The impacts of this vehicle are than scaled as a function of the vehicle mass. The masses of the vehicles considered to calculate the production impacts are the same used in the simulation reported in D5.4.1 to define the emissions and energy consumption of the vehicles when driving in the different scenarios.

Due to the relevance of the battery production, for the three configurations (BEV, DWPT-BS and DWPT-RE) the mass represents the weight of the vehicle without batteries. Impacts from battery production are reported as a separate entry contributing to the final overall impact of the vehicle.

The batteries considered during the simulation of the use phase are lithium-ion batteries. To be coherent with these simulations, the dataset used to model the impacts from battery productions is “Battery, Li-ion, rechargeable, prismatic {GLO}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)”.

To allocate the impacts of production to the vehicle, a lifetime for both the vehicle and the battery has been selected. In line with considerations from other deliverables these values are fixed at 200,000 km for both.

The TTW values have been simulated with the simulation model described in D5.4.1 and are listed in Table 15. To calculate the WTW $CO_2$ emissions and the WTW Energy consumption, the kWh/km required to move the vehicles have been multiplied for the g CO2-eq emission and the energy efficiency for electricity production in Europe expected in 2030 and 2050, which have been provided in D5.4.1 (and summarized in Table 24).

The share of infrastructure derives from impacts evaluated in D5.3.4. The impacts of the infrastructure are allocated to every vehicle equipped with DWPT technology according to the procedure reported in section 6.4.

The aforementioned impacts, after being referred to the functional unit (the km driven) are summed up to obtain the total impact.

Table 25 shows the system level impact of 1 km travelled by a passenger car in the motorway scenario, and the contribution of each sub-system to the final result.

**Table 25: Global Warming per km travelled by passenger cars with different recharging technologies in motorway scenario in 2030. Vehicle and battery lifetime: 200,000 km.**

| Global Warming | BEV | DWPT - BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [g $CO_2$-eq/km] | 92.22 | 95.51 | 95.51 |
| Battery production [g $CO_2$-eq/km] | 8.55 | 7.30 | 8.55 |
| WTW [g $CO_2$-eq/km] | 38.91 | 33.32 | 38.91 |
| Infrastructure [g $CO_2$-eq/km] | - | 0.0046 | 0.0046 |
| Total [g $CO_2$-eq/km] | 139.69 | 136.14 | 142.99 |

The three configurations present almost the same impact in the production phase, because the slightly lower production impact due to lighter vehicle is distributed on the lifetime of 200,000 km.

It is worthwhile recalling that for DWPT-EV, calculations have been carried out assuming an e-Road charging power equal to 50 kW and an 80% WPT efficiency. It generates an extended range of 52 km in the Range Extend option, while for the Battery Shrinking option it causes a reduction of the battery of 14.4% compared to the BEV and DWPT-RE options.

As a result, the DWPT-BS present a lower impact, both for the smaller battery, but especially because of the smaller WTW impact, due to energy consumption reduction during the use phase due to the lighter vehicle.

The impact of the infrastructure is negligible for the DWPT configuration.

In Figure 10 the $CO_2$-eq caused by 1 km travelled using different powertrain is reported, showing the share of the different stages.

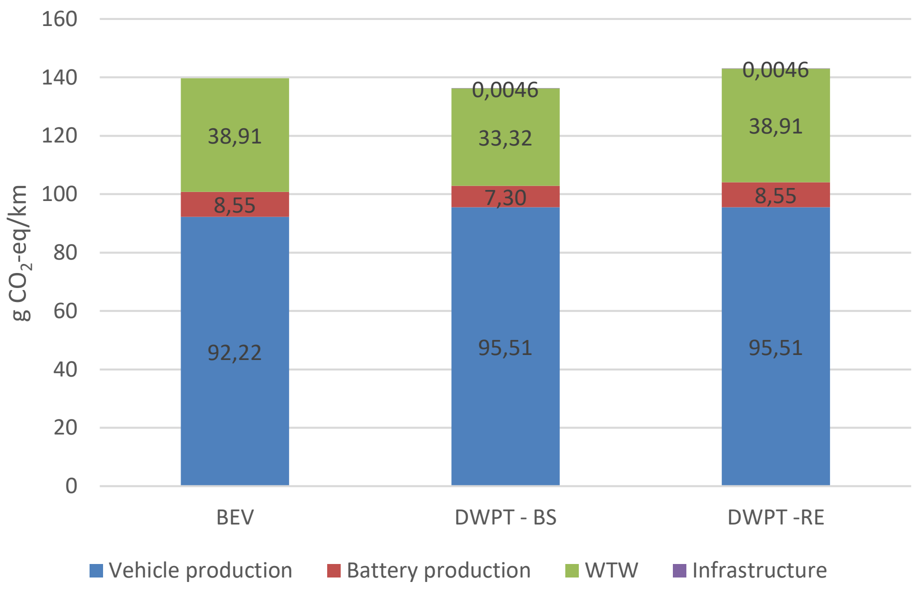


**Figure 10: Global Warming per km travelled by passenger cars with different recharging technologies in motorway scenario in 2030. Vehicle and battery lifetime: 200,000 km.**

For the same scenario (Motorway, 2030, passenger cars) Table 26 reports the results of Cumulative Energy Demand per km travelled.

**Table 26: Cumulative Energy Demand per km travelled by passenger cars with different recharging technologies in motorway scenario in 2030. Vehicle and battery lifetime: 200,000 km.**

| Cumulative Energy Demand | BEV | DWPT - BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [MJ/km] | 1.04 | 1.08 | 1.08 |
| Battery production [MJ/km] | 0.10 | 0.09 | 0.10 |
| WTW [MJ/km] | 0.55 | 0.48 | 0.55 |
| Infrastructure [MJ/km] | - | 0.22 | 0.22 |
| Total [MJ/km] | 1.70 | 1.86 | 1.95 |

When it comes to the CED, the impacts of the WTW phase become more relevant and the infrastructure impacts become visible in the final result.

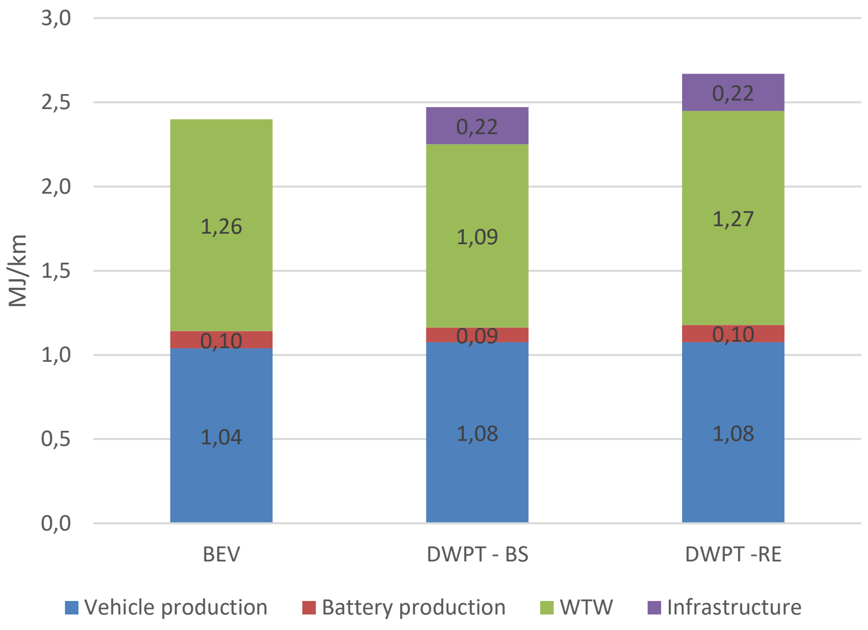


**Figure 11: Cumulative Energy Demand per km travelled by passenger cars with different recharging technologies in motorway scenario in 2030. Vehicle and battery lifetime: 200,000 km.**

These results are expected to change in 2050, mainly because of the changed European electricity mix, which is estimated to reach almost zero $CO_2$-eq emissions per kWh of electricity produced. Also, the penetration of electric vehicles and the exploitation of e-Roads will be increasing.

**Table 27: Global Warming per km travelled by passenger cars with different recharging technologies in motorway scenario in 2050. Vehicle and battery lifetime: 200,000 km.**

| Global Warming | BEV | DWPT - BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [g $CO_2$-eq/km] | 78.47 | 81.75 | 81.75 |
| Battery production [g $CO_2$-eq/km] | 6.44 | 5.53 | 6.44 |
| WTW [g $CO_2$-eq/km] | 0.71 | 0.75 | 0.75 |
| Infrastructure [g $CO_2$-eq/km] | - | 0.0004 | 0.0004 |
| Total [g $CO_2$-eq/km] | 85.62 | 88.03 | 88.94 |

The effect of an almost zero-carbon power sector in 2050 in Europe, lower the impact of WTW, which become lower than 1 g $CO_2$,eq/km, since the use phase occurs in Europe , while the vehicle production decrease only because of the reduced mass and does not benefit significantly of the reduced emissions of the European electricity mix, because the vehicle production is supposed to be worldwide.

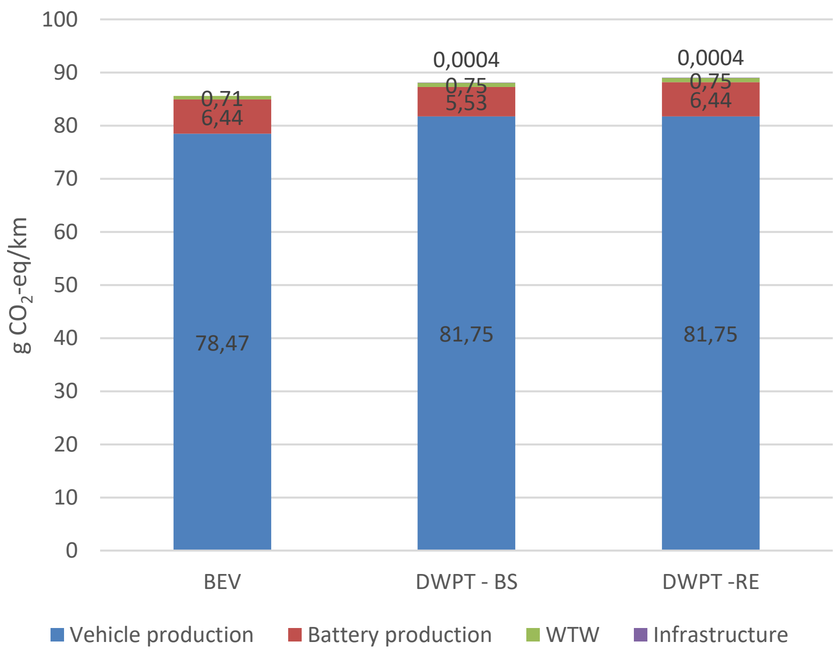


**Figure 12: Global Warming per km travelled by passenger cars with different recharging technologies in motorway scenario in 2050. Vehicle and battery lifetime: 200,000 km.**

The CED for the motorway scenario in 2050 is reported in Table 28 and Figure 13. The overall impact decrease and the share of each subphase is almost the same as in 2030, except for the infrastructure, where the higher exploitation rate reduce it at a negligible part.

Table 28: Cumulative Energy Demand per km travelled by passenger cars with different recharging technologies in motorway scenario in 2050. Vehicle and battery lifetime: 200,000 km.

| Cumulative Energy Demand | BEV | DWPT-BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [MJ/km] | 0.88 | 0.92 | 0.92 |
| Battery production [MJ/km] | 0.08 | 0.07 | 0.08 |
| WTW [MJ/km] | 1.08 | 1.14 | 1.14 |
| Infrastructure [MJ/km] | - | 0.02 | 0.02 |
| Total [MJ/km] | 2.05 | 2.15 | 2.16 |

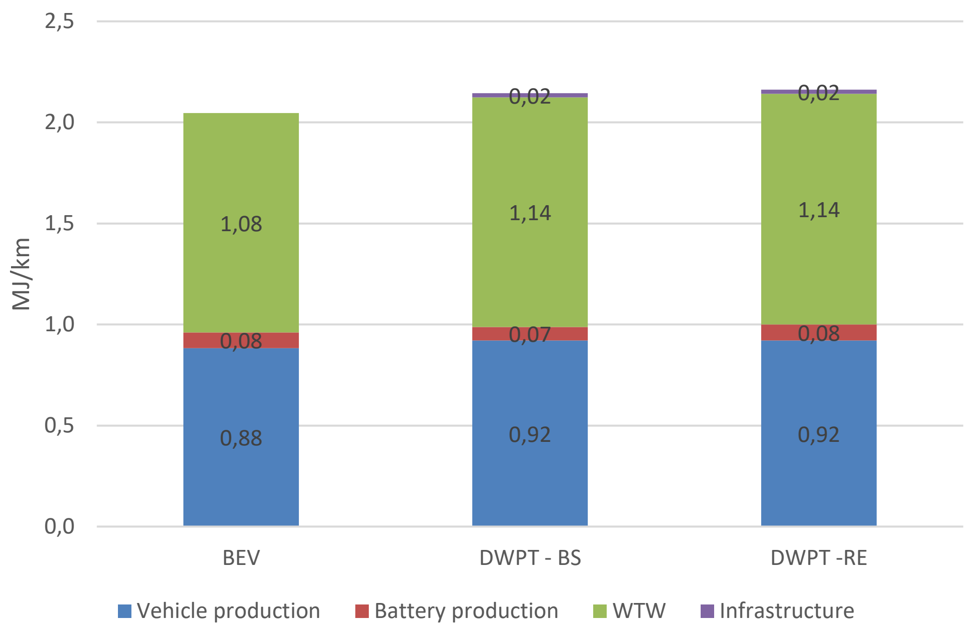


Figure 13: Cumulative Energy Demand per km travelled by passenger cars with different recharging technologies in motorway scenario in 2050. Vehicle and battery lifetime: 200,000 km.

In all the scenarios the difference between the three options (classic plug-in electric vehicle (BEV in the graphs), DWPT in BS option and DWPT in RE option, are negligible: the impact of the infrastructure is negligible because of the high exploitation of the e-Road.

The relevant change is the contribution of the WTW phase through the years. Due to a very ambitious energy policy which expects a 99% reduction of $CO_2$-eq emissions in the power sector, the emissions due to EV recharging (both DWPT or static charging and Plug-in) are close to zero.

**HDVs**

HDVs in motorway scenarios produce the same effects as the passenger cars: the reduction of the battery in the DWPT-BS option is not relevant (from 1358 kg to 1315 kg in 2030 see Table 13). Reduced emissions from a lighter vehicle (vehicle mass + battery) are compensated by a lower transmission efficiency (80% between primary and secondary coil).

**Table 29: Global Warming per km travelled by HDVs with different recharging technologies in motorway scenario in 2030. HDV lifetime: 650,000 km; one battery replacement.**

| Global Warming | BEV | DWPT-BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [g $CO_2$-eq/km] | 102.02 | 103.62 | 103.62 |
| Battery production [g $CO_2$-eq/km] | 36.11 | 34.94 | 36.12 |
| WTW [g $CO_2$-eq/km] | 297.73 | 294.20 | 294.44 |
| Infrastructure [g $CO_2$-eq/km] | - | 0.000009 | 0.000009 |
| Total [g $CO_2$-eq/km] | 435.86 | 432.76 | 434.18 |

Compared to the SUVs case, the production share is lower, because of a higher expected lifetime (650,000 km vs. 200,000 km).

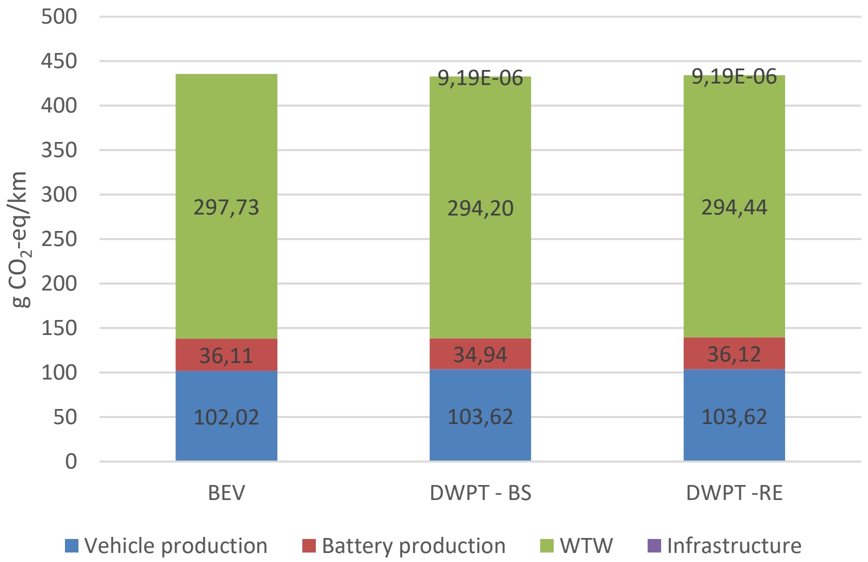


**Figure 14: Global Warming per km travelled by HDVs with different recharging technologies in motorway scenario in 2030. HDV lifetime: 650,000 km; one battery replacement.**

The Cumulative Energy Demand reflects the same trend as $CO_2$-eq, except for what concern the infrastructure (see Figure 15 and appendix for the numeric results).

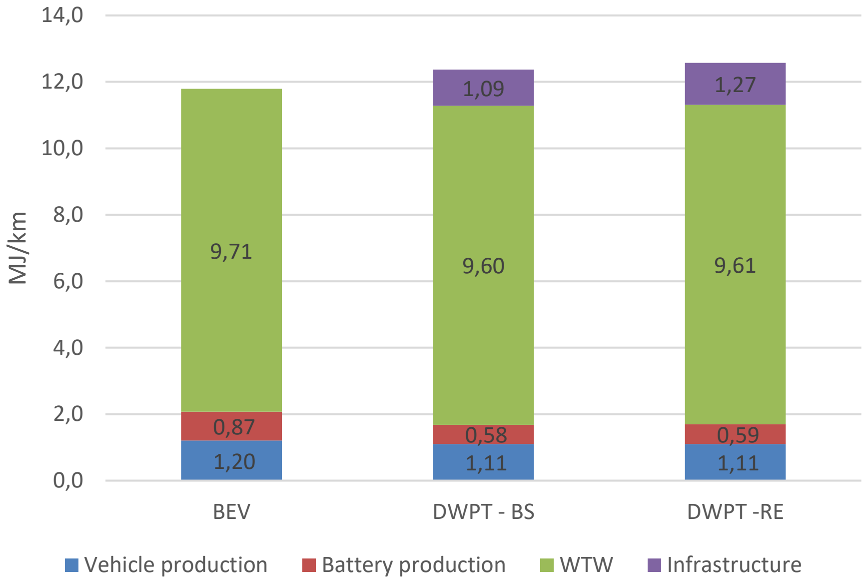


**Figure 15: Cumulative Energy Demand per km travelled by HDVs with different recharging technologies in motorway scenario in 2030. HDV lifetime: 650,000 km; one battery replacement.**

The scenario at 2050 (Figure 16) shows the same effect as LDV, whit a share from WTW phase almost null because of the relevant share of renewable emissions in the 2050 European electricity mix (Table 24). For numeric values and Cumulative Energy Demand results see the appendix.

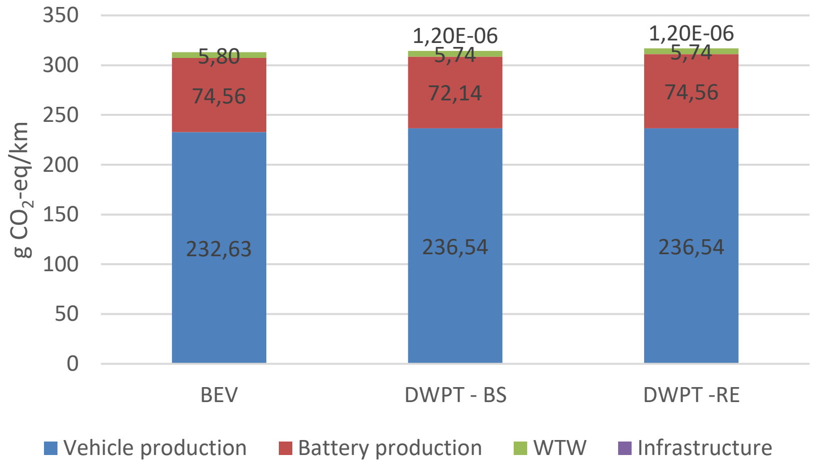


**Figure 16: Global Warming per km travelled by HDVs with different recharging technologies in motorway scenario in 2050. HDV lifetime: 650,000 km; one battery replacement.**

## 7.2 Periurban scenario

Results from the analysis are reported in Table 30.

**Table 30: Global Warming per km travelled by HDVs with different recharging technologies in periurban scenario in 2030. HDV lifetime: 650,000 km; one battery replacement.**

| Global Warming | BEV | DWPT-BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [g $CO_2$-eq/km] | 102.02 | 103.62 | 103.62 |
| Battery production [g $CO_2$-eq/km] | 30.39 | 29.40 | 30.39 |
| WTW [g $CO_2$-eq/km] | 241.38 | 240.72 | 240.97 |
| Infrastructure [g $CO_2$-eq/km] | - | 0.0032 | 0.0032 |
| Total [g $CO_2$-eq/km] | 373.78 | 373.74 | 374.98 |

Even in this scenario, the battery reduction is negligible and does not allow for significant $CO_2$-eq emissions or energy consumption reductions (for CED see table in appendix).

However, differently from the motorway scenario for HDVs, here the relevance of the infrastructure is almost null already in 2030, thanks to its high exploitation rate.

The relative difference remains the same between the three technologies also at 2050, when a European mix relying on renewable brings WTW emissions to zero (Table 24).

Table 31: Global Warming per km travelled by HDVs with different recharging technologies in periurban scenario in 2050. HDV lifetime: 650,000 km; one battery replacement.

| Global Warming | BEV | DWPT-BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [g $CO_2$-eq/km] | 92.64 | 94.20 | 94.20 |
| Battery production [g $CO_2$-eq/km] | 22.95 | 22.20 | 22.95 |
| WTW [g $CO_2$-eq/km] | 4.66 | 4.66 | 4.66 |
| Infrastructure [g $CO_2$-eq/km] | - | 0.0008382 | 0.0008382 |
| Total [g $CO_2$-eq/km] | 120.24 | 121.06 | 121.80 |

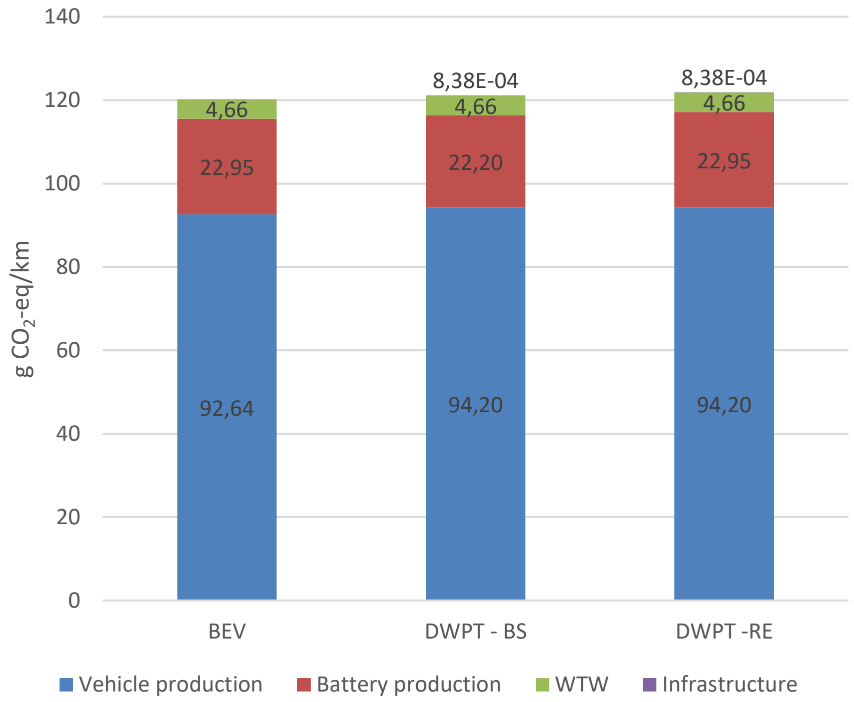


Figure 17: Global Warming per km travelled by HDVs with different recharging technologies in periurban scenario in 2050. HDV lifetime: 650,000 km; one battery replacement.

## 7.3 Urban scenario

The urban scenario, presents the performances of a bus recharging on dedicated lines along the path and at stops.

It is the most promising scenario as entry point of DWPT technology in the transport sector, especially for cities that already have with trolley lanes. Also, from the environmental pint of view is the one that allows for the higher $CO_2$-eq and energy savings, due to the peculiarity of bus routes in the cities (predefined trips, lots of stops, reserve lines…).

In this scenario only the application of DWPT as battery shrinking option is considered viable since they do not require a range extension from the infrastructure. Predefined routes and manifold recharging spots make this kind of transportation detached from range anxiety problems.

However, in order to presents the results in a homogeneous way with respect to previous scenarios, also a range extended option has been considered.

LCA results from this technology are reported in Table 32 and Figure 18 (for CED results see appendix).

**Table 32: Global Warming per km travelled by buses with different recharging technologies in urban scenario in 2030. Bus lifetime: 650,000 km one battery replacement.**

| Global Warming | BEV | DWPT-BS |
|---|---|---|
| Vehicle production [g $CO_2$-eq/km] | 89.19 | 90.55 |
| Battery production [g $CO_2$-eq/km] | 30.47 | 3.15 |
| WTW [g $CO_2$-eq/km] | 162.12 | 179.45 |
| Infrastructure [g $CO_2$-eq/km] | - | 0.019 |
| Total [g $CO_2$-eq/km] | 281.77 | 273.16 |

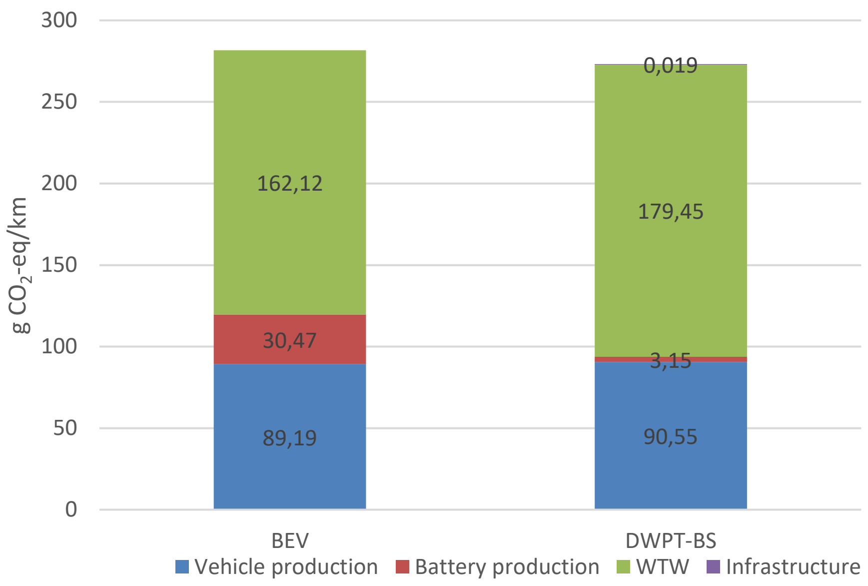


**Figure 18: Global Warming per km travelled by buses with different recharging technologies in urban scenario in 2030. Bus lifetime: 650,000 km; one battery replacement.**

DWPT technology allows for a significant reduction in the battery size, drastically reducing the emissions due to the battery production. However, higher energy consumption during use phase makes it still a slightly worst option compared to a plug-in BEV, due to the lower transmission efficiency (80%).

In the 2050 scenario, when the energy mix is almost zero, the impact of the production phase becomes the most relevant, making the DWPT technology a suitable option in reducing $CO_2$-eq emissions. See Figure 19.

**Table 33: Global Warming per km travelled by buses with different recharging technologies in urban scenario in 2050. Bus lifetime: 650,000 km; one battery replacement.**

| Global Warming | BEV | DWPT-BS |
|---|---|---|
| Vehicle production [g $CO_2$-eq/km] | 76.97 | 78.29 |
| Battery production [g $CO_2$-eq/km] | 19.33 | 1.99 |
| WTW [g $CO_2$-eq/km] | 2.86 | 3.24 |
| Infrastructure [g $CO_2$-eq/km] | - | 0.01 |
| Total [g $CO_2$-eq/km] | 99.16 | 83.54 |

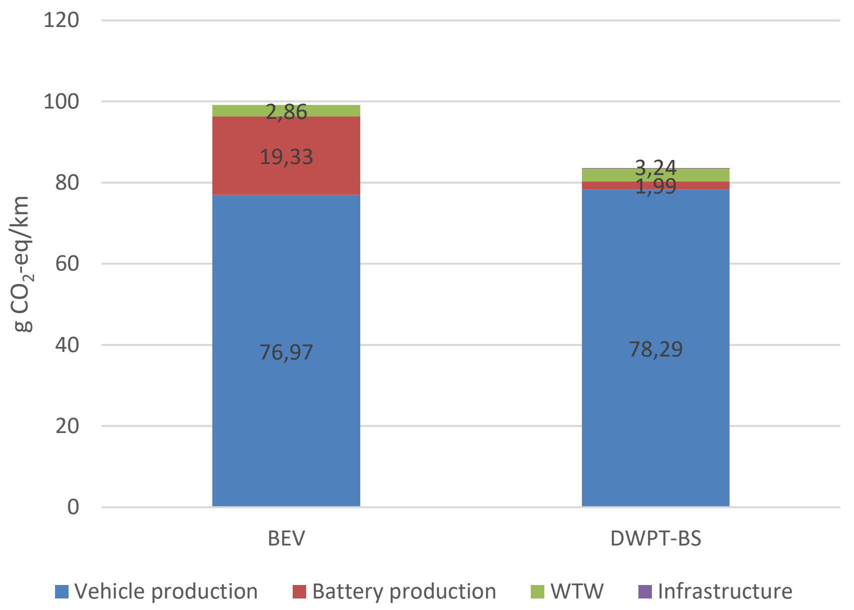


**Figure 19: Global Warming per km travelled by buses with different recharging technologies in urban scenario in 2050. Bus lifetime: 650,000 km; one battery replacement.**

For CED results please see appendix.

# 8 CONCLUSIONS

This deliverable analysed from an environmental point of view the possible effects on Global Warming and the Cumulative Energy Demand due to the introduction of DWPT.

Three scenarios have been selected as most appropriate for the introduction of such technologies. The motorway scenario consists of an e-Corridor exploited both by passenger cars and Heavy-duty vehicles, while the urban and periurban scenarios are meant for bus exploitation and HDV exploitation respectively.

For each scenario, the effects by a Battery Electric Vehicle and a vehicle using DWPT recharging technology, in two options: battery shrink (BS) option and range extend (RE), have been calculated.

The major aspect common to all the scenarios is that the complete LCA results are not so different between the three vehicle types. This equivalence makes more important the business model analysis in D5.5.2, as a decision may be taken based on cost issues.

Another relevant aspect is that the share of the infrastructure is negligible in almost every scenario due to its high exploitation. This happens because the infrastructure is supposed to be built in high-density areas, and a high penetration of EVs and DWPT technology is expected.

Detectable shares of the infrastructure can be seen in the urban scenarios, where the urban e-Road is used only by the urban bus fleet. It is worth noting that the impacts of the bus fleet have been expressed in g $CO_2$-eq/km to allow for an easy comparison with the other scenarios, but It has to be considered that the function of an urban bus is rather to transport persons from one place to another. If the values would be expressed in terms of persons/km, the specific impacts of the infrastructure would decrease even more.

In every scenario, the Battery-Shrink option allows for a more significant reduction of the battery size, which results in a reduction in the impacts due to the production of the batteries. The reduced mass of the vehicle also allows a slight reduction in the TTW energy consumption to be achieved during the use phase. However, these slight advantages are offset by the lower efficiency of DWPT recharging systems compared to conventional plug-in recharging systems. Similar considerations apply to DWPT-RE. Therefore, the three recharging options (BEV, DWPT – BS, DWPT – RE) present similar environmental impacts, as already mentioned.

It is worth noting the overall reduction of the impacts through the years: the European energy mix is expected to rely more and more on renewable sources, while the improvements in the lightweight materials used in the production of the vehicles and the increased density of the batteries will be reducing the energy consumption during the use phase.

However, predictions on battery energy density and vehicle composition at 2050 are highly uncertain and have to be considered as a broad guideline for future research and policy orientation.

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# APPENDIX

**Table 34: Global Warming and Cumulative Energy Demand per km travelled by passenger cars with different recharging technologies in motorway scenario in 2030 in Europe. Vehicle and battery lifetime: 200,000 km.**

| Cumulative Energy Demand | BEV | DWPT-BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [MJ/km] | 1.04 | 1.08 | 1.08 |
| Battery production [MJ/km] | 0.10 | 0.09 | 0.10 |
| WTW [MJ/km] | 1.26 | 1.09 | 1.27 |
| Infrastructure [MJ/km] | - | 0.22 | 0.22 |
| Total [MJ/km] | 2.40 | 2.47 | 2.67 |

| Global Warming | BEV | DWPT-BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [g $CO_2$-eq/km] | 92.22 | 95.51 | 95.51 |
| Battery production [g $CO_2$-eq/km] | 8.55 | 7.30 | 8.55 |
| WTW [g $CO_2$-eq/km] | 38.91 | 33.32 | 38.91 |
| Infrastructure [g $CO_2$-eq/km] | - | 0.004605 | 0.004605 |
| Total [g $CO_2$-eq/km] | 139.69 | 136.14 | 142.99 |

**Table 35: Global Warming and Cumulative Energy Demand per km travelled by passenger cars with different recharging technologies in motorway scenario in 2050 in Europe. Vehicle and battery lifetime: 200,000 km.**

| Cumulative Energy Demand | BEV | DWPT-BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [MJ/km] | 0.88 | 0.92 | 0.92 |
| Battery production [MJ/km] | 0.08 | 0.07 | 0.08 |
| WTW [MJ/km] | 1.08 | 1.14 | 1.14 |
| Infrastructure [MJ/km] | - | 0.020781 | 0.020781 |
| Total [MJ/km] | 2.05 | 2.15 | 2.16 |

| Global Warming | BEV | DWPT-BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [g $CO_2$-eq/km] | 78.47 | 81.75 | 81.75 |
| Battery production [g $CO_2$-eq/km] | 6.44 | 5.53 | 6.44 |
| WTW [g $CO_2$-eq/km] | 0.71 | 0.75 | 0.75 |
| Infrastructure [g $CO_2$-eq/km] | - | 0.0004343 | 0.0004343 |
| Total [g $CO_2$-eq/km] | 85.62 | 88.03 | 88.94 |

**Table 36: Global Warming and Cumulative Energy Demand per km travelled by HDVs with different recharging technologies in motorway scenario in 2030 in Europe. HDV lifetime: 650,000 km; one battery replacement.**

| Cumulative Energy Demand | BEV | DWPT-BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [MJ/km] | 1.20 | 1.11 | 1.11 |
| Battery production [MJ/km] | 0.87 | 0.58 | 0.59 |
| WTW [MJ/km] | 9.71 | 9.60 | 9.61 |
| Infrastructure [MJ/km] | - | 1.087245 | 1.269728 |
| Total [MJ/km] | 11.79 | 12.37 | 12.58 |

| Global Warming | BEV | DWPT-BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [g $CO_2$-eq/km] | 102.02 | 103.62 | 103.62 |
| Battery production [g $CO_2$-eq/km] | 36.11 | 34.94 | 36.12 |
| WTW [g $CO_2$-eq/km] | 297.73 | 294.20 | 294.44 |
| Infrastructure [g $CO_2$-eq/km] | - | 0.000009 | 0.000009 |
| Total [g $CO_2$-eq/km] | 435.86 | 432.76 | 434.18 |

**Table 37: Global Warming and Cumulative Energy Demand per km travelled by HDVs with different recharging technologies in motorway scenario in 2050 in Europe. HDV lifetime: 650,000 km; one battery replacement.**

| Cumulative Energy Demand | BEV | DWPT-BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [MJ/km] | 3.65 | 3.71 | 3.71 |
| Battery production [MJ/km] | 0.45 | 0.43 | 0.45 |
| WTW [MJ/km] | 8.83 | 8.74 | 8.74 |
| Infrastructure [MJ/km] | - | 0.02 | 0.02 |
| Total [MJ/km] | 12.92 | 12.90 | 12.92 |

| Global Warming | BEV | DWPT-BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [g $CO_2$-eq/km] | 71.58 | 72.78 | 72.78 |
| Battery production [g $CO_2$-eq/km] | 45.89 | 44.40 | 45.89 |
| WTW [g $CO_2$-eq/km] | 5.80 | 5.74 | 5.74 |
| Infrastructure [g $CO_2$-eq/km] | - | 0.0004343 | 0.0004343 |
| Total [g $CO_2$-eq/km] | 123.26 | 122.92 | 124.41 |

**Table 38: Global Warming and Cumulative Energy Demand per km travelled by HDVs with different recharging technologies in periurban scenario in 2030 in Europe. HDV lifetime: 650,000 km; one battery replacement.**

| Cumulative Energy Demand | BEV | DWPT-BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [MJ/km] | 1.20 | 1.22 | 1.22 |
| Battery production [MJ/km] | 0.37 | 0.35 | 0.37 |
| WTW [MJ/km] | 7.88 | 7.85 | 7.86 |
| Infrastructure [MJ/km] | - | 0.15 | 0.15 |
| Total [MJ/km] | 9.45 | 9.58 | 9.60 |

| Global Warming | BEV | DWPT-BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [g $CO_2$-eq/km] | 102.02 | 103.62 | 103.62 |
| Battery production [g $CO_2$-eq/km] | 30.40 | 29.41 | 30.40 |
| WTW [g $CO_2$-eq/km] | 241.38 | 240.72 | 240.97 |
| Infrastructure [g $CO_2$-eq/km] | - | 0.003206 | 0.003206 |
| Total [g $CO_2$-eq/km] | 373.79 | 373.75 | 374.99 |

**Table 39: Global Warming and Cumulative Energy Demand per km travelled by HDVs with different recharging technologies in periurban scenario in 2050 in Europe. HDV lifetime: 650,000 km; one battery replacement.**

| Cumulative Energy Demand | BEV | DWPT-BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [MJ/km] | 1.12 | 1.14 | 1.14 |
| Battery production [MJ/km] | 0.28 | 0.27 | 0.28 |
| WTW [MJ/km] | 7.10 | 7.09 | 7.10 |
| Infrastructure [MJ/km] | - | 4.0E-02 | 4.0E-02 |
| Total [MJ/km] | 8.49 | 8.54 | 8.55 |

| Global Warming | BEV | DWPT-BS | DWPT-RE |
|---|---|---|---|
| Vehicle production [g $CO_2$-eq/km] | 92.64 | 94.20 | 94.20 |
| Battery production [g $CO_2$-eq/km] | 22.95 | 22.20 | 22.95 |
| WTW [g $CO_2$-eq/km] | 4.66 | 4.66 | 4.66 |
| Infrastructure [g $CO_2$-eq/km] | - | 0.0008382 | 0.0008382 |
| Total [g $CO_2$-eq/km] | 120.24 | 121.06 | 121.80 |

**Table 40: Global Warming and Cumulative Energy Demand per km travelled by buses with different recharging technologies in urban scenario in 2030 in Europe. Bus lifetime: 650,000 km; one battery replacement.**

| Cumulative Energy Demand | BEV | DWPT-BS |
|---|---|---|
| Vehicle production [MJ/km] | 1.03 | 1.05 |
| Battery production [MJ/km] | 0.37 | 0.04 |
| WTW [MJ/km] | 5.29 | 5.86 |
| Infrastructure [MJ/km] | - | 0.89 |
| Total [MJ/km] | 6.69 | 7.83 |

| Global Warming | BEV | DWPT-BS |
|---|---|---|
| Vehicle production [g $CO_2$-eq/km] | 89.19 | 90.55 |
| Battery production [g $CO_2$-eq/km] | 30.47 | 3.15 |
| WTW [g $CO_2$-eq/km] | 162.12 | 179.45 |
| Infrastructure [g $CO_2$-eq/km] | - | 0.019 |
| Total [g $CO_2$-eq/km] | 281.77 | 273.16 |

**Table 41: Global Warming and Cumulative Energy Demand per km travelled by buses with different recharging technologies in urban scenario in 2050 in Europe. Bus lifetime: 650,000 km; one battery replacement.**

| Cumulative Energy Demand | BEV | DWPT-BS |
|---|---|---|
| Vehicle production [MJ/km] | 0.91 | 0.93 |
| Battery production [MJ/km] | 0.23 | 0.02 |
| WTW [MJ/km] | 4.35 | 4.93 |
| Infrastructure [MJ/km] | - | 0.67 |
| Total [MJ/km] | 5.50 | 6.55 |

| Global Warming | BEV | DWPT-BS |
|---|---|---|
| Vehicle production [g $CO_2$-eq/km] | 76.97 | 78.29 |
| Battery production [g $CO_2$-eq/km] | 19.33 | 1.99 |
| WTW [g $CO_2$-eq/km] | 2.86 | 3.24 |
| Infrastructure [g $CO_2$-eq/km] | - | 0.01 |
| Total [g $CO_2$-eq/km] | 99.16 | 83.54 |