Life Cycle Assessment of a heavy metro train

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NOMENCLATURE:

AB: AnsaldoBreda;
ADPe: Abiotic Depletion Potential elements;
ADPf: Abiotic Depletion Potential fossil;
AP: Acidification Potential;
CED: Cumulative Energy Demand;
EoL: End of Life;
EP: Eutrophication Potential;
EPD: Environmental Product Declaration;
E_{RR}: Electricity per Round Route;
FAETP: Fresh water Aquatic Eco-Toxicity Potential;
FU: Functional Unit;
GHG: GreenHouse Gas;
GWP: Global Warming Potential;
HSR: High Speed Rail;
HTP: Human Toxicity Potential;
HVAC: Heat Ventilation Air Conditioning;
ICE: Inter City Express;
LC: Life Cycle;
LCA: Life Cycle Assessment;
LCI: Life Cycle Inventory;
LCIA: Life Cycle Impact Assessment;
MAETP: Marine Aquatic Eco-Toxicity Potential;
MIPS: Material Input Per Service;
MS: Material Sheet;
ODP: Ozone Depletion Potential;
OEMs: Original Equipment Manufacturers;
PCR: Product Category Rule;
PEE: Potential Environmental Effect;
PG: Product Group;
PKT: Passenger Kilometres Travelled;
POCP: Photochemical Ozone Creation Potential;
PU: Process Unit;
SI: Supporting Information
TETP: Terrestrial Eco-Toxicity Potential;
TS: Transport Sheet;
VKT: Vehicle Kilometres Travelled;
VO: Vehicle Occupancy.

Keywords:
Life Cycle Assessment; heavy metro train; environmental impact; eco-design; energy consumption

1. Introduction

1.1. The transportation sector

Our global society is strongly dependent on transportation with development trends indicating a substantial growth in this sector over the coming decades (Hawkins at al., 2012). The transportation industry (including all the transport modes, from air to surface traffic) is currently the second largest contributor to anthropogenic GreenHouse Gas (GHG) emissions within the European Union. Around 20% of these emissions are generated by road transportation, including both private/public and passenger/freight vehicles (Witik et al., 2011). Globally, light-duty vehicles account for approximately 10% of total energy use and GHG emissions (Solomon et al., 2007). According to a study commissioned by the World Business Council for Sustainable Development (2004), light-duty vehicles ownership could increase from roughly 700 million to 2 billion over the period 2000-2050. These patterns forecast a dramatic increase in gasoline and diesel demand that will have implications on energy security, climate chang and urban air quality (Hawkins at al., 2012).

In light of these considerations, environmental analyses and eco-design solutions have been applied in depth to all the Life-Cycle (LC) stages of automotive vehicles and components (Berzi et al., 2013; Cappelli et al., 2007; Mayyas et al., 2012). In this context, many Life Cycle Assessments (LCAs) (Chanaron, 2007; Finnveden et al., 2009; ISO14040, 2006; ISO 14044, 2006) of both conventional (Finkbeiner et al., 2006; Schmidt et al., 2004; Spielmann and Althaus, 2006)) and innovative (Alves et al., 2009; Du JD et al., 2010; Duflou et al., 2009; Luz et al., 2010; Mayyas et al., 2011; Vinodh and Jayakrishna, 2011; Zah et al., 2006) alternatives for personal transportation have been performed to understand how the associated impacts can be reduced. However, less interest has been paid to the transportation by railway.;Some studies limit their field of investigation to the railway sector, others make a comparison between railway and different types of transportation emphasising the influence that they have on specific areas. The results for the multi-mode studies, particularly when considering the impact to Global Warming, suggest railways can be a more environmentally preferred mode of transportation when compared with other modes such as roadways.

Stodolsky et al. (1998) compared the environmental profile of rail and on-road transportation modes. Energy use and emissions are examined for the modes “truck” and “rail” relative to freight transport and taking into account the whole vehicle LC. Using secondary data for energy use and emissions, the article identifies the use stage as the greatest contributor to environmental impacts for both modes. Transport by freight train requires less energy and produces approximately one third of the emissions of transport by truck.

Rozycki et al. (2003) conducted a screening LCA of the German high-speed passenger train ICE. Data collection was based on inventory values supplied by railway experts and internal documents of rail operators. In the study resource consumption caused by traction, manufacturing and maintenance of the train as well as construction and operation of the supporting infrastructures and buildings were considered. As reference for the impact assessment, the 100-person-kilometre unit was as the functional unit, with impact categories of Cumulative Energy Demand (CED), cumulative Material Input Per Service unit (MIPS) and CO_2 emissions. The results state that the use stage represents the greatest contribution to CED, while infrastructure and train manufacturing/maintenance contribute 13%. In terms of MIPS, traction energy accounts for 31%, with the rest arising from infrastructure and train/manufacturing processes. As one might expect, CO_2 emissions were dominated by energy-related processes.

Struckl and Wimmer (2007) conducted a cradle-to-grave, screening-level LCA of a metro train produced by SIEMENS for operation in the Oslo area. Their assessment included a range of categories describing impacts to health, the environment and resource use. A contribution analysis by stage of the Global Warming impacts identified the phase as the most relevant, followed by material acquisition and manufacturing. A detailed analysis of contributions coming from single vehicle systems denotes that traction and heating have the greatest influence on the impact caused by the use stage. The impacts during material acquisition and manufacturing are predominantly associated with the car body and boogies.

A comparative LC energy and emissions inventory for three U.S. metropolitan regions is presented by Chester et al. (2009). The study considered different transport modes (automobile, diesel rail, electric rail and ferry service) and captures both vehicle operational (direct fuel and electricity consumption) and non-operational (vehicle manufacturing, roadway maintenance, infrastructure operation and material production) components. Life cycle inventories for the three regions were developed using surveys and existing inventory datasets for the various modes of transportation. Functional units based on either the Passenger Kilometres Travelled (PKT) and Vehicle Kilometres Travelled (VKT) were used as the basis for comparison. The automobiles were identified as the dominant source of impact, accounting for 86-96% of the regional energy use and emissions. Disaggregation of transportation modes between off-peak and peak travel time denotes the significance of automobile emissions to system-wide emissions but the increase of VO in public transit and the consequent improvement of the per-PKT performance can offset this.

Chester and Horvath (2009) compared the LC energy and GHG emissions for different transportation typologies in the US (buses, trains, and airplanes), including the supply chain and production of vehicles, infrastructures and fuel. Secondary data sources from publicly available literature were used to model the selected transportation modes. The results, calculated with respect to the Passenger Kilometres Travelled (PKT) indicate both energy consumption and GHG emissions are better for commuter and light rail systems when compared with buses (urban diesel) and aircraft (small, midsize and large). A contribution analysis by stage determined the dominant share of both energy use and emissions for road and air modes is associated with operational components, while these values for railways were more strongly influenced by non-operational components. Sensitivity analysis based on variation of Vehicle Occupancy (VO) found the relative performance of modes was highly dependent on the number of passengers.

Chester and Horvath (2010) continued their work with the goal to assess the environmental profile of a High Speed Rail (HSR) connecting four American cities on a route of approximately 1200 km. A LC energy and GHG analysis was used to compared the impacts associated with traveling this distance for multiple transportation modes, including heavy rail transit, automobiles and aircraft. The life cycle inventories were based on secondary sources and contained preliminary design estimates for the energy inputs and emissions associated with the production, operation and maintenance of a HSR system, including infrastructure construction. Train manufacturing and maintenance data are assumed to be the same as a similar German vehicle, the Inter City Express (ICE) and modelled in SimaPro (PRé Consultants, 2013) using the Ecoinvent database (Frischnecht et al., 2004; Swiss Centre for Life Cycle Inventories, 2013). The inventory results, normalised with respect to PKT and calculated for a variable VO, show that HSR energy and GHG performance is dominated by train operation, with significant contributions from infrastructure construction and electricity production. In comparison with the other modes, HSR has the potential to consume the least amount of energy and produce the lowest level of GHGs per PKT, with the comparative reduction of these values increasing as the VO increases.

Chester and Horvath (2012) expanded their work to address mobility in the California corridor by another LCA. A PKT LC inventory including vehicle, infrastructure and energy production is developed for future (efficient and electric) automobiles, HSRs and aircraft. The analysis takes into account emerging fuel-efficient vehicles, new train designs and production of consumed electricity from renewable resources. The results denote that human health and environmental damage potentials are often dominated by non-propulsion components (vehicle manufacturing, infrastructure construction and energy production). The high-speed rail again has the potential to reduce transportation impacts. The key hotspots identified for improvement were operation consumption and occupancy of the train, infrastructure construction and fossil fuel intensity of the electricity mix.

Recently Chester et al. (2013) conducted a LCA comparing the new rapid bus transit and light rail lines in Los Angeles. The analysis included the manufacturing and maintenance of both the vehicles and their respective infrastructure in addition to energy production for propulsion during use. Energy consumption, GHG emissions and criteria pollutants were evaluated using both attributional and consequential LCA to understand both the near and long term impacts. Based on the results, infrastructure, vehicle and energy production components drive the resulting impacts for both transportation modes. Reductions in these impacts is possible by improving the efficiency of the power generation technologies associated with either production or vehicle propulsion. In addition, shifts of transit riders from automobiles to bus and rail vehicles would reduce city GHG emissions.

Recently, great attention was paid to the development of Environmental Product Declarations (EPDs) (International EPD System, 2013a) in the railway sector. An EPD is a certified environmental declaration based on LCA in accordance with the ISO 14040 standards (ISO 14040, 2006). More specifically, ISO 14025 (2010) defines EPD as “quantified environmental data for a product with pre-set categories of parameters, but not excluding additional environmental information”. In this perspective worldwide manufacturers deal with LCA analyses in order to collect data for EPDs of their vehicles. To date, examples of published EPDs exist for a large variety of vehicles like trams, metros and regional and intercity trains (AnsaldoBreda 2010a, 2011; Bombardier 2010a, 2010b, 2010c, 2012a, 2012b; CAF Construcciones y Auxiliar de Ferrocarriles 2011a, 2011b; SIEMENS 2005).

The overview of the studies presented above and the EPDs recently obtained by the main Original Equipment Manufacturers (OEMs) confirm the railway sector is a strategic area for future reduction of environmental impact due to transportation. From thethe LCA analyses presented above, it can be concluded that:

- LCAs focus on a single or limited set of environmental indicators, with energy consumption and GHG emissions being the most common;

- Secondary sources have primarily been used for inventory modeling;

- Only a small number of studies for trains and, in particular, heavy metro vehicles are available that have yet to be critically compared.

1.2. Objectives of the paper

This study involves a full cradle-to-grave LCA of a heavy metro train. In comparison to existing studies, this work examines a broader range of impacts to human and ecosystems health (Joint Research Centre, 2011) using primary data supplied by vehicle manufacturers whenever possible to reduce the uncertainty of results.
The final objectives of the study are:

- Determine the detrimental LC stages ("hotspots") for a metro train based on a broader set of impact categories and establish a baseline for comparison with similar vehicles;

- Identify potential product improvements to support recommendations for future design strategies;

- Compare the impacts of a metro train with similar vehicles.

2. Methods

As stated by the Product Category Rules (PCR) 2.0 (International EPD System, 2013b), the metro train (metro) object of the present study belongs to the passenger transportation category "Passenger service type - Urban - High passenger capacity". The vehicle is manufactured by AnsaldoBreda (AB) and is destined to operate in the metropolitan network of Rome; Table 1 summarises its main technical/operational features.

AB metro	
N° coaches	6
Total length	110 [m]
Width	2.85 [m]
Mass	193 [t]
Max seated passengers	194
Traction	Electric
Max. speed	90 [km/h]

Table 1. AB metro main technical and operational features

According to PCR 2.0, metro components are allocated into five Product Groups (PGs) named depending on technical reference area; table 2 reports distribution of vehicle mass between PGs.

Materials	
Product group	**% of total mass**
1. Car body	19.7
2. Interior, windows and doors	16.9
3. Boogies and running gears	44.2
4. Propulsion and electric equipment	16.5
5. Comfort systems	2.7
Total vehicle	100

Table 2. Distribution of vehicle mass between PGs

2.1. Goal and scope

With the scope to estimate as comprehensively as possible the effects on eco-system due to the metro LC, the present LCA quantifies:

- Material, Energy, Hydric resources consumption and Waste production;
- Potential Environmental Effects (PEEs) regarding both human and ecosystem health;
- Recoverable/Non-recoverable quantity of materials constituting the metro.

2.2 Functional Unit

The main function of a passenger rail vehicle is the transportation of a given number of passengers over a predefined distance: the FU chosen to conduct the LCA of the metro is the VKT assuming normal operational passenger load as stated by paragraph 6.2 of UNI EN 15663 (2009) (80% of seats occupied and 3.2 passengers/m^2 in standing area) and a 30-year lifetime.

System boundaries

The metro LC consists of three stages: material acquisition, manufacturing, use and end of life. The stages are shared in Process Units (PUs) which, in turn, include single processes. Table 3 summarises PUs and processes for each LC stage.

	Stage	**Process Unit (PU)**	**Process**
Metro Life Cycle	Material acquisition	Raw materials extraction and production	Production of electricity, heat, steam and fuel for raw materials extraction and production (considering both vehicle components and spare parts for maintenance) Raw materials extraction and production processes
		External transportations	Fuel production for transportation of materials and manufactured components/assemblies from suppliers facilities to AB assembly plants
	Manufacturing	Manufacturing and assembly	Production of electricity, heat, steam, fuel and auxiliary material for manufacturing and assembly activities Manufacturing and assembly processes
		Internal transportations	Fuel production for transportation of components and assemblies between AB plants Fuel production for delivery of the vehicle to the customer
	Use	-	Production and supply of electricity for vehicle operation during 30 years life-time
	End of life	Recovery	Production of electricity, heat, steam and fuel for vehicle disassembly and shredding Production of electricity, heat, steam and fuel for materials recycling
		Disposal	Waste incineration (energy recovery) Landfilling of waste materials

Table 3. Process Units and processes composing LC stages

2.2. Life Cycle Inventory (LCI)

2.2.1. Data collection

Data collection has been performed for all PUs included in LC stages. Data gathered come directly from real operators of processes.

2.2.1.1 MATERIAL ACQUISITION

Regarding PU "Raw materials extraction and production", data collection consists of determination of typology and quantity of materials constituting the whole vehicle. Collection has been performed by compiling Material Sheet (MS) for each component present in the metro; compilation of MSs has been realised by both AB suppliers (for components manufactured externally) and AB personnel (for components manufactured internally) by direct measurements on specific components/assemblies. The mass of each material constituting the component is reported in MS; furthermore, percentage of recycled used to produce the component and percentage of recyclable at EoL are indicated. Figure 1 summarises material composition of the vehicle, obtained by unifying data from all collected MSs.

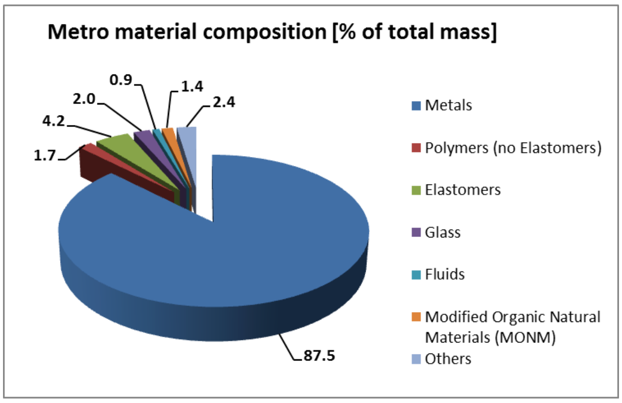


Figure 1. Data collection for PU "Raw materials extraction and production": metro material composition

Concerning components and substances substituted in maintenance (e.g. battery, brake disc, brake pad, oil, etc), data collection consists of quantification of substituted components/materials both in preventive maintenance (planned activities) and in corrective maintenance (unexpected activities to reactivate functionality against malfunctioning or breakages) during metro LC.
The number of components and quantity of materials involved in preventive maintenance have been evaluated based on AB maintenance specifications; estimations for corrective actions have been deduced from maintenance operation of similar AB vehicles. Table A in the SI (Supporting Information) Appendix reports the % of total mass substituted during metro LC for each component replaced in maintenance (preventive and corrective).

Data collection relative to PU "External transportations" characterises transportation of raw materials and manufactured components/assemblies from suppliers facilities to AB plants. For each transport executed, truck typology, travelled distance and transported mass have been reported in a Transport Sheet (TS); compilation of TSs has been performed by AB suppliers who deal with transportation. Table B in the SI Appendix summarises external TSs data with regard to the production of a single vehicle.

2.2.1.2. MANUFACTURING

Data collection concerning PU "Manufacturing and assembly" regards inputs/outputs involved in manufacturing and assembly processes conducted in AB plants. These can be summarised as follows:

- Production of electric parts, boogies and motors;
- Carpentry operations in assembly of car-body structures;
- Car surface treatments and painting;
- Car-body fitting.

Data come from AB and have been obtained by direct measurements on real manufacturing processes performed inside AB plants. Table C in the SI Appendix summarises the percentage of input/output flows exchanged with environment due to PU "Manufacturing and assembly" with regard to the production of a single vehicle.

Data collection relative to PU "Internal transportations" characterises:

- Internal transportations of metro components and assemblies between AB plants of Naples and Reggio Calabria;
- Delivery of the vehicle to the customer.

The typology of information and the collection modality are the same of PU "External transportations". Data are from AB suppliers who physically perform transports. Table D in the SI Appendix reports a summary of internal TSs data with regard to the production of a single vehicle.

2.2.1.3 USE

Data collection regarding Use stage is constituted by the amount of electricity consumed by the vehicle. Since the metro is not yet operative, this data has been obtained by calculations directly conducted by AB; by travel simulations based on physical and operational features of vehicle and route, average Electricity consumption per Round Route (E_{RR}) has been determined. Consumption contemplates also energy absorption of auxiliary devices like Heat Ventilation and Air Conditioning (HVAC), lighting, communication system and pneumatic braking, including quantity of electricity sent back to the supply line by recovery braking. In AB travel simulations, VO has been assumed as the maximum established for operational conditions, all seats occupied and 6 passengers/m^2 in standing areas. Table E in the SI Appendix reports metro average per-PKT E_{RR} considering maximum operational VO (all seats occupied and 6 pass/m^2).

2.2.1.4 END OF LIFE

Necessary data for PUs “Recovery” and “Disposal” is the quantity of each material which composes the vehicle. Material composition of the metro is needed to determine the amount of material involved in each specific recovery and disposal process. Such data coincide with those included in MSs, collected for PU “Raw materials extraction and production” of Material acquisition stage.

Correlation of LCI data to FU

Since data collection refers to the whole metro LC, all LCI data have been related to the FU by following relation:

$$D_{FU} = D_{LC}/N$$

Where:

D_{FU} = Generic LCI data expressed with regard to FU
D_{LC} = Generic LCI data expressed with regard to LC
N = Number of kilometres travelled during lifetime

“N” has been calculated based on the estimation of 30 years for vehicle lifetime; route lengths, timetables (working days/holidays) and service frequencies directly furnished by AB have been taken into account in the calculation.
The only exception is represented by use electricity consumption whose value refers to the energy absorbed on the single round route (E_{RR}) and not during the entire LC. In this case, the following equation has been used:

$$E_{FU} = E_{KT} = E_{RR}/N_{RR}$$

Where:

E_{FU} = Use Electricity consumption expressed with regard to FU
E_{KT} = Average use Electricity consumed per Kilometre Travelled
N_{RR} = Number of kilometres travelled in Round Route

2.2.2. Modelling

GaBi6 software has been used to:

secondary LCI data regarding raw material extraction/production and End of life processes To environmentally characterise all stages which compose metro LC, an analytical model reproducing real processes, based on LCI data collection, has been created; for the development of such model, GaBi6 software (PE International, 2013) has been used.

2.2.3. Assumptions

Calculation of use electricity consumption with regard to the FU load configuration

Use electricity consumption provided by AB takes into account maximum operational VO (all seats occupied and 6 pass/m^2). To determine consumption with respect to the FU load configuration (referring to normal operational occupancy, 80% of seats occupied and 3.2 pass/m^2) as well as to other VOs, an analytical model for the use electricity consumption in function of VO has been developed.
The model is based on Barrero et al. (2008), in which data on electricity consumption of a vehicle similar to the AB metro both for tare mass, passenger capacity and installed power are reported with regard to different load configurations. By linear interpolation of Barrero data, a linear relation between number of passengers and vehicle consumption has been determined. From this relation, consumption of Barrero metro has been determined for the VOs

- Empty vehicle (0 passengers)
- All seats occupied and 6 pass/m^2

obtaining that the percent reduction of consumption from maximum operational VO to empty vehicle is equal to 16.3%. Finally, the analytical model to calculate the consumption in function of number of passengers has been determined as:

$$E_n = E_{max} ((1- (16.3/100)) * (N_{max}-n)/N_{max})$$

Where:
n = Number of passengers
E_n = Use Electricity consumption with "n" passengers
E_{max} = Use Electricity consumption referring to maximum operational VO
N_{max} = Number of passengers referring to maximum operational VO

This relation has been used to determine normal operational consumption of the AB metro referring to FU load configuration, starting from consumption related to maximum operational VO obtained by AB calculations; by the same equation, consumption referring to load configurations examined in sensitivity analysis is determined.

Note: Since Barrero reports only the total number of passengers without any subdivision in seated and standing, in order to estimate the % fraction of seated passengers, the following assumption, valid for AB metro, has been extended to Barrero vehicle:

$$(\text{N° seats}) / (\text{Standing area in m}^2) = 1.15$$

Modelling
The assumptions made in GaBi6 modelling are described below.

- Since the entire metro LC takes place in Italy, the Italian energy mix has been used to model production of energy consumed in both manufacturing and use phase
- MSs supply only mass of material physically on the vehicle; during surface treatments a certain quantity of solvent is loss in application and drying of enamels/plasters. To consider this phenomenon, the quantity of lost solvent is estimated as percentage of the applied product; table F in the SI Appendix reports solvent percentage with regard to total mass of applied enamel/plaster in metro surface treatments
- Production processes of some materials/substances are not characterised in GaBi6 database; table G in the SI Appendix reports GaBi6 processes adopted as surrogate for the real ones.

Calculation of recoverable mass
Recoverable percentage of total vehicle mass depends not only on material typology but also on modalities of combination with other materials. Nowadays a specific regulation which indicates EoL treatments of materials involved in railway vehicles does not exist and a forecast of EoL activities looks very unreliable since the useful lifetime of the vehicle is about three decades long.
The categories by which materials constituting the metro have been classified are assumed from PCR 1.0 (International EPD System, 2009) while allocation in EoL treatments of mass of each category has been determined by the mean value of the % intervals proposed in Appendix B "General material recycling figures and common EoL treatment methods" of PCR 1.0. Efficiency of recycling/recovery processes has been assumed from PCR 2.0 (International EPD System, 2013b) which refers to UNIFE (2013).
For the calculation of recyclability/recoverability rate, following relations, based on the method proposed by ISO 22628 (2002), have been used:

$$R_{cyc} = (\Sigma\, (m_{P\ Recyc\ i} + m_{D\ Recyc\ i} + m_{M\ i} + m_{Tr\ i}) / m_V) * 100$$

$$R_{rec} = (\Sigma\, (m_{P\ Recyc\ i} + m_{P\ Recov\ i} + m_{D\ recyc\ i} + m_{D\ recov\ i} + m_{M\ i} + m_{Tr\ i} + m_{Te\ i}) / m_V) * 100$$

$$m_L = m_V - (\Sigma\, (m_{P\ Recyc\ i} + m_{P\ Recov\ i} + m_{D\ recyc\ i} + m_{D\ recov\ i} + m_{M\ i} + m_{Tr\ i} + m_{Te\ i}))$$

Where:

i = Material subscript
R_{cyc} = Vehicle recyclability percentage
R_{rec} = Vehicle recoverability percentage
$m_{P\ Recyc}$ = Mass of material taken into account at the pre-treatment and effectively recyclable
$m_{P\ Recov}$ = Mass of material taken into account at the pre-treatment and effectively recoverable as energy
$m_{D\ Recyc}$ = Mass of material taken into account at the dismantling and effectively recyclable
$m_{D\ Recov}$ = Mass of material taken into account at the dismantling and effectively recoverable as energy
m_M = Mass of material taken into account at the metallic separation and effectively recyclable
m_{Tr} = Mass of material taken into account at the non-metallic residue treatment and effectively recyclable
m_{Te} = Mass of material taken into account at the non-metallic residue treatment and effectively recoverable as energy
m_L = Mass of material destined to landfilling
m_V = Total mass of vehicle

Table H in the SI Appendix summarises the resulting set of percentages regarding mass allocation to EoL treatments and EoL partial masses assumed in the study.

2.3. Life Cycle Impact Assessment (LCIA)

A series of LCIA methods such as Eco-indicator 99 (Goedkoop and Spriensma, 2000), CML (Centre for Environmental Studies - Leiden, 2013) and Impact 2002+ (Jolliet et al., 2003) exist (Althaus et al., 2010, Joint Research Centre, 2010). The method used for the impact assessment of the metro LC is the CML 2001 (Centre for Environmental Studies - Leiden, 2013). Impact category indicators are reported below:

- ✓ Abiotic Depletion Potential elements (ADPe);
- ✓ Abiotic Depletion Potential fossil (ADPf);
- ✓ Acidification Potential (AP);
- ✓ Eutrophication Potential (EP);
- ✓ Fresh water Aquatic Eco-Toxicity Potential (FAETP);
- ✓ Global Warming Potential (GWP);
- ✓ Human Toxicity Potential (HTP);
- ✓ Marine Aquatic Eco-Toxicity Potential (MAETP);
- ✓ Ozone layer Depletion Potential (ODP);
- ✓ Photochemical Ozone Creation Potential (POCP);
- ✓ Terrestrial Eco-Toxicity Potential (TETP).

3. Results

Metro LCA results are reported concerning the established FU (per-VKT) and separated in three macro-sections:

- LCI: Resources consumption and waste production;
- LCIA: Potential environmental effects;
- Materials recoverability.

3.1. LCI: Resources consumption and waste production

LCI results relative to resources consumption and waste production are reported in the tables I-N of the SI Appendix.

3.2. LCIA: Potential Environmental Effects

Per-VKT data referring to PEEs are reported for each LC module in table 4.

POTENTIAL ENVIROMENTAL EFFECTS				
	LC Module			
ENVIRONMENTAL IMPACTS **Data for 1 km Vehicle Travelled (VKT)**	**UPSTREAM**	**CORE**	**DOWNSTREAM**	**TOTAL LC**

			Use	EoL	
Abiotic Depletion Potential elements, ADPe [kg Sb-eq]	3.48E-06	2.38E-07	1.32E-06	8.06E-08	**5.12E-06**
Abiotic Depletion Potential fossil, ADPf [MJ]	3.79E+00	7.88E+00	1.26E+02	2.76E+00	**1.41E+02**
Acidification Potential, AP [kg SO_2-eq]	1.56E-03	1.05E-03	2.36E-02	6.03E-04	**2.68E-02**
Eutrophication Potential , EP [kg Phosphate-eq]	1.03E-04	8.36E-05	1.58E-03	1.03E-04	**1.87E-03**
Fresh water Aquatic Eco-Toxicity Potential, FAETP [kg DCB-eq]	4.90E-03	6.81E-04	1.40E-02	1.23E-03	**2.08E-02**
Global Warming Potential, GWP [kg CO_2-eq]	2.85E-01	3.55E-01	8.79E+00	9.69E-01	**1.04E+01**
Human Toxicity Potential , HTP [kg DCB-eq]	3.74E-01	1.24E-02	3.01E-01	4.45E-02	**7.32E-01**
Marine Aquatic Eco-Toxicity Potential, MAETP [kg DCB-eq]	2.56E+02	1.92E+01	4.80E+02	3.62E+01	**7.92E+02**
Ozone Depletion Potential, ODP [kg CFC-11eq]	2.68E-09	1.30E-10	3.43E-09	3.47E-10	**6.59E-09**
Photochemical Ozone Creation Potential, POCP [kg Eth-eq]	1.02E-04	7.03E-05	1.85E-03	7.61E-05	**2.10E-03**
Terrestric Eco-Toxicity Potential, TETP [kg DCB-eq]	7.79E-03	1.38E-03	2.47E-02	3.33E-03	**3.72E-02**

Table 4. Per-VKT PEEs

3.3. Materials recoverability

Table O in the SI Appendix reports allocation to EoL partial masses with regard to both spare parts (corrective and preventive maintenance) and vehicle components.

Vehicle recoverability percentages considering both spare parts and vehicle EoL are expressed in table 5.

MATERIALS EoL [% in mass]			
Reuse (components)	**Recycling (materials)**	**Energy recovery (materials)**	**Landfilling**
0	87.4	4.7	7.9
Total Recycling			
87.4			
Total Recoverability			
92.1			
TOTAL VEHICLE			
100			

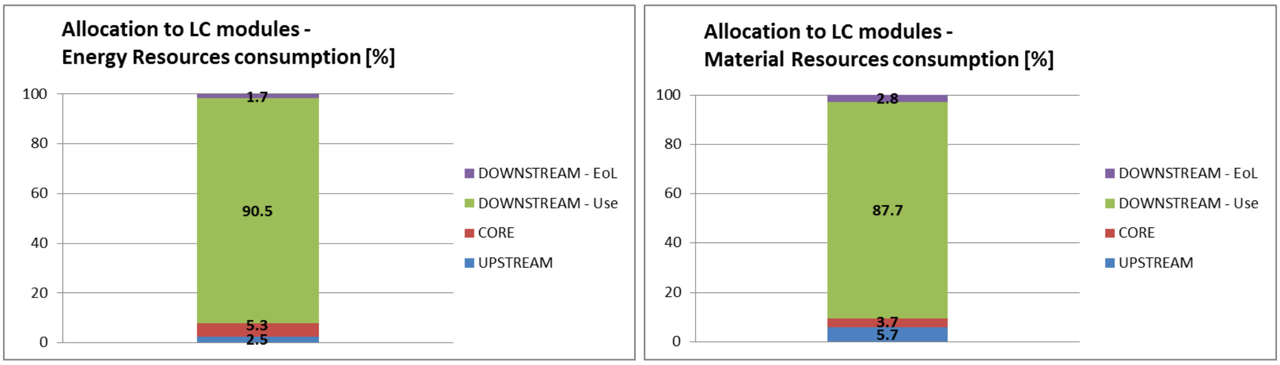
Table 5. Metro recoverability percentages

4. Discussion

4.1. Results interpretation

4.1.1. LCI: Resources consumption and Waste production

Figure 2 details allocation to LC modules of Energy, Material and Hydric Resources consumption and Waste production.



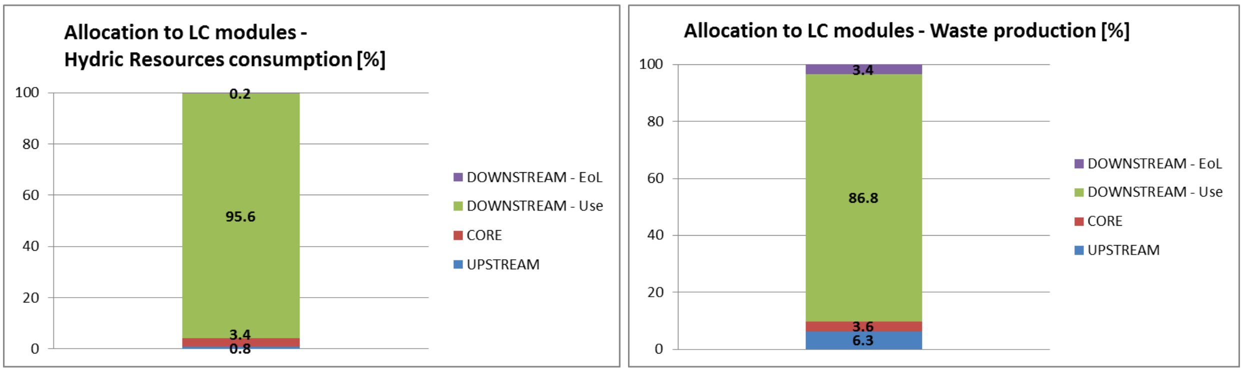


Figure 2. Allocation to LC modules of Resources consumption and Waste production

For all categories considered, the most largely relevant module is the DOWNSTREAM and in particular PU "Use". With respect to Resources consumption, Use amounts 90.5% for Energy Resources, 87.7% for Material Resources and 95.6% for Hydric Resources while referring to Waste production it totals 86.8%. This fact is due to the production of the large amount of electricity that metro consumes during its 30-year lifetime; allocation to PUs of consumed electricity reported in Figure 3 clearly confirms Use as the most energy intensive. Due to the long-lasting metro lifetime, the decisive predominance of Use with respect to the other PUs is largely predictable. Such outcome agrees with Kaebernick et al. (2003), who, in the light of 23 LCAs of different products, theorises the division of products into two groups; passive products, for which the main LC impact is attributable to manufacturing and active products, for which usage results as the most environmentally detrimental LC phase. Considering UPSTREAM module, it contributes about 6% to both Material Resources consumption and Waste production in virtue of extraction and manufacturing processes of materials involved in vehicle construction; lower contributions (2.5% and 0.8%) regard Energy and Hydric Resources consumption. CORE module presents its highest effect (5.3%) on Energy Resources consumption because of energy absorption required by assembly and manufacturing of both vehicle components and spare parts; about 3.5% concerns Material and Hydric Resources consumption and Waste production. DOWNSTREAM-EoL contributes 3.4% to Waste production as consequence of EoL dismantling and treatment processes; for the other categories contributions decrease till a minimum of 0.2% for Hydric Resources consumption.

ELECTRICITY CONSUMPTION [kWh]

Data for 1 km Vehicle Travelled (VKT)	LC Module				
	UPSTREAM MODULE	CORE MODULE	DOWNSTREAM MODULE		TOTAL LC
			Use	EoL	
Electricity consumption	995502	216466	83575342	200345	84987655

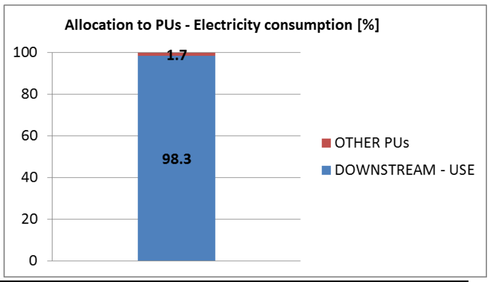


Figure 3. Quantities and allocation to PUs of consumed electricity during metro LC

Analysing the typology of consumed resources, for Energy Resources major contributions are represented by Natural gas (46.3%), Renewables (16.8%), Hard coal (15.8%) and Crude oil (12.1%); minor contributions concern Uranium (7.0%) and Lignite (2.0%) (Figure 4.a). Non-Renewable resources exceeds the Renewable ones for each PU resulting in 83.2% with respect to total LC (Figure 4.b); the maximum percentage of 17.5% for Renewables ascribable to PU "Use" is due to the fact that Italian electricity mix considers notable shares from hydro power, biomass/solar energy and wind power.

For Material Resources consumption (Figure 4.c), Limestone shows the greatest influence (47.0%) followed by Bauxite (15.5%); lower contribution concern Quartz sand (8.5%), Copper ore (7.4%), Sodium chloride (7.1%) and Iron ore (4.0%). The large amount of Limestone is due to the production of electricity consumed in PU "Use" and in metallurgic processes of UPSTREAM module; Bauxite quota is ascribable to the production of metallic structures of UPSTREAM module, mainly vehicle car-body and boogies.

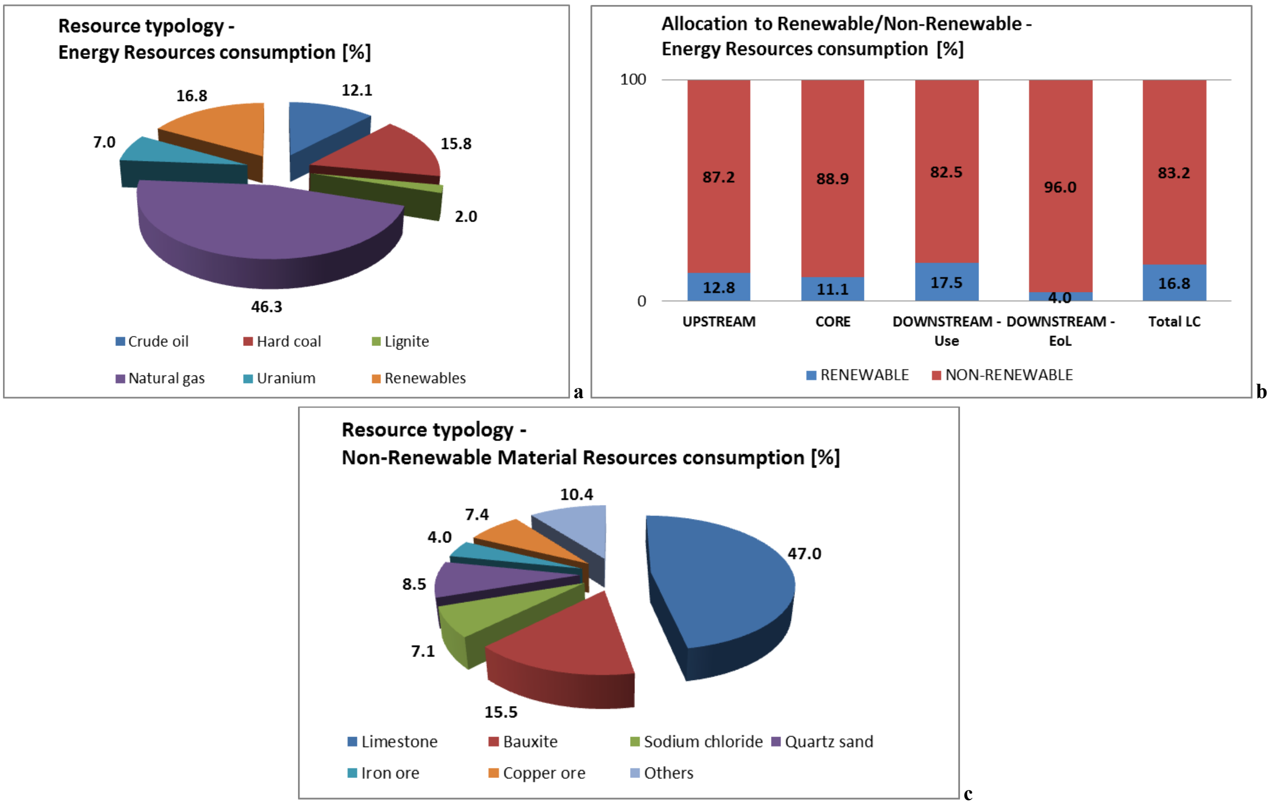


Figure 4. Resource typology of Energy Resources consumption (a);
Allocation to Renewable/Non-Renewable of Waste production (b); Resource typology of Non-Renewable Material Resources consumption (c)

Waste Production concerns almost exclusively Non-Hazardous waste for all LC phases; the higher percentage of Hazardous (13.7%) occurs for DOWNSTREAM-EoL, due to the production of scrap and residue from dismantling processes. Figure A in the SI Appendix reports allocation to Hazardous/Non-Hazardous of Waste production.

4.1.2. LCIA: Potential Environmental Effects

For the PEEs (Figure 5), DOWNSTREAM-Use represents the most influential PU for nine of eleven analysed impacts; for these impacts, contribution of Use varies from a minimum of 52.1% (for ODP) to a maximum of 89.8% (for ADPf). The energy intensity of DOWNSTREAM-Use and the strong dependence on fossil fuels of the Italian electricity mix determine such outcome; the combustion of large quantities of fossil fuels necessary to produce electricity consumed during operation causes huge emissions of unburned hydrocarbons, sulphur and azote oxides which have a substantial influence on the overall PEEs. The only exceptions are ADPe and HTP, for which UPSTREAM represents the most relevant module (respectively 68.0% and 51.1%); also for ODP, UPSTREAM quota (40.7%) is notable. Concerning ADPe, UPSTREAM covers a large portion of impact because of the consumption of abiotic elements involved in the construction of vehicle and spare parts. UPSTREAM contribution to HTP and ODP is mainly due to atmospheric emissions (primarily organ chlorine compounds) caused by manufacturing processes of:

- Rubber and plastic;
- Epoxy and acrylic resins used in the production of painting enamels.

For the other PEEs, UPSTREAM quota decreases: 32.4% for MAETP, 23.6% for FAETP and 20.9% for TETP, till a minimum of 2.7% for ADPf and GWP.

Contributions attributable to CORE and DOWNSTREAM-EoL remain under 10% for all PEEs.

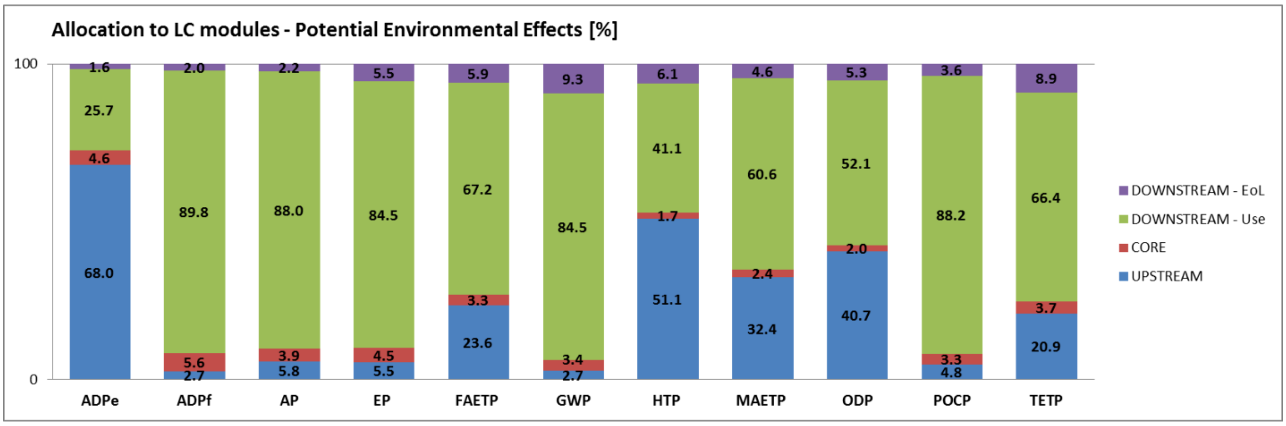


Figure 5. Allocation to LC modules of PEEs

Figure 6 reports allocation to PGs of ADPe and HTP with regard to the most influential module for such impact categories, the UPSTREAM. Regarding ADPe, "Propulsion and electric equipment" is the PG with the highest quota (about 45%) followed by "Boogies and running gears" (31.8%) and "Comfort systems" (11.9%); minor percentages are due to "Interiors, windows and doors" (6.6%) and "Car body" (4.9%). For HTP, modules "Propulsion and electric equipment", "Boogies and running gears" and "Interiors, windows and doors" are substantially equivalent at a percentage of about 25%; "Car body" accounts for 15.8% while "Comfort systems" reaches 10.2%. It can be concluded that main impacts are caused by PGs which present greater quantities of metallic materials (in particular Aluminium, Copper and High Alloyed Steel) whose production is characterised by high energy intensity and emissions to the environment.

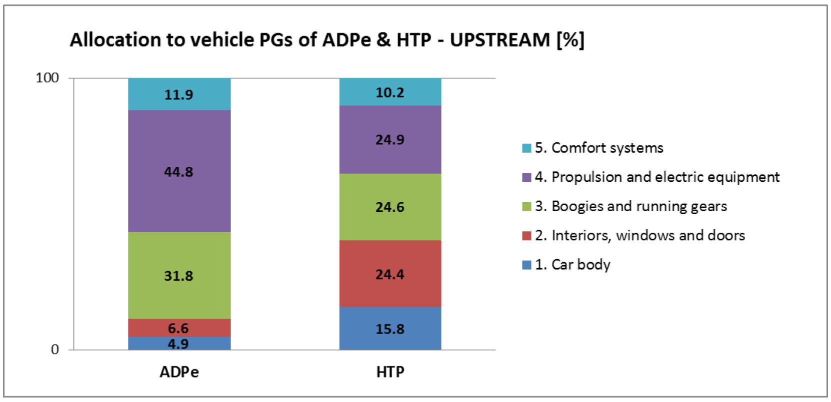


Figure 6. Allocation to PGs of ADPe & HTP for UPSTREAM module

4.1.3. Recyclability/Recoverability rate

According to the results of paragraph 3.3., figure 7 shows EoL destination of materials involved in vehicle LC in terms of recoverability percentage rate. Data are reported with respect to total mass (considering both spare parts and vehicle) and are shared as follows:

- Maintenance (preventive & corrective) materials;
- Vehicle materials;
- Maintenance & vehicle materials.

As shown, the recoverability percentage referring to maintenance (91.0%) is less than the one referring to vehicle (93.9%); this leads to an overall quota of recoverable material amounting to 92.1% with the remaining 7.9% destined to landfilling. The lower recoverability of materials referring to maintenance is mainly due to the large quantity of brake pads substituted during lifetime and mainly made of non-recoverable materials.

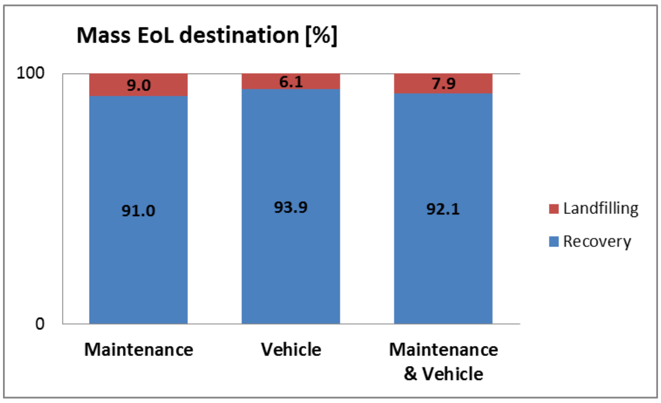


Figure 7. Material EoL destination for Maintenance, Vehicle and Maintenance & Vehicle

4.2. Sensitivity analysis

Sensitivity analysis is based on examination of LCIA results for three different VOs.

- High VO: all seats occupied and 6 pass/m^2, taking into account load conditions during peak times;
- Normal VO (FU): all seats occupied and 3.2 pass/m^2 (normal operational VO and reference for FU), taking into account load conditions during off peak times;
- Low VO: 40% of seats occupied and 0 pass/m^2, taking into account load conditions during night and weekend.

Sensitivity analysis is divided in two sections: the first one inspects LCIA results with respect to VKT, the second one analyses the same results referring to PKT.

4.2.1 VKT analysis

VKT analysis aims to highlight the influence on the per-VKT results of variation of use electricity consumption due to mutations in VO.

Figure 8 reports the per-VKT results for high and low VO expressed as percentage of impact in FU conditions (normal occupancy); average fluctuation between low and high VO has resulted (-6.4% ÷ +4.6%). Greater variations with regard to FU conditions are observed for those categories whose impact is mainly caused by PU “Use” (see paragraph 4.1.2.): ADPf (-8.4% ÷ +6.1%), AP (-8.3% ÷ +6.0%), POCP (-8.3 ÷ +6.0%), GWP (-7.9 ÷ +5.8%) and EP (-7.9% ÷ +5.8%).

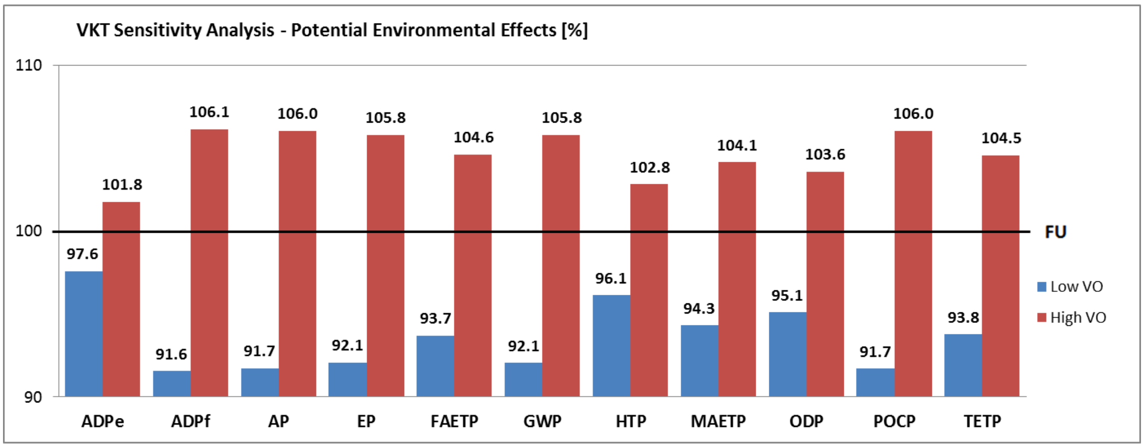


Figure 8. VKT sensitivity analysis: per-VKT PEEs (% of impact in FU conditions)

Allocation to LC modules of the per-VKT impacts is poorly influenced by variation of VO: gaps between results referring to FU VO and low/high VO remain under 2.5% for all the considered PEEs. Figures B-G in the SI Appendix report impacts allocation to LC modules of AP, EP, GWP, HTP, ODP and POCP for each of the three levels of VO.

4.2.2 PKT analysis

PKT analysis aims to underline the influence on the per-PKT results of VO. While the per-VKT performance is related to the operation of the vehicle and depends on technological improvements, the per-PKT performance captures the energy and emissions intensity of moving passengers and is a result of VO rate.

Figure 9 reports the trend of the per-PKT results in function of VO. Impact is quantified as percentage of impact obtained by taking into account consumption in conditions of normal VO; similarly, VO is expressed as percentage of normal VO. To stress the variation of results due to a mutation in VO, data are displayed in the interval (Low VO - High VO).

Dotted line represents trend of whichever generic per-PKT impact taking into account conditions of normal VO and maintaining use consumption constant on VO varying; since it does not consider the variation of consumption in function of VO, such line symbolises the limit curve representing the theoretical impact on which VO rate has no influence. Equation of the per-PKT generic impact is the following:

$$\text{PKT Impact} = (100 / \text{VO}) * 100$$

As shown, passing from low to high VO rate the impact becomes about 15 times greater.

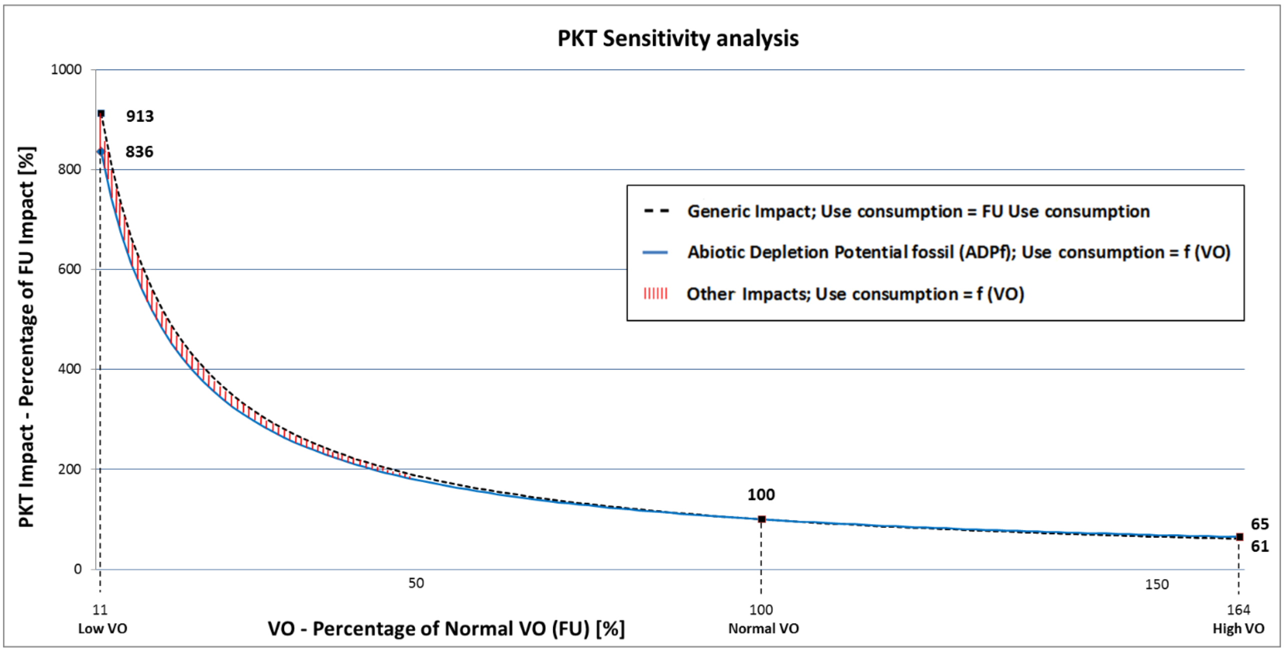


Figure 9. PKT sensitivity analysis: per-PKT LCIA results depending on VO

If the variation of use consumption in function of VO is considered, PEEs results move away from limit curve of generic impact: the greater the influence of consumption, the greater the gap from limit curve. In this case each impact category is represented by a distinct curve depending on its variability in function of vehicle consumption.

For all categories, per-PKT impacts present:

- Lower impacts than limit curve for VOs minor than normal VO;
- Higher impacts than limit curve for VOs major than normal VO.

Abiotic Depletion Potential fossil (ADP_f) is the impact category most affected by variation of consumption in function of VO (see paragraph 4.2.1.) and in fact it presents the greater gap from limit curve (blue curve in figure 9); consequently, passing from low to high VO rate, its per-PKT result shows the lowest variability. Maintaining the same shape, curves relating other impact categories are included between limit curve and the ADP_f one (red area in figure 9).

In conclusion PKT analysis makes it possible to evaluate the influence that variation of consumption at varying of VO has on the per-PKT results. Passing from low to high VO rate, the per-PKT impacts increase differently depending on which impact category is considered; ADPf (impact category more affected by variation of consumption in function of

VO, see paragraph 4.2.1.) becomes 12.9 times greater while ADPe (impact category less affected by variation of consumption in function of VO, see paragraph 4.2.1.) becomes 14.3 times greater.

5. Conclusions

The analysis of LCA results leads to:

- Identification of LC modules that present greater environmental improvement potentials;
- Development of environmental design strategies.

The results of the study show that DOWNSTREAM-Use is largely the most influential PU for most of the considered PEEs; this fact is due to the energy intensity of the PU since it absorbs almost the overall amount (98.3%) of electricity consumed in the whole LC. The production of this large quantity of electricity determines huge consumption of resources and emissions to the environment; in particular combustion of fossil fuels causes emissions of unburned hydrocarbons, sulphur and azote oxides which have a strong influence on the considered PEEs. The only two impact categories for which DOWNSTRAM has not been revealed as the most relevant module are ADPe and HTP; in these cases the greatest contribution is given by UPSTREAM (respectively 68.0% and 51.1%). Also for ODP, UPSTREAM quota (40.7%) is notable. Concerning ADPe, UPSTREAM covers a large portion of impact because of resources consumption and emissions involved by raw materials extraction and production processes regarding both vehicle and spare parts; UPSTREAM contribution to HTP and ODP is mainly due to atmospheric emissions (primarily organ chlorine compounds) caused by manufacturing processes of rubber and plastic on one side and epoxy/acrylic resins for the production of painting enamels on the other side.
The analysis of contributions to ADPe and HTP coming from single PGs has evidenced that greater impacts are caused by “Propulsion and electric equipment” and “Boogies and running gears”; the explanation is the presence in these PGs of greater quantities of metallic materials (in particular Aluminium, Copper and High Alloyed Steel), whose production is characterised by high environmental impacts if compared with other materials. CORE and DOWNSTREAM-EoL give a contribution which remains under 10% for all the considered impact categories.
By analysing EoL destination of materials involved in vehicle LC, recoverability rate has resulted 92.1%. Of this quota, 87.4% is the amount destined to material recycling while the other 4.7% to energy recovery; the remaining 7.9% has been considered as waste to landfilling.

Sensitivity analysis based on variation of VO between a minimum (“Low VO”) and a maximum (“High VO”) has been conducted on both per-VKT and per-PKT LCIA results (PEEs). VKT analysis highlights a remarkable influence of use electricity consumption on the per-VKT results; with regard to data obtained in conditions of normal VO (FU occupancy), average fluctuation between low and high VO is shown (-6.4% ÷ +4.6%) while variation in allocation of impacts to LC modules is negligible. On the other hand, PKT analysis stresses the influence that variation of consumption at varying of VO has on the per-PKT results. Depending on the specific impact category, passing from low to high VO, the per-PKT impacts become 12.9 ÷ 14.3 times greater.

Examination of LCA results and evidence of sensitivity analysis lead to location of greater improvement potentials in

- PU “DOWNSTREAM-Use”
- UPSTREAM module

and the main strategy clearly appears to be the reduction of energy consumption involved by the whole metro LC. To this end, the more feasible and incisive approaches are:

- Reduction of mass;
- Increase of efficiency during operation;
- Increase of recyclability rate.

The first solution can decrease the environmental impacts involved by both DOWNSTREAM-Use and UPSTREAM; for DOWNSTREAM-Use, mass reduction means lower requirement of electricity for vehicle operation while for UPSTREAM a reduction of materials quantity to be processed would involve a reduction of resources consumption and

emissions to environment due to raw materials extraction and production processes. At the present state of the art, the use of lightweight materials represents the most practicable approach to achieve vehicle mass reduction.
The second solution aims to obtain environmental benefit in the only PU "DOWNSTREAM-Use". This can be obtained by increase of efficiency of such operations which present the higher quota of energy consumption, like traction and heating. In this context, feasible strategies are:

- Using gearless traction motor with permanent magnet motor;
- Reduction of driving resistance wheel/rail;
- Using capacitors for energy storage;
- Improvement in efficiency of car-body insulation.

The third solution envisages environmental improvements in the UPSTREAM module alone. Through the adoption of materials characterised by a higher percentage of recyclability, remarkable energy and emissions saving is achievable by elimination of a part of resources consumption and emissions due to raw materials extraction and production processes.

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