Journal of Cleaner Production 87 (2015) 787–799

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Life Cycle Assessment of a heavy metro train

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ARTICLE INFO

Article history:
Received 31 January 2014
Received in revised form
6 August 2014
Accepted 10 October 2014
Available online 27 October 2014

Keywords:
Life Cycle Assessment
Heavy metro train
Environmental impact
Eco-design
Energy consumption

ABSTRACT

The railway system represents one of the most resource-efficient answer to the ever-growing demand for transport service. Development trends for the following years project substantial increase in this sector. To date, environmental effects caused by railway transport services have been rarely inspected systematically and existing studies focus on single typologies of environmental aspects, like energy consumption and air emissions. The article presents a predictive Life Cycle Assessment (LCA) of a heavy metro train that will operate in the urban area of Rome. A predictive analysis on recyclability/recoverability at the end of life has also been performed according to the ISO 22628. The LCA inventory captures the whole vehicle Life-Cycle (LC) subdivided in four stages: Material acquisition, Manufacturing, Use and End of life. In comparison with existing studies, this work examines a broader range of impacts to human and ecosystems health using primary data supplied by vehicle manufacturers whenever possible to reduce the uncertainty of results. Results show that Use is largely the most influential stage for the majority of the considered impact categories. This fact is due to the energy intensity of Use stage since it accounts for almost the entire amount (98.3%) of electricity consumed during vehicle LC. Material acquisition is the second most influential stage based on resource consumption and emissions during extraction of Iron and Bauxite: vehicle parts that mainly contribute to impacts of Material acquisition are body structure and bogies. The impacts associated with Manufacturing and End of life are low compared to the other stages. The projected recyclability and recoverability rates at the end of life stage are respectively 87.4% and 92.1%. A sensitivity analysis of the LCA results stresses the influence of vehicle occupancy on the electricity consumption during operation and the overall LCIA results. In light of LCA results, major improvement potential is identified in the reduction of electricity consumption during use stage, primarily due to Traction and Heating systems. The key recommendations for future design strategies are the decrease of vehicle mass by the application of lightweight materials for metro construction and the improvement of efficiency of the Heating system.

1. Introduction

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 change 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; ISO 14040, 2006; ISO 14044, 2006) of both conventional (Finkbeiner et al., 2006; Schmidt et al., 2004; Spielmann and Althaus, 2006)) and innovative (Alves et al., 2010;

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http://dx.doi.org/10.1016/j.jclepro.2014.10.023
0959-6526/

Nomenclature

AB	AnsaldoBreda
ADP_e	Abiotic Depletion Potential elements
ADP_f	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

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 modes for the transportation of freight. Energy use and emissions were examined taking into account the whole vehicle LC. Using secondary data for energy use and emissions, the paper identifies the use stage as the greatest contributor to environmental impacts for both modes.

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 operation represents the greatest contribution to impacts: use stage contribution is 64%, 31% and 70% respectively to CED, MIPS and CO_2 emissions, these latter being dominated by energy-related processes.

Struckl and Wimmer (2007) conducted a cradle-to-grave, screening-level LCA of a light 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 identifies the use 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 bogies. To date the work of Struckl and Wimmer is the only published scientific paper regarding LCA of a metro train.

A comparative LC energy and emissions inventory for three U.S. metropolitan regions was presented by Chester et al. (2009). The study considered different transport modes (automobile, diesel rail, electric rail and ferry service) and captured 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 the Vehicle Kilometres Travelled (VKT) were used as the basis for comparison. The automobiles are identified as the dominant source of impact, accounting for 86–96% of the regional energy use and emissions. The paper shows also an interesting interpretation of the results by disaggregation of transportation modes between off-peak and peak travel time: automobile involves significant emissions to system-wide emissions but the contribution of larger shares on public transit and its improved per-PKT performance can offset this.

Another comparative study is the one performed by Chester and Horvath (2009) who evaluated 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 determines the dominant share of both energy use and emissions for road and air modes is associated with operational components, while these values for railways are more strongly influenced by non-operational components. According to Chester et al. (2009), sensitivity analysis based on variation of Vehicle Occupancy (VO) finds the relative performance of modes is 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. An LC energy and GHG analysis was used to compare the impacts associated with travelling 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 an HSR system, including infrastructure construction. Train manufacturing and maintenance data were 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. Completely in accordance to Chester et al. (2009), increase in VO emphasises the convenience of passenger railway transportation if compared with other mobility modes, especially automobile.

Chester and Horvath (2012) expanded their work to address mobility in the California corridor. A PKT LC inventory including vehicle, infrastructure and energy production was developed for future (efficient and electric) automobiles, HSRs and aircraft. The analysis took 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). Similarly to Chester and Horvath (2010), the paper stresses the potential of high-speed rail to reduce transportation impacts: the key hotspots identified for improvement are operation consumption and occupancy of the train, infrastructure construction and fossil fuel intensity of the electricity mix.

Recently Chester et al. (2013) conducted an 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 stage. Energy consumption, GHG emissions and criteria pollutants were evaluated using both attributional and consequential LCA (Joint Research Centre, 2010b) 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: as already highlighted by Chester et al. (2009), 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 preset 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, 2010, 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 the review of existing literature regarding environmental studies of railway vehicles 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 modelling;
- Only a small number of studies for trains and, in particular, heavy metro vehicles are available that have yet to be critically compared.

This study involves a full cradle-to-grave LCA of a heavy metro train that will be operative in the city of Rome. In comparison to existing studies, this work examines a broader range of impacts to both human and ecosystems health using primary data supplied by vehicle manufacturers whenever possible to reduce the uncertainty of results.

2. Material and methods

LCA was performed according to the ISO standards and takes into account the Product Category Rules (PCR) developed by the International EPD System (2013b).

2.1. Goal and scope

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.

With the scope to estimate as comprehensively as possible the effects on eco-systems 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 which constitute the vehicle.

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. The total number of kilometres travelled during metro lifetime has been

Table 1
AB metro main technical and 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]

evaluated taking into account route lengths, timetables (working days/holidays) and service frequencies.

2.3. Application and system boundaries

As stated by the PCR 2.0, 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 the main technical/operational features of the metro.

According to PCR 2.0, metro components are subdivided into five Product Groups (PGs) named depending on technical reference area. Table 2 reports contribution analysis by PG of vehicle mass.

The metro LC consists of four stages: Material acquisition, Manufacturing, Use and End of Life. The stages are divided into Process Units (PUs) which, in turn, include single processes. Table 3 summarises PUs and processes for each LC stage.

2.4. Life Cycle Inventory (LCI)

Collection of primary data has been performed for all PUs that compose vehicle LC and the gathered data come directly from real operators of processes. The database version 6.106 of software GaBi (PE International, 2013) has been used as source for secondary data.

2.4.1. Material acquisition

Regarding PU "Raw materials extraction and production", data collection deals with the determination of typology and quantity of materials that constitute the vehicle. The collection has been performed by filling out Material Sheet (MS) for each component/assembly of the metro with the intensive involvement of AB personnel and suppliers. Fig. 1 summarises material composition of the vehicle, obtained by unifying data from all the MSs.

The components and substances (e.g. batteries, brake disks, brake pads, compressor oil, etc) substituted both in preventive (planned activities) and in corrective maintenance have been taken into account. The AB specifications have been used to calculate the number of components and quantity of substances replaced in preventive maintenance. Data coming from maintenance of previous AB metros have been adopted as estimations for corrective maintenance. Table A of the SI (Supporting Information) Appendix reports the contribution analysis by component/substance of total mass replaced in maintenance.

Table 2
Contribution analysis by PG of vehicle mass.

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

Table 3
Process Units and processes composing LC stages.

	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 components constituting the vehicle and components replaced in maintenance)
			Raw materials extraction and production processes
		External transportations	Fuel production for transportation of raw materials 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 recovery
			Incineration (energy recovery)
		Disposal	Landfilling of waste materials

The production processes of some materials/substances are not characterised in commercial databases: Table B of the SI Appendix reports GaBi6 processes adopted as surrogate for the real ones.

Data collection relative to PU "External transportations" concerns the transportation of raw materials from suppliers facilities to AB plants. For each haulage, the actual data on truck typology, travelled distance and transported mass have been reported in Transport Sheet (TS). Table C of the SI Appendix sums up data collection for external transportations.

2.4.2. Manufacturing

Data collection concerning PU "Manufacturing and assembly" regards inputs/outputs involved in manufacturing and assembly of vehicle components. Such activities are summarised as follows:

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

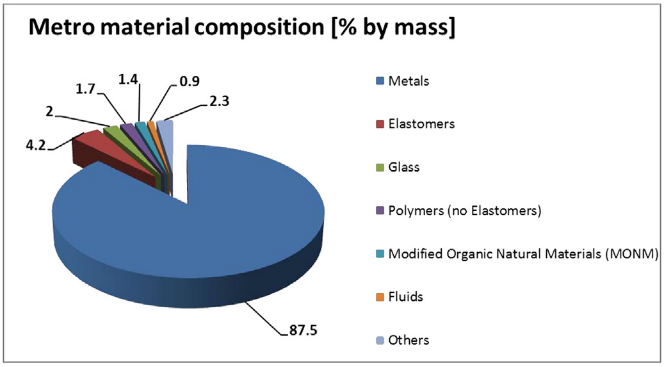

Fig. 1. Data collection for PU "Raw materials extraction and production": metro material composition.

The data come from AB measurements on real manufacturing processes. Table D of the SI Appendix summarises input/output flows exchanged with environment due to PU "Manufacturing and assembly".

During surface treatments a certain quantity of solvent is loss in application and drying of enamels/plasters: the quantity of lost solvent is estimated as percentage of the applied product and added to the values reported in MSs. Table E of the SI Appendix reports solvent percentage with regard to total mass of applied enamel/plaster in metro surface treatments.

Data collection on PU "Internal transportations" deals with:

- Transportations of components and assemblies of the metro between AB plants (Naples and Reggio Calabria);
- Delivery of the vehicle to the customer.

The information typology and collection modality are the same of PU "External transportations". Table F of the SI Appendix reports a summary of internal TSs data.

2.4.3. Use

LCI primary data regarding Use stage is the per-Vehicle Kilometre Travelled (per-VKT) electricity consumption of the metro. Since the vehicle is not yet operative, the consumed electricity has been obtained by calculations conducted by AB: the average Electricity consumption per Round Route (E_{RR}) has been determined by travel simulations based on physical and operational features of vehicle and route. The 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 4 shows metro average per-VKT E_{RR}.

Table 4
Metro average per-VKT E_{RR} considering maximum operational VO (all seats occupied and 6 pass/m^2).

Average "per-VKT E_{RR}" [kWh/VKT]			
	Outward route	Return route	Total
Absorbed energy	39.37	35.76	75.13
Recovered energy	19.14	20.35	39.49
Consumed energy	20.23	15.41	35.64

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 VO, 80% of seats occupied and 3.2 pass/m^2) as well as to the load configurations examined in the sensitivity analysis, an analytical model of the electricity consumption in function of VO has been developed.

The model is based on Barrero et al. (2008), in which electricity consumption of a vehicle similar to the AB metro both for tare mass, passenger capacity and installed power is 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. By 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%.

From this data, the analytical model of 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 = Electricity consumption with "n" passengers
$E_{\max}$ = Electricity consumption referring to maximum operational VO
$N_{\max}$ = Number of passengers referring to maximum operational VO

Note: Barrero reports only the total number of passengers without any subdivision in seated and standing. In order to estimate the percentage of seated passengers with respect to the total number, the following assumption, valid for AB metro, has been extended to the Barrero vehicle:

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

Concerning the secondary data collection, the Italian electricity mix has been used to characterise production of energy consumed in the Use stage.

2.4.4. End of life

To determine the typology of recovery and disposal treatments as well as the quantity of material involved in each specific process, it has been referred to standards developed by the International EPD System (International EPD System, 2014) and UNIFE (UNIFE, 2014):

- The categories by which to classify materials and the typology of EoL treatments have been assumed from PCR 1.0. (International EPD System, 2009);
- For each category of material, the percentage by mass involved in each EoL treatment 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).

Table 5
Summary of the per-VKT LCI results.

LCI results: resources consumption & waste production					
LCI results data for 1 km vehicle travelled (VKT)	LC stage				Total LC
	Material acquisition	Manufacturing	Use	EoL	
Energy resources consumption (non-renewable) [MJ]	4.04E+00	8.57E+00	1.37E+02	2.98E+00	1.52E+02
Energy resources consumption (renewable) [MJ]	5.93E-01	1.07E+00	2.89E+01	1.24E-01	3.07E+01
Material resources consumption [kg]	8.17E-01	5.27E-01	1.25E+01	4.05E-01	1.42E+01
Hydric resources consumption [kg]	4.79E+02	2.00E+03	5.65E+04	1.30E+02	5.91E+04
Waste production [kg]	8.97E-01	5.09E-01	1.24E+01	4.80E-01	1.42E+01

For the calculation of recyclability/recoverability rate, following relations, based on the method proposed by ISO 22628 (2002), have been used:

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

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

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

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 G of the SI Appendix sums up the resulting set of percentages regarding mass allocation to EoL treatments and EoL partial masses assumed in the study.

2.5. Sensitivity analysis procedures

A sensitivity analysis has been performed to stress the influence of VO on LC impacts. The analysis is based on the 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.

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

2.6. Life Cycle Impact Assessment (LCIA)

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

✓ Abiotic Depletion Potential elements (ADPe);
✓ Abiotic Depletion Potential fossil (ADPf);
✓ Acidification Potential (AP);
✓ Eutrophication Potential (EP);

Table 6
Per-VKT potential environmental effects.

LCIA results: potential environmental effects					
LCIA results data for 1 km vehicle travelled (VKT)	LC stage				Total LC
	Material acquisition	Manufacturing	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**
Terrestrial Eco-Toxicity Potential, TETP [kg DCB-eq]	7.79E-03	1.38E-03	2.47E-02	3.33E-03	**3.72E-02**

Table 7
Metro recoverability rates.

RECOVERABILITY RATES [% 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			

✓ 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

3.1. LCI, LCIA and recoverability

Metro LCA results are separated in three macro-sections:

- LCI results: resources consumption and waste production;
- LCIA results: Potential Environmental Effects (PEE);
- Recoverability rates.

Table 5 summarises LCI results with regard to resources consumption and waste production. Detailed LCI results subdivided into typologies of resource/waste are reported in the tables H-M of the SI Appendix.

Per-VKT Potential Environmental Effects for each LC stage are reported in Table 6.

Metro recoverability rates are showed in Table 7. Table N of the SI Appendix reports allocation to EoL partial masses of each component/assembly of the vehicle and component/substance replaced in maintenance.

3.2. Interpretation

3.2.1. LCI: resources consumption and waste production

Fig. 2 shows contribution analysis by stage of energy, material and hydric resources consumption and waste production.

For all the categories the most largely relevant stage is the Use: with regard 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%. The high contribution of the Use stage is due to the production of the large amount of electricity that metro consumes during its 30-year lifetime: the contribution analysis by stage of consumed electricity (Fig. 3) clearly confirms Use as the most energy intensive. The Material acquisition stage contributes about 6% to both material resources and waste, primarily due to raw materials extraction and manufacturing processes while lower contributions (2.5% and 0.8%) regard energy and hydric resources. The Manufacturing stage presents its highest effect (5.3%) for energy resources because of energy absorption required for assembly and manufacturing. For material/hydric resources consumption and waste production the Manufacturing quota is about 3.5%. The End-of-life stage contributes 3.4% to waste as consequence of EoL dismantling and treatment processes; for the other categories the contribution decreases till a minimum of 0.2% for hydric resources.

Analysing the typology of consumed resources, for energy resources the highest contribution comes from Natural gas (46.3%) followed by Renewables (16.8%), Hard coal (15.8%) and Crude oil (12.1%) (Fig. 4a). The non-renewable resources exceeds the renewable ones for each stage resulting in 83.2% with respect to the total LC (Fig. 4b). The maximum percentage of 17.5% for renewables ascribable to Use stage is due to the fact that the Italian electricity mix considers notable shares from hydro power, biomass/solar energy and wind power (Fig. 10).

For material resources consumption (Fig. 4c), Limestone quota is the highest (47.0%) followed by Bauxite (15.5%). The large amount of Limestone is due to the production of electricity consumed by

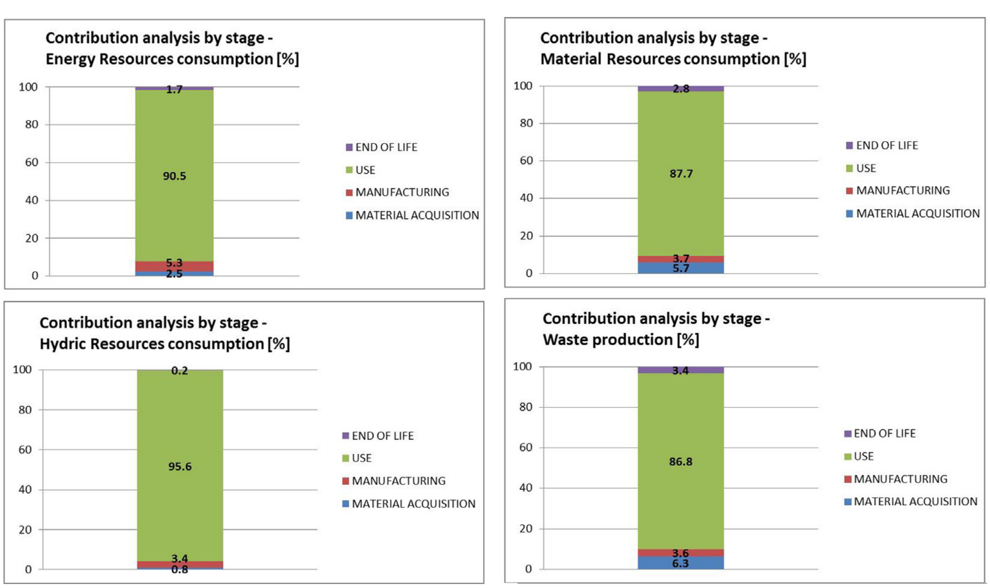

Fig. 2. Contribution analysis by stage of resources consumption and waste production.

ELECTRICITY CONSUMPTION [kWh]					
	LC Stage				TOTAL LC
Data for 1 km Vehicle Travelled (VKT)	Material acquisition	Manufacturing	Use	EoL	
	0.200	0.043	16.688	0.040	16.970

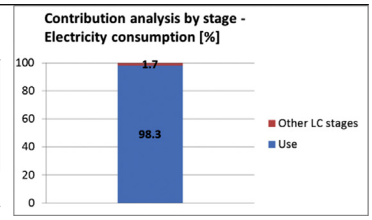

Fig. 3. Quantities and contribution analysis by stage of consumed electricity during metro LC.

the vehicle during operation while the Bauxite quota is mainly ascribable to extraction of raw materials for the construction of metallic structures (primarily bogies and car-body).

Waste production concerns almost exclusively non-hazardous waste for all the LC stages. The higher percentage of hazardous waste occurs for the End of Life stage (13.7%) and it is due to the production of scrap and residue from dismantling processes. Figure A in the SI Appendix reports the contribution analysis based on dangerousness of wastes.

3.2.2. LCIA: potential environmental effects

For the PEEs (Fig. 6), Use represents the most influential stage for nine of eleven analysed impacts. For these impacts, the contribution of Use varies from a minimum of 52.1% (for ODP) to a maximum of 89.8% (for ADP_f). The energy intensity of Use stage 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 vehicle operation involves emission of unburned hydrocarbons, sulphur and azote oxides which have a substantial influence on the overall PEEs. The contribution analysis by metro system of the absorbed electricity during operation (Fig. 5) identifies “Traction” (41.7%) and “Heating” (30.6%) as the most energy intensive systems.

Material acquisition is the most relevant stage for ADP_e and HTP (respectively 68.0% and 51.1%) while for ODP and the eco-toxicity categories its contribution is anyway notable. Concerning ADP_e, Material acquisition covers a large portion of impact because of the consumption of abiotic elements involved in the construction of vehicle and components replaced in maintenance. The contribution of Material acquisition to HTP, eco-toxicity categories 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, contribution of Material acquisition stage decreases: 32.4% for MAETP, 23.6% for FAETP and 20.9% for TETP, till a minimum of 2.7% for ADP_f and GWP.

The quota attributable to Manufacturing and End-of-Life stages remains under 10% for all the PEEs.

Fig. 7 illustrates contribution analysis by PG of ADP_e and HTP with regard to Material acquisition stage. Regarding ADP_e, “Propulsion and electric equipment” is the PG with the highest quota (about 45%) followed by “Bogies and running gears” (31.8%). For HTP, “Propulsion and electric equipment”, “Bogies and running gears” and “Interiors, windows and doors” are substantially equivalent at a percentage of about 25%. It can be concluded that the main impacts are caused by PGs which present the greatest quantities of metallic materials (particularly Aluminum, Copper and High Alloyed Steel) these latter being characterised by high energy intensity and emissions to the environment of raw materials extraction and production.

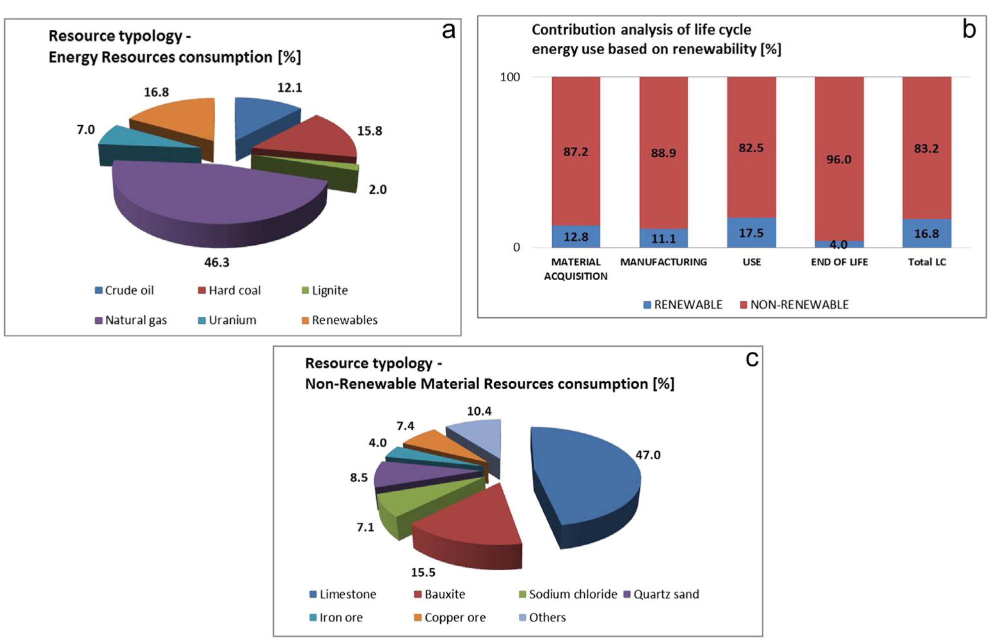

Fig. 4. Resource typology of energy resources consumption (a); Contribution analysis of LC energy use based on renewability (b); Resource typology of non-renewable material resources (c).

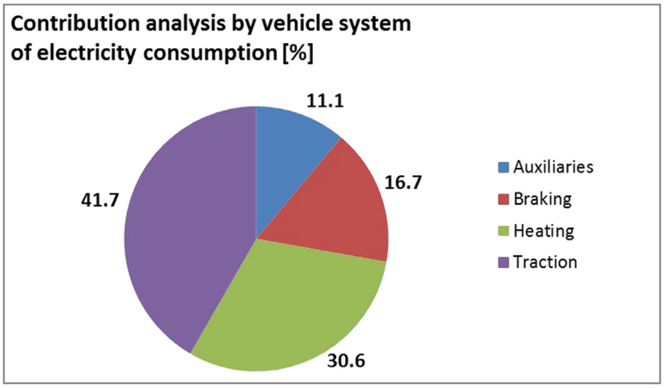

Fig. 5. Contribution analysis by vehicle system of electricity consumption during operation.

3.2.3. *Recyclability/recoverability rate*

Fig. 8 displays EoL destination of materials involved in vehicle LC: the data are reported with respect to total mass and include both vehicle and components replaced in maintenance. As shown, the overall quota of recoverable material amounts to 92.1% with the remaining 7.9% destined to landfilling. The recoverability rate referring to components replaced in maintenance (91.0%) is less than the one referring to vehicle (93.9%): this is mainly attributable to the large quantity of brake pads substituted in maintenance and totally non-recoverable.

3.3. *Sensitivity analysis*

3.3.1. *VKT analysis*

The VKT analysis highlights the influence of VO on the per-VKT results. Fig. 9 reports the per-VKT results for high and low VO expressed as percentage of FU impact (referred to normal operational VO). The highest variations with regard to normal VO are observed for those categories whose impact is mainly caused by Use stage (see paragraph 3.2.2.): ADP_f (−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%).

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

3.3.2. *PKT analysis*

The PKT analysis underlines the influence of VO on the per-PKT results. 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.

Fig. 10 displays the trend of the per-PKT results in function of VO:

- Impacts are quantified as percentage of FU impact (this latter referring to normal operational VO);
- VO is expressed as percentage of normal operational VO;
- Data are displayed in the range (low VO − high VO).

Dotted line ("limit curve") represents the trend of the generic per-PKT impact obtained in FU conditions (normal operational VO) and maintaining constant the consumption with VO variation. The equation of the limit curve is the following:

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

As shown, passing from low to high VO the generic per-PKT impact decreases from 913% to 61%.

If the variation of consumption in function of VO is considered, the per-PKT PEEs move away from the limit curve and each impact category is represented by a distinct curve: the greater the contribution to category of Use stage, the greater the gap from the limit curve.

For all the categories, the per-PKT impacts present:

- Lower value than limit curve for VO minor than normal operational VO;
- Higher value than limit curve for VO major than normal operational VO.

ADP_f is the category whose impact is more affected by Use stage (see paragraph 3.2.2.). Consequently it presents the greater gap from the limit curve (blue (in web version) curve in Fig. 10) and from low to high VO it passes from 836% to 65%. Curves relating to the other impact categories are included between the limit curve and the ADP_f one (red (in web version) area in Fig. 10).

4. Discussion

The results show that Use is largely the most influential LC stage due to the impacts involved by production of electricity that the metro consumes during its long-lasting operation. This is also confirmed by results of the VKT sensitivity analysis: the variation of VO involves remarkable variation of consumption during operation that in turn considerably affects the per-VKT LC impacts (see paragraph 3.3.1.). The leading role of Use with regard to the other LC stages appears totally in accordance with Chester and Horvath (2009, 2010, 2012), Chester et al. (2009, 2013) and Rozychi et al. (2003) despite both tare mass and performances of the analysed vehicles differ considerably. Based on these results, the AB metro

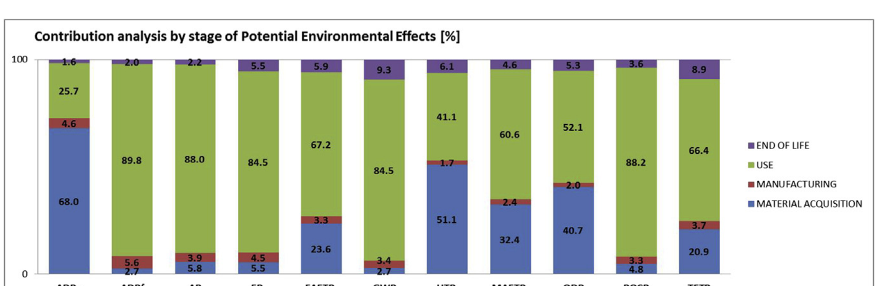

Fig. 6. Contribution analysis by LC stage of PEEs.

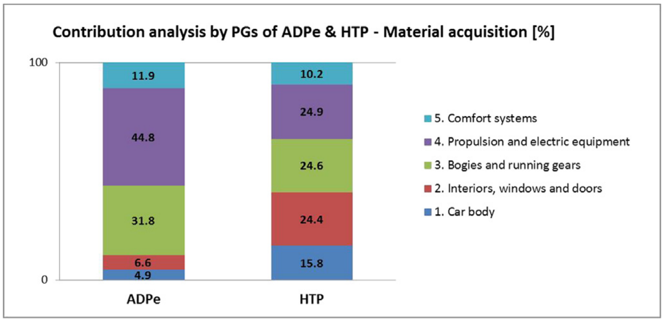

Fig. 7. Contribution analysis by PG of ADPe & HTP for Material acquisition stage.

can be defined an "active product", that is a product for which usage is the most environmentally detrimental stage because of its considerable duration (Kaebernick et al., 2003).

Material acquisition is the most influential LC stage for ADP_e and HTP: the contribution analysis by PG of ADP_e and HTP evidences that a large share of impact is caused by PGs "Car body" and "Bogies and running gears". The predominant contribution of the car-body and bogies to impact involved by Material acquisition stage is confirmed by Struckl and Wimmer (2007) who quantified more than 60% the quota to GWP attributable to such PGs.

Based on the quantification of a broader set of impact categories, the article struggles to create a baseline for comparison with other similar vehicles. To date the only published scientific paper regarding LCA of a metro vehicle is the one performed by Struckl and Wimmer (2007), dealing with the metro of Oslo. As already outlined in the introduction section, there are also other railway vehicles whose EPDs were published: these latter are trains having technical and operational characteristics (tare mass, passengers capacity, travelled kilometres during lifetime, elevation profile of the route, etc) which substantially differ from the ones of the AB metro. Nevertheless, some of them can be used as reference for comparison with regard to some specific aspects:

- ZARAGOZA TRAM, a CAF tram for operation in Zaragoza (Spain);
- SPACIUM, a BOMBARDIER regional train for operation in France;
- TALENT 2, a BOMARDIER regional train for operation in German;
- REGINA Intercity X55, a BOMBARDIER intercity train for operation between the cities of Stockholm and Gothenburg.

Fig. 11a. shows Use stage contribution to total LC GWP for AB metro, metro Oslo and the other cited trains while Fig. 11b. illustrates the composition of the electricity mix for the production of

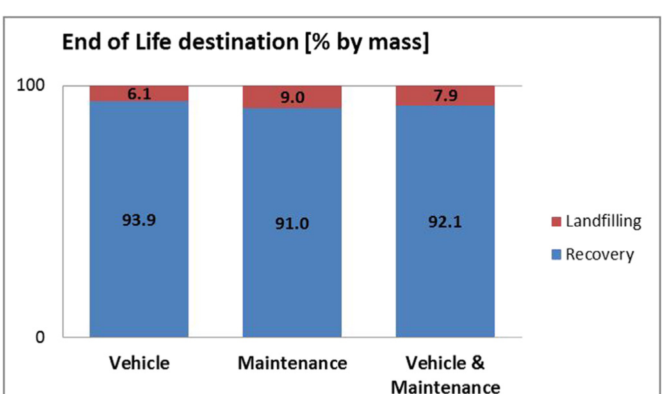

Fig. 8. Material EoL destination for Vehicle, Maintenance and Vehicle & Maintenance.

energy consumed during operation. It can be noted that trains with the highest Use stage contribution use electricity produced mainly from fossil resources.

On the contrary, the vehicles which consume electricity coming from mixes mainly based on renewable resources present lower Use stage contribution to GWP: particularly, the REGINA Intercity X55 has the lowest Use stage contribution (36.3%) because its electric power is sourced exclusively from hydro and wind power. As already highlighted by Chester and Horvath (2012), it can be concluded that fossil fuel intensity of the electricity mix represents the main key-point in order to reduce the environmental impacts of railway (electric) vehicles.

Another interesting comparison can be made between the material recoverability rates of AB metro and metro Oslo (Fig. 12). Despite recoverability is strongly dependent not only on the typology of materials which constitute the vehicle but also on the supposed EoL scenario (recycling/recovery and disposal treatments), the total recoverability rate of the metros are similar. The results show that despite the total recoverability exceeds 90%, room for improvement exists, particularly to enhance the recyclability.

The individuation of hotspots of the AB metro LC leads to location of greater improvement potentials in the Use and Material acquisition stages. To this end, the more feasible and incisive approaches are:

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

The first approach can contribute to decrease the environmental impacts involved by both Use and Material acquisition stages. For the Use stage, mass reduction means lower requirement of electricity for vehicle traction. For the Material acquisition, a reduction of mass would involve a reduction of resources consumption and emissions to environment due to raw materials extraction and production. The application of lightweight design represents the most practicable solution to achieve vehicle mass reduction. The key points of lightweight design are:

- Lowering the parts count by integration of separate components and functions into a single module;
- Reduction of components mass by structural re-design;
- Substitution of traditional materials by lightweight ones.

However striving for reduced weight as the only objective will not necessarily result in a reduced environmental impact of the vehicle of the future. The environmental improvement expected with the development of innovative lightweight materials has to be evaluated along the whole vehicle LC. At this scope an in-depth evaluation of both the benefit in the Use stage and the different effects on Manufacturing and End of Life stages is necessary.

The second approach leads to reduction of electricity consumption of Use stage and it can be primarily achieved by interventions on the most energy intensive systems, "Traction" and "Heating". In this context, feasible strategies are:

- Reduction of driving resistance wheel/rail;
- Improvement in efficiency of car-body insulation;
- Using lost heat of brake resistors for the heating system.

The third approach envisages environmental improvements in the Material acquisition and EoL stages and it is based on:

- Adoption of recyclable and recycled materials whereas it is possible;

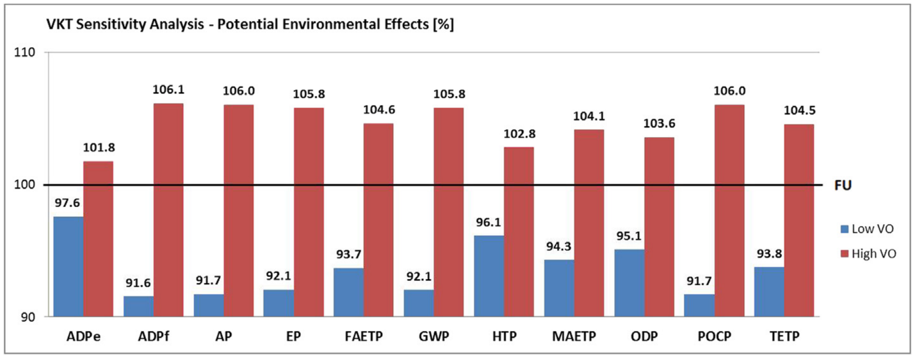

Fig. 9. VKT sensitivity analysis: per-VKT PEEs (% of FU impact).

- Design solutions aimed to simplify the dismantling of components made of recyclable materials;
- Reduce the families of materials for each component.

The sensitivity analysis stresses the opposite effect that vehicle occupancy has respectively on the per-VKT and the per-PKT LC impacts. Passing from low to high VO:

- The per-VKT PEEs grow since vehicle consumption increases;
- The per-PKT PEEs strongly decrease despite increase of vehicle consumption;
- The difference between impact categories are attributable to the fact that Use stage contributes differently for each category.

Assuming as reference the per-PKT results, it can be stated that railway vehicles can strongly reduce the impact of transportation by increasing the VO. Such outcome is according to Chester et al. (2009) and Chester and Horvath (2010) who evidenced that increase in VO involves environmental benefits that are higher in railway in comparison with the private transportation modes, particularly automobile: at this regard Chester et al. (2009, 2013) recommend shift of car riders and passengers from automobile to bus and rail vehicle.

5. Conclusions

The overview of existing literature has evidenced the poor interest in environmental analysis of railway vehicles, especially metros. By performing a predictive Life Cycle Assessment (LCA) of a heavy metro train the paper struggles to reduce this gap. The study has been performed according to the ISO 14040 standards and takes into account the PCR developed by UNIFE. For the LCI data collection, primary data have been provided by metro manufacturer while available databases have been used as source for secondary data. Unlike previous LCAs on similar vehicles, the environmental profile is assessed through a broader range of LCIA impact categories, referred to the CML 2001 method. The study is completed with an investigation on the recyclability/recoverability of the metro. A sensitivity analysis aimed to define the variation of environmental impacts depending on Vehicle Occupancy (VO) has been also carried out.

According with previous studies on similar vehicles, LCA results show that Use is largely the most influential LC stage for the majority of the impact categories. The predominance of Use is due to its energy intensity and the strong dependence of the Italian electricity mix on fossil fuels. Contribution analysis by vehicle system of electricity consumed during operation reveals that “Traction” and “Heating” are the most energy intensive, amounting respectively 41.7% and 30.6%. For ADP_e and HTP the highest contribution is coming from Material acquisition stage: contribution analysis by PG of ADP_e and HTP evidences that the greatest impacts are caused by “Propulsion and electric equipment” and “Bogies and running gears”. Impacts involved by Manufacturing and End of Life are low compared to the other stages. The analysis of materials destination at EoL quantifies total recoverability (material & energy recovery) 92.1% with the remaining part considered as waste to landfilling.

In light of hotspots of AB metro LC, major improvement potential is identified in the reduction of electricity consumption involved by

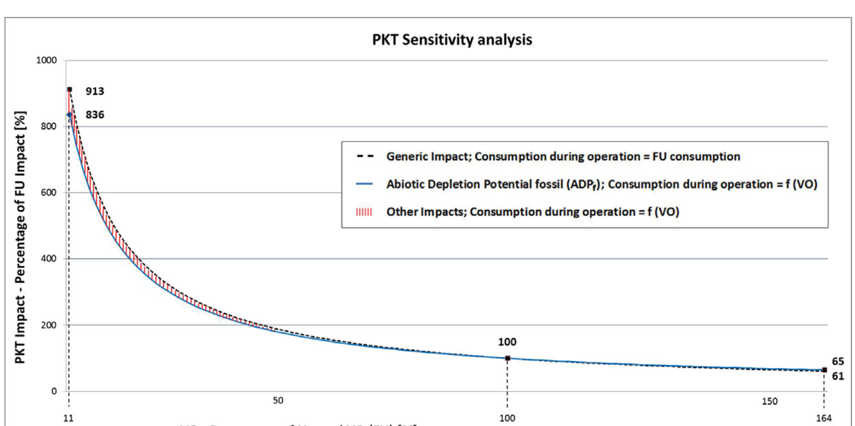

Fig. 10. PKT sensitivity analysis: per-PKT LCIA results depending on VO.

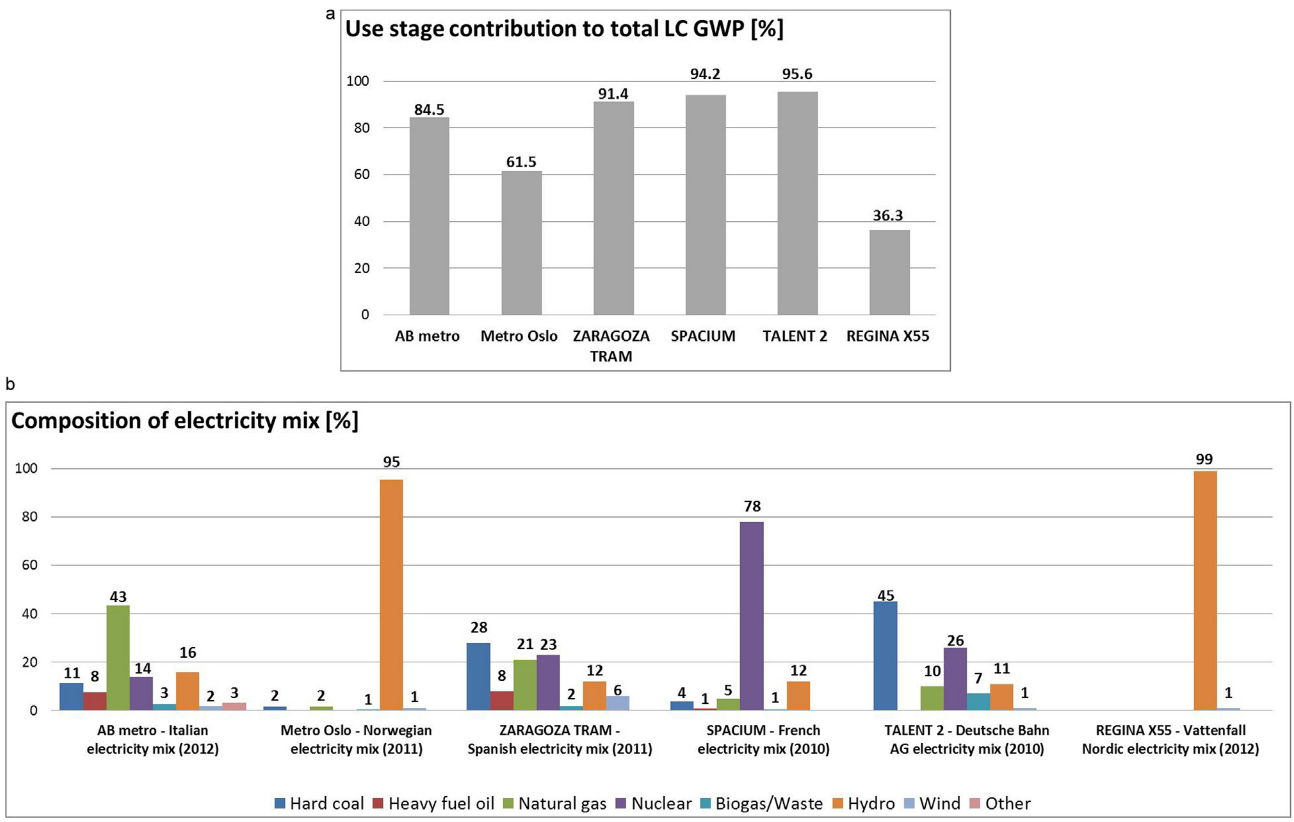

Fig. 11. Use stage contribution to total LC GWP for AB metro, metro Oslo and other railway vehicles (a); Composition of electricity mix for production of electricity consumed by vehicles (b).

Use stage. Since "Traction" system accounts for almost 42% of the Use stage consumption, the main approach is the reduction of vehicle mass to lower energy absorption for drive. At this scope, the application of lightweight design represents the most practicable solution. However striving for reduced weight as the only objective will not necessarily result in a reduced environmental impact of vehicle LC. Indeed the improvement expected in the Use stage by the adoption of lightweight materials has to be evaluated and compared with the effects on Manufacturing and End of Life stages. Another complementary strategy to reduce Use stage consumption is the increase in efficiency of the "Heating", the second most energy intensive system: this can be fulfilled by improvement of efficiency of car-body insulation and recovery of lost heat of brake resistors. The last recommendation is the increase in recyclability rate by a shrewd choice of materials and a new design which simplifies the separation of recyclable materials at EoL.

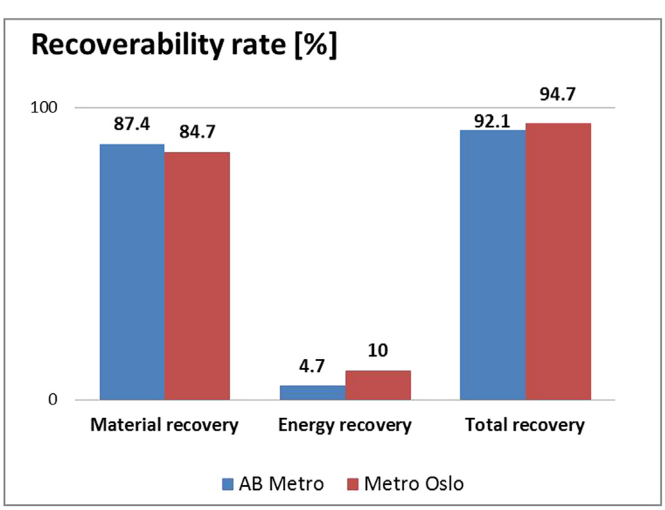

Fig. 12. Comparison between recycling and recoverability rate of AB metro & metro Oslo.

Sensitivity analysis quantifies the PEEs in function of VO. On one hand the growth of VO causes a deterioration of the per-VKT impacts due to the major consumption during operation. On the other hand increase in number of passengers involves great convenience in terms of per-PKT impacts. The environmental advantages achievable by increasing occupancy of the AB metro suggests to re-examine the mobility inside the city of Rome.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2014.10.023.

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