PROCEEDINGS OF ECOS 2015 - THE 28TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
JUNE 30-JULY 3, 2015, PAU, FRANCE

A comparison of the environmental sustainability of conventional, electric and hybrid vehicles

***Lidia Lombardi*[a], *Laura Tribioli*[b], *Raffaello Cozzolino*[c] *and Gino Bella*[d]**

[a] *Niccolò Cusano University, Rome, Italy, lidia.lombardi@unicusano.it*
[b] *Niccolò Cusano University, Rome, Italy, laura.tribioli@unicusano.it*
[c] *Niccolò Cusano University, Rome, Italy, raffaello.cozzolino@unicusano.it*
[c] *Niccolò Cusano University, Rome, Italy, gino.bella@gmail.com*

Abstract:

Atmospheric pollution in urban areas is mainly caused by the transportation sector. One possibility to reduce this contribution is to switch to electric or hybrid vehicles, which are characterized by null or significantly reduced emission at the end-of-pipe, i.e. operation. However, additional components are required for realizing electric and hybrid vehicles and on a life cycle perspective the effectiveness of switching towards these solutions should be assessed. With this purpose, in this study, four types of vehicles were compared by Life Cycle Assessment: a conventional gasoline vehicle; a pure electric vehicle; a plug-in hybrid gasoline-electric vehicle; a plug-in hybrid fuel cell-battery vehicle. The considered electric and hybrid vehicles were obtained by repowering a conventional vehicle. This way, the attention can be focused only on the powertrain differences and inefficiencies, with the added value of avoiding further assumptions. The selected impact indicators for reporting the Life Cycle Assessment results are Cumulative Energy Demand and Climate Change.
For the conventional gasoline vehicle, almost the entire values calculated for Climate Change and Cumulative Energy Demand indicators are due to the fuel use (more than 99%). For the electric and hybrid vehicles, this contribution is reduced in the range 70-91% (depending on the vehicle and on the indicator), as the construction phase, dominated by the battery manufacturing process and fuel cell manufacturing processes, conquers a higher relative importance.
Nevertheless, the electric and hybrid vehicles allow for a significative reduction, in the range 29-48% (depending on the type of vehicle and on the indicator), of Climate Change and Cumulative Energy Demand indicators with respect to the case of gasoline conventional one.

Keywords:

sustainable mobility, fuel cell, life cycle assessment, climate change, cumulative energy demand

1. Introduction

Transport sector generates a considerable contribute to urban atmospheric pollution. European regulations require reducing end-of-pipe emissions of conventional vehicles [1]. One possibility to strongly reduce stack emissions is to substitute them with electric ones [2]. However, battery electric vehicles (BEV) have not yet large range and a short-term possibility is to operate with hybrid electric vehicles, in which a thermal engine is coupled with the electric powertrain, or other alternative powertrains, e.g. fuel cell vehicles, with a significative lowering of end-of-pipe emissions [3].

However, comparing different types of vehicles – conventional, electric or hybrid – only on end-of-pipe emissions basis does not seem a fair way. As a matter of fact, electric or hybrid vehicles have lower end-of-pipe emissions, but the environmental load for producing the charging electricity is simply moved to another site, i.e. the power plant site.

From this point of view, it seems that a wider analysis should be carried out in order to evaluate the environmental sustainability of alternative mobility as, for example, a life cycle approach, including not only the driving phase, i.e. end-of-pipe emissions, but also the environmental impacts generated while producing electricity and the loads connected with the vehicle construction and dismantling. As a matter of fact, electric or hybrid vehicles require the use of batteries, which are rather environmentally unfriendly devices.

According to this perspective, a wider approach should be used including all the life cycle stages of the vehicles, applying a Life Cycle Assessment (LCA) approach, as already done by several authors who highlighted in general the beneficial environmental effects of introducing electric and hybrid vehicles [4-5].

In particular, the aim of this work is the comparison of the environmental performances, by LCA, of four types of vehicles: a conventional gasoline vehicle; a pure electric vehicle; a plug-in hybrid gasoline-electric vehicle; a plug-in hybrid fuel cell-battery vehicle. Several studies have already been carried out, aimed at comparing the life cycle impact of different kind of powertrains, but this is usually done by investigating the environmental sustainability of the entire vehicle rather than comparing the differences among the powertrains [7-8]. In those analyses, one should take into account that the vehicles are often produced by different manufacturers, most likely with different processes and, as a matter of fact, these data are rather unavailable, causing the study to be somehow rough. Hence, in the present study, the same vehicle has been supposed to be re-engineered as to completely change its powertrain and represent the different vehicles to be compared. This way, the attention can be focused only on the powertrain differences and inefficiencies, with the added value of avoiding further assumptions.

In the following, the analysis that was carried out is reported and described according to the LCA phases [9]: goal and scope definition, inventory analysis, impact assessment and interpretation and improvement, in terms of sensitivity analysis.

2. Life cycle assessment: goal and scope definition

The goal definition is the first phase of the LCA in which the purpose of the study is described. It identifies and defines the object of the assessment.

The goal of this study is to compare, on a life cycle perspective, the environmental performances of four types of vehicles: a conventional gasoline vehicle; a pure electric vehicle; a plug-in hybrid gasoline-electric vehicle; a plug-in hybrid fuel cell-battery vehicle. The electric and hybrid vehicles were obtained by repowering a conventional vehicle, substituting the thermal powertrain with the appropriate elements for each of the three possibilities [10-11], in order to keep a fair study case for comparison.

The original vehicle was a GM Chevrolet Malibu, which is equipped with a gasoline straight-4 pistons LE5 engine of the GM Family II [12], whose main specifications are summarized on the left of Table 1.

Table 1. Engine and Motor Specifications, [12-13]

Internal Combustion Engine		*Electric Motor*	
Rated Power	104 kW@ 6500 rpm	Rated Power	75 kW
Maximum Torque	176 Nm@ 5000 rpm	Max/Min Peak Torque	270 Nm@3000-4200 rpm
Compression Ratio	11.2:1	Max/Min Rated Torque	130 Nm@0-5500 rpm
Displacement	2.384 L		

The electric vehicle was modeled by maintaining the same Malibu vehicle glider, but replacing the engine with a GVK210X permanent magnet electric motor [12], whose main specifications are listed on the right of Table 1.

In the repowered hybrid electric vehicle, the internal combustion engine is connected to the transmission shaft by a clutch and is coupled by a belt to the electric motor. The vehicle has a parallel configuration, characterized by a pre-transmission architecture, chosen for its simple and economically convenient implementation in re-engineered powertrains.

The powertrain of the plug-in hybrid fuel cell-battery vehicle consists of a polymer electrolyte (PEM) fuel cell (FC) and a battery pack, linked together to an electric motor by means of a DC/AC inverter. Thanks to the specific efficiency map [10-11], the motor can be directly linked to the front wheels without any transmission ratio and the gearbox is no more required. The FC can provide power directly to the electric motor or to the battery, or battery and FC can supply, simultaneously, power to the front motor. The PEM stack is composed by 750 cells in series, each of an effective area of 120 cm^2, supplying a rated power of 21 kW, for a total occupied volume of around 0.7 m^3 [11].

In order to make a fair comparison, the electric motor is the same for both the electric and hybrid vehicles. The battery pack, even adopting the same technology, has a 33-kWh energy capacity in the pure electric vehicle, and is downsized to a 13-kWh pack for the hybrid powertrains, thanks to the extended range allowed by the presence of fuel cell and engine, respectively.

The functional unit is represented by the total length of the driving path – equal to 200000 km – considering a life time for the vehicles of 10 years and 20000 km/y of driving, divided into about 11000 km/y on extra-urban/ highway routes and about 9000 km/y on urban roads.

The boundary of the studied system, represented in a simplified way in Fig. 1, for each type of vehicle, includes three distinct phases for the vehicle life cycle: construction, use and end-of-life. For each of them, the entering energy and material flows were considered. For each material and each energy carrier flow, the inventory was reconstructed up-stream to raw materials extraction, through the use of appropriate records available in ecoinvent 2.2 [14].

In particular, during the use phase, the production processes of the specific energy carrier – gasoline, electricity, hydrogen - was considered, including the sub-process that is usually addressed to as well-to-wheel contribution in several works related to vehicle LCA [15]. Concerning electricity, main results are presented with reference to Italian electric energy mix record, available in ecoinvent database. The sensitivity to this assumption will be explored considering different country energy mixes.

For the construction phase, according to the aim of the study, that is the comparison among the different powertrains, only the contributions provided by the components, which differ from one vehicle to the other, were considered, as summarized in Table 2. As a matter of fact, the impacts derived from the construction of the other vehicle components (for example the chassis, tires, etc.) was not included, being the same for the four vehicles and giving the same contribution to the final parameters that will be compared. On the other side, a detailed analysis of the materials present in the different components of the vehicle is rather uncommon in vehicle LCA studies [4-5]. Generally, these studies consider and report as input to the construction phase the overall amount of materials required for the entire vehicle, without details for the single components. For this reason, several estimations and assumptions were required to obtain values of amount of materials present in each component.

Concerning the end-of-life phase, the possibility of recycling the main materials present in the considered components was included, as better detailed in the inventory paragraph. According to the life cycle perspective, the recycling of a given amount of a material is considered as avoided production of the same amount of material from raw substances. This is transformed into an avoided effect in the environmental balance, i.e. negative values of the environmental impacts.

Table 2. Powertrain components which differ in the four types of vehicle.

Type of vehicle	*Gasoline*	*Electric*	*Gasoline-electric*	*Fuel cell-battery*
Components	Thermal engine Transmission Catalytic converter	Electric motor Inverter Battery	Thermal engine Transmission Catalytic converter Electric motor Inverter Battery	Fuel cell H_2 tank Electric motor Inverter Battery

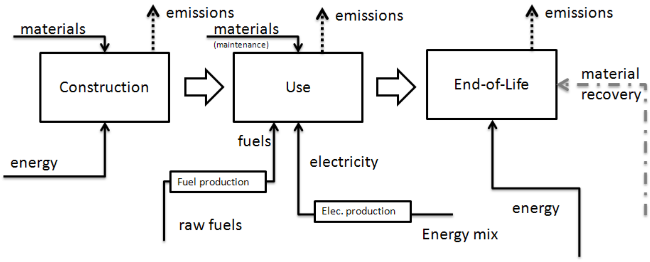

Fig. 1. Simplified description of the boundaries of the studied systems.

3. Life cycle assessment: inventory analysis

In this phase, all the inputs and outputs occurring in the life cycle of the systems previously defined are inventoried to perform a quantitative description of all flows of materials and energy across the system boundary, either into or out of the system itself.

3.1 – Construction

As already mentioned above, for the materials flows related to the construction phase, only the components listed in Table 2 were considered, namely: engine, transmission system (i.e. differential and gearbox), catalytic converter, electric motor, inverter, fuel cell, hydrogen tank and battery packs.

For the engine, manufacturer datasheets are available online, which include a list of the main materials composition [12]. Starting from this list, the inventory for the engine and the transmission system was carried out by using [16] as baseline and adjusting the data by discussing the issue with experts. Engine and transmission are common to both conventional and hybrid electric vehicles, which are also equipped with a catalytic converter, whose materials composition was determined as in [17]. A detailed list of the materials and weights considered for these components is provided in Table 3.

The electric motor and the inverter are the same for the pure electric and hybrid vehicles, and their materials compositions were determined by literature surveys [7-8] and are listed in Table 4.

The fuel cell consists of an air-cooled Ballard Nexa^{TM} stack and the data considered in this study were retrieved from: an estimation based on measured data available from a 1-kW experimental stack, data available online from the manufacturer website [18] and literature surveys, used as baseline, [7-8]. For the hydrogen storage, one Quantum's Q-lite^{TM} Type IV tank at 200 bars was considered, [19]. Materials compositions and weights are provided in Table 5 for the fuel cell and the hydrogen tank.

For the battery manufacturing phase, data were extracted from [20], where the inventory for a 10-kWh battery - weighting 107 kg - for a plug-in vehicle is reported. The inventory was scaled for our 13-kWh battery, based on the ratio of their capacities.

3.2 – Use

The use phase includes the energy carriers consumption – gasoline, electricity, hydrogen – and the maintenance.

In order to properly evaluate the fuel/energy consumptions related to the use phase of each configuration, a simulator - developed in Matlab/Simulink - was used. The tool has already been presented in [10] for the conventional and gasoline hybrid vehicles and in [11] for the fuel cell hybrid vehicle, and consists of a quasi-static forward-looking model of the entire vehicle. It includes a driver's model based on a PID controller, steady-state performance maps for each power source, i.e. engine, motor and fuel cell, a zero-dimensional equivalent circuit model for the battery, and it computes vehicle velocity and fuel consumption by solving the longitudinal dynamics of the vehicle. Being modular in nature, a modification of the same simulator has allowed modeling the pure electric vehicle, as well.

Table 3. Materials and weights considered for ICE, transmission system and catalytic converter, [12], [16-17].

Internal Combustion Engine		**Transmission**		**Catalytic Converter**	
Material	**Weight [kg]**	**Material**	**Weight [kg]**	**Material**	**Weight [kg]**
Cast aluminum	80	Cast iron	70	Kaolin	0.194
Composite	0.3	Cast Aluminum	10	Talc	0.357
Molybdenum and iron alloy	6			Alumina	0.370
Iron	34			Aluminum hydroxide	0.172
Steel	2			Silica	$96 \cdot 10^{-3}$
				Rare earth oxide	$10.7 \cdot 10^{-3}$
				Lanthanum oxide	$3.02 \cdot 10^{-3}$
				Platinum	$0.25 \cdot 10^{-3}$
				Rhodium	$0.05 \cdot 10^{-3}$
				Stainless Steel (409)	3.865
				Cardboard	0.8376
TOTAL	122.3	TOTAL	80	TOTAL	5.9

Table 4. Materials and weights considered for motor and inverter, [7-8].

Electric Motor		**Inverter**	
Material	**Weight [kg]**	**Material**	**Weight [kg]**
Copper	4	Copper	2
Steel	49	Insulation material	0.2
Rare Earth	1.5	Silica	0.5
		Ferrite	5
TOTAL	54.5	TOTAL	7.7

Table 5. Materials and weights considered for FC and hydrogen tank, [18-19].

Fuel Cell		**Hydrogen Tank**	
Material	**Weight [kg]**	**Material**	**Weight [kg]**
Graphite	23	Aluminum	20.13
Steel	13	Glass Fiber	36.6
PTFE polymer	11	Steel	40.27
Electronic components	1.4		
Platinum	0.15		
TOTAL	48.55	TOTAL	61

For evaluation of fuel/energy consumptions, a set of different driving cycles was considered to achieve the aforementioned 11000 km/y of extraurban/highway missions and 9000 km/y of urban paths. A Federal Highway Driving Schedule (FHDS) was considered for reproducing highways, while for the extraurban paths, four standard schedules - Federal Urban Driving Schedule (FUDS), Artemis Extra Urban, Vail and NREL - plus two real driving cycles - Arco Merano and Aachen - were employed. The urban pathway was simulated by using a 45-km Artemis Urban cycle in order to reproduce a typical round trip between home and workplace, and this cycle was assumed to be repeated 213 times per year.

Results obtained with the aforementioned tool are listed in Table 6 for each of the four configurations.

From simulations, the 33-kWh battery of the pure electric vehicle has been demonstrated to guarantee a range of 90 km on average (i.e. considering mixed pathways), while the 13-kWh battery pack of the hybrid vehicles allows for an average all-electric range of around 30 km. Under these considerations, the electric vehicle battery needs at least one charge during extraurban/highway trips (total lengths from 140 to 270 km), while the urban mission can be accomplished two times per battery full charge. At the end of each driving pattern, the battery charge was considered to be fully restored, regardless of the value of the final state of charge (SoC).

On the other hand, owe to the extended range guaranteed by the presence of engine and fuel cell, respectively, the hybrid powertrains do not require an on-going charge during extraurban/highway trips, but the control strategy, implemented in each simulator [10-11], assures that a 0.3 final SoC is achieved at the end of each trip. This value was selected as a trade-off between the need of using the highest amount of energy stored in the battery and the need of preventing battery wear. Hence, the electricity consumption for the hybrid vehicles can be easily calculated as the electric energy required to restore battery full charge from 0.3 SoC.

Table 6. Fuel/Energy total consumptions for each vehicle, [10-11].

Type of vehicle	**Driving Mission**	**Gasoline kg**	**Hydrogen kg**	**Electricity kWh**
Conventional	ExtraUrban + Highway	7137	0	0
	Urban	6345	0	0
	TOTAL	**13482**	**0**	**0**
Pure Electric	ExtraUrban + Highway	0	0	10602
	Urban	0	0	8099
	TOTAL	**0**	**0**	**18701**
FC/battery	ExtraUrban + Highway	0	817	760
	Urban	0	616	16199
	TOTAL	**0**	**1433**	**16959**
Hybrid electric	ExtraUrban + Highway	3075	0	760
	Urban	761.6	0	16199
	TOTAL	**3837**	**0**	**16959**

Finally, for hydrogen production, an autothermal natural gas reforming process was considered, with a conversion efficiency of around 85% [21]. Thus, a total amount of 5101 kg of natural gas is needed to produce the hydrogen consumed during ten years. The CO_2 emissions from natural gas reforming were accounted for.

The impacts related to the production processes of gasoline, natural gas and electricity were considered using the appropriate record of ecoinvent. In particular, main results were calculated with the assumption that the electric and hybrid vehicles are used in Italy, and the Italian electric energy mix was used for recharging operations. Further calculations, considering the usage of the electric and hybrid vehicles in other countries, such as USA and France, were also performed by using the appropriate record of ecoinvent for electricity. No specific assumptions were made for other electric consumptions during the life cycle of the four vehicles, thus the energy mix change will not influence the CC and CED values of the conventional gasoline vehicle.

For the maintenance stage, within the functional unit of 200000 km, the tires were supposed to be replaced the same number of times for each configuration and thus, for the same reasoning applied to the other components common to all the vehicles, these elements were not considered in the analysis. For the engine oil, a complete replacement after 20000 km was considered [22].

The battery packs, even being of different sizes, were all considered to be replaced at least once during the vehicles life span. This cautious assumption is mainly due to the plug-in nature of these vehicles, which makes the battery experience several charging and discharging cycles, which often result in an irreversible battery damage.

3.3 – End-of-life

For the end-of-life phase, batteries were assumed to be disposed, since the new recycling technology, needed for LiFePO4 batteries, is not yet commercially available [20]. Disposal process was modeled according to the ecoinvent record “1 kg Disposal, Li-ions batteries, mixed technology/GLO S”.

For each device, the consumptions for the dismantling phase were accounted for on the basis of the total weight (using the ecoinvent record “1 kg Dismantling, industrial devices, mechanically, at plant/GLO S”). Then, for steel, iron, ferrite, iron alloys, cast iron and copper recycling at 80% was assumed; for aluminum, cast aluminum, platinum and rhodium recycling at 90% was assumed. For all the remaining materials disposal to landfill was assumed.

4. Results: impact assessment

Results are presented according to Life Cycle Impact Assessment, which examines the mass and energy inventory input and output data for a product system to translate these data to better identify their possible environmental relevance and significance. This translation uses, where possible, numerical indicators for specific subjects or categories, that reflect in some manner the system environmental loading or resources depletion for that category. These indicators, then, constitute an environmental loading and resources depletion profile for a system. This profile, with possible further analysis and weighting, is intended to provide an additional useful perspective on the possible environmental significance in one or more general areas of resources, natural environment and human health.

In this study, environmental indicators according to Cumulative Energy Demand (CED) and Climate Change (CC) methods were used, as calculated by SimaPro 7.3 software [23].

CED indicator is the sum of different impact categories divided into non-renewables (fossil, nuclear and primary forest) and renewables (biomass, wind, solar, geothermal and water). The underpinning idea for the CED calculation is that all energy carriers have an intrinsic value. This intrinsic value is determined by the amount of energy withdrawn from nature. The intrinsic value of energy resources is expressed in MJ-equivalents, in order to make comparable the different impact categories. In order to get a total (cumulative) energy demand, each impact category is given the weighting factor 1. The compared systems are concerned with energy conversion, being their purpose the conversion of different types of energy – i.e. gasoline, electricity, hydrogen – into the useful effect of passenger mobility. For this reason, the CED indicator was selected as an important indicator, in reference to the systems purpose, for describing the differences in energy resources use of the compared systems.

Similarly, when energy conversion is the main topic, the other inalienable environmental indicator to be calculated is CC, being a direct effect of fossil energy resource use.

CC indicator is calculated considering the different gaseous emissions according to their global warming potential (GWP): values published by the IPCC’s Fourth Assessment Report [24]. CC is expressed in kg of equivalent CO_2.

At the time of writing, additional modeling of other impacts is on-going, including direct impacts on the human health, strongly related to the end-of-pipe emissions, in order to obtain a broader characterization of the compared processes.

4.1 – Contribution analysis

Figures 2 show the percentage contributions from the different life cycle phases, namely construction, use and dismantling, to the total values of CC and CED for the four analyzed vehicle life cycles. First of all, one should notice that the two selected indicators behave according to the same trends for the four cases, as expected, being the CED dominated by the fossil energy consumption and the CC directly linked to such exploitation. Hence, for this comparison there is not any added value in considering both of them, while we anticipate that different behaviors are highlighted when different energy mixes will be considered.

Looking at the conventional vehicle case (Fig. 2a), the use phase contributes for about 99,8% to the total of both CC and CED, with the consumption of fuel being responsible for about 99,6%, while maintenance represents the 0.05-0.2%, for CC and CED, respectively. The construction contribution to CC and CED is only 1-1.1%, respectively. The end-of-life phase has a negative contribution (CC:-0.7%; CED:-0.9%), thanks to the avoided effect related to material recycling. Thus, in the sustainable mobility perspective, it is evident that reducing the impact of the fuel consumption use is the main route to be pursued.

The situation is, instead, rather different for the electric vehicle case (Fig. 2b). The use phase contributes for about 70.1-73.9%, CC and CED, respectively, with the electric consumption being responsible for about 42.1% to CC and 49.4% to CED and maintenance for 28.0% to CC and 24.4% to CED. Construction phase contribution is 28.4-24.9%, to CC and CED, respectively. In this case the contribution from energy carrier consumption – i.e. electricity – is about halved with respect to the conventional vehicle. The maintenance phase, including the manufacturing of a new battery, contributes with almost the same share of the construction phase. The battery manufacturing represents the main source of impact for the construction, as reported in Table 7. For the pure electric vehicle, also the end-of-life phase provides a positive impact, mainly because of the battery disposal.

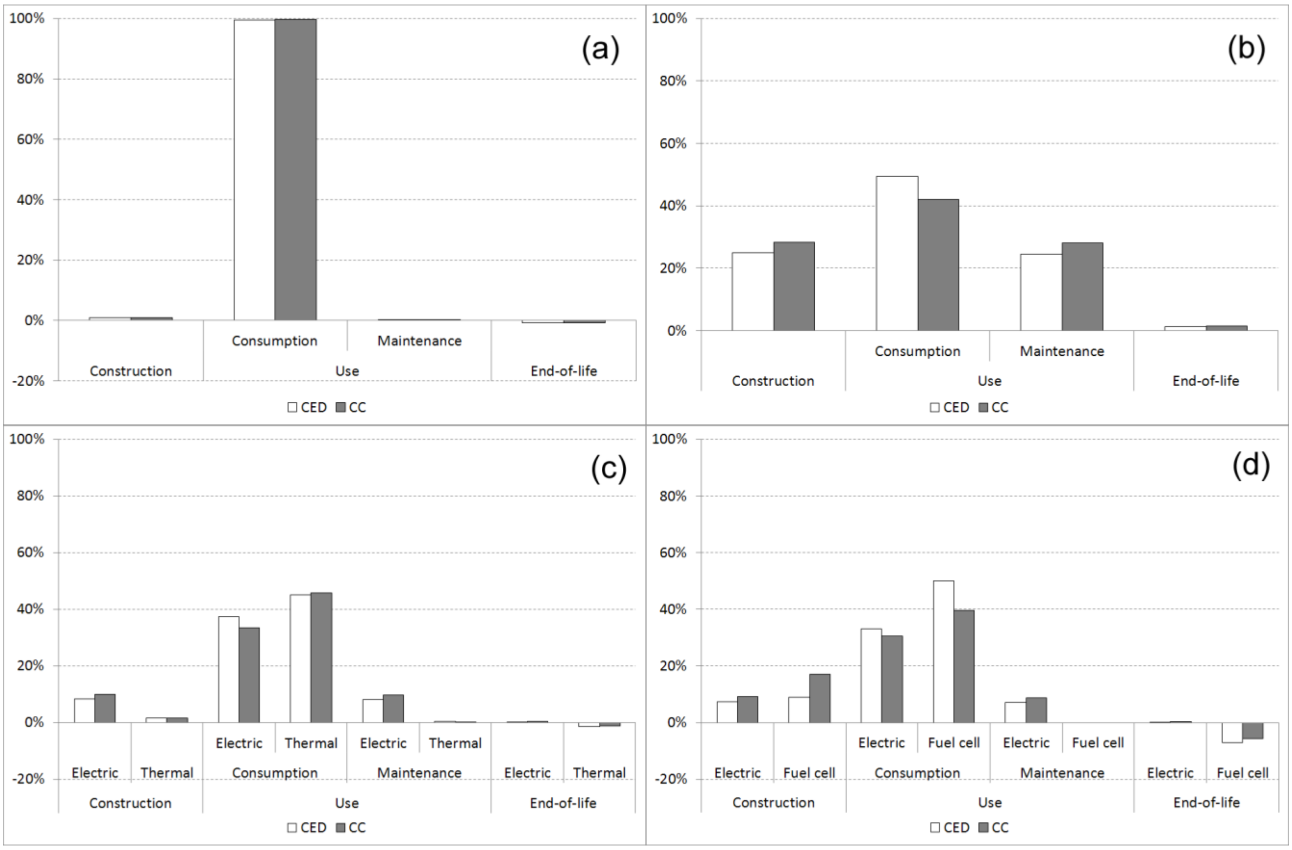

Fig. 2. Contributions to the CC and CED indicators from the different life cycle phases of: (a) the conventional gasoline vehicle; (b) the pure electric vehicle; (c) the plug-in hybrid gasoline-electric vehicle; (d) the plug-in hybrid fuel cell-battery.

For the plug-in hybrid gasoline-electric vehicle case (Fig. 2c), the use phase represents 89.1-91% of total CC and CED, respectively, with the energy carriers consumption being responsible for about 79.3% to CC and 82.6% to CED and maintenance for 9.8% to CC and 8.4% to CED. The impact of the energy carriers consumption is divided between electricity and gasoline as 33.4% and 45.9% for CC and as 37.4% and 45.2% for CED. Construction phase contribution is 11.6% to total CC, with 10% from electric part, and 10.1% to total CED, with 8.4% from electric part. End-of-life contribution is negative and equal to -0.7% to CC and -1.1% to CED, with the negative values coming from the recycling of the materials from the devices of the conventional part.

For the plug-in hybrid fuel cell-battery vehicle case (Fig. 2d), the use phase represents 79.0-90.4%, of total CC and CED respectively, with the energy carriers consumption being responsible for about

70.2% to CC and 83.2% to CED and maintenance for 8.9% to CC and 7.1% to CED. The impact of the energy carriers consumption is divided between electricity and hydrogen as 30.6% and 39.6% for CC and as 33.2% and 50.1% for CED. Construction phase contribution is 26.2% to total CC, with 17.1% from fuel cell part, and 16.5% to total CED, with 9.1% from fuel cell part.

Table 7. Contributions of the manufacturing of different devices to the construction phase of the pure electric vehicle.

	Construction phase		
	Motor	**Inverter**	**Battery**
CED [%]	1.4%	0.2%	98.4%
CC [%]	1.1%	0.1%	98.8%

4.2 – Comparison

In order to make a sort of scoring – according to the selected environmental impact indicators – of the four different types of powertrains, the total values calculated for CED and CC are reported in Fig. 3. The scoring according to CC agrees to the one according to CED, as expected, and for the reasons already mentioned above. The best performances are achieved by the pure electric vehicle, while the worst ones are provided by the conventional gasoline vehicle, confirming that the long-term solution for the sustainable private mobility is the electric propulsion. Substituting a conventional gasoline vehicle with the corresponding pure electric one provides a reduction of the total value of CC of about 46% and a reduction of the total value of CED of about 48%.

The use of the plug-in hybrid gasoline-electric vehicle in place of the conventional gasoline one allows for the reduction of 38% and 37% of CC and CED, respectively. Thus, even if a lower benefit is accomplished with respect to the pure electric case, the replacement of gasoline vehicles with gasoline-electric hybrid ones still would supply a substantial improvement in reducing the contribution to global warming and energy resources depletion from private mobility sector.

The use of a plug-in hybrid fuel cell-battery vehicle in place of a conventional gasoline one offers the lowest reduction, but still of valuable amount, being the CC and CED values lower than 32% and 29%, respectively, with respect to the values calculated for the gasoline case.

Table 8 shows the values of specific production of CC per unit of traveled distance, over the life cycle (i.e. 200000 km).

Table 8. Specific CC production per unit of travelled distance (g/km).

Pure electric vehicle	Plug-in hybrid gasoline-electric vehicle	Plug-in hybrid fuel cell-battery vehicle	Conventional gasoline vehicle
143	163	178	263

4.3 - Sensitivity analysis to energy mix assumption

As we stated in the goal and definition section, the main results presented in the previous paragraph were calculated with reference to Italian electric energy mix record, available in ecoinvent database. Of course, if we modify this assumption, results change, according to the different country energy mixes. With the aim of representing different energy mixes, we considered the cases of USA and France. The calculated values of the overall CC and CED indicators for the life cycle of the electric and hybrid vehicles are shown in Fig. 4 and Fig. 5, respectively.

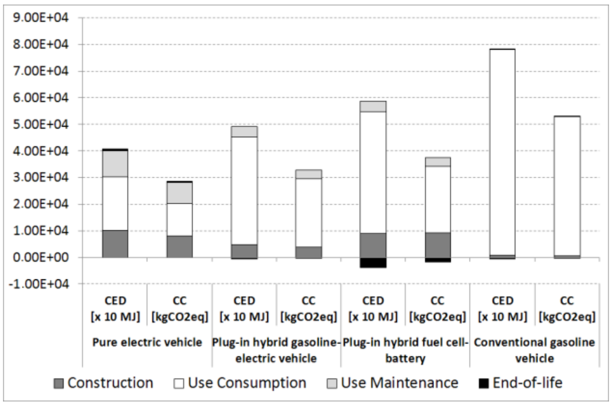

Fig. 3. Comparison of total values of CC and CED indicators for the different vehicles.

In the USA electricity production, the fossil fuel use is higher than in Italy and thus the CC specific emission per unit of produced electricity is higher (0.214 $kgCO_2eq/MJ$ in USA vs. 0.178 $kgCO_2eq/MJ$ in Italy). The CED specific value per unit of produced electricity is higher in USA than in Italy, as well (3.558 MJ/MJ in USA vs. 2.983 MJ/MJ in Italy).

In France, the fossil fuel use is lower than in Italy and thus the CC specific emission per unit of produced electricity is lower as well (0.026 $kgCO_2eq/MJ$ in France). The CED specific value per unit of produced electricity is, instead, higher in France than in Italy, mainly because of the prominent use of nuclear energy (3.411 MJ/MJ in France).

The substitution of a conventional gasoline vehicle with an electric one in the USA reduces the CC indicator by 41% (the reduction is 46% in Italy). The same substitution in France reduces the CC indicator by 65%. France emerges as the best country, among the three, for applying the electric vehicle with the aim of reducing greenhouse effect. On the contrary, there is not such a difference when considering the CED indicator. Italy is the best country, among the three, for applying the electric vehicle with the aim of reducing energy natural resource depletion.

Thus, performing specific evaluations for different countries is very important and it is also very important to include in future studies the analysis of expected changes in the countries energy mixes, considering the wished increase of the renewable share and the reduction of carbon dioxide emissions, according to a dynamic view of the studied systems. In this perspective, the massive introduction into the market of both electric and hybrid vehicles for the private mobility can play an even more significative role in reducing the contribution of this sector to global warming.

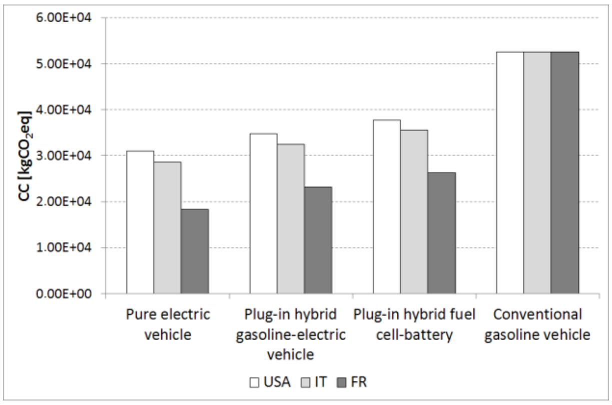

Fig. 4. Comparison of total values of CC indicator for the different vehicles in Italy, France and USA.

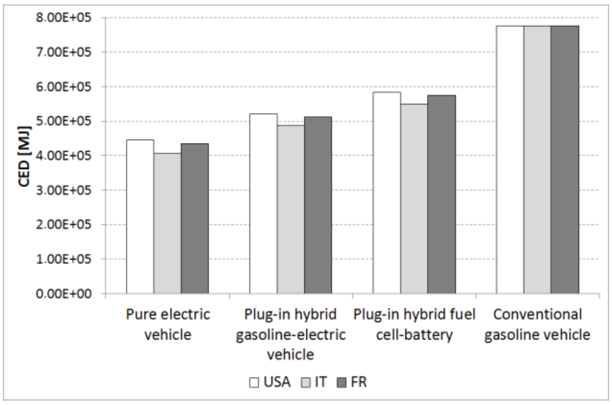

Fig. 5. Comparison of total values of CED indicator for the different vehicles in Italy, France and USA.

6. Conclusions

In this study we compared, by means of Life Cycle Assessment (LCA), the environmental performances of four types of vehicles: a conventional gasoline vehicle; a pure electric vehicle; a plug-in hybrid gasoline-electric vehicle; a plug-in hybrid fuel cell-battery vehicle. The electric and hybrid vehicles were obtained by repowering a conventional vehicle, substituting the thermal powertrain with the appropriate elements for each of the three alternative possibilities, in order to keep a fair study case for comparison. As indicators of the environmental impacts of the studied systems, we selected Cumulative Energy Demand (CED) and Climate Change (CC).

Analyzing the contributions of the different life cycle phases to the total values of the calculated indicators, we highlighted that, while for the conventional gasoline vehicle almost the entire values calculated for CC and CED indicators are due to fuel usage (fuel represents more than 99% of the total CC and CED), for the electric and hybrid vehicles, this contribution is reduced in the range 70-91%, depending on the vehicle and on the indicator (fuel/energy carriers represent a contribution between 70 and 90% of the total CC and CED), as the construction phase, dominated by the battery and fuel cell manufacturing processes, conquers a higher relative importance.

Nevertheless, the electric and hybrid vehicles allow for a significative reduction, in the range 29-48% (depending on the type of vehicle and on the indicator), of CC and CED indicators with respect to the case of gasoline conventional one. The best results are provided by the pure electric vehicle, confirming that the switch to such type of vehicles for the private mobility – on the medium-term perspective when the driving range will be improved - would allow for a significative contribution to the reduction of global warming and fossil resource depletion. However, also the gradual substitution of hybrid vehicles to conventional ones in the short-term perspective – feasible thanks to the already available improved range of driving distance with respect to the actual ranges reachable by pure electric vehicles – would supply significative reduction of global warming and fossil resource depletion.

The reported results are strongly dependent on the type of electricity - i.e. electricity with fossil, renewable and nuclear origin, according to the country specific energy mix - that is used to feed the electric and hybrid vehicles. Thus, it is very important performing specific evaluations for different countries. It is even more important to consider that the assumptions made for the country energy mixes will change progressively in the future, with the expected increase of the renewable share and the reduction of carbon dioxide emissions for electricity production. In this perspective, the switch from gasoline vehicles to electric/hybrid ones will be even more favorable.

References

[1] Directive 98/69/EC of the European Parliament and of the Council of 13 October 1998 relating to measures to be taken against air pollution by emissions from motor vehicles and amending Council Directive 70/220/EEC. Available at: <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31998L0069>

[2] X. Mosquet, M. Devineni, T. Mezger et al., “Powering autos to 2020: the era of the electric car,” Boston Consulting Group, 2011.

[3] Chan, C.C., “The state of the art of electric and hybrid vehicles”, Proceedings of the IEEE, 2002, vol. 90, no. 2, pp. 247-275.

[4] Nanaki E.A., Koroneos C.J. “Comparative economic and environmental analysis of conventional, hybrid and electric vehicles e the case study of Greece”, Journal of Cleaner Production, 53, 2013:261-266

[5] Faria R., Marques P., Moura P., Freire F., Delgado J., de Almeida A.T. “Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles”, Renewable and Sustainable Energy Reviews, 24, 2013:271–287.

[6] Faria R., Moura P., Delgado J., de Almeida A.T. “A sustainability assessment of electric vehicles as a personal mobility system”, Energy Conversion and Management, 61, 2012:19–30.

[7] Kudoh Y., Nansai K., Kondo Y., Tahara K., Life cycle CO2 emissions of FCEV, BEV and GV in actual use, Proceedings of the 23rd International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exposition 2007 - Sustainability: The Future of Transportation, EVS 2007

[8] Bartolozzi I., Rizzi F., Frey M., Comparison between hydrogen and electric vehicles by life cycle assessment: a case study in Tuscany, Applied Energy, 101, 2013: 103–111.

[9] ISO 14040:2006, 2006. Environmental management–life cycle assessment – principles and framework. International Organisation for Standardisation (ISO), Geneva.

[10] Tribioli, L., Barbieri, M., Capata, R., Sciubba, E., Jannelli, E., Bella, G. "A Real Time Energy Management Strategy for Plug-in Hybrid Electric Vehicles based on Optimal Control Theory", Energy Procedia, 2014, 45:949–958.

[11] Tribioli, L., Cozzolino, R., Barbieri, M. (2014), "Optimal Control of a Repowered Vehicle: Plug-in Fuel Cell against Plug-in Hybrid Electric Powertrain", AIP Conference Proceedings, 1648, 570014 (2015); ICNAAM2014, Rhodes, 22-28/09/2014; http://dx.doi.org/10.1063/1.4912800

[12] GVM_catalogue.pdfGeneral Motors Engine Guide. GM 2.4 Liter l4 Ecotec LEA Engine Datasheet. Available at: <http://gmauthority.com/blog/gm/gm-engines/lea/>

[13] Parker GVM Global Vehicle Motor Catalogue. GVK210-150DQW Datasheet. Available at: <http://www.parker.com/literature/SSD%20Drives/Literature/192_300108_>

[14] Swiss Centre for Life Cycle Inventories. The ecoinvent Database. Available at:< http://www.ecoinvent.org/database/>[accessed 05.02.2015]

[15] Donateo, T., Ingrosso, F., Lacandia, F.. Pagliara, E., "Impact of Hybrid and Electric Mobility in a Medium Sized Historic City", SAE Technical Paper 201362460077, ISSN 014867191., 2014.

[16] Schweimer, G. W.; Levin, M. *Life Cycle Inventory of the Golf A4*; Volkswagen: Wolfsburg, Germany, **2000**. Available at: <http://www.volkswagenag.com/content/vwcorp/info_center/en/publications/2007/01/Golf_A4__Life_Cycle_Inventory.-bin.acq/qual-BinaryStorageItem.Single.File/golfa4_english.pdf>

[17] Belcastro E. L., Life Cycle Analysis of a Ceramic Three-Way Catalytic Converter, Thesis, Virginia Polytechnic Institute and State University, April 23, 2012. Available at: <http://scholar.lib.vt.edu/theses/available/etd-05072012-130457/unrestricted/Belcastro_EL_T_2012.pdf >

[18] Ballard Nexa^{TM} Power Module User's Manual. Fuel cell stack datasheet. Available at: <http://my.fit.edu/~swood/Fuel%20Cell%20Manual.pdf>

[19]Quantum Technologies High Pressure Lightweight CNG Type IV Cylinders Datasheet. Available at: <http://www.qtww.com/assets/u/21InchFamily.pdf>

[20] Zackrisson M., Avellán L., Orlenius J., 2010. Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles - Critical issues. Journal of Cleaner Production 2010; 18:1519-1529.

[21] Cozzolino R., Tribioli L., On-board diesel autothermal reforming for PEM fuel cells: simulation and optimization", AIP Conference Proceedings, 1648, 570013 (2015); ICNAAM2014, Rhodes, 22-28/09/2014; http://dx.doi.org/10.1063/1.4912799 [22] Castrol Edge Website. Engine Oil Specifications. Available at: <http: castroledge.it/products/oil range>.

[23]PRé Consultants. SimaPro LCA Software. Available at:<http://www.pre-sustainability.com/simapro>[accessed 05.02.2015]

[24] Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., Miller H.L., Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.