The private and social monetary costs and the energy consumption of a car. An estimate for seven cars with different vehicle technologies on sale in Italy

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Abstract:

This paper estimates the total private and social cost of seven cars (the gasoline VW Polo, the diesel Ford Fiesta, the CNG Fiat Punto Evo Natural Power, the LPG Alfa Romeo MiTo, the Hybrid Toyota Yaris, the BEV with leased-battery Renault Zoe and the BEV Peugeot iOn.), making use of the Italian data with reference to the vehicles' purchase and maintenance costs, fuel and electricity costs, energy mix, pollution and noise costs. Among the selected cars, the diesel Ford Fiesta currently performs best from the private and social cost as well as energy consumption point of view. From the social point of view, both the Toyota Yaris (Hybrid) and the Alfa R. MiTo (bi-fuel LPG) perform as well as the BEVs, and the absolute difference with the conventional fuel cars is quite small. A scenario analysis is also performed to evaluate how the cars' ranking is affected by how many years a car is kept, by how many kilometers per year a car is driven, by the subsidies enacted by the Italian government, by an increase in the price of fuel and by a decrease in the price of the batteries.

Keywords: private costs, social costs, electric vehicles

Acronyms

BEVs: Battery electric vehicles	Li-ion: Lithium-Ion batteries
CH_4: Methane	LPG: Liquefied Petroleum Gas
CNG: Compressed Natural Gas	Ni-MH: Nickel–metal hydride batteries
CO: Carbon monoxide	NMVOC: Non-Methane Volatile Organic Compounds
CO_2: Carbon dioxide	NO_x: Nitrogen oxide
E85: Ethanol	PHEVs: Plug-in hybrid electric vehicles
EVs: Electric vehicles	$PM_{2.5}$: Particulate matter (2.5 micron diameter)
FC: Fuel-Cell vehicles	PM_{10}: Particulate matter (10 micron diameter)
FC-HEV: Fuel-Cell Hybrid electric vehicles	PV: Present value
FC-PHEV: Fuel-Cell Plug-in Hybrid electric vehicles	SO_x: Sulfur oxide
GHG: Greenhouse gas emissions	SO_2: Sulfur dioxide
GWP: Global Warming Potential	TtW: Tank-to-Wheel
HEVs: Hybrid electric vehicles	WtT: Well-to-Tank
ICEVs: Internal combustion engine vehicles	WtW: Well-to-Wheel
Leased BEV: BEV with battery leasing	VOCs: Volatile Organic Compounds

1. Introduction

The movement of people and goods is crucial for economic and social development. Yet, it consumes considerable amounts of energy and generates various environmental impacts including global and local polluting emissions.

As vehicle ownership is forecasted to increase worldwide dramatically, from the current 700 million to 2 billion vehicles over the period 2000-2050, in order to achieve a better balance between the pros and cons of transportation, governments enact incentives and regulations to develop new vehicles and foster the use of cleaner fuels. The automotive industry reacts developing many vehicles' powertrain\fuel options (compressed natural gas; liquefied petroleum gas; hybrid; range extender; battery electric; hydrogen, fuel cell, etc.). Within a given infrastructural and regulatory framework, the consumer ultimately decides which vehicle to buy and use on the basis of his\her preferences for a number of attributes, including purchase and operating costs, energy and environmental efficiency.

Both governments and consumers base their decision on the existing and prevailing scientific knowledge. However, the scientists who try to advise on the lifetime costs of different vehicle and to assess their energy and environmental efficiency are faced with a difficult task since there are many uncertainties due to lack of data, insufficient knowledge, uncertain data sources, high variability in the measurements, errors, etc..

Moreover, developing a unique and easy-to-communicate indicator, valid across countries and relatively time-invariant, which would be valuable both for policy makers and consumers', is not feasible for the many reasons.

First, the indicator contains heterogeneous components: economic costs are expressed in monetary terms; energy consumption is expressed in energy units (e.g., Mega Joules); environmental impacts are expressed in g/km for the various air pollutants (CO_2, CO, NO_x, PM_{10}, $PM_{2.5}$ and so on); noise impact in decibel. Expressing all these components in a unique unit of measurement, for instance in monetary terms, as it is usually done in cost-benefit analysis, has many advantages but it is fraught with difficulties.

Second, the objectives are heterogeneous and, at times, conflicting. They can span from satisfying mobility needs at minimum economic cost, to reducing total energy consumption, to reducing energy dependency (that is, minimizing the energy consumption from imported fuels), to cutting energy consumption derived from fossil fuels, to diminishing political dependency, to curbing cutting global pollution and\or urban pollution, etc.. There are clear conflicts and trade-offs among these objectives.

Third, the impact measurements are location specific. For instance, the energy content and the energy impact depend on the energy mix (i.e. the share of renewable sources used for energy generation) used in a specific location (country or region). The impact of air pollutants depends on the characteristics of the locations where they are released (American cities are quite different from the European ones, large cities differ from small towns, etc.).

Forth, economic variables such as vehicles' purchasing costs, insurance costs, fuel costs, subsidies are country-specific due to different market structures, firms' strategies or purchasing power.

Fifth, technological innovation develops very rapidly so that an indicator estimated with today's parameters, based on historical data, could not be valid tomorrow. Forecasting future developments is, however, intrinsically difficult and subject to great uncertainty.
Lastly, social, cultural and political factors are crucial in determining not only the goals but also the economic values to be used in the analysis, so that it is crucial to develop country- or region-specific indicators.
Keeping all these difficulties in mind, with the intent of contributing to the existing literature and with a specific focus on Italy, this paper: a) reviews the current literature; b) sets up a model able to assess the energy use, the environmental and lifetime ownership costs of 7 car types (gasoline; diesel; CNG; LPG; HEV; BEV, leased BEV) with a specific brand and with reference to the Italian car market.

2. Literature review

Although there is an abundant literature on the comparison among vehicles with different technologies, with reference to private and social monetary costs and to the energy and environmental impacts, for a variety of reasons, few consensus results have emerged.
A recent survey by Hawkins et al. (2012) reviewed 55 studies from peer-reviewed and gray literature containing environmental, energy or material assessments. Their focus is mostly on the comparison between internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and electric vehicles (EVs). Their conclusion is that very few full life cycle inventory studies exist and that one exists for EVs. They further add that "In general, more studies include the life cycle inventory of fuels and electricity than the life cycle inventory of the vehicle itself. Details pertaining to key vehicle components such as the battery or drivetrain are even less documented. GWP is the most frequently reported result followed by acidification (SO_2, NO_x), smog (CH_4, NMVOC, NO_x), and toxicity impacts. Considering the complexity of the vehicle supply chain, there are few well-populated and transparent life cycle inventory datasets for EVs, a situation which is likely to cause significant error associated with omission or insufficient representation of production processes" Hawkins et al. (2012).
Various factors can explain this lack of knowledge and consensus.
A crucial factor is that the HEVs, PHEVS and EVs are still a relatively new technology with a scarce penetration and uncertain prospects compared to ICEVs. As a consequence, some features are yet not well-documented. For instance, with regards to batteries: a) the battery chemistry and size are not yet fully-established; the Li-ion and a Ni-MH batteries are most widely used, with different materials availability for battery production (the materials for the latter are mainly in Chinese hands); b) the battery lifetime is still unknown (it varies in the range of 150,000-300,000 km and the expected lifetime for Li-ion batteries appears to have more than doubled in the last 10 years (Zackrisson et al., 2010), the end of life impact of the battery (down-cycling, reuse, and recycling) is not yet fully researched; c) battery management systems, electronic controls, and temperature control systems are still under research and improvement.
Moreover, the battery and electricity supply chain is very complex. Many and very diverse electricity production possibilities and mixes are available, the interaction with the infrastructure is yet to be experimented (both the infrastructure used to transmit and distribute electric energy and the infrastructure for charging the EVs such as grid-to-battery and battery-to-grid systems). The

effect of the time of the day used for charging on the overall energy efficiency is an example of a relatively unknown issue.

Furthermore, the influence of temperature, vehicle load, and acceleration patterns on the EV performance is yet to be explored.

All these aspect make the environmental, energy and cost impact assessment on the HEVs, PHEVs and EVs quite difficult.

2.1. Environmental efficiency

Table 1 lists a series of recent results concerning the environmental impact of different vehicle technologies.

Table 1 – *Environmental impact studies*

Authors	Country	Pollutant considered	Main results
Baptista et al. (2009)	Portugal	CO_2; HC; CO; NO_X; PM	WtT (CO2/km): ICEV Gasoline: 24.5; ICEV Diesel: 23.7; EV (Electricity): 72.9; FC-HEV: 95.4; FC-PHEV: 56.7; PHEV Gasoline: 40.1 TtW (CO2/km): ICEV Gasoline: 143; ICEV Diesel: 124.4; EV (Electricity): 0; FC-HEV: 0; FC-PHEV: 0; PHEV Gasoline: 65.7 WtW (CO2/km): ICEV Gasoline: 167.5; ICEV Diesel: 152.1; EV (Electricity): 72.9; FC-HEV: 95.4; FC-PHEV: 56.7; PHEV Gasoline: 105.8 TtW HC (g/km): ICEV Gasoline: 0.121; ICEV Diesel: 0.120; EV (Electricity): 0; FC-HEV: 0; FC-PHEV: 0; PHEV Gasoline: 0.116 TtW CO (g/km): ICEV Gasoline: 0.164; ICEV Diesel: 0.397; EV (Electricity): 0; FC-HEV: 0; FC-PHEV: 0; PHEV Gasoline: 0.174 TtW NOX (g/km): ICEV Gasoline: 0.157; ICEV Diesel: 0.490; EV (Electricity): 0; FC-HEV: 0; FC-PHEV: 0; PHEV Gasoline: 0.090 TtW PM (g/km): ICEV Gasoline: 0; ICEV Diesel: 0; EV (Electricity): 0; FC-HEV: 0; FC-PHEV: 0; PHEV Gasoline: 0
Barkenbus (2007)	Usa	CO_2	A vehicle using gasoline emits 100 lbs.CO_2 for driving 100 miles, while an EV emits only 34 lbs.CO_2.
Boureima et al., (2009)	Belgium	CO_2	The greenhouse effect of the LPG, HEV and BE vehicles are respectively 20.27%, 27.44% and 78.27% lower than for gasoline vehicles. The assessment of the impact on human health and air acidification give the best environmental score to the BEVs.
Boureima et al., (2011)	Belgium; Europe	CO_{2eq}	WtT (gCO2eq/km): Petrol: 37; Diesel: 26.0; FCHEV: 110.1; EV: 56.5 TtW (gCO2eq/km): Petrol: 144; Diesel: 128; FCHEV: 0; EV: 0 WtW (gCO2eq/km): Petrol: 181; Diesel: 154; FCHEV: 110,1; EV: 56,5
Campanari et al., (2009)	Italy	CO_2	If 100% renewable energy sources are used to generate electricity, the BEV features zero emissions. If an average primary source mix in electricity generation or a 100% coal or natural gas feeding is used, the BEV performances are much lower, especially if the driving range requirement becomes significant (e.g. several hundred kms) due to the progressive increase in the battery weight
CEI-CIVES (2010)	Italy	CO_2; CH_4	Total emissions (gCO2eq/km) for different cars: EV: 54.6 Renault Fluence, 61.4 Mitsubishi iMiev HEV: 107.6 Toyota Prius, 121.7 Honda Jazz Gasoline: 134.6 Opel Corsa, 120.5 Suzuki Alto 1000cc Diesel: 126.4 Fiat Grande Punto, 100,6 Smart ForTwo CNG bi-fuel: 135.9 Fiat Panda 1400cc, 176.5 Opel Zafira 1600cc
Concawe et al., (2007)	Europe	GHG	In the TtW phase, the GHG emissions are (gCO2eq/km): Gasoline: 138.8 – 143.3; Diesel: 127.8 – 131.1; LPG bi-fuel: 125.7; CNG bi-fuel: 108.2; HEV: 119.6 – 120.5
Concawe et	Europe	GHG	WtT GHG balance (gCO2eq/MJf): Gasoline: 12.5; Diesel: 14; LPG: 8;

al., (2007)			CNG: 8; Electricity: 130
Concawe et al., (2007)	Europe	GHG	WtW GHG (gCO2eq/km): Gasoline: 165 – 180; Diesel: 150 – 160; HEV: 175 – 190; CNG bi-fuel: 130 – 145; LPG bi-fuel: 140
Delucchi and Lipman, (2006)	Usa	GHG and Oil-use; Air pollution; Noise	Values for the external cost analysis: - GHG + oil use damages ($/gal): ICEV: 0.059 – 0.371; HEV MM: 0.053 – 0.427 ; HEV AM: 0.053 – 0.427; HEV AF: 0.053 – 0.427 - Air pollution + noise damages (cents/mi): ICEV: 0.26 – 5.26; HEV MM: 0.14 – 4.01; HEV AM: 0.14 – 4.01; EV AF: 0.14 – 4.01
De Nigris (2011)	Italy	CO_2; PM; NO_X; SO_2	Forecasts 2030, benefits achievable with the presence of electric vehicles in the Italian vehicle fleet: -16,1% CO (Mg); -30,9% SO2 (Mg); -15,8% PM_exhaust (Mg); -23,5% Nox (Mg); -15,5% NMVOC (Mg); -26,0% NH3 (Mg); -24,8% CO2 (Mg). Considering a LCA, in 2030 EVs CO_2 emissions will be roughly half than gasoline ICE and a bit lower than HEVs.
Dincer et al., (2009)	Usa	GHG, CO NOx, SOx VOCs	ICE: 21,4 kg/100km GHG emissions; 0,06 kg/100km AP emissions HEV: 13,3 kg/100km GHG emissions; 0,037 kg/100km AP emissions BEV: 12 kg/100 km GHG emissions, 0,0448 kg/100 km AP emissions
Doucette and McCulloch, (2011)	Usa; France; China; India	CO_2	Usa: BEVs simulated provided a reduction in operating CO_2 emissions compared to their ICE-based counterparts; but BEVs are still far to be "zero-emission" vehicles. France: widespread BEV adoption could lead approximately a 90% reduction in CO_2 emissions. China: the ICE version of the VW Polo BlueMotion emits less CO_2/km than every BEV version. Two-wheeled BEV offers the largest reduction. India: the low range Polo BEV is the only Polo that emits less gCO2/km than its ICE version. Two-wheeled BEV offers the largest reduction.
EABEV, (2009)	Europe	CO_2	Each kWh transmitted to the wheels (WtW) emits nominally around: Petrol-engined vehicle: 1490 g/CO_2; Diesel-engined vehicle: 1380 g/CO_2; Electric vehicle with lead-acid batteries: 738 g/CO_2; Electric vehicle with lithium batteries: 616 g/CO_2. Average CO_2 emissions of electric cars in some European countries (g/km): Sweden: 5; France: 11; Belgium: 35; EU15: 54; Germany: 73; UK: 78; Netherlands: 78; Denmark: 102; Luxemburg: 131. WtW emissions for the models considered (gCO2eq/km): Toyota Prius: 122; REVAi: 50; EV1 NiMH 1999: 50; QUICC!: 63; Tesla Roadster: 56.
Faria et al., (2012)	Europe; Portugal; France.	CO_2	Considering the 2010 EU energy mix: Gasoline: 2,58 MT CO_2/year; Diesel: 2,0 MT CO_2/year; HEV: 1,8 MT CO_2/year; PHEV: 0.46 + 1.15 MT CO_2/year; BEV: 1,01 MT CO_2/year.
Geringer and Tober, (2012)	Austria; Europe	CO_{2eq}	Greenhouse gas emissions in Austria (gCO2eq/km): Urban motorist: Diesel car: 128; E-car: 48 Interurban motorist: Diesel car: 126; E-car: 50 Greenhouse gas emissions in Europe (gCO2eq/km): Urban motorist: Diesel car: 132; E-car: 109 Interurban motorist: Diesel car: 129; E-car: 116
Hawkins et al., (2012)	Norway; Europe	GWP; VOC; CH_4; N_2O; SO_X; PM_{10}; CO; NO_X.	Comparison of life cycle GWP per km driven (gCO2eq/km): Mercedes S ICEV, Premium Gasoline: 315; Generic ICEV, Gasoline: 290; Generic ICEV, Diesel: 271; BEV Coal: 231; BEV Coal IGCC*: 185; VW GOLF A4 ICEV, Diesel: 177; Smart ForTwo ICEV, Diesel: 135; Honda Insight HEV, Gasoline: 132; BEV NGCC**: 120; BEV Hydro: 48. Other life cycle emissions: EVs have less VOC, CH_4, N_2O, than ICEVs but higher SO_X. No significant differences for PM_{10}, CO, NO_X.
Hawkins et al., (2012)	Europe	*** GWP; TAP; PMFP; POFP;	Life Cycle Assessment. With European electricity and 150.000 km of lifetime: EVs less GWP by 20% to 24% compared to gasoline ICEVs and by 10% to 14% relative to diesel ICEVs. Almost half of the EV's life cycle GWP is associated with vehicle production (gCO2eq/km): EV: 87 – 95 (battery production: 35 – 41%; electric engine: 7 – 8%;

		HTP; MDP; FETP; TETP; FDP.	other powertrain components: 16 – 18%); ICEVs: 43. TAP: similar for ICEVs and EVs. The 70% is caused by SO_2 emissions (European mix does not lead significant improvements relative to ICEVs). PMFP: similar for ICEVs and EVs, but European electricity leads a potential increase relative to ICEVs. POFP: EV allows a 22% reduction with UE mix relative to ICEVs. HTP: EV options have 180 – 290% greater impacts compared to ICEVs alternatives. Electricity from natural gas allows substantial benefits relative to other mixes. FETP, FEP: pattern similar to HTP. Electricity from natural gas allows substantial benefits relative to other mixes. TETP: no clear difference among vehicle options. MDP: EVs have roughly three times that of ICEVs. FDP: EVs may decrease it by 25 – 36% with the UE mix.
Helland, (2009)	Norway; Switzerland; UK; Netherlands.	CO_2	For urban driving the reduction amounts to: Norway: 95%; Switzerland: 90%; UK: 40% – 60%; Netherlands: 30% - 50% (depending on the fuel efficiency of the combustion engine car) .
Helms et al., (2010)	Germany	CO_2; SO_2.	Considering 120.000 km/year and 70% of urban cycle: BEVs: 22 tCO_2-equivalents; 60 kgSO_2-equivalents PHEVs: 23 tCO_2-equivalents; 59,5 kgSO_2-equivalents
Huo et al., (2009)	Usa; California.	VOCs NO_X $PM_{2.5}$ PM_{10} CO	Gasoline: 0,3 (g/mi) WtW NOx; 0,28 (g/mi) WtW VOC; 0,09 (g/mi) WtW PM_{10}; 0,039 (g/mi) WtW $PM_{2.5}$; 3,65 (g/mi) WtW CO Diesel: 0,25 (g/mi) WtW NOx; 0,09 (g/mi) WtW VOC; 0,07 (g/mi) WtW PM_{10}; 0,03 (g/mi) WtW $PM_{2.5}$; 0,6 (g/mi) WtW CO HEV: 0,22 (g/mi) WtW NOx; 0,20 (g/mi) WtW VOC; 0,07 (g/mi) WtW PM_{10}; 0,03 (g/mi) WtW $PM_{2.5}$; 3,6 (g/mi) WtW CO BEV (US energy mix):; 0,28 (g/mi) WtW NOx; 0,025 (g/mi) WtW VOC ; 0,45 (g/mi) WtW PM_{10}; 0,11 (g/mi) WtW $PM_{2.5}$; 0,10 (g/mi) WtW CO
IEA (2011)	Europe		The results of the IEA Mobility Model show that widespread vehicle electrification would increase electricity demand by 9% at most and at the same time result in around 1.6 billion tonnes less of CO_2 emissions (or a total of 2.8 billion tonnes less with the decarbonisation of the electricity sector).
Lucas et al., (2012)	Portugal	CO_{2eq}	WtT (gCO2eq/km): Gasoline: 24.5; Diesel: 23.7; EV: 72.9 TtW (gCO2eq/km): Petrol: 144; Diesel: 128; EV: 0 WtW (gCO2eq/km): Petrol: 168.5; Diesel: 151.7; EV: 72.9
Ma et al., (2012)	UK; California	GHG	UK 2015 full life cycle GHG (g CO2 eq/km): ICEV: 201,2 – 175,8; HEV: 154,9 – 166,6; BEV average grid: 109,2 – 147,6; BEV marginal grid: 151,7 – 219,8
Menga and Ceraolo (2011)	Italy	CO_2; CO; NO_X; PM; HC; SO_2	Gaseous local effects, accounting real usage of vehicles: Diesel: 0.5 g/km CO; 0 mg/km HC; 600 mg/km NO_X; 2.0 mg/km PM; Petrol: 3.0 g/km CO; 150 mg/km HC; 60 mg/km NO_X; 0 mg/km PM; ICE Natural Gas: 1.5 g/km CO; 50 mg/km HC; 60 mg/km NO_X; HEV diesel: 0.3 g/km CO; 360 mg/km NO_X; 1.2 mg/km PM; HEV petrol: 1.8 g/km CO; 50 mg/km HC; 35 mg/km NO_X; 0 mg/km PM; PHEV: 0.9 g/km CO; 45 mg/km HC; 18 mg/km NO_X; 0 mg/km PM; BEV: 0 g/km CO; 0 mg/km HC; 0 mg/km NO_X; 0 mg/km PM Global Warming Potential accounting real usage of vehicles: Diesel: 216 g/km $CO2_{eq}$; 1410 mg/km NO_X; 74.3 mg/km SO_2; Petrol: 230 g/km $CO2_{eq}$; 519 mg/km NO_X; 81.03 mg/km SO_2; ICE Natural Gas: 203 g/km $CO2_{eq}$; 168 mg/km NO_X; 6.8 mg/km SO_2; HEV diesel: 182 g/km $CO2_{eq}$; 780 mg/km NO_X; 77.0 mg/km SO_2; HEV petrol: 196 g/km $CO2_{eq}$; 294 mg/km NO_X; 84.0 mg/km SO_2; PHEV: 133 g/km $CO2_{eq}$; 166 mg/km NO_X; 89.2 mg/km SO_2; BEV: 85 g/km $CO2_{eq}$; 48 mg/km NO_X; 108.2 mg/km SO_2;
Michalek et al., (2011)	Usa	GHG VOCs SO_2	Air emission costs per vehicle lifetime ($\$_{2010}$): Conventional vehicles: 2,025 GHG; 312 CO; 104 $NO_{X;}$ 109 PM_{10}; 327 $PM_{2,5}$; 413 SO2; 227 VOC

		$PM_{2.5}$ PM_{10} NO_X CO	HEV: 1,533 GHG; 310 CO; 85 NO_X; 99 PM_{10}; 296 $PM_{2,5}$; 486 SO2; 183 VOC PHEV20: 1,471 GHG; 227 CO; 83 NO_X; 101 PM_{10}; 292 $PM_{2,5}$; 557 SO2; 157 VOC PHEV60: 1,734 GHG; 174 CO; 99 NO_X; 123 PM_{10}; 333 $PM_{2,5}$; 896 SO2; 141 VOC BEV240: 1,824 GHG; 18 CO; 129 NO_X; 200 PM_{10}; 476 $PM_{2,5}$; 1939 SO2; 82 VOC
Samaras and Meisterling, (2008)	Usa	GHG	Use phase, with the average U.S GHG intensity of electricity: PHEVs reduce GHG emissions by 38 – 41% compared to conventional vehicles and by 7 – 12% compared to HEVs. PHEVs reduce life cycle GHG emissions by 32% compared to CVs, but have small reductions compared to HEVs.
Sharma et al., (2013)	Australia	CO_{2eq}	Total life cycle emissions (Tonnes of CO_{2eq}): CV Class-E: 61.5; HEV Mild Class-E: 56.3; HEV Parallel Class-E: 42.5; HEV Series Class-E: 41.7; PHEV Class-E: 51.1; BEV Class-E: 51.2; CV Class-B: 26.6; BEV Class-B: 31.1 Low carbon and improved technology scenario (Tonnes of CO_{2eq}): CV Class-E: 44.8; HEV Mild Class-E: 40.5; HEV Parallel Class-E: 29.4; HEV Series Class-E: 28.8; PHEV Class-E: 20.7; BEV Class-E: 18.9; CV Class-B: 18.4; BEV Class-B: 11.1
Shen et al., (2012)	China	GHG	WtW GHG emissions for selected pathways in 2010 (g CO2 eq/km): PISI Gasoline: 249; DISI Gasoline: 212; DICI Diesel: 195; HEV Gasoline: 167; DISI CNG pipeline 300: 202; DISI CNG pipeline 4200: 214; BEV China mix: 164; PHEV China mix/gasoline: 167; HFC: 167
Svensson et al., (2007)	Norway; Europe	CO_2; NO_X	Emissions with Norway mix: Gasoline ICE: 0.23 kg/km CO_2; 0.13 g/km NO_X; Gasoline HEV: 0.12 kg/km CO_2; 0.3 g/km NO_X; Diesel ICE: 0.19 kg/km CO_2; 0.27 g/km NO_X; CNG bi-fuel: 0.17 kg/km CO_2; 0.3 g/km NO_X; EV: 0 kg/km CO_2; 0 g/km NO_X Emissions with European mix: Gasoline ICE: 0.23 kg/km CO_2; 0.13 g/km NO_X; Gasoline HEV: 0.12 kg/km CO_2; 0.3 g/km NO_X; Diesel ICE: 0.19 kg/km CO_2; 0.27 g/km NO_X; CNG bi-fuel: 0.17 kg/km CO_2; 0.03 g/km NO_X; EV: 0,07 kg/km CO_2; 0.14 g/km NO_X
Eberhard and Tarpenning, (2009)	Usa	CO_2	Well-to Wheel CO_2 emissions (g/km): Honda CNG: 166; Honda FCX: 151.7; VW Jetta diesel: 152.7; Honda Civic VX Gasoline: 141.7; Toyota Prius hybrid: 130.4; Tesla Roadster Electric: 46.1 (electricity from Natural Gas).
Thiel et al., (2010)	Europe	CO_2	WtW CO_2 emissions: Gasoline: 160g/km; Diesel: 145 g/km; HEV: 131 g/km; PHEV: 88 g/km; BEV: 60 g/km
Thomas, (2012)	Usa	GHG	BEVs alone: less of 7.5% in LDV GHGs emissions reduction; BEVs + PHEVs: GHGs reduced by less than 25% Fuel Cell Vehicles (H_2produced by NG): 40% GHG reduction
Torchio and Santarelli, (2010)	Europe	GHG, NO_X PM, SO_X	Gasoline: 0,7 cent.€/km; Diesel: 0,72 cent.€/km; CNG: 0,52 cent.€/km; Hybrid: 0,6 cent.€/km; BEV: 0,79 cent.€/km
Stavanger, (2009)	Norway; Switzerland; UK; Netherlands.	CO_2	For urban driving the reduction amounts to: Norway: 95%; Switzerland: 90%; UK: 40% – 60%; Netherlands: 30% - 50% (depending on the fuel efficiency of the combustion engine car)

*Coal integrated gasification combined-cycle
**Natural gas combined-cycle
*** (GWP) Global Warming Potential; (TAP) Terrestrial Acidification Potential; (PMFP) Particulate Matter Formation Potential; (POFP) Photochemical Oxidation Formation Potential; (HTP) Human Toxicity Potential; (MDP) Mineral Depletion Potential; (FETP) Freshwater eco-toxicity potential; (TETP) Terrestrial eco-toxicity potential; (FDP) Fossil Depletion Potential.

The results listed in Table 1 can be summarized as follows.

Electric cars have a global warming potential (GWP) lower than the conventional ICEVs. This result is, however, strongly dependent on how electricity is produced and distributed. When carbon intensive sources are used, the GWP of the EVs is comparable or, in some cases, even worse of some advanced ICEVs. The reason for this can be easily understood looking at figure 1 (Hawkins et al., 2012, SI): the GWP of the various energy sources is very different and the energy mix used is crucial for the end results.

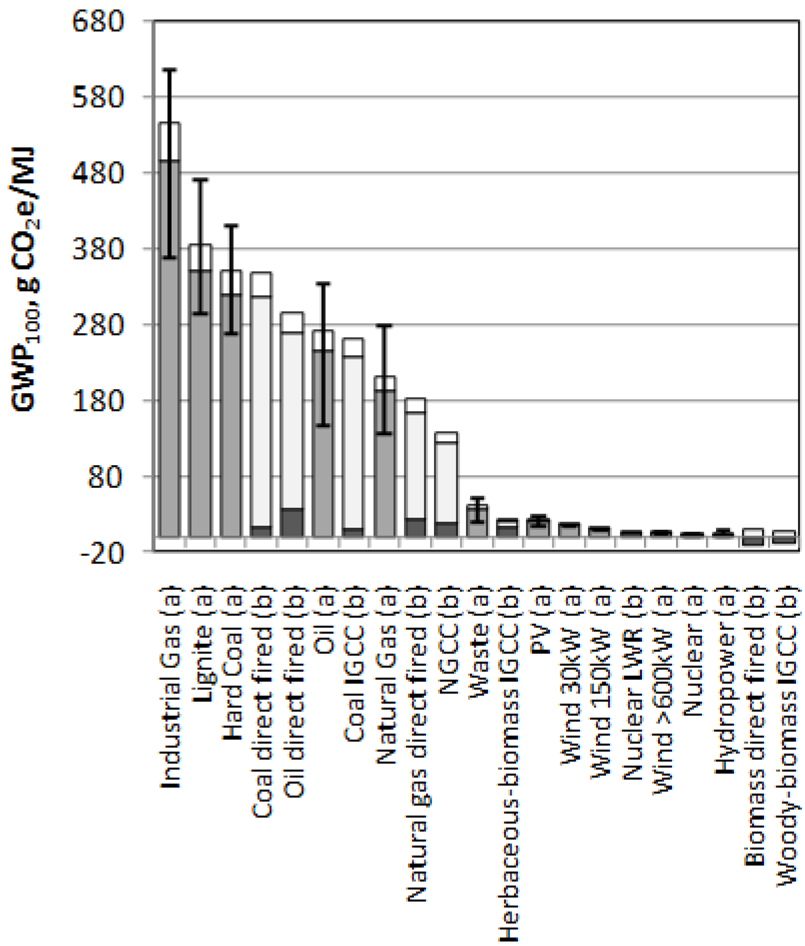

Figure 1 – Global warming potential of various energy sources. Source: Hawkins et al. (2012, SI)

Distinguishing between fuel and car production and the use, it is evident that ICEVs generate global warming pollution mostly in the car use phase while EVs in the fuel and car production phase.

Focusing on local air pollutants, when the US energy mix is taken into account, in global terms the NO_x emissions are similar for ICEVs and EVs, the VOC and CO emissions are higher for the ICEVs while the PM_{10} e $PM_{2.5}$ e l'SO_2 emissions are higher for BEVs. ICEVs emit mostly local pollutants in the car use phase while BEVs in the fuel and car production one. ICEVs' local pollution emissions are spatially widespread and occur in urban areas, whereas EVs local pollution emissions are spatially concentrated and do not occur in urban areas: this characteristic makes them highly appealing to the general public.

There are only few studies that attempt to differentiate between the effects of harmful pollutants linked to the location of emission. The paper by Huo, Wu et al. (2009) is a recent one. They propose an interesting WtW assessment of some pollutants (NO_x, PM_{10}, $PM_{2.5}$, CO, VOCs), focused on North America and performed using the GREET model. A particular feature of their WtW study is that the pollutant emissions have been separated into total and urban emissions to emphasize the location effect. They assess the well-to-wheels (WtW) emissions for nine vehicle/fuel systems: conventional gasoline vehicles, conventional diesel vehicles, ethanol (E85) flexible-fuel vehicles (FFVs) fueled with corn-based ethanol, E85 FFVs fueled with switch grass-based ethanol, gasoline hybrid vehicles (HEVs), diesel HEVs, electric vehicles (EVs) charged using the average U.S. generation mix, EVs charged using the California generation mix, hydrogen fuel cell vehicles (FCVs). The estimates are obtained using the emission and fuel economy factors reported in Figure 2 and considering that in the US a share of energy production takes place in urban areas.

Emission factors (g/mile) and fuel economy (mile per gasoline equivalent gallon) of selected vehicle technologies.

Vehicle technology	VOC Exhaust	NO_x	PM_{10} Exhaust	$PM_{2.5}$ Exhaust	CO	Fuel economy
GV	0.095	0.069	0.0081	0.0075	3.492	23.5
DV	0.06	0.08	0.009	0.0084	0.534	28.2
E85 FFV	0.095	0.069	0.0081	0.0075	3.492	23.5
Gasoline HEV	0.051	0.058	0.0081	0.0075	3.492	34.8
Diesel HEV	0.047	0.07	0.009	0.0084	0.534	37.6
EV	0	0	0	0	0	82.3
H_2 FCV	0	0	0	0	0	54

Figure 2 – Emission factors and fuel economy. Source: Huo, et al. (2009, p. 1798)

Urban share of some key activities.

	Percentage (%)		Percentage (%)
Petroleum Pathway		*Corn ethanol pathway*	
Crude, recovery and processing	2.0	Manufacture of fertilizers	0
Crude, transportation		Farming	0
Ocean tanker	5.0	Crop transportation	0
Pipeline	5.0	Ethanol production	0
Fuel production	65.0	Ethanol transportation	
Fuel transportation		Barge	12.0
Ocean tanker	10.0	Rail	10.0
Barge	12.0	Truck, from plant to terminal	7.0
Pipeline	10.0	Truck, from terminal to station	68.5
Rail	10.0		
Truck, from terminal to station	68.5		
Electricity generation		*NG-to-H_2 pathway*	
Residual oil-fired power plants	39.0	NG recovery and processing	1
Natural gas-fired power plants	43.0	Hydrogen production	70
Coal-fired power plants	16.0	*Vehicle miles traveled*	
Nuclear power plants	11.0		
Biomass-fired power plants	0.0	all light-duty vehicles	62.2

Figure 3 - Urban share of some key activities. Source: Huo, et al., (2009, p. 1799)

The results show that WtW emissions of the vehicle/fuel systems differ significantly not only in quantities but also with respect to locations and sources, both of which are important in evaluating the overall impact of alternative vehicle/fuel systems. E85 FFVs increase total emissions but reduce urban emissions by up to 30% because the majority of emissions are released from farming equipment, fertilizer manufacture, and ethanol plants, all of which are located in rural areas. HEVs reduce both total and urban emissions because of the improved fuel economy and lower emissions. While EVs significantly reduce total emissions of VOCs and CO by more than 90%, they increase total emissions of PM_{10} and $PM_{2.5}$ by 35–325%. However, EVs can reduce urban PM emissions by more than 40%. FCVs reduce VOCs, CO, and NO_x emissions, but they increase both total and urban PM emissions because of the high emissions that occur during hydrogen production. This study emphasizes the importance of specifying a thorough life-cycle emissions inventory that can account for both the locations and sources of the emissions to perform a fair comparison of alternative vehicle/fuel options in terms of their full environmental impacts.

Therefore, the location and sources of pollutant emissions could be more important than their total amount when evaluating fuel-cycle air pollutant emissions of alternative vehicle/fuel systems. Thus, a fair fuel-cycle comparison of air pollutant emissions among various alternative vehicle/fuel systems should specify the locations and sources of the emissions. Unfortunately, to the best of our knowledge no such a study exists for the European Union.

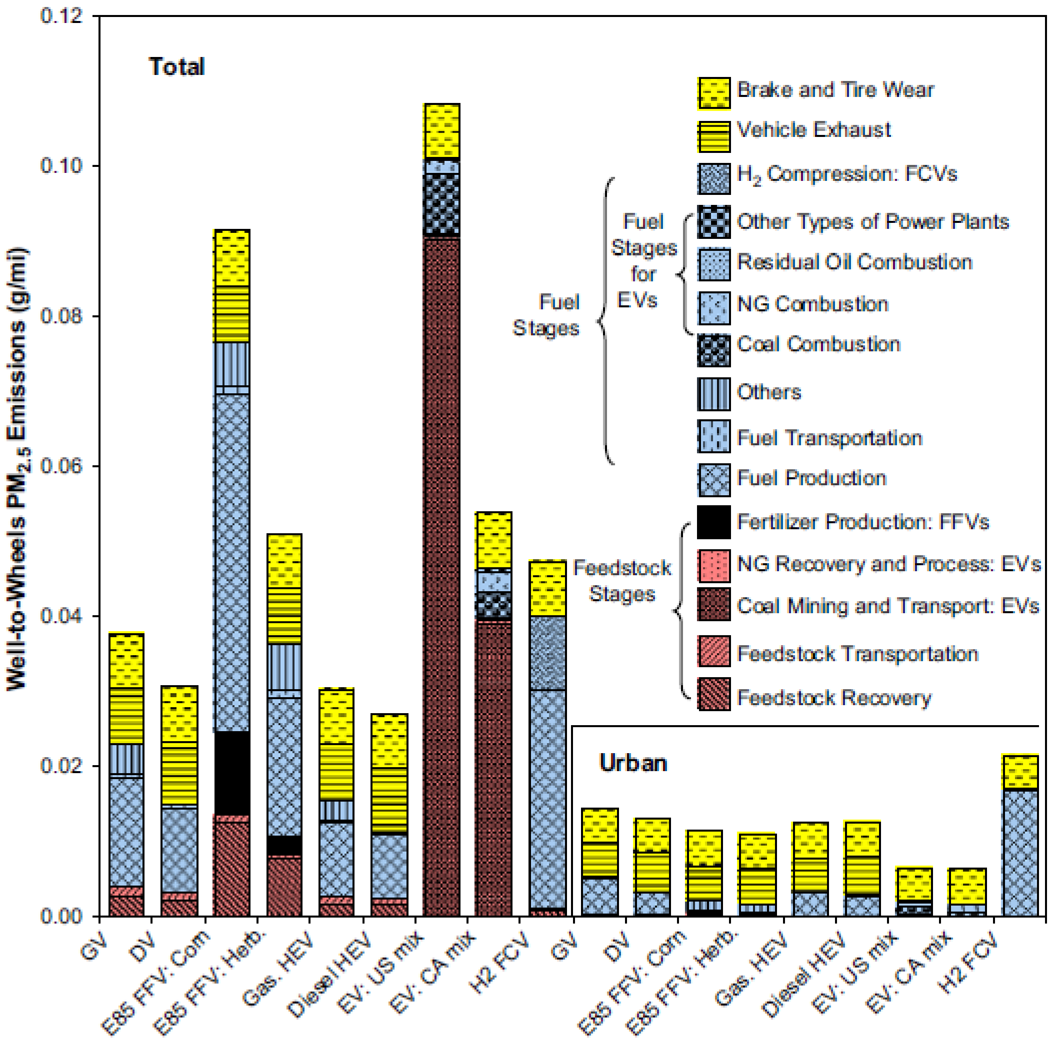

Figure 4 – WtW $PM_{2.5}$ emissions. Hou et al. (2009, p. 1802)

A recent National Petroleum Council (2012) study confirms that the BEVs are a very promising instrument to reduce urban air pollution. The estimates of such study are reported in Figure 5.

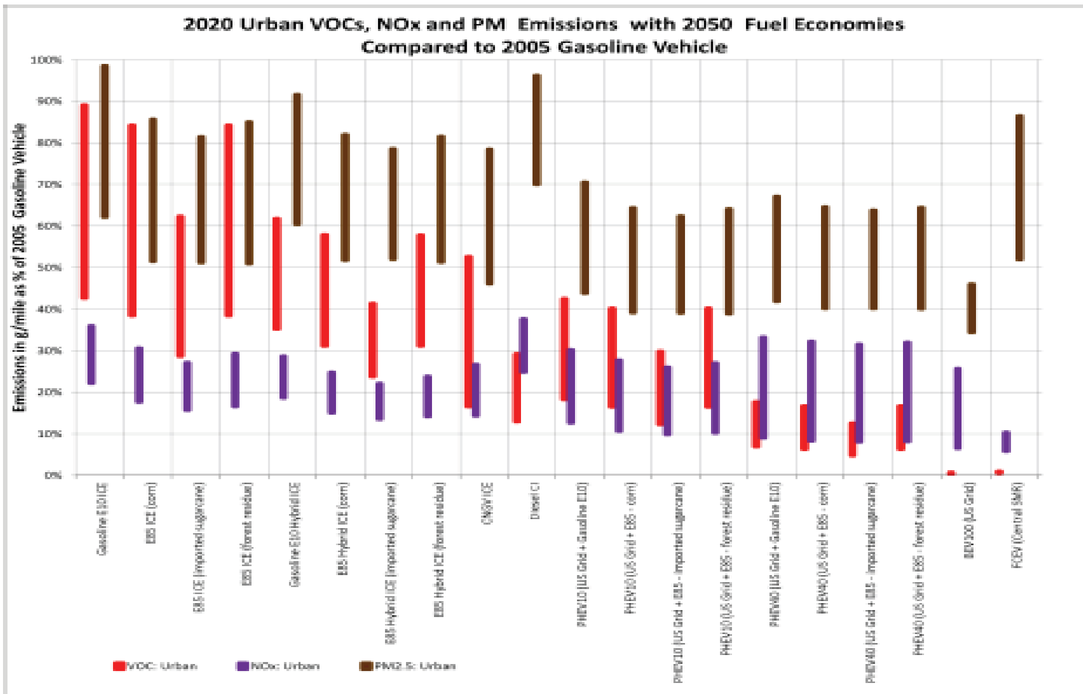

Figure 3 - 2020 Urban VOCs, NOx and PM Emissions Compared to a 2005 Gasoline Vehicle

Figure 5 – Urban pollutants emissions

They result from an analysis performed using GREET 1.8d to compare 2020 CAPs emissions of the fuel-vehicle systems in the study to a 2005 gasoline vehicle CAPs emission on a per mile basis. 2020 was used as the basis of comparison because it is the most forward-looking horizon available in GREET 1.8d. While urban VOC and urban NO_x contribute most to ground-level ozone in populated areas, all of the fuel-vehicle systems are comparable to or lower than the 2005 gasoline vehicle baseline emissions.

2.2. Energy efficiency

Saving energy and reducing environmental emissions is desirable for many reasons including preventing the depletion of primary energy sources and reducing oil dependence. The energy and environmental efficiency of the different powertrain/fuel options is traditionally evaluated via a Well-to-Wheels (WtW) assessment, which is composed of two stages: the fuel cycle stage (Well-to-Tank, WtT) and the powertrain stage (Tank-to-Wheels, TtW). These two stages made up a sort of lifecycle analysis of a powertrain/fuel option.

Table 2 – *Energy impact studies*

Authors	Country	WtT	TtW	WtW
Baptista et al., (2009)	Portugal	Energy (MJ/km): ICEV Gasoline: 0.27 ICEV Diesel: 0.27 EV (Electricity): 1.06	Energy (MJ/km): ICEV Gasoline: 1.96 ICEV Diesel: 1.67 EV (Electricity): 0.57	Energy (MJ/km): ICEV Gasoline: 2.23 ICEV Diesel: 1.94 EV (Electricity): 1.63

		FC-HEV: 0.62 FC-PHEV: 0.31 PHEV Gasoline: 0.55	FC-HEV: 1.08 FC-PHEV: 0.55 PHEV Gasoline: 1.13	FC-HEV: 1.70 FC-PHEV: 0.86 PHEV Gasoline: 1.68
Concawe, et al., (2007a,b,c)	Europe	WtT total energy balance (MJ_{xt}/MJ_f): Gasoline: 0.14 Diesel: 0.16 LPG bi-fuel: 0.12 CNG bi-fuel: 0.13 Electricity: 1.8	Average fuel consumption MJ/100 km: Gasoline: 187.9 – 190 Diesel: 172.1 – 176.7 LPG bi-fuel: 190 CNG bi-fuel: 188.3 HEV: 161.7 - 163	WtW energy requirements (MJ/100 km): Gasoline: 220 Diesel: 210 – 200 HEV: 165 – 190 CNG bi-fuel: 225 – 240 LPG bi-fuel: 210
EABEV (2009)	Europe		Energy transmitted to the wheels: Diesel: 22%; Petrol: 18%; EV: 60 – 72%. Final energy (kWh/100km): Toyota Prius: 44; REVAi: 11; EV1 NiMH 1999: 11; QUICC!: 14; Tesla Roadster: 13.	Primary energy transmitted to the wheels: Diesel: 18%; Petrol: 15%; EV: 22 – 26%. Primary energy (kWh/100km): Toyota Prius: 55; REVAi: 30; EV1 NiMH 1999: 30; QUICC!: 39; Tesla Roadster: 34.
Faria et al., (2012)	Europe Portugal France		Engine efficiency: Gasoline: 18-25% Diesel: 35-40% BEV: 85-95%	
Geringer et al., (2012)	Austria; Europe		Energy requirements in European cities (kWh/100km): Urban motorist Diesel: 42.8; E-car: 22.8 Interurban motorist: Diesel: 42.0; E-car: 24.2	Energy requirements in European cities (kWh/100km): Urban motorist Diesel: 48.4; E-car: 64.2 Interurban motorist: Diesel: 47.5; E-car: 68.1
Hacker et al., (2009)	Europe		Total efficiency: Electric propulsion: 60-80% Conventional propulsions: 15-20% Energy consumption (kWh/100km): BEV: 10 - 34 PHEV: 12 - 27	
Hawkins et al., (2012)	Europe		Fuel consumption in the use phase (MJ/km): Mercedes A160, A170, A180 ICE: 0.42 Nissan Leaf: 0.48	
Helms et al., (2010)	Germany		Fuel consumption in the use phase (MJ/km): BEVs: 0.72 – 0.9	
Lucas et al., (2012)	Portugal	WtT (MJ/km): Gasoline: 0.27 Diesel: 0.27 EV: 1.06	TtW (MJ/km): Gasoline: 1.98 Diesel: 1.76 EV: 0	WtW (MJ/km): Gasoline: 2.25 Diesel: 2.03 EV: 1.06
Menga and Ceraolo (2011)	Italy			WtW 2010 primary energy (Wh/km): Diesel: 770; Petrol: 797; ICE Natural Gas: 905; HEV diesel: 658; HEV petrol: 742; PHEV: 632; BEV: 547

Perujo and Ciuffo, (2010)	Italy		EVs energy consumption (kWh/100km): Small cars: 10.00 Mid-size: 15.38 Large: 19.44 Light Duty Vehicles: 20.00	
Richardson, (2013)			Engine efficiency: ICEV: 15 - 18% BEV: 60-70%	
Sharma et al., (2012)	Australia		Fuel and electricity real consumption (Class-E cars): CV: 12.5 l/100km; HEV mild: 11 l/100km; HEV parallel: 7.2 l/100km; HEV series: 6.9 l/100km; PHEV: 1.4 l/100km + 0.17 kWh/km; BEV: 0.18 kWh/km	
Shen et al., (2012)	China	Energy consumptions for the representative vehicle in 2010 (MJ/km): PISI Gasoline: 0.71; DISI Gasoline: 0.60; DISI CNG: 1-1.17; DICI diesel: 0.5; HEV gasoline: 0.46; PHEV Gasoline: 1.05; BEV: 1.15	Energy consumptions for the representative vehicle in 2010 (MJ/km): PISI Gasoline: 2.63; DISI Gasoline: 2.24; DISI CNG: 2.17; DICI diesel: 2.10; HEV gasoline: 1.74; PHEV Gasoline: 0.89; BEV: 0.55	Total energy consumed per vehicle distance traveled for selected pathways in 2010 (MJ/km): PISI Gasoline: 3.34; DISI Gasoline: 2.84; DICI Diesel: 2.6; HEV gasoline:2.2; DISI CNG pipeline 300: 3.17; DISI CNG pipeline 4200: 3.34; BEV China mix: 1.7; PHEV China mix/gasoline: 1.94
Siddikou et al., (2011)	Belgium; Europe	Energy use (MJ_{eq}/km): Petrol: 0.76 Diesel: 0.53 FCHEV: no ref. EV: 1.18	Energy use (MJ_{eq}/km): Petrol: 1.98 Diesel: 1.76 FCHEV: 1.25 EV: 0.54	Energy use (MJ_{eq}/km): Petrol: 2.74 Diesel: 2.29 FCHEV: 1.25 + no ref. EV: 1.68
Svensson et al., (2007)	Norway; Europe	Efficiencies: Gasoline: 83% Diesel: 88% Natural gas: 94% Electricity: 93%	Efficiencies: Gasoline HEV: 32% Gasoline ICE: 16% CNG bi-fuel: 17% Diesel ICE: 19% EV: 80%	Efficiencies with Norway mix: Gasoline ICE: 14% Gasoline HEV: 27% Diesel ICE: 17% CNG bi-fuel: 16% EV: 74% With European mix only EV changes: 28%
Eberhard and Tarpenning, (2009)	Usa	Well-to-station efficiency (%): Honda CNG: 86 Honda FCX: 61 VW Jetta diesel: 90.1 Honda Civic VX Gasoline: 81.7 Toyota Prius hybrid: 81.7 Tesla Roadster Electric: 52.5	Energy efficiency (km/ MJ): Honda CNG: 0.37 Honda FCX: 0.57 VW Jetta diesel: 0.53 Honda Civic VX Gasoline: 0.63 Toyota Prius hybrid: 0.68 Tesla Roadster Electric: 2.18	Energy efficiency (km/ MJ): Honda CNG: 0.318 Honda FCX: 0.348 VW Jetta diesel: 0.478 Honda Civic VX Gasoline: 0.515 Toyota Prius hybrid: 0.556 Tesla Roadster Electric: 1.145
Thomas, (2012)	Usa			Cut in petroleum consumption: BEVs alone: less than 25%; BEVs + PHEVs: less than

				67%; Fuel Cell Vehicles (H_2produced by NG): 100%
Torchio and Santarelli, (2010)	Europe	Gasoline: 0,25 MJ/km Diesel: 0,30 MJ/km CNG: 0,35 MJ/km Hybrid: 0,2 MJ/km BEV: 1,8 MJ/km	Gasoline: 1,95 MJ/km Diesel: 1,80 MJ/km CNG: 1,85 MJ/km Hybrid: 1,7 MJ/km BEV: 1 MJ/km	Gasoline: 2,2 MJ/km Diesel: 2,1 MJ/km CNG: 2,2 MJ/km Hybrid: 1,9 MJ/km BEV: 2,8 MJ/km

Table 2 lists a number of studies which compare the relative efficiency of the many fuel/powertrain models. They do not come to unique conclusions. Focusing on the WtW estimates, in some studies the BEVs results as more efficient than the ICEVs (Baptista et al., 2009; Lucas et al., 2012; Menga et al., 2011; Shen et al., 2012; Siddikou et al., 2011; Svensson et al., 2007); in other studies the opposite is true (Geringer et al., 2012; Tesla Motors, 2009; Torchio and Santarelli, 2010). Apart from the obvious data uncertainties, these lack of consensus shows that the results and, consequently, the ranking between the different powertrain/fuel options in terms of energy efficiency, crucially depend on the energy mix and are, therefore, very much country-dependent. The estimates provided in this paper will be based for the energy consumption mostly on Torchio and Santarelli (2010) since they make assumption very close to the Italian context.

Interestingly, Torchio and Santarelli (2010), adopting a multicriteria framework, develop a global index which takes into account jointly the energy and environmental aspects, making use of the costs associated to energy consumption and pollutants emissions. They analyze the European market and include in a traditional WtW evaluation five components (energy use, GHG, NOx, PM and SOx emissions). They estimate that the energy costs prevail (70 and 85%) over the environmental ones, and among the external costs analyzed, the main contribution is attributable to GHG emissions. The most energy and environmental efficient vehicle is the fuel cell (FC) hybrid vehicle with central hydrogen. The vehicle with a hybrid internal combustion engine (ICE) fueled by natural gas-derived fuels performs very well, whereas conventional biofuels do not.

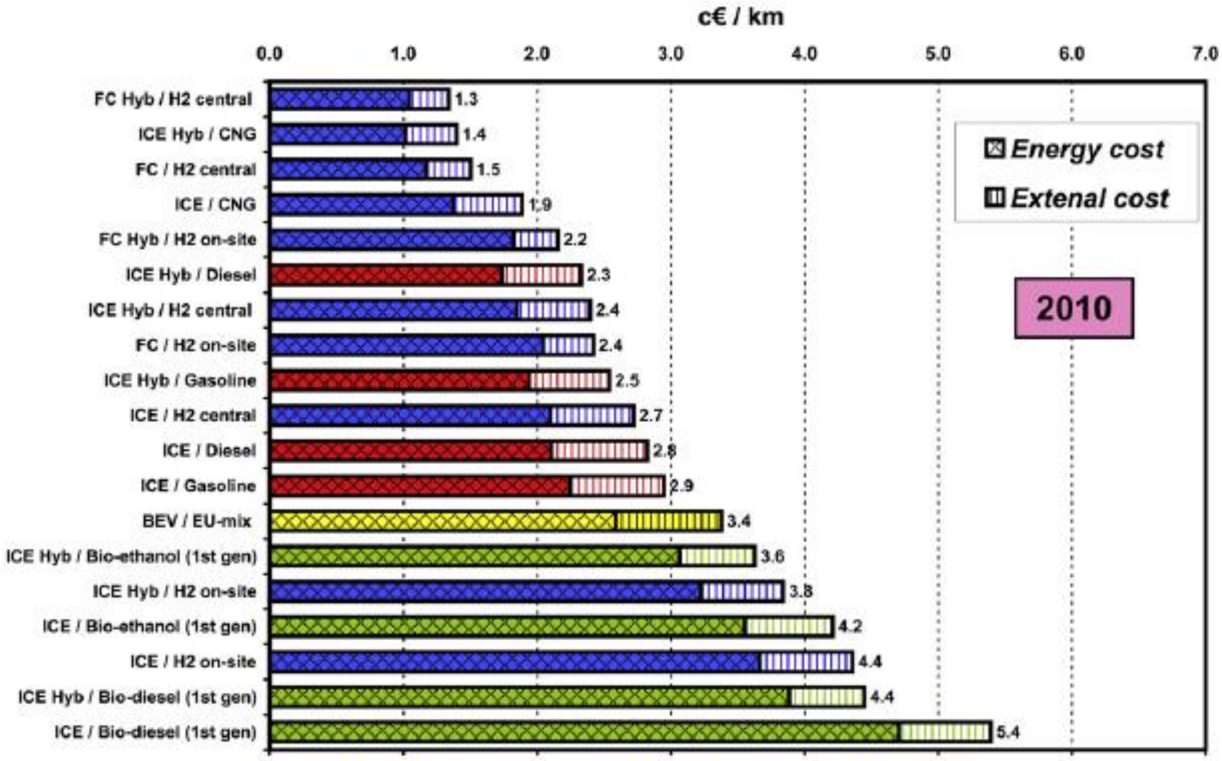

Figure 6- Energy and external costs of cars. Source: Torchio and Santarelli (2010, p. 4168)

An interesting finding is that the global index for battery electric vehicle from a European mix depends heavily on the driving range. In fact, the BEV has a very good efficiency level when a battery[1] that allows a range of 100 km is used, whereas it is less efficient than an ICE vehicles (assumed with a Euro 5 emission technology) when a battery allowing a 600 km range is considered.

2.3. Lifetime ownership costs

A set of studies deals not only with energy and environmental efficiency, but estimates user's lifetime ownership costs to estimate market penetration. A recent and thorough review of these studies is presented in Michalek et al., (2011), to which we refer, including, Delucchi and Lipman (2001; 2010), Plotkin et al., (2009) and Kromer and Heywood (2007).
Faria et al., (2012) compare 5 types of cars: a common diesel and gasoline ICEV, an HEV, a PHEV and a BEV. The Volkswagen Golf is used as a prototypal example of this gasoline and diesel type of cars, the Toyota Prius, Chevrolet Volt and Nissan Leaf, respectively are used as HEV, range

[1]Batteries are made of stacked cells where chemical energy is converted to electrical energy while supercapacitors store the energy in the form of static electricity. To achieve the desired voltage and current levels the cells/supercapacitors are electrically connected in series and parallel. Some of the available chemistries are Lead–acid, Nickel–Cadmium, Nickel– Metal Hydride, Nickel–Iron, Zinc–Air, Iron–Air, Sodium–sulfur,Lithium–Ion, Lithium–Polymer, etc. Batteries are rated in terms of their energy and power capabilities. Other important characteristics of batteries are efficiency, life span (in number of charge/discharge cycles), operating temperature, depth of discharge (usually batteries are not fully discharged or they could be damaged), self discharge rate (batteries cannot retain their rated capacity when stored during long periods) and energy density.

extender and BEV. The authors evaluate the ownership cost for each type of vehicle to provide a basis for determining the economic value of the investment, accounting for purchase and operational costs as well depreciation. The operational cost, per year, is calculated based on a total distance driven of 15,000 km and the average fuel prices for EU in 2011 and the average EU electricity rate. Two estimates are reported: after 5 years and after 10 years (Figure 7).

Economic comparison between the considered vehicle technology. The considered costs were the capital cost, Government deductions and ownership costs per year (which include fuel/electricity, maintenance, repair and taxes). The total costs of ownership and depreciation after 5 and 10 y are also presented. The calculation was based on driving 15,000 km/year and average fuel prices for 2011 in EU (1.35 €/l for diesel, 1.48 €/l for gasoline 95 and 0.16 €/kWh for electricity).

	ICEV		HEV	PHEV	BEV	Future BEV
	Diesel	Gasoline				
Capital cost (€)	22200	20300	25000	42000	35000	25000
Deductions (€)	–	–	–	–	5000	–
MRT (€/year)	500	500	500	350	300	300
Fuel (€/year)	850.5	1376	843	213.1	–	–
Electricity (€/year)	–	–	–	433.5	430.6	430.6
Ownership (€/year)	1350	1876	1343	996.6	730.6	730.6
After 5th year						
Ownership (€)	7096	9861	7059	5239	3841	3841
Depreciation (€)	11276	10311	12698	21333	17777	12698
TCO (€)	18372	20172	19757	26572	21618	16539
After 10th year						
Ownership (€)	15125	21018	15046	11166	8186	8186
Depreciation (€)	15749	14402	17735	29796	24830	17735
TCO (€)	30874	35420	32781	40962	33016	25921

Figure 7 – Economic comparison between vehicle technologies. Source: Faria et al. (2012, p. 25)

After 5 years, the diesel ICEV is the cheapest, followed by the HEV, the gasoline ICEV, the BEV and the PHEV. The BEV is € 3,246 more expansive than the diesel ICEV. After 10 years, the diesel ICEV is still the cheapest, followed this by the HEV, the BEV, the gasoline ICEV, and the PHEV. Hence, the BEV becomes cheaper than the gasoline ICEV but is € 2,142 more expansive than the diesel ICEV. The price difference declines because the lower operational costs are allowed more time to compensate the depreciation costs. Note that the BEV enjoys a € 5,000 subsidy.

Faria, Moura et al. (2012) argue that the higher initial cost of the BEV is due to the battery pack, estimated between 400 and 600 €/kWh[2]. If, as claimed by the US Advanced Battery Consortium, the price will drop in 2020, the price per kWh will be approximately 250 €, or 4,000–6,000 € for a 16–24 kWh battery pack: then the BEV will become in the future (see last column Figure 6) the cheapest alternative, both after 5 and 10 years. Hence, Faria et al., (2012) conclude that "electric mobility seems increasingly beneficial, both from an environmental and from an economical point of view when compared to conventional mobility".

Michalek et al., (2011) assess the economic value of life-cycle air emissions and oil consumption from ICEVs, HEVs, PHEVs, and BEVs. They estimate the lifetime private cost paid to own and operate each vehicle type plus the cost of the oil premium and damages caused by lifetime emissions charged to the owner at the time of purchase, assuming no change in driving patterns. Their estimates are reported in Figure 8.

[2]The battery pack used in the Nissan Leaf has an estimated cost of 530 €/kWh (12,720 € for the 24 kWh battery) and the Chevrolet Volt battery has an estimated cost of 420 €/kWh (6720 € for the 16 kWh battery) corresponding to 35% and 16% of the total cost of the vehicle, respectively.

	CV	HEV	PHEV20	PHEV60	BEV
Base vehicle cost	23,019	24,800	25,666	25,729	20,497
Initial battery cost	0	2,068	2,632	8,730	31,953
Battery replacement cost	0	0	0	0	0
Gasoline cost	12,386	8,847	7,189	6,226	0
Electricity cost	0	0	788	2,314	5,282
Scheduled maint.	4,380	3,962	3,235	3,235	2,232
Charger/instl.	0	0	1,200	2,400	2,400
Net cost	39,786	39,677	40,709	48,635	62,364

Figure 8 - Lifetime ownership costs in $\$_{2010}$. Source: Michalek et al. (2011, p. 34)

They find that the HEVs have an advantage on the conventional ICE vehicles (CV), whereas the PHEV20[3] is slightly more costly. On the contrary, the PHEV60 and the BEV have a net cost substantially higher. No subsidy or tax break is included. The paper also evaluates, in a very detailed manner, air emission damages and oil premium cost under three different scenarios: base, optimistic and pessimistic (Figure 9).

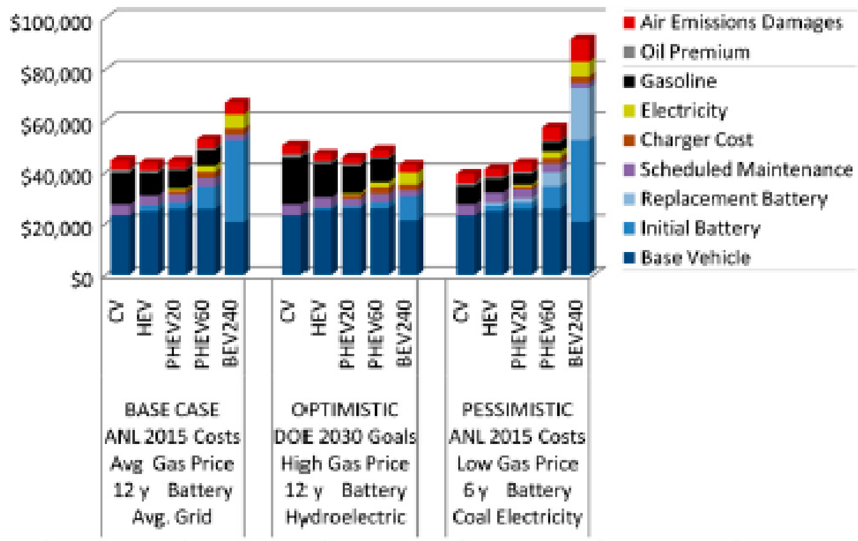

Fig. 2. Net present value of lifetime private ownership cost, emissions externality damages, and oil premium costs ($\$_{2010}$). ANL 2015 costs, Argonne National Laboratory cost estimates for the year 2015; DOE 2030 goals, US Department of Energy targets for vehicle cost in the year 2030; high, low, and average gas prices are for US weekly averages in 2008–2010; vehicle life is assumed to be 12 y.

Figure 9 - Lifetime costs in $\$_{2010}$. Source: Michalek et al., (2011, p. 3)

The authors argue that "plug-in vehicles with large battery packs may either reduce or create more life-cycle damages than HEVs depending largely on GHG and SO2 emissions from electricity and battery production. Even if future marginal electricity production and battery manufacturing processes will substantially reduce emissions with respect to today's averages, the emission damage and oil premium reduction potential of PHEVs is small compared to ownership costs: optimally

[3] The number represents the distance travelled with battery pack, 20 km (PHEV20) or 60 km (PHEV60), whereas the BEV is equipped with a 240-km battery pack (and no gasoline engine).

efficient (Pigovian) fees charged to correct for externality damages would not provide much leverage for incentivizing the adoption of PHEVs with large battery packs unless their costs drops to competitive levels".

The lifetime ownership cost of a BEV varies largely between scenarios. It is highest in the base case and in the pessimistic scenario and lowest in the optimistic scenario, reflecting the many uncertainties still existing. The author suggests that they have the potential to offer the greatest reductions in emissions and oil consumption at competitive cost "if air emissions from electricity generation are substantially reduced, battery prices drop dramatically, gasoline prices rise, high-power charging infrastructure is sufficiently deployed, and battery life is increased beyond vehicle life. Strong policy and support for research and development are needed to pursue this optimistic future; however, such outcomes are not guaranteed because of uncertain technological, economic, and political factors". In the near term, they favor HEVs and PHEVs with small battery packs. They also underline that the results are "US-specific findings may not extend to other countries. For example, it is possible that, in some European countries, the combination of higher petroleum prices, lower-emission electricity, higher population density, greater use of diesel, and shorter driving distances could make plug-in vehicles more attractive both for ownership cost and externality damage reduction."

Although EV's operating costs are roughly half that of conventional vehicles, the higher purchase cost allows a payback period of more than 10 years [Faria et al., (2012); Thiel et al., (2010)]. For same payback period is estimated for HEVs: neither these vehicles have a more affordable price than EVs, they have operative costs slightly lower than gasoline ones. As a result of the above considerations, HEVs and EVs do not represent, actually, cost effective solutions [Barkenbus (2007); Lipman et al., (2006); Faria et al., (2012); Michalek et al., (2011); Prud'homme et al., (2012); Thiel et al., (2010)]. Due to the market penetration of these alternative vehicles would be possible only if they will be economically competitive with conventional ones, although not exclusively, in many industrialized countries the governments have set subsidies in order to render them economically convenient.

3. A methodology to estimate the private and social costs of alternative powertrain cars

This section provides estimates of the private and social costs of different powertrain cars to individuals and to society. A comparative evaluation of different fuel cars is made from three important viewpoints: private costs, social costs and energy consumption. The analysis is focused on these three topics, in order to evaluate which solution could have the highest potential to achieve a sustainable mobility with less oil dependency, less impact on air quality and human health and an increased energy efficiency.

3.1. Private costs

The private cost of a car is estimated as a lifetime cost, that is, the cost of holding a car for a certain number of years, driving a given annual average distance at the prevailing fuel costs. These three variables will vary in the simulation model presented below.

The lifetime private cost of a car includes the following components:

Lifetime private cost = Vehicle Capital Cost + PV of the annual operating costs – residual value of the car

The Vehicle Capital Cost is determined by the retail price minus the subsidy granted by some governments on alternative fuel vehicles.

The present value of all annual operating costs includes all costs incurred during the lifetime of the vehicle (insurance, maintenance and repair, registration fee, etc.), depending on the annual kilometers driven, the number of years t considered and given the hypothesized social discount rate r.

PV of the annual operating costs = $\sum_t annual\ operating\ costs\ _t \frac{1}{(1+r)^t}$

The following costs have been considered to determine the *Annual Operating Cost*:

1) *Annual Fuel cost* depends on the urban and interurban fuel consumption of the car, on the percentage of urban and interurban trips and on the fuel prices. For conventional ICEVs and HEVs, fuel cost has been calculated as follows:

   *Annual Fuel Cost = (Average annual kilometers driven/100) * Fuel efficiency * Fuel Price*

   The fuel efficiency is the quantity of fuel consumed to drive 100 km. It depends on the share of urban\interurban trips driven by the user.
   In the case of bi-fuel vehicles, one can distinguish between a primary and a secondary fuel. For instance, CNG and LPG cars can run with both these fuels (called primary) or with a secondary fuel (gasoline). Depending on prices, availability and preferences each driver chooses whether to use the primary only, both or a combination of the two. In the model, the simplified assumption is made that the driver consumes completely both fuel tanks. The annual fuel cost is, hence, estimated as follows:

   Primary fuel range (km) = $\frac{Primary\ fuel's\ tank\ capacity}{Fuel\ efficiency\ of\ the\ primary\ fuel}$ * 100

   Secondary fuel range (km) = $\frac{Secondary\ fuel's\ tank\ capacity}{Fuel\ efficiency\ of\ the\ secondary\ fuel}$ * 100

   Total Car Range (km) = Primary fuel range (km) + Secondary fuel range (km)

   Then, dividing the average annual kilometers driven by the total car range, one obtains the total number of primary and secondary fuel tank refillings necessary to run the annual distance considered. The annual fuel cost is then estimated multiplying the number of refillings by the cost of each refill.
   For EVs, the following formula has been used:

*Annual electricity Costs = Average annual kilometers driven * (Battery Capacity in kWh/Range in km) * Electricity average retail price per kWh*

2) *Annual battery leasing fees:* only for EVs with battery leasing. The amount depends both on the average annual kilometers driven and on the contract length in years.
3) *Average annual insurance cost:* the amount of this annual cost varies among individuals according to the person's age, accident record, city of residence, etc.. Given the high variability, the average Italian value for to 2011 has been used, assuming it to be equal across vehicle types.
4) *Annual ordinary maintenance and repair cost:* usually this cost is incurred every several years (1 years) or after a number of kilometers (15,000 km). In the model the average Italian value referred to 2011 has been used, assumed to be equal across all vehicle types.
5) *Annual extraordinary maintenance and repair cost:* costs related to brakes, shock absorbers, tires and friction. In the model an average Italian value referred to 2011 has been used, assumed to be equal across vehicle types.
6) *Average annual parking costs:* it includes garage costs and parking fees. In the model has been used an average Italian value referred to 2011, assumed to be equal across vehicle types but for electric vehicles that are often exempted from the parking charge in city centres.
7) *Annual Vehicle Excise Duty:* In Italy, its amount now depends on the horsepower and the European air pollution standards as presented in Table 3:

Table 3 - *Parameters for Vehicle Excise Duty calculation*

European Standards	KW 0-100 (€/KW)	KW >100 (€/KW)
0	3	4.5
1	2.9	4.35
2	2.8	4.2
3	2.7	4.05
4	2.58	3.87
5	2.58	3.87

Source: (ACI, 2012)

Furthermore, the Italian government gives discounts for alternative fuelled. More in detail: for CNGs and LPGs the road tax is only the 25% of the amount for a corresponding gasoline car, while for EVs there is a total exemption for the first five years. After this period, the taxation regimen will it will be applied the same scheme of the above types. No deductions are available for HEVs.

The annual operation costs for each year are discounted assuming a discount rate equal to 5%.

3.2. The social cost

Buying a car does not entail only private costs. An estimate of the social costs of the different fuel cars is needed. To achieve this goal, the main externalities have been considered namely greenhouse gases (CO_2, NO_2, CH_4), local air pollutants (NO_X, SO_X, PM) and noise. Following Michalek et al., (2011) air pollution assessment consider the entire life cycle including production and fuel utilization, from WtW, subdivided into WtT and TtW. On the contrary, noise estimations only refer to the car use phase. Hence:

Social Costs = WtW Global Air Pollution Cost + WtW Local Air Pollution Cost + TtW Noise Cost

The WtT emission index takes into account the pollutant mass (*mp*) emitted in the extraction, chemical processing and transport phase (Table 4):

$$WtT_p\ (g/MJf) = \frac{mp\ WtT}{Ef}$$

Table 4 - Well-to-Tank environmental values for the analyzed powertrains

Powertrain	WtT_{NOx} g/MJ_f	WtT_{PM} g/MJ_f	WtT_{SOx} g/MJ_f	WtT_{GHG} g/MJ_f
ICE (Gasoline)	0.042	0.002	0.067	12.5
ICE (Diesel)	0.036	0.001	0.059	14.2
ICE (bi-fuel CNG)	0.011	0.001	0.017	14
ICE (bi-fuel LPG)	0.011	0.001	0.017	14
ICE Hyb (Gasoline)	0.042	0.002	0.067	12.5
ICE Hyb (Diesel)	0.042	0.002	0.067	12.5
BEV (Battery Electric Vehicle)	0.277*	0.008	0.358*	135.8*

Source: Torchio et al., (2010, p. 4161) and *our estimates

Where *Ef* is the energy contained in the fuel mass stored in a vehicle tank (g/MJf).
The TtW emission index takes into account the pollutant mass (mp) emitted by a car usually expressed in grams of pollutant emitted by a car per km (g/km), related to a reference distance (Table 5).

$$TtW_p\ (g/km) = \frac{mp\ TtW}{D}$$

Table 5 - Tank-to-wheels environmental values for the analyzed powertrains

Powertrain	TtWNOx g/km	TtWPM g/km	TtWSOx g/km	TtWGHG g/km
ICE (Gasoline)	0.06	0.005	0.001	139.6
ICE (Diesel)	0.18	0.005	0.001	131.1
ICE (bi-fuel CNG)	0.06	0.005	0.001	107.9
ICE (bi-fuel LPG)	0.06	0.005	0.001	107.9
ICE Hyb (Gasoline)	0.052	0.004	0.001	120.1
ICE Hyb (Diesel)	0.052	0.004	0.001	120.1
BEV (Battery Electric Vehicle)	0	0	0	0

Source: Torchio et al., (2010, p. 4162)

This index depends on the fuel and powertrain combination. Usually a standard drive cycle should be adopted. Thus, the link between WtT_p and WtT^*_p is:

WtT^*_p *(g/km) =* WtT_p *(g/MJf)*$*$ TtW_e *(MJf/km)*

The TtW energy factors are presented in Table 6.

Table 6 – TtW energy factors

Powertrain	TtW_e MJ_f/km
ICE (Gasoline)	1.89
ICE (Diesel)	1.77
ICE (bi-fuel CNG)	1.88
ICE (bi-fuel LPG)	1.88
ICE Hyb (Gasoline)	1.63
ICE Hyb (Diesel)	1.63
BEV (Battery Electric Vehicle)	1.11

Source: Torchio et al., (2010, p.4162)

Finally, the WtW emission index gives the total pollutant emitted from a fuel production pathway and powertrain combination. The formula is reported below.

WtW_p *(g/km) =* WtT^*_p *(g/km) +* TtW_p *(g/km)*

Therefore, the present value of the external WtW cost is:

$$PV(WtW\_\ \text{Global Air Pollution Cost})\ (€) = \{\textstyle\sum_t [WTT * p \left(\frac{g}{km}\right) * WTTp\ External\ Cost\ (cent.€/g)_t] \frac{1}{(1+r)^t} + \sum_t [TTW * p \left(\frac{g}{km}\right) * TTWp\ External\ Cost\ (cent.€/g)_t] \frac{1}{(1+r)^t}\} * Average\ Yearly\ Kilometers$$

The same process has been used for NO_X, SO_X, PM emissions that are the main impact for the air pollution. The monetary estimates of these pollutants emissions *"consist of health costs, building/material damages, crop losses and costs for further damages for the ecosystem (biosphere, soil, water)"* (Maibach et al., 2008) (Table 7).

Table 7 – External costs per pollutant €/g

Air pollutant	WtT	TtW
NOx	0.0095	0.0095
SOx	0.0087	0.0087
PM rural	0.06838	0.06838
PM urban	0.12134	0.12134
PM metropolitan	0	0.3755
GHG	0.000025	0.000025

Source: Van Essen H. (2011)

The environmental costs are estimated as follows:

WtW_p *(€) =*WtT^*_p*(g/km)**WtT_p *External Cost (€/g)+* TtW^*_p *(g/km)**WtT_p *External Cost (€/g)*

These values are multiplied for the average kilometer driven per year and actualized.

Noise costs have been calculated considering vehicle-per kilometer costs (€/v-km) of this externality, obtained by "*Handbook on estimation of external costs in the transport sector"* (Maibach et al., 2008). The costs are estimated as follows:

Noise Cost = Noise Urban Cost + Noise Interurban Cost

With

Noise Urban Cost *(€)= Yearly Kilometers * % Urban Kilometers * Average Urban Noise Cost*

Noise Interurban Cost *(€)= Yearly Kilometers * %* Interurban *Kilometers * Average* Interurban *Noise Cost*

All costs are actualized. It is assumed that EVs have a 90% reduction in noise emissions, while HEVs 20%.

3.3. Energy use

The estimation of the energy consumption for the different cars considered, following Torchio et al., (2010) and Concawe et al., (2007) can be performed with reference to the WtT and TtW components. The estimates have been performed using the European Union has a reference term.

The WtT component for the fuels considered in our model has been estimated by Concawe et al., (2007) considering the typical pathways, defined as the combination of steps necessary to turn a resource into a fuel and bring that fuel to a vehicle. A list of results, reported by Torchio et al., (2010) is presented in Table 8.

Table 8 - Well-to-tank energy values for the analyzed fuels

	WtTe MJx/MJf	WtTe' MJt/MJf
Gasoline	0.14	1.14
Diesel	0.16	1.16
CNG (Compressed Natural Gas)	0.19	1.19
LPG	0.12	1.12
Electricity (EU-mix)	1.52	2.52

Source: All values except the one for LPG are taken from Torchio et al., (2010, p. 4161).
WtTe MJx/MJf is the expended primary well-to-tank energy.
WtTe' MJt/MJf is the total well-to-tank energy, where the superscript ' means that the energy WtT index is the ratio between the total energy and the fuel energy, that is to have 1 gasoline unit one consumes 1,14 units of energy.

The WtT expended energy (i.e. excluding the energy content of the fuel itself) per unit energy content of the fuel (LHV basis) is used to estimate the WtW energy consumption via the following formula:

Total WtW energy (MJ/km) = TtW energy (MJf/km) x (1 + WtT total expended energy (MJxt/MJf))

where TtW energy represents the energy consumed by the vehicle per unit of distance covered. Table 9 presents the energy values for the powertrains analyzed.

Table 9 - Tank-to-wheels energy values for the analyzed powertrains

Powertrain	TtWe MJf/km	kwh/km*
ICE (Gasoline)	1.89	0.53
ICE (Diesel)	1.77	0.49
ICE (bi-fuel CNG)	1.88	0.52
ICE (bi-fuel LPG)	1.9	0.53
ICE Hyb (Gasoline)	1.63	0.45
ICE Hyb (Diesel)	1.46	0.41
BEV (Battery Electric Vehicle)	1.11	0.31

*The figures expressed in Mega Joules are converted into Kwh using the 0,277778 conversion factor.

Table 10 presents the resulting WtT, TtW and WtW energy consumption values expressed in kWh per km.

Table 10 - Tank-to-wheels energy values for the analyzed powertrains

	WtT	TtW	WtW
ICE (Gasoline)	0.07	0.53	0.60
ICE (Diesel)	0.08	0.49	0.57
ICE (bi-fuel CNG)	0.10	0.52	0.62
ICE (bi-fuel LPG)	0.06	0.53	0.59
ICE Hyb (Gasoline)	0.06	0.45	0.52
ICE Hyb (Diesel)	0.06	0.41	0.47
BEV (Battery Electric Vehicle)	0.47	0.31	0.78

It can be noticed that, although the Battery Electric Vehicles are the most efficient in the TtW (usage) phase, they are the worst in the WtT (fuel production) phase thus, resulting the lowest efficient vehicle.

The result for the Battery Electric Vehicle differs from the one presented by Coccia (2010), and estimated with reference to Italy only.

Table 11 - WtW energy use for alternative fuel cars

Energy Consumption (kWh/km)	Gasoline	Diesel	HEV	EV
Well-to-Tank	0.11	0.08	0.07	0.16
Tank-to-Wheel	0.49	0.47	0.32	0.16
Well-to-Wheel	0.60	0.55	0.39	0.32

Source: (Enel, 2010)

Concawe, Eucar et al. (2007) report in Figure 9 a value equal to about 1,9 MJx/MJf, with reference to the 1999 EU energy mix.

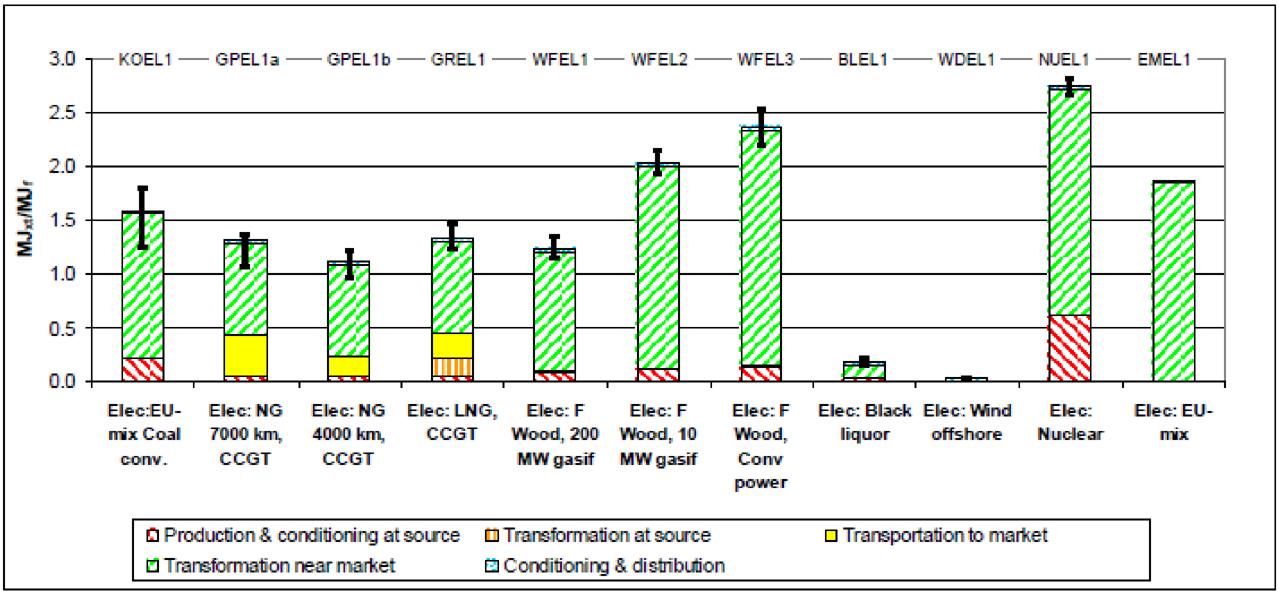

Figure 9 – Total energy balance for various electricity pathways. Source: *Concawe, Eucar, JRC/IES (2007, p. 84)

Performing the calculations reported in Table 12, we estimate that the 2007 energy mix is equal to 1,35 MJx/MJf and the 2010 Italian energy mix is equal to 1,08 MJx/MJf. The energy savings achieved in the EU are due to the different energy mix, using less nuclear[4] and more wind. The higher efficiency of the Italian mix is due to the large use of the natural gas and of the inexistence of nuclear power plants.

Table 12 – The European and Italian energy mix and energy efficiency

	EU 1999*	Energy effiency factors	EU 1999	EU 2007	EU 2007	Italy 2010	Italy 2010
Nuclear	37.50	2.70	101.25	17.00	45.90	0.00	0.00
Coal	22.00	1.60	35.20	30.00	48.00	10.80	17.28
Oil	9.60	1.60	15.36	7.00	11.20	7.00	11.20
Gas	15.50	1.30	20.15	21.00	27.30	44.90	58.37
Hydro	12.40	0.10	1.24	15.00	1.50	16.30	1.63
Wind	0.40	0.10	0.04	7.00	0.70	2.70	0.27
Waste	1.80	0.30	0.54	1.00	0.30	2.70	0.81
Other Renew	0.30	0.10	0.03	2.00	0.20	2.10	0.21
Imports	99.50					13.50	18.24
Total		1.35	1.75	100.00	1.35	100.00	1.08

*Concawe, Eucar, JRC/IES (2007, p. 51)

If 2010 Italian energy mix is assumed the WtW BEV values drops from 0,777 kWh per km value to 0,641 kWh per km, which is a value still higher than the one for the other vehicles but much closer to the CNG vehicle one.

[4] Concawe, Eucar, JRC/IES (2007, p. 84) estimates that nuclear energy is the least energy efficient both in terms of production and condition at the source and especial in terms of transformation near the market.

In the model, the energy consumption has been estimated multiplying the kilometric energy use by the total kilometres.

4. Estimates and simulations

The model developed could be used to evaluate the base case scenario and the impact of different parameters such as annual kilometers driven, years of usage, percentage of urban and interurban travels holding all other parameters constant (ceteris paribus condition) on the relative performance of the alternative powertrain cars.

4.1. The base case scenario

The comparison takes place among 7 different car models, six of which belonging to the market segment B ‘small cars’: the gasoline VW Polo, the diesel Ford Fiesta, the CNG Fiat Punto Evo Natural Power, the LPG Alfa Romeo MiTo, the Hybrid Toyota Yaris, the BEV with leased-battery Renault Zoe and one belonging to car market segment A “mini cars” the BEV Peugeot iOn. This market segment has been chosen because most of these powertrains are applied on this car class while in other segments some powertrains are not used (e.g. CNG powertrains are not installed on “large cars” and hybrid powertrains not on “mini cars”).

The main assumption of the base case scenario is that a car is kept 5 years, it travels 10,000 kilometers per year and 80% of the trips take place on urban roads. The price of electricity is assumed to be equal to 0,182 €/kWh. All detailed assumptions are listed in the Appendix.

Private costs

Under the scenario assumptions, Table 13 shows that from a private point of view Ford Fiesta (Diesel) is the cheapest car, followed at close distance by VW Polo (Gasoline), Toyota Yaris (Hybrid) and Fiat Punto (bi-fuel CNG). Alfa R. MiTo (bi-fuel LPG) is more expensive and the two BEVs are even more expensive, with Peugeot iOn (BEV) being the most expensive.

Table 13 - Private costs

	VW Polo (Gasoline)	Ford Fiesta (Diesel)	Fiat Punto (bi-fuel CNG)	Alfa R. MiTo (bi-fuel LPG)	Toyota Yaris (Hybrid)	Peugeot iOn (BEV)	Renault Zoe (L_BEV)
Vehicle capital cost	15.060	14.750	17.250	20.600	17.800	28.318	21.650
Annual fuel cost	1.353	838	1.073	1.167	627	194	191
Operating cost per km	0	0	0	0	0	0	0
Annual operating cost	2.715	2.172	2.420	2.595	2.017	1.261	2.206
Total cost (PV)	27.402	24.624	28.252	32.398	26.971	34.051	31.677

These results are mainly to be attributed to the huge differences in the purchasing costs. In fact, the very low operating cost of Peugeot iOn (BEV) does not offset, in just 5 years with 10,000 km per year, the purchasing cost difference. Different scenarios will be discussed below.

Environmental costs

Global pollution, local pollution and noise pollution are considered separately (Table 14).

Table 14 - Global pollution costs for the Green House Gases (CO_2) – values in 2010 €.

	VW Polo (Gasoline)	Ford Fiesta (Diesel)	Fiat Punto (bi-fuel CNG)	Alfa R. MiTo (bi-fuel LPG)	Toyota Yaris (Hybrid)	Peugeot iOn (BEV)	Renault Zoe (L_BEV)
WtT GHG	27	29	30	30	23	171	171
TtW GHG	159	149	123	123	136	0	0
WtW	186	178	153	153	160	171	171

With regards to global pollution, the cost imposed by the cars under the base case scenario conditions (5 years, 10,000 km per year) range from 76 to 93 €. Fiat Punto (bi-fuel CNG) and Alfa R. MiTo (bi-fuel LPG) are the best, followed by Toyota Yaris (Hybrid). The two BEVs have a smaller impact while VW Polo (Gasoline) has the highest. The two BEVs are slightly better that Ford Fiesta (Diesel). Of course, the BEVs emit in the WtT (fuel production) phase while the other in the TtW (car use) phase.

Table 15 - Local pollution costs

	VW Polo (Gasoline)	Ford Fiesta (Diesel)	Fiat Punto (bi-fuel CNG)	Alfa R. MiTo (bi-fuel LPG)	Toyota Yaris (Hybrid)	Peugeot iOn (BEV)	Renault Zoe (L_BEV)
WtT NOX	34,3	27,5	8,9	8,9	29,6	132,7	132,7
WtT PM\ rural	11,8	5,5	5,8	5,8	10,1	27,6	27,6
WtT PM urban	20,9	9,8	10,4	10,4	18,0	49,0	49,0
WtT SOX	50,1	41,3	12,6	12,6	43,2	157,0	157,0
TtW NOX	25,9	77,7	25,9	25,9	22,5	0,0	0,0
TtW PM metrop.	85,4	85,4	85,4	85,4	68,3	0,0	0,0
TtW PM urban	27,6	27,6	27,6	27,6	22,1	0,0	0,0
TtW PM rural	15,5	15,5	15,5	15,5	12,4	0,0	0,0
TtW SOX	0,4	0,4	0,4	0,4	0,4	0,0	0,0
WtW NOX	60,2	105,3	34,8	34,8	52,0	132,7	132,7
WtW PM rur/met	97,1	90,9	25,9	91,2	78,4	27,6	27,6
WtW rur/urb	39,3	33,1	13,0	33,4	32,2	27,6	27,6
WtW rur/rur	27,3	21,0	0,0	21,4	22,6	27,6	27,6
WtW urb/met	106,2	95,1	23,2	95,7	86,3	49,0	49,0
WtW urb/urb	48,4	37,3	136,5	38,0	40,0	49,0	49,0
WtW urb/rur	36,4	25,3	159,6	25,9	30,4	49,0	49,0
WtW SOX	50,5	41,7	13,0	13,0	43,6	157,0	157,0
WtW tot rur/met	207,8	237,8	73,8	139,1	174,0	317,3	317,3
WtW tot rur/urb	150,0	180,0	60,9	81,3	127,8	317,3	317,3
WtW tot rur/rur	138,0	168,0	47,9	69,3	118,2	317,3	317,3
WtW tot urb/met	216,9	242,1	71,0	143,6	181,9	338,7	338,7
WtW tot urb/urb	159,1	184,3	184,4	85,8	135,7	338,7	338,7
WtW tot urb/rur	147,1	172,3	207,5	73,8	126,0	338,7	338,7

Global pollution costs are presented in Table 15. It is rather complex since it reports the results for three pollutants (NO_x, SO_x, PM), while differentiating for PM according to location (rural, urban, metropolitan). The BEVs have zero emission in the TtW phase, but are highly pollutant in the WtT one. The opposite is true for the other cars. The worst scenario for non-BEV cars is in the metropolitan areas where, under the base case scenario conditions (5 years, 5000 km per year) they impose on society, in the TtW phase, a cost of about 13 € for NOx, 42.7 € for PM and 0.2 € for SO_x as opposed to the zero costs imposed by BEVs.

However, when the two phases are jointly considered as WtW, the BEVs are superior to the other cars only with regards to PM, but not with respect to NOx and, in particular, not to SOx. All pollutants jointly considered, the BEVs impose higher pollution costs than their competitors, a conclusion somewhat different from the popular vulgata. Crucial for these conclusion are the costs connected to NOx and SOx emissions in the energy production phase. Other two issues need call for attention: 1) the evaluation of NOx and SOx pollution costs is unfortunately highly uncertain and based on few studies (Externe been one of the most important ones) and 2) this result is based on the 2010 Italian energy mix.

The absolute costs amount to a maximum of 169.3 €. Particularly low values (24 to 37 €) are reached for the Fiat Punto (bi-fuel CNG) when fuel production takes place in rural areas.

Table 16 - Noise pollution costs

	VW Polo (Gasoline)	Ford Fiesta (Diesel)	Fiat Punto (bi-fuel CNG)	Alfa R. MiTo (bi-fuel LPG)	Toyota Yaris (Hybrid)	Peugeot iOn (BEV)	Renault Zoe (L_BEV)
Noise Cost	153	153	153	153	122	15	15

With regards to noise the BEVS have a clear advantage over all other ICE cars by more than 100-138 €.

Table 17 - Total social costs

	VW Polo (Gasoline)	Ford Fiesta (Diesel)	Fiat Punto (bi-fuel CNG)	Alfa R. MiTo (bi-fuel LPG)	Toyota Yaris (Hybrid)	Peugeot iOn (BEV)	Renault Zoe (L_BEV)
Total rur/met	699	721	532	597	578	519	519
Total rur/urb	641	663	519	540	532	519	519
Total rur/rur	629	651	506	528	522	519	519
Total urb/met	708	725	529	602	586	541	541
Total urb/urb	650	668	643	544	540	541	541
Total urb/rur	638	656	666	532	530	541	541

Table 17 sums up all social costs. They vary between 725 and 506 €, which is much lower than the private costs. Thanks to the lower noise costs the BEVs present often the lowest values in most circumstances. The cost difference with conventional ICE cars varies between 98 to 202 €, that is about maximum 40 € per year. The cost difference with bi-fuel and hybrid ICE cars is much lower and sometimes negative.

These results do not vary when the car is kept longer than 5 years or driven longer. They are just increased by the factor of increase.

Energy consumption

As far as energy consumption is concerned, the most efficient car is, by far, the Toyota Yaris (Hybrid). The BEVs, notwithstanding the excellent levels of energy use in the TtW phase, given the current energy mix, which are, however, more than compensated by the large energy consumption in the WtT phase, results in the lowest energy efficient cars.

Table 18 - Energy consumption

	VW Polo (Gasoline)	Ford Fiesta (Diesel)	Fiat Punto (bi-fuel CNG)	Alfa R. MiTo (bi-fuel LPG)	Toyota Yaris (Hybrid)	Peugeot iOn (BEV)	Renault Zoe (L_BEV)
WtT(kWh)	3.675	3.934	4.961	3.165	3.170	16.650	16.650
TtW(kWh)	26.250	24.585	26.110	26.390	22.640	15.415	15.415
WtW (kWh)	29.925	28.519	31.071	29.555	25.810	32.065	32.065

4.2. Simulation 1: varying the annual distance driven

The relative performance of the 7 powertrain\fuel cars are compared when the average annual kilometers driven increase from 5,000 to 25,000 km per year, holding all other variables constant.

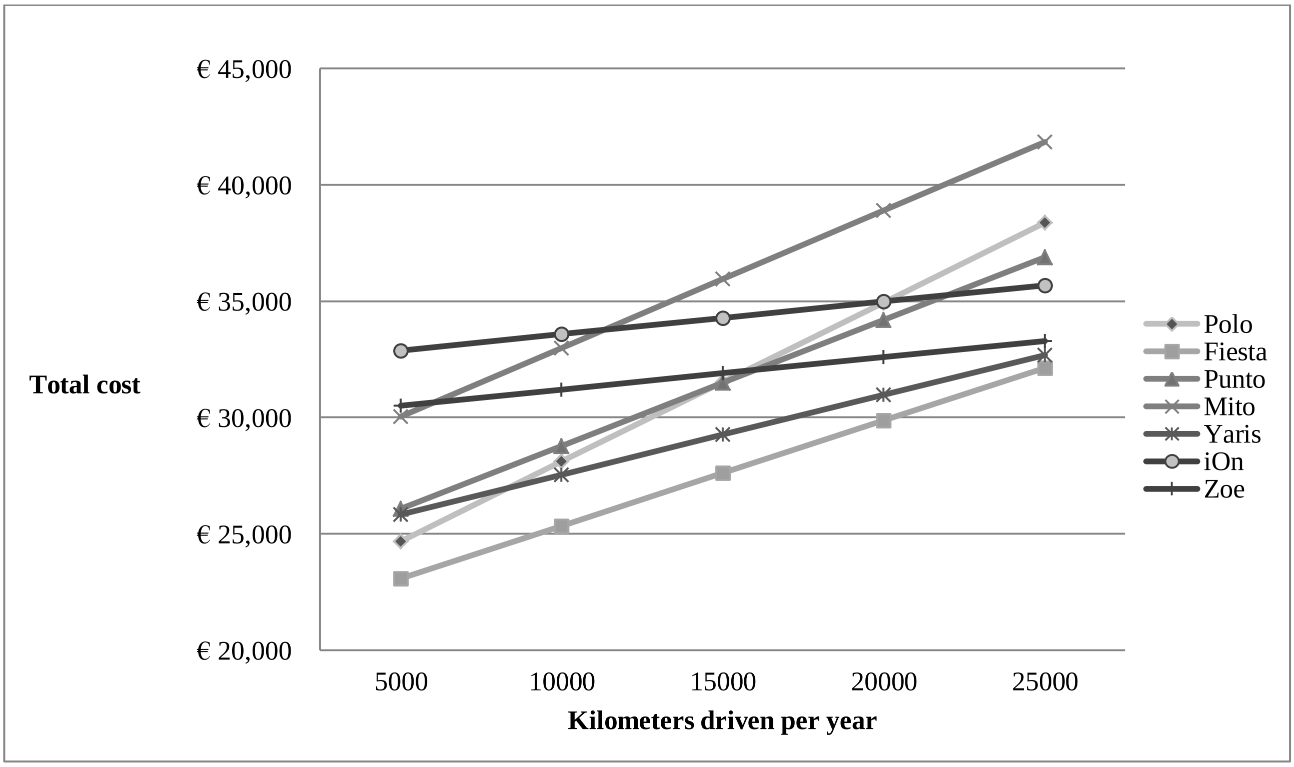

Figure 10 - Total cost for 5 usage years and different annual kilometers

The results are illustrated in Figure 2 with reference only to the total (private + social) costs. As the proportion between fixed (purchase) and variable (operating) costs is very different among cars, the increased distance travel improves the relative ranking of the cars with low annual operating costs. The diesel Ford Fiesta is always the cheapest choice, but the Hybrid Toyota Yaris and the BEVs improve their relative ranking. When 25,000 km per year are driven, the Hybrid Toyota Yaris is very close to the diesel Ford Fiesta and the BEVs jump from the last rankings to the third and fourth position.

4.3. Simulation 2: varying car holding length

The number of years that a car is kept is increased from 5 to 10 years and 10,000 km driven per year are assumed, holding constant all other assumptions.

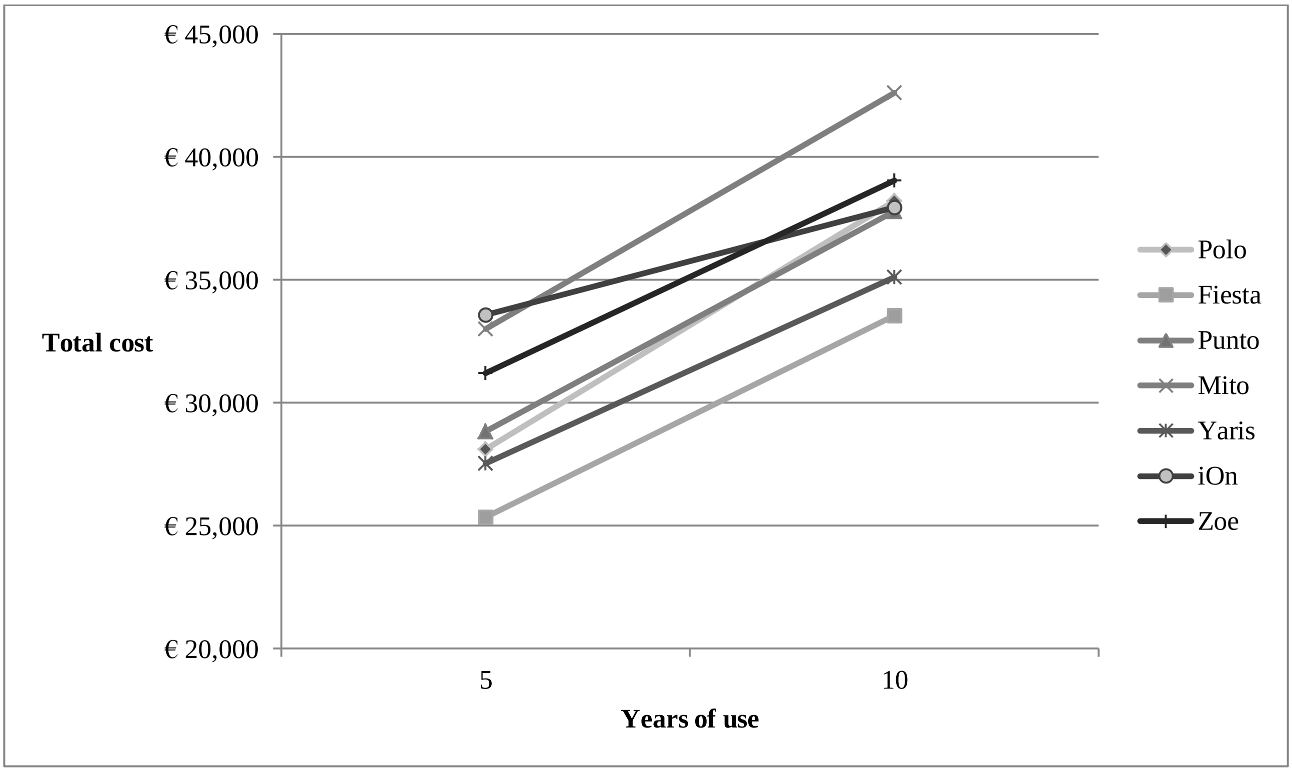

Figure 11 - Total cost for different usage years, given 10.000 km driven per year

The new assumption allows a better amortization of the BEV Peugeot iOn's cost for buying the battery. Its ranking improves from 7th to 5th. Renault Zoe with leased battery does not benefit much from the longer car holding.

4.4. Simulation 3: current Italian subsidies (car held 5 years).

The Italian Parliament recently passed a law that grants the subsidies, summarized in Table 19, for the cars considered in this paper.

Table 19 - *Italian subsidies in 2013 for the cars considered*

VW Polo (Gasoline)	Ford Fiesta (Diesel)	Fiat Punto (bi-fuel CNG)	Alfa R. MiTo (bi-fuel LPG)	Toyota Yaris (Hybrid)	Peugeot iOn (BEV)	Renault Zoe (L_BEV)
-	€ 2,000	-	-	€ 3,560	€ 5,000	€ 4,330

Their impact is simulated jointly with the increase in the kilometers driven.

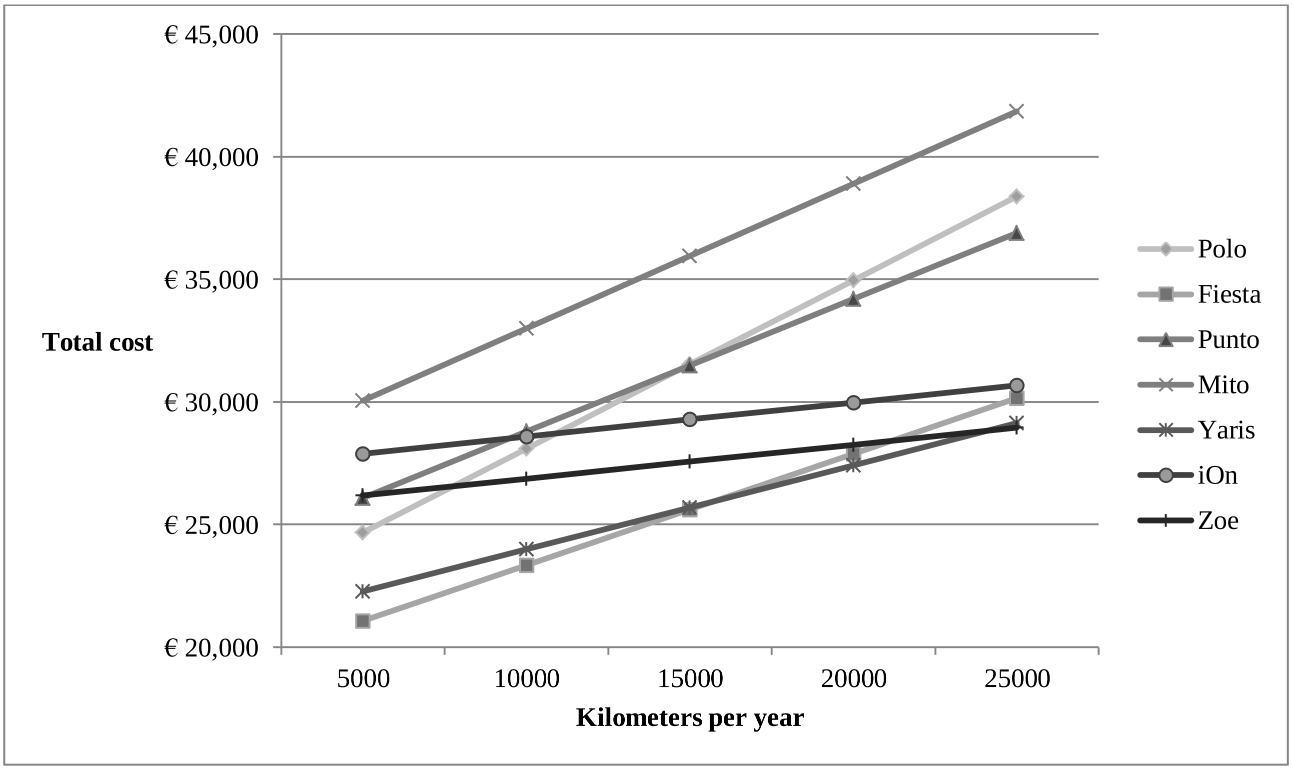

Figure 12 - Total cost for different kilometers driven, given the Italian subsidies for less polluting cars in 2013 and 5 usage years

For the first time, when more than 15,000 km per year are driven, the Hybrid Toyota Yaris becomes the cheapest car from a private plus social point of view. The BEVs, having reduced their initial gap, become more competitive also when only 5,000 km per year are driven. With 25,000 km per year the with leased-battery Renault Zoe overcomes the diesel Ford Fiesta.

4.5. Simulation 4: current Italian subsidies (car held 10 years).

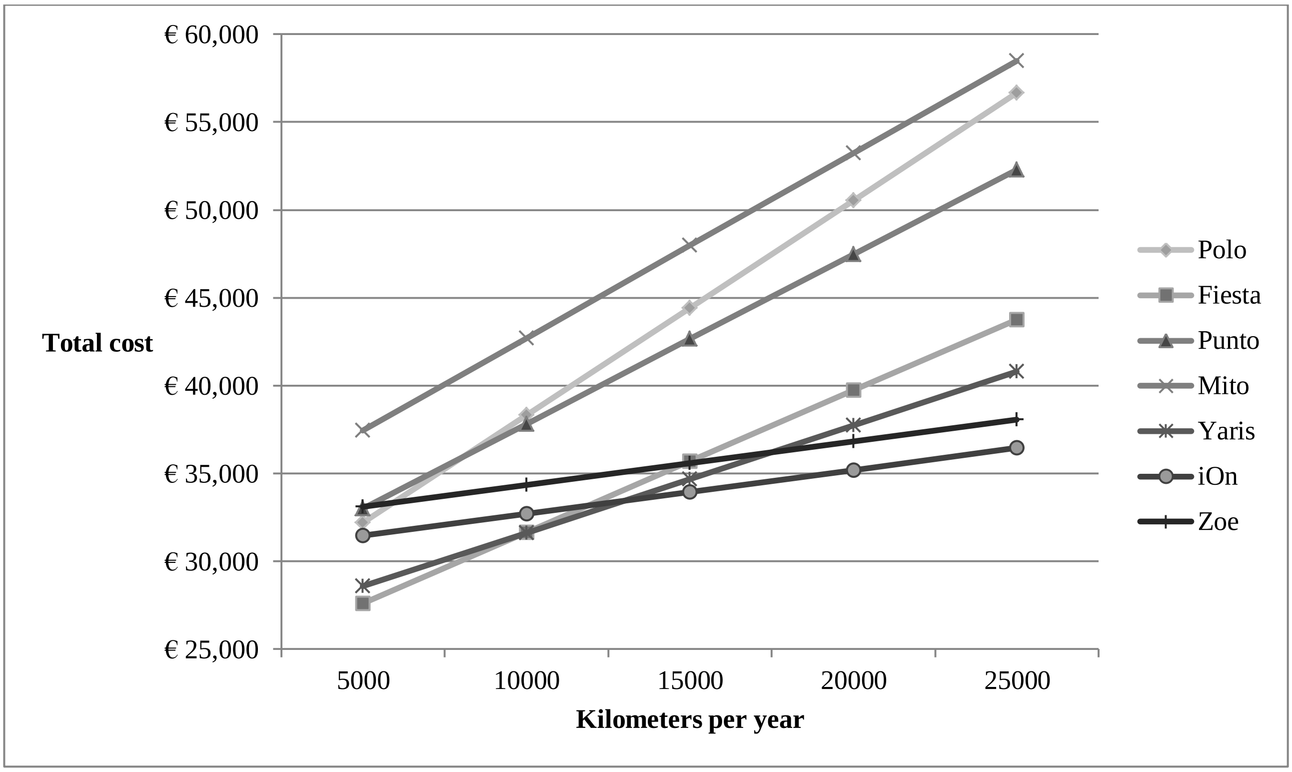

Figure 13- Total cost for different kilometers driven, given the Italian subsidies for less polluting cars in 2013 and 10 usage years

When the cars are held 10 years instead of 5 years the above conclusions are re-enforced. Hybrid Toyota Yaris is very competitive and the BEVs become the best choices when more than 15,000 km are driven per year.

4.6. Simulation 5: increasing the gasoline and diesel price by 10% and 20%

This simulation assumes gasoline and diesel prices are increased by 10% and 20%, when holding the car 5 or 10 years with 10,000 kilometers driven per year.

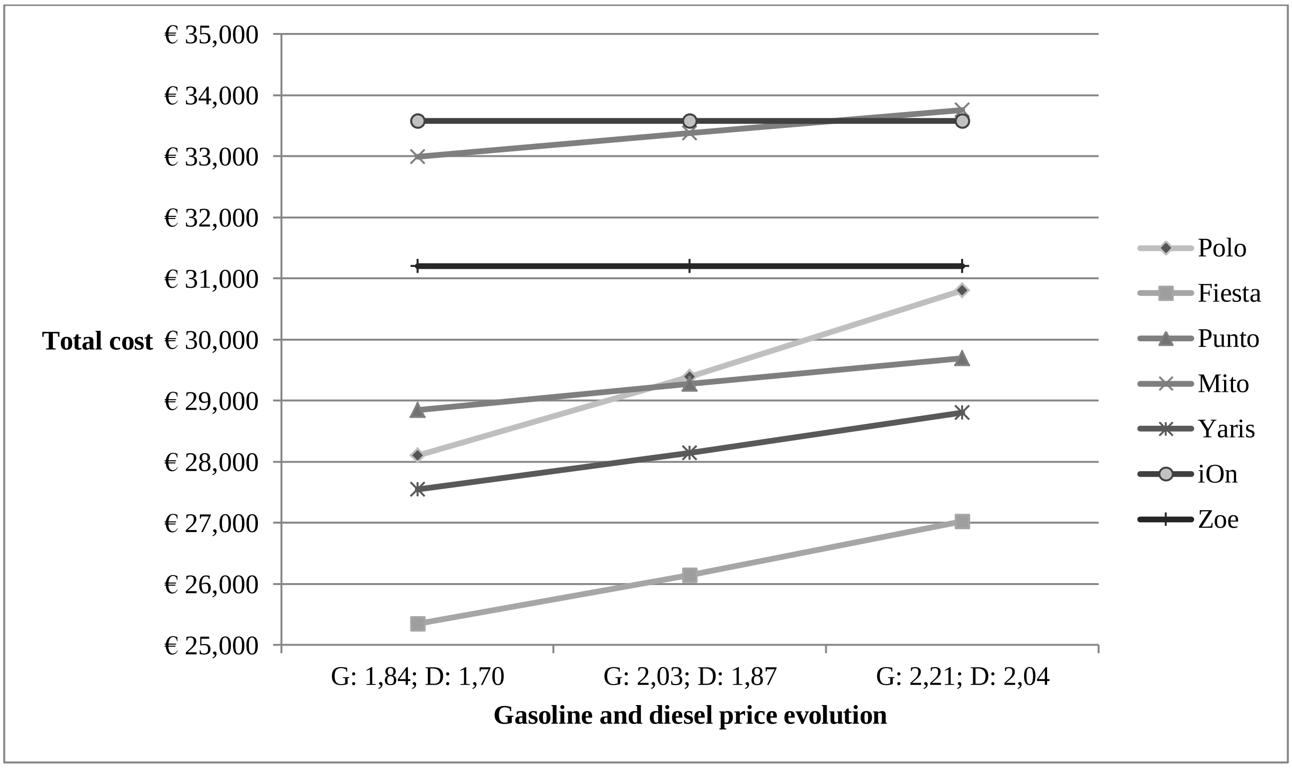

Figure 14 - Total cost with conventional fuel prices increase of 10% and 20%, given 5 usage years and 10.000 kilometers driven per year

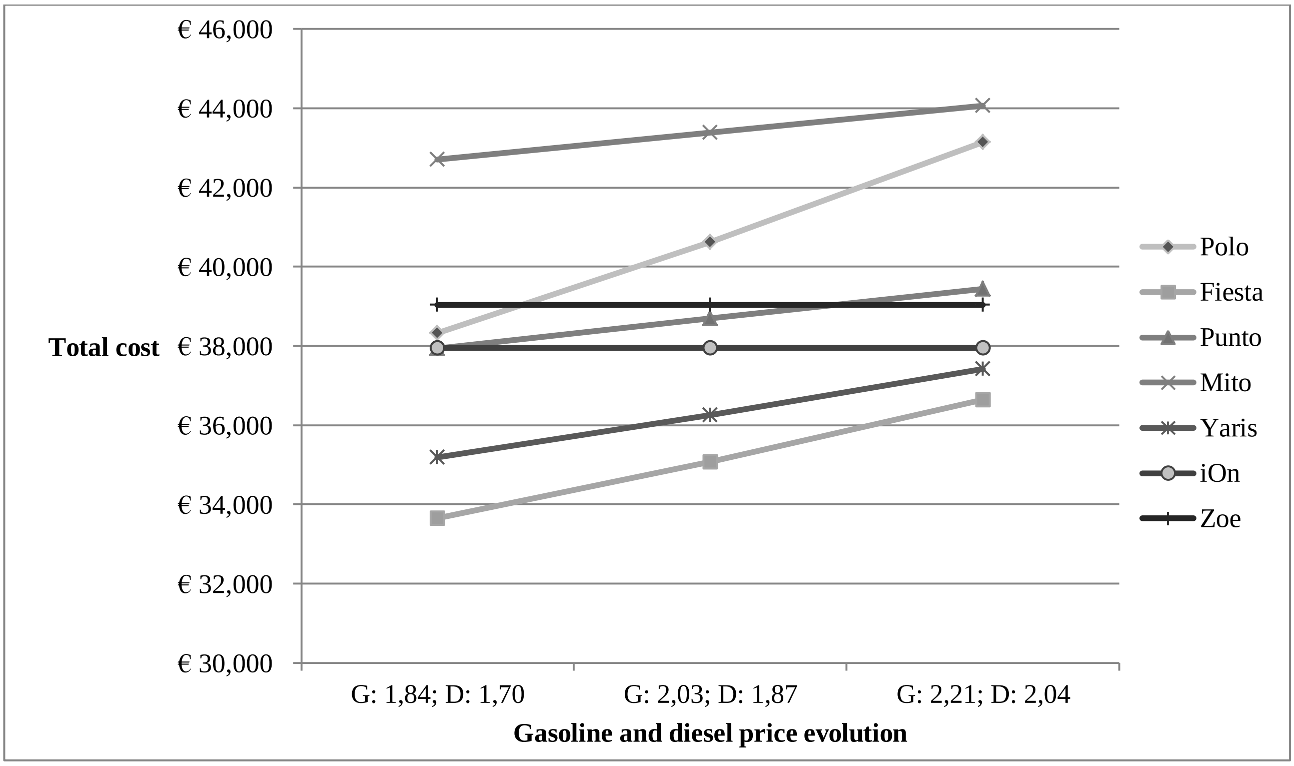

Figure 15 - Total cost with conventional fuel prices increase of 10% and 20%, given 10 usage years and 10.000 kilometers driven per year

The second scenario is obviously more effective in altering the previous ranking. The BEVs benefit the most from the fuel price increases.

4.7. Simulation 6: a battery price decrease

Following McKinsey forecasts, battery costs are assumed to decrease in the years 2020 and 2025. The two scenarios assume 10,000 kilometers per year and 5 or 10 years.

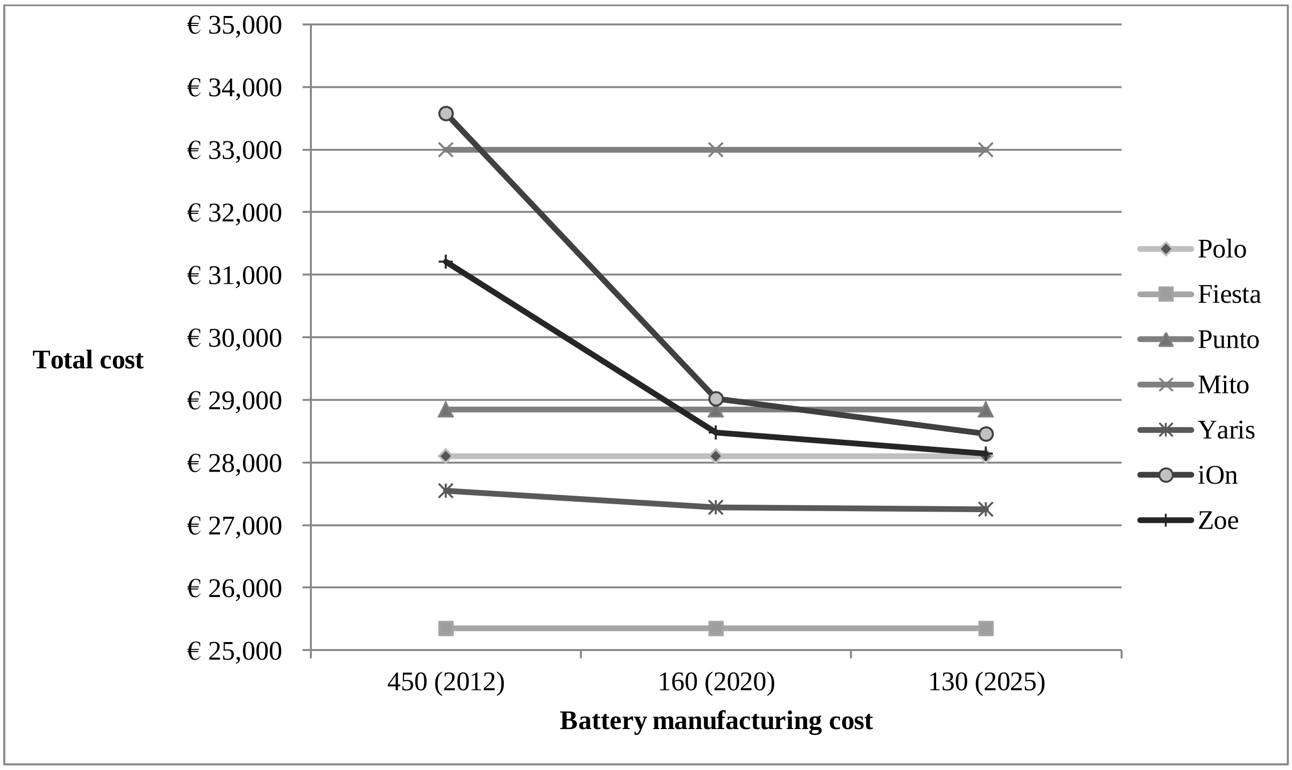

Figure 16 - Total cost with McKinsey battery manufacturing costs forecasts, given 10.000 kilometers driven per year and 5 usage years

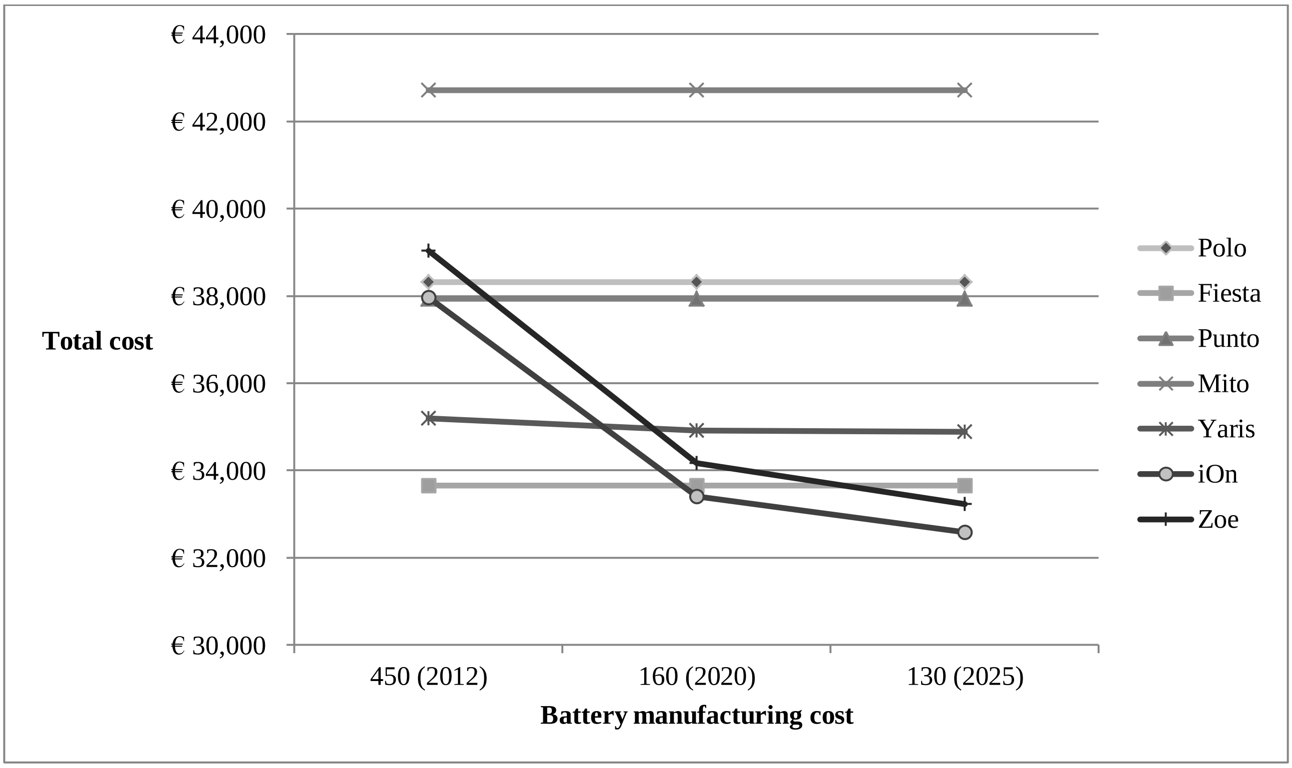

Figure 17 - Total cost with McKinsey battery manufacturing costs forecasts, given 10.000 kilometers driven per year and 10 usage years

As expected, the forecasted technological improvements would greatly improve BEVs (and slightly the Hybrid Toyota Yaris) competitive position.

5. Conclusion and policy implications

This paper estimates the total private and social cost of 7 cars, making use of the Italian data with reference to the vehicles' purchase and maintenance costs, fuel and electricity costs, energy mix and pollution costs.

Among the 7 cars compared, the diesel Ford Fiesta currently performs best from the private and social cost as well as energy consumption point of view.

From the social point of view, which includes greenhouse gas, local pollution and noise both the Toyota Yaris (Hybrid) and the Alfa R. MiTo (bi-fuel LPG) perform as well as the BEVs, and the absolute difference with the conventional fuel cars is quite small. Given the large number of cars, at city or nation level, however, these differences could make up to million euros.

Of course, the BEVs have their strong point in the zero emissions levels in the car use phase, where the health related costs of air pollution are presumably higher.

From an energy-saving point of view, with the current mix, the BEVs are the worst performing cars and the Toyota Yaris (Hybrid) is the best performing one.

The scenario analysis shows the following.

- Assuming that a car is kept 5 years, when 5,000 km per year are driven, the diesel Ford Fiesta is the cheapest choice, followed by the gasoline VW Polo. The BEVs are the most expensive. The Hybrid Toyota Yaris becomes the second cheapest car when about 9,000 km per year are driven. The BEVs improve their relative ranking (becoming third and fourth cheapest) when 15,000 or more km per year are driven.
- Assuming that a car is driven 10,000 km per year are driven, increasing the number of years that a car is kept makes the BEV Peugeot iOn more competitive, thanks to the lower operative costs: it becomes the forth cheapest car.
- Assuming that a car is kept 5 years, the subsidies enacted by the Italian government improves the relative ranking of the less polluting cars. The Hybrid Toyota Yaris overcomes the diesel Ford Fiesta as the cheapest cars when more than about 12,500 km are driven, with the BEVs becoming competitive when 20,000 km are driven. This trend is obviously reinforced when a car is kept 10 years.
- If gasoline and diesel prices are increased by 10% and 20%, the relative ranking does not drastically changed assuming that a car is kept 5 years, while the relative cost differences are rather altered when a car is kept 10 years.
- If, as forecasted by McKinsey, the battery costs decrease from the current 450 €/kWh to 160 €/kWh or to 130 €/kWh, the BEVs would become very competitive. If a car is kept 10 years, they would be the cheapest ones.

These results are focused on the financial aspects of a car choice, more specifically on the total (private + social) cost. Of course, they are by no means the only variables that determine the selection of a car: cultural factors, the car appearance and driving style being other important determinants. When the BEVs are considered, “range anxiety”, the use of the car as the first or second car, the existence of a (fast) charging infrastructure, potential favorable parking or access regulations together with environmental attitudes are known as further important co-determinants of the choice of a BEV, together with the financial factors.

The usual caveats about the data uncertainties about the emission factors, the energy content factors and, especially, the environmental cost factors do apply.

A further important caveat is that this analysis has dealt with 7 specific cars and cannot be easily generalized to all cars using the same fuel or powertrain, due to the very many engine sizes and different performances that do exist. This caveat applies specifically to the hybrid or electric vehicles where the actual configurations are rapidly changing and evolving.

Appendix 1 – The estimate of the private cost

Table 20 -

MODEL INPUTS	VALUE	DESCRIPTION
CAR PARAMETERS:		
VW Polo 1.4 Comfortline gasoline:		
Purchase price (€)	15,060	*www.quattroruote.it*
Horsepower	85	Equivalent to 62 KW. *www.quattroruote.it; Aci (2012)*

European Standard	5	*www.quattroruote.it*
Urban gasoline use (l/100km)	8	*www.quattroruote.it*
Interurban gasoline use (l/100km)	4,7	*www.quattroruote.it*
Mixed gasoline use (l/100km)	7,34	Value calculated considering fuel use and urban/interurban percentages of km driven.
CO2 emissions (gCO2/km)	139	Value referred to the Tank-To-Wheel stage. *www.quattroruote.it*
Ford Fiesta Ikon 1.4 TDCi diesel:		
Purchase price (€)	14,750	*www.quattroruote.it*
Horsepower	70	Equivalent to 51 KW. *www.quattroruote.it; Aci (2012)*
European Standard	5	*www.quattroruote.it*
Urban diesel use (l/100km)	5,3	*www.quattroruote.it*
Interurban diesel use (l/100km)	3,5	*www.quattroruote.it*
Mixed diesel use (l/100km)	4,94	Value calculated considering fuel use and urban/interurban percentages of km driven.
CO2 emissions (gCO2/km)	110	Value referred to the Tank-To-Wheel stage. *www.quattroruote.it*
Fiat Punto Natural Power 1.4 Easy bifuel (gasoline-CNG):		
Purchase price (€)	17,250	*www.quattroruote.it*
Horsepower	77	Equivalent to 57 KW. *www.quattroruote.it; Aci (2012)*
European Standard	5	*www.quattroruote.it*
Urban gasoline use (l/100km)	7,9	*www.quattroruote.it*
Interurban gasoline use (l/100km)	5,4	*www.quattroruote.it*
Mixed gasoline use (l/100km)	7,4	Value calculated considering fuel use and urban/interurban percentages of km driven.
Urban CNG use (kg/100km)	5,4	*www.metanoauto.com*
Interurban CNG use (kg/100km)	3,5	*www.metanoauto.com*
Mixed CNG use (kg/100km)	5	Value calculated considering fuel use and urban/interurban percentages of km driven.
CO2 emissions (gCO2/km)	149	Value referred to the Tank-To-Wheel stage. *www.quattroruote.it*
Alfa Romeo MiTo 1.4T Upload bifuel (gasoline-LPG):		
Purchase price (€)	20,600	*www.quattroruote.it*
Horsepower	120	Equivalent to 88 KW. *www.quattroruote.it; Aci (2012)*
European Standard	5	*www.quattroruote.it*
Urban gasoline use (l/100km)	8,5	*www.quattroruote.it*
Interurban gasoline use (l/100km)	5,2	*www.quattroruote.it*
Mixed gasoline use (l/100km)	7,84	Value calculated considering fuel use and urban/interurban percentages of km driven.
Urban LPG use (l/100km)	10,9	*www.alfaromeopress.com*
Interurban LPG use (l/100km)	6,8	*www.alfaromeopress.com*
Mixed LPG use (l/100km)	10,1	Value calculated considering fuel use and urban/interurban percentages

		of km driven.
CO2 emissions (gCO2/km)	145	Value referred to the Tank-To-Wheel stage. *www.quattroruote.it*
Toyota Yaris1.5 hybrid Lounge:		
Purchase price (€)	17,800	*www.quattroruote.it*
Horsepower	100	Equivalent to 74 KW. *www.quattroruote.it; Aci (2012)*
European Standard	5	*www.quattroruote.it*
Battery capacity (kWh)	0,936	*www.hybrid-sinergy.eu*
Urban gasoline use (l/100km)	3,5	*www.quattroruote.it*
Interurban gasoline use (l/100km)	3	*www.quattroruote.it*
Mixed gasoline use (l/100km)	3,4	Value calculated considering fuel use and urban/interurban percentages of km driven.
CO2 emissions (gCO2/km)	79	Value referred to the Tank-To-Wheel stage. *www.quattroruote.it*
Peugeot iOn full electric:		
Purchase price (€)	28,318	*www.quattroruote.it*
Horsepower	67	Equivalent to 49 KW. *www.quattroruote.it; Aci (2012)*
European Standard	Zero E.	*www.quattroruote.it*
Battery capacity (kWh)	16	*www.quattroruote.it*
Range (km)	150	*www.quattroruote.it*
Energy use (kWh/100km)	10,7	Value obtained dividing the battery capacity for the range and multiplying the result for 100. This value has been used for urban and interurban drives.
CO2 emissions (gCO2/km)	0	Value referred to the Tank-To-Wheel stage. *www.quattroruote.it*
Renault Zoe full electric with battery leasing:		
Purchase price (€)	21,650	*www.renault.it*
Horsepower	89	Equivalent to 65 KW. *www.renault.it; Aci (2012)*
European Standard	Zero E.	*www.renault.it*
Battery capacity (kWh)	22	*www.renault.it*
Range (km)	210	*www.renault.it*
Energy use (kWh/100km)	10,5	Value obtained dividing the battery capacity for the range and multiplying the result for 100. This value has been used for urban and interurban drives.
CO2 emissions (gCO2/km)	0	Value referred to the Tank-To-Wheel stage. *www.quattroruote.it*
SUBSIDIES FOR LESS POLLUTING CARS:		
2012 (€)	-	Subsidies are not available in Italy in 2012.
2013 (€)	20% of the purchase price	However the subsidies have a cap: Max 5,000€ if CO2 emissions <= 50 g/km; Max 4,000€ if CO2 emissions <= 95 g/km; Max 2,000€ if CO2 emissions <= 120g/km. *D. Lg n.83 22/06/2012, Art. 17-decies*
PV(AOC) - PRESENT VALUE OF ANNUAL OPERATING COSTS:		
Social rate of discount *r (%)*	5	Average discount rate applied in the following papers: *Anair et al., (2012); Lave et al., (2000); Ogden et al., (2004); Prud'homme et al., (2012); Thiel et al., (2010).*
Average insurance cost	715	Value referred to the Italian context in 2011. *Aci - Censis Servizi, (2011)*

(€/year)		
Average ordinary maintenance costs (€/year)	140	Value referred to the Italian context in 2011. For EVs a 50% reduction has been assumed. *Aci - Censis Servizi, (2011)*
Average extraordinary maintenance cost (€/year)	128	Value referred to the Italian context in 2011. For EVs a 50% reduction has been assumed. *Aci - Censis Servizi, (2011)*
Average yearly parking cost (€/year)	218	Value referred to the Italian context in 2011. It includes garage costs and parking fees). *Aci - Censis Servizi, (2011)*
CNGs road tax reduction (%)	75	Road tax is only the 25% of that required for a corresponding gasoline car. *Aci, (2012)*
LPGs road tax reduction (%)	75	Road tax is only the 25% of that required for a corresponding gasoline car. *Aci, (2012)*
EVs road tax reduction (%)	100	Total exemption for the first 5 years, after the same scheme for the above types has been applied. *Aci, (2012)*
HEVs road tax reduction (%)	0	No deductions. *Aci, (2012)*
Gasoline price (€/l)	1,843	Average value for the first semester of 2012. *Aci, (2012)*
Diesel price (€/l)	1,697	Average value for the first semester of 2012. *Aci, (2012)*
Compressed natural gas (CNG) price (€/kg)	0,919	Average value for the first semester of 2012. *Aci, (2012)*
Liquefied petroleum gas (LPG) price (€/l)	0,824	Average value for the first semester of 2012. *Aci, (2012)*
Electricity price (€/kWh)	0,182	Average value for the first semester of 2012. *http://www.autorita.energia.it*
Battery leasing fee (€/month)	79	Monthly fee referred to the Renault Zoe, assuming a 36 months leasing and 12,500 kilometers driven per year. *www.renault.it*
TtW_NC - NOISE COSTS:		
Full electric cars noise reduction (%)	20	Thanks to a limited full electric range, a small noise reduction has been assumed.
Hybrid cars noise reduction (%)	90	Because the electric motor operates quietly, we have considered only noise produced by wheels during the car use.
(NUC) Urban noise external cost (€/km)	0,0082	Average daily value, obtained assuming that 90% of travels are made during the day and 10% are made during the night. "*Handbook on estimation of external costs in the transport sector" (Maibach et al., 2008, p.73)*
(NIC) Interurban noise external cost (€/km)	0,0007	Average daily value considering suburban and rural travels, obtained assuming that 90% of travels are made during the day and 10% are made during the night. "*Handbook on estimation of external costs in the transport sector" (Maibach et al., 2008, p.73)*
ENERGY EFFICIENCY:		
Gasoline cars:		
WtT_ (kWh/km)	0,11	Value obtained transforming JRC results expressed in MJ/100km in kWh/km. Value refers to 2010. *JRC, (2008); www.convertitore-unità.info*
TtW_ (kWh/km)	0,49	Value obtained transforming JRC results expressed in MJ/100km in kWh/km. Value refers to 2010. *JRC, (2008); www.convertitore-unità.info*
Diesel cars:		
WtT_ (kWh/km)	0,08	Value obtained transforming JRC results expressed in MJ/100km in

		kWh/km. Value refers to 2010. *JRC, (2008); www.convertitore-unità.info*
TtW_ (kWh/km)	0,47	Value obtained transforming JRC results expressed in MJ/100km in kWh/km. Value refers to 2010. *JRC, (2008); www.convertitore-unità.info*
CNG cars:		
WtT_ (kWh/km)	0,103	Value obtained transforming JRC results expressed in MJ/100km in kWh/km. Value refers to 2010. *JRC, (2008); www.convertitore-unità.info*
TtW_ (kWh/km)	0,537	Value obtained transforming JRC results expressed in MJ/100km in kWh/km. Value refers to 2010. *JRC, (2008); www.convertitore-unità.info*
LPG cars:		
WtT_ (kWh/km)	0,06	Value obtained transforming JRC results expressed in MJ/100km in kWh/km. Value refers to 2010. *JRC, (2008); www.convertitore-unità.info*
TtW_ (kWh/km)	0,53	Value obtained transforming JRC results expressed in MJ/100km in kWh/km. Value refers to 2010. *JRC, (2008); www.convertitore-unità.info*
Hybrid cars:		
WtT_ (kWh/km)	0,07	Value obtained transforming JRC results expressed in MJ/100km in kWh/km. Value refers to 2010. *JRC, (2008); www.convertitore-unità.info*
TtW_ (kWh/km)	0,32	Value obtained transforming JRC results expressed in MJ/100km in kWh/km. Value refers to 2010. *JRC, (2008); www.convertitore-unità.info*
Full electric cars:		
WtT_ (kWh/km)	0,16	*Enel S.p.A, (2010)*
TtW_ (kWh/km)	0,16	*Enel S.p.A, (2010)*
BATTERY MANUFACTURING COSTS FORECASTS:		
2012 (€/kWh)	450	Value referred to lithium-ion batteries. *McKinsey, 2012*
2020 (€/kWh)	160	Value referred to lithium-ion batteries. *McKinsey, 2012*
2025 (€/kWh)	130	Value referred to lithium-ion batteries. *McKinsey, 2012*

Appendix 2 – The air emissions of the Italian 2010 energy mix

The aim is to estimate the air emissions resulting in Italy in 2010 from the production of electricity with the Italian energy mix. Such emission coefficients will be used to assess the contribution of electricity using vehicles to air pollution.

The air pollutants emission factors of the different power plants used in our estimate are presented in Table 21.

Table 21 - Emission factors for electricity generation for the different power plants

Fuel	carbon dioxide	sulphur oxides	nitrogen oxides	
Coal	2249.00	13.00	6.00	lbs/MwH
	283.37	1.64	0.76	g/Mj
Natural gas	1135.00	0.10	1.70	lbs/MwH
	143.01	0.01	0.21	g/Mj
Oil	1672.00	12.00	4.00	lbs/MwH
	210.67	1.51	0.50	g/Mj
Nuclear energy	0.00	0.00	0.00	lbs/MwH
	0.00	0.00	0.00	g/Mj
Municipal Solid Waste	2988.00	0.80	5.40	lbs/MwH
	376.48	0.10	0.68	g/Mj
Hydro and non-Hydro renewable source	0.00	0.00	0.00	lbs/MwH
	0.00	0.00	0.00	g/Mj

Source: http://www.epa.gov/cleanenergy/energy-and-you/affect/air-emissions.html

The emissions factors calculated in Table 21 have been used to estimate the average emission per pollutant per Mega-Joule of energy produced with the 2007 and 2010 EU energy mixes and the 2010 Italian energy mix (Table 22).

Table 22 - Average emission per pollutant per Mega-Joule of energy produced

	EU mix-2007*	CO2	SOx	NOx	EU mix-2010**	CO2	SOx	NOx	Italian mix 2010	CO2	SOx	NOx
Coal	0,30	85,01	0,49	0,23	0,28	79,34	0,46	0,21	0,11	30,60	0,18	0,08
Natural gas	0,21	30,03	0,00	0,04	0,25	35,75	0,00	0,05	0,45	64,21	0,01	0,10
Oil	0,07	14,75	0,11	0,04	0,02	4,21	0,03	0,01	0,07	14,75	0,11	0,04
Nuclear energy	0,17	0,00	0,00	0,00	0,27	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Municipal Solid Waste	0,01	3,76	0,00	0,01	0,00	0,00	0,00	0,00	0,03	10,17	0,00	0,02
Hydro and non-Hydro renewable source	0,24	0,00	0,00	0,00	0,18	0,00	0,00	0,00	0,21	0,00	0,00	0,00
Foreign imports									0,14	16,11	0,07	0,04
	1,00	133,55	0,60	0,31	1,00	119,31	0,49	0,28	1,00	135,83	0,36	0,27

*Zervos and Kjaer (2009)

**Torchio and Santarelli (2010, p. 4161)

*** GSE (2010)

The 2010 Italian average emission per pollutant per Mega-Joule of energy produced are then used to estimate the air pollution of the energy consuming vehicles.

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