A sustainability assessment of electric vehicles as a personal mobility system

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Abstract

This paper presents a study of the economic and environmental balances for Electric Vehicles (EVs) versus Internal Combustion Engine Vehicles (ICEVs). The analyses were based on the Well-to-Wheel (WTW) methodology, a specific type of Life Cycle Assessment (LCA). WTW balances were carried out taking into account different scenarios for the primary energy supply and different vehicle technologies. The primary energy supply includes non-renewable sources (fossil fuels and nuclear) and Renewable Energy Sources (RESs). Vehicle technologies include Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs) and Plug-in Hybrid Electric Vehicles (PHEVs). The generation scenarios considered in the study include the present European Union (EU) average mix and a planned increasing contribution from RESs. For the BEV, several real world driving cycle scenarios were investigated, using a custom built data acquisition system, in order to characterize the main factors that contribute to the overall energy consumption, associated cost and emissions. In terms of environmental impact, for the average EU electricity mix, BEVs have less than a half of the emissions than an ICEV. However, the ownership costs during its life cycle (about ten years) are similar to an equivalent ICEV, despite the lower operational costs for BEVs. The likely battery price reduction, leading to a lower investment cost, will gradually tip the balance in favour of EVs.

Keywords: Electric Vehicles, Hybrid Vehicles, Greenhouse Gas Emissions, Well-to-Wheel Balances, Ownership Cost.

1. Introduction

The overall transportation sector is responsible for 30% of all fossil fuel emissions in the EU [1]. With the increasing cost of energy and climate change constraints leading to pressure to mitigate GHG emissions, the automotive industry is one of the sectors that shows major investments in R&D, in order to reduce emissions and the dependence from fossil fuels. Alternatives fuels like

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biofuels, produced in a sustainable way, and electrified vehicles, used in increasing numbers, are seen as a possible solution [2] [3] [4].

Powertrain electrification has been advocated for decades, as an alternative for ICEVs, due to zero tailpipe emissions and higher efficiency, by using an electric motor instead of an Internal Combustion Engine (ICE). Typical ICE efficiency is 28-30% while electric motors achieve 85-95% [5]. The main obstacle for the mass adoption of EVs has been the battery, due to the low energy density capability, limiting the vehicle range. Advances in battery technology over the last decades namely the lithium-Ion technology, led to the viability of mass manufacturing of EVs.

Electric vehicles can be classified, based on their design, as [5] [6] [7]:

- Series or Parallel HEVs, powered by an electric motor and a ICE, both connected to the wheels via a torque coupler and supplementing each other when needed.
- Series or Parallel PHEVs, which have a small battery that provides a range between 30-80 *km*. When the battery is depleted the drive system uses an ICE as a range extender. PHEVs are an evolution of the HEVs and could be plugged in to the grid to charge the batteries, increasing the fuel efficiency.
- Full BEVs powered only by an electric motor and with a larger battery, providing a range up to 450 *km*.

Despite the improvements in battery technology, BEVs at the moment are still unable to reach the range of ICEVs. This may cause range anxiety, associated to the fact that the car takes from thirty minutes,in fast-charge mode, to several hours, in slow charge mode to achieve full charge. While the ICEVs takes a few minutes to fill up the tank. Since HEVs and PHEVs share the characteristics of a BEV and ICEV, range anxiety is eliminated.

The PHEVs and BEVs energy saving potential needs to be assessed in order to identify the advantages of the different technologies and where efficiency could be improved. The WTW studies intends to evaluate the amount of energy given at the vehicle wheels related with the amount of energy captured form the source, taking into account the steps covered by the Well-to-Tank (WTT) and by Tank-to-Wheel (TTW) energy conversion.

2. The Road Transport System in Europe: Vehicle and Crude Oil Processing Emissions and Fleet Evolution

2.1. Vehicles CO_2 Emissions

Road transport in EU is responsible for near 20% of all Carbon Dioxide (CO_2) emissions, with passenger cars contributing with 12%. The target fixed by Kyoto Protocol was an 8% reduction of emissions in all sectors compared to 1990 levels by 2008-2012. Relative CO_2 emissions from transport have risen rapidly in recent years, from 21% of the total emissions in 1990 to 28% in 2004 [1] and EU transport emissions currently contribute with 3.5% of the global CO_2 emissions. The emissions standards define the acceptable limits for exhaust emissions from new vehicles and are defined in directives staging the progressive introduction of increasingly stringent standards.

To reduce these emissions, EU proposes:

- A legislative framework to reduce CO_2 emissions from new vehicles. This will provide the car industry with sufficient lead time and regulatory certainty.

- Average emissions from new vehicles sold in the EU would be required to reach the 120 gCO_2/km target by 2012. No more than 130 gCO_2/km based on improvements in vehicle technology and an additional cut up to 10 gCO_2/km for complementary measures (improvements for car components with the highest impact on fuel consumption: air conditioning system, tires, carbon content of fuel, use of biofuels). Efficiency requirements will be introduced for these car components.

- For vans, the fleet average emission targets would be 175 gCO_2/km by 2012 and 160 gCO_2/km by 2015, compared with 201 gCO_2/km in 2002.

- Support for research efforts aimed at further reducing emissions from new cars to an average of 95 gCO_2/km by 2020.

- Measures to promote the purchase of fuel-efficient vehicles, notably through improved labeling and by encouraging taxes based on vehicles CO_2 emissions.

- An EU code of good practice on car marketing and advertising to promote more sustainable patterns.

These regulations are only to CO_2 emissions while other Greenhouse Gases (GHGs) are not regulated.

2.2. GHG Emissions from Crude Oil Extraction and Refining

The International Energy Agency (IEA) predicted that global crude oil consumption will increase 27% during the next two decades, from 83 MMbbl/d (million barrels of oil per day), in 2009, to 102 MMbbl/d, in 2030. Crude oil extraction, transport and refining, accounts in average, for about 18% of WTW of GHG emissions [8]. The quantification of the WTW emissions is divided in five components associated with the petroleum production: i) extraction, ii) flaring and venting, iii) fugitive emissions, iv) crude oil transport and v) refining.

In Europe the crude oil comes from a large number of oil fields around the world and each of them has specific GHG emissions, depending on the type. The carbon intensity of crude oil ranges from 4 to 50 gCO_{2e}/MJ (grams of CO_2-equivalent per megajoule), with an average of 13±2 gCO_{2e}/MJ (Figure 1).

Additional emissions from fuel combustion in motor vehicles are about 73 gCO_{2e}/MJ ($\approx$152 gCO_{2e}/km, for gasoline with 34.8 MJ/l and a consumption of 6 $l/100km$). In 2009, 13 MMbbl/d of crude oil where imported to Europe, which can be divided in three categories based on extraction to refining GHG emissions per unit of energy: 6 MMbbl/d with 4-9 g CO_{2e}/MJ (associated with low flaring of natural gas, minimal fugitive emissions, etc); 6.4 MMbbl/d with 9-19 gCO_{2e}/MJ (associated with substantial flaring and fugitive emissions) and 0.3 MMbbl/d with 19-50 gCO_{2e}/MJ (associated with substantial flaring and/or exploration of tar sands) (Fig.1) [8]. Flaring contributes to GHG emissions through the release of CO_2 during combustion and throw the presence of methane in unburned gas when the combustion is less than 100%.

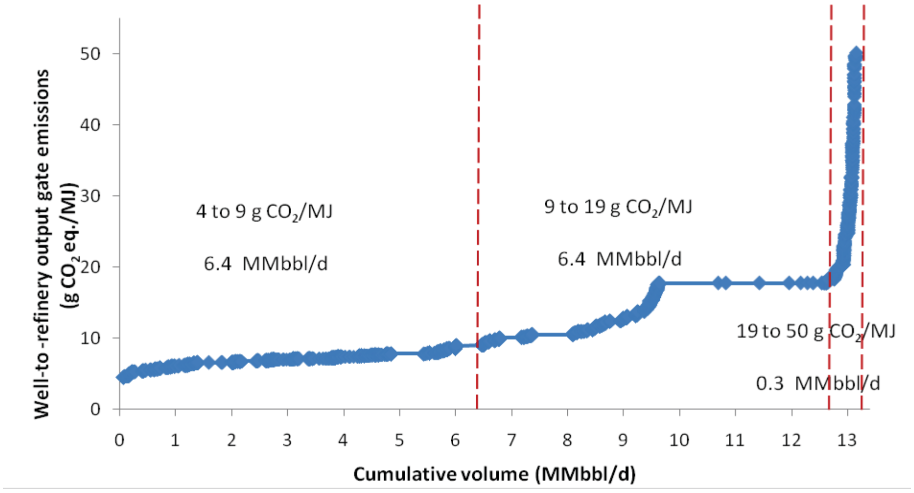

Figure 1: Extraction to refining GHG emissions associated with imported crude oil [8].

Methane has a global warming potential 25 times higher than CO_2. Extraction of crude oil from tar sands, a very energy intensive process, contributing to high GHG emissions and the IEA projects that 8% (8.9 MMbbl/d) of the world crude oil will come from this source in 2035 [9].

2.3. Vehicle Fleet

Today, powertrain electrification is more expensive, when compared with ICE technology, mainly due to the cost of the batteries, with a price of 400-600 €/kWh in 2010. However, due to mass production, is expected that the price per kWh to fall 25-65% over the next 5-10 years [10] [11]. Depending on the vehicle architecture the battery requirements will vary. A PHEV will typically require a battery capacity of 8-16 kWh for a 40-80 km range, since it has a ICE to power a generator, while a BEV will require a battery capacity of 24 kWh for a 160 km range, still far from the range of an ICEV but enough to commute daily.

Due to improvements over the past decade, mainly in diesel engine efficiency, in 2010 the average CO_2/km emissions for new vehicles were 140.3 gCO_2/km, a reduction of 5.4 gCO_2/km since 2009 and 31.9 gCO_2/km since 2000.

Diesel vehicles represent 51.3% of the vehicle fleet, an increase of 20.3% since 2000. The share of Alternative Fuel Vehicles (AFVs), including EVs, also increased from 0.1% in 2000 to 3.5% in 2010 [12]. In 2010, from the 13 million new vehicle registrations, 61.6% of the vehicles emit less than 140 gCO_2/km, 29.7% emit between 101-120 gCO_2/km and 2.9% emit less than 100 gCO_2/km (Figure 2).

To compare the different technologies, a vehicle representative of each category was considered, based on the market relevance and with the best technology available. Since 2008, the top selling vehicle in Europe is the Volkswagen Golf and is used to characterize the common diesel and gasoline ICEV. HEV, PHEV and BEV are represented by the Toyota Prius, Chevrolet Volt and Nissan Leaf respectively. The vehicles purchase cost was based on the average price for each vehicle in the European market and in manufacturer data [13] (Table 1). For ICEVs the emissions data was obtained from the vehicle manufacturer. Vehicle emissions must comply with the existing

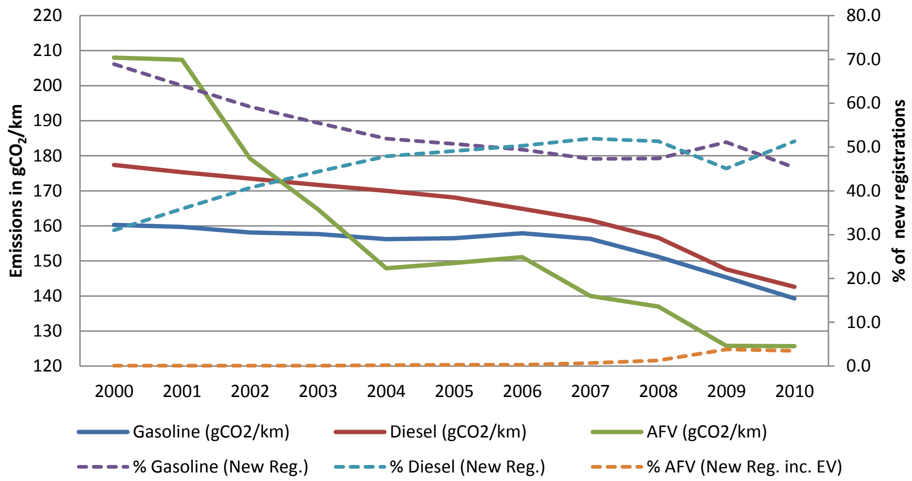

Figure 2: CO_2 emissions and fuel type share, for new vehicles registrations in EU [12].

emissions standards and are calculated using Government approved drive cycles (e.g. New European Drive Cycle (NEDC) in EU, Federal Test Procedure 75 (FTP-75) and Supplemental Federal Test Procedures (SFTP) in United States).

To access the impact of a vehicle in terms of emissions, the manufacturing, use and recycling phase should be take into account. In terms of structure, ICEs and EVs share similar basis, such as chassis and the body. On the other hand, BEVs neither need a fuel tank, exhaust system and catalyst and the five or six speed gearbox is normally replaced by a single speed [14].

Several LCA studies show that the environmental impacts of vehicles are dominated by the operation phase regardless of whether a gasoline fueled ICEV or an electricity fueled BEV is used, being the gasoline vehicle the one with the higher environmental burden. BEV and ICEVs have a similar global warming potential during the manufacturing phase around 2.5 $MT\ CO_{2e}$, not considering the battery production. The share of the total environmental impact of electric mobility caused by the battery is 15% [15]. The battery is among the most critical components, in terms of emissions, due to the necessary materials needed for manufacturing, such as Lithium, Copper and Aluminum. According to [16], 10 $kWh\ LiFePO_4$ batteries used in PHEVs, tend to have a higher impact in the manufacturing phase than in use phase, for a electricity mix dominated by renewable sources. Depending on the manufacturing process of the Lithium-Ion battery, the emissions could go from 1.7 $MT\ CO_{2e}$ to 2.7 $MT\ CO_{2e}$ per battery.

3. Energy Losses in Electric Vehicles

In EVs the main energy losses occur at three main subsystems. At the Energy Storage System (ESS), the fuel tank equivalent in a EV; at the Powertrain (PT), the group of components that generate power and deliver it to the wheels, and at the Power Electronics Module (PEM), responsible for the motor control, charging and regenerative braking [17] [18].

Table 1: Characteristics from the representative vehicles considered for each category.

	ICEV				
	Diesel	Gasoline	HEV	PHEV	BEV
Cost (€)	22200	20300	25000	42000	35000
Deductions (€)	-	-	-	-	5000
Emissions (gCO_2/km)	118	144	88	37	0
Consumption ($l/100km$)	4.2	6.2	3.8	6.4	0
Combustion Engine	1.6l	1.4l	1.8l	1.4l	-
Electric Motor (kW)	-	-	30	111	80
Battery Capacity (kWh)	-	-	1.3	16	24
Battery Weight (kg)	-	-	53.3	197	300
Battery Type	-	-	NiMH	Li-Ion	Li-Ion
Range (km)	700+	700+	700+	580 (80EV + 500ER)	160
Curb Weight (kg)	1240	1290	1370	1715	1521

Note: For PHEV the fuel consumption is given for gasoline consumption only.

3.0.1. Energy Storage System (ESS)

The ESS is nowadays constituted by batteries, available in several chemistries, and also by Supercapacitors. The electronics used for the ESS monitorization (temperature, voltage, current etc) and control are also part of the ESS. 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. The batteries used in EVs are deep cycle batteries, with an energy capacity normally in the range of 10-40 kWh and with an efficiency of about 70%-95% [19]. Lithium-Ion batteries are the most common in EVs because they have a specific energy up to 300 Wh/kg and a high specific power (up to 10 kW/kg). For comparison Lead-acid batteries have a specific energy density between 20 and 30 Wh/kg and a specific power up to 400 W/kg [20]. One disadvantage of the batteries is their internal resistance, which increases both with cycling and age. This parameter will cause a voltage drop under load and reduces the maximum current draw and affects the charge/discharge rate. Typically is in the order of milliohms and this reduction is observed by heat generation [21] [22] [23] [24].

3.0.2. Powertrain (PT)

The powertrain refers to a group of components that generate mechanical power and deliver it to the road, and include the ICE or/and electric motor, transmission, drive shaft, differential and drive wheels.

For ICEVs, diesel engines are more common in Europe than gasoline, due to their higher fuel efficiency, and the most sophisticated ones achieve an efficiency of about 35-40% in the ideal speed range, declining beyond this speed. Gasoline engines have an efficiency 18% to 25%, meaning that around 80% of available energy is lost as heat.

In EVs, the most common types of electric motors are permanent magnet motors and Alternate Current (AC) induction motors. When compared with internal combustion engines the use of electrical motors leads to an increase of efficiency. Depending of the type of the electric motor the efficiency can go from 85% up to 95% [25].

The difference between mechanical output and electrical power input is due to four different kinds of losses: electrical losses, magnetic losses, mechanical and stray losses. The electrical losses, also known as Joule losses, are expressed by I^2R, and consequently increase with the motor load. Electrical losses appear as heat generated by the electric current flowing through conductors. Magnetic losses occur in the steel laminations of the stator and rotor, due to hysteresis and Eddy currents. Mechanical losses are due to friction in the bearings, ventilation and windage losses. Stray load losses are due to leakage flux, harmonics of the air gap flux density, non-uniform and inter-bar currents distribution, mechanical imperfections in the air gap and irregularities in the air gap flux density. In permanent magnet motors the overall weight and volume can be significantly reduced, for a given torque, resulting in a higher torque to weight ratio, because of the absence of rotor winding and rotor losses, leading to a higher efficiency [26] [27].

In the drivetrain, responsible to transmit the torque generated by the engine/motor to the road, the primary loss sources are the differential and final drive, with further losses stemming from within the transmission. Within the transmission of an ICEV, as much as 30% to 40% of power loss can be attributed to the oil pump, with the clutch contributing another 20% to 25%. The rest of the loss within the transmission comes from gear meshing, bearings, bushings and drag on the gears caused by the gear oil. Differential losses tend to be considerably larger, especially in the case of rear and all-wheel drive vehicles where the torque path is turned 90° as it enters the rear differential and exits toward the wheels. In the case of hypoid-type gears (where the gear tooth profile is both curved and oblique), commonly used in rear wheel drive differentials, losses are usually 6% to 10%, while losses from the drive shaft are 0.5% to 1% of total losses [28] [29].

The gear-less or single gear design used in some EVs eliminates the need for gear shifting, giving to the vehicle a smoother acceleration and braking, the power is delivered directly through the main-shaft of the transmission, so the only loss sources are windage, friction and drag, resulting in total at-the-wheel losses as low as 1.5% to 2%.

3.0.3. Power Electronics Module (PEM)

The PEM controls motor torque, battery charging, regenerative braking, and it monitors things like the voltage delivered by the energy storage system, the speed of rotation of the motor, and the temperatures of the motor and power electronics.

In most commercial HEV systems, the power converter is a bidirectional converter plus an inverter. The DC-DC converter interfaces the battery and the inverter with variable DC bus voltages, so that the inverter can always operate at its optimum operating point. Other component to be taken into account, both for PHEVs and BEVs efficiency, is the charger typically with 91-94%

efficiency.

The WTW analysis can be broken down in two stages entitled WTT and TTW. The WTT stage, also called upstream stage, incorporates the feedstock or fuel production/extraction and processing/conversion to final energy, as well as fuel or electricity delivery to the vehicle. The TTW stage, also called downstream stage, deals with vehicle operation itself. The WTW analysis is used to assess the total energy consumption and the associated emissions for the whole fuel cycle, including their carbon footprint, for motor vehicles.

Table 2 and Table 3 summarize the efficiency of each systems along the energy path to power an EV. WTT and TTW global efficiency was calculated using (1) and (2). The electrical values for the WTT efficiency is used to access the power loss from the production to the consumer and determine the real energy required to fully charge a battery, and associated emissions based on the electricity generation mix.

Table 2: WTT system efficiency for the electric powertrain, considering the transmission and distribution losses in a power system network, using a fast charger (L1) and a standard charger (L2), with Lithium-Ion batteries as energy storage

	Efficiency (%)	
	Min.	Max.
Transmission	98	99
Distribution	91	93
Charger (L1)	95	97
Charger (L2)	91	94
Global (w/L1)	84.7	89.3
Global (w/L2)	81.1	86.5

Table 3: TTW system efficiency for the electric powertrain, with Lithium-Ion batteries as energy storage

	Efficiency (%)	
	Min.	Max.
Battery	93	99
Inverter	90	98
Electric Motor	85	96
Drivetrain	87	93
Global	61.9	86.6

The emissions from electricity generation mix is calculated based on the production share of each type of power plant (Table 5) and fuel used in them (Table 4) during the year.

$$\eta_{WTT} = \eta_{trans.} \cdot \eta_{dist.} \cdot \eta_{charger} \tag{1}$$

$$\eta_{TTW} = \eta_{batt.} \cdot \eta_{inv.} \cdot \eta_{electricMotor} \cdot \eta_{trans.} \tag{2}$$

4. Electricity Generation and CO_2 Emissions

To correctly assess the sustainability of an EV based mobility system, the way electric energy is generated is an important factor. Almost all electrical generation technologies apply the principle of electromagnetic induction, in which mechanical energy, mainly provided by a turbine, forces an electrical generator to rotate. Turbines are driven directly by a fluid which can be water or by gases produced from burning fuel to boil water using coal, natural gas or oil. The process of generating electric energy can be achieved by several ways, each one with their own environmental impact depending from the energy source. Electricity generation based on a RES, such as hydro, sun or wind, have near zero GHG emissions, while generation based on a fossil source, such as coal or fuel oil, have the highest GHG emissions. Despite nuclear and RES based electricity generation stages not causing any GHG emissions during operation phase, they are not a zero emissions energy source. The upstream supply stage, power plant construction and decommissioning require energy involving indirect emissions. Nuclear energy has an estimated emissions of 10-130 gCO_{2e}/kWh, wind and hydro 10-25 gCO_{2e}/kWh, solar photovoltaic 30-100 gCO_{2e}/kWh and fossil 600-1200 gCO_{2e}/kWh [30] [31] [32] [33]. On Table 4 are presented the emissions associated with the fuel burning while on Table 5 are presented the emissions per unit of energy by power plant energy source.

Table 4: *GHG* emissions by fuel type. [34]

	Pollutant (g/GJ)				
Fuel	CO_2	SO_2	NOx	CO	PM
Hard coal	94600	765	292	89.1	1203
Brown coal	101000	1361	183	89.1	3254
Fuel oil	77400	1350	195	15.7	16
Other oils	74100	228	129	15.7	1.91
Gas	56100	0.68	93.3	14.5	0.1

The use of RESs is seen as a key element to reduce the dependence from fossil fuels and GHG emissions [38] [4] [39]. Over the past decade, EU has invested heavily in order to increase the share of RES to electricity generation and contributing directly to the reduction of CO_2 emissions

Table 5: *GHG* emissions, per unit of energy, by power plant energy source.

		Pollutant (g/kWh)		
Fuel Type	Plant Efficiency (%)	CO_2	SO_2	NO_x
Coal	37 (36-43)	916	9.3	3
Fuel Oil	37 (23-43)	777	3.1	2.1
Natural Gas (CCGT)	58 (55-60)	354	0	0.9
Hydro	87 (85-90)	12	0.04	0.04
Wind	37 (35-40)	10	0.02	0.02
PV	15 (12-18)	90	0.28	0.03

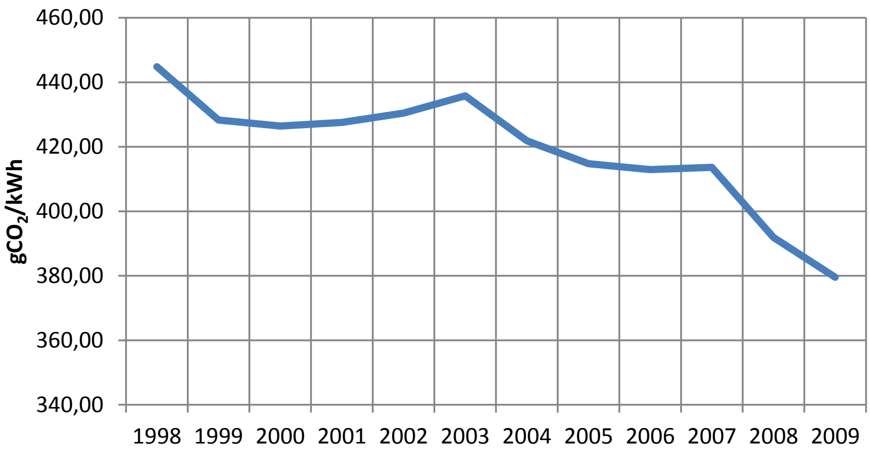

Figure 3: CO_2 emissions per unit of energy associated to electricity generation, in EU [35] [36].

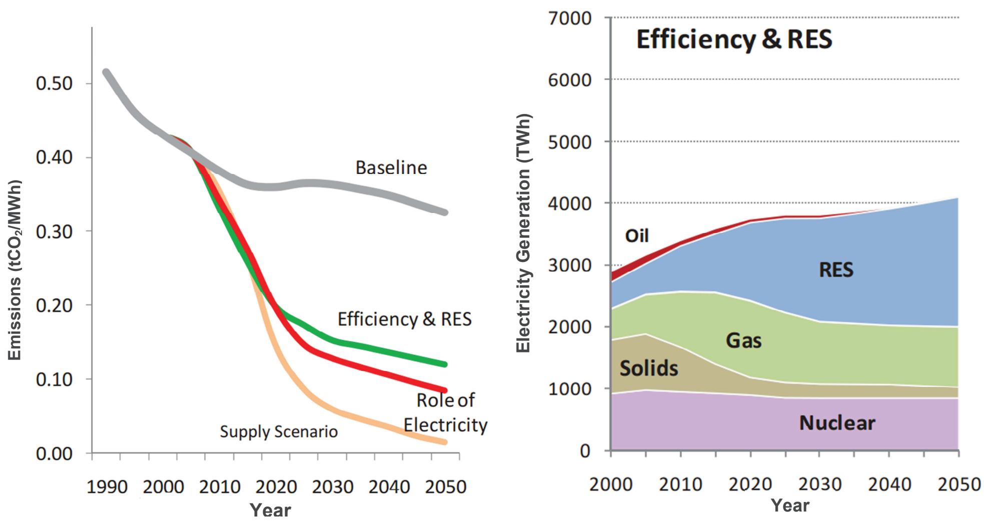

Figure 4: Projected CO_2 emissions per unit of energy (left) and fuel source share associated to electricity generation (right) in a Efficiency and RES scenario in EU until 2050. The Baseline scenario represents a non sustainable future in terms of environmental impact [37].

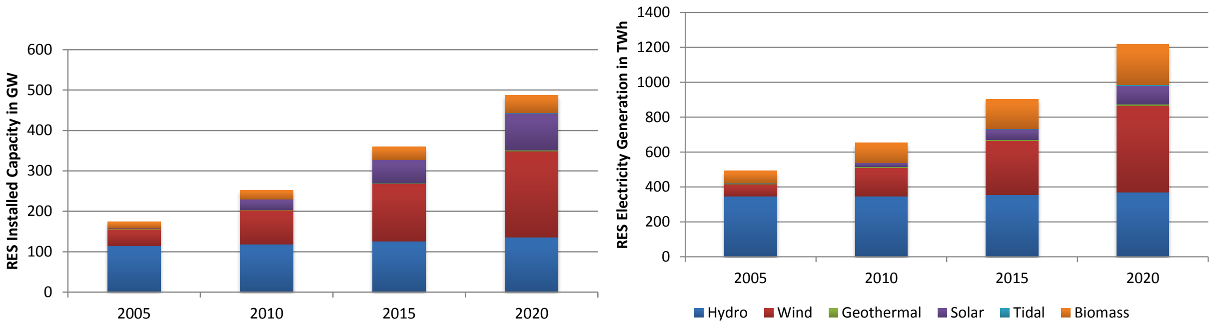

Figure 5: Projected evolution of RES installed capacity (top) and electricity generation (bottom) in EU [40].

(Figure 3). In 2020 a 20% share of renewable energy is expected, contributing, also with others measures such as the increasing of energy efficiency, to achieve a reduction of 20% of GHG emissions (compared with 1990 levels) (Figure 4). It also should be noted that the reductions on CO_2 emissions are not only due to the investment in RES, but also associated with fluctuating weather conditions, namely strong precipitation and wind, contributing to a bigger hydroelectric and wind contributions to electricity generation.

4.1. Expected Contribution of RES Over the Next Decade

Over the next years in EU, the investment in RES for electricity generation will continue in order to reduce the dependency from fossil sources, going from a 19% share in 2010 to 25% in 2015 and 31% in 2020 in a reference scenario. In a scenario with increased efficiency is estimated that renewable energy sources contribute with 26% in 2015 and 34% in 2020 [40]. A contribution of nearly 40% is also considered realistic. Projections estimate that RES contribution, considering 2010 as reference year with 652.4 TWh, will increase to 901.9 TWh by 2015 (38.2%) and to 1216 TWh by 2020 (86.5%).

Solar, wind and wave energy sources will be ones with the highest growth, from 2010 to 2020, in terms of installed capacity (250% for solar, 151% for wind, 950% for wave, 100% for geothermal, 92% for biomass and 15% for hydro). However, wind and hydro will continue to be the renewable energy source with the highest share, both in terms of installed capacity and electricity generation (370.1 TWh for wind, 494.6 TWh for hydro, 231 TWh for biomass, 103.3 TWh for solar, 10.9 TWh geothermal and 6 TWh for tidal) (Figure 5) [40].

This increase in the contribution of RES alone to the total electricity generation, with 30-40% by 2020, will lead to a reduction in the electricity mix emissions of 14-66 gCO_2/kWh, when compared with 2009 values, to 312-364 gCO_2/kWh. Additional efficiency measures will lead to additional reductions in CO_2 emissions from electricity generation.

5. Ownership Cost and Associated Emissions

The ownership cost for each type of vehicle was taken into account, to provide a basis for determining the economic value of the investment, accounting purchase and operational costs as well depreciation cost (25% in the first year and 10% in the following years) were considered. The operational cost, per year, was calculated based on a total driven distance of 15000 km and the average fuel prices for EU in 2011 (1.35 and 1.48 € for diesel and gasoline respectively), and for the electric vehicles, was considered the average EU electricity rate of 0.16 $€/kWh$ [41]. It should be noted that in certain countries, such as Portugal, the customer can choose from a plan where the electricity cost varies with the time of day. In Portugal during the day the electricity cost is 0.14 $€/kWh$ while at night is 0.077 $€/kWh$, which translate to a reduction of 50% in the electricity cost per year if the EV is charged at night.

$$\eta_{cost} = \eta_{trans.} \cdot \eta_{dist.} \cdot \eta_{charger} \tag{3}$$

An inflation rate of $2.5\%/year$ was also considered. The use scenario considered for the PHEV, was 85% in electric mode (use during the week for commute) and 15% in range extended mode (longer trips, for instance at the weekends). Insurance, maintenance, repairs and taxes (referenced as MRT), were also considered, based on the typical insurance and maintenance rate for each vehicle, and are summarized on Table 6. For the case of the BEV an average incentive of 5000 €, applied in several EU member states, was also considered. This incentive for early adopters is expected to end in the following years, however the BEVs price reduction due to mass market will compensate it. The MRT cost for ICEVs and HEV was considered the same, since all of them have a combustion engine working all the time, needing oil and filters replacement. BEVs have the lower MRT cost since they don't need fuel filters replacement or oil changes, PHEVs have a slightly higher cost due to oil and filters replacement, however much less frequent than ICEVs.

In terms of environmental impact, fuel extraction and refining emissions were considered and added to the emissions related with diesel or gasoline used to operate the vehicle. For PHEVs and BEVs, WTT overall efficiency was considered to calculate the real energy generated to fully charge the batteries. The battery replacement for EVs was not considered, since current Lithium-Ion batteries manufacturers assure a 70-80% capacity after eight years to ten years, which is practically the life cycle of a vehicle.

The ICE emissions were calculated using (4), taking into account the emissions from fuel burning, extraction and refining. EV emissions were calculated using (5), taking into account the average EU electricity mix for 2009, with an average value of 378 gCO_2/kWh. The Portuguese electricity mix (365 gCO_2/kWh), with approximately 35-40% from renewable energy sources, and the French electricity mix (78 gCO_2/kWh), with a contribution mainly from nuclear, were also included to demonstrate the effect of electricity mixes in the emissions. For the EVs emissions, WTT efficiency, from Table 2, was also considered to calculate the total energy used to fully charge the battery. On Table 7 is presented the environmental impact for the considered vehicles, while on Table 8 is presented the projected environmental impact for EVs taking into account the evolution of the electricity generation scenario.

$$E_{ICE} = \frac{D \times C}{100} \times (e_{burn} + e_{ref}) \tag{4}$$

Table 6: 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 five and ten years are also presented. The calculation was based on driving 15000 $km/year$ 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					
	Diesel	Gasoline	HEV	PHEV	BEV	Future BEV
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 5^{th} year						
Ownership (€)	7096	9861	7059	5239	3841	3841
Depreciation (€)	11276	10311	12698	21333	17777	12698
TCO (€)	18372	20172	19757	26572	21618	16539
After 10^{th} year						
Ownership (€)	15125	21018	15046	11166	8186	8186
Depreciation (€)	15749	14402	17735	29796	24830	17735
TCO (€)	30874	35420	32781	40962	33016	25921

Table 7: Emissions for the considered vehicle technology, driving 15000 $km/year$ and for three different generation scenarios. The PHEV and BEV emissions, due to electricity generation, were calculated taking into account the electricity generation mix and WTT efficiency.

	Emissions ($MT\ CO_2$/year)				
	ICEV				
2009 Electricity Mix	Diesel	Gasoline	HEV	PHEV	BEV
EU (378 gCO_2/kWh)	2.0	2.58	1.8	0.46+1.15	1.02
Portugal (365 gCO_2/kWh)	2.0	2.58	1.8	0.46+1.11	0.98
France (78 gCO_2/kWh)	2.0	2.58	1.8	0.46+0.24	0.21

Note: For PHEV the emissions are divided in fuel burning and electricity generation emissions.

Table 8: Estimated emissions for the considered vehicle technology considering the evolution of the generation scenario presented in Figure 4 and the regulated emissions for ICEVs vehicles, driving 15000 km/year.

	Emissions ($MT\ CO_2$/year)				
	ICEV				
EU Electricity Mix	Diesel	Gasoline	HEV	PHEV	BEV
2010 (360 gCO_2/kWh)	2.0	2.58	1.8	0.46+1.15	1.01
2020 (230 gCO_2/kWh)	1.66	2.29	1.8	0.46+0.73	0.65
2030 (160 gCO_2/kWh)	1.66	2.29	1.8	0.46+0.51	0.45
2040 (150 gCO_2/kWh)	1.66	2.29	1.8	0.46+0.48	0.42
2050 (135 gCO_2/kWh)	1.66	2.29	1.8	0.46+0.43	0.38

Note: For PHEV the emissions are divided in fuel burning and electricity generation emissions. For ICEVs, after 2020, was considered a 95 gCO_2/km for diesel and 127 gCO_2/km for gasoline.

$$E_{EV} = \frac{D}{12} \times \frac{\frac{E_{batt}}{\eta_{wtt}}}{R} \times e_{mix} \tag{5}$$

Where D, is the total distance traveled in a year, in km; C is the vehicle fuel consumption, in $l/100km$; e_{burn} and e_{ref} are the emissions associated to fuel burning, extraction and refining respectively, in gCO_2/l; E_{batt} and R are the EV battery capacity, in kWh, and the respective range, in km; e_{mix} are the average emissions, in gCO_2/kWh, for the electricity mix.

It should be noted that these results take into account average values for the European market leading to uncertainties. Costs associated to the ownership and depreciation of the vehicle are very brand and market dependent. The fossil fuel prices are affected by a number of factors, not only by the inflation considered over the life time of the vehicle, resulting in a higher cost per year for fuel to ICEVs and consequently a higher Total Costs of Ownership (TCO). An higher total cost of ownership for ICEVs due to higher fuel prices, will reduce the number of years that an PHEV or BEV needs to equalize the investment when compared with a ICEV.

Analyzing the ownership cost and depreciation after five years (Table 6), depreciation is by

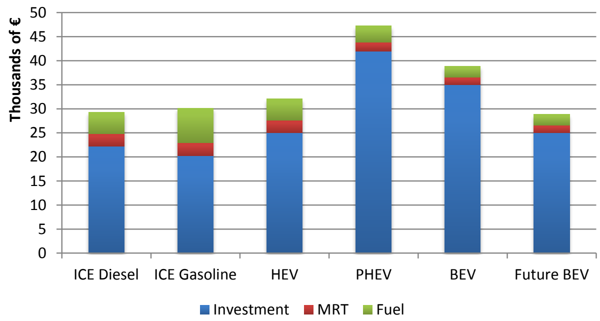

Figure 6: Share of the investment and ownership costs after five years for the vehicle technology analyzed

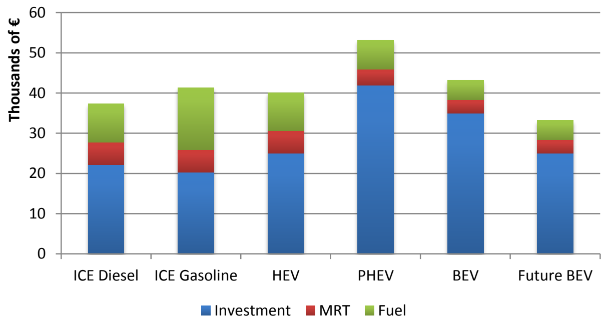

Figure 7: Share of the investment and ownership costs after ten years for the vehicle technology analyzed

far the largest cost factor, representing 50-61% for ICEVs, 64% for HEV and 80-83% for PHEV and BEV, followed by fuel cost, representing 24-36% for ICEVs, 22% for HEV and 10-12% for PHEV and BEV. MRT has the lowest contribution with 7% for the PHEV and BEV and 13% for the remaining vehicles (Figure 6 and Figure 7).

PHEVs and BEVs have the lowest operating costs due to the price of electricity, and low usage of the ICE of the PHEV to recharge the battery, and reduced maintenance when compared with traditional ICEVs. However due to the high initial cost it takes more than ten years to match the initial and ownership cost of an ICEV. This higher initial cost is due to the battery pack, currently with an estimated cost between 400-600 €$/kWh$). The battery pack used in the Nissan Leaf has an estimated cost of 530 €$/kWh$ (12720 € 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. The US Advanced Battery Consortium has a target of 280 €$/kWh$ by mid-decade, leading to a reduction of more than 33% in the cost of the battery for the PHEV and 45% for the BEV [42]. The 170 €$/kWh$ target for 2020, is unlikely to be achieved according to [11] but an estimated price reduction of 60-65%, based on 2009 prices, is possible. Based on this estimate, in 2020, the price per kWh will be approximately 250 €, or 4000-6000 € for a 16-24 kWh battery pack.

Currently early adopters and governments are driving the demand for EVs. However, by 2020 with the price reduction of EVs, due to advances in battery technology and mass production, the mass market buyers will be influenced by the lower total cost of ownership of EVs versus ICEVs at the time of buying a new vehicle.

Considering that in 2020 a BEV will cost less 10000 € than in 2010 with the same characteristics (Future BEV in Table 6), due to battery price reduction and mass production, the total cost of ownership will be approximately less 5000 € after 5 years and 7000 € after 10 years.

Is easily noticeable in Table 7 that EVs are the most environmentally friendly, contributing with approximately half of the emissions of a diesel ICE in the worst case scenario.

6. Impact of the Driving Style in Energy Consumption

6.1. Driving cycles and factors that influence power consumption

EVs manufacturers usually provide the estimated range for a battery at full capacity based on a specific drive cycle like the NEDC or FTP-75 in the USA [43]. Driving cycles are produced by different countries and/or organizations to assess the performance, fuel consumption and emissions and could be from two different types: Transient Cycles, involving constant speed changes for a typical road driving, and Modal Cycles, involving periods at constant speeds. The use of drive cycles is important to compare vehicles and validate if they meet certain requirements. However certain factors that play an important role in the overall performance of a EV are not considered. One parameter that contributes heavily for the overall energy consumption is the gravitational energy or elevation profile, increasing the energy consumption when compared with a flat profile. Since EVs are equipped with an electric motor that can work as a generator and charge the battery when going downhill, the elevation profile can be beneficial to the overall energy consumption by reducing it and is not accounted in the NEDC and FTP-75 driving cycles. The energy recovered when braking is also not accounted and could play a major effect in the energy balance.

Others factors that influence directly the energy balance are the driving style and the auxiliary equipment in the vehicle. The auxiliary equipment such as the radio and air conditioning system, being this one the main auxiliary system draining battery, reduce the driving range since they are using battery power. At low speeds is recommended to circulate with the windows open rather than with the air conditioner ON, avoiding this extra power requirement. Despite the auxiliary systems contribution to reducing the EV range, the main factor that contributes to the vehicle range, with a full battery, is the driving style. An aggressive driving style, with fast accelerations, leading to run the electric motor at full power draining a lot of energy, and heavy braking, leading to the use of the mechanical brakes instead of the regenerative braking, will reduce drastically the vehicle range. A driving style with slow accelerations, moderated speed and braking early, minimizing the amount of time that the electric motor runs at full power and maximizing the energy recovered through regenerative braking, maximizes the vehicle range.

The total power required to move a vehicle at a certain speed is obtained by the sum of the power required to overcome each individual force acting on the vehicle. The main forces acting over the vehicle for a constant velocity are the aerodynamic drag and rolling resistance, being the power required to overcome them given by Equation 6 and 7 respectively.

$$P_{drag} = \frac{1}{2} \cdot \rho \cdot Cd \cdot A \cdot (v - v_{wind})^3 \qquad (6)$$

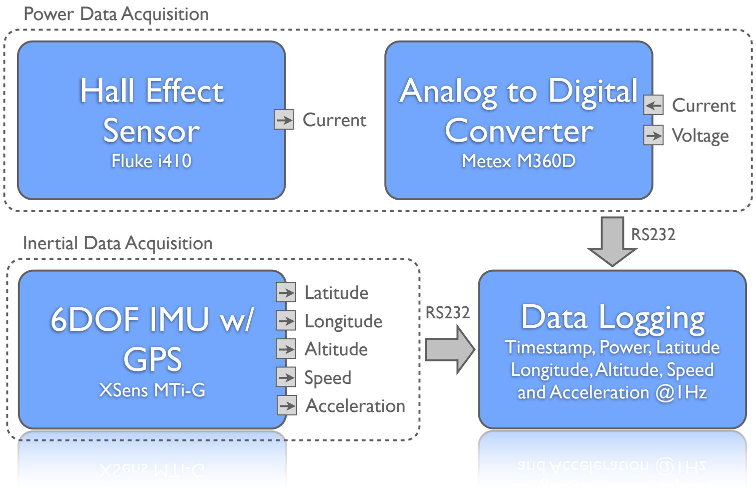

Figure 8: Data acquisition system installed on a Nissan Leaf.

$$P_{friction} = m \cdot g \cdot v \cdot Crr \cdot cos(\alpha) \tag{7}$$

Where Crr is the rolling coefficient, Cd is the drag coefficient, ρ is the air density, m is the vehicle mass, A is the vehicle frontal area, v and v_{wind} correspond to the vehicle and wind velocity respectively.

Taking into account a given acceleration and the slope of the terrain, Equations 8 and 9 are used to calculate the additional power required to to accelerate the vehicle and overcome the slope, respectively.

$$P_{acc} = m \cdot a \cdot v \tag{8}$$

$$P_{slope} = m \cdot g \cdot v \cdot sin(\alpha) \tag{9}$$

Where a is the vehicle acceleration, g is the gravity acceleration and α is the terrain slope, in degrees.

Equation 10 represents the total power required to overcome the forces acting over the vehicle considering the motor and transmission efficiency and the auxiliary power required for the radio, lights etc.

$$P_{total} = \frac{P_{acc} + P_{slope} + P_{drag} + P_{friction}}{\eta_{motor} \cdot \eta_{trans}} + P_{aux} \tag{10}$$

6.2. Results for real word driving cycles

In order to measure the parameters required to assess the energy balance of an EV, a data acquisition system was installed on a Nissan Leaf. The system is constituted by a 6 degrees of freedom

Xsens MTi-G Inertial Measurement Unit (IMU), with a three axis accelerometer, gyroscope and magnetometer, GPS and barometric sensor for instantaneous position and speed measurements; a Fluke i410 current clamp and a METEX M3640D multimeter, for instantaneous power measurements, connect to a computer through RS-232 for data logging (Figure 8). The computer stores the vehicle position, elevation and power consumption/regeneration at 1 Hz rate. With this system is possible to correlate the power consumption with the terrain profile and with the driving style of the driver.

On Table 9 are presented several driving cycles with different driving styles and speed profile to demonstrate how they affect the energy consumption. Since the speed is a key factor that affect the overall energy consumption, a column specifying the percentage of the distance traveled under 50 km/h (shown in Table 9 column $\leq$50 (% of path))was added to facilitate the analyses. The experimental data was obtained at several speeds in a road with an approximately constant slope. The error between the real data and the model data is due to several factors that could not been accurately taken into account, namely the slope along the full extent of the road and wind direction and speed.

Table 9: Results for real world driving cycles, for urban and extra urban routes with different driving styles.

		Energy			Speed (km/h)		
Type	Lenght (km)	Out (Wh)	In (Wh)	Total (Wh/km)	Max./Median	$\leq$50 (% of path)	Observations
Urban	12	2275	574	141.8	73/16	98.7	Fast acceleration
Urban	16	2257	729	95.5	61/42	99.8	Slow acceleration
Urban	16	3106	619	155.4	86/43	47.0	Fast acceleration
Urban	17	2848	552	135.1	96/58	56.0	
Urban	16	2861	835	126.6	86/47	41.0	
Urban	17	2649	883	103.9	82/45	78.5	ECO mode
Urban	17	2616	787	114.9	71/42	56.7	ECO mode
Urban	20	3938	1353	129.3	77/37	88.4	
Extra Urban	16	2785	716	129.3	100/60	40.7	ECO mode
Extra Urban	16	3190	675	157.2	115/63	46. 5	Fast acceleration
Extra Urban	20	3561	726	141.8	118/75	43.8	
Extra Urban	16	2799	511	143.0	100/67	37.7	
Extra Urban	16	2739	613	132.8	100/77	19.6	
Extra Urban	16	2757	548	138.1	85/70	24.0	

In Figure 9 the power requirements to overcome a specific slope at a specific speed, based on the power model (Equation 10) and experimental data, are presented, considering the vehicle parameters m=1540kg, A=2.7m, Crr=0.01, Cd=0.28, ρ =1.23) and $\eta_{motor}.\eta_{trans}$ = 0.84 obtained from the Nissan Leaf specifications. In Figure 11 is presented the breakdown of the power required to overcome the main forces acting on the vehicle and can be observed that at high speeds the majority of the power is used to overcome aerodynamic drag. It should be noted that the power data obtained, for negative slopes, in the experimental runs and presented on the graphs was taken

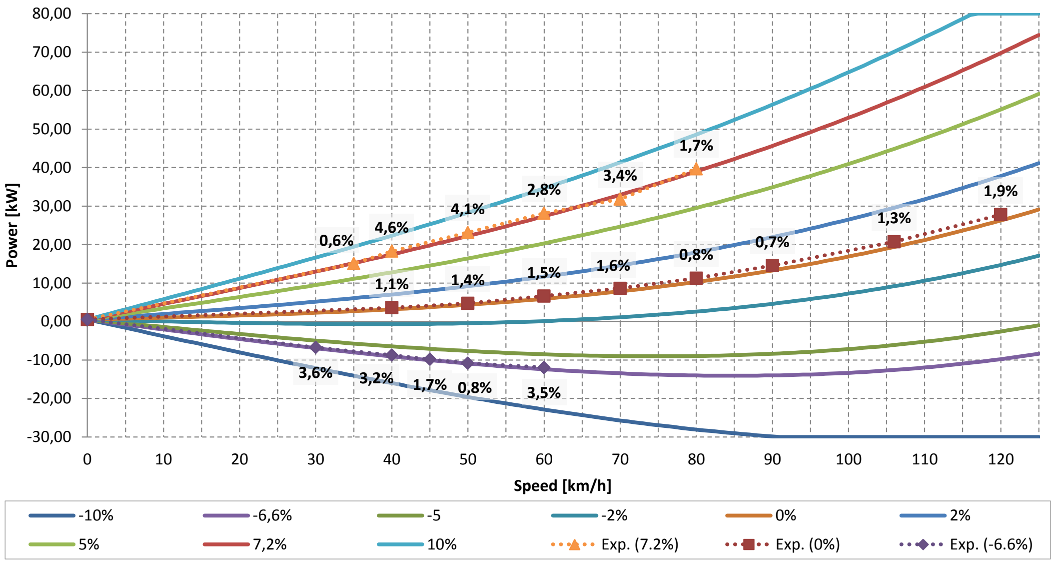

Figure 9: Power required to maintain a constant speed for several degrees of inclination and experimental runs (Exp.) on an average slope of 0%, 7.2% and -6.6%. The values near the experimental points correspond to the error, in percentage, between the mathematical model (Equation 10) and real data.

with the vehicle cruising downhill. Pushing the brake pedal, leads to a complete different set point of the regenerative braking setup and consequently to higher power drawn from the regenerative braking.

In terms of specific energy consumption per unit of distance (Figure 10), it is approximately constant at low speeds, between 10 and 60 km/h, since the aerodynamic force at these speeds is relatively low when compared with the rolling resistance, the main force acting on the vehicle. From 60 km/h the energy consumption starts to grow relatively fast due to the power required to overcome the aerodynamic force, the main force acting on the vehicle, that grows with the cube of the speed. The breakdown of the power required to overcome the main forces acting on the vehicle is presented in Figure 11. At high speeds it can be observed that the majority of the power is used to overcome the aerodynamic drag.

The experimental data was obtained at several speeds in a road with an approximately constant slope. The error between the real data and the model data is due to several factors that could not been accurately taken into account, namely the slope along the full extent of the road and wind direction and speed.

In Figure 12 is shown the data acquired by the data acquisition system (Figure 8) installed in a Nissan Leaf for a 16 km route with two different driving styles, an ECO mode (selected on the vehicle) and a normal style, in a mixed urban (areas with sudden speed change due to traffic lights and traffic itself) and extra-urban environment (areas with constant speed). The ECO driving style avoids fast acceleration (minimizing the energy spent in this phase) and heavy braking (avoiding the use of mechanical brakes, maximizing the energy recovered through regenerative braking) while the normal driving style is done with the vehicle ECO mode OFF.

For the ECO mode in urban environment the energy balance was 2.649 kWh spent and 0.883

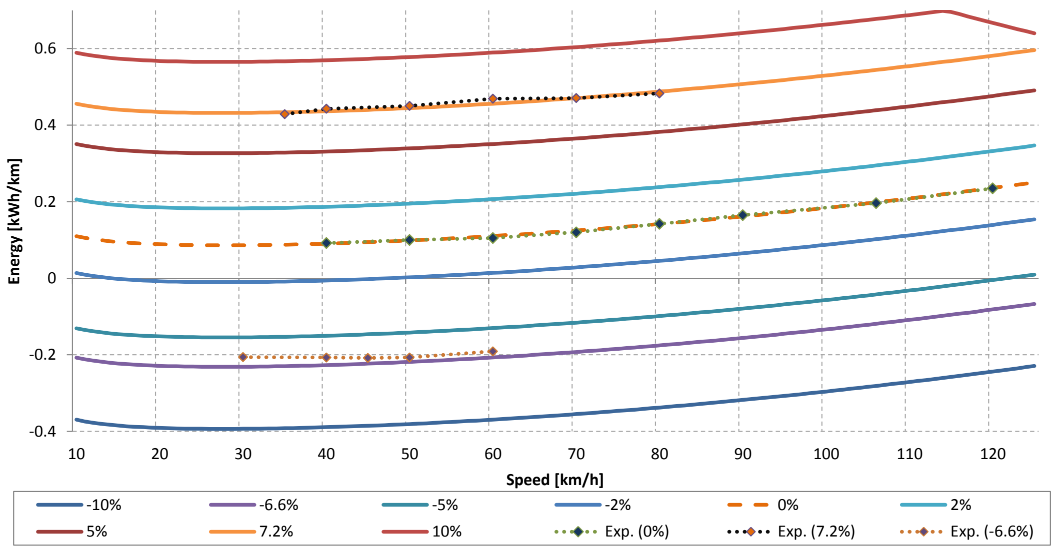

Figure 10: Energy consumption per unit of distance required to maintain a constant speed for several degrees of inclination and experimental runs (Exp.) for 0%, 7.2% and -6.6%.

kWh recovered through regenerative braking, for a balance of 104 Wh/km, while for the normal driving the energy balance was 2.743 kWh spent and 0.776 kWh recovered, for a balance of 123 Wh/km. Table 9 shows additional driving cycles. Since the Nissan Leaf has a 24 kWh battery, driving in the ECO mode is possible to achieve a range of 200 km, higher than the 160 km announced by Nissan (must be noted that the 160 km range provided by the manufacturer was based on the FTP-75). A 25% increase in the BEV range, from 150 to 200 km, with a eco-driving style, contributes to a reduction of 24.7% in CO_2 emissions, from 1.11 to 0.89 $MT\ CO_2/year$, and a 25% reduction in the cost of electricity for a year, from 430.6 to 344.5 €. Without regenerative braking, the energy balances, for the urban course were, 155 and 171 Wh/km, with a estimated range of 154 and 140 km for the ECO and normal drive style respectively, while for the extra-urban course the energy balances were 174 and 199 Wh/km for the ECO and normal drive style.

From the results presented is easy to notice that the driver behavior has a direct and big influence in the vehicle range. From the tests realized an important behavior was noticed to emerge: the driver started to become aware how he can recover energy (by starting to decelerate sooner avoiding the use of the mechanical brakes) and minimize energy spending (smooth acceleration and moderating the speed). The direct effect of this emerging behavior is the reduction of cost per distance traveled and the increase of vehicle range.

7. Conclusion

The electrification of the transportation system seems a promising solution, both in terms of GHG emissions reduction and for decreasing the dependence from fossil fuels in the transportation sector. The use of a BEV instead of an ICEV typically avoids the use of approximately 600 to 900 l of fuel per year per vehicle.

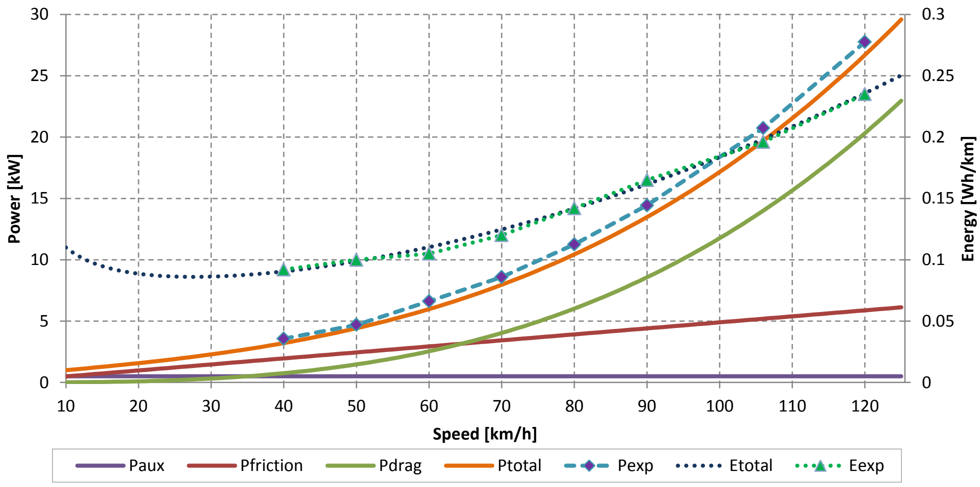

Figure 11: Details of the total power (P_{total}) required to overcome each force acting on the vehicle (P_{aux}, $P_{friction}$ and P_{drag}), in kW, and specific energy consumption (E_{total}) for a flat surface, in kW/km. Power (Pexp) and specific energy consumption (Eexp) from experimental runs are also presented.

In terms of GHG emissions, the impacts of BEV and PHEV depends directly on the electricity generation mix. For the present EU mix, the emissions reduction impact is substantial, and will be reduced even more in the future due to the increasing use of renewable energies in the energy mix. In terms of cost, a BEV is more expensive than a ICEV, due to the high cost of the battery, and it could take the entire vehicle life to compensate the initial investment. Due to the BEV operational costs being less than a half of the ICEV and due to the likely battery price reduction, leading to a lower investment cost, the economic balance will gradually tip in favor of EVs.

The paper describes a novel economic and environmental study mainly for electrical vehicles, based on experimental tests in real world driving conditions in order to assess the overall energy consumption with a high level of detail using a developed data acquisition system.

For a BEV, recently introduced in the market, a set of tests was performed, to quantify the power consumption in each instant and which vehicle load is responsible for that consumption. This information is very important since it allows knowing exactly to where the power consumption is going and how to reduce the energy consumption. With this data the user can adapt his driving style to maximize the distance traveled with one charge and consequently reduce the cost per unit of distance traveled.

In conclusion, the paper suggests that electric mobility seems increasingly beneficial, both from an environmental and from a economical point of view when compared to conventional mobility.

8. Acknowledgments

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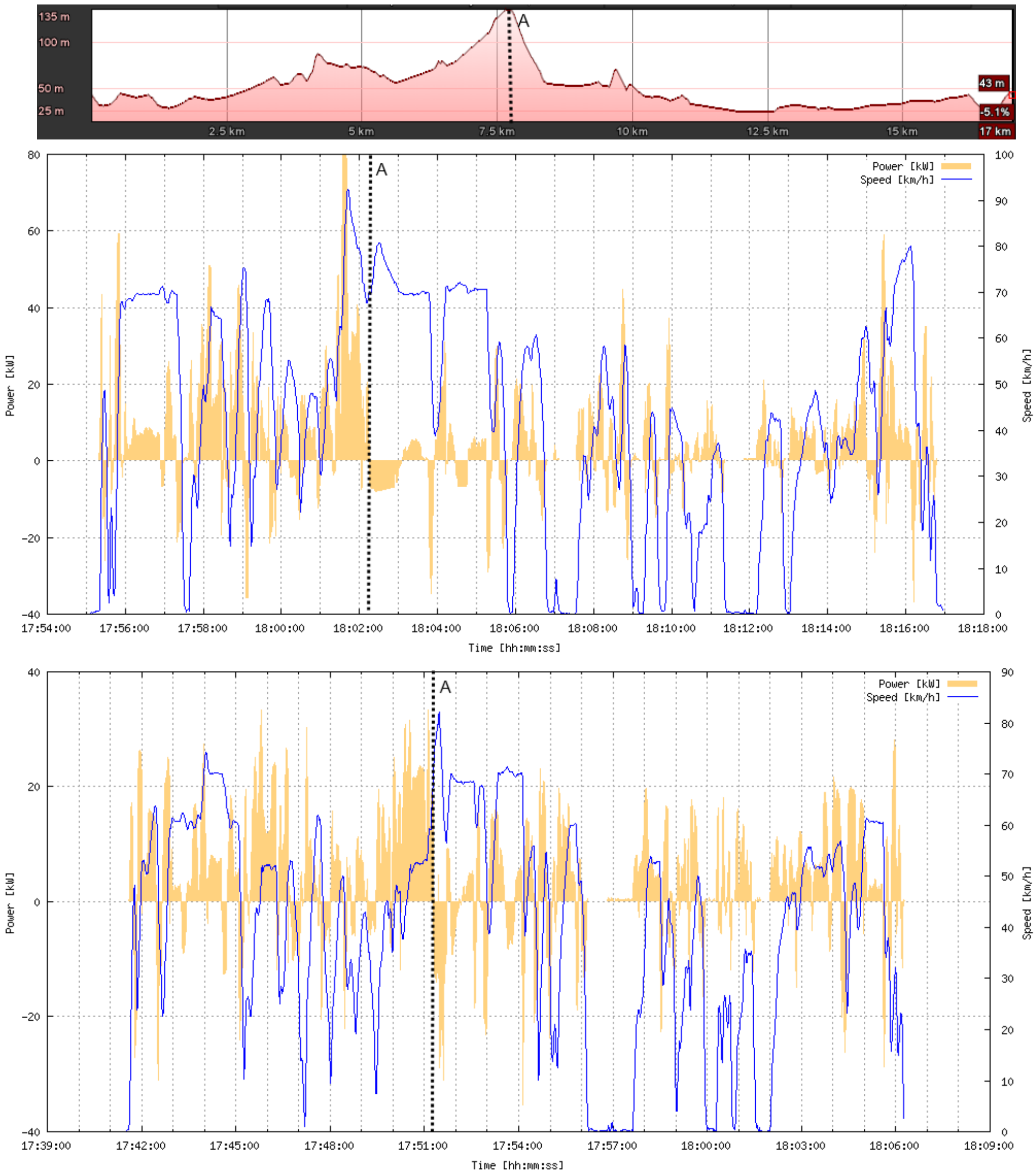

Figure 12: Power and speed for a mixed driving cycle in urban and extra-urban environment for a 16 *km* trip with the elevation profile represented on top, in a Normal (middle graph) and ECO (bottom) driving styles. The power consumption with negative values, in parts of the driving cycle, is associated with regenerative braking.

9. Acronyms

AC Alternate Current

AFV Alternative Fuel Vehicle

BEV Battery Electric Vehicle

ESS Energy Storage System

EU European Union, the values in the paper consider the 27 member countries since 1 January 2007

EV Electric Vehicle

FTP-75 Federal Test Procedure 75

GHG Greenhouse Gas

HEV Hybrid Electric Vehicle

ICE Internal Combustion Engine

ICEV Internal Combustion Engine Vehicle

IMU Inertial Measurement Unit

IEA International Energy Agency

LCA Life Cycle Assessment

MRT Maintenance, Repair, Insurance and Taxes

NEDC New European Drive Cycle

PEM Power Electronics Module

PHEV Plug-in Hybrid Electric Vehicle

PM Particulate Matter

PT Powertrain

RES Renewable Energy Source

SFTP Supplemental Federal Test Procedures

TCO Total Costs of Ownership

TTW Tank-to-Wheel

WTT Well-to-Tank

WTW Well-to-Wheel

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