



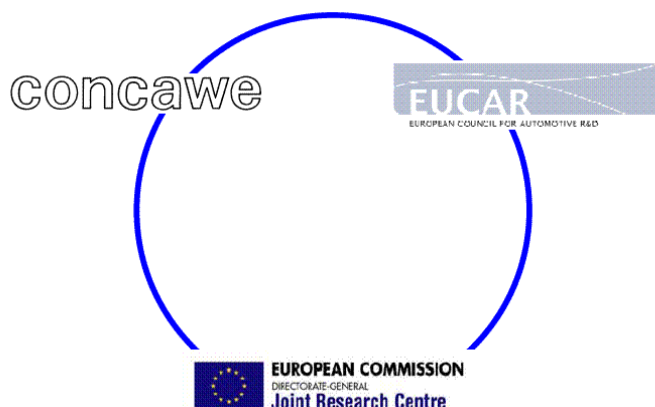
Well-to-wheels Analysis of Future Automotive Fuels and Powertrains in the European Context

APPENDIX 2 WTW GHG-Emissions of Externally Chargeable Electric Vehicles

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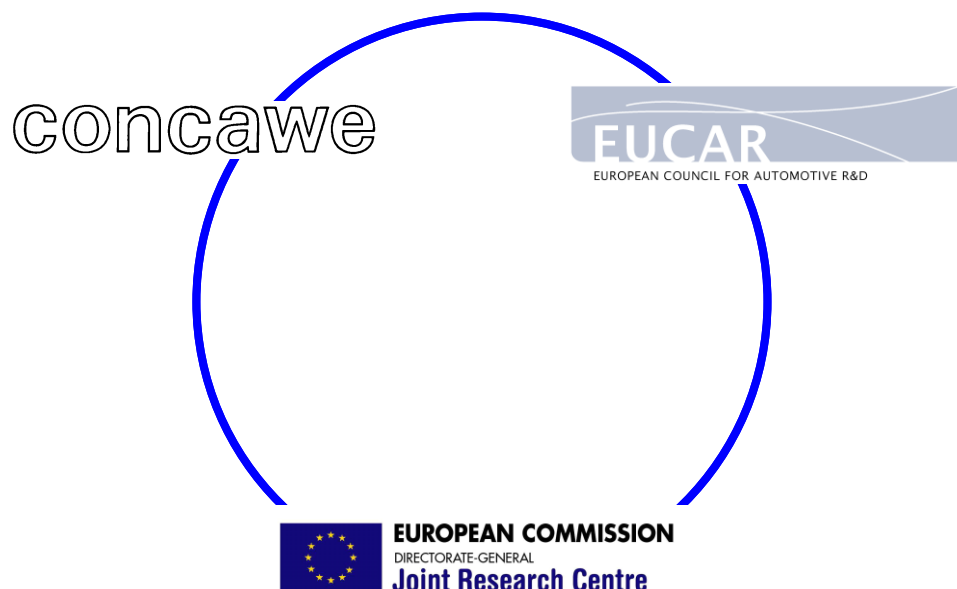
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WELL-TO-WHEELS ANALYSIS OF FUTURE AUTOMOTIVE FUELS AND POWERTRAINS IN THE EUROPEAN CONTEXT



Appendix 2

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Notes on version number:

This document reports on the third release of this study replacing version 2c published in March 2007. The original version 1b was published in December 2003.

This is a partial revision of version 2c in that it does not include an update of section 8 on cost and availability.

WTW GHG-Emissions of Externally Chargeable Electric Vehicles

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1 Abbreviations

The following terms and abbreviations are used within this appendix. In many cases they are explained in more detail at the relevant text passages, where they are introduced or defined or explained.

Abbreviation	Description
BEV	Battery Electric Vehicle
cd	Charge depleting: test condition when vehicle test is started with battery at maximum level of battery state of charge. During test, battery energy is depleted until minimum state of charge is reached and vehicle switches to charge sustaining operation mode.
cs	Charge sustaining: test condition when vehicle test is started with battery at minimum level of battery state of charge. During test, battery charge is sustained within certain limits, defined by manufacturer's calibration strategy.
EE	Electric Energy Consumption
E-REV	Extended Range Electric Vehicle
FC	Fuel Consumption
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine Vehicle
NOVC HEV	Not Off-Vehicle Chargeable HEV = not externally chargeable HEV
OEM	Original Equipment Manufacturer (in our context: vehicle manufacturers)
OVC HEV	Off-Vehicle Chargeable HEV = externally chargeable HEV
SOC	State Of Charge
UN ECE	United Nations Economic Commission for Europe
xEV	Umbrella term for all considered electric vehicle concepts: PHEV + E-REV + BEV + FCEV. FCEV are excluded in this report, they are covered in the WTW study

2 Introduction

Version 2 of the WTW study exclusively dealt with conventional internal combustion vehicle (ICEV) and hybrid electric vehicle (HEV) and FCEV concepts, which don't have the capability to store externally generated electricity onboard.

Due to global climate challenges and the high reliance of the road transport sector on fossil fuels, the automotive industry increasingly investigates further sustainable propulsion alternatives:

- to reduce the dependence on petroleum,
- to expand the global energy portfolio and
- to reduce the carbon footprint of driving

Therefore the OEM's advanced propulsion strategies are aiming at increased fuel efficiency (reduction of fossil fuel consumption) and energy diversity (displacement of fossil fuels).

Based on the accelerated technological development and affordability of electric energy storing devices (e.g. Li-Ion batteries), electrification concepts of the automobile are becoming increasingly important in this respect. This leads to a range of new electrified vehicle and powertrain concepts that will enter the market in the foreseeable future.

As these vehicle concepts will use electricity from the grid as sole energy source or in addition to the on-board stored consumable (liquid or gaseous) fuel, the GHG methodology of current WTW study must be extended to take into account the GHG-emissions of the utilized grid energy in order to determine the GHG emissions of such vehicle concepts.

To be able to compare the GHG balance of externally chargeable electric vehicles that can store a certain amount of externally generated energy onboard for the use of mechanical propulsion, it is necessary to take account of the GHG-emissions of the utilized electric energy from the grid.

This appendix explores the methodology to assess the GHG emissions of certain externally chargeable electric vehicle concepts with different levels of utilization of grid electricity:

- PHEV: an externally chargeable hybrid electric vehicle with limited electric performance and electric range ("urban capable" PHEV), although the possibility to drive in electric mode is expanded by the possibility to plug the battery on the grid
- E-REV: externally chargeable hybrid electric vehicle with full performance in electric mode and with an auxiliary ICE engine for extended range
- BEV: a pure battery electric vehicle since there is no ICE, but only an electric motor to propel the vehicle, with full performance in electric mode and enlarged - but still limited - electric range

3 Approach

The vehicle data for the reference vehicles in the initial WTW study was simulated based on defined performance criteria of an average compact size vehicle.

Currently the automotive industry gains first experience with different electrified vehicle concept layouts (“xEV”), system architectures, operating strategies for the use of electric propulsion parts, component and battery properties and future possibilities. Therefore no final picture for a generic modeling of reference vehicles like in the initial WTW study is currently available.

The vehicle data utilized for the GHG calculations of the considered electric vehicle concepts (xEV: = PHEV + E-REV + BEV) is based on the experience of OEMs with current prototypes and development vehicles.

As all the different xEV concepts are very much differing in the way they are designed (degree of electrification; targeted customer group; basic vehicle architecture; utilization of additional CO₂-efficiency measures like light weight design and aero dynamic measures; calibration strategies), it was not possible to generate one dataset for each electric vehicle category.

Therefore for each electric vehicle category a range of the relevant parameters (e.g. electric energy consumption; fuel consumption; battery capacity; electric driving range) was defined. This range of parameter reflects the experience with the various xEV concepts currently followed by the OEMs. However it must be considered, that the communicated numbers are less mature than the ones simulated for conventional vehicles, and therefore reflect a lower level of confidence.

For this reason, further updates of this WTW study will consider to model and simulate the electric vehicle concepts more accurately. At that point in time there may also be more reliable data available of first serial production electric vehicle concepts to verify the assumptions taken within this appendix.

Nevertheless the results of the appendix at hand should allow the interested parties and policy makers to generally assess the benefits as well as the limitations of electrifying the road transport sector with respect to energy usage and to GHG emissions.

The methodology to assess the GHG emissions of xEV concepts is based on the official test procedure UN ECE R101 that is used to certify fuel consumption, electric energy consumption, range and CO₂-emissions of electrified vehicle concepts (including PHEV, E-REV, BEV) on a TTW basis.

By this, the GHG emissions of xEV can be compared to the ones of conventional vehicles.

For simplification reasons, the assessment is restricted according to following considerations:

- Currently only externally chargeable hybrid electric vehicles (“OVC HEV”) with gasoline engine are considered, diesel OVC HEV are not yet considered







- OVC HEV are only compared to fossil fuel (gasoline) – impact of biofuels is not considered in calculation/comparison
- Fuel Cell vehicles are not considered in this appendix (they are already covered in the initial study)
- Auxiliaries and their energy consumption are not considered as they are not considered in the test procedure (consistently with WTW methodology)
- The data range for xEV categories reflects a compact size vehicle similar to the reference vehicle of the initial WTW study. However, based on the additional weight of the traction battery, the xEV concepts are about 200kg – 300kg heavier than the reference vehicle.
- There is a smooth transition between the three considered xEV categories. Depending on the degree of certain design characteristics, an xEV could be assigned to different categories or fall in between two categories (e.g. a PHEV with a strong electric driving performance and a high electric range could also be considered an E-REV)

The basic assumptions about the vehicle configurations are outlined in more detail in chapter 8.

4 Definition of externally chargeable HEVs and pure battery electric vehicles BEVs

Conventional hybrid electric vehicles (HEV) draw their propulsion energy exclusively from a consumable fuel stored onboard the vehicle. In contrast, externally chargeable HEVs can draw a part of their propulsion energy from electric energy that was generated outside the vehicle and is stored onboard the vehicle in a battery. Finally, pure battery electric vehicles draw their complete propulsion energy from externally produced electricity that is stored onboard (see *Table 4-1* and Figure 4-2).

Table 4-1: Vehicle- and Powertrain- Configurations considered in WTW study – with new items #4 and #5 added with WTW Appendix 2

			Energy Source		Abbreviation Synonym	Name / Description
			external energy sources - stored onboard	internally generated energy - stored onboard		
WTW V2	1	Conventional ICE Vehicle	 consumable fuel	-	ICEV	Internal Combustion Engine Vehicle
	2	Conventional HEV - not externally chargeable	 consumable fuel	electricity: - regenerative braking - generated onboard from consumable fuel	NOVC HEV	Not Off-Vehicle Chargeable HEV
	3	Fuel Cell Electric Vehicle	 consumable fuel	in case of FC HEV: electricity: - regenerative braking - generated onboard from consumable fuel	FCEV	Fuel Cell Electric Vehicle
WTW V3	4	HEV - externally chargeable	 consumable fuel	electricity: - regenerative braking - generated onboard from consumable fuel	OVC HEV	Off-Vehicle Chargeable HEV
			 electricity		PHEV E-REV	Plug-In HEV Extended-Range EV
	5	Battery Electric Vehicle	 electricity	electricity: - regenerative braking	BEV	Battery Electric Vehicle

Regarding externally chargeable HEVs (“off-vehicle charging HEV”, OVC HEV), it is necessary to further distinguish several unique powertrain configurations, that show different vehicle characteristics and efficiencies.

4.1 Plug-In HEV ('PHEV')

In general PHEV are conventional HEV with off-board charging capability. PHEV are in most cases mainly propelled by the combustion engine, with some support by the electric motor and limited capability of pure electric driving. Normally these PHEV are derived from conventional full hybrid architectures with an increased battery capacity. Therefore they show limited benefits by underlying constraints of the base hybrid system if a conventional full hybrid architecture is the base. The propulsion system is designed to share electric and combustion energy and has therefore a limited electric performance for urban driving conditions only. There are different operating strategies for PHEV:

- PHEV with Initial EV Operation: starts as an EV then switches to hybrid operation. Always requires engine on for full performance

- PHEV with blended operation: starts and drives like a conventional hybrid with engine on

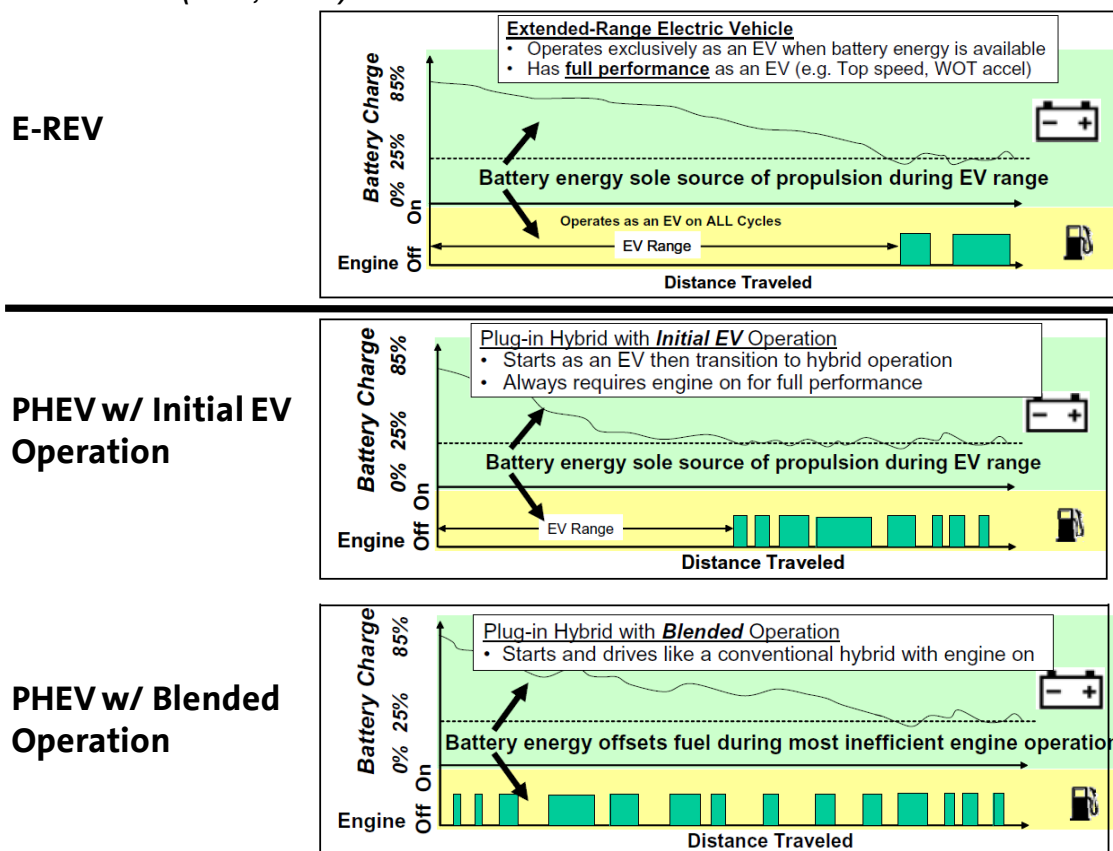
4.2 Extended-Range Electric Vehicle ('E-REV')

In contrast to PHEVs, an E-REV operates as an electric vehicle when battery energy is available with full performance provided by the electric drive train exclusively. The auxiliary energy supply, which can be a small combustion engine or a fuel cell, is only engaged when the energy from battery is not available. Thus the generator/combustion engine can be operated at a favorable engine speed range with high efficiencies in the charge sustaining driving condition, as the vehicle is predominantly propelled by the electric motor. However, the total efficiency of such a concept is also impacted by the efficiency of transformation from mechanical to electric to mechanical energy.

An electric vehicle with range extender potentially offers the opportunity to overcome the “range anxiety” that customers might experience with pure electric vehicles, and thereby increases the acceptance for electric vehicle concepts, if the total efficiency is sufficient.

Figure 4-1 explains the different OVC concepts based on the battery state of charge profile and the combustion engine operation profile.

Figure 4-1: Explanation of OVC concepts based on the battery state of charge profile and the combustion engine operation profile (SAE, 2008)



4.3 Battery Electric Vehicles BEV

A battery electric vehicle is solely propelled by an electric motor and has no additional combustion engine or fuel cell on board. If the battery energy is depleted, the vehicle cannot be moved further until the battery is recharged or changed.

4.4 Utilization of the different OVC HEV architectures

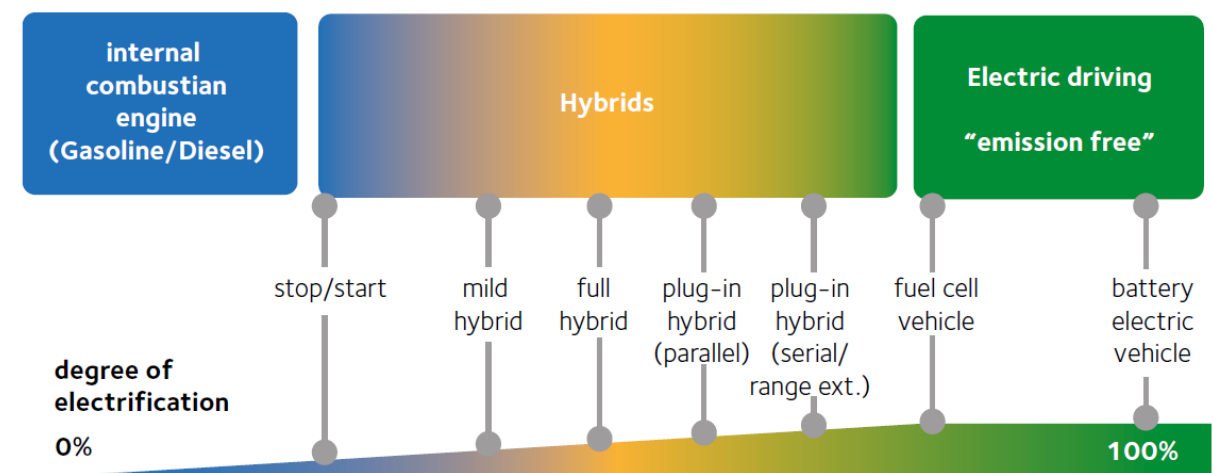
There are different reasons for choosing a certain electrification concept. As PHEVs are mainly based on conventional hybrid architecture with limited possibility to utilize onboard stored electric energy, the main focus of these concepts is keeping the main properties of conventional vehicles but displace a certain amount of fossil fuel. The degree of the limit depends on the used battery capacity, however. PHEVs are a further step towards an “emission free” electric driving.

The next step to reach this goal is an Electric Vehicle with Range Extender (E-REV). An Electric Vehicle with Range-Extender (E-REV) offers potentially the advantage to overcome the range anxiety. Both concepts, PHEVs and E-REV are actually a bridge and enabler of future electric vehicle mobility, as it eliminates the problem whether first to install the charging infrastructure or to bring the vehicle technology to the market. These concepts allow designing hybrid electric vehicles that are fully suitable for daily use without restrictions regards range or trunk capacity.

E-REV with full electric performance offers the opportunity of purely electric propulsion if operated in charge depleting mode.

Finally, BEV enables purely electric propulsion without local emissions in use. Nevertheless, based on the current battery technology limitations, there are some restrictions regarding usages under all conditions. Therefore this concept currently is mainly of interest for urban vehicle configurations.

Figure 4-2: Electrification of the Powertrain (EUCAR, 2009)



5 Methodology to assess GHG-emissions from externally chargeable HEVs

The total GHG balance of off-vehicle charging HEV (OVC HEV) and electric vehicles is not only determined by the consumption of an onboard stored consumable fuel, but also by the origin of the consumed electric energy that was produced outside of the vehicle and stored onboard.

This creates the need to establish a methodology to assess the overall WTW GHG emissions of OVC HEV to make them comparable to conventional vehicles and conventional hybrid electric vehicles.

5.1 Standardized Measurement Procedure for HEV

The TTW emissions of conventional vehicles and HEV are determined by the application of the standard European driving cycle (NEDC) and the related measurement procedures according to the applicable regulation UN ECE R101.

For the purpose of certification of externally chargeable HEV, regulators have also laid down rules to determine the fuel consumption, CO₂-emissions, electric energy consumption and electric range. The measurement procedure is similar to the one for conventional combustion powertrains and the same test cycle (NEDC) is applied. Nevertheless, to account for the additional external electric energy consumed, the methodology had to be adapted as follows:

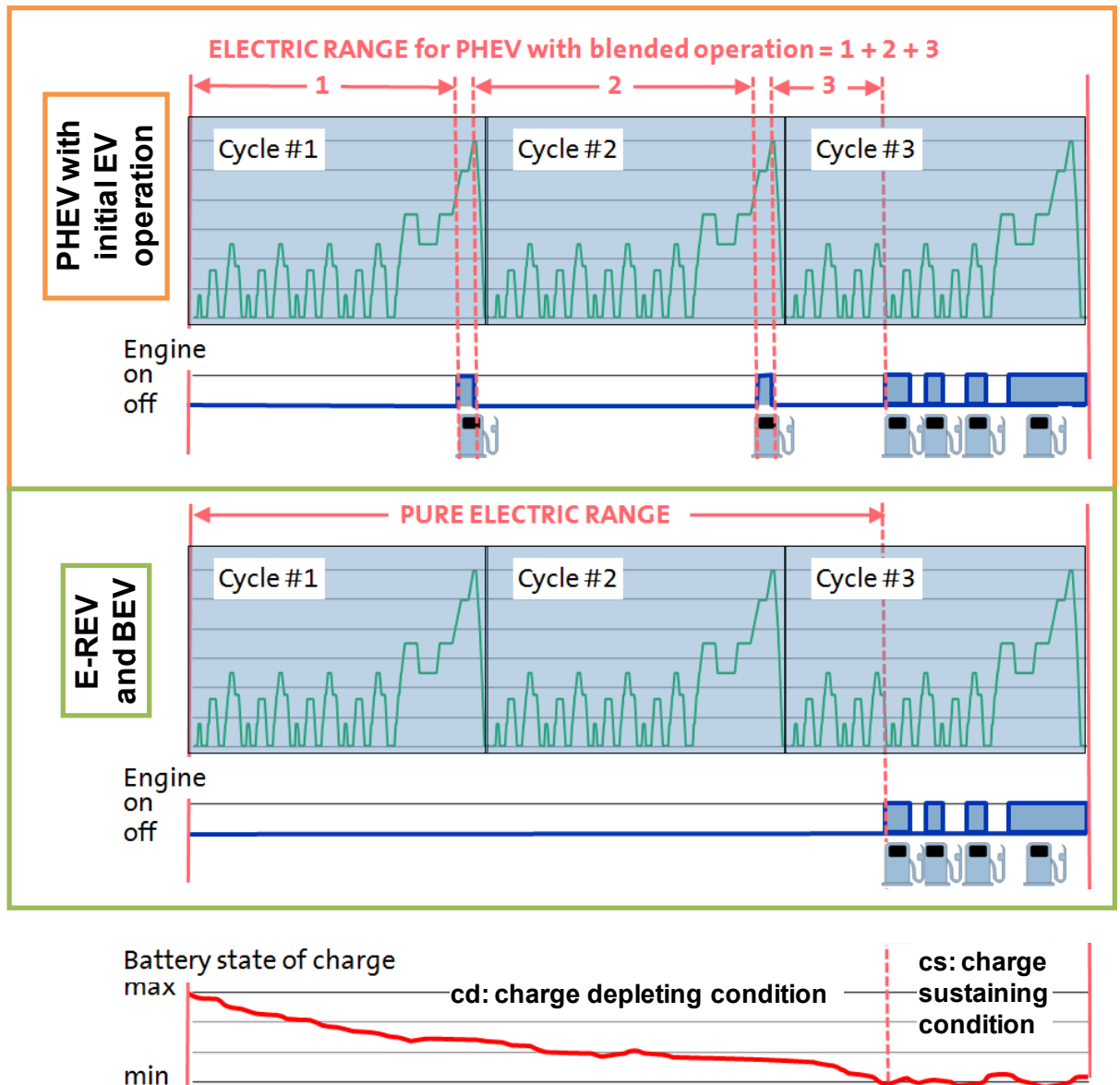
- for OVC HEV
 - In addition to the fuel consumption and CO₂-emissions values, the electric energy consumption is measured and the electric range is determined
 - The tests are carried out under two test conditions, determined by the battery “State of Charge” (SOC)
 - Weighted averages for: 1.) fuel consumption, 2.) CO₂-emissions and 3.) electric energy consumption are calculated from the results of these two test conditions
- for BEV
 - Only the electric energy consumption is measured and the electric range is determined
 - To determine the electric energy consumption, the BEV is tested by driving two consecutive NEDC cycles
 - The electric energy consumption is the average of the electric energy consumption for the test distance covered
 - There is no weighting of test results

5.1.1 Determination of the Range

For externally chargeable electric vehicle concepts (pure battery electric vehicles (BEV) and off-vehicle charging HEVs (OVC HEV), the legislation provides different possibilities to determine the range, depending on the operation strategy of the xEV (see *Figure 5-1*). The so called “OVC-range” gives an indication of the **total distance** covered until the energy imparted by external charging of the battery is depleted. In

contrast, the “Electric Range” determines the distance that can be driven **purely electrically** on one fully charged battery. The distance travelled with the ICE operating is excluded. This “Electric Range” is the relevant figure to consider when determining the electric energy consumption of xEV concepts and the related GHG emissions.

Figure 5-1: *Definition of electric range and operation modes (cd and cs) – illustrative example only, e.g. a BEV does not have the “engine on” option of course*



5.1.2 Fuel consumption, CO₂-emissions and electric energy consumption test procedure

Test procedure for OVC HEV

The vehicles are tested under two test conditions:

- Condition A – test with fully charged electrical energy/storage device: “charge depleting” condition (cd)
- Condition B – test with electrical energy/storage device at minimum SOC: “charge sustaining” (cs)

The test cycle is the same as for vehicles with ICE and NOVC HEV (“EU NEDC”).

For each of the two test conditions, the following values are determined:

1. Fuel Consumption (“FC”) for Cond. A
2. CO₂-Emissions (“CO₂”) for Cond. A
3. Electric Energy Consumption (“EE”) for Cond. A
4. FC for Cond. B
5. CO₂ for Cond. B
6. EE for Cond. B

The electric energy consumption determined by this test procedure (EE; cd EE; cs EE) is measured at the mains socket and therefore already considers the charging efficiency and the charging losses. This value directly correlates to the electric energy provided from the grid and is used to determine the GHG emissions originating from the grid electricity utilized by the vehicle.

Test results of OVC HEV: Averaging and Weighting

To be able to determine the weighted average value for the two test conditions, one has to make an assumption about the weighting of the two conditions: how often and how long is the vehicle operated in each condition? For the purpose of the testing procedure applicable in Europe, the average distance travelled in charge sustaining operation mode before the battery is recharged is assumed to be 25 km by the legislator.

$$X = \frac{(X^{cd} \times \text{range}) + (X^{cs} \times 25)}{(\text{range} + 25)}$$

With:

X: denotes one of the emission values (fuel consumption or electric energy consumption or CO₂ emissions)
X^{cd}: denotes one of the emission values in charge depleting operation mode
X^{cs}: denotes one of the emission values in charge sustaining operation mode
range: electric range of the OVC HEV

This equation can be equally expressed in the following way:

$$X = UF \times X^{cd} + (1 - UF) \times X^{cs}$$

With

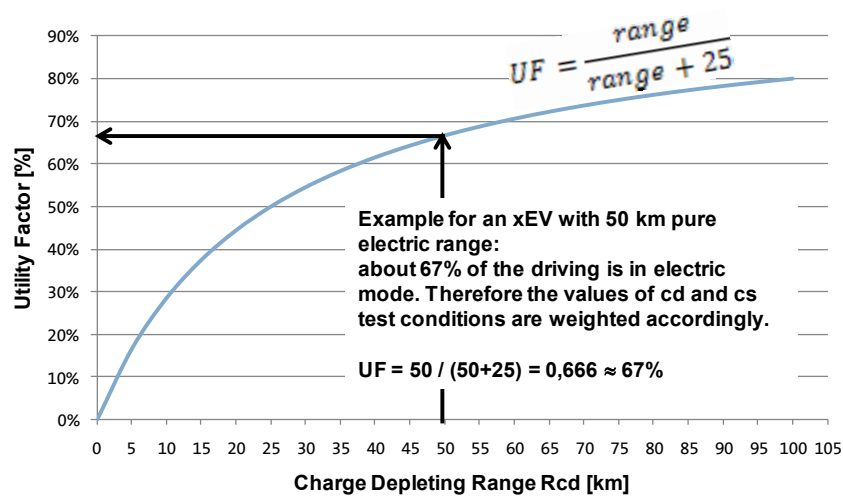
$$UF = \frac{range}{range + 25}$$

With

UF: Utility Factor – percentage of driving in charge depleting mode

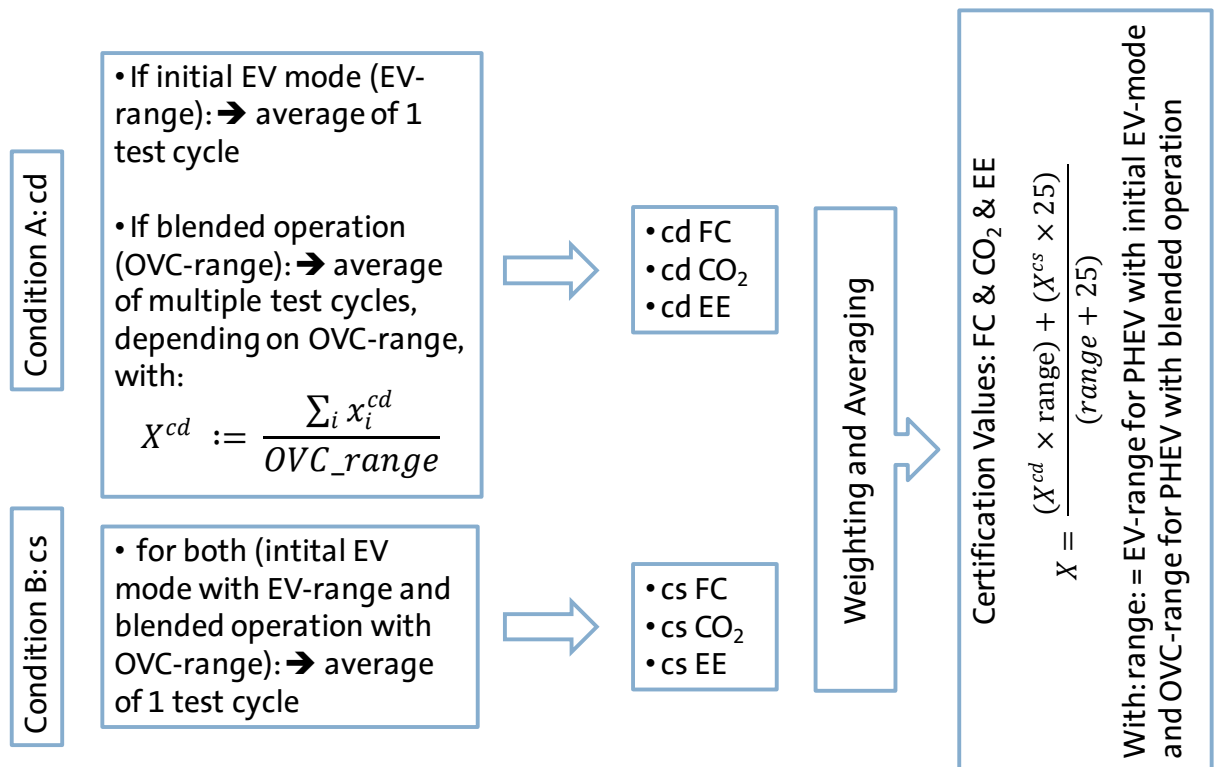
Thus, with this implicitly defined “Utility Factor” UF, the emission values for the charge depleting and the charge sustaining mode are weighted as a function of the electric range, see **Figure 5-2**.

Figure 5-2: Representation of the implicit utility factor of regulation UN ECE R101



By weighting the two conditions cd and cs in this way, one derives an average weighted fuel consumption and CO₂-emission number that can be compared to the certification numbers of conventional vehicles (see **Figure 5.3**).

Figure 5-3: ECE R101: Test- and Calculation Methodology – Weighting and Averaging of the Test Results



For vehicle concepts with pure electric operation and without ICE operation during charge depleting operation like E-REV, there are no fuel consumption and GHG-emissions associated to combustion of a consumable fuel at charge depleting operation mode.

In this case the equation for the weighted average of the fuel consumption and CO₂ emission results becomes:

$$X = \frac{X^{cs} \times 25}{range + 25} \quad (\text{for fuel consumption and CO}_2 \text{ emissions only})$$

In contrary, it is assumed that within charge sustaining operation mode no consumption of externally charged electric energy occurs, as per definition the charge sustaining mode starts when battery energy is depleted. Therefore during charge sustaining operation no further electrical energy from the battery is available (despite potentially some electrical energy from regenerative braking, but not originating from the electric grid). With this, the equation for the electric energy consumption reduces to:

$$X = \frac{X^{cd} \times range}{range + 25} \quad (\text{for electric energy consumption only})$$

Test procedure for battery electric vehicles (BEV)

As pure battery electric vehicles have an electric motor as sole propulsion source, there are no fuel consumption and exhaust emissions associated to these vehicles. Therefore the electric energy consumption is the only “emission” to be considered.

To determine the electric energy consumption of pure electric vehicles, they are driven two times on a chassis dynamometer through the standard driving cycle (“NEDC”) that is also used for conventional vehicles or hybrid electric vehicles.

Thus, there are no further averaging or weighting of the test results required.

5.2 Proposed GHG evaluation methodology to determine WTW emissions of electrified vehicle concepts

Up to now, for conventional vehicles and HEVs, only the GHG-emissions of onboard consumable fuels had to be considered. With the utilization of electrical energy that is externally produced and stored onboard, the GHG emissions of this electrical energy consumption must be considered in addition.

Assuming the electrical energy coming from renewable wind energy, these GHG-emissions will be zero. If the electricity is produced from coal, there will be significant GHG-emissions associated with the use of the electric energy in the vehicle.

Thus, the overall GHG-emission of an OVC HEV is also a function of the GHG intensity of the utilized electricity.

The WTW GHG emissions of OVC HEV are therefore the sum of the WTW GHG emissions associated with the combustion of the fossil fuel plus the amount of GHG emissions associated with producing and distributing the electricity to recharge the batteries:

$$CO2_{WTW} := CO2_{fuel_{WTW}} + CO2_{factor_{grid}} \times EE_{@ plug}$$

With:

$$CO2_{fuel_{WTW}} := CO2_{TtW} + \frac{14,2}{73,3} \times CO2_{TtW}$$

$$CO2_{TtW} := CO2 \text{ emissions according to test procedure}$$

$$WtT \text{ emission factor for petrol: } 14,2 \frac{g \text{ CO}_2}{MJ}$$

$$TtW \text{ emission factor for petrol: } 73,3 \frac{g \text{ CO}_2}{MJ}$$

$$CO2_{factor_{grid}} := \text{emission factor of the electric grid @ mains socket (production and distribution)}$$

$$EE_{@ plug} := \text{electric energy consumption @ plug (mains socket) according to test procedure}$$

For pure electric vehicles (BEV) the WTW CO_{2eq} emissions are only associated to the CO_{2eq} emissions of the consumed electricity that is externally produced, and thus the equation for BEV reduces like follows:

$$CO2_{WtW} := CO2_{factor_{grid}} \times EE_{@ plug}$$

5.3 Further improvement of the methodology

The above proposed methodology is a simple approach to approximate the GHG saving potentials of externally chargeable HEVs, based on anyhow available certification data.

For resource reasons, it was decided to abstain from additional “Advisor” vehicle simulations for the considered HEV and BEV configurations, but rather to utilize data obtained from the member company’s research and development programs.

Nevertheless, it is assumed that this approach delivers reasonable results that are sufficient to determine the impact of increased powertrain electrification on the GHG-emissions in the transport sector.

However, there are a lot of external parameters that influence the impact the GHG-emissions of electric vehicles and that are not yet considered:

- Charging strategy (overnight charging every night; intermediate charging during the day)
- Vehicle to Grid communication (“smart grid”)
- Electricity source depending on charging strategy; utilization of marginal electricity mix

Therefore the proposed methodology may be further elaborated in future, as knowledge on HEV and BEV configurations evolve, insight in “smart grid” opportunities develops and consumer charging behavior and consumer daily driving patterns are better explored.

6 GHG-Emissions from electricity

As explained above, the WTW GHG emissions are a function of the GHG intensity of the electricity charged to the xEV traction battery. This GHG intensity depends on various factors like:

- the type of electricity and its source (renewable; natural gas; mineral oil; coal; nuclear power)
- the national electricity mix
- the regional electricity mix
- the transmission/distribution losses of the grid
- the customers' contract with the electricity provider
- the time when the vehicle is charged (“marginal electricity mix”)
- future development of the respective electricity mix (fuel switch; increased share of renewable;..) and infrastructure changes (reduction of transmission losses; decentralized power generation;..)

Due to this fact, the WTW GHG emissions are not calculated for a certain electricity mix, but are given as a function of the GHG intensity of the electricity. It is then up to the user of this study to choose the electricity pathway that is most suitable for the respective analysis.

Nevertheless, for a holistic assessment of the impact of electrified vehicle concepts on the European road transport sector, one may want to choose the current EU-mix as a starting point.

The JEC WTW study uses a number of electricity pathways that are described in detail in WTT Appendix 2 (JRC, EUCAR, CONCAWE, 2011). The assessment of the electricity pathways includes the following process steps: extraction of the resource and processing – transport of the resource – distribution of the resource – power generation – electricity distribution. **Figure 6.1** shows an example of GHG calculation for electricity produced from natural gas (piped 7000km, with Combined Cycle Gas Turbine CCGT) as presented in *WTT Appendix 2*.

Table 6-1: GHG calculation of example of electricity pathway in WTT Appendix 2

		Standard step	Energy expended (MJx/MJelec)				Net GHG emitted (g CO ₂ eq/MJelec)			CO ₂	CH ₄	N ₂ O
			Total primary			Fossil				g/MJ	g/MJ	g/MJ
			Best est.	min	Max		Best est.	min	Max			
GPEL1a	Piped NG, 7000 km, CCGT											
	NG Extraction & Processing	1	0.05	0.03	0.11		7.2			2.5	0.19	0.000
	NG Transport	3	0.36				28.1			19.1	0.35	0.001
	NG Distribution (HP)	3	0.02				1.1			1.0	0.00	0.000
	Power generation (CCGT)	4	0.84	0.80	0.88		104.6			102.9	0.01	0.005
	Electricity distribution (LV)	5	0.03				0.0			0.0	0.00	0.000
Total pathway			1.31	1.09	1.39	1.31	141.0	128.0	145.8	125.6	0.55	0.006

Table 6-2 below shows selected electricity pathways that can be used for further analysis:

Table 6-2: Excerpt from WTT Appendix 2: selected electricity pathways as indication for GHG intensity from electricity

Pathway	Description	Net GHG emitted (g CO ₂ eq/kWhelec) Best estimate	Net GHG emitted (g CO ₂ eq/MJelec) Best estimate
GPEL1a	Piped NG, 7000km, CCGT	508	141
KOEL1	Coal, state-of-the-art conventional technology	968	269
OWEL1a	Electricity from municipal waste (local power plant)	28	8
OWEL1b	Electricity from municipal waste (large power plant)	100	28
WWEL1	Waste wood, 200 MW gasifier + CCGT	19	5
EMEL1	EU-mix electricity	467	130
WDEL1	Wind turbine (offshore)	0	0
NUEL1	Nuclear	16	4

The two pathways KOEL1 (coal) and EMEL1 (EU-mix electricity) are also represented as vertical lines within the figures (e. g. **Figure 8.1**) of *chapter 8* for orientation.

These values represent the current technical state of the art and current EU Mix. Because significant fleet penetrations of electric vehicles are expected in 2020 and beyond, it is relevant to look at the future development of GHG emissions of power generation.

The European Commission set an outlook on the carbon intensity for the power generation by 2030 in the publication "EU energy trends to 2030 — Update 2009" (EC 2010). Compared to the 2010 GHG emissions, the "Baseline 2009" assumes reductions of carbon intensity of -13% by 2020 and -43% by 2030.

EURELECTRIC, the Union of European Electricity Industry, has set up a future scenario in a study called "Power Choices" (EURELECTRIC, 2010), which indicates a potential way to carbon-neutral electricity in Europe by 2050. The results of this studied scenario can be used as an indication for future decarbonization potentials in xEV power supply. Approximate outlooks for the carbon intensity reduction of EU-grid mix is ~ -28% by 2020 and ~ -67% by 2030 both compared to 2010.

Weak points of both publications are that they use the emissions at power plant level only and do not use Well-to-Tank methodology and they also cover CO₂-emissions per kWh alone and not GHG emissions in CO₂-equivalents per kWh. Hence, an additional source shall be considered.

The Renewable Energy Snapshot 2010 (JRC 2010) shows the renewable share in electricity generation was almost 20% in 2009. If we use the EU grid mix (at WTT level) of 467 g CO₂eq/kWh and assume that the renewable share is 0 g CO₂eq/kWh, then the 80% non-renewable electricity generation emits 584 g CO₂eq/kWh. In the Renewable Energy Snapshot 2010 the JRC estimates that 35% to 40% of the electricity has to come from renewable energy sources by 2020. For the purpose of the WTW analysis an average renewable electricity share of 37.5% is chosen. Due to the uncertainty of the GHG emission development, it is supposed that the specific GHG emissions of renewable and the non-renewable electricity production remain at current levels.

Applying these assumptions leads to the estimate of 365 g CO₂eq/kWh, a reduction of approx. -22% compared to the EU-mix electricity of 467g CO₂eq/kWh. This reduction value for 2020 is in the range of the EURELECTRIC (-28%) and EC (-13%)

publications. An outlook beyond 2020 is not done in this report but it is fair to assume a continued decrease in EU mix electricity GHG emissions.

7 OVC HEV and BEV Vehicle Configurations

There are three xEV concepts considered: E-REV, PHEV and BEV. For each of these concepts a set of relevant data was established based on current experience with prototype- and development- vehicles. Due to the spectrum of various design solutions for each category, for most parameters a range was defined rather than an individual value.

Definition of xEV categories as used in this study:

Plug-In Hybrid Electric Vehicle (“PHEV”):

- HEV with off-board charging capability
- Limited electric performance depending on performance of electric motor
- PHEV with Initial EV Operation: starts as an EV then transition to hybrid operation. Always requires engine on for full performance
- PHEV with Blended operation: starts and drives like a conventional hybrid with engine on

Extended-Range Electric Vehicle (“E-REV”):

- Operates exclusively as an EV when battery energy is available
- Has full performance as an EV (e. g. top speed, acceleration)
- Auxiliary energy supply (e.g. a small ICE) only engaged when energy from battery is not available

Battery Electric Vehicle (“BEV”):

- Pure battery electric vehicle
- Only energy source: externally produced electricity, stored on-board
- Electric range mainly depending on battery size
- Cannot be driven further after battery has depleted

The most relevant data to categorize the xEV concepts and to execute the calculations are summarized below:

	Useable Battery Capacity	Range	Charging Efficiency	cd electric energy consumption @ plug	additional mass (against Reference Vehicle)
	[kWh]	[km]	[%]	[kWh / km]	[kg]
PHEV	3 - 6	20 - 40	85	0,16 - 0,19	200 - 300
E-REV	7 - 12	60 - 80		0,13 - 0,18	
BEV	13 - 22	120 - 160		0,13 - 0,16	

8 WTW Calculation Results

As outlined in *chapter 5*, the WTW results of externally chargeable vehicles depend on the vehicle configuration (e. g. electric range) and the GHG intensity of the utilized electricity. For comparing the results of externally chargeable vehicles with the results of conventional vehicles (as shown in *WTW Appendix I*), it is proposed to evaluate the WTW GHG-emissions of the different xEV categories as a function of the GHG intensity of the utilized electricity.

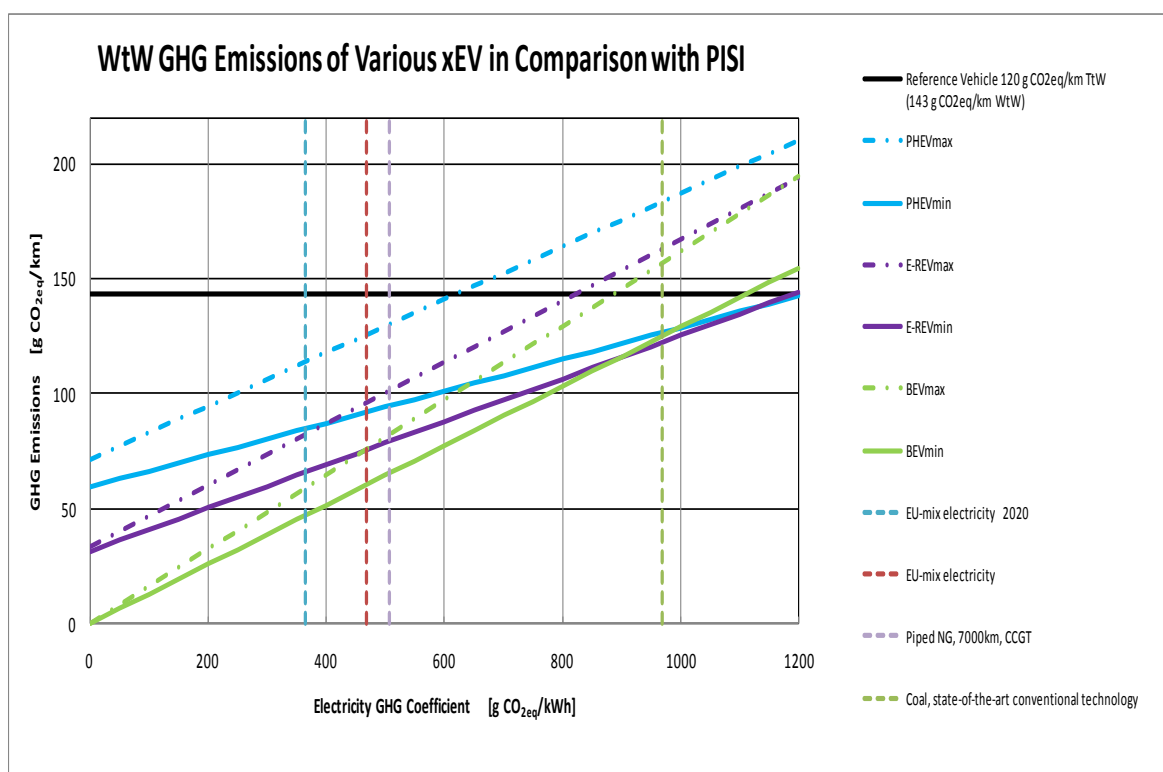
Based on the methodology laid down in *chapter 5*, one can easily create numbers for typical xEV configurations.

shows the WTW GHG-emissions of different OVC HEC and BEV configurations as a function of the GHG intensity of the electricity. For comparison, the WTW GHG emission of a conventional ICE reference vehicle with 120 g CO_{2eq}/kWh on TTW basis (which equals 143 g CO_{2eq}/kWh on a WTW basis) are shown.

As the GHG-emissions of conventional ICE vehicles are independent of the GHG intensity of the electricity, these vehicles are shown up as straight horizontal lines in the graph.

The curves of the xEV categories in contrast are continuously ascending straight lines. The starting points as well as the gradient of the curves depend on the vehicle efficiency and the vehicle configuration.

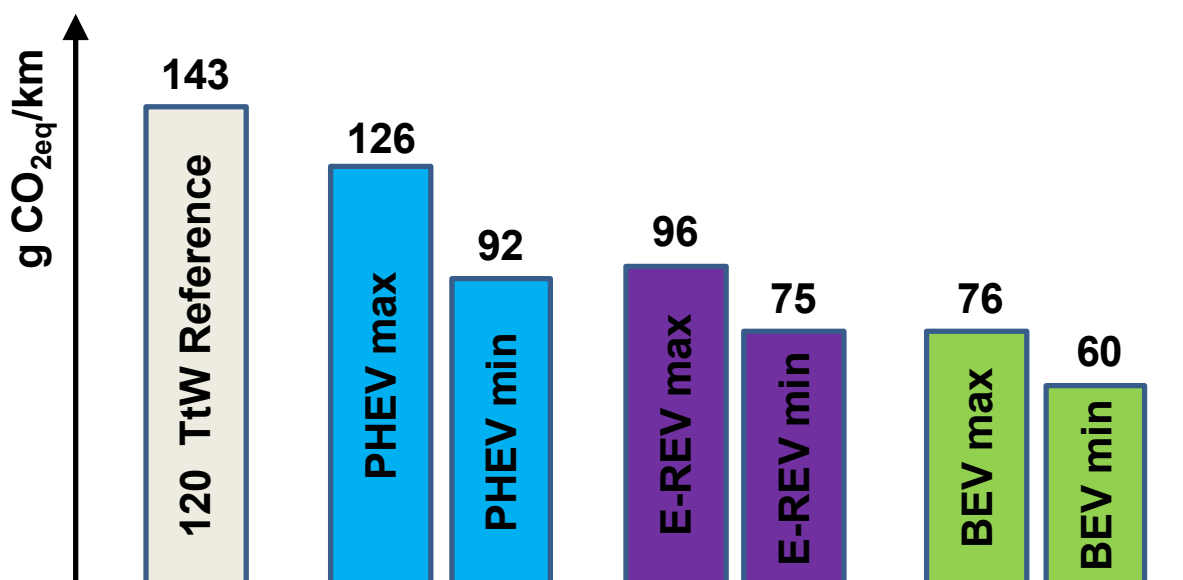
Figure 8-1: WTW GHG-emissions of different OVC Vehicle concepts as function the GHG intensity of the utilized electricity



Within the spectrum of xEV concepts and the assumptions taken in this report, the BEV shows the lowest GHG emissions and PHEV the highest, with E-REV concepts ranging in-between. However, based on the variety of design concepts and operating strategies, the GHG emission ranges of the xEV concepts are widely overlapping, especially for higher electricity GHG intensities above the current average EU mix.

For pure electric vehicles (BEV), the WTW GHG emissions are zero if the charged electricity is provided through renewable energy sources assuming the specific emissions to be 0 g CO_{2eq}/kWh. Depending on the mix, with an increased GHG intensity of the electricity, the WTW GHG emissions of BEV are increasing. At a GHG intensity of the electricity of about greater than 900 g CO_{2eq}/kWh, the BEV starts emitting more than the ICE reference vehicle. At the EU electricity mix of about 467 g CO_{2eq}/kWh the BEV emits about half as the reference vehicle, see **Figure 8-2**.

Figure 8-2: WTW GHG Emissions @ EU Electricity-Mix (467 g CO_{2eq}/kWh)

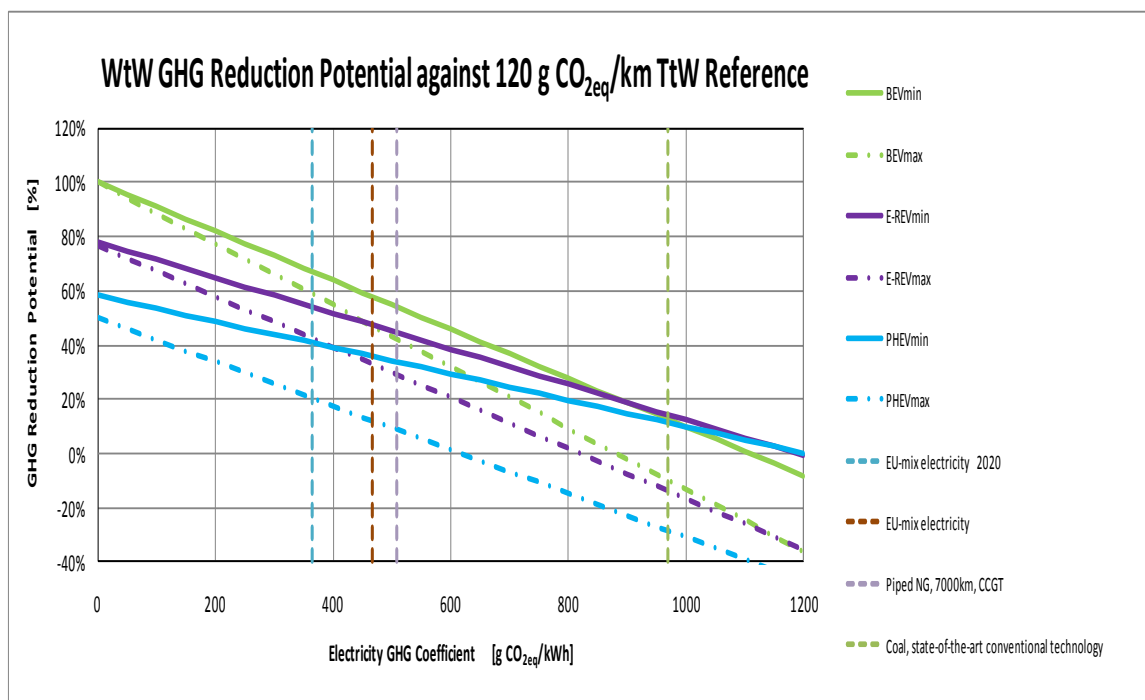


The PHEV concepts mark the upper spectrum of the GHG emission range of the considered xEV concepts. The curves for the PHEV configurations are starting at WTW GHG emission levels of about 60 – 70 g CO_{2eq}/kWh for pure renewable electricity utilization. The PHEV curve in the best case intersects with the “worst” BEV configuration approximately at an electricity GHG intensity of about 650 g CO_{2eq}/kWh. Beyond that point, this PHEV configuration performs better than the BEV. Reason is the fact, that at a certain point – depending on the vehicle configuration and the share of electric drive versus ICE utilization – the GHG emissions related to the electricity are becoming dominant over the GHG emissions associated to the on-board combustion of the fossil fuel. For this PHEV configuration, the GHG emission at EU electricity mix is about 64% of the reference vehicle. In the worst case, the PHEV configuration always shows higher CO_{2eq} emissions than the E-REV and the BEV. In the worst case, the WTW CO_{2eq} emissions of the PHEV are becoming worse than the ICE reference at about 600 g CO_{2eq}/kWh GHG intensity of the electricity.

The E-REV configuration is ranging in the middle between PHEV and BEV. The curves for the E-REV configuration are starting at about 30 g CO_{2eq}/kWh GHG emission levels, even for pure renewable electricity utilization. This results from the described test procedure for externally chargeable hybrid-electric vehicles (PHEV and E-REV) that establishes a weighted average fuel consumption determined from the two test conditions (charge depleting operation and charge sustaining operation). The E-REV curve in the best case intersects with the worst BEV configuration approximately at GHG intensity of EU mix. Beyond that point, this E-REV configuration performs better than the BEV. This is based on the fact, that at a certain point – depending on the vehicle configuration and the share of electric drive versus ICE utilization – the GHG emissions related to the electricity are becoming dominant over the GHG emissions associated to the on-board combustion of the fossil fuel. In this case, the GHG emission of the E-REV for EU electricity mix is also about half of the reference vehicle. In the worst case, the E-REV configuration always shows higher GHG emissions than the BEV, with the distance to the BEV becoming closer with higher GHG intensities of the utilized electricity. Up to a GHG intensity of about 800 g CO_{2eq}/kWh, the E-REV always performs better than the ICE reference. The “best” E-REV configuration always performs better with regard to WTW GHG emissions compared to the “best” PHEV configuration.

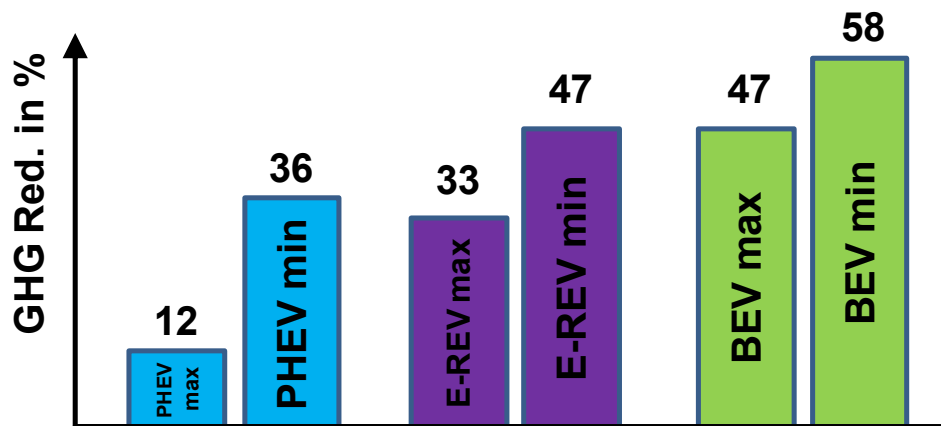
Another possible illustration is presented in **Figure 8-3**, representing the GHG-emission savings of different OVC HEC and BEV configurations as a function of the electricity GHG intensity in comparison to the conventional vehicle baseline. In this case the ICE reference again is a vehicle with 120 g CO_{2eq}/kWh on a TTW basis (which equals 143 g CO_{2eq}/kWh on a WTW basis).

Figure 8-3: GHG emission savings of different OVC and BEV vehicle configurations as a function of the GHG intensity of the utilized electricity in comparison to the conventional vehicle baseline (@ 120 g CO_{2eq}/kWh TTW = 143 g CO_{2eq}/kWh WTW)



All xEV concepts show the highest GHG saving potentials in the range of about 50 – 100%, when utilizing pure renewable electricity. With increasing GHG emissions of the electricity, the GHG savings are declining. Theoretically, at very high GHG emissions of the electricity (beyond 650 – 900 g CO_{2eq}/kWh), the GHG saving of the worst case of either xEV category are getting negative, meaning that in this case these xEV concepts would emit more CO_{2eq} than the ICE reference on a WTW basis. However, for the EU electricity mix of about 467 g CO_{2eq}/kWh, all xEV concepts show GHG emission savings of about 30% – 60%, with only the “worst” PHEV having a lower potential of about 12% saving, see **Figure 8-4**.

Figure 8-4: WTW GHG Reduction @ EU Electricity Mix compared to Reference
 (120 g CO_{2eq}/km TTW equal to 143 g CO_{2eq}/km WTW)



9 Discussion & Conclusions

As already discussed and outlined in chapters 5 and 8, the climate impact of externally chargeable HEV and BEV strongly depends on two main factors:

1. The utilization of electric energy from the grid versus the utilization of fossil fuel (which is a function of the initial pure electric range and the calibration strategy) and
2. The GHG intensity of the grid electricity.

In case of utilization of renewable electricity only, WTW GHG emissions in the range of 0 – 70 g CO_{2eq}/kWh can be demonstrated with the considered xEV concepts. Battery electric vehicles (including externally chargeable HEV with initial electric mode for travel distances below the pure electric range) in that case have no WTW GHG emissions at all. In case of OVC concepts with blended operation strategies (e.g. PHEV), the GHG emissions are in the upper range of 60 – 70 g CO_{2eq}/kWh. Considering the weighted average between the charge depleting condition and the charge sustaining condition for E-REV concepts as determined by the standardized test procedure delivers significantly lower GHG emissions.

With increasing GHG emissions from the considered electricity mix, the WTW GHG emissions of the OVC concepts are also constantly rising. Compared to an ICE reference vehicle (@ 120 g CO_{2eq}/km TTW = 143 g CO_{2eq}/kWh WTW), PHEV show higher GHG emissions if the electricity mix shows emissions beyond 600 g CO_{2eq}/kWh and E-REV and BEV beyond about 850 - 900 g CO_{2eq}/kWh in the worst case. Beyond 1100 to 1200 g CO_{2eq}/kWh electricity mix emissions, all best case OVC concepts have higher WTW GHG emissions than the ICE reference.

Considering the electricity mix at about 467 g CO_{2eq}/kWh the OVC concepts with a range of 60 – 96 g CO_{2eq}/kWh still perform much better than the ICE reference. Only the PHEV in the worst case shows slightly higher WTW emission of about 126 g CO_{2eq}/kWh, but still staying below the ICE reference.

Thus, for current EU-mix, total WTW GHG emission savings of up to 58% are possible. When utilizing renewable electricity, up to 100% GHG savings are possible with pure BEV and battery electric vehicles with range extender for travel distances below the pure electric range. OVC concepts with blended operation strategies or range extender with travel ranges beyond the electric range still show GHG emission savings of about 50 – 80%.

Finally, the conducted assessment showed the large GHG saving potential of different OVC concepts compared to an ICE reference vehicle of the same vehicle category. However, the potential savings are dependent on a lot of factors like the architecture and calibration strategy of the OVC concepts as well as the GHG emission of the electricity mix used to externally charge the batteries.

As a consequence, to further increase the environmental benefits of OVC concepts, it is essential to improve the electric range by further improving the battery technology, the overall vehicle/powertrain efficiency, weight reduction, aerodynamic measures, and so on.

In addition, the reduction of the GHG intensity of the electric grid as well as development of technologies for charging predominantly renewable energy (“wind to vehicle”) in smart grids are the most important enablers of future sustainable electric propulsion.

As outlined before, further updates of the WTW study may reconsider the input data based on better established data derived from increasing experience with serial production vehicles and more detailed simulations. However, for holistic assessments of the impact of electric vehicle concepts on the European transport sector, the data provided with this appendix is sufficient and accurate.

10 References

EUCAR. (2009). *The Automotive Industry – Focus on future R&D Challenges*.

EC – EUROPEAN COMMISSION. (2010). EU energy trends to 2030 — Update 2009; http://ec.europa.eu/energy/observatory/trends_2030/doc/trends_to_2030_update_2009.pdf

EURELECTRIC. (2010). *Power Choices - Pathways to Carbon-Neutral Electricity in Europe by 2050; Full Report*. <http://www.eurelectric.org/PowerChoices2050/>

JRC, EUCAR, CONCAWE (2011): *JEC Whell-to-Wheels Report*. <http://ies.jrc.ec.europa.eu/jec-research-collaboration/downloads-jec.html>

JRC – Institute for Energy. (2010). Renewable Energy Snapshots 2010, EUR 24440 EN

SAE. (2008). 2008-01-0458: *The Electrification of the Automobile: From Conventional Hybrid, to Plug-in Hybrids, to Extended-Range Electric Vehicles*. SAE TECHNICAL PAPER SERIES.

UNECE. *Regulation No. 101*. <http://live.unece.org/trans/main/wp29/wp29regs101-120.html>

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Abstract

WELL-TO-WHEELS ANALYSIS OF FUTURE AUTOMOTIVE FUELS AND POWERTRAINS IN THE EUROPEAN CONTEXT

The JEC research partners [Joint Research Centre of the European Commission, EUCAR and CONCAWE] have updated their joint evaluation of the well-to-wheels energy use and greenhouse gas emissions for a wide range of potential future fuel and powertrain options.

This document reports on the third release of this study replacing Version 2c published in March 2007.

The original version was published in December 2003.

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