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Comparison of Energy Consumption and Costs of Different Plug-in Electric Vehicles in European and American Context

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Abstract

With increasingly stringent CO_2 fuel economy regulations, the number of electrified vehicle options available to customers from car manufacturers has significantly increased in recent years. However, the market penetration of these vehicles significantly varies based on the powertrain configurations as well as the policies of the countries. To better understand the potential impact of current and future Plug-in Electric Vehicles (PEVs) on vehicle energy consumption, technology cost, cost of ownership and market penetration, a task force was formed by the Implementing Agreement for co-operation on Hybrid and Electric Vehicle Technologies and Programmes (IA-HEV). The task is composed of five integrated sections: vehicle energy consumption, component cost, vehicle cost, total cost of ownership (TCO) and market penetration. This paper discusses the methodology developed for estimating ownership costs. We also present the vehicle energy consumption and cost results developed for several powertrain configurations and standard driving cycles. The comparison of cost calculations for the U.S. and two of the largest European markets, Germany and France, show the importance of vehicle costs (particularly battery costs for PEVs), residual value, and the difference in taxes and incentives between the three countries.

Keywords: Cost of ownership, PHEV (plug-in hybrid electric vehicle), electric vehicle, energy consumption

1 Introduction

The electrification of automotive powertrains is a highly effective lever to reduce CO_2 emissions of passenger cars. In recent years, the number of electrified powertrain options available to consumers has increased significantly. However, the sales of these vehicles remain at a relatively low level [1]. One key reason for this is the additional cost of an electrified vehicle in comparison to a conventionally fuelled vehicle. The costs to acquire and operate a vehicle play an important role in the purchase decision of the majority of potential customers [2; 3; 4]. The total cost of ownership (TCO) calculation has been used extensively to compare different powertrain options and derive potential market shares for these [5].
To better understand the potential impact of current and future Plug-in Electric Vehicles (PEVs) on vehicle energy consumption, technology cost, cost of ownership and market penetration, a task force was formed by the Implementing Agreement for co-operation on Hybrid and Electric Vehicle Technologies and

Programmes (IA-HEV). The task itself is composed of five integrated sections:

- vehicle energy consumption
- component cost
- vehicle cost
- total cost of ownership (TCO)
- market penetration

Costs of ownership of hybrid and electric vehicles have been examined under IA-HEV Task 15 which indicated certain hybrid configurations may be more economical to own than others, but relatively simple models of ownership costs were used [6; 7]. More comprehensive metrics for ownership cost have been developed to compare the economics of different drivetrain vehicles in different markets. Extending the previous work of this task, this article examines the TCO for four different powertrains in three different countries for the year 2020. TCO are calculated for four different use cases, showing a variation of the vehicle's service time and yearly mileage. The objective is to show the competitiveness of PEVs and the influence of (monetary) policy measures in terms of the consumer's ownership cost.

2 Methods and Data

2.1 Relevant Cost of Ownership

The TCO considers all costs to a customer related to the purchase and operation of a vehicle during its service time. The exact definition of the TCO varies greatly. Hence, Mock [2] specifies a measure of vehicle ownership costs that are relevant to a consumer's purchase decision. This cost measure is termed as relevant cost of ownership (RCO). The RCO may be reported as a cost (net present value e.g,, in dollars) or, as is done here, in cost per km.

The RCO includes the investment cost (C_{Invest}), the up-front amount paid for the vehicle, including the purchase price and any fees, taxes, and incentives or disincentives (e.g., tax credit or bonus/malus "feebate"). Also relevant are all operating costs, which include the costs of fuel/energy (C_{Energy}), maintenance and repair (C_{Maint}) and any annual fees or taxes (C_{Fees}). Furthermore, a resale or residual value (V_{Res}), depending on a vehicle's age and total mileage, is considered [8]. The RCO (C_{RCO}) is the sum of the investment cost and the present value of the annual costs subtracted by the expected residual value [9]. Other cost factors, as insurance, risk aversion to new technology, and uncertainty of benefits of advanced technology to consumers [10] are not included. Also not included is the cost of limited range of the BEV (160 km). These might be important influences but are subjective, widely variable among consumers, and difficult to quantify [11]. However, neglect of the effective cost of the range limitation of the BEV might result in ownership cost estimates that appear low in comparison with the other powertrains.

RCOs were calculated for different powertrain options of a midsize passenger car (EU segment: D), using data and methods described below for energy prices and driving cycles relevant to France, Germany and the U.S. For the U.S., RCOs were calculated for two regions: the ten states that offer the most generous incentives for PEV purchase, as identified by a recent study of state incentives [12], and the remainder of the U.S.. The ten US states offering the most valuable incentives are: Arizona, California, Colorado, Georgia, Hawaii, Illinois, Louisiana, Pennsylvania, South Carolina, and Washington.

$$C_{RCO} = C_{Invest} + \sum_{t}^{N} \frac{\left(C_{Energy,t} + C_{Maint,t} + C_{Fees,t}\right)}{(1+i)^t} - \frac{V_{Res}}{(1+i)^N} \qquad (1)$$

$$C_{RCOperkm} = \frac{C_{RCO}}{N \cdot M} \qquad (2)$$

where

N =	ownership period, years
i =	interest rate
$C_{RCOperkm}$ =	relevant cost of ownership per km
M =	annual mileage in km

An interest rate of 1% was used here, representing a real, risk-free rate. Consumers often assign a low value to future energy savings [13; 14], which can be represented as a high effective discount rate. Rather than vary the interest rate, we examine two ownership periods, 4 and 12 years, to represent two different consumer perspectives of savings and costs.

2.2 Vehicle Simulation

Passenger cars of different powertrain configurations and component technologies were simulated using the Autonomie toolkit [15; 16]. The powertrains included are:

- Conventional spark-ignited (SI)
- Conventional compression-ignited (CI)
- Plug-in hybrid electric vehicle (PHEV), with SI combustion engine and a 32 km charge-depleting range
- Battery electric vehicle (BEV) with a 160 km range.

Vehicles technologies, in terms of cost of performance, are intended to be representative of vehicles that will be offered for sale in the year 2020. Each vehicle was sized to meet similar performance criteria (including acceleration and gradability). Vehicles were then simulated under the Urban Dynamometer Driving Schedule (UDDS), Highway Fuel Economy test (HWFET) and the New European Driving Cycle (NEDC) in order to estimate the fuel economy under each driven cycle. To represent on-road fuel economy under conditions relevant to U.S. driving, the UDDS and HWFET fuel economies were combined in accordance with the U.S. EPA/NHTSA "derived MPG-based formulas" used to report combined, adjusted ("window sticker") fuel economy values based on the UDDS and HWFET values [17]. The vehicle erngy consumption were calculated according to the standard test procedures of each country.
Characteristics of the four vehicles used in the presented analysis are listed in Table 1.

Table 1. Vehicle characteristics.

		Conv SI	Conv CI	PHEV	BEV
Vehicle mass	kg	1393	1456	1541	1437
ICE power	kW	114	99	82	
Electric motor 1/2 power	kW			60 / 47	101 / 0
Battery capacity, rated	kWh			8.6	32.0
Vehicle manuf. Cost	USD_{2010}	14,618	16,708	19,556	20,876
Of this, Battery pack manuf. cost	USD_{2010}			2,140	6,921
Fuel consumption, adjusted, UDDS/HWFET	MJ/km	2.629	2.274	1.013	
Electricity consumption, adjusted, UDDS/HWFET	MJ/km			0.283	0.739
Fuel consumption, NEDC	MJ/km	2.145	1.816	0.644	
Electricity consumption, NEDC	MJ/km			0.257	0.564

*The PHEV was modeled as having a split powertrain with blended operation in CD mode.

2.3 Vehicle Ownership Cost Assumptions

Cost models were used to estimate manufacturing costs for major vehicle components and subassemblies, which were then summed to give the total manufacturing cost of each vehicle [16]. Cost model parameters were assigned values based on input from U.S. DOE vehicle technology managers and industry experts, who provided a range of values from highly optimistic to pessimistic. Here, intermediate values for cost parameters were used. Vehicle retail price equivalent (RPE) values were calculated from vehicle manufacturing costs by applying an RPE factor of 1.5 [18].
For the purpose of comparing RCO, the same manufacturing costs and RPE factor were used for France, Germany, and the U.S., which neglects different costs of labor, materials and overhead in different countries, as well as possible pricing strategies used by automakers in different markets. The focus here is on the influences of incentives, driving distances, fuel prices, and ownership period on ownership costs.

Energy costs were estimated for the year 2020 based on the cost of crude oil projected in that year by the U.S. Energy Information Agency Annual Energy Outlook 2014 (AEO) Reference case [19]. These are what drivers would pay for fuel and electricity including taxes and are shown in Figure 1 and in Table 2.

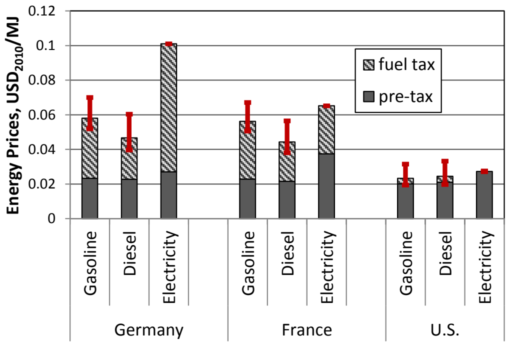

Figure 1: Energy prices assumed for year 2020 in the three countries. The top of each bar indicates the price driver pay. The hatched area is the tax portion. Error bars indicate ranges used in analyzing sensitivity to crude oil prices.

In the figure, error bars indicate the ranges of prices from the AEO 2014 Low Oil Price and High Oil Price cases (Brent spot prices 66.3 and 114.6 USD_{2010} per barrel, respectively), which were used to analyze sensitivity to crude oil price variations. The portion of the (Reference case) price that is tax is shown as hatched. Prices shown for the U.S. are national averages. Constant electricity prices were assumed, neglecting alternative rate structures, e.g., time-of-use, tiered rates, or special rates for PEVs.

Table 2. Energy prices assumed for Year 2020 (One USD_{2010} = 0.7929 EUR_{2010}).

	France	Germany	U.S.
	EUR_{2010} per l	EUR_{2010} per l	USD_{2010} per gal
Diesel	1.43	1.48	3.05
Gasoline	1.26	1.33	3.56
	EUR_{2010} per kWh	EUR_{2010} per kWh	USD_{2010} per kWh
Electricity	0.19	0.29	0.01

Investment costs include the vehicle manufacturing direct costs, manufacturer mark-up (accounted for by an RPE factor), sales tax or value-added tax (VAT), both applied to the retail price, incentive (or bonus/malus premium/charge) and initial registration/licensing fees or taxes. For the BEV in the U.S., the cost of home electric vehicle service equipment (EVSE) is also included in the investment cost. Given the capacity of the BEV, charging times using only a Level 1 charger do not meet the requirements of most consumers. A recent survey of California drivers found that only 12% of Nissan Leaf owners did not have Level 2 EVSE at home [20]. Due to the higher voltage level (240 V), EVSE cost are not considered for the European countries.

$$C_{Invest} = \left(C_{Manuf}\right)\left(F_{RPE}\right)(1 + VAT) - C_{Incentives} + C_{Fee,init} + C_{Batt\ repl} \qquad \text{France, Germany} \qquad (2)$$

$$C_{Invest} = \left(C_{Manuf}\right)\left(F_{RPE}\right)(1 + Tax_{Sales}) - C_{Incentives} + C_{Fee,init} + C_{Batt\ repl} + C_{Home\ EVSE} \qquad \text{USA} \qquad (3)$$

where

C_{Manuf}	=	Feebate (bonus/malus) or incentive, see Table 3
F_{RPE}	=	retail price equivalent, or mark-up, factor = 1.5 [18]
VAT	=	values-added tax (20% in France, 19% in Germany)
$C_{Incentives}$	=	Feebate (bonus/malus) or incentive, see Table 3
$C_{Fee,\ init}$	=	Fees payable upon vehicle purchase, see Table 3
Tax_{Sales}	=	State sales tax
$C_{Batt\ repl}$	=	Battery replacement (PHEV and BEV)
$C_{Home\ EVSE}$	=	Average cost of installing Level 2 EVSE, U.S. = 1,396 USD_{2010} [23]

U.S. registration and licensing fees and sales taxes on vehicle vary by state, or even county or city, and by many other factors. Averages of typical values of state sales taxes and fees payable upon vehicle purchase for a midsize sedan were estimated from data obtained from Edmunds [21] and averages, weighted by new vehicle registrations for year 2013 were calculated for the

U.S. Averages for the 10 states with most generous PEV incentives were calculated using PHEV or BEV market shares as weights. Registration fees for France and Germany are based on the European Automobile Manufacturers Association's ACEA Tax Guide [22].

U.S. state-level incentives were taken from a recent study [12], which included rebates, tax credits, reduced annual taxes and fees, HOV access, and lower fuel costs (due to lower tax or energy costs, or higher vehicle efficiency when using electricity), but not subsidies or incentives for home EVSE purchase or installation. It was assumed that BEV owners in the U.S. would install Level 2 EVSE at an estimated total cost for \$1,500 (1,396 USD_{2010}) [23]. EVSE incentives for home installation were averaged over the ten states and subtracted from the EVSE cost estimated for these states.

The projection for the bonus-malus-system in France in 2020 is based on extrapolation of the current regulation. Hence, vehicles with lower CO_2-emissions than 30 g/km (NEDC) receive a bonus between 189 USD_{2010} and 2649 USD_{2010}. For those vehicles with CO_2-emissions higher than 105 g/km (NEDC) a malus between 441 USD_{2010} and 6558 USD_{2010} is added. In Germany, the current legislation does not provide any incentives for PEV. Hence, these were not taken into account.

Battery replacement costs were included for the PHEV and BEV in the 12 year ownership case, since several automaker offer battery pack warranties for 8 years or 160,000 km, whichever occurs first. The replacement costs were estimated in the year 2028 from the projected manufacturing costs of 1,710 and 4,850 USD_{2010} for the PHEV and BEV, respectively. The cost applied to the 12 year ownership RCO was one half of the replacement cost with markup and tax, assuming that battery packs in half of the PEVs would need replacement in the 12-yr ownership period.

Maintenance and repair costs for France and Germany were estimated using the approach of Propfe et.al. [8]. U.S. maintenance and repair costs were taken from the Argonne AFLEET tool [24], except these costs for CI conventional vehicles were taken to be the same as for SI conventional maintenance and repair costs as indicated in a recent comparison of ownership costs for gasoline and diesel vehicles [25]. Annual taxes, registration and other fees were estimated for the U.S. based on data obtained from AAA [26]. No annual taxes were taken into account in France, consistent with the ACEA Tax Guide [22]. In Germany, the annual taxes were based on the displacement of the internal combustion engine as well as the CO_2-emissions of the vehicle as in the current legislation. Vehicles with CO_2-emissions 95 g_{CO2}/km and higher are charged 2.52 USD_{2010} per g/km over the 95 g_{CO2}/km limit. In addition, for SI conventional vehicles and PHEV another 2.52 USD_{2010} per 100 cm³ engine displacement are added. For CI conventional vehicles the rate amounts to 11.98 USD_{2010} per 100 cm³.

Residual values in all three countries after a service time of four years were calculated using regression equations developed by Propfe et.al [8] for each powertrain type. These equations were developed from European vehicle sales data and may not accurately model resale values in the U.S. Resale values are uncertain, particularly for PEVs, since the used PEV market is very immature. Residual values were estimated as a fraction of the total investment cost rather than purchase price, since the investment costs was assumed to more closely approximate the transaction cost as it include incentives and fees, since evidence suggests that incentives decrease residual values [27]. A residual value of zero was assumed after a service time of twelve years.

3 Results and Discussion

3.1 Relevant Cost of Ownership

The RCO in USD_{2010}/km for the four markets France, Germany, U.S. non-PEV states, and U.S. PEV states is shown in Figure 2 for the reference case oil price. The upper two plots (a) and (b) show the RCO values for a 12-year ownership period, and the lower two plots (c) and (d) show RCO values (narrow, dark bars) for the 4-year ownership case, taking residual value into account (shown as negative).

The bars in Figure 2 show the RCO disaggregated into costs per km of investment, energy, maintenance, repair and annual fees (M&R&F), and battery replacement (for PEVs).

Uniformly, across all results displayed in Figure 2, initial investment cost comprises the largest portion of RCO (followed by residual value, in cases where it is relevant). Annual costs comprise a smaller portion, especially over short time horizons, and, more specifically, annual costs associated with maintenance, repair, and fees comprise a larger portion than energy. Battery.

Table 3. Values for initial fees, incentives, and EVSE cost for year 2020 [USD_{2010}/MJ]. Incentives are shown as positive if they decrease the cost and negative if they increase the cost.

		Conv SI	Conv CI	PHEV	BEV
France	Incentives	-6,558	-2,522	0	2,649
	Initial fee	40	40	0	0
Germany	Incentives	0	0	0	0
	Initial fee	63	63	63	63
U.S. “PEV” states	Incentives	0	0	6,806	10,465
	Initial fee	186	186	186	186
	EVSE cost	0	0	0	1,204
U.S. remainder	Incentives	0	0	4,104	6,982
	Initial fee	137	137	137	137
	EVSE cost	0	0	0	1,396

replacement cost (PHEV and BEV) is the smallest component, except for the BEV in U.S.

Comparing RCOs between countries, PEVs compare favorably with conventional drive vehicles in France and the U.S. (in both PEV incentivized and other states); whereas, in Germany, the favorable PEV RCO may depend on battery replacement.

In the case of a 12,000 km yearly mileage and a twelve year ownership period shown in Figure 2 (a), PEVs have lower RCOs in France and in the U.S. states with the most generous incentives (“PEV” states). Although this is due in part to incentives, as discussed in section 3.3, lower energy costs for PEVs lead to lower RCO.

At 20,000 km per year, relatively efficient if more expensive vehicles travel a greater number of miles over which to amortize initial investment cost and accrue per-mile energy savings, so, accordingly, in the 20,000 km/a shown in Figure (b), PEV RCOs are lower than those of conventional vehicle RCOs in all countries. It should be noted that the effective cost of the limited range of the BEV (160 km) was not included in this analysis. Depending on driving needs and the variability of driving distances, it may not be feasible for some drivers to use a limited-range BEV 20,000 km per year.

The influence of battery replacement costs is modest for the PHEV, but sufficient to increase the RCO for the BEV to slightly higher than that of the PHEV in Germany. Longer-life batteries can make PEV with large batteries more economical to own.

In the cases of four year ownership period, the RCO, shown in Figure 2 shown in (c) and (d) as dark, narrow bars, is strongly influenced by the residual value. The residual value was taken to be a fraction of the investment cost (purchase price including taxes and fees minus incentives), and is therefore higher in France and Germany than in the U.S. In addition, the residual value is reduced by purchase incentives, which has the effect of reducing the influence of incentives on the RCO of PEVs.

However, resale values that increase with purchase price also decrease the influence of the higher cost of PEVs on RCO, which is notable for Germany, which having no incentive for PEVs show high investment costs and residual values for PEVs. Therefore, despite the higher purchase prices of PEVs, they show lower RCO values for a four year ownership period.

Residual values for PEVs are uncertain since the used market for these vehicles is only beginning and resale value data in this nascent market are limited and may not be representative of residual value retention of PEVs in the year 2020.

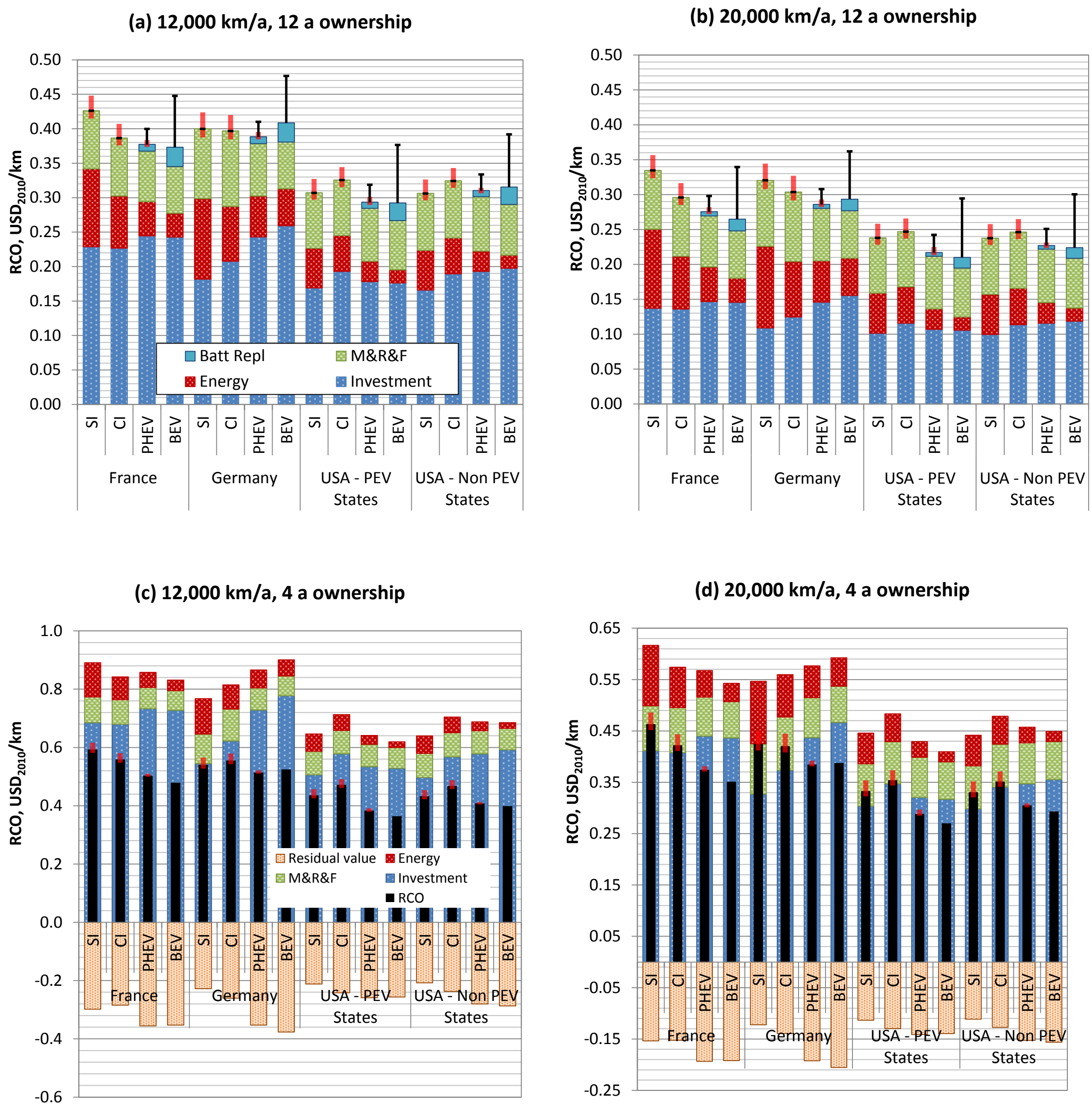

Figure 2: RCO for the four powertrains in the four regions estimated for (a) 12,000 km/year and 12-year ownership period, (b) 20,000 km/year and 12-year ownership period, (c) 12,0000 km/year and 4-year ownership period, and (d) 12,000 km/year 4-year ownership period. Red error bars indicate ranges of RCO under a range of crude oil prices, and black error bars in (a) and (b) show the ranges of RCO with a 30% increase in battery prices. Dark, narrow bars in (c) and (d) show the RCO (the sum of all the components).

3.2 Sensitivity of RCO to fuel prices and battery costs

RCO values were calculated over the ranges of fuel prices shown in Figure 1, which were taken to represent the response of prices to changes in crude oil prices (from roughly 20-40% above to roughly 10-15% below the AEO Reference case). The red error bars in Figure 2 show the corresponding range in RCO values. Generally, these are not highly sensitive to fuel prices. Electricity prices were not varied, since these are not correlated with crude oil prices and are generally less volatile [28]. For this reason, the RCO of the PHEV is much less sensitive to, and that of the BEV is independent of oil prices in this study, showing how PEV technology offers a hedge against oil price uncertainty. The sensitivity of the RCOs of SI and CI vehicles to fuel prices is lower for the four year ownership cases, since the fraction of the RCO that is fuel cost is smaller.

The RCO is independent of annual driving distance since it is cost per km (and fuel economy is assumed not to change with vehicle age), but the fraction of the RCO that is fuel cost is higher for the 20,000 km per year case than for the 12,000 km per year case, since more fuel is used over the ownership period. Sensitivity of the RCO to battery prices was analyzed by calculating RCOs with battery pack manufacturing costs 30% higher than that in Table 1; however battery replacement costs were unchanged. This sensitivity analysis was done only for the 12-year ownership period. The thin, black error bars in Figure 2 (a) and (b) show the effect on the PEV RCOs. The increase in RCOs for the BEV is quite large, making the BEV RCO higher than that of the other powertrains in each region and for both low and high mileage cases. Furthermore, the increase in PHEV RCOs is significant, so that in only the PEV states of the U.S. at 20,000 km per year case is the RCO of the PHEV lower than or equal to that of the other powertrains. Low battery costs are need to make PEVs economical to own, and longer driving distances favor PEVs, since the investment cost is a larger fraction of the RCO.

3.3 Policies

In order to examine effects of policy instruments such as tax rates, fees, and incentives in the three countries, the RCO values were further disaggregated to show pre-tax investment and fuel costs and taxes, fees for energy and vehicle purchase and ownership, and incentives. These disaggregated RCO values are shown in Figure 3 for the case of 12,000 km per year and twelve year ownership period. The stippled areas of bars show the pre-tax portion, and the hatched areas show the portion due to taxes and fees. Taxes on maintenance and repair and on battery replacement were not broken out and are not shown. The hollow portion at the tops of bars shows the portion due to incentives (the bonus in France and tax credits and other incentives in the U.S.). The total height of the bars, including the hollow portion is the RCO without incentives.

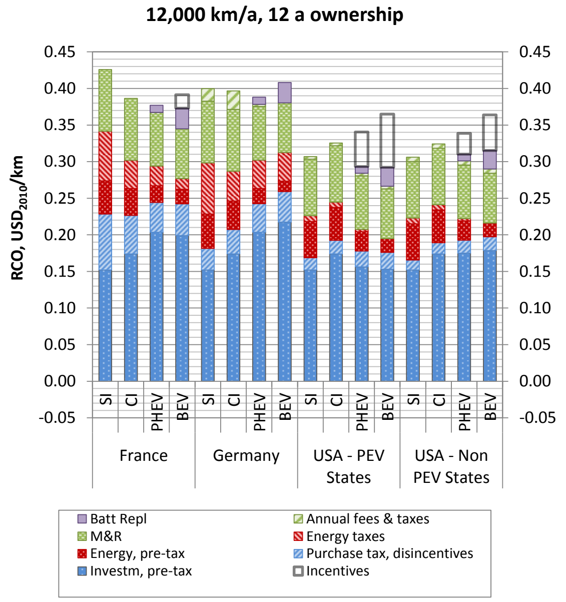

Figure 3: RCO for the four powertrains in the four regions estimated for 12,000 km/year and 12-year ownership period, disaggregated into pre-tax and tax portions, showing the RCO for with no incentives (top of hollow areas) and with incentives (top of filled areas).

Taxes and fees and the incentives per vehicle-km vary widely between the three countries for each vehicle. The difference in RCO values due to incentives for PEVs is apparent from the hollow portion at the tops of the bars for the PHEV and BEV. Incentives in the U.S. are specifically for plug-in vehicles having a battery capacity greater than 4 kWh, which is the case for the PHEV and BEV considered here. In France, where the bonus-malus system applies to all powertrains, the dependence on CO_2 emissions per km favors the BEV. In Germany, there are no purchase incentives for PEVs. The large incentives in the U.S. lower the RCO of the PEVs to just a little higher than that of the conventional SI vehicle in non-PEV states and lower than the conventional vehicles in the PEV states. Pre-tax energy costs are higher in the U.S. than in France or Germany due to the lower fuel efficiency estimated for the U.S. due to the more aggressive driving cycle (adjusted, combined UDDS/HWFET) than for Europe (for which the NEDC was used). The NEDC fuel efficiencies used here may not be realistic in light of evidence that actual on-road fuel consumption in European driving can be significantly higher (by more than 30%) than values measured in the NEDC [29].

In France, even though the bonus/malus incentives are less than the incentives in the U.S. PEV states, they are sufficient to decrease the RCO of the BEV lower than the other drivetrains. The high RCO for SI vehicles in France is due in large part to the large taxes and disincentives, in particular the large malus premium. This is not as high for CI vehicles which, being more fuel efficient, also have lower fuel costs per kilometer.

In Germany, despite the lack of incentives, the RCO of the PEVs is not much higher than the conventional vehicle RCO, owing to the higher fuel efficiency (lower energy costs per km), lower annual fees for PEVs, and in particular, high fuel taxes. Electricity tax in Germany (including fees for electricity distribution and due to the Renewable Energy Act) is relatively high, contributing to a slightly higher RCO for the PEVs.

Annual fees and taxes on vehicles contribute smaller amounts to the RCO, but these are significant in Germany, where they are higher for SI and CI vehicles than for PEVs.

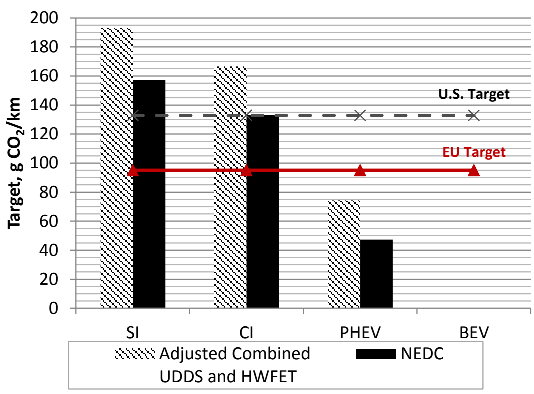

Figure 3: Carbon dioxide emissions per vehicle-km from the four powertrains under the US (adjusted, combined UDDS and HWFET) drive cycle and the NEDC drive cycle. Approximate targets for the year 2020 are shown for the U.S. and the EU

Carbon dioxide emissions per vehicle-km were calculated from the fuel consumption of each vehicle under the two drive cycles. These were compared with approximate carbon dioxide emission targets for the U.S. and the EU. The U.S. target for year 2020 is for a midsize car with a 46 ft^2 footprint (the product of wheel base and average track width) is 171 gCO_2/mi (133 gCO_2/km). This was adjusted upward by 25%, since adjusted fuel economy values were used to calculate the CO_2 emissions. Based on current legislation, an EU target for 2020 of 95 gCO_2/km was assumed [30].

The conventional vehicle emissions exceed the targets, while the PEVs are well below. Although targets are not standards (standards are set for automakers' fleets, not individual vehicles), this indicates that significant shares of PEVs in a fleet of vehicles can help the fleet to meet the standards, given the estimated fuel economies of the conventional vehicles.

4 Conclusion and Outlook

The relevant cost of ownership of conventional vehicles and PEVs were estimated for the year 2020 for France, Germany and the U.S. The components of RCO ranked by importance are initial investment cost, residual value, maintenance/repair/fees, energy costs, and possible battery replacement costs.

Within all three national contexts, longer ownership periods and greater annual mileages proved more favorable to PEV RCOs, due to the greater distance over which to amortize initial investment cost and accrue per-km energy savings. Additionally, examining CO_2 emissions shows that PEVs can contribute to meeting emissions targets in Europe and the U.S.

Sensitivity analysis revealed relatively small RCO changes due to oil price uncertainties, but showed that PEVs can still provide some hedge against oil price volatility—and potentially critical RCO changes due to battery technology sensitivities, wherein high-cost batteries yield unfavorable electric-drive RCOs in all cases.

This novel, internationally comparative RCO framework offers a foundation on which to build future analyses, including additional relevant powertrain configurations (i.e., gasoline-powered hybrid vehicles, battery electric vehicles with range extenders, etc.), more detailed consideration of real-world driving cycles and patterns, vetting RCO market implications with real-world PEV sales, and even the expansion of the study into other countries (with unique policies and markets).

References

[1] IEA-HEV, International Energy Agency, Implement Agreement for Co-operation on Hybrid and Electric Technologies and Programmes, Hybrid and Electric Vehicles – The Electric Drive Accelerates, Annual Report, 2014.

[2] Mock, P. Entwicklung eines Szenariomodells zur Simulation der zukünftigen Marktanteile und CO2 Emissionen von Kraftfahrzeugen (VECTOR21). Universität Stuttgart, Stuttgart, 2010.

[3] Plötz, P., Gnann, T., Wietschel, M. Modelling Market Diffusion of Electric Vehicles with Real World Driving Data – Part I: Model Structure and Validation. Ecological Economics, Volume 107, 411-421, November 2014.

[4] KPMG. Global Automotive Executive Survey 2014. http://www.kpmg.com/de/de/bibliothek/2014/seisei/2014-global-automotive-executive-survey.aspx, accessed February 10, 2015.

[5] Al-Alawi, B. M. Bradley, T. H., Review of hybrid, plug-in hybrid, and electric vehicle market modeling studies. Renew. Sust. Energ. Rev. 21, 190–203, 2013.

[6] Santini, D., Plug-in Hybrid Electric Vehicles, IA-HEV Task 15 Report, http://www.ieahev.org/assets/1/12/IA-HEV_Task_15_Report_Final_Feb__2014_%281%29.pdf.

[7] Santini, D., Zhou, Y., Stephens, T., Vyas, A., Kim, N. and Gallagher, K., Cost Effective Annual Use and Charging Frequency for Four Different Powertrains, SAE Technical Paper 2013-01-0494, 2013.

[8] Propfe, B., Redelbach, M., Santini, D., Friedrich, H. E. Cost Analysis of Plug-In Hybrid Electric Vehicles including Maintenance & Repair Costs and Resale Values. Electric Vehicle Symposium 26, Los Angeles, USA, 2012

[9] Redelbach, M., Özdemir, E. D., Friedrich, H. E. Optimizing battery sizes of plug-in hybrid and extended-range electric vehicles for different user types. Energy Policy, 73, 158-168, 2014.

[10] Greene, D. L., Uncertainty, loss aversion, and markets for energy efficiency, Energy Economics 33, 608-616.

[11] NRC, 2013, National Research Council Committee on Transitions to Alternative Vehicles and Fuels, Transitions to Alternative Vehicles and Fuels, National Academies Press, Washington, DC, 2013.

[12] Jin, L., Searle, S., Lutsey, N. Evaluation of State-level U.S. Electric Vehicle Incentives, The International Council for Sustainable Transportation, October, 2014, http://www.theicct.org/sites/default/files/publications/ICCT_state-EV-incentives_20141030.pdf, accessed February 8, 2015

[13] Helfand, G., Wolverton, A,. Evaluating the consumer response to fuel economy: A review of the literature. International review of Environmental and resource Economics, *5*(2), 103-146, 2011

[14] Greene, D. L., Evans, D. H., Hiestand, J., Survey evidence on the willingness of U.S. consumers to pay for automotive fuel economy, Energy Policy 61, 1539–1550, 2013.

[15] Autonomie, Argonne National Laboratory, see: http://www.transportation.anl.gov/modeling_simusimula/PSAT/autonomie.html

[16] Moawad, A. and Rousseau, A. Light-Duty Vehicle Fuel Consumption Displacement up to 2045, Argonne National Laboratory report ANL/ESD/11-4, December, 2013.

[17] U.S. Environmental Protection Agency and the U.S. Department of Transportation National Highway Traffic Safety Administration Revisions and Additions to Motor Vehicle Fuel Economy Label, Federal Register, Vol. 76, No. 129, July 6, 2011.

[18] Vyas, A., Santini, D. and Cuenca, R. "Comparison of Indirect Cost Multipliers for Vehicle Manufacturing," Technical memorandum in support of Electric and Hybrid Vehicle Cost Estimation Studies, Argonne National Laboratory, Argonne, IL, April, 2000.

[19] U.S. Department of Energy, Energy Information Administration Annual Energy Outlook 2014, May, 2014, http://www.eia.gov/forecasts/aeo/, accessed February 14, 2015.

[20] Tal, G., Nicholas, M. S., Davies, J., Woodjack, J. Charging Behavior Impacts on Electric VMT: Evidence from a 2013 California Drivers Survey, Transportation Research Board Annual Meeting, Washington, DC, January, 2014.

[21] Edmunds, What New Car Fees Should You Pay? http://www.edmunds.com/car-buying/what-fees-should-you-pay.html, accessed February 7, 2014.

[22] ACEA, Tax Guide 2012. European Automobile Manufacturers Association, Brussels, 2012

[23] Electric Power Research Institute, "Total Cost of Ownership Model for Current Plug-in Electric Vehicles", Palo Alto, CA 3002001728, 2013.

[24] Burnham, A. User Guide for AFLEET Tool 2013 User Guide for AFLEET Tool 2013 User Guide for AFLEET Tool, Argonne National Laboratory report, October 2013,

https://greet.es.anl.gov/afleet, accessed 8 Feb 2015

[25] Vincentric, 2013 Diesel Analysis, http://vincentric.com/Home/IndustryReports/DieselAnalysisNovember2013.aspx, accessed February 10, 2015.

[26] AAA, AAA Digest of Motor Laws, http://drivinglaws.aaa.com/laws/title-and-registration-fees/, accessed February 10, 2015.

[27] Holweg, P., Kattuman, A., The Incentive Whiplash: Sales Discounts and the Dynamics of Residual Value in the Automobile Industry, 2006, http://www.eea-esem.com/files/papers/EEA-ESEM/2006/2414/IncentiveWhiplash.pdf, accessed February 14, 2015.

[28] European Parliament, The Impact of the Oil Price on EU Energy Prices, IP/A/ITRE/ST/2013-03, February, 2014, http://www.europarl.europa.eu/RegData/etudes/etudes/join/2014/518747/IPOL-ITRE_ET%282014%29518747_EN.pdf, accessed February 14, 2015.

[29] Mock, P., Tietge, U. Franco, V., German, J., Bandivadekar, A., Ligterink, N., Lambrecht, U., Kühlwein, J. and Riemersma, I., From Laboratory to Road: A 2014 update, The International Council for Clean Transportation, September, 2014.

[30] European Union, Regulation (EU) No 333/2014 of the European Parliament and of the Council of 11 March 2014 amending Regulation (EC) No 443/2009 to define the modalities for reaching the 2020 target to reduce CO_2 emissions from new passenger cars, 2014.

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