IA-HEV 2014 Task 15 Report

Plug-in Hybrid Electric Vehicles

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Operating Agent

IEA INTERNATIONAL ENERGY AGENCY
HYBRID & ELECTRIC VEHICLE IMPLEMENTING AGREEMENT

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This study was authorized by the Implementing Agreement for co-operation on Hybrid and Electric Vehicle Technologies and Programmes (IA-HEV). Since 1993, IA-HEV has completed three 5-year phases and is currently in year 5 of Phase 4. Each phase has its own unique emphasis and objectives that aim to further the IA-HEV vision.

VISION: The electric drive will be used as the predominant transportation mode in a sustainable transport system that is preferably powered by renewable energy and does not produce harmful emissions.

MISSION:

- To supply objective information to governmental policy makers and decision makers at the national level, as well as to industry decision makers from utilities and automotive and component suppliers.
- To facilitate international collaboration in pre-competitive research and demonstration projects, and to function as a promoter for Research, Development, Demonstration, and Deployment (RDD&D) involving shared resources from multiple countries.
- To reduce energy consumption and harmful emissions and improve local and global air quality.

STRATEGIC OBJECTIVES FOR PHASE 4 (2009–2015):

- Produce objective information for policy and decision makers on hybrid and electric vehicle technology, projects, and programmes and their effects on energy efficiency and the environment.
    - This objective is carried out by topic-specific Task groups, which produce general and market studies, assessments, demonstrations, comparative evaluation of various options for applying these technologies, technology evaluations, and more.
- Disseminate the information it produces to the International Energy Agency (IEA) community, national governments, industries, and to other interested organizations.
- Collaborate on pre-competitive research projects and related topics and investigate the need for further research in promising areas.
- Collaborate with other transportation-related IEA Implementing Agreements and collaborate with specific groups or committees interested in transportation, vehicles, and fuels.
- Provide a platform for reliable information on hybrid and electric vehicles.

MEMBERS: Austria, Belgium, Canada, Denmark, Finland, France, Germany, Ireland, Italy, the Netherlands, Portugal, Republic of Korea**,** Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States.

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[1] The Swedish Energy Agency was the fourth of four IA-HEV participants originally voting in 2008 and 2009 to authorize Task 15. However, the Agency did not provide country experts to support the work of the Task.

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Key Findings

Consensus General Findings

- For the lithium-ion battery technologies evaluated (and in the context of recent fuel prices), parallel- and input-split (IS) plug-in hybrid electric vehicles (PHEVs) with 15–50 km (9–31 mi) of charge-depleting (CD) range have been estimated to be the most promising way to convert large quantities of grid electricity to miles of vehicle travel. Output-split (OS)-and/or series range-extended electric vehicles (ER-EVs) with ranges from 30–70 km (19–44 mi) and/or 150-km (93 mi) all electric vehicles (AEVs) were estimated to be less financially attractive.

- Unless oil prices increase, the broad success of battery electric drivetrains with long ranges and consistent all-electric operation capability (i.e., ER-EVs and/or AEVs) requires development of a less expensive, next generation of battery technology/chemistries.

- High fuel prices are important to the financial viability of and political support for electric drive.

- For personal use, the plug-in vehicles evaluated herein best fit the driving patterns typical of motorists in suburbs and towns, not of those in dense core city markets.

- For cost effectiveness, intensive use (in terms of both days per year and kilometres/day of use) is required.

Operating Agent's Summary of Technical Findings

- In an overview assessment of trade-offs between battery pack cost and desirable generic plug-in electric vehicle (PEV) pack kWh (powertrain technologies were not investigated), a German country expert paper estimated that battery costs must decline to 150 Euros per kWh before PEV packs of more than 15 kWh become somewhat attractive. Other participating U.S. and German country experts did not project that battery pack prices would fall to this level with current lithium-ion battery chemistries. At the pack costs projected by the others, PEVs with 5- to 10-kWh packs were consistently estimated to be most desirable in the trade-off analysis. For other papers estimating total cost of ownership for selected detailed powertrain simulations, the most financially attractive PEVs (i.e., parallel and input-split PHEVs) had packs with energy storage ranges of 3–11 kWh, a finding that was broadly consistent with the more generic trade-off analysis.

- Sharp declines in battery cost/kWh were projected by both German and U.S. country expert papers when moving from hybrid electric vehicles (HEVs) to blended-mode PHEVs. These cost reductions per unit increase of battery pack kWh slowed significantly for longer-range PHEVs and ER-EVs and for AEV packs. U.S. battery pack modelling indicated that cost declines slow once electrode thickness limits are reached (HEV packs use thin electrodes). Patterns vary by battery pack chemistry.

- Once electrode thickness limits are reached, battery pack energy cannot be increased without simultaneously increasing peak power. Given motorists' general desire for vehicles with long electric drive range, this technical property favoured development of output-split ER-EVs and AEVs with all-electric driving capability, thereby steering resources away from development of long-range PHEVs occasionally using engine power during battery pack charge depletion.

- Moderate-range PHEVs with battery pack power of about 60 kW (much lower than those of ER-EVs and AEVs and more than those of current HEVs) are estimated to be the most financially attractive first step toward mass vehicle electrification, particularly if charging at low kW at work and home. With moderate PHEV CD range, a 60-kW pack was estimated by U.S. experts to come at very low net cost relative to a PHEV with half as much pack power. In fact, a 60-kW pack was estimated to allow all-electric driving in nearly all intra-urban circumstances. When compared to delays in pack depletion in blended mode operation of PHEVs with 30 kW or less of peak pack power, the resulting rapid pack depletion assures effective use of supplemental daytime charging when available.

- The AEV is projected to be cost effective only in special circumstances where consumers use the vehicle intensively, yet require very little inter-urban driving. High initial cost (dominated by the battery pack) and high depreciation were estimated to deter AEV success.

- Current vehicle fuel use tests based on only two driving conditions (urban and extra-urban; city and highway) appear likely to overlook key driving patterns for the core market for parallel and input-split HEVs and PHEVs. For AEVs and for PHEVs and ER-EVs during CD operation, simulations imply that kWh/km (kWh/0.6 mi) consumption is highly nonlinear with average speed, causing a need for at least three estimates of kWh/km (kWh/0.6 mi) — at (1) urban, (2) suburban/rural, and (3) limited access highway driving conditions.

- Off-board vs. on-board thermal management for designs using all-electric operation requires study. Range reduction of AEVs at high and low ambient temperatures is a deterrent to market success.

- Vehicle-to-grid (V2G) discharging cannot aid in any early market success to be experienced by plug-in vehicles. Charging demand management (i.e., avoiding utility generation peaks) can help, however, so research and development (R&D) on simple, inexpensive charging management strategies is very desirable in the near term; V2G is a long-term option.

- For coal-intensive utilities, the implementation of smart utility metering and time-of-use electricity rates to incentivize the low–cost, overnight charging of plug-in vehicles is not environmentally desirable. This aspect of the smart grid needs to be decoupled from environmental advocacy for plug-in vehicles.

- Least-cost dispatch models used by electric utility financial evaluators do not credit wind and/or solar power use to plug-in electric vehicles. Formalized ties (such as purchase of Wind/Solar Energy Credits) or direct controls (for which meters would be required) may be necessary so that plug-in vehicles can receive credit for wind or solar use.

- Multiple methods of allocating coal, nuclear, natural gas, and renewable energy to the charging of PEVs were used by different experts from participating countries. There is no agreed-upon method of allocation.

- Even if a consistent method of evaluation is used, full fuel cycle emissions will be highly variable, depending on the regional and local electric generation mix.

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Acronyms, Abbreviations, and/or Definitions

General

CARB	California Air Resources Board. The regulatory agency with authority to specify more aggressive, environmentally motivated technology regulations for vehicle emissions than mandated in the rest of the United States. CARB has created technical incentives and forcing regulations for various plug-in vehicle technologies since the 1990s. PHEVs generally earn "partial" credits compared to AEVs.
CD	Charge depleting. The state of charge (SOC) of the battery declines until the battery is nearly discharged; CD mode is used after a battery charge in all types of plug-in HEVs and exclusively in AEVs.
CS	Charge sustaining. The SOC of the battery does not vary significantly; CS is always used in HEVs and used in all types of plug-in HEVs once the battery charge has been depleted.
CAFE	Acronym for U.S. Corporate Average Fuel Economy regulations.
DI	Direct injection. The most efficient method available of injecting fuel into a cylinder.
Electric machine	What are often labelled motors and/or generators are actually capable of operating in either manner — as a motor or a generator. An electric machine can be a motor-generator, or could be constrained to operate only as a generator or motor. In vehicles with electric drive, the electric machines typically can operate both as a motor and a generator.
FC	Fuel cell.
FIT	Feed-in-tariff. A legal requirement that operators of the grid must accept (and pay a specified amount for) input of renewable electrical energy. The FIT legally places renewables first in the dispatch order.
Fuel consumption	Fuel per unit distance moved. The forms presented and used in this document are as follows: litres per XX kilometres for gasoline, kilowatt-hours per XX kilometres for electricity.

GHG	Greenhouse gases (carbon dioxide, methane, and nitrous oxide for the studies cited here).
ICE	Internal combustion engine. The type used in conventional powertrains, either spark ignited (gasoline) or compression ignited (diesel).
kWh	Kilowatt-hours. Standard measure of energy use by electric vehicles and the electrical portion of energy use by PHEVs.
kW	Standard measure of electric power.
kph	Kilometres per hour.
L/100 km	Litres per 100 km (62 mi) — a measure of fuel consumption.
RPS	Renewable performance standard. A requirement that a specified share of electricity be provided by renewable resources, such as solar and wind.
TCO	Total cost of ownership.

Driving Cycles

Artemis Urban	Urban drive cycle developed by monitoring cars in Europe. The cycle is 3.4 km (2.1 mi) in length, with an average speed of 22.5 km/h (14 mi/h). Used to estimate European urban "on-road" estimates in Figure 1.
Artemis Road	Rural route drive cycle developed by monitoring cars in Europe. It is 13.7 km (8.5 mi) in length, with an average speed of 47.5 km/h (29.5 mi/h). Used to estimate European extra-urban "on-road" estimates in Figure 1.
Artemis Motorway	High-speed inter-urban driving cycle developed by monitoring cars in Europe. Autobahn driving included. The cycle is 62 km (38 mi) in length, with an average speed of 92.8 km/h (57.6 mi/h). Used to estimate European Motorway "on-road" estimates in Figure 1.
NEDC	New European Driving Cycle. The official driving cycle used both for official regulatory certification of European vehicles' fuel consumption

	and for consumer information. The cycle is 11 km (7 mi) in length, with an average speed of 33.6 km/h (20.8 mi/h).
UDDS	Urban dynamometer driving schedule, which is 12.1 km (7.5 mi) long and averages 31.4 km/h (19.5 mi/h). This cycle is used for official U.S. estimates of corporate average fuel economy, as well as for the U.S. Environmental Protection Agency's (EPA's) "5-cycle" test to estimate "real-world" fuel consumption for consumer information purposes.
HWY	Highway dynamometer driving schedule, which is 16.6 km (10.3 mi) long and averages 77 km/h (48 mi/h). Only this cycle and the UDDS are used for official U.S. estimates of corporate average (certification) fuel economy. They are also two of the cycles used in the EPA's "5-cycle" test to estimate "real-world" fuel consumption for consumer information purposes.
LA92	A driving cycle derived from Los Angeles, California, driving in 1992. Average speed is 40 km/h (25mi/h). The average and maximum acceleration rates are similar to those of the European Artemis Urban cycle but with a much lower stop frequency. Used to estimate U.S. urban "on-road" estimates in Figure 2.
KC2	A driving trace for a single vehicle within a sample of vehicles driven in Kansas City, in the United States. Average speed is 49 km/h (31 mi/h). Used to estimate the U.S. suburban "on-road" estimates in Figure 2.
US06	A dynamometer driving schedule representing aggressive, high-speed driving; it is 13 km (8 mi) long, with an average speed of 77 km/h (48 mi/h), but with a top speed that is 34% higher than that of the HWY cycle and with a maximum acceleration rate that is 157% greater than that of the HWY cycle. It is much more aggressive than nearly all U.S. driving cycles. This cycle, broken down into a city and highway portion, is used only in the EPA's "5-cycle" test to estimate "real-world" fuel consumption for consumer information purposes. Only the highway portion of it was used in this study.
US06 Highway	A portion of the US06 cycle, averaging 97 km/h (60 mi/h), that accounts for the majority of the weight of the HWY fuel consumption estimate used for consumer information in the United States. It is used to estimate U.S. case highway "on-road" estimates in Figure 2.
US06 City	A portion of the US06 cycle, averaging 35 km/h (22 mi/h), that accounts for a minority of the weight of the CITY fuel consumption

	estimate used for consumer information in the United States. Although about the same average speed as the UDDS cycle, it has been estimated to require four times as much power due to very high rates of acceleration (Santini and Burnham, 2013). It has about 30% higher peak acceleration than the European Artemis urban cycle, which was the design cycle determining peak electric power values for all-electric operation of base case PHEVs. The US06 City cycle also has nearly twice the average acceleration rate as the Artemis Urban cycle. It was not used in this study.
SC03	A dynamometer driving schedule representing slightly more aggressive driving than the UDDS, averaging 35 km/h (22 mi/h). This cycle is used only in the EPA's "5-cycle" test to estimate "real-world" fuel consumption for consumer information purposes. It was not used in this study.
New U.S. "5-cycle" window sticker fuel consumption	A recently developed, weighted average of several driving tests, using information from tests using the UDDS, HWY, US06 City, US06 Highway, and SC03 driving cycles. It adds cold (−6.67°C [20°F]) operation (using the UDDS cycle) and hot (35°C [95°F]) operation with air conditioning on, using the SC03 cycle. Resulting fuel consumption is higher than the inverse of the old window sticker fuel economy value(s). Both city and highway values are estimated, as well as a weighted average of the two — the combined cycle. The new 5-cycle method better represents fuel use in "real-world" or "on-road" driving than did prior estimates, which were based on only two cycles, the UDDS and HWY, run at 24°C (75°F). In this report, the UDDS, HWY, and US06 Highway portion were used in simulations. Extreme temperature effects were not simulated.

Powertrain Descriptors

CV	Conventional vehicle. Without a modifier, the acronym implies a gasoline ICE in this document.
HEV	Hybrid electric vehicle (always gasoline in this document). Uses CS operation only.
PHEV	Plug-in hybrid electric vehicle (always gasoline in this document). After charging, CD runs first, then CS.
PHEVXX	Where "XX" is filled in by the number of kilometres of the vehicle's CD range as measured by a specified drive cycle. In this report, "XX" provides an estimated urban driving range, which should be thought

of as driving within the core city of a large metropolitan area. Range can vary considerably if the vehicle is driven differently.

Blended CD	Where both battery electricity and fuel-derived mechanical power are used in CD.
ER-EV	Extended range electric vehicle. Although a type of vehicle in the United States called an extended range electric vehicle (EREV) is included in this definition, the definition is not confined to this vehicle type. In the United States, the term EREV is attached to a particular powertrain technology called the output-split powertrain. Our use of ER-EV is more generic. Indeed, some regard an ER-EV as a kind of PHEV. However, in this report, we emphasize the role of electrical power in determining the cost and performance of different electric drive vehicles. Thus, the distinguishing factor in this report is a power level of the battery pack (and electric machines) that allows all-electric operation in all driving conditions and even in the event of very hard acceleration.
AEV	All-electric vehicle. A vehicle achieves motion by use of battery electric energy and power only. Most AEVs have been designed with one electric machine, as is the case in this report.
PEV	Plug-in electric vehicle of any type — PHEV, ER-EV, or AEV.
Series	No mechanical power goes to the wheels. Only electric drive can power the wheels, and two on-board electric machines are required. This system often has no transmission, using only one gear. The engine runs a generator that can charge the battery, power the motor, or do both.
Parallel	This is a powertrain with only one electric machine. Engine power pathways include these: (1) from engine to electric machine (as generator) to battery and later back to the electric machine (then acting as a motor), or (2) from engine to transmission to driveline to wheels. Both the electric drive and mechanical drive, in parallel, can simultaneously power the wheels. This system can use either a manual or automatic transmission.
Split	A very complex system where two electric machines are used to provide a mix of attributes of the series and parallel powertrains. A planetary gear system is used instead of a transmission. The planetary gear system is comparable to an automatic transmission because no manual shifting is involved. In this report, two types of split powertrain are evaluated. The input-split has the planetary gears between the

engine and the two electric machines, whereas the output-split places the planetary gears between the two electric machines.

Charging Infrastructure

V2G	Vehicle-to-grid, a package of technologies that could allow parked PHEVs to be used to back up the grid or to stabilize fluctuations in electrical load on the grid. Electrons flow from the vehicle back into the grid, perhaps supporting a load several miles distant.
EVSE	Electric vehicle supply equipment — an apparatus that safely connects the plug-in electric vehicle to an electrical circuit. The EVSE may include sophisticated measurement and electronic transactions software to enable convenient, accurate charging and payment record keeping.
Level 1	A descriptor of a standard for EVSE set by the Society of Automotive Engineers that uses alternating current (AC). This EVSE category applies to low power level charging in the United States. The Level 1 EVSE that is sold with plug-in vehicles usually operates at 1.4 kW, though lower and higher kW levels are allowed and are in use.
Level 2	A descriptor of a standard for EVSE set by the Society of Automotive Engineers that uses AC. This EVSE category applies to residential charging at about the same kW level in both Europe and the United States (~3.3 kW). ER-EVs and PHEVs are generally set to a maximum of about 3.3 kW charging, whereas most AEVs now use higher standard power. AEV Level 2 charging at 6–10 kW is also enabled by this EVSE standard.

Power Plants

GT	Gas turbine electric power plant (is inefficient and used infrequently for peak demand).
NGCC	Natural gas combined cycle electric power plant (is efficient and used frequently).

Batteries

NiMH	Nickel metal hydride (a battery chemistry used in many existing HEVs and some previous models of AEVs).

Li-ion	Lithium-ion (a “family” of battery chemistry candidates for many recently introduced HEVs, PHEVs, and AEVs).
SOC	State of charge of a battery pack. Full = 100%, empty = 0%.
LFP-G	Battery chemistry: lithium-iron phosphate cathode with graphite anode.
LMO-G	Battery chemistry: lithium manganese oxide cathode with graphite anode.
LMO-TiO	Battery chemistry: lithium manganese oxide cathode with titanate anode.
NCA-G	Battery chemistry: nickel-cobalt-aluminum cathode and graphite anode.
NMC	Battery chemistry: lithium nickel manganese cobalt oxide cathode.

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1 Introduction

Within member countries participating in the International Energy Agency (IEA) Implementing Agreement (IA) on Hybrid and Electric Vehicles (HEV), the transportation sector ranks high in national oil use and greenhouse gas (GHG) emissions. Plug-in electric energy for transportation is seen as one way of reducing oil use and GHG emissions and/or improving local air quality. Using electricity from the grid — because it reduces oil use per mile of service delivered — leads to greater energy security. The ability of vehicles using plug-in electric drive to eliminate oil use has become more attractive in recent years as (1) its technical and economic feasibility have improved; (2) oil prices have increased significantly on average, and (3) oil prices have become more volatile. In recent years, concerns about possible actual restrictions of supply have emerged. Depending upon the mix of generation sources used, the number of kilometres of vehicle energy provided via the grid can modestly or even dramatically reduce GHG emissions. Modest reductions are possible when natural gas is used to generate electricity. Dramatic reductions are possible, however, when zero-emission sources of electricity generation — such as nuclear, wind, or solar — are used. Even when fossil fuel power plants are used, plug-in electric vehicles (PEVs) can eliminate tailpipe emissions and noise, reducing the exposure of populations near roadways. Improving knowledge about damage to health from particulate matter has led to an increased emphasis on eliminating tailpipe and “upstream” emissions caused by motor vehicles, driving up the costs of conventional powertrains.

Thus, more than ever, achieving a low consumption of refined petroleum products per kilometre of operation is becoming a principal and primary focus for powertrain product development, with reduced overall carbon emissions also a high priority. By implementing the positive synergism between electric drive and internal combustion, hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs) enable sharply reduced fuel consumption. The PHEV concept is increasingly seen as an excellent, implementable powertrain that is a logical first step toward a long-run transition to more sustainable transportation.

Accordingly, in 2008 and 2009, under the IEA IA-HEV umbrella, four nations — Canada, France, Sweden, and the United States — formally agreed to initiate a study of PHEVs. The study was managed at no charge to other participants by a Canadian operating agent — Charles Thibodeau — through 2010. From 2008 to 2010, active study participants were Canada, France, and the United States. In 2010, Canada could no longer sustain its support. At that time, Germany joined the IEA IA-HEV and indicated a desire to join Task 15. From 2011 to 2013, the study was managed at no charge to other participants by an operating agent from the United States — Danilo J. Santini. From 2011 to 2013, active study participants were France, Germany, and the United States. Although Sweden formally supported the task at the outset, the Swedish Energy Agency was unable to support country experts to contribute to the study.

This study has focused on PHEVs rather than on “pure” all-electric vehicles (AEVs). PHEVs are capable of operating entirely on electric power for a limited number of km and then operating as hybrid electric vehicles (HEVs), using gasoline efficiently for the remainder of longer trips. The study examines PHEV powertrains with four separate designs. Two of these four are assigned the acronym “extended range electric vehicles” (ER-EVs) because they have enough battery pack power to allow all-electric operation in all driving conditions and even in the event of very hard acceleration. A variety of different battery power and energy levels are incorporated into the four different PHEV powertrain systems. A search of the results yields the lowest total cost of ownership (TCO) by powertrain type, and within that powertrain type, the lowest-cost combination of battery pack power and energy.

A combination of circumstances has led many nongovernmental organizations, automotive companies, and governments to bank upon the promise of both the technological and financial success of HEVs, PHEVs/ER-EVs, and AEVs. These are significantly more powerful and more energy-dense battery technologies made possible by lithium-ion chemistries and by much higher average gasoline prices than were experienced in the 1990s.

2 Objectives

2.1 2008–2010

When the study was originally designed under Canadian management, the original work plan was rather ambitious. At the initial organizational meeting in 2008, four different topical subtasks were adopted under Task 15. These were as follows:

1. Advanced battery technologies and components
2. Merits and policy issues
3. Charging and grid issues
4. Marketability and impacts

After some significant progress was made on these tasks in 2008 and 2009, a task extension and revision to the work plan was adopted during the transition of nations and operating agents. In addition, because of sustained high oil prices, the IEA IA-HEV membership began expanding, and support for new tasks emerged. In effect, some items within the subtask work intended in the 2008 plan became new tasks under the IEA IA-HEV management.

2.2 2011–2013

The remaining topical subtasks — redefined for a narrowed Task 15 focus — were:

1. Powertrain attributes and vehicle lifetime use costs
2. Policy issues and marketability

During the 2011–2013 time period, multiple country experts from Germany, France, and the United States met, exchanged views, and planned subtask research. Both Germany and France had participating country experts from two research organizations, while the United States provided two experts and the Operating Agent from one institution (see pages iv and v). France hosted two country expert meetings in 2011, and the United States hosted the final meeting in 2012. A subtask meeting with the Operating Agent and two German country experts was held in Switzerland, with IEA IA-HEV support, which also took place in 2011.

For subtask 1, country experts from France's IFP Energies Nouvelles and the United States' Argonne National Laboratory (Argonne) Center for Transportation Research conducted joint vehicle simulation/modelling research on powertrain attributes for multiple types of plug-in hybrids, with varying amounts of electric drive power and energy, as well as different powertrain configurations (DaCosta et al., 2012). Country experts from France's IFP Energies Nouvelles, the Institute of Vehicle Concepts at the

German Aerospace Center, and Argonne's Center for Transportation Research collaborated on the topic of lifetime vehicle use costs, incorporating selected cases from the vehicle and powertrain modelling results (Rousseau et al., 2012). Subsequently, U.S. country experts simulated an expanded subset of some types of powertrains, focusing on those available in the United States (Santini et al., 2013b). From the time of approval of the modified workplan until Task 15 completion, fifteen papers were completed with one or more participating country experts co-authoring each of the papers. Five presentations were delivered, and two supporting reports on battery technical attributes and costs were produced. A workshop on Batteries in Extreme Temperatures was co-hosted under Task 10 leadership in October 2012.

These publications and the workshop findings support the completion of this summary report of Task 15.

Topics covered in the prepared papers include the following:

1. The best consumer niche(s) for multiple PHEV technology options (papers addressing this topic include: Zhou, Vyas, and Santini [2012]; Propfe et al. [2012]; Plotz, Kley, and Gnann [2012]; Rousseau et al. [2012]; Santini et al. [2012]; Santini et al. [2013b]; and Santini and Burnham [2013]).
2. Evaluation of vehicle purchase and operations costs (Propfe et al. [2012]; Rousseau et al. [2012]; and Santini et al. [2013b]).
3. Effects of taxes — road, registration, fuel, etc. (addressed by Dallinger et al., a participating country expert from Germany's Fraunhofer Institute in a 2010 conference paper).
4. Vehicle regulation impact on powertrain choice (DaCosta et al. [2012]; Rousseau et al. [2012]; and Santini et al. [2013b]).
5. Infrastructure/charger attributes and costs (Santini [2011]; Rask, Bohn, and Gallagher [2012]; Gnann, Plotz, and Kley [2012]; and Santini et al. [2012]).
6. Choice of marginal, incremental, or average for evaluation method (Elgowainy et al. [2012a,b]; Dallinger, Wietschel, and Santini [2012]; DaCosta et al. [2012]; and Santini and Burnham [2013]).
7. Net petroleum use reduction (DaCosta et al. [2012]; Rousseau et al. [2012]; Santini et al. [2013b]; and Santini and Burnham [2013]).
8. GHG reduction vs. hour/season of charging; generation type (Elgowainy et al. [2012a,b]; DaCosta et al. [2012]; Dallinger, Wietschel, and Santini [2012]; and Santini and Burnham [2013]).

3 Results

Since the restructuring of Task 15, seventeen project-supporting publications were published, and five presentations were delivered. Seven of these were conference papers delivered at the Electric Vehicle Symposium 26 (EVS26) meeting in May of 2012. Immediately after this conference, a final Task 15 meeting was held and a consensus was developed on key findings to be emphasized in this report. This consensus was reported by vice operating agent Aymeric Rousseau at the IA-HEV Executive Committee meeting in Stuttgart, Germany, in October of 2012. Six publications developing supporting analysis, and a joint workshop under Task 10 followed the final Task 15 meeting.

From December 2007 through December 2009, four activities were concluded, the findings of which were very important for task progression: a meeting on the world lithium supply, a session on the cold-temperature performance of PHEVs, a conference workshop on battery issues, and a workshop evaluating grid-connected vehicles in support of integration of wind into the grid. Highlights of these events and activities follow.

3.1 World's Supply of Lithium, 2008

In December 2008, a meeting on the "World's Supply of Lithium," which was co-sponsored under the IA's Task 10 and Task 15, was conducted in Charlotte, North Carolina, in the United States. The general conclusions indicated that lithium (Li) availability will not be an issue.

There could, however, be legitimate concern about reliance on other materials. Examples include cobalt and rare earths (neodymium and dysprosium for magnets and motors). Rare earths may require an order of magnitude increase in mine production in the next 10 to 12 years.

3.2 Extreme Temperature Performance of Electric Drive Vehicles, 2009

In September 2009, during the PHEV Conference in Montreal, Canada, two sessions were organized by the Canadian Operating Agent, Charles Thibodeau, and country agent, Isobel Davidson. A special session on battery issues was organized and hosted by Davidson, and a regular conference session on the cold temperature performance of electric drive vehicles was organized and hosted by Thibodeau. Davidson's session reinforced the argument that world lithium supplies can support widespread adoption of more vehicles with electric drive, although potential political difficulties in managing the growth of lithium production were discussed. Also discussed were efforts to create a cell combining a lithium iron phosphate (LFP) anode with a titanate (TiO) cathode, as well as efforts to develop an improved lithium manganese oxide with graphite (LMO-G) cylindrical cell and battery pack for use in a PHEV with 16 km (10 mi) of range. The former chemistry has not been adopted by manufacturers of PHEVs or ER-EVs (the focus of this task). The latter has been adopted in several PHEVs. Efforts to develop a small PHEV delivery van using advanced lead acid batteries were also discussed. No commercial PHEVs using lead acid batteries have since been introduced.

3.2.1 Extreme Temperatures: Conference Session Results, 2009

General 2009 conclusions regarding extreme temperature performance are as follows:

- Extreme conditions, such as the cold winters and hot and/or humid summers found in the interior regions of several major industrialized nations of the Northern Hemisphere, pose unusual challenges to the performance of batteries when compared to islands and coastal locations with less severe temperature fluctuations.

- For early personal-use PHEVs developed by retrofitting HEVs, which used a combination of nickel metal hydride (NiMH) and retrofitted lithium-ion packs, the average fuel and electricity consumption rose as temperature dropped. This result occurred because the efficiency of the battery dropped as temperature decreased. In addition, the amount of time required to charge increased. However, a presentation for HEV urban buses using a NiMH pack showed no temperature penalties *on average*. The bus was driven many hours per day, making the cold start portion of the day small relative to the PHEV tests. For personal-use PHEVs, which are driven for far fewer hours per day than buses, results implied that pre-heating when plugged in could be very effective in counteracting the range-reducing effects of cold starts. However, the net effects on GHGs would require study, because fossil-based grid-electric heating of the pack may not be as efficient as heating derived from engine waste heat.

- Very high temperature areas in the United States also cause losses to PHEV operating efficiency and contribute to incomplete battery charging. However, for the range of ambient temperatures evaluated, the operating efficiency effects of extreme cold were considerably more dramatic than for extreme heat. An issue that was not addressed in the presentations is the effect of extreme temperatures on the calendar life of battery packs.

- Battery packs need designs for salt-related intrusion problems from either road-salt used in cold weather conditions or coastal water-related “salt-fog.”

3.2.2 Analytical Reactions to the Conference Session, 2011–2013

The Rask, Bohn, and Gallagher (2012) presentation documented hot temperature limitations during early testing of charging of a hot battery, and also reported on several hot condition charging limitations from the Nissan Leaf Owners Manual. In the battery tests, vehicle air conditioning was used to bring battery pack temperature down, with a pack charge kW limitation imposed until battery temperature was at an acceptable level. Elgowainy et al. (2012a) evaluated the “charge by departure” option currently provided by multiple plug-in vehicles, although it was not linked to battery pack thermal management. This option could allow not only pre-conditioning of cabin air but also of battery pack temperature. Elgowainy et al. (2012a) documented other grid benefits of this charging pattern when compared to charging immediately after plugging in. The range limitations of pure electric vehicles in extreme conditions were anecdotally discussed as a market-limiting attribute in Santini et al. (2013b).

The *Workshop Batteries at Temperature Extremes With an Emphasis on Lithium-Ion Batteries for Vehicles* was held on October 22, 2012, in Montreal, Canada. Consumer experience and laboratory testing of commercial PHEVs and AEVs is robustly confirming the generic nature of the issues reported above for the first generation li-ion battery packs (Lohse-Busch, 2012). With regard to calendar life effects, which had not been addressed in the 2009 session, unanticipated rates of decay of battery energy storage capability in very hot climates have been observed by some U.S. electric vehicle owners, though investigations also attributed the loss to intensity of use (MyNissanLeaf Wiki, 2013). Shortening of life due to high ambient temperature and resulting high battery pack temperature is theoretically anticipated, but in-use calendar lifetimes are not yet sufficient to illustrate the degree to which this result will hold true for early li-ion technology.

With respect to dealing with cold temperature-related loss of efficiency and range, PHEVs and ER-EVs have a distinct advantage relative to AEVs. Where the AEV’s loss of range in cold temperatures could cause them to fail to complete desired trips, PHEVs and ER-EVs would not be prevented from being used in cold temperatures, thanks to the motive power available from the engine. Battery pack performance loss in some PHEV designs should nevertheless leave them functional as HEVs, so long as the battery has only lost power and energy without a catastrophic failure. However, in the latter case, if a battery replacement is necessary, it will be significantly less costly than would be the replacement of an AEV battery. One of the published papers (Propfe et al., 2012) did project a much more rapid decline of AEVs’ resale value compared to that of PHEVs, significantly damaging the four-year AEV ownership cost examined in the paper.

3.3 Grid-Connected Vehicles and Renewable Energy

In November 2009, an international workshop entitled *Grid Connected Vehicles and Renewable Energy Workshop – Exploring Synergies* was conducted in Frederica, Denmark. A final workshop report was issued, and results were presented at the June 2010 IA-HEV Executive Committee meeting in London, United Kingdom.

The focus of this workshop was to better understand how different electricity systems from different regions and jurisdictions around the world will provide/acquire power to/from grid-connected vehicles and to learn from different approaches and therefore take better advantage of the opportunities these vehicles present. Although the event was sponsored under Task 15, the focus of European participants leaned toward the purely all-electric vehicles rather than plug-in hybrid vehicles. U.S. presentations, such as those by Hadley (2009) and Santini (2009), did focus on PHEVs. Because PHEVs, although spending the same number of hours parked overnight, do not store as much electric energy as AEVs, they cannot accept as much overnight charge when empty as an AEV can. Accordingly, the electric vehicle supply equipment (EVSE) and dwelling unit circuits can be less powerful (and less costly) for PHEVs than for AEVs. In the United States, the standard household plugs only support 1–1.4 kW, whereas more than 3 kW are supported in Europe. Thus, when increases in charging power above 1–1.4 kW are desired by customers in the United States, costs of new circuits must be added to the vehicle cost.

3.3.1 Findings and Outcomes Reported in 2009 at the Denmark Workshop

3.3.1.1 Renewable Energy Supply

Those countries that have an above-average renewable energy capacity were considered more ready than others to supply “green” electricity to these vehicles; however, the implementation of “smart grid” systems was seen as essential to effectively managing these loads, particularly if these vehicles make up a significant portion of their total vehicle fleet.

3.3.1.2 Promotion of Renewable Energy through Grid-connected Vehicle Energy Use

Switching to renewables reduces use of fossil fuels, contributes to price stabilization for vehicle operating costs, and minimizes the impact of oil price fluctuations. Life cycle costs to the consumer could be reduced if GHG credits and/or Renewable Energy Credits are provided and owned by the vehicle purchaser and user.

3.3.1.3 Marketing Strategies for Both Vehicles and Renewables

Public education, with an emphasis on educating politicians and supporting accurate advocacy from related associations, is needed. Charging strategies include encouraging utilities to install public charging stations and encouraging motorists to charge their vehicles at off-peak times, particularly at night.

3.3.1.4 Regulatory/Policy Options

Recommendations to promote migration toward these vehicles include the following: maintain subsidies and tax rebates, consider building codes requiring inclusion of charging infrastructure, use smart meters, and develop codes and standards for vehicles. Options to promote use of renewable energy sources are: the Renewable Portfolio Standard (RPS), Feed-in Tariffs (FITs), federal subsidies and tax incentives, and renewable energy purchase and use by government entities.

3.3.2 Analytical Reactions to Workshop, 2011–2013

3.3.2.1 Nighttime Charging and Wind Generation Are Not Easily Matched

Elgowainy et al. (2012b) documented, for a projected coal-dominated 2030 generation mix (Illinois, USA) that if the usual rules of least cost dispatch are applied to the allocation of generation sources for the charging of PHEVs, only from 0% to 1% of charging would properly be assigned to wind, despite the fact that wind will account for about 20% of generation. Dallinger, Wietschel, and Santini (2012) also demonstrated for Germany in 2030 (with a base load also dominated by coal) that under least marginal cost dispatch, wind and solar would be allocated only 1–7% of generation on behalf of plug-in vehicles, despite the fact that renewables were projected to provide more than 60% of generation. In both studies, more wind was allocated in the event of smart charging, but more coal generation was also allocated, so that total GHGs were worse when the wind share was higher. Use of the concept of least-cost dispatch does not allow plug-in vehicles to be credited with wind power generation, even if wind has a significant overall share of generation. These studies also imply that if coal provides the base-load capacity of a utility or country, smart charging designed to lead to charging at the lowest-cost time will lead to higher GHGs.

In both studies, uncontrolled charging beginning when the vehicle is plugged in resulted in lower GHGs than the smart charging case, which placed charging in the middle of the night.

Dallinger, Wietschel, and Santini (2012) also examined the case where either customers or regulators required generation of wind electricity equivalent to the demand placed on the system by plug-in vehicles. It is possible in the United States for consumers to purchase renewable energy credits that would place this requirement on their utilities, although at a higher cost of electricity. In the 2030 scenario for Germany, this case did lead to approximately the amount of GHG reductions that would result from exclusive use of wind. This result occurred primarily because inflexible coal-fired power plants had to be replaced by flexible (with high “ramp rate” capability) natural gas power plants to accommodate the added wind generation in the system.

Santini and Burnham (2013) addressed the question of desirability of use of plug-in vehicles in combination with wind, rather than hydrogen fuel cell vehicles (FCVs), for use of the wind to provide kilometres of service. One advantage of hydrogen is as a storage medium for renewable electricity, which can provide long-term storage more readily than with batteries. However, this storage capability would come at a sustainability cost. Santini and Burnham (2013) estimated that wind generation supporting all-electric operation of an AEV, ER-EV, or PHEV (at lower speeds), rather than wind-to-electrolysis-to-hydrogen for a fuel cell vehicle, would use half as much wind energy when providing a given amount of kilometres of service. Implications are that for any source of electricity, all-electric operation of PEVs would provide about twice the km of service as the electricity-to-electrolysis-to-hydrogen-to-FCV pathway.

An advantage of plug-in hybrids charged at 3+ kW (standard plugs in Europe have this capability; U.S. plugs do not) is that their charging can be completed in far fewer hours when they are plugged in overnight or at work. Without smart controls there is potential to shape charging demand if consumers voluntarily alter the timing of start and/or end of charging and/or by emphasis on overnight charging or daytime (workplace) charging as the primary charge point. Santini and Burnham found that the diurnal timing of greatest average wind supplies worldwide most commonly occurs during the day, although in the interior of the United States, the maximum occurs during nighttime hours. Accordingly, charging strategies for harvesting wind via timing of charging should vary by geographic location. Apparently, it is uncommon on a worldwide basis for the maximum wind supply to occur at night, which is generally agreed to be the easiest, most cost-effective time for most consumers to charge vehicles.

3.3.2.2 Daytime Charging

With regard to daytime charging possibilities, the following researchers — Plotz, Kley, and Gnann (2012); Santini, Zhou, and Vyas (2012); Zhou and Vyas (2012); Zhou, Vyas, and Santini (2012); and Santini et al., 2013a — have addressed the opportunities and/or effects of how daytime workplace charging interacts with battery size and/or total daily kWh of charge achievable.

Dallinger and his colleagues (2013) estimated that promotion of both work and home charging with management of the time and rate of charging would be significantly better than simply having uncontrolled charging at home. Country expert Plotz and colleagues (Gnann et al., 2012) estimated that work charging would be more effective than public charging and would allow plug-in vehicles with 5- to 10-kWh batteries to increase their share relative to vehicles with batteries of 20–25 kWh. In other words, in addition to having benefits relative to integrating renewables into the grid, workplace charging could enhance the success of PHEVs relative to AEVs.

3.3.2.3 Charging Power vs. Grid Stability

In the 2011–2013 period, German country expert D. Dallinger (Dallinger et al., 2012; 2013) contributed analyses of the large-scale market penetration of fleets of plug-in vehicles combining PHEVs and AEVs. In both of these studies, he assumed 4 kW for PHEV grid connection and 8 kW for AEV connections. In the United States, this assumption is only workable if future PHEV and AEV customers select “Level 2” EVSE, which adds cost for the PHEV consumer. In 2009, Hadley predicted increasingly severe grid load management problems with uncontrolled charging in the event of use of 6-kW charging. Dallinger et al.'s 2013 analysis is also critical of uncontrolled charging under his assumptions of 4 and 8 kW per plug-in vehicle. Dallinger and co-authors find that controlled charging is desirable for good grid stability in the event of massive market penetration of PHEVs with 4-kW chargers and AEVs with 8-kW charge rates.

In contrast to Dallinger et al. (2012, 2013), Santini, Zhou, and Vyas (2012) and Santini et al. (2013 a,b) took a different approach to minimization of grid impacts. Because Hadley had pointed out in 2009 that grid impacts would be minimal in the event of charging power limits of 1.4 kW, Santini and colleagues considered how much might be accomplished by commuter PHEVs charged at home and at work with only 1.4 kW peak load on the grid. Consistent with Gnann et al. (2012), this approach also implied that PHEVs with packs between 5 and 10 kWh would be preferable to PHEVs with packs larger than 10 kWh (Santini et al., 2013b). Hadley generally found that 1.4 kW charging led to a higher fraction of charge being provided with natural gas combined cycle (NGCC) power plants, which are more efficient than the alternative of simple cycle gas turbine (GT) promoted by the higher-power charging cases (2 kW and 6 kW, respectively).

3.3.2.4 Regional Variation in Renewable Supply Relative to Grid Peak Loads

The interactions concerning diurnal and seasonal wind and solar generation in Germany vs. the United States have shown that there are important differences. Not only do the renewable generation patterns differ, the seasonal grid load peaks are different — Germany has a winter peak, whereas most of the United States has a summer peak. Onshore wind patterns in the United States appear to be different from the rest of the world in general, as noted by Santini and Burnham (2013). On average, U.S. onshore wind patterns appear to better match the more probable practice of performing overnight charging of plug-in vehicles than German offshore wind patterns. In addition, because U.S. electrical demand peaks in the summer, the potential to link workplace charging and solar energy is estimated by Dallinger et al. (2013) to be more likely in the United States than in Germany. Considering both onshore wind and solar generation, Dallinger et al. (2013) simulate a much better match between renewable energy and plug-in vehicles in California than in Germany.

3.3.2.5 Grid-to-vehicle Transmission and Control vs. Vehicle-to-grid (V2G)

In a 2011 presentation in Switzerland, Santini noted cost problems with V2G. At the same meeting, Urs Muntwyler (2011), Chairman of the IEA IA-HEV agreed, stating in his presentation that "controlled one-way charging seems the most appropriate way" and "bi-directional charge is still a research topic." He noted that it would be difficult to make money on V2G, consistent with Santini's (2011) point that it is too costly. Dallinger, Gerda, and Wietschel took this perspective in their 2013 analysis, accordingly assuming only one-way charging control in their simulations for the year 2030.

As these discussions show, even though the original task, “charging and grid issues,” was officially dropped when a revised work plan was developed in 2010, several 2011–2013 Task 15 analyses contributed significantly to increased knowledge in this area.

3.4 2011–2013 Subtasks

The revised work plan narrowed the scope of further work between two subtasks: (1) powertrain attributes and vehicle lifetime use costs, and (2) policy issues and marketability.

3.4.1 Powertrain Attributes and Vehicle Lifetime Use Costs

This study assesses the marketability and cost effectiveness of oil use reduction per kWh of the installed battery pack energy capacity when grid-connected HEVs, PHEVs, and ER-EVs compete head-to-head in the marketplace on available models. The aim is to predict the best market niches for large reductions in fuel use per year of operation. The vehicles studied include AEVs, diesels, and advanced gasoline (Santini and Burnham, 2013). Among participating research institutions, good methodological agreement was achieved on the simulation of CV and PEV powertrain attributes (Da Costa et al., 2012). For examination of lifetime vehicle costs, considerable progress was also made on methodology; however, the level of consensus and degree of finality was lower than in the case of simulation of powertrain attributes (Rousseau et al., 2012).

3.4.1.1 Key Findings

Key findings related to subtask 1 are as follows.

- ***3.4.1.1.1 High fuel prices are important to the financial viability of and political support for electric drive.*** Gasoline prices in recent years have been considerably higher than in the 1990s when manufacture and launch of AEVs was initially attempted using NiMH battery packs. Propfe et al. (2012), Rousseau et al. (2012), and Santini et al. (2013b) each estimated 2020 cases where plug-in hybrids could compete financially with gasoline vehicles under 2012 average gasoline and electricity prices. However, gasoline prices include taxes that are not imposed on electricity, so 2020 plug-in electric vehicles at present gasoline and fuel prices succeed in part because use of electricity evades taxes. Santini et al. (2013b) estimated that a further real gasoline price increase of 43% (with no increase in electricity prices) would make many different plug-in vehicles not only competitive but, in many cases, actually a superior choice to gasoline vehicles.

- ***3.4.1.1.2 For personal use, the plug-in vehicles evaluated best fit use patterns and/or driving cycles common in suburbs and towns, not those in dense core***

city markets. For cost effectiveness, intensive use is required. Propfe et al. (2012), Rousseau et al. (2012), and Santini et al. (2013b) estimated financial success only in simulations where plug-in vehicles were driven far more intensively than the average vehicle. Rousseau et al. (2012) showed that the average annual use is least in major cities. Zhou, Vyas, and Santini (2012) examined frequency of daily use as a factor, and Santini et al. (2013b) tested sensitivity to this aspect of vehicle use.

- ***3.4.1.1.3 Unless oil prices increase, broad success of battery electric drive with greater range and all-electric operation requires development of a less expensive next generation of battery technology/chemistries.*** Santini et al. (2013b) estimated that an increase in gasoline prices of 43% would make nearly all of the intensively used plug-in vehicles that were simulated financially superior to conventional gasoline vehicles. In terms of numbers of vehicles, a small share of vehicles could be successful, but about half of fuel use could be targeted for significant reduction by such vehicles. Considering generic PHEVs, Kley, Dallinger, and Wietschel (2010) investigated the effect of declining battery cost on the probable mix of battery pack nominal kWh ratings for PHEVs for German consumers. Their estimates implied a kWh capacity of 5 to 10 kWh, which led to the largest share of the market in terms of share of vehicles. However, as battery prices dropped, PHEVs with more kWh became increasingly attractive. PHEVs with less than 5 kWh had a very small share of the market when pack prices dropped to 300 Euros, with each 5 kWh bracket from 5–25 kWh capturing a far larger share than for the 0- to 5-kWh pack capacity. An increase in the financial viability of larger packs was also observed in Santini et al. (2013b) as gasoline prices increased, holding battery pack costs constant. At EVS26, Plotz, Kley, and Gnann (2012) showed that, although lowered battery pack costs favour larger battery pack sizes when vehicles are charged overnight at the residence, the addition of workplace and public charging causes this result to shift, with the 5- to 10-kWh range for battery packs retaining a relatively constant share at the expense of the larger packs. This analysis did not consider the costs of charging infrastructure, however — only its availability. Santini et al. (2013a) addressed the trade-off between the costs of adding range via larger battery packs vs. adding infrastructure to allow more than one charge per day. The authors noted that inexpensive workplace charging is a substitute for additional battery pack capacity for commuter vehicles. However, they also noted that installation of workplace charging is more expensive than it is at single-family dwelling units. In the case of excessive costs for charge points at work, higher-capacity battery packs and more powerful charge circuits at the dwelling unit would be the least-cost solutions.

3.4.1.2 Investigation Details

This subtask evaluated each of the items described in the bullets below, with a sensitivity analysis performed across the items in parentheses.

- ***3.4.1.2.1 Drivetrains (parallel, input-split, output-split, series range extended, AEV).*** This area is one where Task 15 far exceeds the detail in prior analyses, many of which used only a few generic PHEVs. In Da Costa et al. (2012), simulation results for 19 different powertrain configurations are presented. The four types of plug-in hybrid powertrains were simulated with a minimum of three battery pack sizes for each, resulting in 16 different combinations of battery pack power and energy storage capabilities. The parallel and input-split cases were each simulated with three different CD range designs — nominally 15, 30, and 50 km (9.3, 18.6, and 31 mi). These cases had battery pack power levels varying from 26 to 61 kW. The output-split and series cases were each simulated with nominal 30, 50, and 70 km (18.6, 31, and 44 mi) CD design ranges. Design range had to be achieved on either of two urban driving cycles — one U.S. (UDDS) and one European (Artemis Urban). Santini et al. (2013b) added two low battery pack power (26-kW) input-split PHEVs.

  The output-split and series powertrains were designed to operate in all-electric mode in most driving conditions. The powertrains had battery pack power levels from 100 to 149 kW. Task 15 varies the power rating of battery packs of PHEVs evaluated over a wider range than most PHEV evaluations. Santini et al. (2013b) conclude that the most financially viable power level is about 60 kW in either parallel or split PHEVs, rather than the more than 100-kW level in ER-EVs. At the same CD design range, an input-split PHEV with a 60-kW pack was estimated to have a slightly lower TCO than one with a 26-kW pack despite higher initial costs. Initial and lifetime costs were much lower than for the output-split ER-EVs with 100-kW packs. Further investigation of the power level of the lifetime least-cost battery pack is desirable.

- ***3.4.1.2.2 Glider, or the vehicle minus the powertrain (weight, rolling resistance, drag area, front-wheel drive [FWD] vs. rear-wheel drive [RWD]).*** This topic is addressed by Santini and Burnham (2013) and Rask, Lohse-Busch, and Santini (2013). FWD is superior to RWD for PHEVs driven in real-world conditions (Rask, Lohse-Busch, and Santini, 2013). The interaction of glider design and powertrain design should be considered more routinely in future studies (Santini and Burnham, 2013).

- ***3.4.1.2.3 Transmission type (planetary, continuously variable transmission [CVT], auto manual, automatic, single speed).*** The simulations used in DaCosta et al. (2012), Rousseau et al. (2012), and Santini et al. (2013b) each account for the type of transmission that is being paired with the powertrains simulated.

- ***3.4.1.2.4 Charging equipment (Levels 1 and 2 AC; circuit upgrades, meters).*** Europe and the United States have fundamentally different standard residential plugs, with the former capable of charging at than 3 kW, and the latter at less than half as much. Standardized electric vehicle supply equipment that comes with PHEVs allows charging at either standard plug, with little variation in design, reducing cost of manufacture.

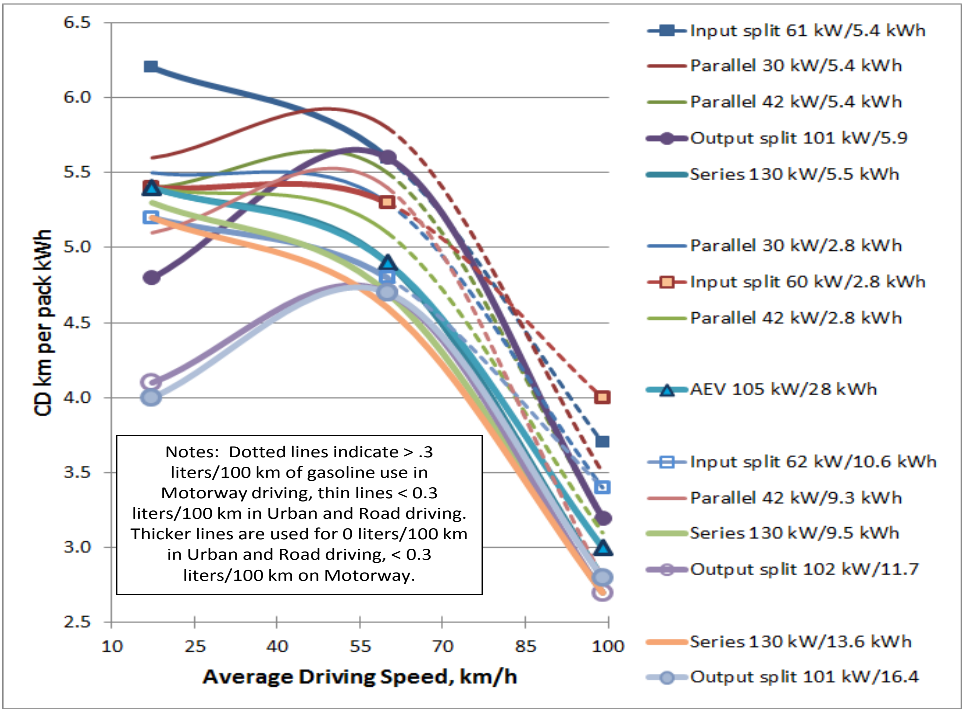
- ***3.4.1.2.5 Fuel and electricity use: on-road vs. certification test.*** Contrasts between simulation results for European and U.S. certification driving were illustrated and discussed in Rousseau et al. (2012). In the United States, there are two sets of fuel economy tests, with different driving cycles and procedures with respect to auxiliary loads. One set is used for Corporate Average Fuel Economy (CAFE) regulatory certification and one for consumer information. The latter cycles result in higher fuel consumption estimates (and electric drive savings) than the former. In Europe, the same driving cycles are used for regulatory certification and consumer information. Differences between information presented to U.S. and European consumers were illustrated. The higher consumption predictions for the fuel consumption method of the adjusted U.S. consumer window label vs. the lower consumption predictions of U.S. and European regulatory certification estimates were illustrated by estimates presented in DaCosta et al. (2012). By conducting simulations on the European "Artemis" field-test-developed driving cycles, the study illustrated the magnitude of the difference in "on-road" fuel consumption experienced by European consumers compared to that predicted in official ratings. Among all driving cycles used for simulation in the study, the U.S. Highway cycle used for regulatory compliance predicted the lowest percentage in fuel savings from hybridization. U.S. supplementary simulations of the input-split powertrain type with only 26 kW of battery electric power predicted increasingly long distances to deplete the battery pack as average speed and relative aggressiveness of on-road driving cycles increased (Santini et al., 2013b). However, when battery pack power was 30 kW or above, the distances to battery pack depletion (range) declined for highway driving cycles (i.e., U.S. CAFE HWY, U.S. US06 Highway, European Artemis Motorway), with greatest declines for the on-road cycles (Da Costa et al., 2012; Santini et al., 2013b). The large difference in engine use results during CD operation between 26- and 30-kW battery pack power levels occurs across two different powertrain types (input-split at 26 kW vs. parallel at 30 kW). In light of this result, the precise cause merits re-examination.

  For on-road PEV driving with battery packs of 30 kW or more, it was found that pack depletion occurred within a much shorter distance in U.S. highway driving and European motorway driving than in urban, suburban, or local rural driving (Figures 1 and 2).

  Further, it was observed that the greatest charge-depleting efficiency levels obtained for the output-split powertrains during simulation were consistently greater in suburban or local rural driving than in urban driving. This property was consistently estimated for the United States and Europe (Figures 1 and 2). However, the input-split results were inconsistent across the United States and

Europe, with greatest efficiency levels reached in urban driving in Europe but in suburban driving in the United States. On-road evaluations of series and parallel designs were not evaluated by U.S. participants. As with input-split PHEV results, AEV results were inconsistent, with European simulations also implying best efficiency in urban applications and U.S. simulations implying best efficiency in suburban driving.

One result that was consistent across all simulations of PEVs with 30 kW or more of battery pack power was a sharp increase in kWh/100 km (62 mi) and thus a sharp drop in distance to depletion in highway and motorway driving relative to other driving (Figures 1 and 2). This property implies significant dissatisfaction with AEVs by consumers who wish to drive long distances between cities with a minimum of refuelling stops.



Notes: Dotted lines indicate > .3 liters/100 km of gasoline use in Motorway driving, thin lines < 0.3 liters/100 km in Urban and Road driving. Thicker lines are used for 0 liters/100 km in Urban and Road driving, < 0.3 liters/100 km on Motorway.

Figure 1: Estimates of charge-depleting km achieved per kWh of battery pack on three European Artemis driving cycles for 15 powertrain simulations

Another observation is that the simulations often predict lower on-road efficiency for U.S. urban and suburban driving than for European urban and rural driving. Figures 1 and 2 are plotted to the same vertical axis minimum and maximum to illustrate this finding. Finally, the on-road results show a highly nonlinear pattern of on-road efficiency, with peaks implied in suburban and local rural driving. This property implies that "combined" cycle kWh/km (kWh/0.6 mi) consumption estimates developed by a weighted average of two driving cycles will inevitably create an incorrect estimate. For the United States, the implication is that the consumer window label for kWh use per km (kWh/0.6 mi) for combined cycle driving by plug-in vehicles may be too high. The New European Driving Cycle (NEDC) cycle estimates for European vehicles, on the other hand, severely underestimated the kWh/km (kWh/0.6 mi) that would actually be obtained in French or German motorway driving.

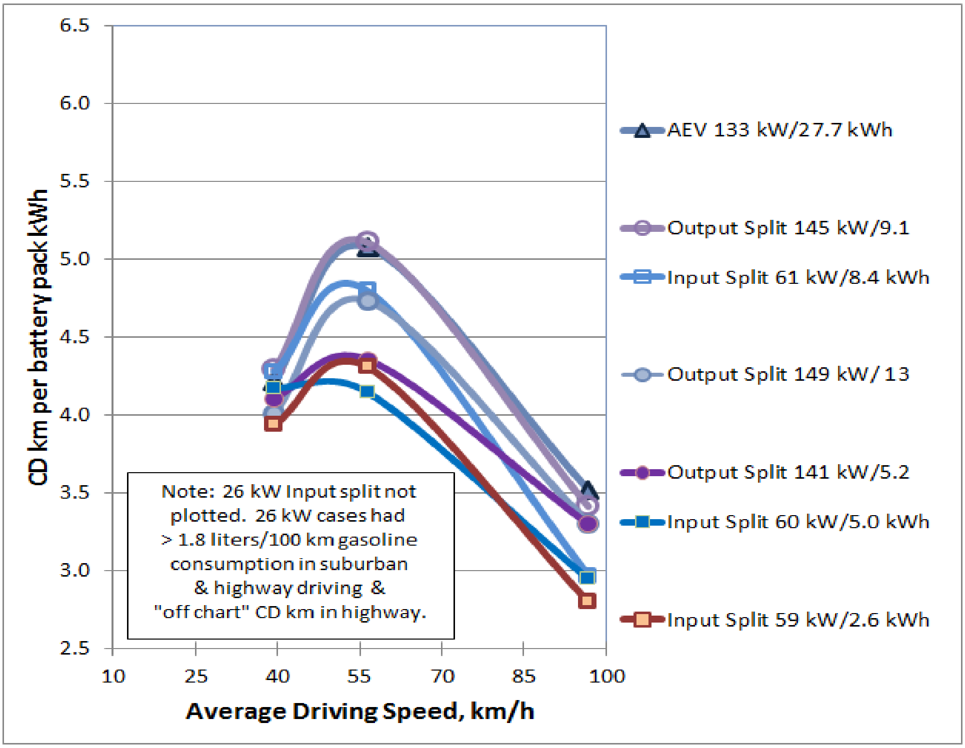


Figure 2: Estimates of charge-depleting km achieved per kWh of battery pack on three U.S. "on-road" driving cycles for 7 powertrain simulations

- ***3.4.1.2.6 Thermal management, battery, and electric machines.*** The public domain U.S. BatPaC model of lithium-ion battery attributes and costs went through two editions during the study period (Nelson et al., 2011; 2012; Gallagher, Dees, and Nelson, 2012). The first edition evaluated only air thermal management; the second added liquid thermal management. Very significant volumetric energy and power density increases were predicted by switching from air to liquid thermal management. It appears that many early PHEVs are using air thermal management; a future evolution or option using liquid thermal management in the same vehicle package could allow increased range without any increase in battery pack volume. Six chemistries are included in the BatPaC model. Cost-effectiveness analyses conducted by U.S. analysts used a lithium-manganese-oxide (LMO) chemistry (Rousseau et al, 2012; Santini et al., 2013b). The German Aerospace Institute (DLR) used a proprietary battery cost model. A nickel-manganese-cobalt (NMC) lithium-ion chemistry was used for plug-in vehicle batteries in the vehicle cost estimates developed by DLR (Propfe et al., 2012; Rousseau et al., 2012). (BatPaC simulations can be made by other experts given that it is a public domain model.) A nickel-cobalt-aluminum (NCA) lithium-ion chemistry was used for the hybrid vehicle battery in the vehicle cost estimates developed by DLR (Propfe et al., 2012; Rousseau et al., 2012).

BatPaC simulations indicated that electrode thickness limits cause a shift in the incremental cost effectiveness of an increase in battery pack energy. Once electrode thickness limits are binding (but only then), more pack power must be added as kWh are added. The kWh level at which power additions are technically unavoidable differs by chemistry, and will differ as electrode thickness limits change. Another implication of this technical trade-off is that moving from a high-power HEV battery, which has electrode thickness well below manufacturing and cell reliability/lifetime limits, toward a low W/Wh battery for a PHEV can be accomplished at relatively modest cost until the electrode thickness limits are reached.

A “flip side” of this property is that there are circumstances where battery design constraints prevent any battery pack cost savings by reducing pack power requirements.

Estimates presented in Santini et al. (2013b) indicate that costs of battery pack power for PHEVs and AEVs are not a significant issue. According to those estimates, the costs of electric machines and power electronics are more important causes of increases in PHEV to ER-EV costs as electric power output is increased.

- ***3.4.1.2.7 Pack life management strategies, tendencies.*** Introduction of plug-in electric vehicles was accompanied by publication of user manuals. These user manuals were reviewed for instructions on recommended charge management. The extensive recommendations for the Nissan Leaf battery pack with air thermal management were summarized in Rask, Bohn, and Gallagher (2012). Limitations on use of full charging and fast charging were noted. Rask, Bohn, and Gallagher also included an illustration that two different battery redesigns to allow greater use of fast charging would involve significant penalties in terms of battery pack cost, volume, and mass. One case involved a switch of chemistries from $LiMn_2O_4$-Graphite (an LMO-G chemistry) to $LiMn_2O_4$-$Li_4Ti_5O_{12}$ (an LMO-TiO chemistry) (31% cost increase, 58% volume increase, 62% mass increase); another involved using thinner electrodes and more electrode, copper, and aluminum surface area in the LMO-G chemistry (26% cost increase, 16% volume increase, 19% mass increase).

- ***3.4.1.2.8 Maintenance and component replacement costs.*** The German DLR four-year initial ownership cost estimates of Propfe et al. (2012) included depreciation predictions and maintenance and repair predictions. In addition, significantly lower maintenance and repair costs of the two vehicles with large battery packs and direct drive transmissions were predicted (series ER-EV and AEV); however, the AEV depreciation costs were predicted to be high owing to an absence of a large secondary market for a limited-range vehicle.

- ***3.4.1.2.9 Overview of characterizations of drivetrain lifetime costs.*** None of the three papers written on lifetime costs of different powertrains included all four types examined in the comparative simulations. Propfe et al. (2012) examined German driving cases. They included a parallel HEV, two parallel PHEVs (15- and 30-km [9.3- and 18.6-mi] CD), a series ER-EV, an AEV, and an FCV, but did not include either an input-split or output-split powertrain. With very high annual utilization, HEVs and the two PHEVs had essentially identical four-year costs of ownership, lower than any other case examined (Figure 3). FCV costs were highest. Rousseau et al. (2012) examined one parallel, one input-split (PHEV 30), and one series (ER-EV 70), but no output-split or AEV.

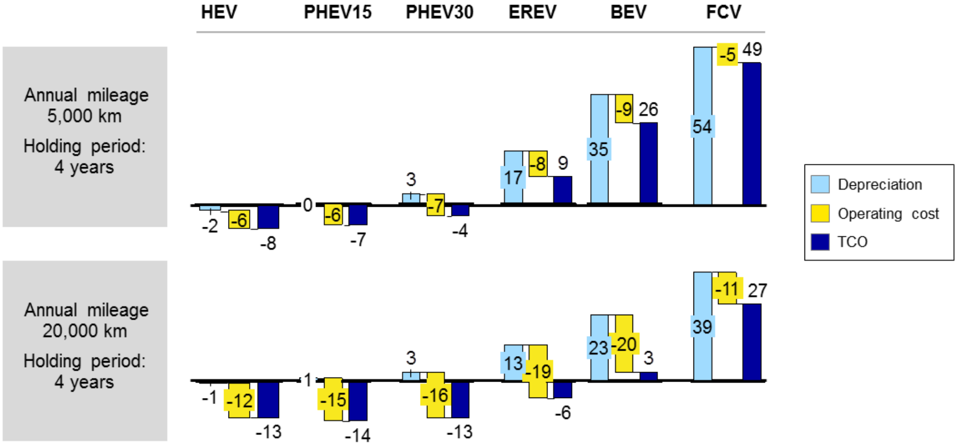


Figure 3: German case TCO comparison of electrified powertrain architectures relative to ICE (in %) in the year 2020 for users with different annual mileages (Source: Propfe et al., 2012). Note: the PHEV 15 and PHEV 30 are parallel, the EREV is a series ER-EV, and the BEV is an AEV.

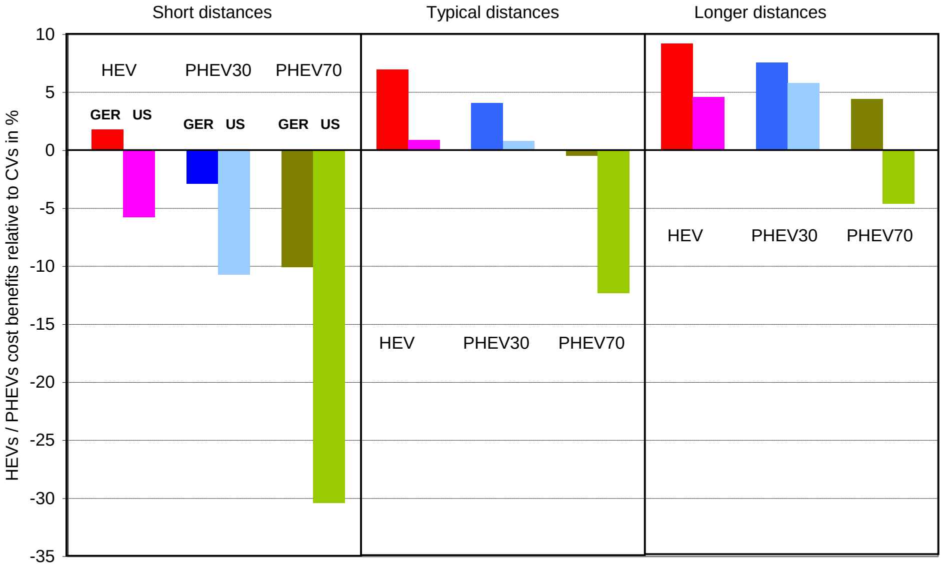


Figure 4: German vs. U.S. percent improvement of PHEV ownership cost (TCO) vs. CV, by drivetrain and distance/yr (Source: Rousseau et al., 2012). Note: PHEV 30 is parallel and PHEV 70 is a series ER-EV.

Driving patterns and fuel costs used were appropriate to the nation examined (Germany and the United States). At the estimated average driving speeds chosen, the simulated series ER-EV powertrains were heavier and less efficient than others evaluated (Da Costa et al., 2012) and had higher estimated lifetime costs of ownership (Propfe et al., 2012, Figure 3; Rousseau et al., 2012, Figure 4).

In Germany, the HEV had lowest cost (Figure 4). For the United States, at the lowest annual use rate (6,550 km/yr [4,070 mi/yr]), the conventional vehicle had lowest TCO. At average and high use rates, the HEV and input-split PHEV 30 had about the same lifetime TCO, which were lower than for the conventional vehicle or the series ER-EV (Figure 4).[2] The series ER-EV in Germany was consistently rated much better than it was in the United States.

Santini et al. (2013b) evaluated only U.S. conditions, and only input-split PHEVs, output-split ER-EVs, and one AEV. When adding two input-split PHEV cases with low electric power to those of Da Costa et al., (2012), Santini et al. (2013b) implemented a version of the previously developed “Manufacturing Streamline Limit” method (Saucedo, 2010) of sizing components for a family of PHEVs and HEVs (Figure 5, 26-kW case).

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[2] Figures 3 and 4 are reproduced from the original papers. Thus, a good PEV result is negative in Figure 3 and positive in Figure 4.

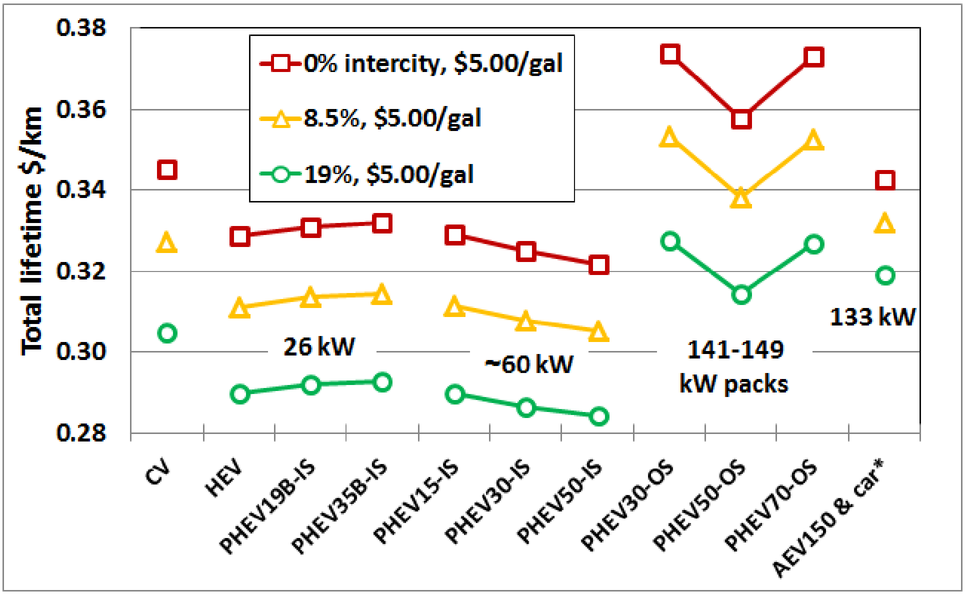

Figure 5: Total lifetime U.S. dollars/km estimates for various types of electric drive vehicles (at the gasoline price of $5.00/gallon, 263 days of use/yr, 1+ average charge/day including workplace charging, ten years of constant urban driving of 16,300 km/yr (10128 mi/yr), with interurban driving of 0 km/yr [indicated in red], 1,510 km/yr (938 mi/yr) [yellow], or 3,810 km/year (2,367 mi/yr) [green])[3] (Source: Santini et al., 2013b). Note: PHEV "ISs" are input-split, and PHEV "OSs" are output-split ER-EVs.

In this approach, electric machines, inverters and transmissions are sized for the requirements of the version with the largest battery pack and held constant for any other PHEVs and an HEV. This approach increases the volume of production of components by deploying the same components to multiple powertrains, thereby reducing component cost. This approach is that used by Ford with its "Energi" PHEVs, which use the same electric machines and other power electronic components as HEVs. In Ford's case, the powertrain with common components is shared across two vehicle gliders, the C-Max and Fusion. Toyota also retains the same electric machines and power electronics in both its Prius HEV and PHEV. For the 26-kW case examined, the HEV had a lower TCO than did the PHEV models. However, in the high gasoline price case illustrated in Figure 5, the two PHEVs with 60-kW battery packs and 30 km (18.6 mi) or more of urban range were estimated to have lower TCO than any members of the 26-kW HEV and PHEV family.

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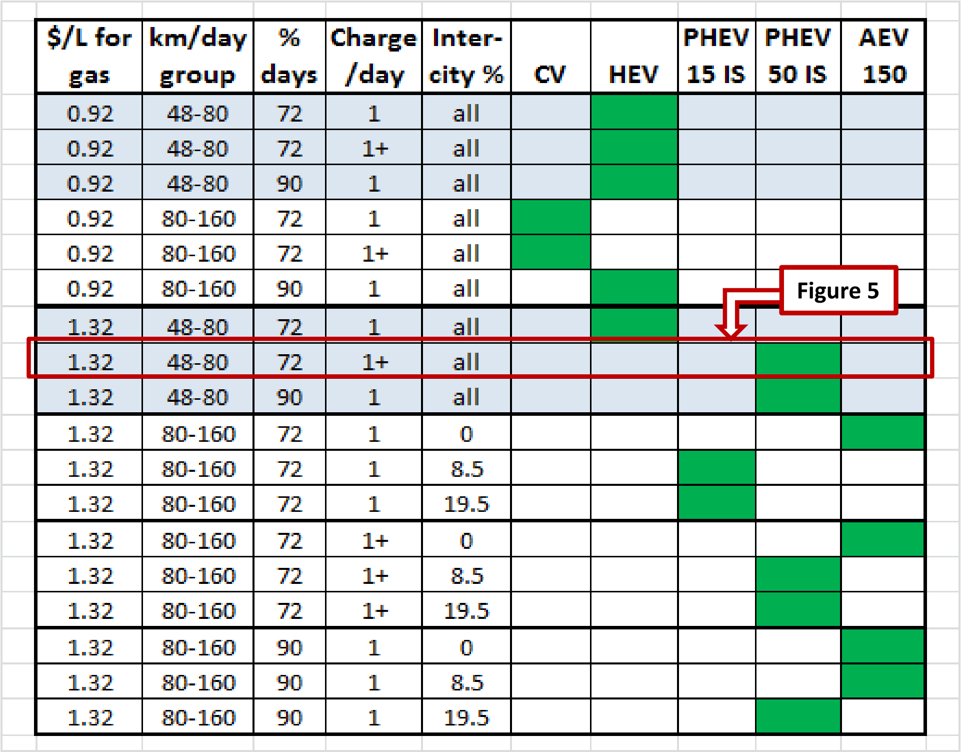
[3] Figure 5 also uses a different visual format for comparison of powertrains relative to Figures 3 and 4. Here, total costs are plotted rather than percentage differences relative to the conventional vehicle.

In the paper by Santini et al. (2013b), the case with higher gasoline prices resulted in selection of a very intensive daily use niche where the lifetime costs of ownership of an AEV were lower than for the CV and any PHEV or ER-EV (see Figure 6, where averages are 80–160 km/day [50–100 mi/day]). However, achievement of this low average cost of operation required the pack to last the life of the vehicle and implied that many of the customers in this market niche would need to deplete the battery pack more than once per day (the actual range in this niche would likely be well below the AEV's nominal 150-km (93-mi) value, due to high-speed driving), implying between 2,600–3,900 deep discharges over the ten-year vehicle life. Unfortunately, such a use pattern would likely lead to a need to replace the pack during the simulated ten-year period of ownership.



$/L for gas	km/day group	% days	Charge /day	Inter-city %	CV	HEV	PHEV 15 IS	PHEV 50 IS	AEV 150
0.92	48-80	72	1	all		🟩			
0.92	48-80	72	1+	all		🟩			
0.92	48-80	90	1	all		🟩			
0.92	80-160	72	1	all	🟩				
0.92	80-160	72	1+	all	🟩				
0.92	80-160	90	1	all		🟩			
1.32	48-80	72	1	all		🟩			
1.32	48-80	72	1+	all				🟩	
1.32	48-80	90	1	all				🟩	
1.32	80-160	72	1	0					🟩
1.32	80-160	72	1	8.5			🟩		
1.32	80-160	72	1	19.5			🟩		
1.32	80-160	72	1+	0					🟩
1.32	80-160	72	1+	8.5				🟩	
1.32	80-160	72	1+	19.5				🟩	
1.32	80-160	90	1	0					🟩
1.32	80-160	90	1	8.5					🟩
1.32	80-160	90	1	19.5				🟩	

Figure 5

Figure 6: Estimated lowest cost alternative for specified patterns of use (Source: Santini et al., 2013b). Note: HEV and PHEVs use input-split powertrain. Parallel PHEVs are not evaluated.

This result suggests that a greater R&D focus is needed on a battery's deep discharge cycle life to assure battery lifetime under this pattern of use. Alternatively, it implies that development of lower-cost battery chemistries is necessary for AEVs to meet the needs of more typical (but not typical) U.S. vehicle owners (who drive 48–80 km/day [30–50 mi/day]). The size of the 80–160 km/day (50–100 mi/day) market niche is probably quite small. Figure 5 presents results for the $1.32 per litre gasoline cost case for the 48–80 km/day (30–50 mi/day) group, a very large portion of the U.S. market, where the PHEV is always lower in TCO than the AEV. Figure 5 includes all powertrain cases investigated; Figure 6 includes only selected cases that proved to have the lowest TCO in at least one of the combinations of price and use assumptions. The two input-split PHEVs in Figure 6 have battery packs with 60 kW of peak power.

- ***3.4.1.2.10 Subtasks not addressed.*** None of the publications completed under Task 15 have addressed the two topics below, which were a part of the revised plan.
  - Control and communication equipment (on and/or off PHEV), and
  - Electric machines (permanent magnet [PM] vs. induction).

3.4.2 Policy Issues and Marketability

3.4.2.1 Emissions Estimation

Policy issues that concern participating country experts are addressed. Selected issues relate to effectiveness of use of resources (e.g., kilometres of service obtained and oil use reduced per unit of energy resource extracted or harvested) and GHGs (i.e., carbon dioxide [CO_2], methane [CH_4], and nitrous oxide [N_2O]). Elgowainy et al. (2012a,b); DaCosta et al. (2012); Dallinger, Wietschel, and Santini (2012); and Santini and Burnham (2013) each examine the gasoline and life cycle GHG emissions trade-offs under a range of different accounting approaches. An overall theme is that the least marginal cost dispatch methodology does not allow an evaluator to credit plug-in vehicles with use of wind power (or, by inference, any "nondispatchable" renewable). Thus, images of plug-in vehicles with wind towers in the background are logically inconsistent under the least marginal cost dispatch rules used by most evaluators of allocation of generation to final demand. Dallinger, Wietschel, and Santini (2012) presented a case where a legal or regulatory link of total renewable (wind) generation amount to the requirements of a plug-in vehicle fleet can lead to an estimate of approximately full incremental energy generation for plug-in vehicles at nearly zero CO_2 emissions. Consumers in the United States can purchase renewable energy credits (at a higher cost) equivalent to the generation that they expect to be used for their plug-in vehicles.

Dallinger, Schubert, and Wietschel (2013) extend the linkage of wind and plug-in vehicle charging from the regulatory/legal link evaluated at EVS26 in 2012 to an actual, real-time technical control link between wind and solar generation to rate of charging of battery packs. In this case, the renewable generation and vehicle charging are technically linked in real time rather than simply required to be equal to one another over some averaging period. This more costly linkage can take advantage of the relatively high power level of the distribution infrastructure used in Germany and France. Plug power of 3 kW and above can allow charge rates to vary overnight or during working hours at workplaces and still fill the battery packs of the PHEVs and ER-EVs that we have simulated by the time of their departure.

Although "least marginal cost dispatch" only addresses control of generation, this alternative system strategy implements variable demand (i.e., PHEV charging rate). One might call it "least marginal cost receipt." Put another way, including the vehicle batteries in the system amounts to adding storage to create demand when it is needed. As noted earlier, one-way control from the grid to the vehicle is assumed, given concerns over costs of V2G. Dallinger, Gerda, and Wietschel (2013) find that a combination of workplace and home charging is particularly valuable, creating more theoretical opportunity for response to renewable generation. The patterns of wind and solar generation were found to better match likely patterns of vehicle charging in California than in Germany. It is noted that use of solar is facilitated greatly if solar can be installed where vehicles are parked during the day. However, use of solar generation also implies that the sophisticated control equipment must be installed at two charging locations (home and workplace).

As was found in Hadley (2009) and in Elgowainy et al. (2012a), the pattern of consumer charging has the potential to create new load peaks or to smooth load. Time-of-day tariffs were regarded by Dallinger et al. (2013) as problematic because they tend to cause bunching of charge start-ups at the time for which rates change, as California field tests are showing (Smart, 2012).

Analyses have been conducted that address utility systems in regions (or nations) dominated by (1) coal baseload (Elgowainy et al., 2012b; Dallinger, Wietschel, and Santini, 2012; Da Costa et al., 2012); (2) nuclear baseload (Da Costa et al., 2012); or (3) natural gas baseload (Elgowainy et al., 2012a; Da Costa et al., 2012; Santini and Burnham, 2013). Illustrating the complexity and uncertainty in how to assign generation, the authors of these papers chose different methods of estimating the mix of generation types attributable to plug-in vehicles, including (1) least marginal cost analysis (Elgowainy et al., 2012a,b; Dallinger, Wietschel, and Santini, 2012), (2) current average annual generation (Da Costa et al., 2012), (3) scenario differences (Dallinger, Wietschel, and Santini, 2012), and (4) generator type life cycle pathway (Santini and Burnham, 2013). In least marginal cost dispatch evaluations, smart overnight charging was problematic in causing increased carbon emissions only when coal was the baseload generation source. When natural gas or nuclear is the baseload source, smart charging will both result in reduced carbon emissions by PHEVs and ER-EVs compared to conventional vehicles and result in lowered overall electricity costs to the consumer. This finding is explicitly addressed for the natural gas baseload in Elgowainy et al. (2012a) and inferred for the nuclear baseload.

3.4.2.2 Vehicle Design Motivators

The original design decision for the vehicles simulated in Task 15 was to require the majority of the plug-in vehicles simulated to have real-world, all-electric operations capability in urban driving (Da Costa et al., 2012). Such vehicles were said to have "all-electric range" (AER), despite the fact that that was not the case for all driving conditions. The decision to use the real-world vehicle driving results for European urban drivers led to a predicted requirement for battery pack peak power of 42 kW for the parallel powertrain, with the input-split powertrain requiring about 60 kW. Two 30-kW parallel "mild" PHEVs were simulated. Neither was able to meet the AER requirement. Santini et al. (2013b) added two input-split PHEVs with 26-kW packs. These were also unable to meet the AER requirement. None of the PHEVs were simulated to be able to drive all electrically on the European "Artemis" Motorway cycle, which characterizes driving on limited access highways such as the Autobahn.

ER-EVs had battery pack peak power from 100 to 135 kW. The 100-kW, output-split ER-EVs were simulated to be able to drive all electrically in all U.S. conditions, including on limited access highways. However, they could not drive all electrically on portions of the Autobahn without a speed limit — as simulated by the Artemis Motorway cycle. The more powerful 135-kW Series ER-EV was simulated to be capable of all-electric operation under any driving condition (see Da Costa et al., 2012). The extension of the highway CD distance in the PHEVs with 26-kW packs can represent a financial disadvantage because these vehicles cannot charge as often as those with more powerful packs. The ability to achieve more than one charge per day was found to be a financial advantage (Santini et al., 2013b). Chevrolet Volts with 3.3-kW EVSE, similar to the input-split ER-EV 50, have been achieving 1.5 charges per day in the hands of early enthusiasts (Smart, 2012). A problem for consumer education is that (compared to urban driving) CD range declines on limited access highways for plug-in vehicles with 30-kW or higher battery packs (Da Costa et al. 2012, Figure 1; Santini et al., 2013b, Figure 2) while range for the conventional vehicle increases. This pattern is likely to be counterintuitive for initial purchasers of plug-in vehicles.

In the United States, California is using regulatory incentives to move toward zero emissions vehicles. Current incentives give credit to PHEVs with less peak battery pack power than required to obtain an "AER" rating under Task 15's chosen definition. Developers of vehicles might plausibly expect that the long-term goal of California is more ambitious, hoping for all-electric operation under all conditions. Task 15 did not simulate any PHEVs for the current California credit system. Instead, the AER goal is one that should produce PHEVs that would reliably run all electrically in urban "emission free zones," a concept prevalent in Europe. In so doing, even though it was not an explicit goal, PHEV designs were developed that will readily meet the minimum PHEV credit requirements under current California Air Resources Board (CARB) rules. Such vehicles are candidates to be a standardized solution that could meet both European and U.S. goals for minimum all-electric capability. These vehicles are reliably capable of all-electric operation on the networks of urban streets where they share the rights of way with pedestrian sidewalks, bicycle paths, and/or public transit lanes and guideways.

The zero tailpipe emissions capability in such locations is clearly more valuable in most cases than on limited access highways where such sharing of rights of way is very uncommon.

With considerably more battery pack power, the ER-EVs are capable of all-electric operation (until the pack is depleted) anywhere within a large metropolitan area, including the area's limited access highways, which usually have a lower speed limit than for such highways in rural areas. With a dense network of workplace and public charging, such vehicles could have the capability of operating all electrically nearly all of the time when within the metropolitan area. Obviously, such a goal is more ambitious, and might be expected to be more costly. It was, in fact, estimated to be more costly. One problem is that the hours and kilometres capability for all-electric operations drops significantly as average speed increases (DaCosta et al., 2012). Thus, an across-town trip on limited access highways in very large metropolitan areas may still lead to charge sustaining (engine on) operation.

The desire to maximize all-electric operations capability requires that larger packs be encouraged. Although the financial viability evaluations imply that only smaller packs are desirable at the reference gasoline prices and battery pack costs, either an increase in gasoline prices (Santini et al., 2013b) or a decrease in battery pack cost (Kley, Dallinger, and Wietschel, 2010; Dong and Lin, 2012) can enable PHEVs with longer range and/or series ER-EVs to become financially competitive.

Apparently hoping to encourage a mix of PHEV designs, the United States provides a subsidy for battery backs of from 4 kWh to 16 kWh nominal capacity. Investigations of participating country experts indicate that if charging infrastructure is inexpensive, subsidy of battery pack kWh at the upper end may not be as cost effective as subsidy of charging infrastructure. In a "technical analysis" (not financial), Gnann, Plotz, and Kley, (2012) estimate that an increase of pack size from 5 to 10 kWh is more effective than investment in away-from-home charging infrastructure. Beyond 10 kWh, Plotz, Kley, and Gnann (2012) estimate that "semi-public" (i.e., workplace) charge points would sharply reduce the need for a PHEV pack of 10–15 kWh. Thus, a major question is the cost of workplace charging vs. the cost of adding battery pack from about 10 kWh and higher (Santini, Zhou, and Vyas, 2012). In the Task 15 simulations, the step from 10 kWh and higher involves switches of powertrains and increases of battery pack power (Da Costa et al., 2012), so for these cases, there is some bias against increasing pack kWh. Santini et al. (2013 a,b) investigated the technical feasibility and cost effectiveness of workplace charging for four different Task 15 powertrains. They found that not only is a pack's kWh important, the kW level is also important. The PHEV pack with 26 kW was never the most cost-effective plug-in option. Available information suggested that investigation of the trade-off between adding pack kWh vs. adding charging infrastructure at work is not likely to lead to a definitive conclusion that either one should be favoured.

3.4.2.3 Charging Patterns and Incentives for Their Modification

Gnann, Plotz, and Kley (2012) deduced that increases of power level above that in the standard residential plug did not appear to be very productive — either in the United States or Europe. One potential reason for such power increases would be to allow rapid charges for vehicles that returned home during the day for short periods. In Europe, with higher kW plugs, increasing residential plug kW capabilities would seldom be necessary. Even in the United States, the need would be limited. Santini, Zhou, and Vyas (2012) investigated the rate of returns to the house and found that only 13% of vehicles returned to the house during the day. Santini, Zhou, and Vyas (2012) and Santini et al. (2013b) examined the adequacy of workplace charge points operating at kW ratings equivalent to standard U.S. household plugs and concluded that such workplace charge point power levels should be the best solution in most circumstances. Dwell times at parking places were usually long enough to assure full charging even with standard plug kW ratings. Fast charging with dozens of kW is not needed for PHEVs and ER-EVs given that they can run on gasoline if necessary. An absence of a need for fast charging at high kW reduces pack-life-shortening risks to PHEV and ER-EV battery packs. Limiting charging rates to 1–4 kW greatly reduces the odds that what are called "avalanche" effects will occur on the grid or local distribution system, where many plug-in vehicles either begin or end charging at exactly the same time (Hadley, 2009). **On the whole, charging of PHEVs and ER-EVs can be far less complex and less expensive than it is for AEVs.** Given the much lower probability of avalanche effects, for low kW charging, manual control by the owner is far more acceptable to grid managers than for high kW charging.

Harvesting renewables — matching the time of charging to the time of higher wind or solar supply — is technically feasible in the sense that for most PHEVs, the time plugged in far exceeds the time charging, so there is potential to manage the time of charging within the most lengthy parking events — overnight at the residence and in daylight at work. Simple strategies managed by wireless communication to cell phones and voluntary selection of charging time would probably prove to be the least-cost solutions. Sophisticated controls by aggregators implementing varying charging rates to match wind or centralized solar availability will inevitably require much more expensive equipment to implement. It is also possible to alter the primary focus from overnight charging to daytime workplace charging, but indications are that establishing workplace (semi-public) charge points will be more expensive (Kley, Dallinger, and Wietschel, 2010; Santini et al., 2013a) than for residences because of the long distances to many parking spots from existing electrical service. Generally, the existing infrastructure is most easily used at residential plugs with overnight charging. However, for both wind (Santini and Burnham 2013) and solar energy, the most common peak availability is during daylight hours. Peak wind speeds in the interior of the United States, however, are an exception, where average diurnal wind speeds peak in the evening, after sunset. For solar when conducting onsite residential charging, west-facing solar panels may be most effective given the time of day that most people/vehicles return from work to the dwelling.

3.4.2.4 Electric Generation System Operation and Investment

This subtask examines financial policy effectiveness designed to alter (or retain) initial costs or operating costs in support of market development. Elgowainy et al. (2012a,b) and Dallinger, Wietschel, and Santini (2012) addressed the costs of installing new infrastructure in relation to the pattern of charging chosen by plug-in vehicle owners. Elgowainy et al. (2012a) included the only examination of the charge by departure choice, which is a standard option in multiple plug-in vehicles on the market today. This option moves the time of charging to early morning hours. When combined with low kW charging suitable for PHEVs, this charging strategy moves the demand away from the usual late afternoon and early evening system peaks, allowing charging to take place with expanded use of existing power plants. In the case examined by Elgowainy et al. (2012a), this charging strategy led to a higher percentage of use of combined cycle natural gas generation (97.5%) than time-of-arrival charging and smart charging, and thus the lowest greenhouse gas emissions. Further, similar to the smart charging case, no new generation capacity had to be installed. This charging profile may in the long run be voluntarily selected by most plug-in vehicle owners as they review the recommendations in their owners manuals. Charging by departure should minimize the time that packs sit idle with a full charge, thereby increasing pack life. Further, on cold and hot days when thermal management of the passenger cabin and battery pack prior to departure are desirable, charge by departure will use the least amount of energy for this purpose and will assure that grid electricity provides energy for thermal management rather than gasoline fuel in the engine.

4 Further Work

Many of the participating country experts in Task 15 are interested in conducting another phase of the study of plug-in hybrid and extended-range electric vehicles. As noted, some of the topics that had been planned for coverage in the latest Task 15 phase have not been completed. Further, in many cases, the coverage of the topics that were addressed was limited and merits additional investigation. It is desirable to further scrutinize and cross check the financial viability comparisons. While the collective papers written cover the sensitivity of market potential to gasoline prices, battery pack costs, or infrastructure availability, there is no single paper that covers all three under a consistent methodological approach using the latest BatPaC methodology for battery costs. None of the Task 15 financial viability analyses have investigated regional variation in electricity prices, variation in residential and commercial electricity rates, nor voluntary consumer response to time-of-use rates.

Market share models were nominally available to some of the participating country experts. However, the set of powertrain configurations simulated here would have overstressed the capabilities of the existing models, requiring time-consuming and costly modifications, which were beyond the scope of responsibility of the participating experts. This study shows that there are many possible configurations of PHEVs and/or ER-EVs that may compete against one another. The variety of types of powertrains simulated is already available in the marketplace. However, none of the default versions of the available market share models recognizes that there are so many different kinds of PHEV powertrains available. The distinction between PHEVs and ER-EVs was not made in the available models, much less the possibility for two different powertrain types within each of these two categories. Beyond this consideration, there has so far been a bias against inclusion of moderate-range PHEVs in these models.

The BatPaC model (Nelson et al., 2011 and 2012) clearly shows that, for a given kind of chemistry and pack assembly technology, battery pack costs per kWh vary, steadily declining as the W/Wh ratio declines. While the U.S. analysts from Argonne National Laboratory (Argonne) based battery pack cost estimates on the LMO battery chemistry, the German analysts from DLR assumed an NCA chemistry for the HEV and an NMC chemistry for plug-in vehicles. Subsequent developments imply that a blend of NMC and LMO is often being chosen, so battery chemistry modeling could benefit from updates. The Argonne and DLR battery pack cost estimates have in common a very sharp reduction in dollar or Euro costs per kWh when one shifts from an HEV power battery to energy batteries of 5–10 kWh for PHEVs. However, the reduction of battery pack cost per kWh slows sharply with shifts from 10–30 kWh (Figure 7).

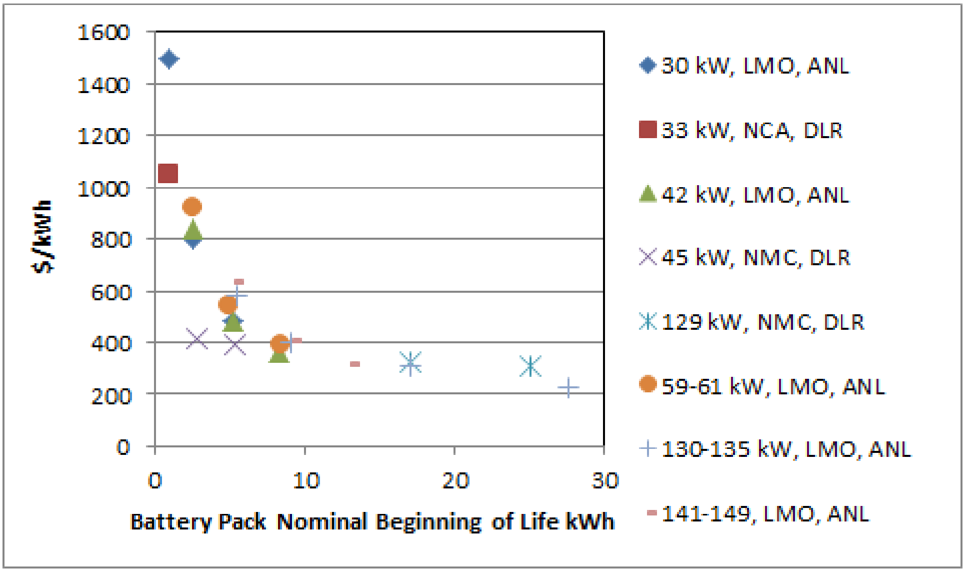


Figure 7: Argonne and DLR estimates of beginning of life battery pack cost per kWh, by peak pack kW and chemistry (Santini et al., 2013b; Propfe et al., 2012)

Each of the Task 15 analyses that examined the TCO of multiple powertrain types (Propfe et al., 2012; Rousseau et al., 2012; Santini et al., 2013b) used only one set of battery pack cost estimates. The Task 15 analysis that did broadly examine effects of variation in battery pack cost (Plotz, Kley, and Gnann, 2012) did not take the relationship shown in Figure 7 into account. Future work should conduct battery pack cost sensitivity analyses, taking the relationships in Figure 7 into account.

The sharp drop of battery pack costs per kWh in Figure 7 intuitively implies that conversions of HEV powertrains to PHEVs making use of the same electric machinery could be cost effective. Figure 5 implies that this is not true at low power (e.g., the 26-kW case), where the PHEVs are less cost effective than the HEVs. A common theme in the three papers that found cases where PHEVs could be more cost effective than the HEV simulated was that the battery pack peak power in the PHEV was higher than in the HEV. The pack power levels for which PHEV TCOs were found to be cost effective relative to HEVs ranged from 34–61 kW for the PHEV cases as compared to 26–32 kW for the HEV cases. It is desirable to examine HEVs with power levels from 34–61 kW to assure that PHEVs with those power levels continue to be estimated to have a financially competitive lowest TCO market niche. In the process of that examination, it is also desirable to conduct sensitivity analyses, not only to battery pack cost, but also to electricity and refined petroleum product prices (gasoline and diesel).

The three papers that evaluated PHEVs vs. ER-EVs consistently estimated PHEVs to have a lower TCO. Santini et al. (2013b) estimated, for the LMO battery pack chemistry simulated, that increases in battery pack cost were not a significant contributor to the increase of the initial cost of the vehicle. In that paper, it was estimated that the rest of the powertrain caused most of the cost increase of the ER-EVs as compared to the PHEV (Figure 8).

In Propfe et al. (2012), the balance of incremental costs vs. the CV between battery and other powertrain changes for the series ER-EV was reasonably even, at about 4,000 € for the pack and 5,000 € for other powertrain components (Figure 9). The series powertrain is less complex than the output-split. When the incremental costs of PEV powertrains were standardized at 1.38 $/€, the European country experts' estimates of costs were consistently higher. For the AEV costs estimated by Propfe et al. (2012, Figure 9), costs other than the battery were estimated to be considerably higher than those estimated by U.S. country experts in Santini et al. (2013b, Figure 8).

The definition and simulation of the portfolio of vehicles took the larger portion of the study period, leaving relatively limited time for financial analyses and methodological comparisons of financial viability analyses. Even then, not all vehicle powertrains were cross checked by both Argonne and IFP Energies Nouvelles. The Argonne-based Santini et al. (2013b) financial results estimate that input-split PHEVs with 60-kW battery packs will have lower lifetime costs of operation than those with 26-kW packs if gasoline prices rise by about 40%. It is suggested that this finding be revisited with cross checks for the parallel as well as the split powertrain technology. Design of parallel and split PHEVs with power adequate to drive only the U.S. UDDS all electrically should be

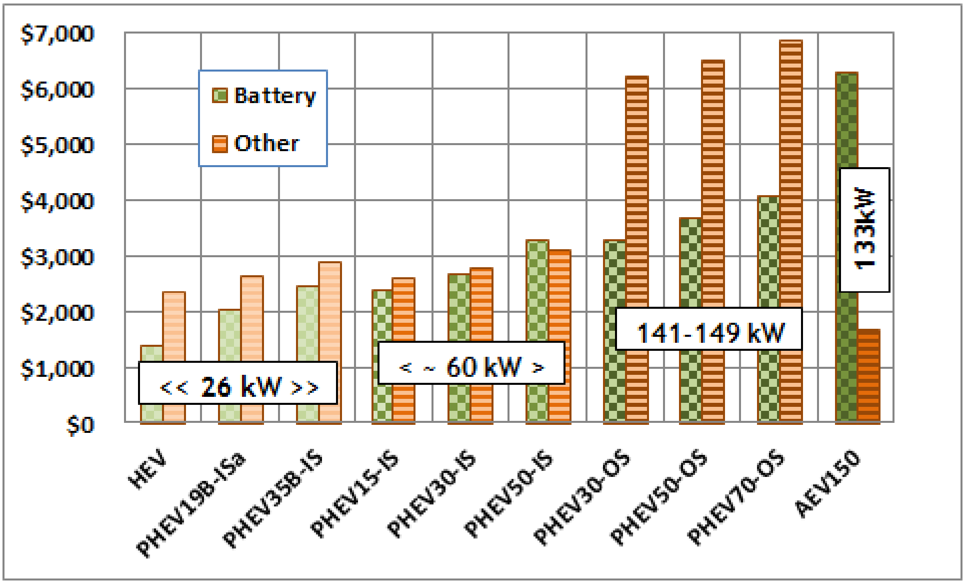


Figure 8: Contributions to increments in PEV price over CV: battery vs. other powertrain changes (United States, Argonne) (Source: Santini et al., 2013b)

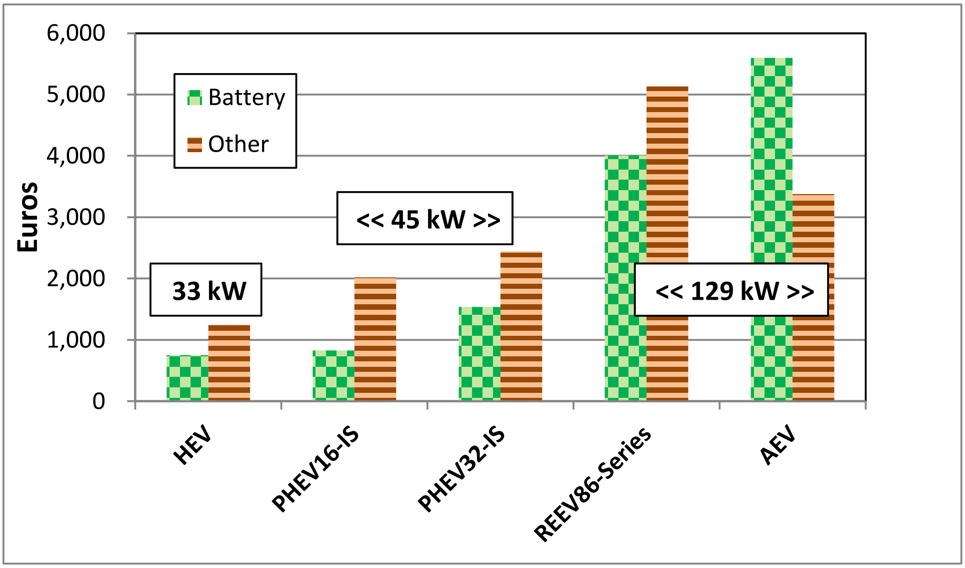


Figure 9: Contributions to increments in PEV price over CV: battery vs. other powertrain changes (Germany, DLR) (Source: Propfe et al., 2012) (Beginning-of-life pack peak kW estimated by operating agent)

completed, followed by lifetime cost comparisons of those PHEVs to ER-EVs designed to just barely provide all-electric operation in the most aggressive acceleration event in the Artemis Urban driving schedule and/or the full US06 driving cycle (only the Highway portion of the US06 cycle was simulated here). Meeting the full US06 cycle is the basis for a higher credit under California regulations than is meeting the UDDS cycle (http://www.arb.ca.gov/msprog/zevprog/zevprog.htm). Thus, there is a regulatory reward in portions of the United States to design future PHEVs with power levels greater than those used in Task 15 for the input-split PHEVs.

Another possibility is to examine what the CARB calls BEVx vehicles, which could be thought of as another version of the ER-EV, given that it is not an AEV. Although IFP Energies Nouvelles did simulate series ER-EVs, the performance rules applied in the simulations required a relatively large engine and generator. CARB wants only a low-kW engine with “limp-home” capability once the battery pack is depleted, with the engine operable only after pack depletion. The associated generator and its supporting power electronics would also require lower peak power, which would make the technology a lower cost than that simulated in Task 15. Although CARB stated that it does not intend to encourage a BEVx configuration with “universal appeal” that is capable of long-range operations as a hybrid (http://www.arb.ca.gov/regact/2012/zev2012/zevfsor.pdf), a possibility in other locations worldwide would be to use such small engines and generators essentially to avoid full battery pack depletion, recharging the battery pack much sooner than for a California BEVx and enabling use of the battery pack to assist the engine when climbing mountain grades. CARB stated that such a vehicle would be indistinguishable from conventional PHEVs (the R&D focus of Task 15). This configuration might allow an ER-EV option that could be standard worldwide using minor control strategy modifications of vehicles designed to obtain California BEVx credits. Relative to the design minima used in Task 15, decisions on different assumptions about minimum acceptable consumer performance requirements, such as when climbing mountain grades, would need to be made.

Issues of certification cycle vs. real-world driving cycle electricity and fuel consumption of PHEVs deserve more attention, including breakouts of the urban and extra-urban portions of the NEDC.

The following topics are suggested for inclusion in a follow-on phase of Task 15, or spin-off to another Task (i.e., items 6 and/or 10).

1. Conduct a systematic cost methodology comparison (multiple TCO models).
2. Compare full-function HEVs, PHEVs, and ER-EVs to advanced conventional powertrains (clean diesel, turbocharged direct injection petrol, CNG, and others).
3. Study powertrain depreciation attributes and impact on vehicle lifetime use costs. In particular, determine whether batteries must be replaced during vehicle lifetime, or vehicle use patterns must be adapted to less capable packs, or both.
4. Using consistent methodologies, evaluate potential causes of increases in market(s) size, such as rising oil prices, lower battery pack costs, economical infrastructure adaptation, changes in consumer perception, etc.
5. Track, evaluate, and/or study methods to desirably alter charging behavior.
6. Given the lack of competitiveness of HEVs and PHEVs for less-than-average vehicle utilization, consider the possibility that available lithium-ion battery chemistries could enable more lifetime cost-efficient micro HEV/PHEVs rather than promotion of use of lead-acid batteries supporting simple start/stop technology.
7. Examine whether a standard peak battery pack and electrical machine power level for both HEVs and PHEVs can be cost effective in spreading component costs across both HEV and PHEV platforms. If such a power level exists, simulations to date suggest that it is in the range of 30–60 kW for the size of car simulated in Task 15. In addition, simulate a PHEV with adequate power to run the US06 City and full US06 cycle all electrically to determine the minimum peak battery and motor kW required to obtain the maximum PHEV credit under CARB regulations.
8. Simulate costs and fuel consumption for what CARB defines as a BEVx using the required control strategy and HEV range specified in CARB regulations. This vehicle type will be a series ER-EV according to the definition used in this study, although with a much less powerful engine and generator. Simulate an ER-EV “spin-off” of the BEVx with a control strategy that uses its small engine and generator essentially to avoid full battery pack depletion, recharging the battery pack much sooner than would be the case for a CARB BEVx and thus enabling use of the battery pack to climb mountain grades. In addition, add a much larger fuel tank to enable a range comparable to that of conventional gasoline vehicles.

9. Simulate plug-in versions of what are called “crossover” SUVs, which are increasingly popular in the United States. Examine the benefits of increased battery pack space created by placement within the chassis below the passenger compartment and body in high seating position vehicles. Consider drag area “costs” in high-speed driving vs. pack space benefits for everyday metro area driving.
10. Critically review methods of computing the GHG emissions that result when different assumptions about electric generation caused by various charging strategies for plug-in vehicles are employed.

There are other topics that were goals of Task 15, but presently are either left incomplete or were not attempted in this initial phase, given limitations of the interests and capabilities of participating country experts and the constraints to follow their sponsored research plans. Nevertheless, a great deal was accomplished. Earlier plans are available for perusal by future country experts, should the recommendations made here prove to be well within the capabilities of country experts participating in the next phase. The process of discovery within the study, as well as many developments outside of the study, led to the “further work” suggestions made here.

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6 Task 15 Research Documents and Selected References

Following are publications related to Task 15 that were co-authored by participating country experts.

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