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Are batteries ready for plug-in hybrid buyers?

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ABSTRACT

The notion persists that battery technology and cost remain as barriers to commercialization of electric-drive passenger vehicles. Within the context of starting a market for plug-in hybrid electric vehicles (PHEVs), we explore two aspects of the purported problem: (1) PHEV performance goals and (2) the abilities of present and near-term battery chemistries to meet the resulting technological requirements. We summarize evidence stating that battery technologies do not meet the requirements that flow from three sets of influential PHEV goals due to inherent trade-offs among power, energy, longevity, cost, and safety. However, we also show that part of this battery problem is that those influential goals are overly ambitious compared to goals derived from consumers' PHEV designs. We elicited PHEV designs from potential early buyers among U.S. new car buyers; most of those who are interested in a PHEV are interested in less technologically advanced PHEVs than assumed by experts. Using respondents' PHEV designs, we derive peak power density and energy density requirements and show that current battery chemistries can meet them. By assuming too aggressive PHEV goals, existing policy initiatives, battery research, and vehicle development programs mischaracterize the batteries needed to start commercializing PHEVs. To answer the question whether batteries are ready for PHEVs, we must first answer the question, "whose PHEVs?"

1. Introduction

In this paper we examine what we call the battery problem: the contention that battery technology is not sufficiently advanced to allow the commercial success of electric-drive vehicles. We investigate the specific case of plug-in hybrid electric vehicles (PHEVs). For instance, Anderman (2008) states that the battery chemistries being developed for PHEV applications are "not ready for commercial introduction" due to limitations in performance, reliability, longevity, safety, and cost—presenting an overall "tremendous" business risk to potential PHEV manufacturers. We contend that potential solutions to the battery problem are not just a matter of technology development and cost reduction, but instead involve a concurrence between battery technology and appropriate PHEV performance goals. The present analysis explores both, with a particular emphasis on the latter—challenging untested assumptions regarding consumer valuation of PHEV capabilities.

1.1. *Efforts to start plugging in*

Why should transportation and energy policy makers, automobile manufacturers, the electricity industry, and consumers be concerned about the battery problem in general, and the case of PHEVs in particular? Spurred by petroleum supply and price disruptions, air pollution policy, and climate change policy, much effort and many resources have been devoted to the development of electric-drive vehicles over the past three decades. In the United States, the federal government initiated efforts to develop alternatives to petroleum-based fuels for transportation in the late 1970s and early 1980s, including the Hybrid and Electric Vehicle Act of 1976. Such actions laid the ground work for the battery, motor, and power and control electronics technologies that emerged during the 1990s (Turrentine and Kurani, 1996). Battery electric vehicles (EVs) garnered renewed attention in the 1990s, stimulated by General Motor's development of the EV-1 (*aka* Impact) and California's Zero Emissions Vehicle (ZEV) mandate. However, after years of further technology development and policy debate, policymakers were convinced by automobile manufacturers in the late 1990s that battery technology was not ready to meet manufacturers' EV performance goals. Some battery technologies later proved successful in less demanding hybrid electric vehicles (HEVs).

Presently, policymaker interest has turned to PHEVs. In response to the U.S. President's 2006 State of the Union address, the U.S. Department of Energy has published a working draft of a PHEV R&D Plan (USDOE, 2007). In California, the Air Resources Board (CARB) amended the ZEV mandate in March 2008 to provide incentives for automakers to produce and sell PHEVs (CARB, 2008).

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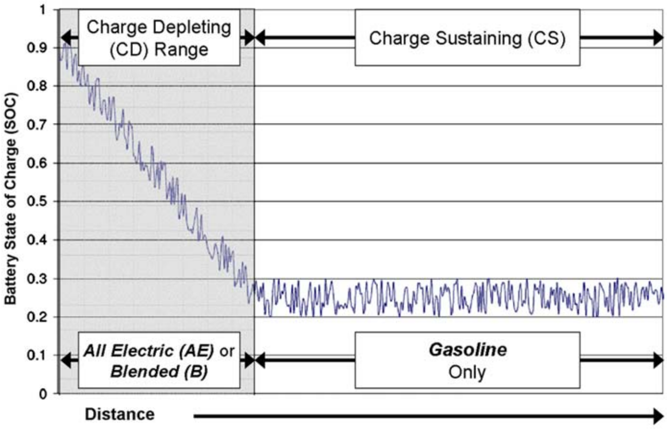

Fig. 1. Illustration of typical PHEV discharge cycle (~65% depth of discharge). *Source*: Adapted from Kromer and Heywood (2007, p. 31). Used with permission from authors.

Relative to other electric-drive and conventional gasoline or diesel vehicles, one advantage of PHEVs is fuel flexibility. A PHEV user could power their vehicle with electricity from the electrical power grid, gasoline (or another liquid fuel), or both. To do so, a PHEV has both an electric motor and a heat engine—usually an internal combustion engine (ICE).[1] However, this flexibility complicates vehicle designs and possible ways of using energy from two different systems, i.e., it is complex but necessary to specify exactly what type of PHEV one is discussing.

Fuel flexibility also complicates efforts to quantify potential PHEV benefits. Studies to date rely on assumptions about vehicle designs, consumer values, driving and recharge behaviors, and the future electricity grid. Focusing on the household market for motor vehicles, researchers estimate that PHEV use could halve petroleum use (Gondor et al., 2007; Axsen and Kurani, 2008) and reduce GHG emissions by 32 percent (Samaras and Meisterling, 2008) to 65 percent (Duvall et al., 2007) relative to conventional vehicles. Across a wide variety of assumptions, including PHEV performance levels, prior research concludes that PHEVs could contribute to air quality, climate change, and energy security goals. But such analyses do not consider which designs PHEV buyers would want, or what design goals should be set. In short, most prior analyses of PHEV impacts assume a given PHEV design and that people will buy those PHEVs. For their part, policymakers are unsure how to regulate PHEV emissions and fuel use and potentially incentivize commercialization under conditions of such technical, behavioral, and market uncertainty.

1.2. *PHEV design concepts*

To reexamine PHEV performance goals, four important design concepts must first be clarified.[2,3] First, a PHEV operates by either depleting (CD) or sustaining (CS) the state of charge (SOC) of its battery as illustrated in Fig. 1. For some distance a charged PHEV is driven in CD mode, gradually discharging the battery. Once the PHEV battery is depleted to a design minimum level, the vehicle switches to CS mode. To maintain battery life, only a portion of the battery's total energy capacity is used—known as the usable depth of discharge (DOD). In CS mode the battery's SOC is sustained by relying primarily on the gasoline engine, using the battery and electric motor to increase the efficiency of the gasoline engine and recapture kinetic energy during coasting and braking, as is now done in HEVs and EVs. The distance a fully charged PHEV can travel in CD mode before switching to CS mode is called CD range. PHEVs' ability to continue to be driven past their CD range using only the gasoline engine in CS mode is their main distinction from pure EVs; CD range in a PHEV (which does not necessarily limit the length of a given trip) holds much different implications for consumer valuation than does CD range in an EV (which does limit trip length).

Second, a PHEV can be designed for either all-electric (AE) or blended (B) operation over its CD range. AE operation uses only electricity from the battery; the engine is not used at all even when high power is demanded. In contrast, B operation uses electricity *and* gasoline to power the vehicle during the CD range, thus requiring a battery that need deliver less power. Note that the possibility of B operation presents another important distinction between PHEVs and pure EVs—the latter only have AE operation.

Third, PHEV designs are commonly described according to CD range; the common notation is PHEV-*X*, where *X* is the CD range in miles.[4] However, this notation does not distinguish whether a PHEV operates as AE or B. Comparisons of PHEVs, even those sharing the same PHEV-*X* designation, must reconcile assumptions regarding CD operation. Further, Kurani et al. (2007) discuss how additional confusion may result from two differing definitions of *X*: (1) as the equivalent number of miles of petroleum displaced by electricity from the battery (Gondor and Simpson, 2007) and (2) as the miles that can be driven before the gasoline engine turns on for the first time, also known as all-electric or zero-emissions range (CARB, 2003). In this article, we identify CD range and operation with the following notation: AE-*X* or B-*X*, where *X* is the CD range in miles.

Fourth, CD performance depends on the assumed drive cycle—a pattern of varying accelerations, speeds, and braking over a specified time used to test fuel economy and battery performance. A drive cycle is usually made up of one or more schedules. In the United States, the U.S. Environmental Protection Agency (EPA) has designed such schedules as the Urban Dynamometer Driving Schedule (UDDS), federal highway schedule (HWFET), and the US06 schedule. Kromer and Heywood (2007) criticize both the UDDS and HWFET as not accurately representing on-road driving, arguing for the use of the more aggressive US06. PHEV battery requirements based on schedules less aggressive than actual driving will overestimate the CD range and gasoline displacement of a given PHEV.

1.3. *Rethinking PHEV goals*

Influential PHEV goals set forth by government, industry, and academic sources include the following. The USDOE's (2007) draft PHEV R&D Plan sets a mid-term (2012–2016) goal of commercializing PHEVs with the capability of AE-20 range and/or B-40 range, progressing towards long-term (2016–2020) commercialization of

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[1] As the ICE in most conventional vehicles is fueled with gasoline (or diesel), in the discussion that follows we will refer to gasoline without precluding the possibility of different future fuels.

[2] These and other PHEV design issues are further described in Axsen et al. (2008).

[3] We distinguish between PHEV goals – the desired performance level of the vehicle – and PHEV battery requirements – the estimated technical battery specifications required to achieve the stated goals that will be addressed in a later section.

[4] To remain consistent with most of the PHEV literature cited in this paper and the PHEV design space presented to the American respondents to our survey, we report CD range and other distance-related measures in miles, where 1 mile = ~1.61 km.

Table 1
Comparing PHEV performance goals and the CD dimensions of the UC Davis PHEV design space.

	Units	Performance goals					CD design space	
		USABC[a]		MIT[b]	EPRI[c]		UCD[d]	
CD range	Miles	10	40	30	20	60	10, 20, or 40	10, 20 or 40
CD operation[e]	Type	AE	AE	B	AE	AE	B or AE	B or AE
Body type	Type	Cross-over SUV	Mid-size car	Mid-size car	Mid-size car	Mid-size car	Mid-size car	Mid-size truck
Electricity use[f]	kWh/mile	0.42	0.30	0.19	0.24	0.24	0.12–0.30	0.15–0.38
Depth of discharge	Percent	70	70	70	80	80	80	80
Drive schedule	Type	UDDS	UDDS	UDDS, HFWET, US06	UDDS, HFWET	UDDS, HFWET	US06	US06
Battery mass[g]	kg	60	120	60	159	302	60, 80, or 120	60, 80, or 120
Vehicle mass[h]	kg	1950	1600	1350	1664	1782	1600	2300

[a] As summarized in Pesaran et al. (2007).

[b] As summarized in Kromer and Heywood (2007).

[c] As summarized in Graham et al. (2001).

[d] Range of potential goals representing a range of feasible near-term PHEV designs presented to respondents in a nationally representative sample of U.S. new car buyers.

[e] Blended (B) or all-electric (AE) operation.

[f] Grid electricity only—equivalent to total available energy capacity divided by CD range. The range of levels in the UCD design space depends on vehicle type and the type of CD operation.

[g] UCD battery mass set to correspond with CD range, i.e., 60 kg for 10 miles of CD range, 80 kg for 20 miles, and 120 kg for 40 miles.

[h] UCD vehicle mass values set to correspond with Graham et al.'s (2001) mid-size car and Duvall et al.'s (2002) mid-size SUV.

PHEVs with AE-40 range and/or B-60 range. Different PHEV designs are assumed by the United States Advanced Battery Consortium (USABC) (as described in Pesaran et al., 2007), the Massachusetts Institute of Technology (MIT) (as described in Kromer and Heywood, 2007), and the Electric Power Research Institute (EPRI) (as described in Graham et al., 2001) to calculate PHEV battery performance requirements. These three sets of PHEV goals are summarized in Table 1 and further explored in this paper.

In this paper, we examine whether part of the battery problem is these assumed PHEV performance levels (goals) and the resulting battery requirements. Without contesting whether PHEVs with AE operation and long CD range will eventually be commercialized, we question whether it is necessary to wait for these PHEV designs in order to start commercializing any PHEVs, and therefore whether other PHEV designs (and their batteries) should be the object of technology development, marketing, and policy. We will show that the battery problem – as many observers describe it – is the product of inadequate attention to a logically prior question: What PHEVs will people buy?

To develop an alternative perspective on the battery problem for PHEVs, we discuss in turn, and then integrate, information from three sources:

1. The three sets of PHEV battery goals and requirements introduced above.
2. Consumers' PHEV design priorities as elicited through a large-sample U.S. survey of new car-buying households in December 2007.
3. The current state of battery chemistries, including nickel-metal hydride (NiMH) and several lithium-ion (Li-ion) batteries, and their potential development trajectories.

The next section compares the PHEV performance goals stated by the USABC, MIT and EPRI to the consumer-based approach applied here. Section 3 discusses the battery requirements derived from these four different goals. Section 4 summarizes the abilities of battery chemistries to meet such requirements. Section 5 summarizes by reevaluating the battery problem in light of consumers' elicited PHEV design priorities and concludes with policy implications.

2. Comparing PHEV performance goals

2.1. Current goals

The USABC goals in Table 1, as summarized by Pesaran et al. (2007), are the more recent and among the most influential.[5] The USABC specifies two PHEV designs from which it derives its battery requirements: an AE-10 crossover SUV and an AE-40 mid-size car. To illustrate the effects of different PHEV performance goals on battery requirements, we also present analyses performed by MIT and EPRI. MIT's goals as taken from Kromer and Heywood (2007), whose vehicle assumptions differed from USABC's in two important ways: (1) MIT's PHEV is a B-30 mid-size car, and (2) their driving simulations used the UDDS, HWFET, and US06 driving schedules rather than just the UDDS. EPRI's goals are taken from Graham et al. (2001), who assumed PHEVs to be AE-20 and AE-60 mid-size cars. Further, EPRI assumed higher battery weights (159 and 302 kg, respectively) than USABC (60 and 120 kg) and MIT (60 kg).[6]

2.2. *Towards consumer-informed goals: which PHEVs would PHEV buyers want?*

We now turn to the question: are these the right goals? Underlying these goals are assumptions about performance on the four PHEV design concepts discussed in Section 1.2. Do the PHEV designs assumed by experts match those that interest consumers? To explore this question, we did not assume one or two specific PHEVs. Rather, we created a PHEV *design space* in which consumers could create their own designs and thus set their own PHEV goals.[7] This design space is also summarized in Table 1. The dimensions of the design space included CD operation – AE or three levels of B operation – and CD ranges of 10, 20 or 40 miles

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[5] The USABC is a partnership between the U.S. Department of Energy (DOE) and U.S. automobile companies.

[6] EPRI assumed a heavier battery because the most likely chemistry for use in a PHEV in 2001 when their report was written, i.e., NiMH, has much lower energy and peak power density than today's more likely prospects, i.e., Li-ion.

[7] EPRI did conduct consumer research as part of their PHEV research program. However, their respondents were only asked to respond to the same two PHEVs described above that EPRI assumed to calculate their battery requirements.

(the latter options correspond to a 60, 80 or 120 kg battery, respectively).[8]

Our design space approach differs from a common approach to estimating consumer demand for alternative vehicles: eliciting consumer preferences or willingness-to-pay (e.g., Bunch et al., 1993; Ewing and Sarigollu, 2000; Potoglou and Kanaroglou, 2007). There are several reasons why we implemented the design space approach. First, we were not willing to assume what a PHEV "should" be. Second, in order to derive consumer-driven battery requirements to compare to experts' assumption-driven requirements we need consumers' complete vehicle designs—it is neither necessary nor sufficient to estimate partial-attribute values or overall WTP. Where willingness-to-pay estimates are typically averaged across a population, or at best, a few segments, our design space technique preserves each individual's design selection and compiles the distribution of consumer interest across the entire sample. Third, constructive design processes are consistent with theories of constructed preferences that view consumer preferences as outcomes of, not inputs to, decision contexts and processes (Bettman et al., 1998). Willingness-to-pay presumes consumers have preferences about the attributes available in a given choice. However, research suggests that most consumers have little experience or understanding of electric drive (e.g., Kurani et al., 1996; Axsen and Kurani, 2008), and have difficulty quantifying their valuation of fuel economy (Turrentine and Kurani, 2007). In this context, design construction affords greater opportunity for learning and comparison of multiple possible designs to consumers' lifestyles and travel. Thus, we allowed respondents to work in a design space that afforded a wide array of potential design options (144 possible combinations for cars and again for trucks, as explained below), rather than presenting only a small set of predetermined designs in "choice" exercises.

This PHEV design space was presented to a sample of 2373 new vehicle-buying households in the U.S. (See Axsen and Kurani (2008) for sample details.) The sample was assessed to be representative of the target population—with distributions of age, income, housing type and other demographic variables matching those of relevant subsamples drawn from the U.S. Census, Current Population Survey, and the National Household Travel Survey. Respondents completed a multi-part questionnaire over the course of several days:

- Part 1 was an on-line questionnaire asking about vehicle ownership, gasoline and electricity expenditures, alternative fuel and electric-drive technology awareness and knowledge, environmental beliefs, and household composition.
- Part 2 was a 24-h diary of driving and vehicle recharging potential by time of day and parking location as identified by the respondents.
- Part 3 was also an on-line questionnaire in which we elicited PHEV designs through a series of design games.

To prepare them for the design games, respondents were provided two types of preparatory information: (1) their 24-h diary exercise served the additional role of reflecting to respondents aspects of their daily travel and potential access to recharging locations and (2) an 8-page PHEV buyers' guide describing basic design options for PHEVs, including stories of different households designing different PHEVs to exemplify why respondents might, or might not, value various PHEV performances and features. Respondents then completed two design games. The first was the PHEV *Development Priority* game in which they created PHEV designs over several iterations. The second was the *Purchase Design* game which was framed in the context of a future vehicle purchase by the household. Information was elicited about any expectations the household may have of price, make, and model of the next new vehicle they would likely buy. Respondents were then presented with this anticipated conventional vehicle, a PHEV version of it offered at a higher price, and the option to upgrade the proffered PHEV at still higher prices.

Table 2
Price of upgrades in the Purchase Design game (prices are incremental to a conventional vehicle identified by each respondent household).

Attributes	Attribute level	"High" price scenario	
		Car	Truck
Base premium		$3000	$4000
Added premiums			
Recharge time	8 h	0	0
	4 h	+$500	+$1000
	2 h	+$1000	+$2000
	1 h	+$1500	+$3000
CD mpg and type[a]	Blended		
	75 mpg	0	0
	100 mpg	+$1000	+$2000
	125 mpg	+$2000	+$4000
	All-electric	+$4000	+$8000
CD range	10 miles	0	0
	20 miles	+$2000	+$4000
	40 miles	+$4000	+$8000
CS mpg	Conventional mpg +10	0	0
	Conventional mpg +20	+$500	+$1000
	Conventional mpg +30	+$1000	+$2000

[a] Metric conversions: 75 mpg = ~3.14 L/100 km, 100 mpg = ~2.35 L/100 km, 125 mpg = ~1.88 L/100 km, and all-electric = 0.00 L/100 km.

The base PHEV design offered to respondents in the *Purchase Design* game was described (in relatively non-technical language) as requiring up to 8 h to completely recharge, providing 10 miles CD range in blended operation (B-10) to achieve 75 miles per gallon (mpg), and improving fuel economy in CS mode by 10 mpg over the conventional ICE vehicle they were considering for purchase.[9,10] Additional upgrades to each of these performance parameters – recharge time, CD range, CD operation (blended or all-electric), and CS fuel economy – were available at higher prices (Table 2 shows the prices for the high price version of the game). For instance, a new conventional car could be upgraded to the base PHEV model for $3000. Alternatively, it could be further upgraded, say, to an AE-20 for a total premium of $9000. PHEV and upgrade prices are comparable to estimates from Markel et al. (2006) and Kalhammer et al. (2007).[11] Again, note that these prices should not be confused with the notion of willingness-to-pay estimates, which this study does not seek to produce.

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[8] The design space also included dimensions of recharge time and CS fuel economy. However, this study only focuses on CD operation and range. See Axsen and Kurani (2008) for a complete description of the PHEV design space.

[9] To remain consistent with most of the cited PHEV literature and the PHEV design space presented to the American respondents to our survey, we report B operation in miles per gallon (mpg), where 75 mpg is ~3.14 l per 100 km.

[10] Fuel economy was based only on gasoline use; it did not account for electricity from the grid.

[11] Still, we note that the prices used in the design exercise are intended only to be internally consistent to the exercise, making the relative price of each improvement plausible. The external validity of the absolute prices, i.e., whether we have correctly guessed the future prices of PHEV performance attributes in the real world, is less relevant at this step of our simulation. Further, the general conclusions we offer are more susceptible to battery prices being radically lower than we use; higher prices reinforce our conclusions.

Table 3
Distribution (%) of PHEV designs by early market potential respondents.

	CD range in miles					
	Prospective car buyer			Prospective truck buyer		
CD type[a]	10	20	40	10	20	40
Blended						
75 mpg	35.95	3.65	1.02	33.35	2.16	0.00
100 mpg	5.08	3.65	1.50	3.95	1.73	0.00
125 mpg	2.48	1.29	0.56	0.68	0.33	1.06
All electric	0.30	0.07	0.20	0.10	0.00	0.87

[a] Metric conversions: 75 mpg = ~3.14 L/100 km, 100 mpg = ~2.35 L/100 km, 125 mpg = ~1.88 L/100 km, and all-electric = 0.00 L/100 km. *Note*: Early market respondents includes 33 percent of the total U.S. new vehicle-buying sample.

While respondents were free to specify any vehicle as their likely next new vehicle, the analysis to convert their PHEV designs into battery requirements simplifies vehicles into two categories: (1) cars (and car-like vehicles) and (2) trucks (and truck-like vehicles). Further, in contrast to USABC's, MIT's and EPRI's battery requirements, ours are more conservatively based solely on the more aggressive US06 drive schedule.

In the present analysis, we focus only on the PHEV designs created by the subset of respondents we defined as belonging to a potential early PHEV market: those who (1) reported an electrical outlet within 25 ft of their home parking space during their diary day, and (2) accepted the proffered base PHEV or designed an upgraded PHEV in the "high" price scenario of the design exercise rather than accept the conventional vehicle.[12] Such respondents make up one-third of the entire sample of U.S. new car-buying households.

In summary, the PHEV goals we present are a distribution created by consumers interested in purchasing a PHEV. This distribution, simplified to show only the possible combinations of CD operation type and range, is presented in Table 3.[13] In a scenario of relatively high battery prices representing near-term estimates, a substantial number of new vehicle-buying households reported that they were interested in vehicles with plug-in capabilities. The majority of these potential early market respondents (69 percent) selected the base B-10 described above, i.e., the PHEV design with the lowest battery power and energy requirements.

3. Understanding battery requirements

3.1. *Batteries for PHEV goals*

To assess the battery requirements to meet the PHEV performance goals from the prior section, we first discuss five requirement categories: power, energy capacity, life, cost, and safety (Table 4), then focus on power and energy. To illustrate the five types of requirements, we focus on the USABC, MIT, and EPRI goals before discussing the battery requirements of the PHEV design space in which our respondents worked.

First, total battery peak power is represented in kW and peak power density in W/kg.[14] Three factors explain most of the variation in power requirements in Table 4. Higher power is required for (1) a larger and/or heavier vehicle, (2) AE rather than B operation, and (3) a more aggressive drive cycle. Required peak power density is determined by these factors, as well as the assumed battery mass.

Second, energy capacity requirements relate to the amount of energy stored in the batteries (kWh) and the energy density (Wh/kg). Energy storage determines CD range; energy density largely determines the mass of the battery system. We report energy capacity as total energy, not available energy. For instance, the USABC's AE-10 requires 3.9 kWh of available energy; their AE-40 requires 11.9 kWh. Given their assumed 70 percent DOD, these available energy values correspond to battery systems storing total energy of 5.6 and 17.0 kWh, respectively, as shown in Table 4.

Third, Table 4 lists three measures of battery life. Calendar life is the ability to limit degradation over time, which may be independent of how often or how hard the battery is discharged and charged. CD cycle life, or deep cycle life, is the number of full discharge–charge cycles over the usable DOD the battery can perform. CS cycle life, or shallow cycle life, refers to SOC variations of only a few percent occurring throughout CD and CS mode. The battery frequently takes in electric energy (charges) from the gasoline engine and from regenerative braking and passes energy to the electric motor (discharges) as needed to power the vehicle or recharge the battery. Although the batteries currently used in HEVs achieve high shallow cycle life, in a PHEV some of the shallow cycles would occur at a lower SOC if the vehicle is driven in CS mode. Shallow cycling at low SOC may have a greater negative effect on battery life than shallow cycling at higher SOC.

Fourth, battery cost is cited as one of the most crucial factors affecting the commercial deployment of electric-drive vehicles, e.g., Kalhammer et al. (2007). The USABC cost requirements are \$300/kWh and \$200/kWh for AE-10 and AE-40 battery packs, respectively.[15] These cost goals are much lower than current prices; Pesaran et al. (2007) estimate that in general, current advanced battery costs range from \$800/kWh to \$1000/kWh or higher.

Fifth, safety is important due to the fact that batteries store energy and contain chemicals that can be dangerous if released or consumed in an uncontrolled manner, such as through short circuits, impacts, overcharging, or high heat (Kalhammer et al., 2007).[16] In electric-drive automotive applications, batteries use management systems that monitor cell voltage and temperature and can take some corrective action when necessary. The USABC's battery requirements do not include specific safety objectives. Safety is typically assessed through abuse tolerance tests; such tests are inputs to a subjective rating of "acceptability" (Doughty and Crafts, 2005).

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[12] Axsen and Kurani (2008) also presented a "low" price scenario; it is not discussed here. PHEV design priorities expressed by respondents were similar in both scenarios, with a higher percentage of respondents either selecting the base PHEV or selecting upgrades to the base PHEV in the "low" price scenario.

[13] While we do not discuss recharge time and CS fuel economy in this analysis, we do note that CS fuel economy upgrades were chosen most frequently—an attribute that affects battery design and cycle life. However, we do not anticipate CS fuel economy to hold significant implications for the two main battery requirements discussed in this paper: peak power density and energy density.

[14] The USABC peak power requirements are based on short acceleration pulses of 2 and 10 s.

[15] These goals are stated as costs to auto manufacturers, and do not include the markup that would be passed on to consumers. Estimates of the markup on advanced automotive batteries from OEM to consumer range from 25 to 33 percent (Kromer and Heywood, 2007).

[16] Not to diminish the importance of safety, but we note that automotive consumers, automotive service and fueling personnel, and emergency first responders have become habituated to handling toxic and highly flammable fuels, i.e., gasoline and diesel.

Table 4
Battery pack requirements for PHEV performance goals.

	Units	USABC[a]		MIT[b]	EPRI[c]	
		AE-10	AE-40	B-30	AE-20	AE-60
Power						
Peak power	kW	50	46	44	54	99
Peak power density	W/kg	833	383	733	340	328
Energy						
Total energy capacity	kWh	5.6	17.0	8.0	5.8	17.9
Total energy density	Wh/kg	93	142	133	37	59
Life						
Calendar life	Years	15	15	15	10	10
CD cycle life	Cycles	5000	5000	2500	2400	1400
CS cycle life	Cycles	300,000	300,000	175,000	200,000	200,000
Cost						
OEM price[d]	$	$1700	$3400	$2560	–	–
OEM price/total kWh	$/kWh	$300	$200	$320	–	–

[a] As summarized in Pesaran et al. (2007).
[b] As summarized in Kromer and Heywood (2007).
[c] As summarized in Graham et al. (2001).
[d] Assuming 100,000 units of production per year.

3.2. *Towards consumer-informed battery peak power and energy requirements*

In this paper, we reevaluate only peak power and energy requirements to meet CD goals, i.e., AE vs. B operation and CD range. The task of reevaluating life, cost, and safety requirements in light of input from consumers is left to future research.

In Table 5 we present peak power and energy requirements for the 24 PHEV designs in Table 3.[17] These requirements are estimated for both car and truck body types using analyses by Burke and Van Gelder (2008), Kromer and Heywood (2007), Graham et al. (2001), and Duvall et al. (2002). In general, the possible power and energy requirements of our design space more than span the variety of requirements from the other three studies presented in Table 4. For example the peak power requirements derived from the PHEV goals of the USABC, MIT, and EPRI range from 44 to 99 kW; the peak power of our PHEV design space spans from 27 to 138 kW.

In Fig. 2 we plot the distribution of battery cell-level peak power and energy requirements (Table 5) we derived from the PHEVs created by respondents (Table 3) on to a modification of Kalhammer et al.'s (2007) Ragone plots representing the trade-off between peak power density and energy density (discussed further in the next section).[18] A region bounded in black represents a range of nickel-metal hydride capabilities and another in grey represents lithium-ion chemistries. For comparison, we also plot the battery cell requirements derived by USABC, MIT, and EPRI. The interpretation of the data markers is different for the PHEV designs (goals) from the survey respondents than for the other three sets of goals. The centers of the grey circles mark the location of the peak power density and energy density requirements derived from the respondents' designs. The sizes of the grey circles are proportional to the number of respondents who chose or designed the PHEV corresponding to those battery requirements. On the other hand, the black circles marking the location of the USABC, MIT, and EPRI requirements have been sized solely to make them perceptible in the figure.

As noted earlier, the majority of potential early market respondents opted for the base B-10 version of the car or truck they were most likely to purchase next, i.e., the PHEV with the lowest peak power density and energy density requirements. Even including respondents who designed more demanding PHEVs, about 85 percent of the potential early market respondents designed PHEVs that required peak power density and energy density within the region of the Ragone plot identified by nickel-metal hydride (discussed below). In contrast, experts' assumed PHEVs all result in much higher peak power and energy density requirements, most of them seemingly beyond the present understanding of the capabilities of lithium-ion. Next, we will further explore the ability of battery chemistries to meet the identified PHEV requirements.

4. What is the present status of battery technology relative to PHEV requirements?

The challenge for PHEV battery development is to find an appropriate balance among the five categories of requirements discussed in Section 3.1 for PHEV applications. But what are those applications? Fig. 2 represents a radical reorientation of battery requirements from the PHEV goals assumed by battery and other technology experts vs. the present desires of prospective consumers. We turn now to this last question: how close are we to being able to build PHEVs that can be sold to our respondents?

There are inherent trade-offs among the five battery requirements discussed in Section 3.1. For instance, higher power density batteries tend to have lower energy density, higher cost, reduced cycle life and potentially greater safety problems than lower power density batteries. Thus, it is not possible to maximize both

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[17] These 24 designs – four possible CD operating states and three CD ranges each for cars and trucks – span the CD dimensions of the design space.

[18] Thus far, we have discussed the performance requirements of a PHEV battery pack. For the remainder of the article, we distinguish between the attributes of a pack versus an individual cell. The battery pack (or system) consists of many individual battery cells, plus a cooling system, inter-cell connectors, cell monitoring devices, and safety circuits. The added weight and volume of these reduce energy density and peak power density of the pack relative to the cell. We apply a packaging factor of 0.75 to account for these effects, i.e., cell values are multiplied by 0.75 to estimate pack values. In addition, the inter-cell connectors and safety circuits of a battery pack can significantly increase resistance, decreasing the pack power rating from that achievable by a single cell. However, for this article we use the same packaging factor for both power and energy density.

Table 5
Battery pack requirements for PHEV goals in UCD design space.

CD type	Units	CD range in miles					
		Car			Truck[a]		
		10	20	40	10	20	40
B (75 mpg)							
Peak power[b]	kW	27[c]	27[c]	27[c]	39	39	39
Peak power density	W/kg	453	340	227	653	490	326
Total energy capacity[d]	kWh	1.5[e]	2.9[e]	5.8[e]	1.9	3.7	7.4
Total energy density	Wh/kg	24	36	48	31	46	62
B (100 mpg)							
Peak power[b]	kW	37[c]	37[c]	37[c]	53	53	53
Peak power density	W/kg	613	460	307	883	662	442
Total energy capacity[d]	kWh	1.7[e]	3.4[e]	6.8[e]	2.2	4.4	8.7
Total energy density	Wh/kg	28	43	57	36	55	73
B (125 mpg)							
Peak power[b]	kW	43[c]	43[c]	43[c]	62	62	62
Peak power density	W/kg	720	540	360	1037	778	518
Total energy capacity[d]	kWh	2.3[e]	4.6[e]	9.1[e]	2.9	5.8	11.6
Total energy density	Wh/kg	38	57	76	49	73	97
AE							
Peak power[b]	kW	96[f]	96[f]	96[f]	138	138	138
Peak power density	W/kg	1600	1200	800	2304	1728	1152
Total energy capacity[d]	kWh	3.8[g]	7.5[g]	15.0[g]	4.8	9.6	19.2
Total energy density	Wh/kg	63	94	125	80	120	160

[a] A "truck" is assumed to require 28 percent higher electricity use and 44 percent higher peak power relative to a "car," as approximated from Graham et al.'s (2001) and Duvall et al.'s (2002) estimates for mid-size car and mid-size SUV PHEV-20s.

[b] Assuming motor efficiency of 85 percent.

[c] Peak power approximated from Burke and Van Gelder (2008) simulations for Toyota Prius with US06 drive cycle—multiplied by 1.36 to scale from ~1300 to ~1600 kg car.

[d] Assuming DOD of 80 percent.

[e] Energy use approximated from Burke and Van Gelder (2008) simulations for Toyota Prius with US06 drive cycle—multiplied by 1.16 to scale from ~1300 to ~1600 kg car.

[f] Peak power approximated from Kromer and Heywood (2007) simulations of optimized Toyota Camry with US06 drive cycle, assuming 85 percent motor efficiency—multiplied by 1.36 to scale from ~1300 to ~1600 kg car.

[g] Energy use approximated from Kromer and Heywood (2007) simulations of optimized Toyota Camry with US06 drive cycle, assuming 85 percent motor efficiency—multiplied by 1.16 to scale from ~1300 to ~1600 kg car.

power and energy densities in the same battery design, let alone simultaneously meeting the most desirable life, cost and safety requirements. Understanding these trade-offs is key to appreciating the complexities and challenges of PHEV battery development. So what is the current state of battery technologies *vis-à-vis* the PHEV battery requirements in Fig. 2?

We review two broad categories of battery chemistries: nickel-metal hydride (NiMH) and lithium-ion (Li-ion). Cell values for peak power and energy density performance of one NiMH and three different Li-ion batteries as tested at UC Davis (Burke, 2007; Burke and Miller, 2008) – lithium iron phosphate (LFP), lithium nickel, cobalt and manganese (NCM) and lithium titanium (LTO) – are plotted in Fig. 3. As in Fig. 2, there are two regions demarcating a range of capabilities for NiMH and Li-ion chemistries.

A comparison of Figs. 2 and 3 reveals the implications that differing PHEV design goals hold for perceptions of the battery problem. It is not merely that the distribution of battery peak power density and energy density requirements derived from prospective consumers' PHEV designs is largely skewed towards lower requirements than the USABC and MIT analyses. It is that these requirements derived from prospective consumers are far within the capabilities of several lithium-based battery chemistries and that even some NiMH batteries can meet energy density – if perhaps not peak power density – requirements of most PHEV designs created by new car-buying households presently interested in PHEVs. We note that it may be unlikely that the NiMH batteries used in HEVs will be able to demonstrate the long deep cycle life that is required for PHEVs applications. It is also uncertain whether the high energy density, long cycle life NiMH EV batteries can be redesigned for PHEV applications by reducing energy density somewhat and increasing peak power density while maintaining high deep cycle and very long shallow cycle life. Hence, Fig. 2 should not be construed as saying present NiMH batteries in HEVs are suitable for PHEVs.

Our results also do not indicate that EPRI's requirements were the right ones all along—EPRI's PHEVs (and their battery masses) are very different from any designed by our respondents. Further, only about one-quarter of one percent of our respondents designed a PHEV that was an AE-20 (or greater) passenger car (the closest approximations in our design space to EPRI's assumed goals).

But what of the other three categories of requirements? We cautiously acknowledge that Figs. 2 and 3 do not capture the only relevant characteristics of battery chemistries—a balance among all five of the requirements discussed above is necessary. To illustrate the importance of the interrelatedness of these five battery requirements above, Table 6 presents a qualitative assessment of the same four batteries adapted from Axsen et al. (2008). NiMH batteries are presently used for most HEVs, and have demonstrated long calendar life, cycle life and safety (Kalhammer et al., 2007). However, because NiMH technology faces limitations in energy and peak power density (compared to the USABC and MIT requirements) and cost (Kalhammer et al., 2007; Anderman, 2008) battery researchers continue to develop Li-ion chemistries for PHEV applications. Li-ion has higher energy and peak power density, allowing lighter and more compact batteries (Kromer and Heywood, 2007), potentially at lower cost (Kalhammer et al., 2007). However, Li-ion does have potential drawbacks in longevity and safety due to higher chemical reactivity, requiring more sophisticated monitoring and control over cell voltage and temperature (Kalhammer et al., 2007), and leading some manufactures to delay commercial deployment (e.g., Shirouzu, 2007).

Taken together, Fig. 3 and Table 6 demonstrate the inherent trade-offs in battery characteristics; higher power density batteries have reduced energy density, cycle life and safety and higher cost. For these reasons, battery research continues to explore new lithium chemistries with inherently lower energy performance (e.g., LFP, LTO) to meet demanding safety and longevity requirements. However, in relation to our consumer-informed battery goals, we have demonstrated the power and energy densities required for commercialization may be much closer to realization than implied by prior assumptions of experts.

5. Summary and conclusions

5.1. What is the battery problem?

To investigate the "battery problem" – the contention that inadequate performance of available battery technologies and their high cost are the main barriers to the commercialization of passenger vehicles with plug-in capabilities – within the context of commercializing PHEVs, we explored a range of experts' and potential consumers' PHEV performance goals, the battery requirements derived from those goals, and the status of battery

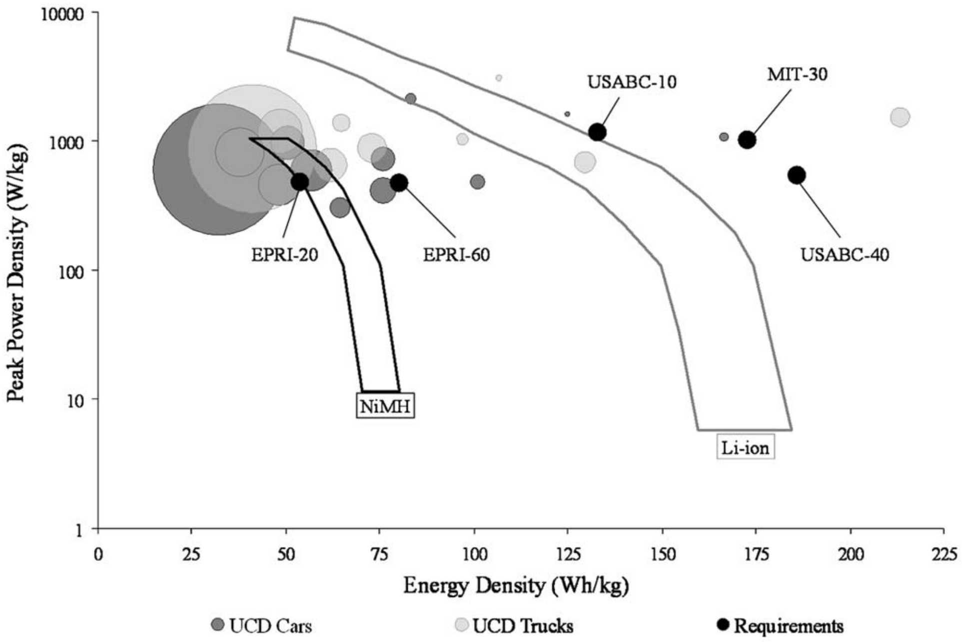

Fig. 2. Distribution of battery requirements for PHEV designs selected by potential early market respondents and USABC, MIT, and EPRI. *Notes*: For UCD Cars and Trucks, the areas of the circles are proportional to the number of respondents who designed the PHEV from which those battery requirements flow. The circles indicating USABC's, MIT's, and EPRI's requirements are sized simply to make them perceptible. The potential early market respondents plotted here account for 33 percent of the entire survey sample of U.S. new car-buying households. Battery specifications are taken from Table 5, assuming: (1) motor efficiency of 85 percent, (2) packaging factor of 0.75, and (3) 80 percent battery DOD.

Source: Chemistry Ragone plots from Kalhammer et al. (2007).

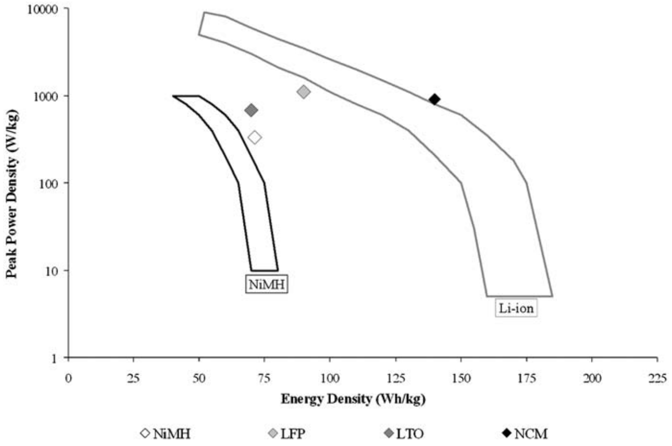

Fig. 3. Battery cell potentials for four battery types.*Notes*: The NiMH battery is assumed to be optimized for PHEV or EV application, with higher energy density than HEV application, and lower voltage to increase peak power (while lowering peak power efficiency). Peak power measured at 60 percent efficiency, at 50 percent SOC. At 90 percent efficiency, tested peak power is 90 W/kg. LFP, LTO and NCM batteries' peak power measure at 90 percent efficiency, 50 percent state of charge.

Source: Chemistry Ragone plots from Kalhammer et al. (2007). Battery cell potential based on testing by A. Burke at UC Davis, April 2008.

technology in meeting those requirements. Our analysis suggests that the battery problem has both technical and perceptual elements. There are technological limitations to the commercialization of PHEVs. Battery development is constrained by inherent trade-offs among five main battery attributes: power, energy, longevity, cost, and safety. Of the battery chemistries discussed, only Li-ion shows the potential to meet the high peak power density and energy density of aggressive PHEV goals, i.e., vehicles with all-electric CD capability and/or CD range over 20 miles. However, Li-ion chemistries continue to face limitations in cycle life, cost, and safety.

However, the research reported here indicates that more important than concerns about technology development *per se* is the perceived problem: the previously untested assumptions regarding the types of PHEVs to be commercialized. Influential PHEV performance/design goals from the USABC, MIT, and EPRI and implicit in the USDOE's (2007) commercialization goals vary according to assumptions concerning CD range, CD operation (all-electric vs. blended), drive cycles, vehicle mass, battery mass, and other issues—most of which are highly uncertain. Subsequently, estimated PHEV battery requirements flowing from these goals are equally uncertain, and thus, so are perceptions of the battery problem. Ultimately, the true requirements of PHEV technology will depend on consumers' valuation of different PHEV designs and capabilities.

To bring U.S. consumers' perspectives to the battery problem, we drew from a recent nationwide, representative survey of over 2000 new vehicle-buying households. The multi-day survey was carefully designed and pre-tested to prepare respondents before eliciting their PHEV design priorities; among other things, each respondent completed a one-day driving and parking diary to assess their own potential to recharge a PHEV, was provided an 8-page PHEV buyers' guide describing design considerations, and completed a preparatory design exercise before completing the *Purchase Intention* game.

In PHEV design games presenting feasibly high prices, the respondents who chose PHEVs tended to design shorter CD-range PHEVs that rely on blended rather than all-electric CD operation. Given these PHEV designs, more aggressive goals may be unnecessary for near-term, even immediate, PHEV commercialization.

In other words, the range of assumptions represented by the USABC, MIT, and EPRI PHEV performance goals do not encompass the types of vehicles potential PHEV consumers say they value.

Table 6
Relative characteristics of potential PHEV battery chemistries.
Source: Adapted from Axsen et al. (2008).

Name	Description	Automotive status	Power	Energy	Life	Cost	Safety
NiMH	Nickel-metal hydride	Commercial production	Low	Low	High	Mod.	High
LFP	Lithium iron phosphate	Pilot	Mod.-high	Mod.	High	Low	Mod.-high
NCM	Lithium nickel, cobalt and manganese	Pilot	Mod.	Mod.-high	Low	High	Mod.
LTO	Lithium titanium	Development	High	Low	High	Mod.	High

Given consumers' PHEV designs, the peak power density and energy density requirements of the majority of potential PHEV buyers in our sample could likely be met with a currently available battery chemistry, e.g., NiMH. We are not saying that existing NiMH batteries in HEVs can be used for PHEVs; there are still life and cost requirements to be considered. For example, the excellent shallow cycle life that NiMH batteries have demonstrated in HEVs may not be taken as an accurate measure of their deep cycle life in PHEVs. However, in contrast to statements by battery researchers indicating that accelerated PHEV development may be a misguided "detour" due to the large gap between present battery performance and performance requirements for PHEVs (Anderman, 2008), we are saying that appropriate batteries may be closer for commercially viable PHEVs than often realized and that the battery problems to be solved for those batteries are radically different from the power/energy/life/cost/safety issues implied by the USABC and others.

So, what is the battery problem? While further battery development across all five categories of requirements is surely advisable to improve both near-term and long-term prospects for many types of electric-drive vehicles, the direction of such development should be more carefully aligned with the distribution of consumer interests in the near and long term. A high priority would be to better match the performance of electric-drive vehicles and their batteries to the demands of their consumers.

5.2. *Policy implications*

Perceptions of the battery problem hold important implications for policy; it was the perceived gap between the capabilities of battery technology and the EV goals assumed by automotive OEMs for potential EV buyers that convinced CARB to modify and reduce ZEV sales requirements in the late 1990s. In the present day, the commercialization potential for PHEVs should be based on analysis of both the state of battery technology and the interests of consumers. As demonstrated in this study, there is a role for less ambitious PHEV designs with shorter CD ranges and blended CD operation in the near term. Such designs would meet the interests of many current vehicle buyers at relatively lower cost premiums, while still significantly contributing to reductions in GHG emissions, air pollution, and petroleum use. Thus, it may not be necessary that USABC's goals be met by a new battery technology before the commercial introduction or success of PHEVs can or should occur.

Of course, policymakers are not just interested in meeting consumer demand, but also in achieving environmental and energy goals. For instance, the commercialization of PHEVs operating all-electrically in CD mode and with longer CD ranges would likely result in larger reductions in petroleum use and greenhouse gas emissions—per vehicle. However, the successful commercialization of such ambitious PHEV designs in the short term would likely require more aggressive policy actions such as high financial incentives, large-scale vehicle demonstrations, and pervasive information campaigns—to overcome not just the higher cost of such added performance, but also the lack of inherent interest observed among a sample of potential PHEV consumers. Thus, while the PHEV performance assumed by the USABC and others provide a possibly useful benchmark for future targets for PHEV battery technology, a near-term focus on less aggressive goals may offset more petroleum and emissions in the long run. However, even assumptions regarding the future strategies for the development of PHEVs should be continually reevaluated from a consumer standpoint to assure alignment with a developing market.

Efforts to meet environmental and energy targets via government regulation and incentives should explicitly acknowledge viable near-term designs of less aggressive electric-drive vehicles—designs that appear to be of greater interest to consumers. For instance, at the time of this writing, CARB is in the process of updating the ZEV mandate to encourage not just PHEVs with all-electric range, but also those designed for blended operation. While these changes will better align manufacturer incentives with the consumer-informed results of this study, CARB could take additional steps to promote the more specific PHEV attributes found to appeal to consumers, such as high fuel economy in both charge-depleting and charge-sustaining operation. Other state and federal electric-drive regulation and incentive programs should undergo similar reevaluations. Because vehicle developers and consumer behavior alike can be shaped by government regulation, regulators must understand the implications of the technological definitions and goals that they establish and incentivize. Allowing incentives only for the most advanced – and as yet to be demonstrated – PHEVs may unnecessarily delay the deployment of any PHEVs and thus the benefits that can flow from them. Worse, by providing incentives only for more aggressive PHEV goals, we risk stalling the market for PHEVs. For example, a new U.S. federal individual tax incentive is contained in the 111th Congress' H.R. 1., i.e., the American Recovery and Reinvestment Act of 2009. However, the incentive – varying from $US 2500 to $US 7500 – specified in Section 1141(d)(1) of the bill is available only to a:

> 'new qualified plug-in electric-drive motor vehicle'…(F) which is propelled to a significant extent by an electric motor which draws electricity from a battery which—(i) has a capacity of not less than 4 kilowatt hours,… (U.S. Congress, 2009).

The 4 kWh lower limit on battery size is difficult to reconcile with the fact that of the people in this study who designed a PHEV for themselves in the high cost design game, over 90 percent designed a PHEV that requires a battery smaller than 4.0 kWh and nearly 75 percent designed a PHEV that requires a battery smaller than 2 kWh.

If the purpose of government financial incentives is to help overcome barriers to commercializing PHEVs, why not use tax incentives to lower the financial barriers to those PHEVs that likely initial consumers value? Within the incentive structure in

H.R. 1, automobile manufacturers may be reluctant to attempt to market a PHEV that has a battery smaller than 4 kWh as such vehicles do not earn the "seal of approval." Why would we risk forestalling the market for PHEVs by withholding the publics' approbation from the very PHEVs consumers tell us will succeed soonest? Suppose the partial answer to these questions is that another purpose of government incentives is to spur and guide the direction of battery development toward the higher peak power and energy densities required for all-electric operation and longer CD range so as to increase the emissions, global warming, and security benefits of substituting electricity for fossil fuels in light-duty vehicles. Goals of inciting commercialization and guiding development may be better served by a sliding time scale in which the minimum qualifying battery size starts now at 2 kWh and is increased every few years—either as part of a set schedule or periodic rulemakings to track and account for actual progress.

In summary, policymakers, automakers, battery developers, and consumers should be aware that the battery problem is both technological and perceptual. At the present time we find a mismatch between the PHEVs that experts assume and ones that consumers (at least, hypothetically) design. An understanding of the fundamental battery issues discussed in this article – including the point-of-view that a better battery is the battery that matches the priorities of its users – should facilitate more grounded debates about the present and future of PHEVs and indeed of all-electric-drive vehicles.

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