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The Future of PHEVs
EXPERT PERSPECTIVES on Plug-in Hybrid Electric Vehicles

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Executive Summary

In preparation for a hearing of the U.S. Senate Energy & Natural Resources Committee on Tuesday, June 22, 2010, Near Zero invited 60 experts on plug-in hybrid electric vehicles to answer 5 questions on the future cost and environmental benefit of PHEVs. Here we summarize the responses we received.

General Comments

One respondent questioned whether subsidies to specific technologies are the best policy mechanism to reduce emissions from the transport sector, suggesting instead that price should reflect CO2 emissions whereby the marketplace will identify technologies that reduce emissions at the lowest cost.[1] Others agreed.

The case of Europe's expanding fleet of diesel vehicles is offered in support of this assertion: improved fuel efficiency has led to increased size and miles traveled and thus little or no reduction in CO2 emissions. This experience explains an argument that any incentives should consider electricity use per mile and the range while in electric mode rather than the energy capacity of the battery.[2]

Two respondents noted externalities such as public health benefits of PHEVs that are not included when comparing manufacturing costs of conventional vehicles, HEVs and PHEVs.[3]

1. What is the current cost of the battery for PHEVs?

Many respondents emphasized the need for a consistent cost basis. Good practice is to quote costs (1) for the battery pack, not the battery cells alone, (2) to measure electrical energy by full nameplate capacity (as compared to the ratio of nameplate capacity to useable capacity, or state of charge utilization, which is typically 50-70% of the nameplate capacity), and (3) of the first commercial cycle of the battery pack (i.e. not recycled).

On this basis, the current cost range in the National Academies' report ($625-875/kWh) is in the middle of estimates by other recent studies: $700-1500/kWh (McKinsey Report, 2009), $1000/kWh (Shiau et al., 2009), $800-1000/KwH (Pesaran et al., 2007), $500-1000/kWh (NRC: America's Energy Future), $560/kWh (DOE), $500/kWh (ZEV report, California Air Resources Board, 2007).

Respondents estimated current cost within a range of $500-1000/kWh.[4]

2. What is the reasonable projected costs of the battery for PHEVs as a function of time into the future (or cumulative amounts of units produced)?

The National Academies' (NA) report projected future costs of $400-560/kWh in 2020, and $360-500/kWh in 2030. These assumptions are higher than some but not all other recent reports: $600/kWh (Anderman, 2010), $420/kWh in 2015 (McKinsey Report, 2009), $350/kWh (Nelson et al., 2009), $168-280/kWh (DOE goals for 2014). In general, respondents supported the NA report by indicating that future cost reductions of Li-ion batteries will be modest, noting that cost of materials is a large fraction (~75%) of current total cost of these batteries.[5] One respondent argued that the cost of battery safety systems in future generations of batteries will decrease and result in significant cost reductions.[6]

1 Lee Schipper
2 Constantine Samaras
3 Benjamin Sovacool, Andrew Simpson
4 Daniel Kammen, Constantine Samaras, Andrew Simpson, Eric Bibeau, Dan Santini, Huei Peng
5 James Katzer, Nate Lewis, Constantine Samaras
6 Thomas Bradley

3. What factors will govern penetration levels of PHEVs vs. HEVs? To what extent will one technology dominate over the other, and what factors will control this dominance?

There seems to be consensus among respondents that the high cost of long-range (>40 miles) PHEVs will keep them from competing with HEVs for the foreseeable future. Without great increases in gasoline prices or decreases in battery costs, gasoline savings are not likely to offset the substantial difference in capital costs (now several thousand dollars).

Several respondents noted social dimensions that will affect ultimate penetration: the entrenchment of conventional vehicles[7], the economic irrationality of some market segments[8], and the possibility of game changing business models (e.g., leasing and reclamation of batteries).[9]

4. Between PHEVs and HEVs, which is likely to make the bigger impact on our CO2 emissions and oil consumption in the next 25 years? In the next 50 years? What are the reasons behind your assertions?

There seems to be consensus among respondents that HEVs will have the greatest impact on both emissions and oil consumption (20-70% less CO2/mile and oil/mile than conventional vehicles) over the next 25 years due to the higher cost of PHEVs, and most see this staying the case over the next 50 years in absence of significant reductions in battery costs or price increases of gasoline. One respondent calculates that the impact of a finite supply of battery capacity is optimized when deployed in HEVs; PHEVs require an order of magnitude more battery capacity than HEVs but do not comparably reduce emissions or oil consumption.

Oil savings and reduced emissions are distinct metrics. Electrifying travel will save oil, but the net effect on CO2 emissions depends on the carbon intensity of electrical generation. Many respondents therefore emphasized the linkage of transport and electricity sectors. At the grid-average carbon intensity, emissions reductions of PHEVs relative to HEVs are small, but reductions grow if marginal generation is from natural gas or renewable sources. If climate policy constrains point source (e.g. electricity sector) emissions but not non-point source (e.g. gasoline vehicle) emissions, PHEVs have an advantage over HEVs because marginal emissions from using PHEVs in electric mode would effectively be zero (assuming any cap does not anticipate this use). Also, if biofuels are used to displace fossil fuels, greater reduction in GHG emissions will come from replacing coal (and powering PHEVs) than replacing gasoline (and driving HEVs).

5. Are the conclusions of the National Academies' (NA) PHEV study accurate? Is there a better source of information available on PHEVs?

Generally, respondents regard the conclusions of the NA report as accurate. Several respondents noted that the study should be repeated in 3-4 years when more cost information is available (several manufacturer-built PHEVs will soon be entering the market, which will aid in providing real world data on costs).

One respondent[10] was more critical, pointing out: (1) The report takes cost estimates from second-

7 Benjamin Sovacool, Vaclav Smil
8 Andrew Simpson
9 Andrew Simpson

10 Thomas Bradley

ary literature (not the primary studies) and studies where cost estimates were not the focus, ignoring the results of studies based on industrial surveys and bottom-up models. (2) The report assesses potential emissions reductions using the current grid-average emissions intensity, whereas any impact will depend upon the emissions intensity of marginal generation (as discussed above). (3) The considerations implicit in lifecycle costs and vehicle payback analysis are not well-documented in the report.

APPENDIX 1 - Expert Participants

Eric Bibeau	University of Manitoba
Thomas Bradley	Colorado State University
C.C. Chan	University of Hong Kong
Hosam Fathy	University of Michigan
Daniel Kammen	University of California, Berkeley
*James Katzer	Iowa State University
Derek Lemoine	University of California, Berkeley
Nate Lewis	California Institute of Technlogy
Ryan McCarthy	University of California, Davis
*Joan Ogden	University of California, Davis
Huei Peng	University of Michigan
*Ed Rubin	Carnegie Mellon University
Constantine Samaras	RAND Corporation
Dan Santini	Argonne National Laboratory
Lee Schipper	Stanford University
Andrew Simpson	Curtin University (formerly Tesla Motors)
Vaclav Smil	University of Manitoba
Benjamin Sovacool	National University of Singapore
William Smith	University College Dublin

Table A1 | List of Participants. Asterisks indicate individuals that served on the National Academies' Committee on Assessment of Resource Needs for Fuel Cells and Hydrogen Technologies.

APPENDIX 2 - References

Kammen, D., S.M. Arons, D. Lemoine, and H. Hummel, "Cost-effectiveness of Greenhouse Gas Emission Reductions from Plug-in Hybrid Electric Vehicles," Chapter 9 in *Plug-in Electric Vehicles: What Role for Washington?* (2009), p. 170-191.

Lemoine, D., D. Kammen, and A. Farrell, "An innovation and policy agenda for commercially competitive plug-in hybrid electric vehicles," *Environmental Research Letters* (2008), v. 3, doi: 10.1088/1748-9326/3/1/014003.

Sovacool, B.K., "Early modes of transport in the United States: Lessons for modern energy policymakers," *Policy and Science* (2009), v. 27, p. 411-427.

Sovacool, B.K., "A transition to plug-in hybrid electric vehicles (PHEVs): why public health professionals must care," *Journal of Epidemiology & Community Health* (2010), v. 64, p. 185-187.
ool, B.K., "A transition to plug-in hybrid electric vehicles (PHEVs): why public health professionals must care," *Journal of Epidemiology & Community Health* (2010), v. 64, p. 185-187.

APPENDIX 3 - Request for Input on PHEVs for Senate Hearing

To: [Expert Panel]

From: [Ken Caldeira, Karen Fries and Steve Davis (i.e. Near Zero)]

Date: June 17, 2010 7:02 AM EDT

Dear experts on plug-in hybrid electric vehicles and related technologies,

Please forgive us for the broad distribution of this email.

There will be a hearing on Tuesday 22 June 2010 in the US Senate Energy & Natural Resources Committee related to plug-in hybrid electric vehicles (PHEVs). There hearing is on S.3495, which is a bill aimed at promoting the deployment of plug-in electric drive vehicles, among other purposes.

We are trying to get an email conversation going among experts on low-carbon emission transportation technologies. We will summarize this email conversational and then send our summary, along with all of the unedited email comments, to the staff of the Senate Energy & Natural Resources committee. We will send this same email to everyone who contributed to the email conversation.

Our goal is only to provide the best possible technical information to the Senate staff. We have no position on this bill and no fixed opinions on PHEVs.

We would like your very concisely expressed views on:

1. What is the current cost of the battery for PHEVs?

While the National Academies and DOE tend to quote costs of around $1,000/kWh, several companies assert that they are nearing costs of $300/kWh.

2. What is the reasonable projected costs of the battery for PHEV's as a function of time into the future (or cumulative amounts of units produced)?

3. What factors will govern penetration levels of PHEV's vs. HEV's? To what extent will one technology dominate over the other, and what factors will control this dominance?

4. Between PHEV's and HEV's, which is likely to make the bigger impact on our CO2 emission and oil consumption in the next 25 years? In the next 50 years? What are the reasons behind your assertions?

5. The National Academies did a study last year entitled 'Transitions to Alternative Transportation Technologies--Plug-in Hybrid Electric Vehicles (summary attached). Are the conclusions of this study accurate? Is there a better source of information available on PHEVs?

Please keep your answers as succinct as possible.

Please either reply to all of the people on this email or some subset of your choice or send your answers to us alone. Most convenient is to send to <discuss@nearzero.org>, which forwards to <kcaldeira@carnegie.stanford.edu>, <sjdavis@carnegie.stanford.edu>, and <kfries@nearzero.org>. If you do not feel comfortable with this, just email to us explicitly.

Thank you for your consideration. Feel free to forward this email to your colleagues.

We will need to close this conversation at 9 AM ET on Monday, 21 June 2010, so that we can summarize and get to staff later that day. We apologize for the short fuse on time to respond.

Regards,

Ken Caldeira <kcaldeira@carnegie.stanford.edu>
Steve Davis <sjdavis@carnegie.stanford.edu>
Karen Fries <kfries@nearzero.org>

PS. If you want to know a little more before answering, please email us with your questions.

APPENDIX 4 - Transcript of Expert Responses (in alphabetical order)

Eric Bibeau

To: [Near Zero + Expert Panel]

From:"Eric Bibeau" <bibeauel@cc.umanitoba.ca>

Date: June 17, 2010 3:35 AM EDT

Hi

please consider the following quick comments:

1. What is the current cost of the battery for PHEVs?

Wind storage battery demo projects are now at $500 /kWhr and an increase in utility storage markets will further decrease that cost.

2. What is the reasonable projected costs of the battery for PHEV's as a function of time into the future (or cumulative amounts of units produced)?

A cost of $300 /kWhr from Asia will be reached giving a useful battery cost of 500/kWhr

3. What factors will govern penetration levels of PHEV's vs. HEV's? To what extent will one technology dominate over the other, and what factors will control this dominance?

Lack of education of people and policy makers will be the major factor because it is not approach correctly

4. Between PHEV's and HEV's, which is likely to make the bigger impact on our CO2 emission and oil consumption in the next 25 years? In the next 50 years? What are the reasons behind your assertions?

If done properly, PHEV. That is if the utilities match each new EV kWhr charged from new renewable generation, then real GHG are achieved. Nothing else really works as effectively and archives a real reductions. All other methods including PHEV from the existing grid has a limited impact.

5. The National Academies did a study last year entitled 'Transitions to Alternative Transportation Technologies--Plug-in Hybrid Electric Vehicles (summary attached). Are the conclusions of this study accurate? Is there a better source of information available on PHEVs?

I see nobody approaching the issue to actually reduce GHG's significantly. Your attached paper is still misguided: fuel cells using hydrogen even from renewables will not decrease GHG because of very low efficiencies. The only way to make an impact on GHG is to have PHEV40 coupled with all new EV loads matched by building new renewable generation. We do not need a portfolio of car powertrain technologies; we need to add a portfolio of generating renewable technologies to match new EV loads. Only the energy companies (utilities) can make a difference but we are too ignorant to proceed along the right path with the right intention behind our actions. Until we have an agreement with utilities that all new EV loads will be matched with the construction of new renewables, we will fall short of the potential to make a difference.

Thomas Bradley

To: [Near Zero + Expert Panel]
From:"Bradley, Thomas" <thomas.bradley@colostate.edu>
Date: June 21, 2010 8:30 AM EDT

In the interest of providing some feedback to this conversation (and the Senate hearing) for why the NAE report is the subject of concern, I offer the following summary critique of some of the methods employed by the NAE. I hope that the short timeframe for feedback makes the informal citations and tone acceptable.

Battery Cost Modeling

First, regarding the battery costs questions, there are a few publications that dedicate substantial detail to defining present PHEV battery cost and their rate of change. These studies use industrial surveys or ground-up battery cost models to determine present and projected PHEV costs. The NAE report does not adopt these reports' findings but instead chooses their battery cost model based on a meta-analysis which includes:

* the citation of studies where cited battery costs are 2 citations removed from primary sources (Shiau et al., referencing Lemoine et al., referencing Kalhammer et al.),

* the citation of studies where battery costs are not the subject of the study and are mentioned only in passing and in round numbers (Pesaran et al., NAE/NAS/NRC and Howell et al.),

* and references that are erroneous or not available (http://www.google.com/search?hl=en&rls=com.microsoft%3Aen-us&q=anderman+%22Gap+Analysis%22+for+batteries&btnG=Search&aq=f&aqi=&aql=&oq=&gs_rfai= http://www.advancedautobat.com/order/Proceedings/toc07.html), although Anderman's general position on battery costs is well known)

The remaining primary references (excluding other uncited Anderman publications) point to lower present costs, and lower future costs than those estimated by the NAE report.

Specifically, the references cited do not support the position that 50% of battery pack costs are due to packaging and electronics and will remain at the same cost ratio in the future. It is unlikely that the degree of battery safety systems required in generation 1 of vehicle battery packs will be required in the future due to incremental developments in cell chemistry and improved manufacturing quality. Perhaps the" battery packaging" referred to in the report is made up mostly of active battery cooling (dedicated liquid cooling or air conditioning systems), which would preclude the simple $/kWh comparisons to other literature. As presented in the report, the methods and assumptions are not clear.

In addition, 50% SOC utilization (the ratio of nameplate capacity to usable capacity) for PHEV batteries is a pessimistic assumption. Again, this seems to be true of the first generation of PHEVs, but it is not relevant for future scenarios as is understood by the studies referenced by NAE to support future costs (Pesaran et al., McKinsey)

These discrepancies and more are presented in more detail and with more authority by Dan Santini and Paul Nelson: http://cta.ornl.gov/trbenergy/trb_documents/2010/Santini%20Session%20538.pdf

Electricity Sector Modeling

The type of analysis performed in the NAE report is an invalid means for quantifying the electric sector GHG emissions of PHEVs. The NAE uses grid-average electricity emissions intensity to calculate the present or future incremental GHG emissions of PHEVs, instead of using the concept of marginal generation or a baseline GHG emissions reference case.

In my opinion (and in the assessment of the NAE committee), the addition of large numbers of PHEVs will influence electricity dispatch and the types of generation that must be added to the electrical grid. The proper way to assess the change in GHG emissions that can be allocated to PHEVs is to compare the GHG emissions of the grid with PHEVs to the GHG emissions of a baseline scenario. This would require a model that can estimate the ways that generation will be dispatched, retired and added over time. The most comprehensive study that describes how this can be done for plug in vehicles is the EPRI NRDC study. In the absence of this type of modeling information, one can estimate these factors using the concept of marginal generation, which is already included in GREET 1.8 and other sources. A detailed discussion of why grid average emissions rates are “highly misleading” is at http://www.cec.org/Storage/50/4261_Executive-Summary_en.pdf

This type of modeling is well understood within the academic community and should be a standard component of electrified transportation impacts modeling.

Lifecycle Costs Modeling

Finally, the NAE report does not present how it translates vehicle performance into a vehicle payback analysis. The NAE report does not document consideration of a variety of factors that are present in other PHEV economic analyses including: salvage value, disposal costs, maintenance costs, loan rates, driving patterns that change with time, taxes, consumer acceptance, battery life, discount rates, vehicle depreciation, a more detailed manufacturing cost markup model, etc. Again, the community has the capability to perform defensible and comprehensive studies of cost of ownership, subsidy requirements, societal benefits, and consumer benefits. Work by NREL, EPRI, and UCB leads the way. The NAE report draws conclusions on these items without performing an acceptably complete analysis.

In general, I believe that the many of the analyses used in the NAE report do not represent the best methods available in the field of vehicle impacts analysis. The societal and environmental impacts of PHEVs is an important subject and should be treated as such with more effort and engagement from the research and industrial community than is represented in the NAE report.

C.C. Chan

To: [Near Zero + Expert Panel]
From:“Prof. C.C. Chan” <ccchan@eee.hku.hk>
Date: June 20, 2010 12:30 PM EDT

Dear All;

Sorry for late response due to my heavy traveling.schedule.

May I only contribute to the following few comments

1. I would like to share with you the attached ppt showing the CO_2 emission with respect to ICE and EV at different countries with different of fuels and CO_2 emission in the electric power gen-

eration plant. It can be seen, in France where the electricity is mainly from nuclear will get the best result of using EV. I got this ppt from Patrick Olive of Michelin when I attended the Challenge Bibendum at Rio Brazil on May 29 - June 4.

2. The key factor of large scale promotion of EV and PHEV lies in the success of batteries. According to my experience and observation, I would use the following figures to measure the economic, safety and reliability for lithium batteries as compared with present use of conventional vehicles:

(1) Cycle life > 1500 cycles

(2) Cost < US$400/kWh

(3) Production scale: some 100,000 to 1 million vehicles, to show it is safe and stable production.

(4) Mileage: 150,000 km, to show it is safe and reliable.

Major effort should be directed to enhance the quality, reduce the cost and able to produce large quantity, safe and reliable batteries.

3. The success of promotion of EV & PHEV lies on three goodness factors: 1. Good product: high performance at reasonable cost; 2. Good infrastructure: efficient and user friendly; and 3. Good business model: innovative business model that can leverage the initial cost and recycle of batteries.

All comments are welcome.

Hosam Fathy

To: [Near Zero]

From:“Hosam Fathy” <hfathy@umich.edu>

Date: June 20, 2010 3:53 PM EDT

Hi Ken:

No problem at all. Always happy to help.

Again, I think the list of experts you’ve put together is truly excellent. My intent wasn’t so much to question your existing list, but rather to suggest a few more names that might add value to it. I’m an engineering system design and control person who has done quite a bit of work recently on PHEVs, so naturally I was able to share quite a few names from my own discipline, but not nearly as many from, say, the public policy arena, etc. Having said that, I would be delighted to help you in the future, whether with putting together a list of names of experts or with answering any questions you might have on the engineering side of PHEVs. I would also be delighted to explore possible collaborations/joint explorations/joint publications in that area. There is a ton of work being done right now on PHEVs, and there is a need for up-to-date literature surveys that archive that work and summarize it. My students have done quite a bit of work lately on the modeling, design, and control of PHEV powertrains, and we would be delighted to try to assemble our knowledge in that area into a nice survey for the community - especially as part of a broader survey that also discusses the policy/environmental/economic aspects of PHEVs. So yes, let’s definitely stay in touch - and thanks for your effort on this front!

Best wishes,
Hosam.

To: Hosam Fathy
From:"Ken Caldeira" <kcaldeira@ciw.edu>
Date: June 19, 2010 4:35 AM EDT

Hosam,

Thanks for this.

In the future, we intend to be much more deliberate. This was our first and unusual case in which we had only 4 or 5 days notice to come up with something and we are not experts in PHEVs. May we call on you in the future to help us to develop our list of experts in this area?

Best,
Ken

To: [Near Zero]
From:"Hosam Fathy" <hfathy@umich.edu>
Date: June 17, 2010 1:23 PM EDT

Dear Ken:

I am happy to provide feedback on some of these questions - to the best of my knowledge. But I prefer to provide these answers privately, as opposed to providing them as part of a broad email discussion. The main reason is that I am not sure I will have the time necessary to engage in a broad discussion on PHEVs by email in the coming days.

Before I answer your specific questions, let me point out the fact that while I believe you've put together a superb list of PHEV experts, it's obvious that no list is ever "complete". So I am taking the liberty to suggest additional names to include on the list. These additional names won't make the list complete, either, but they will add great strength to it. The names I would like to suggest are:

Tony Phillips and Ryan McGee from Ford (experts on HEVs and PHEVs)

Ed Tate and Madhu Raghavan from GM (also HEV/PHEV experts)

Ken Laburteaux from Toyota (also an HEV/PHEV expert)

Giorgio Rizzoni, Yann Guezzennec, Simona Onuri, and Vincenzo Marano from Ohio State (also HEV/PHEV experts)

Huei Peng, Zoran Filipi, Jessy Grizzle, and Jing Sun from Univ. of Michigan (also experts on HEVs/PHEVs)

Greg Keoleain from Univ. of Michigan (expert on life cycle assessment and environmental analysis, as applied to PHEVs)

Ian Hiskens from Univ. of Michigan and Mariesa Crow from Missouri S&T (experts on grid power and its interplay with PHEVs)

Ann-Marie Sastry at Univ. of Michigan (expert on battery systems and battery manufacturing, CEO of Sakti3, a battery maker)

Chris Mi at Univ. of Michigan, Dearborn (expert on PHEV power electronics; built several PHEVs in his own lab; CEO of 1Power, a power electronics company)

Hauk Asgiersson from DTE Energy (also an expert on grid power and its interplay with PHEVs)

John Sullivan at Argonne National Labs (expert on agent-based modeling and environmental impact of PHEVs)

Aymeric Rosseau at Argonne (expert on HEV/PHEV systems)

Now let me try to answer your questions. See below. I apologize in advance if some of my answers are a bit lengthy. I lacked the time to make them succinct.

Best wishes,
Hosam.

1. What is the current cost of the battery for PHEVs?

I am not a battery manufacturing expert, and do not know the cost of PHEV batteries firsthand.

I have seen advanced Lithium-ion battery cost quoted at $700-1000 per kWh by battery manufacturing experts from academia, the national labs and industry.

I have also seen arguments by battery manufacturing experts indicating that the cost of Lithium-ion batteries could be as low as $300 per kWh with advanced/mass manufacturing methods.

It is important to understand that while part of the difference between these figures could be a result of differences in battery chemistry, battery manufacturing technology, and manufacturing volumes (e.g., economies of scale), part of the difference could also be due to differences in what constitutes "battery cost" (e.g., does it include the cost of power electronics and/or disposal/recycling?), and part of the difference could be due to sheer cost uncertainties. Gasoline costs change from day to day, pump to pump, and grade to grade. There are similar - and perhaps much larger - uncertainties associated with the true cost of battery technologies.

2. What is the reasonable projected costs of the battery for PHEV's as a function of time into the future (or cumulative amounts of units produced)?

The numbers you provided above are probably the best guesstimates for PHEV battery cost. We can reasonably hope to see PHEV Lithium-ion battery costs no greater than $1000 per kWh in the future. There is a chance that this figure will remain roughly static even with larger production volumes, but there is also a chance that it may drop as far down as $300 per kWh. Someone with stronger expertise in the battery manufacturing area may be able to give you more precise figures, but the $300-1000 per kWh range seems like a very reasonable guesstimate for PHEV Lithium-ion battery costs in the coming decade or so.

The actual cost of a single PHEV's battery pack will depend on the PHEV's battery size. This is where I can speak with more confidence as an expert. I anticipate that PHEVs will be marketed in a variety of configurations, battery sizes, and vehicle sizes, but one of the most successful choices will probably be the urban compact or sub-compact vehicle with relatively small powertrain components (engine, motor/generators, and battery) and a "power split" transmission configuration that allows these components to work synergistically together to fulfill urban propulsion needs. Vehicles in this category will most likely have an all-electric range below 10-20 miles, and will most likely judiciously blend their usage of fuel and electricity to meet their total daily propulsion needs with minimal energy costs and/or emissions. Their battery packs will most likely be in the 4-8 kWh range in terms of energy capacity, corresponding to a total vehicle energy cost most likely in the $2k-$6k range (assuming a battery cost of $500-800 per kWh).

3. What factors will govern penetration levels of PHEV's vs. HEV's? To what extent will one technology dominate over the other, and what factors will control this dominance?

I will provide a two-part answer to this question. In particular, I will first make a very important remark about the relative dominance of different automotive propulsion technologies, then I will list some of the key factors that may affect PHEV viability/feasibility in the future.

Part 1: As an expert on advanced transportation, I do not believe that any single propulsion technology is a "silver bullet" that will "dominate" other technologies and solutions in the future. Instead of picturing a single silver bullet solution to our future transportation needs, we need to picture a "silver buckshot" of solutions, each ideally suited to its own niche of problems. PHEVs are likely to prove quite valuable as a propulsion solution for smaller vehicles (e.g., midsize, compact, and sub-compact sedans) with relatively shorter commutes (e.g., 20-30 mile round trips) in urban areas, especially if such areas have significant access to clean, renewable energy. As vehicles increase in size (e.g., midsize sedans, large/luxury sedans, SUVs, vans, trucks, etc.), commutes increase in length (e.g., 40+ mile round trips), and trips become more "suburban" (I.e., more highway driving), HEVs become as attractive as - if not more attractive than - PHEVs. For heavy-duty vehicles that frequently need to "stop and go" (e.g., refuse trucks, city buses, construction vehicles, etc.), hybrid hydraulic propulsion (as opposed to hybrid electric) may prove to be among the most attractive solutions. Finally, for vehicles whose duty cycles consist of very long highway commutes at fairly constant speeds (e.g., for the nation's interstate trucking fleet), extremely well-designed and well-optimized conventional powertrains may prove quite competitive compared to their hybrid counterparts. Combustion will continue to be one excellent source of power in many of these vehicles, especially if environmentally friendly biofuels are readily available at a cost competitive with fossil fuels. As fuel cell technology advances, however, it is likely to also find its niche as an alternative to combustion in some particular categories of transportation vehicles. In summary, PHEVs will never dominate over HEVs, and will never be dominated by HEVs - at least in my humble opinion. Each solution is likely to prove superb and perhaps superior to the other within specific transportation niches.

Part 2: The degree to which PHEVs will achieve their anticipated viability in the coming years will depend on a number of key factors. First among these factors is battery lifetime cost. Improvements in the total cost of battery systems over their lifetime are likely to make PHEVs much more viable. It is important to underscore the fact that the "lifetime cost" of a battery depends not just on its upfront manufacturing costs, but also on its useful life, durability, reliability, and end-of-life recycling/disposal/repurposing costs. Cutting the cost of producing a battery in half will have a profoundly positive impact on PHEV viability, but so will doubling its useful life span. This is particularly important given the degree to which the research community may be able to increase battery life both through innovation in battery chemistry and through innovation in battery management and control. The second factor that will affect PHEV viability in the coming years is the degree to which battery energy and power densities can be improved. One big challenge with PHEVs is the fact that today's batteries are "bulky" compared to, say, fossil fuels in terms of energy and/or power capacity per unit mass/volume. Battery technologies with higher energy and power densities may pave the way towards PHEVs with longer all-electric ranges, provided such batteries also have reasonable lifetime costs. Thirdly, PHEV viability will depend critically on the ability of the combined transportation-grid infrastructure's ability to charge PHEVs with clean, renewable, and/or inexpensive electricity without overstressing the grid. Smart charging and smart grid technologies will therefore be critical to the market penetration of PHEVs. Last but most certainly not least, PHEV market penetration is likely to be dominated by consumer psychology. Consumer education is likely to play an enormous role - perhaps more so than some of the above technical factors - in the degree to which PHEVs penetrate the market in the years to come.

4. Between PHEV's and HEV's, which is likely to make the bigger impact on our CO2 emission and oil consumption in the next 25 years? In the next 50 years? What are the reasons behind your assertions?

Again, neither PHEVs nor HEVs are "silver bullets" for CO2 emission reduction, although both will prove in the future to be extremely important elements in a "silver buckshot" of solutions.

The degree to which PHEVs will have a positive impact on the life cycle CO2 emissions of the combined transportation/grid infrastructure will depend to an enormous extent on what sources they obtain their electricity from. If PHEVs are charged with electricity from coal-fired plants, then their impact on the nation's overall CO2 emissions will most probably not live up to today's hype. However, if PHEVs are charged with renewable energy from, say, wind power plants, then their impact on the nation's overall CO2 emissions is likely to be quite profound. This is true today, 25 years from today, and 50 years from today: PHEVs provide a tremendous opportunity for substantial reductions in the nation's CO2 emissions, provided they are charged with renewable energy. PHEVs have the added advantage that, because of their very significant onboard energy capacity, they are uniquely capable of accommodating the intermittencies associated with renewable energy sources such as wind power. In other words, PHEVs provide the tremendous opportunity to store energy when available from intermittent renewable sources such as wind, for later use when needed on the road. The key to turning this vision into reality is to develop smart PHEV charging systems and smart grids that are able to treat the aggregate grid load created by PHEVs as a "dispatchable load". If such PHEV load control solutions become available, then PHEVs will be able to contribute quite significantly to CO2 emission reduction in the short, intermediate, and long term.

5. The National Academies did a study last year entitled 'Transitions to Alternative Transportation Technologies--Plug-in Hybrid Electric Vehicles (summary attached). Are the conclusions of this study accurate? Is there a better source of information available on PHEVs?

I have only read the executive summary of this study. Based on this reading, I have not found anything objectionable in the conclusions of the National Academies' study. It provides quite a bit of information on the key factors affecting PHEVs' future, and its main points and conclusions are fair and reasonable. My only objection to the National Academies' study pertains to one thing it does not emphasize nearly enough, at least in its executive summary. The biggest benefit of PHEVs from an environmental standpoint is likely to be their ability to store intermittent renewable energy (say, from wind power plants) when available for later use on the road when needed. The most critical step towards realizing this goal is to design smart PHEVs and smart grids that are capable of treating overall PHEV-induced grid load as a “dispatchable” load than can be directly controlled to absorb intermittent renewable energy. If such technology is developed (and there are really no major hurdles towards its development), then PHEVs are likely to have a very profound impact on the overall environmental footprint of the transportation sector. In other words, if such technology is developed, then PHEVs are likely to live up to their hype as a blessing for the nation’s CO2 emissions, provided they penetrate the market to a reasonable degree.

To: [Lee Schipper, Near Zero + Expert Panel]

From:“Hosam Fathy” <hfathy@umich.edu>

Date: June 21, 2010 4:41 PM EDT

Hi Lee:

I hesitated to clutter everyone’s inbox with my input earlier, but your question about the impact of trip lengths on PHEVs is extremely important, at least in my humble opinion, so I just wanted to provide my two cents’ worth on it. My student, Scott Moura, has taken a stab at tackling that question in close collaboration with my colleagues Jeff Stein and Duncan Callaway, and I am attaching a paper summarizing the results of this stab. To give you a nutshell summary, we examined a power-split PHEV, reminiscent of the Prius (so our results don’t necessarily apply to, say, the Volt). We allowed the vehicle to have a Lithium-ion battery pack, and we varied the size of this battery pack. For every battery size we considered, we developed a stochastic representation of vehicle trips using a combination of NHTS data (recognizing their great value, and also their limitations), and also using a Markov chain representation of vehicle speed statistics. We then optimized the vehicle’s on-road power management (meaning, the way it blends fuel and electricity on the road) for one very specific objective function, namely, the total dollar cost of fuel and electricity. We performed that optimization using stochastic dynamic programming, and I would be delighted to share an earlier journal paper describing our SDP methods in more detail. The bottom line is that once we did all of the above, we arrived at Figure 8 in the attached paper. It shows the optimal statistics of PHEV energy consumption, in MJ per km (or, alternatively, just dollars per kilometer) versus the size of the PHEV’s battery, for two power management options: “blending” (where you judiciously use fuel and electricity together) and “CDCS” (where you aggressively deplete battery charge first, then sustain it). The precise numbers on the plots are very dependent on our many assumptions outlined in the paper, but the bottom line is this: there is a point of diminishing returns beyond which additional investment in battery capacity does not create dramatic changes in trip energy cost statistics. This point of diminishing returns appears to be in the 10-12 kWh range based on our results, but as I said, our results build on a number of critical assumptions that may change this numerical value a bit. In particular, these results are for a power-split vehicle, not a series vehicle like the Volt. They assume that NHTS data is accurate, and that consumers will continue to drive PHEVs in the future the same way they drive their vehicles today. They also assume that today’s fuel-to-electricity price ratios don’t change dramatically in the future. We can most certainly repeat this analysis for different sets of assumptions, and we have already revisited this optimization framework for new optimization objectives (e.g., battery health). I would be happy to share those publications with you, too.

Best wishes,
Hosam.

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[quoting Lee Schipper's message, "Second Ryan's thoughtful comments..."]

Daniel Kammen

To: [Ken Caldeira]

From:"Daniel Kammen" <kammen@berkeley.edu>

Date: June 17, 2010 8:22 AM EDT

hi ken,

i'm on travel, but will be able to email in later on.

best actual battery costs, are about $600/kWh, despite some claims of half that.

a set of papers analyzing PHEV introduction strategies and costs, for EV and PHEVs is attached.

cheers/dan

James Katzer

To: [Near Zero + Expert Panel]

From:"James Katzer" <jrksail@comcast.net>

Date: June 17, 2010 3:33 PM EDT

1. What is the current cost of the battery for PHEVs?

While the National Academies and DOE tend to quote costs of around $1,000/kWh, several companies assert that they are nearing costs of $300/kWh.

First, the basis is critical to the number and it is often different. The first issue is that the number needs to be for the battery pack that goes in the vehicle, not for the battery only. The second basis issue is the charge basis for the number. Nameplate capacity of the battery pack is the most unambiguous one but is frequently not used. Some numbers are based on the amount of electrical energy used in terms of the state of charge. Thus, if the battery charge range used is 50% then the battery cost ($/kWh) stated will be twice that for a number that is on a nameplate capacity basis.

The number that has firm commercial significance is the cost of the battery pack that goes into the vehicles that are in the first commercial phase. The numbers that are in the NRC study are the estimated costs for the first cycle of battery packs. The automakers that were involved in developing these "to come out soon" vehicles confirmed, in non-confidential discussions, that these were reasonable estimates of these numbers. They are somewhat below the current DOE numbers when put on the same basis.

2. What is the reasonable projected costs of the battery for PHEV's as a function of time into the future (or cumulative amounts of units produced)?

The extent of cost reduction is the biggest issue here. The DOE projects multiple fold cost reductions here, an almost 4-fold in roughly about 4 years (by 2014). In separate discussions with the OEMs, there was almost no support for that level of cost reduction, based on the level of maturity of lithium-ion battery technology for other applications, which is high, and on the experience with battery cost reductions seen for HEVs which have been modest. The NRC report did not attempt to project technical breakthroughs, which are not predictable in extent and timing. The cost reductions projected were consistent with those of the OEMs.

3. What factors will govern penetration levels of PHEV's vs. HEV's? To what extent will one technology dominate over the other, and what factors will control this dominance?

HEVs are commercial and can have a major impact on fuel demand and CO2 emissions and logically should be expected to grow significantly over the several couple decades. That said they are expected to dominate over the near and intermediate term. Cost will limit longer-range PHEV penetration for the foreseeable future. Short-range PHEV's (~10-20 mi) that operate more like HEVs than a PHEV with a longer range, say a ~50 mile range, could be a more significant competitor to HEVs and become more prevalent.

4. Between PHEV's and HEV's, which is likely to make the bigger impact on our CO2 emission and oil consumption in the next 25 years? In the next 50 years? What are the reasons behind your assertions?

The based on 3. Above HEV's will make the largest impact on CO2 emissions and oil consumption over the next 25 years without question. This is also expected to be the situation over the next 50 years also.

5. The National Academies did a study last year entitled 'Transitions to Alternative Transportation Technologies--Plug-in Hybrid Electric Vehicles (summary attached). Are the conclusions of this study accurate? Is there a better source of information available on PHEVs?

The conclusions are reasonably accurate for the time of the study based on the information available at that time. The study stated that in 3-4 years there will be much more cost information available and that at that time it should be repeated base in the larger data base.

Derek Lemoine

To: [Near Zero + Expert Panel]

From:"Derek Lemoine" <dlemoine@berkeley.edu>

Date: June 20, 2010 5:56 PM EDT

Just a couple additional thoughts. First, while Joan's point about the CO2 intensity of PHEVs relative to HEVs is well made, it is also important to consider the regulatory contexts within which these vehicles are likely to be used. If we move towards a sectorally differentiated climate policy that caps electricity sector emissions but not transportation sector emissions, then PHEVs may have a nontrivial GHG advantage over HEVs because the marginal emissions from using PHEVs in electric mode would effectively be zero (unless, perhaps, the cap is adjusted in aticipation of their introduction). Second, if considering policies to decarbonize light duty vehicle fleets via biofuels or electrification, it is worth considering that biomass may be able to displace coal if used in electricity generation (a climatically better outcome than displacing gasoline in vehicles) and that biomass resources for liquid fuels may ultimately be most important for those transportation modes that have a difficult time electrifying.

Nate Lewis

To: [Karen Fries]

From:“Nate Lewis” <nslewis@caltech.edu>

Date: June 17, 2010 9:53 PM EDT

Hi Karen

been in a dark room with briefings all day today and also tomorrow

basically, from what I know, I agree with Katzer

I understand, for example (and have some references somewhere also that I could dig up sometime) that the materials costs are now about 75% of the total costs of Li ion batteries,. Hence I would agree with Katzer that the large cost reductions projected by DOE aren’t likely to happen without some totally new battery chemistry being developed. Most people that I have talked to that are “in the know” agree with this assessment as well.

And with his very correct comments about how quoted costs need to be considered on the basis of charge range used, not total charge. And also the costs/kW-hr also depend on a lifetime projection, which is generally overoptimistic for the low projected costs as well, since most batteries aren’t operated or stored under optimum storage conditions of temperature and discharged at optimal rate nor recharged at optimal rate or at optimal depth of discharge either.

And I know that several firms that have looked into this also agree with Katzer that PHEV’s will generally play second fiddle to HEV’s for a long while, until someone innovates and really finds a different, superior, and/or new battery chemistry that can get us onto a different cost curve than we are on Li-ion rocking chair batteries now.

In general, I think that Katzer below said exactly what I would say in response to the questions.

Hope this is helpful.

I’m in D.C. on June 25 on a reverse site visit for the final four teams (we are one of them) for a DOE Energy Innovation Hub in Fuels from Sunlight ($122 MM over 5 years), so wish us luck..

Best
Nate

Ryan McCarthy

To: [Near Zero + Expert Panel]

From:“Ryan McCarthy” <rwmccarthy@ucdavis.edu>

Date: June 21, 2010 3:38 PM EDT

Hi all,

I appreciate the conversation, and will just add a couple of thoughts here.

It appears well-accepted that PHEVs offer little near-term GHG benefit over HEVs in most reasonable scenarios and applications across the country. (Of course, the behavior of early adopters may vary noticeably from the “average” behavior and aggregate recharging demand and grid impacts that we often simulate in our analyses.)

As for grid impacts, I think some general findings are also well-accepted:

Plug-in vehicles, under almost any possible scenario, increase the load factor of electricity demand, which shifts capacity and generation from power plants with lower capacity factors (peaking plants) to those with higher capacity factors (intermediate or baseload plants). So, large numbers of vehicles should increase the share of coal, nuclear, or combined cycle capacity and generation, and reduce the share from peaking power plants.

Plug-in vehicles will likely provide a flexible load that should help to reduce the costs and backup power plant capacity required to integrate intermittent renewables on the grid.

Load, and thus large-scale grid impacts from vehicle recharging, is likely to remain small relative to non-vehicle electricity demand for the foreseeable future. More significant "grid impacts" in the near-term will be at the local, distribution level - on feeder line infrastructure.

This all leads to perhaps less-well-accepted statements, which I'll just offer as my own opinion:

PHEVs do not provide a very cost-effective means to reduce GHG emissions among average consumers over the next few decades. (Based on my own marginal grid impacts analysis accounting for the impact of several million electric vehicles in California by 2030, a PHEV40 today would emit a similar level of GHGs to a conventional vehicle - or HEV - with a fuel economy of about 70 mpg [reference forthcoming]).

Consumers may accept, and use, plug-in vehicles (all-electric or PHEVs) to provide different functionality than conventional vehicles. Middle class suburban families looking for a new second vehicle could account for many millions of vehicles, before plug-in vehicles have to truly compete with the range of a household's primary vehicle.

Convenience, energy security, low operating cost, other real and perceived negatives associated with oil consumption (spills!), and other attributes may well trump environmental attributes in many consumers' minds, when making purchasing decisions.

Managing load from air conditioners and other appliances may offer much more benefit to the grid as a whole (excepting distribution level impacts of vehicle recharging) then can electric vehicle recharging over the next two decades.

The way the electricity grid operates and evolves may change dramatically - and quickly - compared to the way it has historically. Most grid impacts analyses don't account for the grid-balancing services that could be provided by energy storage or demand response from appliances and technologies besides vehicles.

Best,
Ryan

Joan Ogden

To: [Ken Caldeira + Expert Panel]
From:"Joan Ogden" <jmogden@ucdavis.edu>
Date: June 18, 2010 1:18 AM EDT

Ken et al.,

Here are some thoughts on your questions. I was a member of the NRC Committee that produced the report 'Transitions to Alternative Transportation Technologies--Plug-in Hybrid Electric Vehicles.

Jim Katzer's response described the NRC report assumptions and the issues very well. Here are a few additional points.

1. What is the current cost of the battery for PHEVs?

While the National Academies and DOE tend to quote costs of around $1,000/kWh, several companies assert that they are nearing costs of $300/kWh.

The NRC report quoted battery pack costs in terms of nameplate capacity (or 100% of the charge capacity) rather than the useable capacity (which is typically 50-70% of the nameplate capacity).

The cost range in the NRC report was $625-875/kWh (nameplate basis)

In these same units ($/kWh nameplate) several other recent studies found the following estimates for current costs:

$700-1500/kWh (McKinsey Report)

$1000/kWh (Carnegie Mellon)

$800-1000/KwH (Pesaran et al.)

$500-1000/kWh (NRC: America's Energy Future)

$560/kWh (DOE, adjusted to nameplate basis)

$500/kWh (ZEV report, California Air Resources Bd, 2007)

The NRC assumptions for current costs are in the middle of this range.

2. What is the reasonable projected costs of the battery for PHEV's as a function of time into the future (or cumulative amounts of units produced)?

The NRC PHEV report projected future costs of $400-560/kWh in 2020, and $360-500/kWh in 2030. Other recent reports quoted future costs (in terms of nameplate capacity):

$600/kWh (Anderman)

$420/kWh in 2015 (McKinsey)

$350/kWh (Nelson)

$168-280/kWh (DOE goals for 2014 in terms of nameplate kWh)

The NRC future cost assumptions were higher than some, but not all other studies

3. What factors will govern penetration levels of PHEV's vs. HEV's? To what extent will one technology dominate over the other, and what factors will control this dominance?

PHEVs are likely to be higher price than HEVs by several thousand dollars (according to estimates by MIT (Kromer and Heywood 2007, Bandivedakar et al. 2008), NRC 2009). There would have to be a market pull for consumers to prefer them over HEVs, perhaps associated with lower gasoline consumption or wanting an electric vehicle or subsidies. Gasoline savings alone probably won't offset the higher capital cost of the PHEV vs. the HEV for some time (unless battery costs fall very rapidly or oil prices rise rapidly).

If I had to guess, I'd say that HEV sales will be much higher than PHEVs for a decade or more.

4. Between PHEV's and HEV's, which is likely to make the bigger impact on our CO2 emission and oil consumption in the next 25 years? In the next 50 years? What are the reasons behind your assertions?

HEVs could reduce both GHG emissions/mi and oil use/mi by 20-70% compared to a comparable non-hybrid gasoline internal combustion engine vehicle. (The range is based on different studies and depends on the assumptions and type of HEV.)

The GHG benefit/mile of PHEVs vs. HEVs depends on the marginal grid mix used to charge the PHEV. As many studies have shown (for example, studies by MIT (Kromer and Heywood 2007), EPRI/NRDC and the NRC PHEV report, and a new NREL report quoted in this month's Scientific American), there is little GHG benefit for a PHEV vs. HEV unless the grid is substantially lower carbon than today. If the marginal generation mix is primarily NG-based, PHEV well to wheel GHG emissions are slightly lower than for a gasoline HEV. With coal-fired generation PHEV emissions are higher. For the current US grid mix, it's about the same. Since it will take time to decarbonize the grid, it may be a decade or so before the PHEV offers a lower gCO2/mile than a HEV for the average US grid. (Regionally, this will vary).

PHEVs could reduce gasoline consumption/mi by perhaps 20% (for a PHEV-10) to 55% (for a PHEV-40) compared to a HEV. But the oil reduction impact of PHEVs over the next 25 years will depend on how many PHEVs are sold compared to HEVs.

5. The National Academies did a study last year entitled 'Transitions to Alternative Transportation Technologies--Plug-in Hybrid Electric Vehicles (summary attached). Are the conclusions of this study accurate? Is there a better source of information available on PHEVs?

The assumptions in the NRC study were clearly stated and based on the best information available, but there are uncertainties in future battery costs.

Huei Peng

To: [Near Zero + Expert Panel]
From:"Juei Peng"
Date: June 21, 2010 10:08 AM EDT

1. What is the current cost of the battery for PHEVs?

While the National Academies and DOE tend to quote costs of around $1,000/kWh, several companies assert that they are nearing costs of $300/kWh.

$300/kWh is an optimistic number, and is a future target (usually with no justifications) mostly came from battery companies (and sometimes from DOE or USABC). I would take those numbers with a grain of salt and ask for more information and justification.

It is also important to note that those numbers are sometimes defined as "active material" or sometimes "cell cost", and do not include cost for material/labor/cooling/battery management system cost. It is thus important to ask what is included in the cost for the kw-hr number.

More rigorous numbers all came in the range of $800-$1,000/kWh. A rigorous cost analysis can found from (use Google to find a copy for download) BCG, Batteries for Electric Cars—Challenges, Opportunities and outlook to 2020

2. What is the reasonable projected costs of the battery for PHEV's as a function of time into the future (or cumulative amounts of units produced)?

3. What factors will govern penetration levels of PHEV's vs. HEV's? To what extent will one technology dominate over the other, and what factors will control this dominance?

"Value" is the fundamental factor for market share.

4. Between PHEV's and HEV's, which is likely to make the bigger impact on our CO2 emission and oil consumption in the next 25 years? In the next 50 years? What are the reasons behind your assertions?

Impact = (improvement by each vehicle) x (number of vehicles sold)

I think HEV will have more impact because PHEV as it stands are too expensive (mostly because of battery) and the value it delivers to the consumers is much lower. This will be the case unless a very high gasoline tax is imposed or a high carbon tax is imposed.

Ed Rubin

To: [Near Zero]
From:"Edward S. Rubin" <rubin@cmu.edu>
Date: June 18, 2010 9:10 PM EDT

Ken, Steve, Karen,

Looks like you've stirred up a hornets nest on this one. I was also on the Academy panel so don't really have anything new to add. I'd simply say that for a Congressional audience focused on PHEVs (and their cost), the point Jim made about the different measures used is an important one to emphasize, since that alone can cause reported costs to vary by a factor of 2 to 3 for very same battery! And future technology costs don't always follow those nice learning curves.

On the potential for CO2 reductions, the coupling with the US power sector is also important to emphasize-- ie, if the goal is carbon and oil reductions, the transportation sector and utility sectors must increasingly be linked. And remember that the common assumption that people will recharge during off-peak hours, so no major impact on new capacity needs, is just that -- an assumption. Human behavior might prove otherwise.

Finally, as the Academy report showed, continuing (and significant) subsidies will be needed to make early deployment of PHEVs attractive, especially for longer-range batteries. So the rationale and justification for substantial government backing of specific technologies, vs. gov't. regs and standards limiting the things we don't like, also needs to be emphasized.

Good luck with the hearing. Keep us posted.

Best regards,
Ed

Constantine Samaras

To: [Near Zero + Expert Panel]
From:"Constantine Samaras" <csamaras@alumni.cmu.edu>
Date: June 21, 2010 9:03 AM EDT

Dear Ken, Steve and Karen,

Thank you for getting this excellent conversation started. Below are some additional thoughts for the discussion on PHEVs. You may also be interested in a recent Congressional Staff Briefing on "Electricity as a Transportation Fuel" we participated in, along with some academic and industry colleagues. All presentations and the video are available here: http://bit.ly/9DIdz8.

Thanks again and best regards,
Costa

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1. What is the current cost of the battery for PHEVs?

As others have noted, when discussing costs of PHEV batteries, it's important to clarify that the costs of batteries should be quoted at a battery pack level, which includes all the associated ancillary components and packaging, rather than a cell level. At a pack level, the range that Joan Ogden put forth is what I've seen, with $500-$1000/kWh at the pack level as the most common estimates. It also should be noted that the cost of PHEV batteries doesn't necessarily scale linearly per kWh when comparing smaller batteries with larger batteries (e.g. see Argonne's work in this area, Nelson et al., 2009) and technical requirements for small and large battery packs also vary. So it may be appropriate to think about battery costs for a small PHEV (10-20 mile electric range) and a large PHEV (30-40 mile range).

The current tax credits for PHEVs are based on how many kWhs are in the battery. But it is important to point out that what will ultimately affect the environmental, economic, and energy security impacts of electrified transportation is not battery size, but the efficiency of the vehicle in all-electric mode (kWh/mile). Until we have large-scale feedback and data from the first adopters of mass-produced PHEVs and EVs, we'll have to rely on simulations, projections, and claims for plug-to-wheel kWh/mile figures. We rarely discuss the capacity of vehicle gasoline tanks but instead analyze miles per gallon, and should eventually move toward encouraging the vehicles with the lowest electricity use per mile and the most all-electric miles instead of the largest battery.

2. What is the reasonable projected costs of the battery for PHEV's as a function of time into the future (or cumulative amounts of units produced)?

In addition to the estimates made in the NRC report and other sources previously identified, Anderson (2009) reports that batteries would remain in the $600-$700/kWh range for the short to medium term. Anderson's work models Li-ion production costs and finds that 75% of pack-level costs are material costs, and increased manufacturing yield is one factor to help reduce costs.

Right now, while it's difficult to predict the future costs of batteries, we can understand the impact of various potential future costs through scenario analysis. We are entering a period where a number of manufacturer-built PHEVs will be entering the market. This will aid in providing real world data on costs and other characteristics.

3. What factors will govern penetration levels of PHEV's vs. HEV's? To what extent will one technology dominate over the other, and what factors will control this dominance?

Consumers have a decade of experience with HEVs, and the technological risk of adoption has been greatly diminished. If the market for HEVs (or other high efficiency vehicles) and PHEVs are comprised of the same buyers, HEVs will be dominant unless gasoline prices rise and remain high, batteries are $250/kWh, and a few other scenarios (Shiau et al., 2009). In Shiau's work, we argued that very small PHEVs with a 7-mile electric range were cost competitive with HEVs today under most circumstances, however it is unclear if such a small PHEV is practical from a manufacturing standpoint. After the PHEV early adopters gain experience and remove some of the technological risk of purchasing a new technology, other market actors who were not previously in the HEV vs. PHEV market may emerge.

4. Between PHEV's and HEV's, which is likely to make the bigger impact on our CO2 emission and oil consumption in the next 25 years? In the next 50 years? What are the reasons behind your assertions?

Our work estimated life cycle GHGs from PHEVs and HEVs were about the same as long as the electricity used for charging was about 650-750 gGHG/kWh (Samaras and Meisterling, 2008). It appears that the automobile fleet will have a lot more HEV options (and adoption) than PHEV options in the near to mid-term, so it is likely that in aggregate, HEVs will make a bigger impact on CO2 and oil consumption relative to business as usual. In the next 50 years, PHEVs and electrified transportation have the potential for very large GHG and oil reductions relative to HEVs, but that outcome is predicated on cheap and reliable batteries, relatively expensive gasoline, and a robust low-carbon electricity system.

References:

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Dan Santini

To: [Ken Caldeira] <kcaldeira@carnegie.stanford.edu>

From:"Santini, Danillo J." <dsantini@anl.gov>

Date: June 18, 2010 11:04 AM EDT

See the Automotive Engineering article on M. Anderman's opinions.

At his Advanced Automotive Battery and EC Capacitor Conference on May 19-21 in Orlando FL, in his presentation "Can Li-ion Batteries Support the Proliferation of Plug-in and Electric Vehicles? Status and Prospects", he presented a table saying that an "EV Cell and Pack Price" for a 24 kWh battery pack (as in the Leaf EV) was $800-1300 retail price at 5000 packs per year, and $475-600 at 50,000 packs per year.

Based on 168 40-Ah cells, 302 V nominal.

He did not provide numbers for higher volumes, nor for higher power packs.

Lee Schipper

To: [Ken Caldeira]

From:"Lee Schipper" <mrmeter@stanford.edu>

Date: June 17, 2010 2:51 PM EDT

Ken. Am off for a few days of real holiday, and won't be able to start an email conversation. So these thoughts are just for you.

I no longer believe we can pick winners with congress giving free money away. I believe that without a carbon tax (on everything) and an oil tax, it will be impossible to determine whether PHEV will be a "low carbon technology". We will turn the various tax subsidies into larger cars than otherwise, and even if they are "low carbon", experience with diesels in europe shows the bottom line is veryh small carbon savings per km, and by small, I mean < 5% compared to gasoline cars. I could go on but I won't because of a lack of time (I'm in Europe next week).

Good luck

To: [Near Zero + Expert Panel]
From:"Lee Schipper" <mrmeter@stanford.edu>

Date: June 18, 2010 11:18:23 AM EDT

I have a different approach. Why is Congress or anyone picking winners (PHEV) rather than taxing losers (carbon, oil and so to speak peak load pricing). Seems to me that without these kinds of direct incentives in place ON ALL CARBON AND OIL it is very inefficient economically to subsidize one kind of "solution" when as Joan indirectly suggests we don't know what the carbon or oil benefits are.

From my studies of diesel cars in EUrope (TRR Dec 2009) we do know that the EU Manufacturer "choice" for low carbon new cars, diesel cars, have had little if no Co2 savings (i.e. average new diesel emissions/km in Europe is within 5% of average gasoline emissions/km) because people chose larger diesel than gasoline cars. And diesel cars are driven 50-75% more than gasoline cars. So diesel is not associated with low carbon transport

Of course PHEV could be big CO2 savers, but in the US today, where no policy dare aim at BEHAVIOR (taxes, fees), we cannot take it for granted that because the calculations suggest savings, they will materalize. Don't forget, too, that EV users don't pay road tax on the electricity they charge with the way gasoline or diesel fuel users do. Will EV electrons be like corn ethanol -- untaxed? Haven't we learned our lessons from corn ethanol about the dangers of incentives. Isn't buying smaller cars and using them less the first step to low carbon transport. Do PHEV incentives increase or reduce the incentive to take the bus? In other words, technology earmarks without clear signals to behavior may be the wrong path.

Finally, what are the costs of saved oil and carbon from the various PHEV tax credits? Are we takings oil or Carbon at the same rate across the economy?

My view thus is there should be NO more incentives for "low carbon transportatin" or low carbon anything until there are clear discentives across the board -- CO2 and oil taxes -- and peak load pricing and taxation of electricity used for road vehicles.

Sorry for the harumph, but I think
it's time we went Cold Turkey!

To: [Ryan McCarthy, Near Zero + Expert Panel]
From:"Lee Schipper" <mrmeter@stanford.edu>

Date: June 21, 2010 3:49:47 PM EDT

Second Ryan's thoughtful comments. The big mystery is how consumers will drive and whether they will go for 10 K or 40K is a huge question. What is the marginal kilometer of range worth? Should we subsidize it when it is already cheap compared to gasoline? These are uncomfortable questions that may hound us for years.

Andrew Simpson

To: [Near Zero + Expert Panel]
From:"Andrew Simpson" <agsimpson05@msn.com>
Date: June 21, 2010 7:13 AM EDT

Greetings to all from the land Down Under, and thanks to the previous respondents for their excellent comments.

I've added some comments below within the terms of reference, but also made mention of two items that I believe should be included in the discussion - 1) EVs and 2) renewable electricity.

regards,
Dr Andrew Simpson

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1. What is the current cost of the battery for PHEVs?

While the National Academies and DOE tend to quote costs of around $1,000/kWh, several companies assert that they are nearing costs of $300/kWh.

AS: As was already noted, the basis is critical to the number and PHEV vs EV batteries are quite different. See USABC for differing requirements. Today there are some companies achieving $300/kWh per cell or $500/kWh per pack for EV batteries (nameplate), whereas I agree that PHEV batteries are still in the $500-1000/kWh range (in my view towards the upper end).

2. What is the reasonable projected costs of the battery for PHEV's as a function of time into the future (or cumulative amounts of units produced)?

AS: Generally agree with NRC values suggested for PHEV batteries. Again, note that EV battery costs are fundamentally different and should not be confused.

3. What factors will govern penetration levels of PHEV's vs. HEV's? To what extent will one technology dominate over the other, and what factors will control this dominance?

AS: Agreed with comments on relative pricing. I do, however, believe there is ample evidence to prove the automotive market is not economically rational, therefore we should not be picking winners based on cost-effectiveness alone, especially when externalities are not priced into the analysis. Our world is changing and so are market preferences and social priorities.

A key factor is industry capacity and inertia. HEV production capacity and supply chain is established and poised for significant growth to meet demand. My crystal ball says that in 2020 HEVs will be a standard or readily-available option across the market. I believe there is also a non-financial market pull to add the P-function to HEVs, so I would expect to see this as an increasing option on some HEV products (e.g. plug-in Prius).

PHEV/EV production capacity and supply chain is still under development and highly constrained at present. This will limit penetration for the next decade. Dedicated PHEV products (e.g. Volt) will lag pure EVs coming to market, due to more stringent battery requirements and powertrain packaging/cost integration challenges. I see evidence of this in current product plans and announcements. Dedicated PHEV products will evolve towards pure EV as batteries improve. I believe plug-in infrastructure will build-out commensurate with EV/PHEV uptake rather than creating an "added" barrier. EVs will eat into the market share of both HEVs and PHEVs based on a paradigm shift within certain segments.

New business models will greatly improve consumer economics and boost demand for plug-in products (PHEVs and EVs). These models will assume the battery finance burden and capture residual battery value and leverage vehicle batteries as distributed energy resources. This could be a complete game-changer.

Another potential game-changer is ability to link plug-in vehicles with renewable electricity. It will be very hard to achieve the same result with liquid or gaseous fuels.

4. Between PHEV's and HEV's, which is likely to make the bigger impact on our CO2 emission and oil consumption in the next 25 years? In the next 50 years? What are the reasons behind your assertions?

AS: Over 25 years HEVs will achieve the greatest cumulative impact based on market penetration. Note previous comment about possibility of HEVs evolving into PHEVs though.

I recognize the marginal GHG benefit of plugging into the marginal grid mix, but I believe the ability for motorists to readily link plug-in products to retail green power tariffs should not be discounted for per-vehicle GHG reduction in the near term. Within 50 years I firmly believe we will link electric drive to green power as the cornerstone of a carbon-neutral, oil-independent sustainable transport strategy.

5. The National Academies did a study last year entitled 'Transitions to Alternative Transportation Technologies--Plug-in Hybrid Electric Vehicles (summary attached). Are the conclusions of this study accurate? Is there a better source of information available on PHEVs?

AS: Generally I think the NRC conclusions were reasonable, but I wish the study had also considered EVs. I'll also reiterate my earlier point about not evaluating cost-effectiveness without externality pricing.

Vaclav Smil

To: [Karen Fries]
From:"Vaclav Smil" < vsmil@cc.umanitoba.ca >
Date: June 18, 2010 11:52 AM EDT

Karen:

To answer this before I send away the previous: you are ABSOLUTELY right, whatever HEV they are they will not be around in their millions anytime soon (if you think I have no idea what I am talking about then trust those Germans; they invented the car, the idea of Mercedes or BMW going bankrupt is unthinkable and they know what they are talking about).
As I say in the other mail, all those numbers mean littel: even in the range given here, it makes a great deal of difference if you sell it for 500 or 1,500/unit.

Vaclav

To: [Karen Fries]
From:"Vaclav Smil" < vsmil@cc.umanitoba.ca >
Date: June 18, 2010 2:53 PM EDT

Dear Karen:

But you did (drag me in!) -- and (strangely enough) I have no instantly strong feeling if I need or need not to be. As always, I have already learned a number of interesting things, and it is always good to see how somebody else thinks more or less as I have, and so I liked Lee`s realistic comments. On the other hand it has no legs -- not because it is not an important subject that needs lot more careful studies (a big yes on all counts) but because the country that is so broke, so ungovernable (notice how Obama`s last grand call a few days ago to embark on a new energy era was met in, his own party-dominated, Congress with a massive yawn and with immediate issuance of declarations by the congressional barons that nothing changes and they do not care for any energy changes) has no will to affect any major change: it will have happen to it by drastic external forcing, not by stepwise deliberation. So my naturally inquisitive side says yes, be dragged, my realistic view of the US in a long unstoppable retreat says no.

Raining more than ever, have to go check outside how much water is pooling.

Best
Vaclav

To: [Karen Fries and Lee Schipper]
From:"Vaclav Smil" < vsmil@cc.umanitoba.ca >
Date: June 18, 2010 13:14 PM EDT

Dear Lee:
Karen dragged me into this -- I think it has no legs, and so I was very glad to see yours below: could not agree more on all counts!

Best
Vaclav

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[quoting Lee Schipper's message: "I have a different approach..."]

Benjamin Sovacool

To: [Near Zero + Expert Panel]
From:"Benjamin K. Sovacool" < sppbks@nus.edu.sg>
Date: June 17, 2010 8:40 PM EDT

Ken, Steve, and Karen:

Thanks for getting the discussion started. I think the questions below are very important, but so is the wider issue of some of the benefits of a HEV/PHEV transition beyond economic savings and the question social acceptance. On the topic of broader social benefits, the attached article in Journal of Epidemiology and Community Health might be useful as it elucidates some of the public health benefits to PHEVs. Policymakers in the Senate may find some of these health benefits persuasive.

As for the complex question of social acceptance, even if PHEV costs continue to decline they will likely be insufficient alone to cause a PHEV transition. Some tenacious but often hidden social barriers will likely remain, and unless they, too, are targeted by policy, could prevent drivers and American consumers from adopting vehicles that would benefit them. The attached article in Energy Policy written with my friend Richard Hirsh discusses these in greater detail.

Finally, a quick point about history. In a way we've been here before; many energy analysts may not know it, but at beginning of the 20th century there were more EVs on the road than gasoline powered vehicles. Yet by 1930 America had fully committed to the gasoline car. The factors behind the transition were not only technical and economic, but social and cultural (those interested should see final attached article). That transition provides some insight into what may need to happen going forward if society is truly to embrace PHEVs.

With best wishes from Singapore, where I wish the government was considering a hearing on PHEVs,

Benjamin

William Smith

To: [Near Zero + Expert Panel]
From:"William Smith" <william.smith@ucd.ie>
Date: June 17, 2010 8:40 PM EDT

Dear all,

My response focuses on Question 4 - Between PHEV's and HEV's, which is likely to make the bigger impact on our CO_2 emission and oil consumption in the next 25 years? In the next 50 years? What are the reasons behind your assertions?

Two main points I'd like to make:

The first point is that savings in CO_2 emissions are not necessarily synonymous with savings in oil consumption. Vehicles operating in electric mode are MUCH more energy-efficient than conventional vehicles under URBAN-type driving cycles. For highway-style driving cycles, however, this is not the case. Therefore, oil savings PER MILE are good under urban driving cycles and, for almost any electricity generation mix, CO_2 savings are good as well. Under highway conditions, oil savings per mile are still pretty good, but the CO_2 savings can be small - or negative - depending on the CO_2-intensity of electricity generation.

It is probably reasonable to assume that longer trips can be associated with highway-style driving cycles, and shorter trips with urban-style driving cycles. Analysis of the 2009 NHTS data indicates about 85% of car trips are of 15 miles or less, but that these trips account for only about 45% of car MILES.

So electrification of short trips gives great CO_2 and oil savings per mile, but these trips account for less than half the miles travelled. Electrification of long trips (currently not realistic) yields good oil savings per mile, but small or negative CO_2 savings per mile.

For big oil savings, you need to electrify the longer trips. Unless you have a pretty green grid, most of your CO_2 savings come from electrification of shorter trips.

The second point takes up an issue raised by John Petersen in his blog (http://www.altenergystocks.com/archives/2010/03/plugin_vehicles_combine_immense_risk_with_insignificant_reward_1.html)

If global battery production capacity is finite, how do you get the best bang for your batteries?

I attach a spreadsheet that presents some calculations based on the above.
The main variables considered are:

- global battery production capacity (GWh per annum)
- grid CO_2-intensity (gCO_2 per kWh)
- fuel-efficiency improvement of PHEV and HEV relative to conventional vehicles (CV),
- and fraction of PHEV miles covered under electric power.

It seems that, for any realistic set of assumptions, HEV provide the biggest oil and CO_2 savings. PHEV and BEV come a pretty poor second and third, respectively.

Will Smith
University College Dublin, Ireland