Battery Technology for Electric and Hybrid Vehicles: Expert Views about Prospects for Advancement.

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Abstract

In this paper we present the results of an expert elicitation on the prospects for advances in battery technology for electric and hybrid vehicles. We find disagreement among the experts on a wide range of topics, including the need for government funding, the probability of getting batteries with Lithium Metal anodes to work, and the probability of building safe Lithium-ion batteries. Averaging across experts we find that U.S. government expenditures of \$150M/yr lead to a 66% chance of achieving a battery that costs less than \$200/kWh, and a 20% chance for a cost of \$90/kWh or less. Reducing the cost of batteries from a baseline of \$384 to \$200 could lead to a savings in the cost of reducing greenhouse gases of about \$100 Billion in 2050.

Keywords: Battery; Technology R&D; Uncertainty; Environmental policy

1 Introduction

By many accounts, addressing transportation may be the most challenging part of the climate change problem. In order to reach emissions reductions of 80% or more, we must reduce emissions in the transportation sector by at least 25% – 75%. One approach to achieving these reductions is through electric, hybrid, or plug-in hybrid vehicles. One of the main challenges to producing cost effective vehicles of these kinds is to produce inexpensive, reliable batteries that can mimic many characteristics of internal combustion engines.

In this paper we consider the role of government Research and Development (R&D) funding in achieving advances in battery technology. We have performed expert elicitations to arrive at the relationship between government funding and the likelihood of achieving particular technological targets. We have considered two types of batteries: (1) Lithium-Ion and (2) batteries with Lithium Metal anodes, such as Lithium Sulfur. The first technology is aimed primarily at hybrid and plug-in hybrid vehicles; the second at electric vehicles.

Organization of Paper This paper is part of a larger research project in which we are analyzing a number of climate change energy technologies including solar photovoltaics [3], nuclear power [2], CCS [4], electricity from biomass, wind and solar grid integration, and liquid bio-fuels [6]. See [5] for an overview of the framework for quantifying the uncertainty in climate change technology R&D programs and their associated impacts on emission reductions. The rest of this paper is organized as follows. In Section 2 we describe the expert elicitation process, including the selection of experts, definition of technological endpoints, and the development of a survey. In Section 3 we present the results of the elicitations in some detail. Section 4 provides an illustrative analysis of the elicitation results and Section 5 discusses how success in battery technologies would impact climate change. We briefly conclude in Section 6.

2 Expert Elicitations

Past data on technological advance contains little information about future technological breakthroughs. Yet, current decisions depend on understanding the likelihood of such breakthroughs. For example, sound government technology R&D policy should consider the likelihood of success and the impacts of success, along with the total cost of a program, when making decisions. Moreover, assumptions about technical change play a very important role in the analysis of climate change policy: optimistic assumptions can lead to optimally less stringent near term policies, while pessimistic assumptions have the opposite effect [18]. Thus, it is important to understand what technical possibilities exist, and how the likelihood of these events relate to government policy.

Decision makers facing uncertainty about future prospects necessarily act on subjective beliefs about the likelihood of possible outcomes. Decision analytic methods [15] have been applied productively to R&D in numerous industries (automotive, pharmaceutical, electronics, etc. See for example [9][19][21]) as well as issues relating to societal decisions [14][17].

2.1 The Technologies

We consider here two technologies: Lithium-ion (Li-ion) batteries and batteries with Lithium Metal anodes. The Li-ion batteries we considered use essentially the same chemical mechanism as the current generation of Lithium-ion batteries, but with improvements that will make them appropriate for use as the main power-supply in automobiles. For the second technology, we specifically asked experts to consider a range of batteries with Lithium Metal anodes, including Lithium sulfur, but also including batteries with non-sulfur cathodes.

Not included in the analysis are: liquid batteries, e.g., zinc bromine, which are appropriate for stationary applications but not transportation; lead acid batteries, which will likely improve but not sufficiently to power a fleet of electric vehicles; and nickel cadmium batteries, which have toxicity issues and are also not likely to provide sufficient power.

2.2 Technological Endpoints

In order to assess probabilities, we need well defined endpoints. These endpoints must be clear so that all experts can agree on whether an event has taken place or not [20]. They must make sense to the experts. They must have use for policy analysts. We focussed on five key characteristics: cost, power density, specific energy, lifetime, and recharge rate. We defined our endpoints in discussions with the experts and in reference to USCAR, an umbrella organization for collaborative research among Chrysler LLC, Ford Motor Company and General Motors Corporation.[1]

Our costs are capital costs and are measured in \$/kWh. The power density is related to the acceleration speed and the volume of the batteries. It is measured in W/L. The specific energy is related to the distance the car can travel on a charge and the weight of the car. It is measured in Wh/kg. The lifetime of the battery is measured in years, and the recharge rate in hours. Table 1 shows the specific values that we assessed. For each technology, we considered two endpoints, a more-ambitious high endpoint, and a less-ambitious low endpoint. Most of the values are taken directly from the USCAR document referenced above. The specific energy for Li Metal is based on a rule of thumb, indicating that about 25% of the theoretical limit should be achievable in practice. The theoretical specific energy for Li metal is 2600 Wh/kg, leading the experts to specify 600 as the high endpoint. The capital costs for Li Metal are based on the goal selling prices listed in the USCAR document (\$100-\$150), reduced by 10% to account for profits. The experts felt that these goals were too unlikely for Li-ion, so we chose less restrictive endpoints for this technology.

	Li-ion High Endpoint	Li-ion Low Endpoint	Li Metal High Endpoint	Li Metal Low Endpoint
Specific Energy	200Wh/kg	150Wh/kg	600Wh/kg	200Wh/kg
Power Density	600 W/L	460 W/L	600 W/L	460 W/L
Lifetime	10 years	8 years	10 years	8 years
Recharge rate	3 hours	6 hours	3 hours	6 hours
Capital Cost	\$125/kWh	\$200/kWh	\$90/kWh	\$135/kWh

Table 1: Technological Endpoints for Elicitation

Additionally, there is concern that Lithium-Ion batteries are subject to thermal runaway – they may explode in certain conditions. This is a concern in and of itself; and it also may lead to the problem of car companies not producing such vehicles because of liability issues. So, for Li-ion we have an additional endpoint requiring that they are not subject to thermal runaway.

These endpoints can be compared with the estimated current values for the technology. In 2000 a report by ANL estimated that the cost of Li-ion batteries ranged between \$432 - \$721/kWh [13]. A retail price of \$432/kWh and a specific energy of 100Wh/kg is reported by ThunderSky, a Chinese manufacturing company.[2] Thus, even the less ambitious endpoints above represent significant improvements

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[1] http://www.uscar.org/guest/index.php. For the "Goals.." specifically see http://www.uscar.org/commands/files_download.php?files_i

[2] http://www.batteryspace.com/lifepo4prismaticmodule32v110ah3crate352whceunapproved.aspx

over the current worldwide technology.

2.3 Elicitation Methods

We identified a total of seven experts, listed in Table 2 in alphabetical order, from a mix of universities, national labs, and private firms. With the help of a subset of these experts, plus Ahmad Pesaran from NREL, we put together a survey.

Vincent Battaglia	Lawrence Berkeley National Lab
Elton Cairns	Lawrence Berkeley National Lab
Gary Henrikson	Argonne National Lab
Ted Miller	Ford Motor Company
Giorgio Rizzoni, Yann Guezennec and Suresh Babu	The Ohio State University
Godfrey Sikha	University of South Carolina
Robert Spotnitz	Battery Design, LLC

Table 2: Experts

For both technologies we started with a question related to the technical feasibility of the battery. Specifically, we asked about the probability of achieving 3000 cycles. We followed this with questions about the probability of achieving the high and low endpoints, conditioned on achieving 3000 cycles. Finally, we defined four different funding trajectories, shown in Table 3. The Experts were asked to give us probabilities of success conditional on the U.S. government funding trajectory.

	Years	Low Funding $(000,000)/yr	High Funding $(000,000)/yr
Li-ion	10	30	70
Li Metal	10	10	40

Table 3: Funding Trajectories

Each expert reviewed a simple primer on subjective probability assessments and filled out the survey. We then reviewed their responses with them and asked follow-up questions aimed at reducing the impacts of biases and heuristics. Finally, we sent out a summary of all experts responses, both numerical and verbal, to be reviewed by all the experts, and allowed the experts to amend their answers once more.

3 Elicitation Results

Tables 4 and 5 summarize the set of assessments, giving each expert's probability for each question for each technology.[3] The total probabilities, shown in the bottom rows of the table, are found by multiplying the probability of achieving 3000 cycles, with the probability of achieving success in, say, the high endpoint. Not every expert answered every question. Two of the experts felt they did not have enough expertise with Lithium Metal anode batteries to answer that part of the questionnaire at all. Expert 7 gave his answers verbally as either low, medium, or high. He then defined these to mean: less than 10%; $11\% - 79\%$; and $80\% - 100\%$ respectively. For calculations we have taken the mid point value for each of the ranges, so we use 5%; 45%; and 90% for low, medium, and high respectively.

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[3] The experts are NOT in alphabetical order here to preserve confidentiality.

	Lithium Metal Anodes									
Funding Trajectory	$10M/yr over 10 years					$40M/yr over 10 years				
	Ex. 1	Ex. 2	Ex. 4	Ex. 6	Ex.7	Ex. 1	Ex. 2	Ex. 4	Ex. 6	Ex.7
3000 cycles?	0.05	0.67	0.05	0.2	low	0.2	0.85	0.1	#N/A	low
high endpoint	0.01	0.1	0.95	0.2	low	0.02	0.3	0.95	#N/A	low
low endpoint	0.07	0.4	0.99	#N/A	low	0.5	0.65	0.99	0.6	low
Totals:										
total prob high	0.0005	0.067	0.0475	0.04	0.0025	0.004	0.255	0.095	#N/A	0.0025
total prob low'	0.0035	0.268	0.0495	#N/A	0.0025	0.1	0.5525	0.099	#N/A	0.0025

Table 4: Results for Batteries with Lithium Metal Anodes

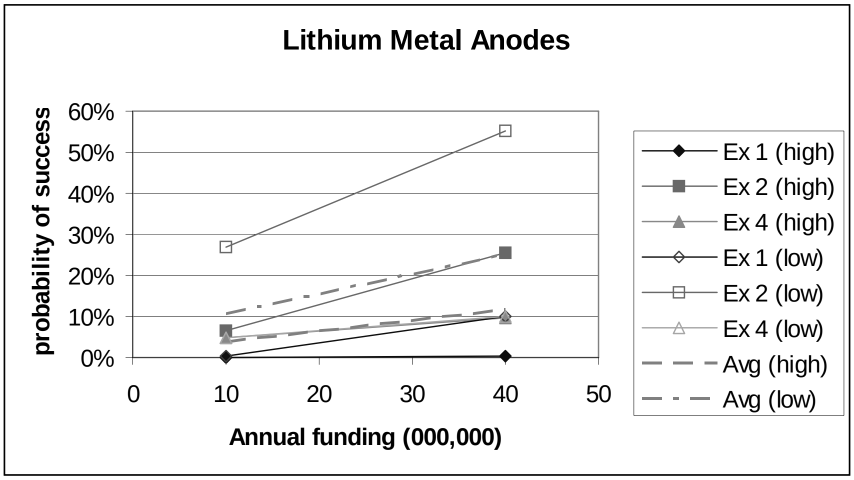

Figure 1: Probabilities of Success for Batteries with Lithium Metal Anodes

Figure 1 shows the results for the three experts that answered all questions. It also shows the average of the three experts. From this we see that Expert 2 is an optimist, with his lowest probability (6.7%) nearly as high as the other experts' highest probability (9.5%). This may be partially related to the fact that Expert 2 felt that a goal of 3000 cycles was not necessary; therefore he gave a probability of achieving 1000 cycles, and answered the rest of the questions conditional on achieving that level of success. Expert 1, on the other hand, felt that the goal of 3000 cycles was crucial, but expressed doubts that it could be achieved at any funding level. Expert 4 noted that achieving 3000 cycles is "not amenable to an Edisonian trial and error approach", but rather will require advances in materials science that are likely to come independent of funding for batteries. Given that the cycling problem is solved, however, Expert 4 felt that "private investment will address the cost problem." He did not feel there was a significant difference in the chance of achieving the high or low endpoints. Expert 7 was highly pessimistic, commenting that significant funding has already been allocated to the cycling problem for many years with few results; and that it is highly unlikely that these batteries would ever cost less than Li-ion, and that Li-ion was not likely to hit this cost goal.

Finally, there are potential safety issues with any battery that uses lithium, and resolving these issues is likely a requirement for any ultimately successful technology. This issue is included explicitly in the assessment for Lithium Ion technology. For Lithium Metal technology, the results in section 4 include sensitivity analysis regarding the difficulty of overcoming safety challenges.

In general the experts felt that the very low cost in the high endpoint was a challenge, and indicated

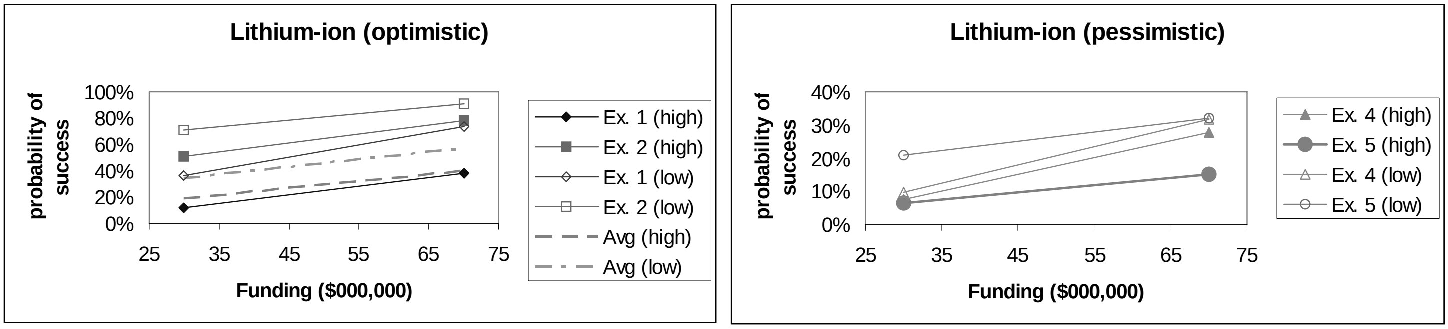

Figure 2: Probabilities of Success for Li-ion batteries

that it would take a great deal of engineering, not just science, to achieve this. Thus, some of the experts felt that the funding trajectory was too low for significant improvement. On the other hand, most of the experts noted that the low endpoints were within reach, assuming a solution for lithium cycling was found. Expert 6 did note that the cost goal of $135/kWh still requires a significant reduction below current costs.

Table 5 shows the results for the Lithium-Ion battery. This is a much more common technology, and thus all the experts were able to comment on at least some of the questions. Figure 2 illustrates the results graphically. We have divided the graph into two parts to make it easier to read, with the "pessimists" represented on the right, with a smaller scale.

	Lithium-Ion													
Funding Trajectory	$30M/yr over 10 years							$70M/yr over 10 years						
	Ex. 1	Ex. 2	Ex. 3	Ex. 4	Ex. 5	Ex.6	Ex.7	Ex. 1	Ex. 2	Ex. 3	Ex. 4	Ex. 5	Ex. 6	Ex. 7
3000 cycles?	0.95	N/A	0.4	0.5	0.875	#N/A	high	0.99	N/A	0.8	0.8	0.925	0.8	High
high endpoint	0.15	0.85	N/A	0.15	0.5	0.5	low	0.4	0.925	N/A	0.35	0.65	#N/A	Low
low endpoint	0.4	0.95	N/A	0.2	0.875	#N/A	low	0.75	0.96	N/A	0.4	0.925	0.75	Medium
thermal runaway high?	0.8	0.6	0.1	0.99	0.15	#N/A	low	0.97	0.85	0.7	0.99	0.25	#N/A	Low
thermal runaway low?	0.95	0.75	N/A	0.99	0.275	#N/A	low	0.99	0.95	N/A	0.99	0.375	#N/A	Low
total high	0.114	0.51	N/A	0.0743	0.0656	#N/A	0.0023	0.3841	0.7863	N/A	0.2772	0.1503	#N/A	0.0023
total low	0.361	0.7125	N/A	0.099	0.2105	#N/A	0.0023	0.7351	0.912	N/A	0.3168	0.3209	#N/A	0.0203

Table 5: Results for Lithium ion batteries

Most of the experts are fairly optimistic about achieving 3000 cycles with Li-ion, commenting that it is already achieving over 1000 cycles, and achieving something close to 3000 with the best technology in lab conditions. On the other hand, Expert 2 again felt the cycling restriction was unrealistic and unnecessary (and therefore answered the other questions unconditionally). Expert 1 did note that for Electric vehicles only 1000 cycles were necessary; 3000 cycles is for a plug-in hybrid.

Experts 1 and 4 both point out that achieving the ambitious cost goal will be tough, and will require considerable development, not just discoveries in the lab. The experts differ, however, on whether firms will step in and do the work, or government funding is crucial for the development stage. Expert 2 also mentioned the tough cost goal, commenting this would require finding a replacement for cobalt. He felt, however, that "research is pretty far along" in finding such a replacement. Expert 5 noted "new materials will allow this energy density to be achieved. These new materials are also more stable and less expensive than those used commercially today."

In terms of avoiding thermal runaway, there are some significant disagreements among the experts.

Among the optimists, Expert 2 felt these issues were amenable to lab work, and did not require costly development, therefore were likely to be achieved at even the low funding level. He noted that ionic liquids, while in infancy, show promise. Expert 3 commented "Nanotechnology based solutions, used in other materials science applications, make this possible, in principle." On the other hand, expert 5 was more cautious and expert 7 thought that thermal runaway is fundamentally a characteristic of the technology – it can be managed or minimized, but is unlikely to be eliminated. Expert 5, however, thought that for lower energy batteries it was possible to find stable materials and avoid the threat.

Overall, Expert 7 is even more pessimistic (relative to the others) in this case, with probabilities more than two orders of magnitude below many of the others.

By following the trajectory of the elicitations we can deduce that some experts see increasing returns to scale (that is, an incremental expenditure leads to an increased incremental gain). Expert 1 shows some increasing returns for both technologies. Most striking, expert 4 clearly shows increasing returns for Li-ion. This is particularly interesting as his rationales largely indicate that government funding is extraneous. The returns to scale we see are primarily in achieving cycling which he sees as amenable to government funding; particularly since it is not clear at this point what the market for such batteries will be. Expert 3 also sees great returns to scale in this particular area.

4 Analysis

In this section we provide an illustrative analysis using the data. For this analysis we use the simple average over the experts for each answer, and then calculated the total probability.[4] We have also assumed that projects will be funded in order of the expected impact per dollar invested.[5] Given this criteria, the funding order is as follows: Lithium Metal anodes at \$10M/year; Lithium-ion at \$30M/year; increase Lithium Metal to \$40M/year; and finally increase Lithium-ion to \$70M/year. This funding order might change, however, if the probability of avoiding safety concerns in Lithium Metal batteries is not high enough. If the probability of avoiding safety issues is below 89%, then Lithium-ion would be funded first at \$30M/year. If the probability is below 68%, then the funding for Li-ion would be increased to \$70M/year before Lithium Metal was funded.

Figure 3 shows how the expected cost of batteries is related to the annual R&D expenditure, under our baseline assumptions. We assume that with no R&D, the best alternative is Nickel-metal hydride batteries, with a minimum cost \$300/kWh [1][12]. Finally, we are using cost only as a proxy for the overall technological advance represented by our endpoints.

The Figure shows that once we average all the experts we get a near-linear relationship, showing neither decreasing nor increasing returns to scale. This implies that every million dollars of annual funding decreases the cost of a kWh by about \$0.90, *on average*.[6] But, the average decrease can be quite misleading, since what we really have is the possibility of breakthrough success (costs on the order of \$90) balanced against little or no improvement.

Figure 4 shows the results in a way that highlights the probabilistic nature, showing how the probabilities of success are related to US R&D spending. We have broken it up into three categories. The

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[4] We note that any single measure should be treated with some caution [16]. More sophisticated methods [10] using the same raw data could further moderate the results, such as averaging odds rather than probabilities. With a small number of experts, and with a goal of gaining general insights rather than making specific funding decisions, the simple average is responsive but robust [22].

[5] While this is a good heuristic that is widely used in industry, it does not always result in the optimal portfolio. Thus, our results are illustrative.

[6] If we use the alternate funding order mentioned above in which Li-ion is funded first, there are slightly decreasing returns to scale after the low investment in Lithium metal, and the average returns are a savings of \$1.25/kWh for every million dollars, for the first \$80 million.

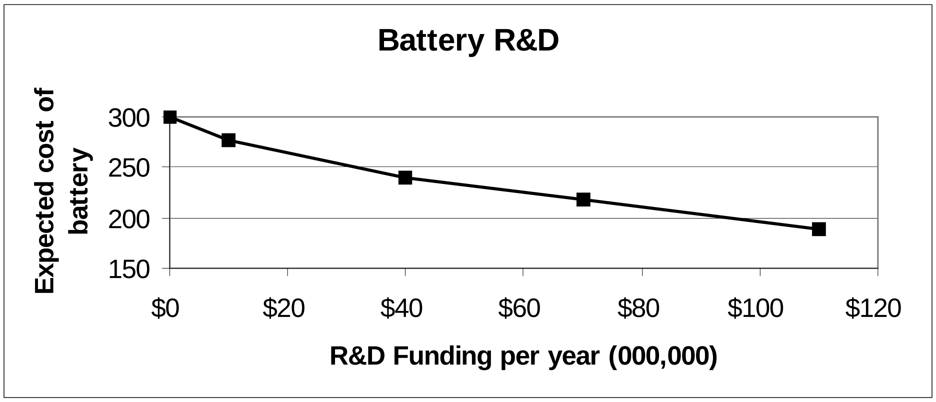

Figure 3: Expected Cost of batteries for different R&D funding levels

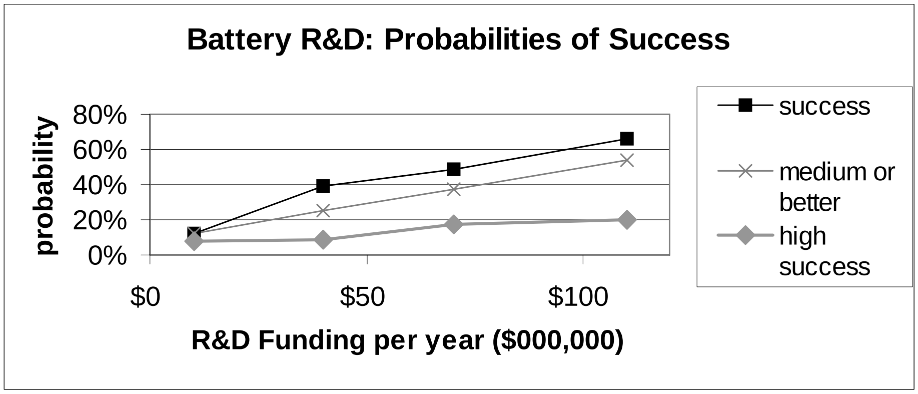

Figure 4: Probability of success for different R&D Funding Levels

highest line shows the probability of any success, that is, the probability that the cost of a kWh will be \$200 or less. The middle line shows the probability that the cost of a kWh will be \$135 or less; the lowest line shows the probability that the most ambitious target will be met with a cost of \$90 or less.

5 Impacts on climate change

Improving batteries has the potential to reduce the cost of combatting climate change, by replacing internal combustion engine vehicles with Plug-in Hybrid Electric Vehicles (PHEVs) or Electric Vehicles (EVs). We investigated the impact that achieving success, as defined above, would have on the *marginal* cost of reducing carbon emissions. The marginal cost is the cost of reducing one more ton of carbon emissions; it tells us what a carbon tax would need to be to induce the appropriate reduction in emissions. For example, Figure 5 shows that a carbon tax of \$500/tC would lead to about a 50% reduction in greenhouse gas emissions.[7]

For this study, we derive Marginal Abatement Cost curves (MACs) for the U.S. for the year 2050 under different assumptions about technological pathways. The analysis was conducted using the MiniCAM integrated assessment model. MiniCAM is a global model that looks out to 2095 in 15-year timesteps. It is a partial-equilibrium model, with 14 world regions that includes detailed models of land-use and the energy sector. See Brenkert et al. [7] and Edmonds et al. [11] for more discussion of the model. Assumptions for technologies other than battery-assisted vehicles are based on the version of MiniCAM used in the Climate Change Technology Program (CCTP) MiniCAM reference scenario [8].[8] See [4][2][3] for more detailed discussions of our methods and assumptions on related technologies.

We ran a total of 8 scenarios along with reference cases – one for each level of success for each technology, under two assumptions about the availability of Electric Vehicles. In one case we assume availability of PHEVs only. We use this as a reference case with the cost of batteries equal to \$384/kWh. In the other case, we assume EVs are available, and that high success in the Lithium Metal Anode technology would be appropriate for EVs.

Figure 5 illustrates our results. We have shown only three cases plus the reference case to highlight the main results. For exposition we will focus on the impact at 80% abatement. We found that having lower cost batteries available has a significant effect on the MAC, lowering it by about 15% even in the case of low success for Li-ion batteries. Moving to high success in Lithium Metal anode batteries leads to a reduction of about 20%. High success in Li-ion, and low success in Lithium Metal are very similar and fall between the two cases we have shown. Finally, if we allow for widespread adoption of EVs and high success in Lithium Metal anode batteries, there is an additional gain, with the MAC reduced by about 25% total below the reference case. To put these in perspective, we estimated the total cost of 80% abatement in the U.S. in the sample year 2050 by integrating the area under the MAC curve in figure 5. The total costs are estimated to be \$860 billion for the reference case and \$750 billion for the low success Li-ion case, resulting in total savings of about \$110 billion per year in 2050. If this is discounted at a rate of 5%, the present value as of 2010 is about \$16 billion per year for the U.S. alone.

6 Conclusions

One way to address climate change, fossil resource depletion, and other environmental problems in the transportation sector is through the development of cost-effective, safe, and reliable battery or battery-assisted vehicles that have the characteristics consumers are looking for. A key hurdle to providing such

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[7] All costs in this section are in 2005 constant dollars.

[8] Report can be accessed at http://www.pnl.gov/science/pdf/PNNL18075.pdf

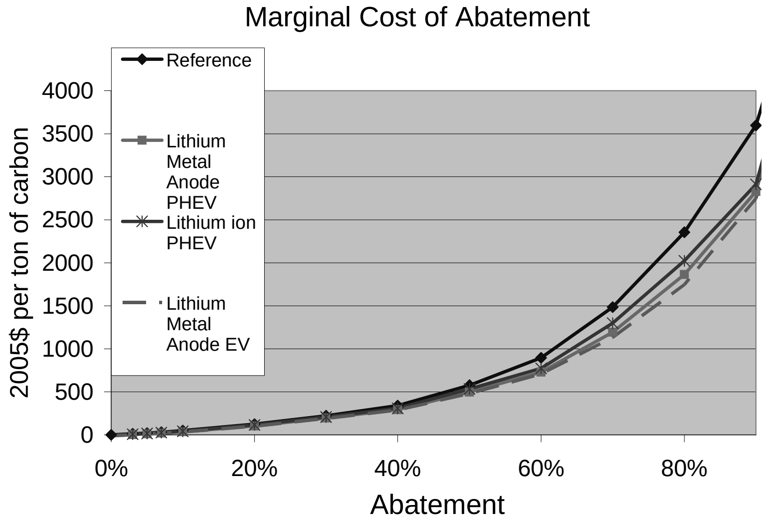

Figure 5: Impact of battery technologies on the Marginal Abatement Cost Curve

vehicles is the development of improved battery technology. We have performed expert elicitations to get at the relationship between U.S. government funding and the prospects for battery technologies.

For batteries with Lithium Metal anodes, such as Lithium-sulfur batteries, we found that a $40M/year research program leads to an average probability of high success of about 16%. However, if we leave out our "optimist", that reduces to about 7%. Furthermore, if we assume that the probability of resolving safety issues is the same for Lithium Metal as it is for Li-ion, about 45%, this further reduces to about 3%. For Li-ion batteries, we found that a $70M/year research program would lead to an average probability of high success of about 35%, including the specification for avoiding thermal runaway. If we drop this specification, the probability increases to about 50%.

The results of our structured assessments reveal a high level of disagreement over solving the thermal runaway problem. This implies that this areas would have a relatively high priority for research investment: either more in-depth elicitations with active discussion among participants, or scientific research aimed at determining how *solvable* this problem is. Moreover, it may be important to address how important the problem is, as one of the experts indicated that firms would simply manage this problem as a liability issue. Similarly, there is disagreement among the experts on the importance of achieving 3000 cycles for batteries with Lithium Metal anodes.

As mentioned above, this elicitation is part of a larger project, covering seven technological categories over a two-year period. Thus, each individual elicitation was relatively quick and inexpensive. Given the large number of potential technologies to combat climate change, and the speed of technological change in these hot areas, quick and inexpensive elicitations have value in pointing to general trends, providing estimates of the value of information, and underlining questions that would need to be addressed in more detailed elicitations. Still, these results should be interpreted with caution. In particular, the number of experts was not as large as in some studies. The mean probabilities from small samples are sensitive to the exact set of experts used; prior work, however, has shown that the incremental value of adding another expert decreases significantly after 3-4 experts [23].

In this paper we have completed an expert elicitation and implemented the data in an economic model in order to derive probability distributions over the impacts of R&D investment on climate change. In order to more fully analyze which programs should be pursued and at what levels, we would need to combine this data with information on climate damages in a full portfolio analysis. Our brief discussion does indicate that reducing the cost of batteries from \$384 to \$200/kWh may lead to an overall reduction in the annual cost of abatement of \$100 billion in the year 2050; therefore, it is worth keeping these technologies on the table.

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References

[1] American Automobile Association and Runzheimer International. Your driving costs, 2005.

[2] Erin Baker, Haewon Chon, and Jeffrey Keisler. NuclearPower: Combining expert elicitations with economic analysis to inform climate policy. Available at SSRN: http://ssrn.com/abstract=1407048, 2008.

[3] Erin Baker, Haewon Chon, and Jeffrey Keisler. Advanced solar R&D: Combining economic analysis with expert elicitations to inform climate policy. *Energy Economics*, 31:S37 – S49, 2009.

[4] Erin Baker, Haewon Chon, and Jeffrey Keisler. Carbon capture and storage: Combining expert elicitations with economic analysis to inform climate policy. *Climatic Change*, 96(3):379, 2009.

[5] Erin Baker, Leon Clarke, Jeffrey Keisler, and Ekundayo Shittu. Uncertainty, technical change, and policy models. Technical Report 1028, College of Management, University of Massachusetts, Boston, 2007.

[6] Erin Baker and Jeffrey Keisler. Expert elicitations on biofuel technologies. *Environmental Science and Technology*, Under Review, 2009.

[7] A.S. Brenkert, S. Smith, S. Kim, and H. Pitcher. Model documentation for the MiniCAM. Technical Report PNNL-14337, Pacific Northwest National Laboratory, 2003.

[8] L. Clarke, P. Kyle, M.A. Wise, K. Calvin, J.A. Edmonds, S.H. Kim, M. Placet, and S. Smith. CO2 emissions mitigation and technological advance: An updated analysis of advanced technology scenarios. Technical Report PNNL-18075, Pacific Northwest National Laboratory, 2008.

[9] R.T. Clemen and R.C. Kwit. The value of decision analysis at Eastman Kodak Company, 1990-1999. *Interfaces*, 31:74–92, 2001.

[10] R.T. Clemen and R.L. Winkler. Combining probability distributions from experts in risk analysis. *Risk Analysis*, 19:187–203, 1999.

[11] J.A. Edmonds, J.F. Clarke, J.J. Dooley, S.H. Kim, and S.J. Smith. Stabilization of CO_2 in a B2 world: Insights on the roles of carbon capture and storage, hydrogen, and transportation technologies. In John Weyant and Richard Tol, editors, *Special Issue, Energy Economics*. 2005.

[12] M. Duvall et al. Comparing the benefits and impacts of hybrid electric vehicle options for compact sedan and sport utility vehicles. Technical Report 1006892, EPRI, 2002.

[13] Linda Gaines and Roy Cuenca. Costs of lithium-ion batteries for vehicles. Technical Report ANL/ESD-42, Argonne National Laboratory, 2000.

[14] Stephen Hora and Detlof Von Winterfeldt. Nuclear waste and future societies: A look into the deep future. *Technological Forecasting and Social Change*, 56:155–170, 1997.

[15] Ronald A. Howard. Decision analysis: Practice and promise. *Managment Science*, 34:679–695, 1988.

[16] D. W. Keith. When is it appropriate to combine expert judgments? *Climatic Change*, 33, 1996.

[17] J. P. Peerenboom, W. A. Buehring, and T. W. Joseph. Selecting a portfolio of environmental programs for a synthetic fuels facility. *Operations Research*, 37:689–699, 1989.

[18] David Popp. ENTICE-BR: The effects of backstop technology R&D on climate policy models. *Energy Economics*, 28:188–222, 2006.

[19] P. Sharpe and T. Keelin. How smithkline beecham makes better resource-allocation decisions. *Harvard Business Review*, 76, 1998.

[20] Carl S. Spetzler and Carl-Axel S. Stael von Holstein. Probability encoding in decision analysis. *Management Science*, 22:340–358, 1975.

[21] Howard Thomas. Decision analysis and strategic management of research and development: A comparison between applications in electronics and ethical pharmaceuticals. *R&D Management*, 15:3–22, 1985.

[22] Detlof von Winterfeldt and Ward Edwards. *Decision Analysis and Behavioral Research*. Cambridge Universtiy Press, Cambridge, U.K., 1986.

[23] Robert L. Winkler and Robert T. Clemen. Multiple experts vs. multiple methods: Combining correlation assessments. *Decision Analysis*, 1:167–176, 2004.