Technology to Market: Cost-Benefit Analysis of AMPED Technologies

Joe Miler, PhD

Program Director: Ilan Gur, PhD
Tech SETA: Russ Ross, PhD
ARPA-E Fellow: Amul Tevar, PhD

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Getting past the Standard Interaction

Hey check out my super-expensive, unreliable gadget that we cooked up in lab and have no idea what to do with!

I’m trying to be polite. Actually, you haven’t told me enough to have any clue of how interesting this is for me.

What they hear: Hey check out my new BMS sensor that can solve all your problems!

What they really mean: Interesting!

Research scientist

OEM Engineer
Getting past the Standard Interaction

Working toward shared goals

LESS

MORE

How do we go from cool technology to scalable technology?

Lab researcher

OEM R&D Engineer
Innovation

People creating value through the implementation of new ideas

» Herman D’hooge, Intel
» Innovation Network
People creating value through the implementation of new ideas

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Technology-to-Market

- Technology
- Market
- Manufacturing
- Team
- Intellectual Property
- Funding
Key Activities for AMPED Teams

- **Research & Development**
  - Year 1
  - Year 2
  - Year 3

- **Market Engagement and Cost-Benefit Analysis (Value Proposition)**
  - Year 2

- **IP Strategy**
  - Year 3

- **Team Development**
  - Year 3

- **Next Stage Plans and Funding**
  - Year 3
The BMS Design Space

Knobs

Outputs

Externalities

Image Sources:
- http://www.computertimes.com/mar07/image214.jpg
- http://www.plmsdevelopments.com/images_if/gauges.jpg
The BMS Design Space

Knobs
- SOC Window
- Controls
- Drive mode
- Pack Size
- Therm. Management
- Cell Format
- Cell equalization
- Circuit Arch.

Outputs
- Safety
- Reliability
- Charge Rate
- Utilization
- Liability
- Secondary Use
- Lifetime
- Initial Cost/Weight/Volume

Externalities
- Operating Temp.
- Drive Profile
- Cell mfg errors
- Collisions
- Consumer demand
- Regulatory
The BMS Design Space
Developing Scalable BMS Technologies

Industry Advice

AMPED Team

Your plan

Scalable BMS Technology
Developing Scalable BMS Technologies

Goal:
Predict system performance with State-of-Art Component vs AMPED Component
Predicting System Performance Improvement

Goal:
Predict system performance with State-of-Art Component vs AMPED Component
Challenge #1: Vast Scope of Information Needed

Example: Novel Sensor

Existing Component Performance Data

**Required Info:**
- Accuracy
- Spatial resolution
- Time resolution
- Durability
- Size

**Resources:**
- Spec Sheets
- Interviews
- Tear-down reports

**Challenges**
- Proprietary
- Highly detailed

Battery Pack Model

**Required Info:**
- No. of sensors
- Sampling rate
- Controls scheme
- Power topology
- Thermal Management

**Resources:**
- Interviews
- Tear-down reports

**Challenges**
- Proprietary
- Inaccessible

Modeling Results

Validation Data for System Performance

**Required Info:**
- Vehicle range
- Charge rate
- Capacity fade
- Safety

**Resources:**
- Internal pack performance reports

**Challenges**
- Proprietary
- Highly coupled outcomes
Challenge #2: Defining the System to Model

Unique to each AMPED team

System model subject to change

- Different vehicle types: HEV, PHEV, AEV
- Different battery designs
- New technologies
Challenge #2: Defining the System to Model

Determining system-level performance is a multivariate, multidisciplinary optimization problem.
Practical Approaches to Determining System-Level Performance Improvements

Approach #1: Seek Expert Advice

**Benefits**
- Expert intuition serves to synthesize complex problem.
- Details can remain proprietary while conclusions are shared.
- Experts are often potential investors and future customers.

**Drawbacks**
- Expert opinions vary dramatically.
- Disruptive technologies are impossible to foresee.
- Motives may vary.

Approach #2: Build a Custom Battery Pack Model

**Benefits**
- Assumptions are clear.
- May break conventional wisdom.
- Existing models provide a launch point.

**Drawbacks**
- Assumptions may be wrong.
- Time-intensive.
- Miss the forest for the trees.
- Quality input data is elusive.
Many Possible Outcomes to Compare

- Extended range
- Increased charge rate
- Reduced initial pack size (cells)
- Reduced non-cell components
- Increased lifetime
- Improved pack safety
- Improved reliability
- Improved life estimation

System Performance

- Charge Rate
- Lifetime

Example: Novel Sensor

Existing Sensor

AMPED Sensor

Expert Advice

Custom Model

How to determine which system level performance improvements to pursue?
Developing Scalable BMS Technologies

- Component Level Innovation
- System Level Technical Performance
- Customer Value Proposition
- Scalable BMS Technology
- Cost Analysis
Reaching the Customer

New AMPED Tech

System Performance Improvements

Extended range
Increased charge rate
Reduced initial pack size (cells)
Reduced non-cell components
Improved pack safety
Full cell yield utilization
Improved reliability
Improved warranty estimation

Value Propositions

Definition:
A quantifiable benefit offered to a customer.
Reaching the Customer

New AMPED Tech

System Performance Improvements

- Extended range
- Increased charge rate
- Reduced initial pack size (cells)
- Reduced non-cell components
- Improved pack safety
- Full cell yield utilization
- Improved reliability
- Improved life estimation

Value Propositions

- Vehicle cost savings
- Increased vehicle adoption
- Regulation compliance
- Increased charger use
- Fleet capacity factor
- Increased cell value
- Decreased warranty cost

Possible Customers

- Automotive OEMs
- Tier 1 Suppliers
- Charge stations
- Fleet operators
- Cell manufacturers
- Grid storage companies
Framework for Assessing Value Propositions

System Performance Improvements

Extended range
Increased charge rate
Reduced initial pack size (cells)
Reduced non-cell components
Improved pack safety
Full cell yield utilization
Improved reliability
Improved warranty estimation

Framek provides:

- Methodical breakdown of value
- Techniques for quantifying value
- Targeted references

<table>
<thead>
<tr>
<th>Value Proposition</th>
<th>Potential Customer</th>
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<td>Vehicle Cost Savings</td>
<td>OEMs, Tier 1s</td>
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Value Proposition: Reduced Initial Pack Size (Cells)

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- Varied cost savings
  - Decreased Bill of Materials (BOM)
  - Reduced powertrain requirements
  - Secondary mass savings
- Very active research area for automotive industry. All major manufacturers have value estimates for lightweighting.
- Value: $3-4/lb (VTP truck study 2012)
- Lightweighting cost models
  - Alexandra Frangi, MIT, 2001 (Tech. Cost Modeling (TCM))
## Value Proposition: Reduced Initial Pack Size (Cells)

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- **Cell Costs**
  - Approximate: $650/kWh (usable)
  - Projected to decrease:
    - ~150-400 $/kWh by 2020)

- **References**
  - DOE
  - Private sector

J. Neubauer, A. Pesaran, B. Williams, M. Ferry, J. Eyer
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- **Handling**
  - Difficult to quantify.
  - Significant interest in improved handling in performance vehicles.
  - Battery results in low center of gravity. Nissan Leaf achieved nearly 1g acceleration with extensive after-market tweak.

- **Trunksize**
  - Secondary benefit, more relevant to late-adopters.
  - Brownstone 2000 looked at luggage space. No other known studies.
### Value Proposition Framework Available

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Spreadsheet of value propositions:
- Full list of value propositions
- Techniques for quantification
- References

Available to all Attendees

Living document… *Input welcome!*

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![Diagram of value proposition framework](image-url)
Effects of Industry Trends on Value Analysis

Trend
Increasing cell energy density

Potential Implications
- Less value of pack-lightweighting
- More value to cell enhancement
- More value to cell safety
- More relative value in reducing non-cell components

Understanding how value propositions are calculated allows you to integrate trends.

Li-Ion Pricing (Red) and Energy Density (Blue)
Source: Buchman 2005, from Anderson 2009
Developing Scalable BMS Technologies

Final remarks on value propositions:

• System-level performance improvements *alone* will not yield a scalable technology.
• Value proposition framework is only a tool for orientation.
• You won’t know actual value until you have actual customers.
• Each customer has its own lens.
• Value propositions are your “technology budget”.
Developing Scalable BMS Technologies

- Component Level Innovation
- System Level Technical Performance
- Customer Value Proposition

Cost Analysis

Scalable BMS Technology
Cost-Analysis for AMPED Technologies

• Expectations
  - Customers do not expect a perfect cost model
  - Customers do need reason to believe value outweigh costs

• A phased approach

Technology Development
- Early R&D
- Prototyping
- Demonstration

Cost-Analysis
- Cost-aware design
- Preliminary Cost Model
- Detailed Cost Model
Cost-Analysis for AMPED Technologies

• Automotive-specific cost considerations
  ➤ Fleet standardization of components
  ➤ Regulatory
  ➤ Warranty

• Available resources
  ➤ Cost-modeling tutorial (ARPA-E)
  ➤ Industry collaboration
  ➤ National Labs and DOE VTP
    – Argonne National Lab (ANL)
    – DOE Vehicle Technologies Program (VTP)
    – National Renewable Energy Lab (NREL)
    – Oak Ridge National Lab (ORNL)
ORNL xEV Modeling Tools

ORNL has expertise in modeling the interactions between technology, infrastructure, behavior, policy and market.

MA3T -- estimate demand for PEV by 1458 consumer segments

Projected combined sales of BEV and PHEV under different scenarios of achieving DOE technical targets for vehicle components.

MOR-PHEV -- Optimize PHEV e-range for U.S. drivers

Range Extension from Charging in 100% of Daily Usable Battery

MOR-BEV -- Optimize BEV range for U.S. drivers

50% NOP = Non-optimality Premium

SED -- Quantify value of electric range and its sensitivity to charging infrastructure, range certainty, distance certainty, battery cost, value of time

\[ S = 365S_0 \int_{R_e}^{+\infty} f(x_e)dx_e \]

\[ E = 365E_0 P_{ed} P_e \]

\[ D = 365D_0 P_{ed} (1 - P_e) \]

Unexpected Distance Variation, (µ,σ)=(70,4)

Expected Daily Distance, (µ,σ)=(40,20)

Unexpected Range Variation, (µ,σ)=(100,20)

Driving Distance or Range (mile)

PHEV Calculator -- Estimate PHEV energy costs for individually-customized travel patterns; based on GPS-validated methods; simple questions for users

<table>
<thead>
<tr>
<th>Annual</th>
<th>Gasoline</th>
<th>Electricity</th>
<th>Total</th>
</tr>
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<tbody>
<tr>
<td>Fuel Costs</td>
<td>$110</td>
<td>$477</td>
<td>$587</td>
</tr>
<tr>
<td>Miles</td>
<td>1,097</td>
<td>10,903</td>
<td>12,080</td>
</tr>
<tr>
<td>Fuel Used</td>
<td>30 gallons</td>
<td>8,974 kWh</td>
<td>–</td>
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Average number of gas station visits per year: about 4.
Summary of ORNL Areas of Expertise

Applications of ORNL analytical tools generate insights about drivers and barriers of the PEV market, at both system and component levels.

• PEV value and travel pattern characterization

• Optimal vehicle design and consumer preferences

• Charging infrastructure—needs and impacts

• Integrated analysis of PEV market and societal value
  – (Working) Impacts of DOE technical targets on EV’s demand and environmental impacts
  – (Working) Sensitivities of EV demand to consumer preferences, energy prices, and range value
Modeling Li-ion Battery Performance and Cost: BatPaC

- Modeling real-world battery packs from bench-scale data
  - Prediction year 2020
  - Total cost of battery pack
  - Mass and volumes
- Battery is designed based on pack requirements and cell chemistry performance

- BatPaC model used by U.S. EPA and DOT for 2017-2025 light duty vehicle rule making
- Support from DOE EERE VTP: Dave Howell, Peter Faguy, and Tien Duong
Modeling Li-ion Battery Performance and Cost: BatPaC

- BatPaC is based in Microsoft Excel® and may be modified to meet individual users’ needs
- Existing BatPaC capabilities includes six Li-ion chemistries, liquid and air thermal management options, uncertainty calculation, etc.

### Iterate Over Governing Eqs. & Key Design Constraints
- Cell, module, & pack format
- Maximum electrode thickness
- Fraction of OCV at rated power

### Battery Pack Components
- Volume
- Mass
- Materials
- Heat generation

### Governing Equations

\[
E = N \cdot C \left( U_{E} - \frac{C}{3} \frac{ASl_{p}}{A} \right)
\]

\[
L = \frac{C}{Q \cdot \rho \cdot \varepsilon \cdot A}
\]

\[
I = \frac{A \cdot N \cdot U_{p} \left( \frac{V}{U} \right)}{N \cdot \left( U_{p} \right) \left( 1 - \frac{V}{U} \right)}
\]

\[
A = \frac{ASl_{p} \cdot P}{N \cdot \left( U_{p} \right) \left( 1 - \frac{V}{U} \right)}
\]

\[
ASl = \frac{\alpha + f(I)}{L} + \beta
\]

### Process Cost

\[
\text{Process cost} = \text{Baseline cost} \cdot \left( \frac{\text{Processing rate}}{\text{Baseline processing rate}} \right)^p
\]

### Total Cost to OEM
- Materials & purchased items
- Individual process steps
- Overhead, depreciation, etc.
- Warranty
NREL’s Battery Ownership Model (BOM)

- **Objective:** Perform accurate techno-economic assessments of HEV, PHEV, and BEV technologies and operational strategies to optimize consumer cost-benefit ratios.

1. Real-world driver aggression profiles
   - 317 real-world, year-long trip histories

2. Trip-by-trip simulation

3. Battery electrical and thermal models
   - 100 city-specific climate histories
   - Advanced vehicle simulation includes full drivetrain consideration, cabin thermal model, HVAC system, and more.

4. Hi-fi battery wear model
   - Accounting: Economics, mileage, fuel use, greenhouse gases, etc.

5. Other Accounting Inputs:
   - Cost of gasoline
   - Cost of electricity
   - Cost of vehicle components
   - Cost of unachievable travel
   - Taxes
   - Purchase incentives
   - Loan parameters
   - Driver discount rate
   - Etc.

Range estimation algorithms inform travel decisions
How the BOM can help AMPED teams

- If your technology can...
  - Decrease battery cost
  - Increase accessible battery capacity
  - Reduce battery wear
  - Improve SOC or SOH estimation
  - Improve battery efficiency
  - Reduce thermal management needs
  - Etc.

- ...then the BOM can quantify it’s value

- AMPED team technology inputs:
  - Up-front component costs (5)
  - Technology performance; e.g. SOC identification algorithms, battery controls strategies, state measurement accuracy, etc. (3)
  - Range estimation algorithms (2)

- BOM outputs:
  - OEM costs
  - Consumer costs
  - Consumer benefits
EV Everywhere Analysis Process Flow, 
*in three steps...*

1. **DOE experts define the bounds of technical possibility** for technology key metrics
   - 90% “low progress” scenario
   - 50% “mid case” scenario
   - 10% “high progress” scenario

2. **Define virtual vehicles** in Argonne National Lab’s *Autonomie* modeling and simulation software

3. **Compare vehicles in a 5-year simple payback framework** within bounds defined by experts
Analysis: 2022 Midsize SI PHEV40

- **Power electronics and motor ($/kW)**: $7, $10, $13
- **Energy Storage ($/kWh)**: $200, $225, $250
- **Lightweighting (% wt reduction)**: 27, 24, 7

Levelized Cost Per Mile ($/mi): $0.45 to $0.50

LCD-implied targets:
- **$/kW**: 5
- **$/kWh**: 190
- **% wt**: 29
Analysis: 2022 Midsize AEV300

- Power electronics and motor:
  - $/kW: 7, 10, 13

- Energy Storage:
  - $/kWh: 125, 175, 250

- Lightweighting:
  - % wt reduction: 27, 24, 7

- LCD-implied targets:
  - $/kW: 4
  - $/kWh: 110
  - % wt reduction: 30
Landscape of xEV Resources from the DOE

- Drive Profiles
- Vehicle Model
  - Battery Pack
  - Thermal
  - Degradation
  - Costs
- Infrastructure
- Market Assessment
- Vehicle Optimization
- Policy and Regulation
- Cost of Ownership

Other notable groups:
- UC Davis - Market studies
- MIT - Lightweighting, Vehicle adoption

What other resources are we missing?
Developing Scalable BMS Technologies

System Improvements
- Difficult finding the right information
- Difficult choosing the right system
- Leverage industry expertise and existing models

Value Propositions
- Critical to achieving a scalable technology
- Many possible paths
- Framework provided for quantifying and tracking value propositions

Cost Analysis
- Phased approach
- Leverage existing resources
Acknowledgments

- ARPA-E
  - Ilan Gur
  - Russ Ross
  - Amul Tevar
  - Tech-to-Market Team
- DOE VTP group
- National Labs
- Many industry collaborators
Questions and Discussion

**Industry**

- How much system performance improvement is needed to get your attention?
- What does it take for you to believe research cost projections?
- What are the key components of an effective pitch?

**Research**

- What other modeling resources are available?
- What industry information is most needed in the research community?

**General**

- What other trends will influence new BMS technologies?
- How will regulations affect value propositions and/or cost modeling?
- What scale-up pitfalls do automotive technologies fall into?