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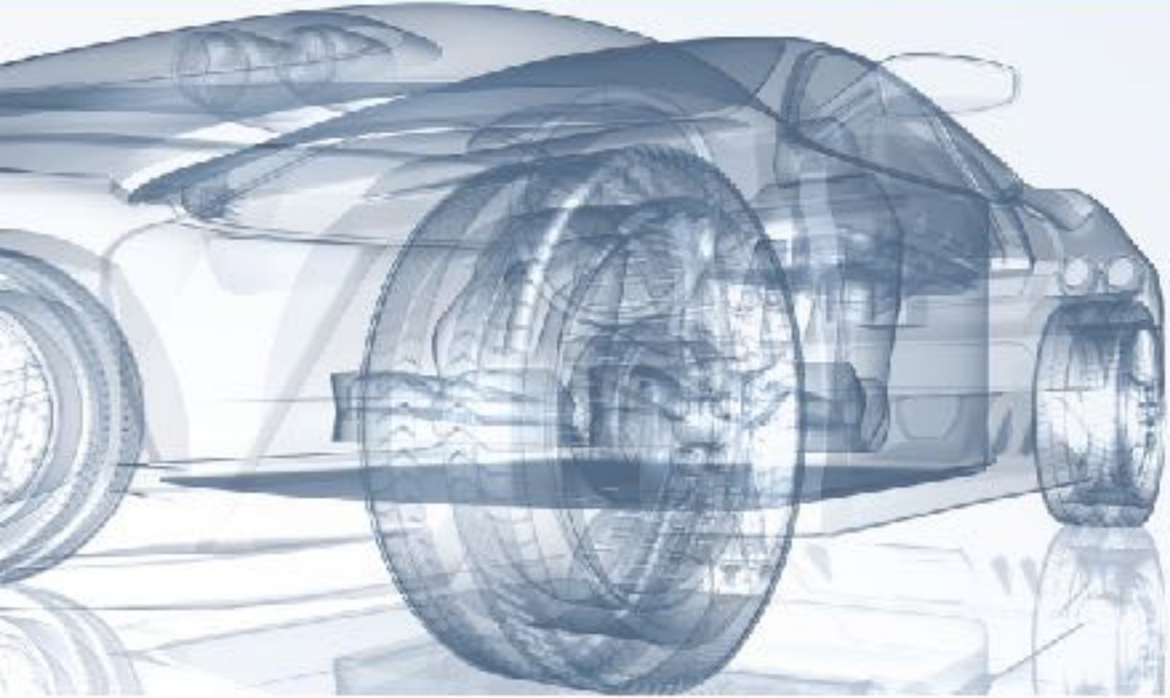

The 30th International Electric Vehicle Symposium & Exhibition

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Predicting the Future Manufacturing Cost of Batteries for Plug-In Vehicles

for the U.S. EPA 2017-2025 Light-Duty Greenhouse Gas Standards

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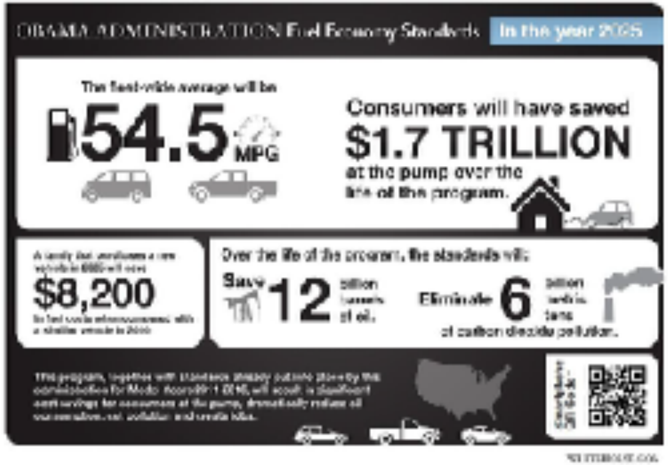
Agenda

- Why EPA models battery costs for PEVs
- Outline of the sizing and costing methodology
- Major inputs, data sources, and how we chose them
- How our battery sizing compares to actual PEVs
- How our projected costs compare to other sources

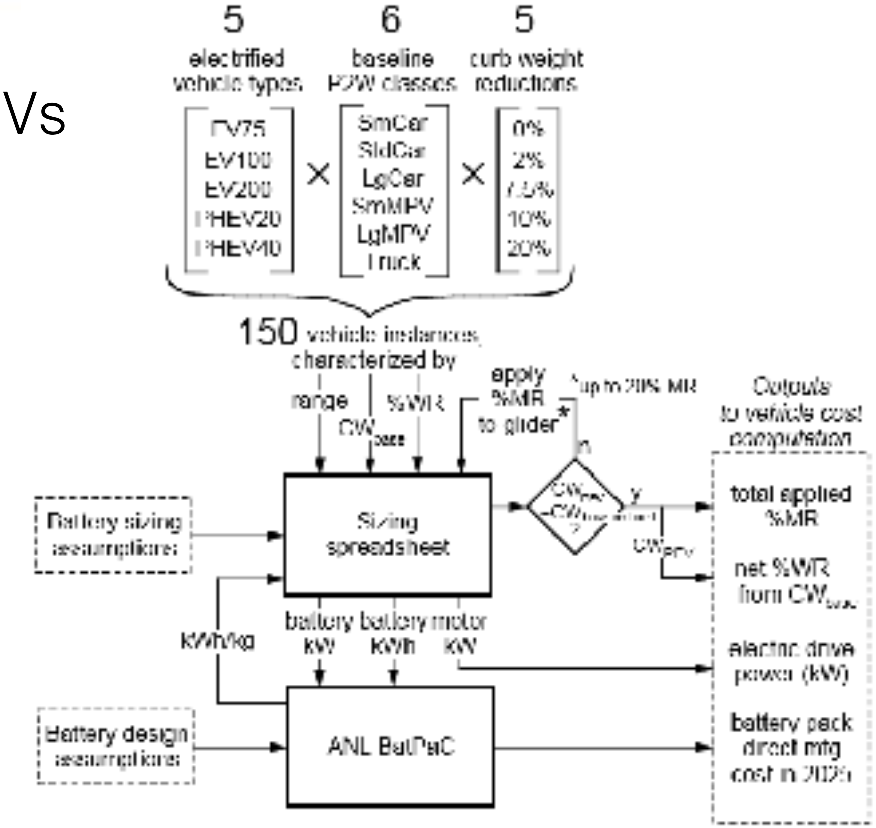
Why does EPA model battery costs?

- The 2017-2025 Light-Duty GHG standards were developed between 2010-2012
- One important consideration was the cost of technologies available to comply with the standards
- Plug-in Electric Vehicles (PEVs) are one of these technologies
- EPA has assessed PEV battery costs several times:
  - When the standards were first developed in 2012
  - In July 2016 for the Draft Technical Assessment Report (TAR)
  - In November 2016 for the Proposed Determination
- The EPA Administrator has announced that he is reconsidering the Jan. 2017 Final Determination, and plans to make a new Final Determination by April 1, 2018
- Staff continues to review new data and information for all technologies, including PEV battery costs



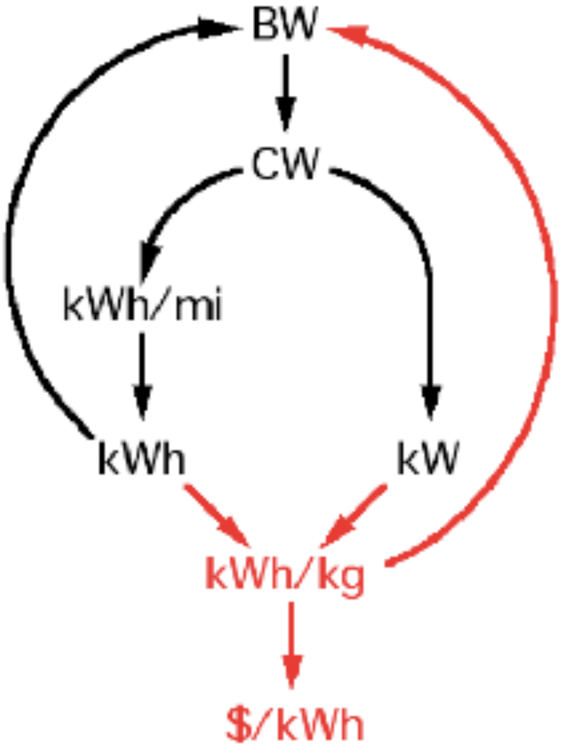
Battery cost modeling approach

1. Define a broad spectrum of PEVs representing the future fleet
2. Determine required battery capacity and power for each
3. Use ANL BatPaC to estimate direct manufacturing cost



Specifying a battery is complex

- Capacity (kWh) and power (kW) are the primary parameters
- Required kWh depends on vehicle energy consumption (kWh/mi)
- kWh/mi depends on vehicle curb weight
- Curb weight depends on battery weight
- Battery weight depends on required kWh and specific energy (kWh/kg)
- kWh/kg depends on kWh and kW
- *Computational shortcuts are tempting, but they can introduce vulnerabilities*

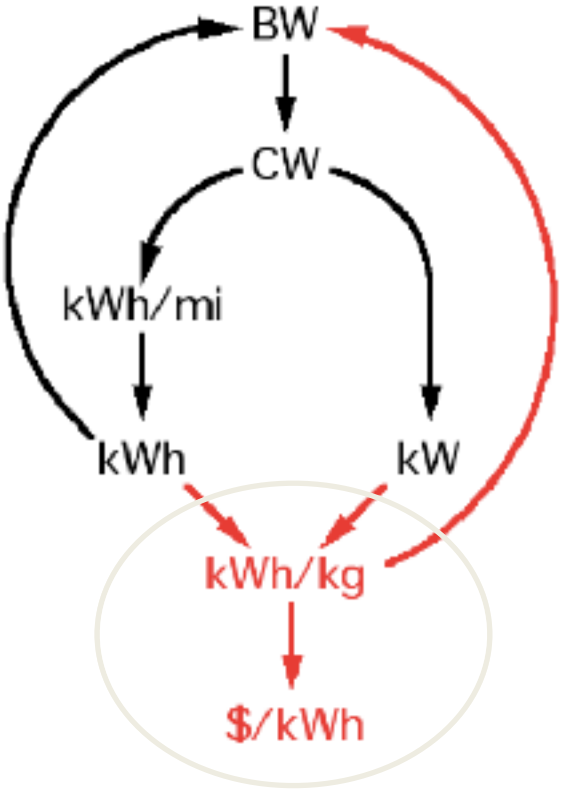


Goal: Avoid vulnerabilities, such as:

- Assuming a constant $/kWh for all vehicles
  - Not sizing the battery specifically to the vehicle class
  - Not accounting for the efficiencies of larger batteries
  - Not accounting for the cost of power
- Assuming a fixed kWh/mile for all vehicles
  - Not accounting for the effect of vehicle weight
  - Not distinguishing between vehicle classes
- Neglecting battery design
  - Not specifying the cell and module topology
  - Not accounting for the scale of production

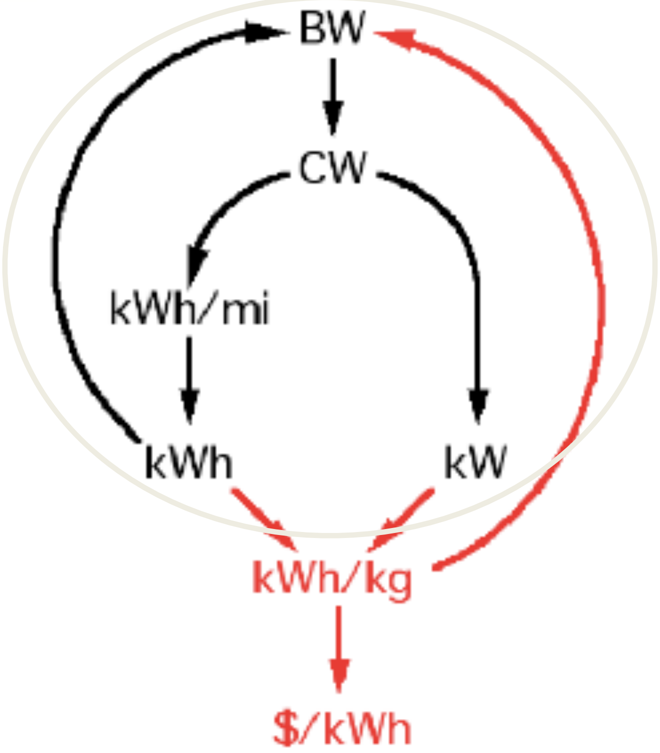
ANL BatPaC is a key component

- Peer-reviewed, bill-of-materials based model by Argonne National Lab
- Key inputs:
  - Gross capacity (kWh)
  - Peak power (kW)
  - Topology (cell and module)
  - Thermal medium
  - Production volume
- Key outputs:
  - Specific energy (kWh/kg)
  - Direct manufacturing cost ($)
- However, it can't help with determining required kWh or kW



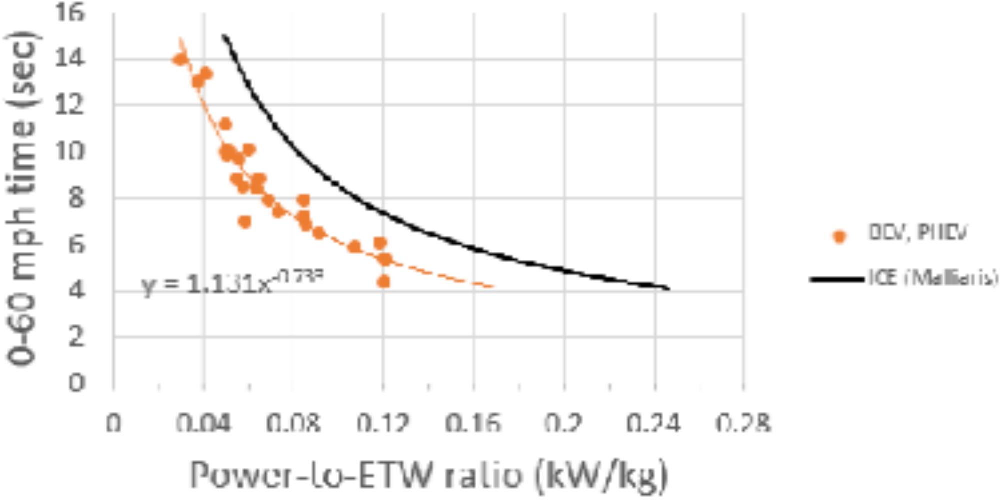
Battery sizing spreadsheet

- Determines kWh and kW for a given vehicle:
  - Curb weight is converted to kW by an empirical equation
  - Curb weight is converted to kWh/mi by another empirical equation
  - Estimates of kWh and kW are fed to BatPaC, which responds with an estimated kWh/kg
  - kWh/kg is used to estimate battery weight
  - The solution converges after dozens of iterations



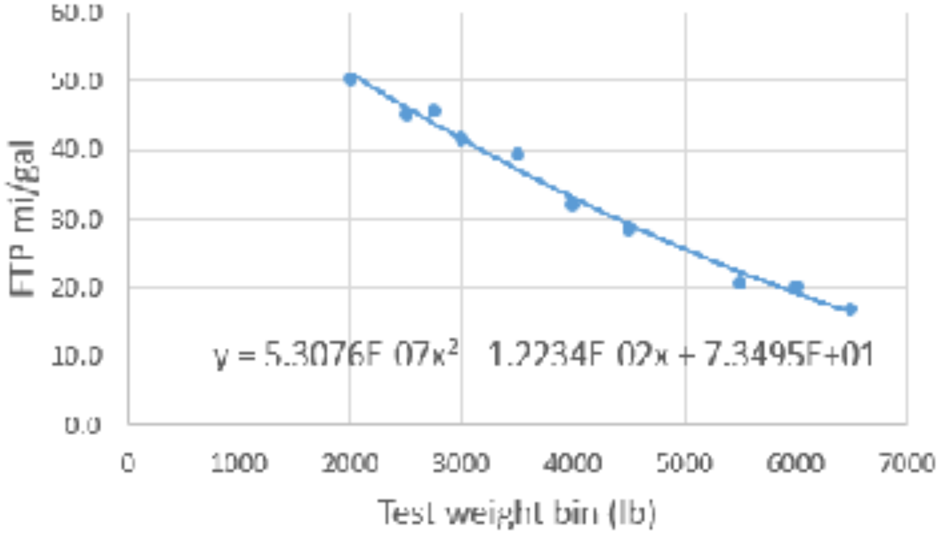
Converting curb weight to kW

- The propulsion motor is sized using an empirical equation that relates 0-60 time to rated peak motor power
- Battery peak power (10 s) is derived from motor power:
  - 10% is added for motor losses
  - Additional 20% for power fade
- Larger batteries usually exceed the specification due to their capacity
- These batteries should therefore support moderate levels of fast charging



Converting curb weight to kWh/mi

- We begin with a polynomial regression for ICE fuel economy (mi/gal) as a function of test weight
- ICE fuel economy is then converted to kWh/mi:
  - Assuming 33,700 kWh/gal
  - Applying factors representing relative efficiency of electric powertrain vs. ICE
  - Applying road load reduction due to reductions in aero and tire losses
- PEV kWh/mi can then be assigned as a function of test weight



Many other variables impact cost

- Driving range
- Range derating factor (for real-world range)
- Topology
  - Cell capacity
  - Cells per module
  - Parallel strings
  - Pack voltage
- Usable SOC window
- Thermal medium (liquid or air)
- Electrode dimensions (thickness, aspect ratio)

Driving range and derating factor

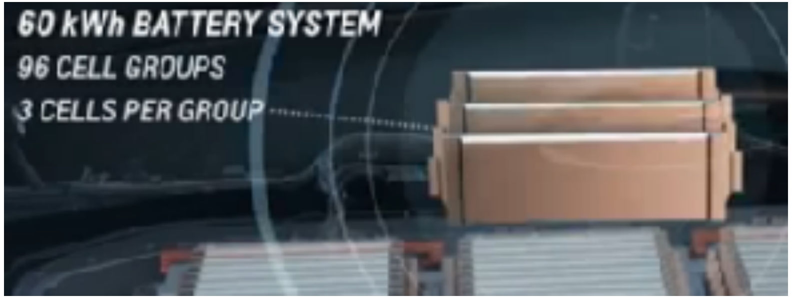
- BEVs were modeled with range of 75, 100, and 200 miles
- Range is an “EPA label” range computed by applying a derating factor to a combined test range (55/45 city/highway)
- For BEV75 and BEV100, derating factor is 70%
- For BEV200, derating factor is 75%
- Based on observed industry practice in certification process
  - Most manufacturers certify with default 70%
  - Longer range Tesla vehicles have used an optional procedure that equates to using 73-77%

Pack topologies are optimized

- For a given pack capacity (kWh), iterate all valid topology possibilities
    - Cells/module (20 to 40, even numbers)
    - Cells in parallel (1 to 4)
    - Modules per row (1 to 4)
    - Number of rows (1, 2, or 4)
- Each topology combination determines a cell capacity (A-hr) and pack voltage (V)
- Choose the topology that has a voltage and cell capacity nearest the target
    - Max cell capacity: BEV 90 Ah, PHEV 50 Ah
    - Pack voltage: ~ 300 V to 400 V

Other influential parameters

- Electrode aspect ratio 3:1
  - Automakers indicate trend toward flat, floor-mounted packs
  - Tabs on short dimension to minimize height (like Chevy Bolt)
- Electrode thickness <= 100 microns
- All packs liquid cooled
- Usable capacities
  - BEV200: 90%
  - BEV75/100: 85%
  - PHEV20/40: 65% - 67%



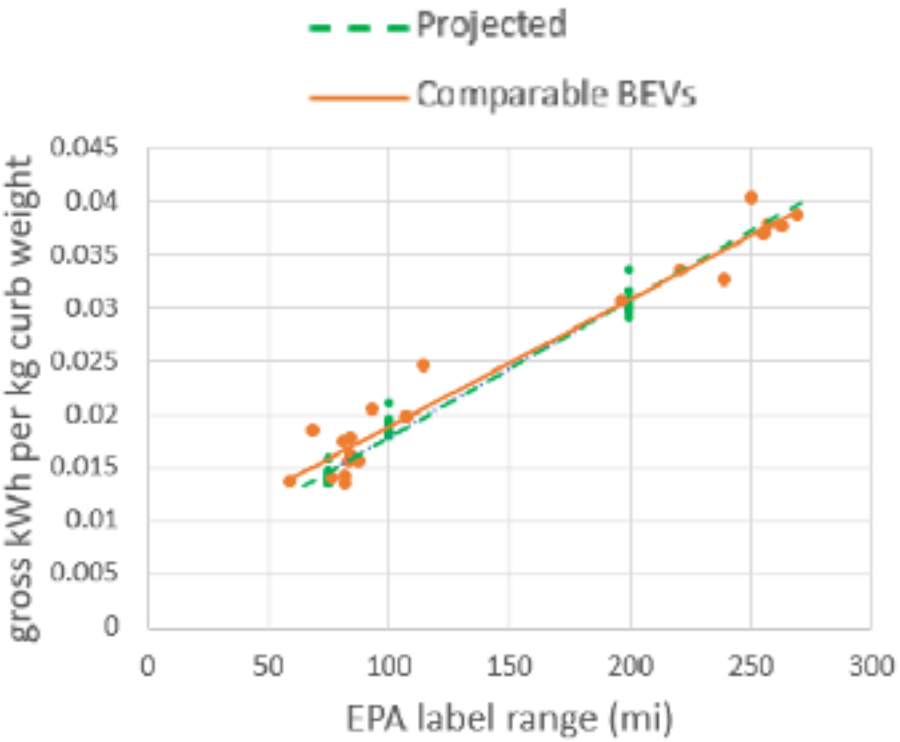
Trend toward flat, floor mounted packs using large, low-profile cells

Validation against specific BEVs

Example	Range (mi)	Curb weight (lb)	Derate factor	Gross kWh	EPA projected gross kWh	Error
Nissan Leaf	107	3340	0.70	30	30.3	1%
Chevy Bolt	238	3580	0.70	60	61.6	3%
Model S P85D	253	4963	0.738	85	88.75	4%
Model S 60	210	4323	0.796	60	57.5	-4%
Model S 85	265	4647	0.796	85	84	-1%

Validation against production BEVs

- When normalized to curb weight, the predicted battery capacities closely track comparable production BEVs
- The methodology is designed to expect slightly more improvement for shorter range BEVs
- Results are similar for PHEVs



Variability in cost per kWh is captured

	PHEV20	PHEV40	BEV75	BEV100	BEV200
CW Class 1	$371-$388	$250-$258	$205-$223	$173-$185	$145-$151
CW Class 2	$352-$365	$242-$251	$193-$211	$165-$177	$137-$144
CW Class 3	$337-$361	$237-$247	$186-$205	$159-$172	$133-$140
CW Class 4	$319-$346	$232-$246	$176-$204	$155-$165	$126-$134
CW Class 5	$277-$309	$227-$241	$160-$189	$146-$155	$115-$124

Comparison to Chevy Bolt costs

- Chevy Bolt = BEV238, 150 kW, 60 kWh, known topology
- GM publicized cell-level costs (not pack-level costs)
- If we can convert them to pack-level costs, we can make a qualified comparison to our projected BEV200 pack costs

BATTERY CELL COST

ABLE TO ACHIEVE LOWER COSTS EARLIER WITH MUCH LESS CAPITAL AND VOLUME DEPENDENCY

Projected Battery Cell Cost Glide Path

TODAY

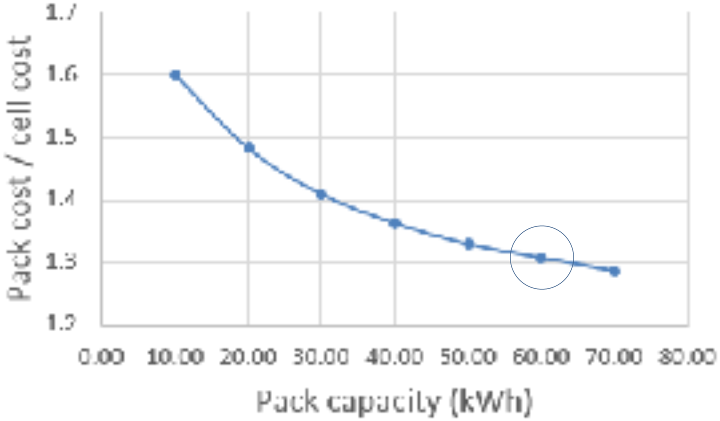
TOMORROW

> *Mark Reuss, GM: "When we launch the Bolt, we will have a cost per kWh of $145, and eventually we will get our cost down to about $100."*

- GM Global Business Conference, October 2015

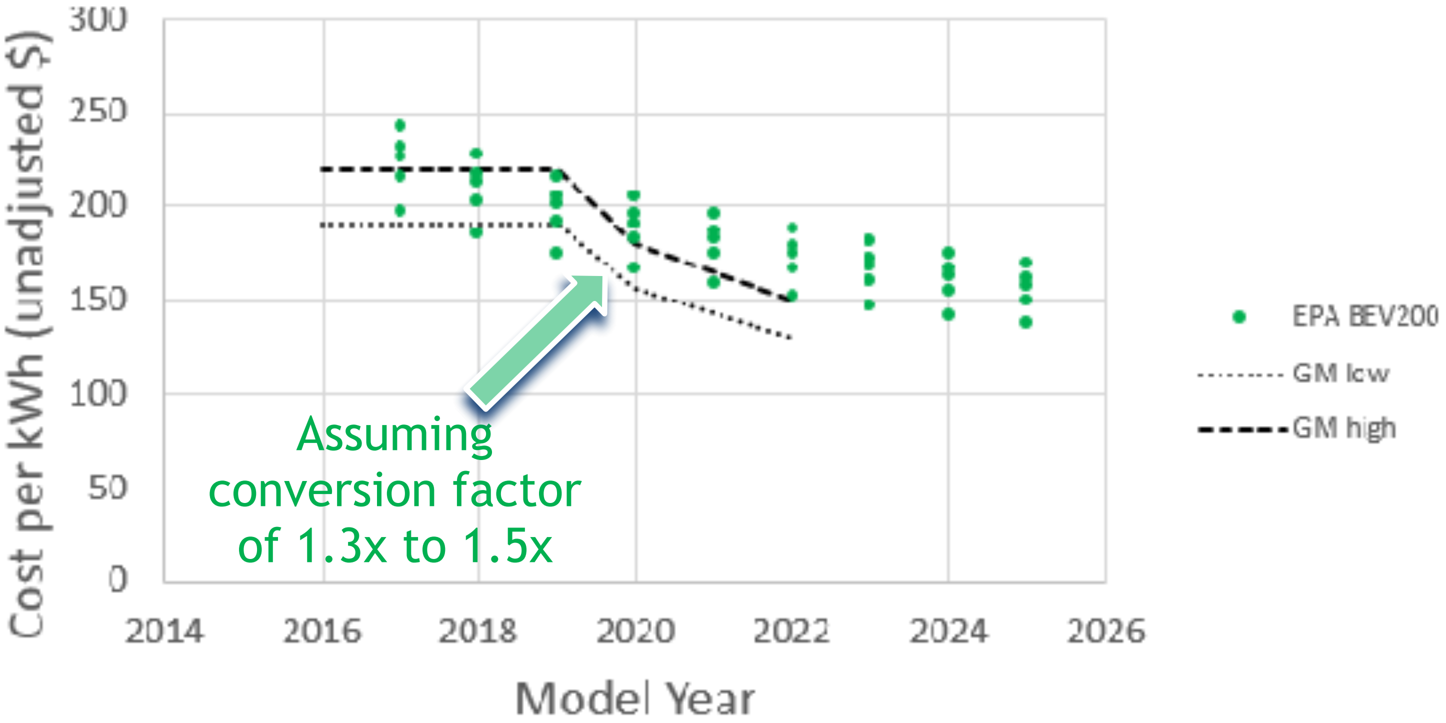
Converting cell cost to pack cost

- BatPaC suggests the ratio of pack cost to cell cost for a 60 kWh pack should be about 1.3
- The 2017 teardown of the Chevy Bolt by UBS suggests a ratio of about 1.44
- We will assume a ratio of 1.3-1.5



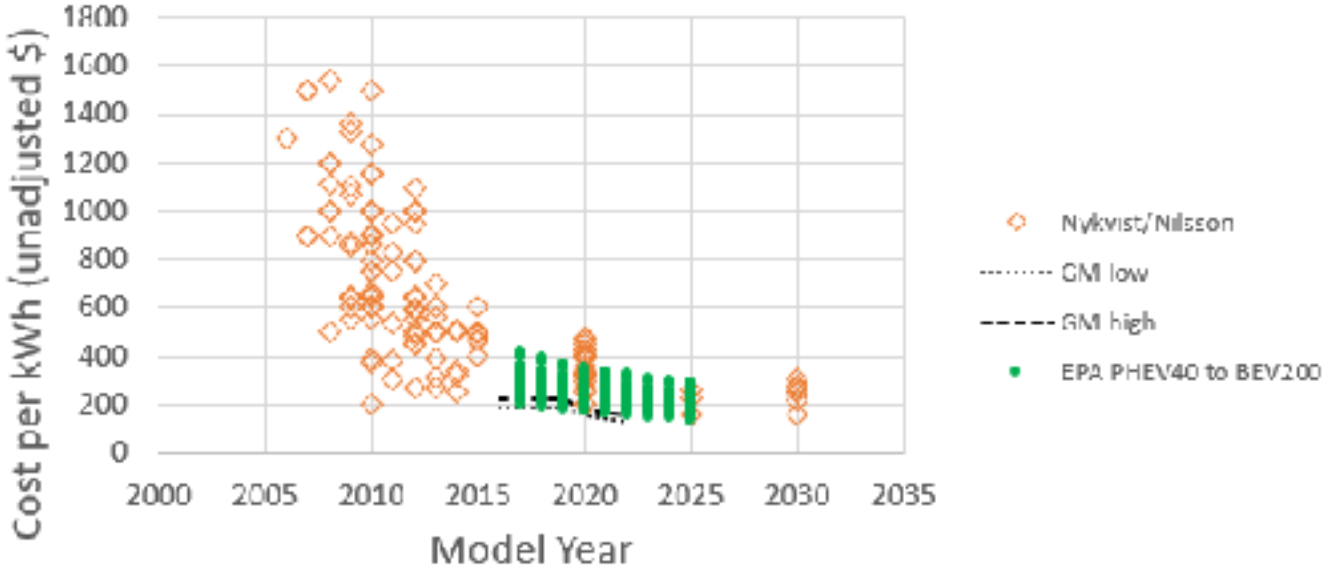
"UBS Evidence Lab Electric Car Teardown – Disruption Ahead?," May 18, 2017.

Comparison to estimated Bolt pack cost



Assuming conversion factor of 1.3x to 1.5x

Comparison to Nykvist & Nilsson



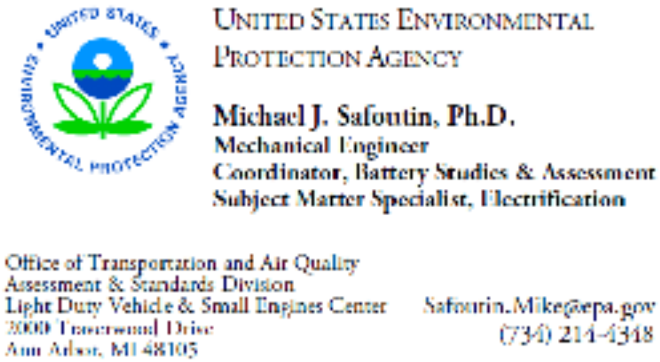
Nykvist, B. and Nilsson, M.; "Rapidly Falling Costs of Battery Packs for Electric Vehicles," Nature Climate Change, March 2015.

Ongoing work

- Battery technology continues to develop rapidly
- Our 2012 estimates went from being considered optimistic to being considered conservative
- We continually monitor trends and developments in the industry
- Our most recent estimates remain close to stakeholder consensus
- We have continued to assess new data and information that has become available this year
  - Plan to model 100, 150, and 200 mile driving ranges
  - New version of BatPaC includes updated material costs
  - Batteries will be designed for specific levels of DC fast charging
  - All non-battery costs have also been updated

Thank you

- For more information on the methodology, inputs, and data sources, see Chapters 2.2.4.5 and 2.3.4.3.7 of the Technical Support Document (TSD) for the 2016 Proposed Determination, EPA 420-R-16-021, November 2016.
- For information on the Midterm Evaluation, visit: https://www.epa.gov/regulations-emissions-vehicles-and-engines/midterm-evaluation-light-duty-vehicle-greenhouse-gas



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