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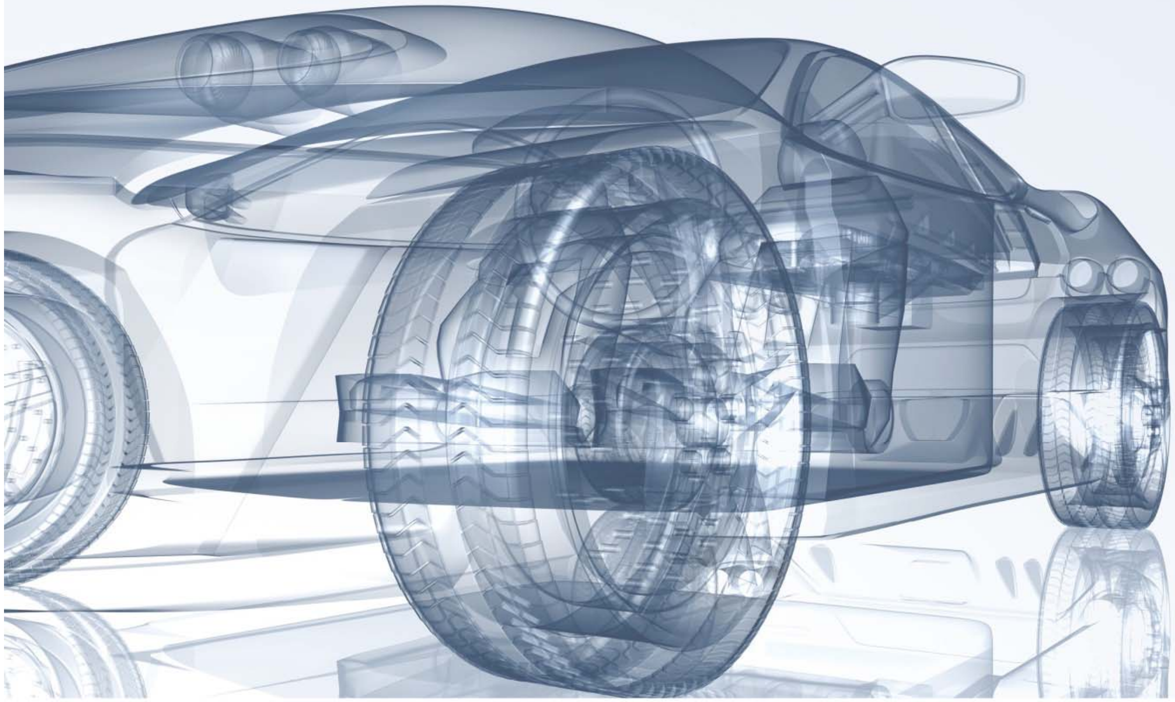

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Predicting the Future Manufacturing Cost of Batteries for Plug-In Vehicles

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

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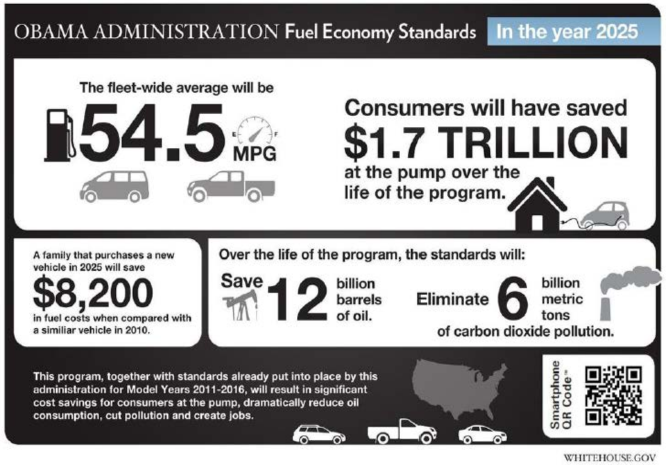
Agenda

- 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

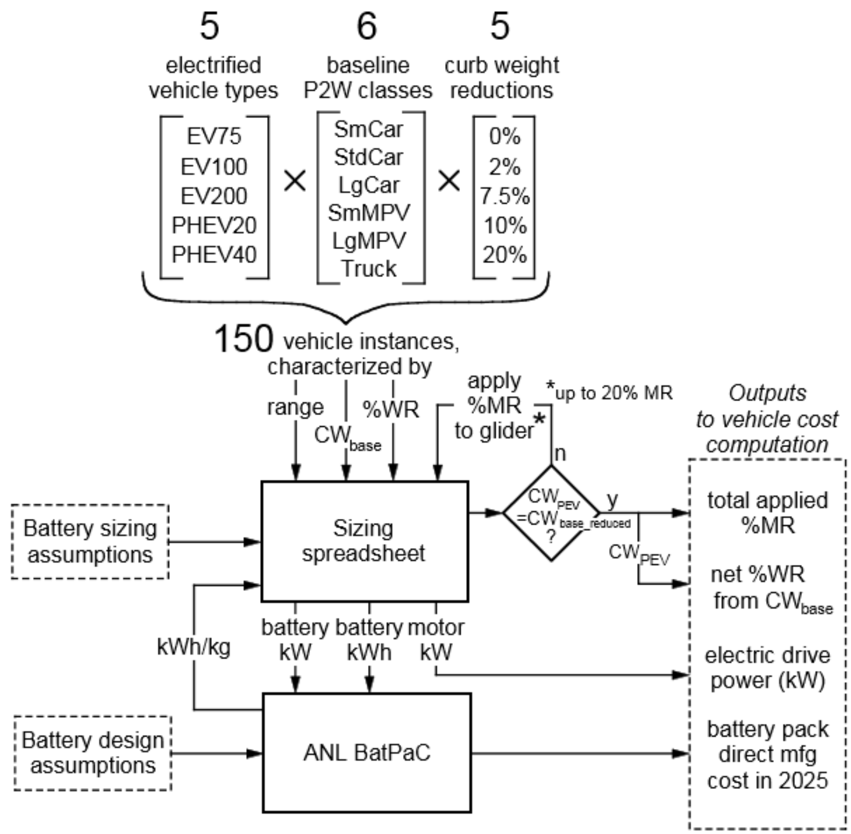


Battery cost modeling approach

1. Define a broad spectrum of PEVs representing the future fleet

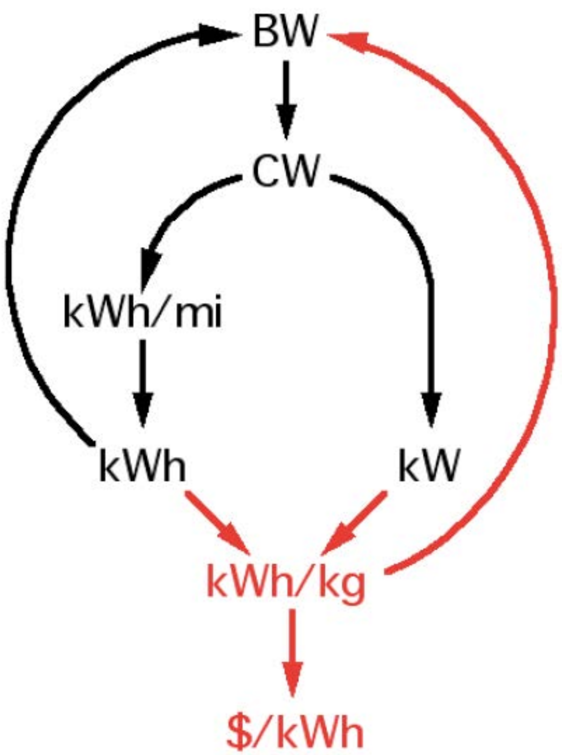
2. Determine required battery capacity and power for each

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*

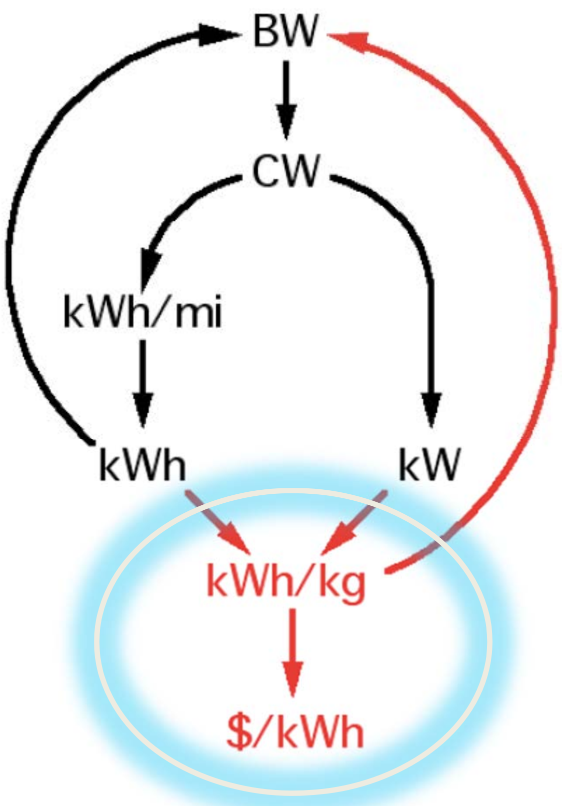


Goal: Avoid vulnerabilities, such as:

- 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

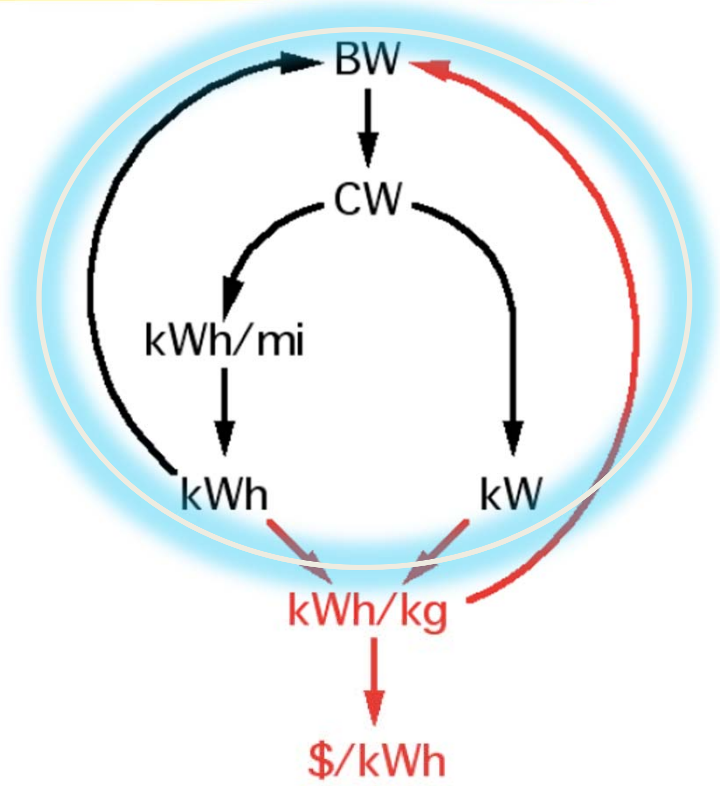
ANL BatPaC is a key component

- 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



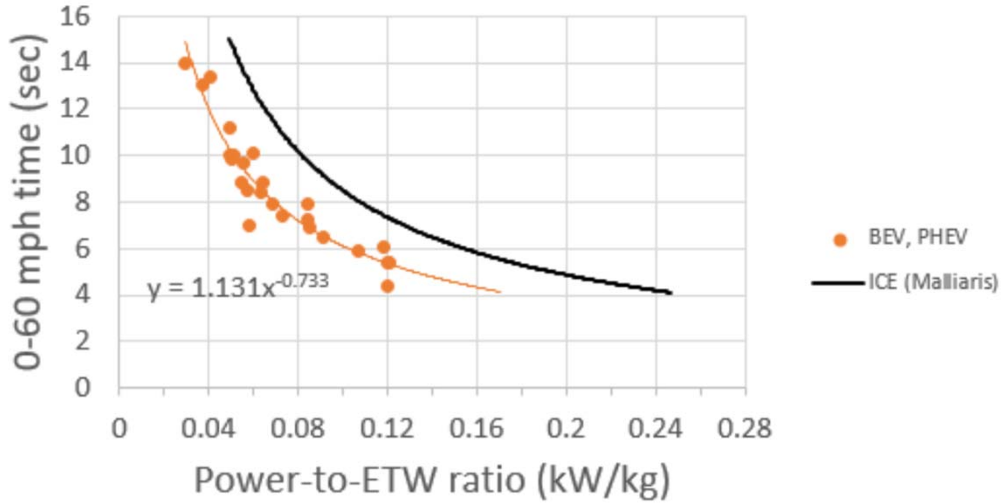
Battery sizing spreadsheet

- 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



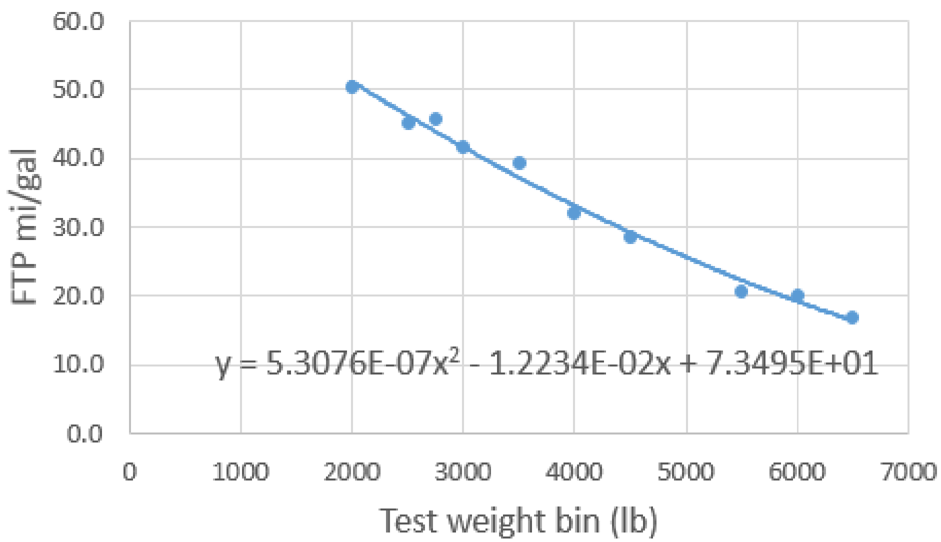
Converting curb weight to kW

- 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%

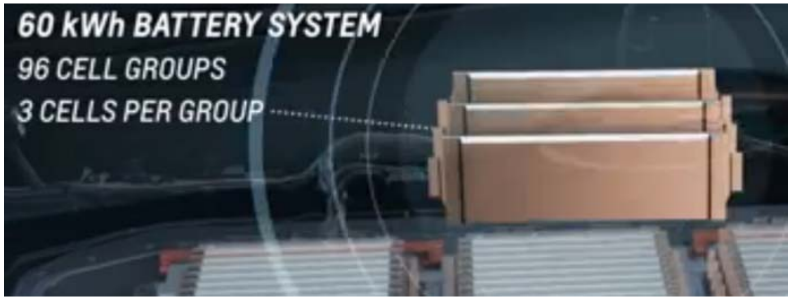
Pack topologies are optimized

- 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

```
while (i < num_kwh) do
begin
  min_error := 100000;
  cells_per_module := 20; //was 24
  while (cells_per_module <= 40) do  //was 36
  begin
    if ((cells_per_module/2) = (cells_per_module div 2)) then //even cells per module
    begin
      cells_in_parallel := 1;
      while (cells_in_parallel <= 4) do
      begin
        if (cells_per_module/cells_in_parallel = cells_per_module div cells_in_parallel) then
        begin
          modules_per_row := 1;
          while (modules_per_row <= 4) do
          begin
            rows := 1;
            while (rows <= 4) do
            begin
              if (rows <> 3) then
              begin
                //do stuff here
                ideal_cells := kwh[i]*1000/(cell_v*desired_ah);
                cells_per_pack := cells_per_module * modules_per_row * rows;
                ocv := cells_per_pack * cell_v / cells_in_parallel;
                cell_ah := kwh[i] * 1000 / cell_v / cells_per_pack;
                if ((ocv <= 400) and (ocv >= 300)) then
                begin
                  if (cell_ah <= maximum_ah) then
                  begin
                    //use this to get closest to max size
                    this_error := abs(maximum_ah - cell_ah);
                    if (this_error < min_error) then
                    begin
                      min_error := this_error;
                      bestyet_[i] := xSTR(kwh[i]) + ',' + xSTR(cells_per_module) + ',' + xSTR(cel
                    end;
                  end;
                end;
              end;
              inc(rows);
            end;
            inc(modules_per_row);
          end;
        end;
        inc(cells_in_parallel);
      end;
    end;
    inc(cells_per_module);
```

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%



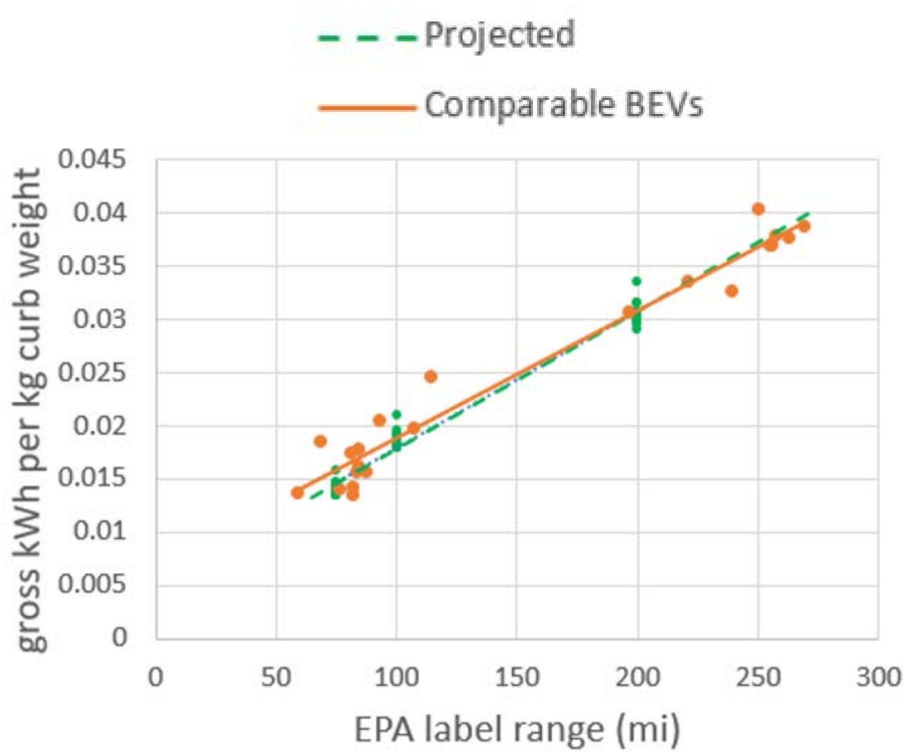
Trend toward flat, floor mounted packs using large, low-profile cells

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

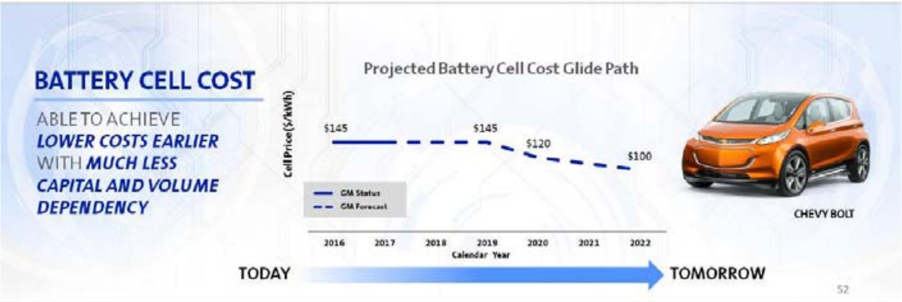


Variability in cost per kWh is captured

	PHEV20	PHEV40	BEV75	BEV100	BEV200
CW Class	$371-$388	$250-$258	$205-$223	$173-$185	$145-$151
CW Class	$352-$365	$242-$251	$193-$211	$165-$177	$137-$144
CW Class	$337-$361	$237-$247	$186-$205	$159-$172	$133-$140
CW Class	$319-$346	$232-$246	$176-$204	$155-$165	$126-$134
CW Class	$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

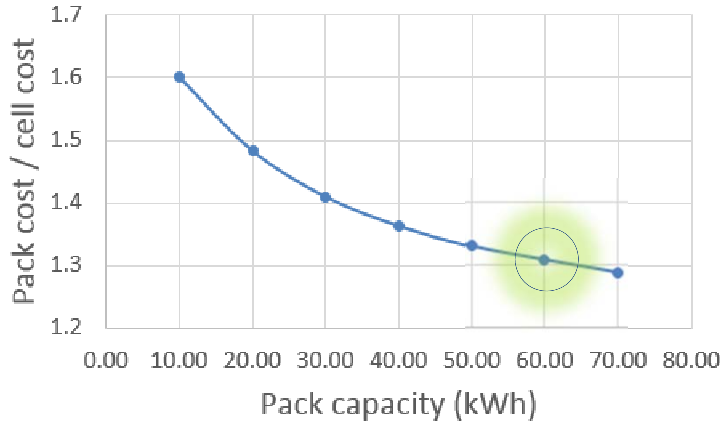


Mark Reuss, GM: "When we launch the Bolt, we will have a cost per kWh of $145, and eventually we will get our cost down to about $100."

- GM Global Business Conference, October 2015

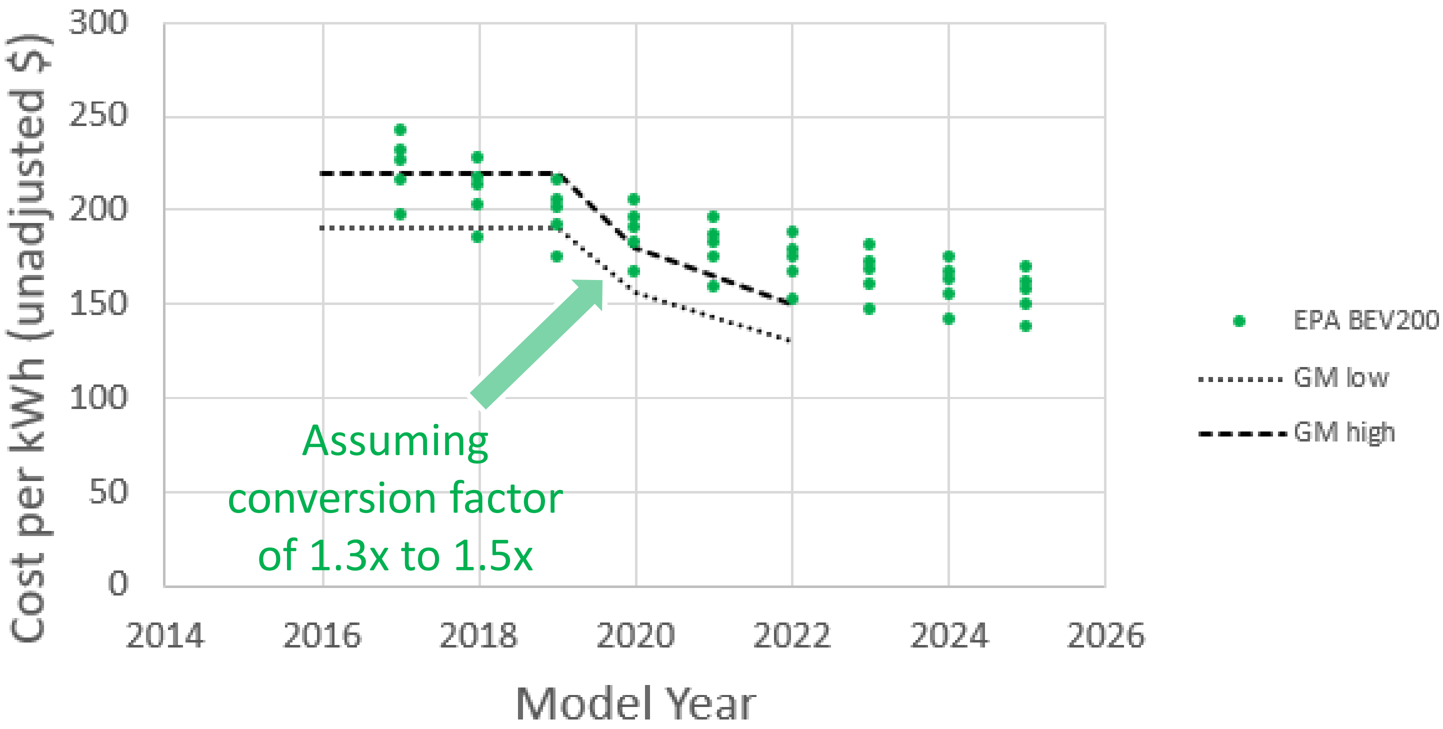
Converting cell cost to pack cost

- 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

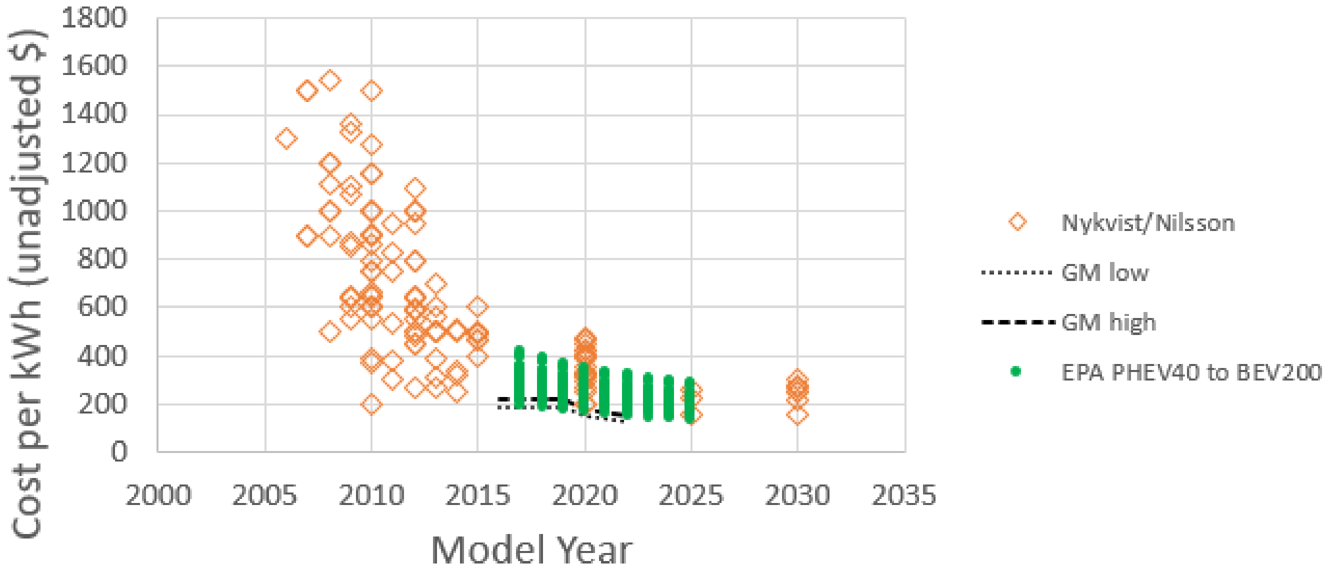


UBS "UBS Evidence Lab Electric Car Teardown – Disruption Ahead?," May 18, 2017.

Comparison to estimated Bolt pack cost



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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