total battery consulting

REPORT EXTRACT

Battery Packs of Modern xEVs

A Comprehensive Engineering Assessment

Report Outline

I. xEV Battery System Key Design Attributes

- **ESS Subsystem Development Areas**
  - Systems design & performance
  - Battery cell/module
  - Battery Management System (BMS) hardware
  - BMS software
    - Application software
    - Algorithms – SOC/SOH
    - Diagnostics/OBD2
  - Mechanical subsystem
  - Thermal subsystem
- **ESS Manufacturing & Quality**

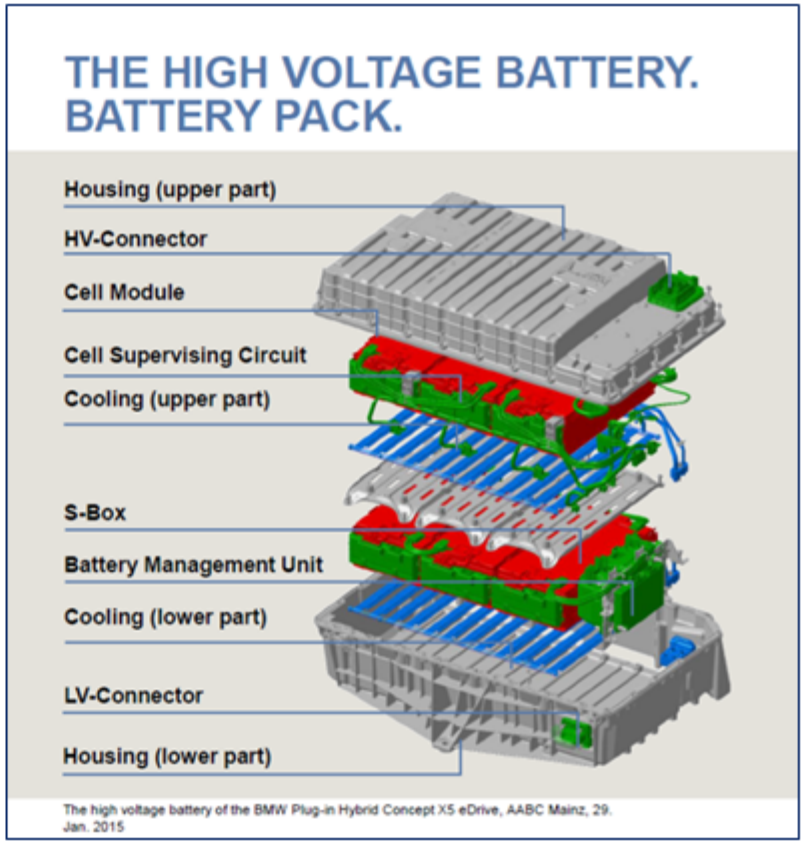


Image by BMW © BMW reserves all rights

Each subsystem has unique specifications along with analysis, design, and testing requirements

Usage Profiles – EV

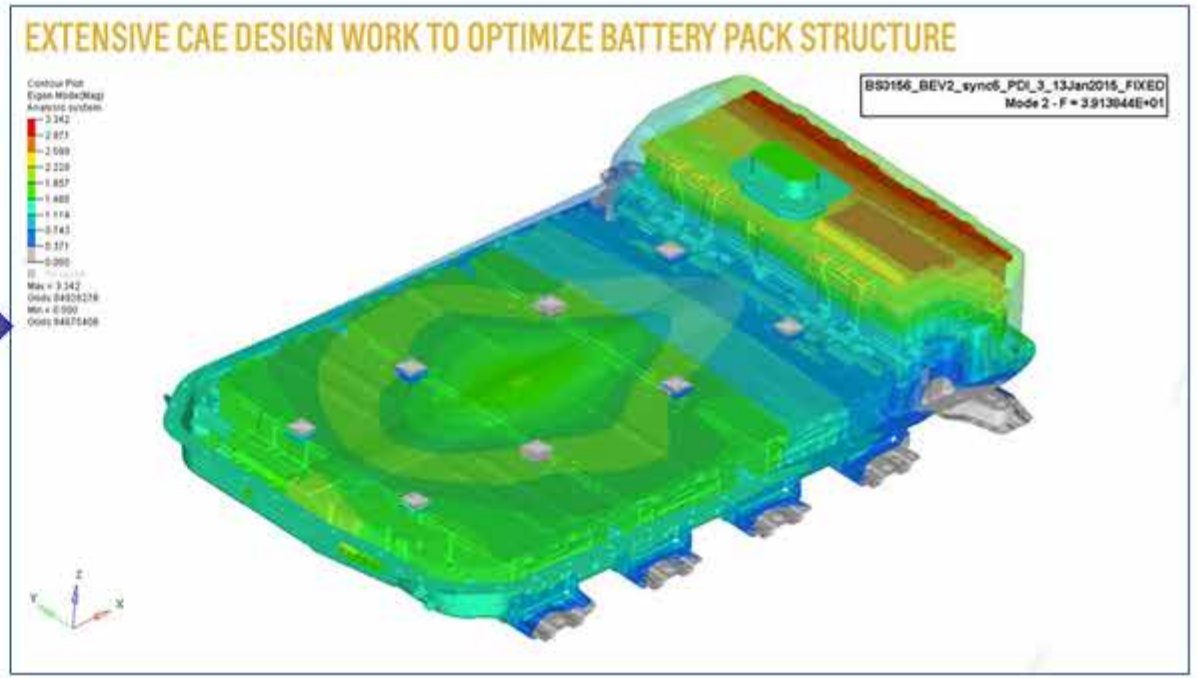
Usage Profiles

- **EV users vary by how deeply they discharge the battery before charging**
  - **EVs w/ large batteries require less cycle count capability than EVs w/ smaller batteries**
    - EV#1 w/ 100-mile range where the driver typically recharges @ 25% range remaining
      - 100,000 miles of vehicle application use = 1,333 75% DOD cycles for battery life
    - EV#2 w/ 200 mile range where the driver typically recharges @ 25% range remaining
      - 100,000 miles of vehicle application use = 667 75% DOD cycles for battery life
    - Note that testing should demonstrate higher capability in lab and in diverse conditions
- **6 key drive profiles per temperature profile**

Driver Usage Profile Matrix	Drive Profile Percentile	10% Drive-cycle (Highway Dominant)	50% Drive-cycle (Suburban Dominant)	90% Drive-cycle (Urban Dominant)
Charge Profile Percentile	Attributes	Longer-Duration Discharges Lower Peak Power	Blended Peaks & Durations	Frequent Chrg/Dischrg Pulses Higher Peak Power
10% Charger (moderate)	Partial-Discharge Cycle Dominant	EV Usage Profile #1	EV Usage Profile #2	EV Usage Profile #3
90% Charger (frequent)	Large-Discharge Cycle Dominant	EV Usage Profile #4	EV Usage Profile #5	EV Usage Profile #6

- CD – Charge Depleting (i.e. electric vehicle mode driving)
- CS – Charge Sustaining (i.e. "engine-on" hybrid driving)
- Testing should be considered at 3 different temperature profiles (cold, nominal, & hot climates)
- Mountain drive profile also to be considered

- **Mechanical Subsystem Requirements Drivers Include:**
  - Structural (i.e. crash integrity, higher-level product mechanical structure)
  - Environmental durability (i.e. shock, vibration, drop, etc.)
  - Mechanical abuse (i.e. road debris impact)
  - Mass targets
  - Packaging volume
  - EMI/EMC
  - NVH
  - Thermal system integration (i.e. insulation requirements)
  - Safety/ASIL targets
  - Cost targets
  - Quality targets

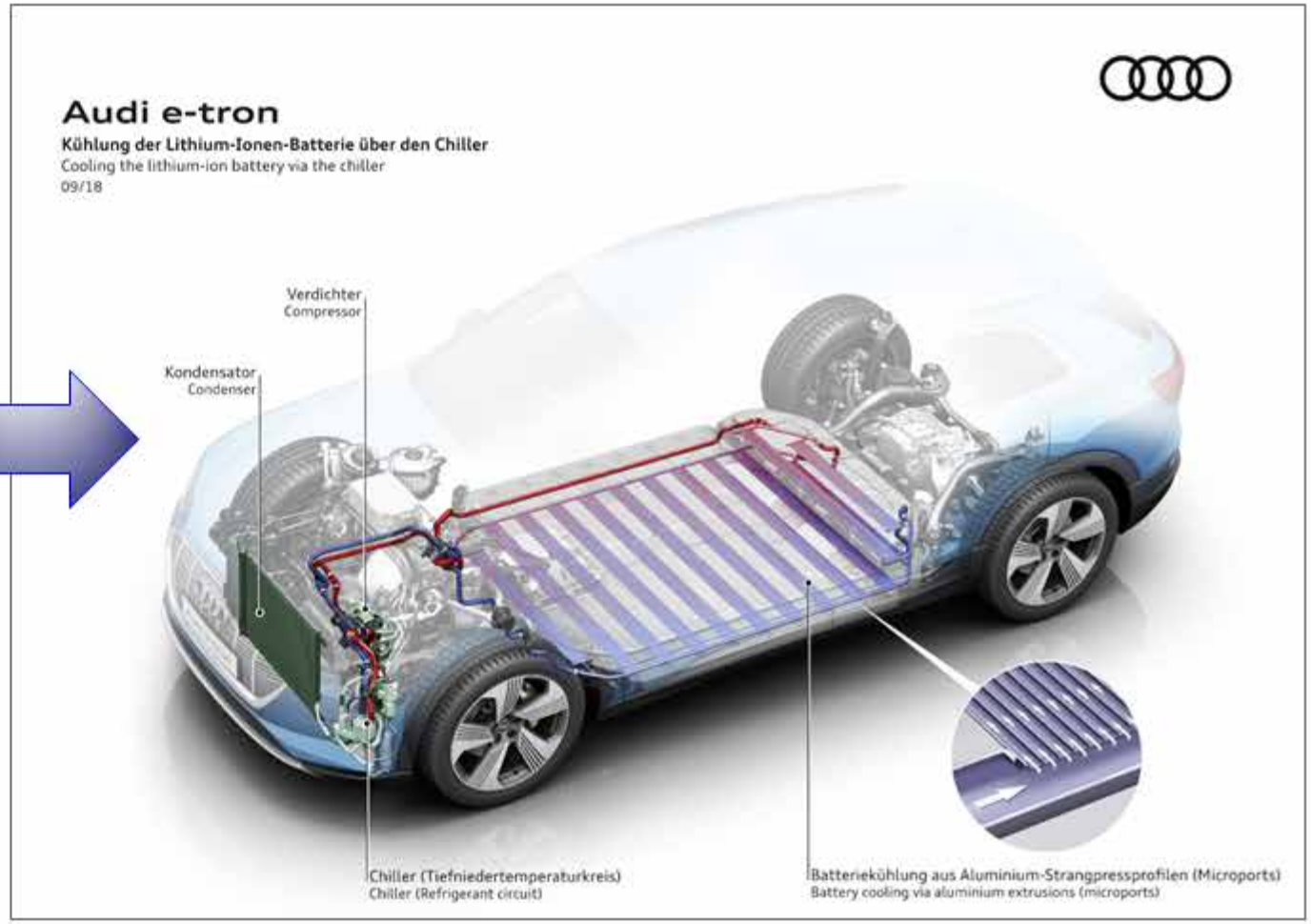


Chevy Bolt Battery Pack

Image by GM: © GM reserves all rights

Mechanical Subsystem

- **Thermal Subsystem Requirements Drivers Include:**
  - Drive-cycle heat rejection
  - DC Fast-charge heat rejection (if DCFC is part of the system)
  - Cold temperature functionality (i.e. battery heating, if required)
  - Environmental durability (i.e. shock, vibration, drop, etc.)
  - System efficiency and power budget
  - Mass targets
  - Packaging volume
  - NVH
  - Mechanical system integration (i.e. insulation requirements)
  - Safety/ASIL targets
  - Cost targets
  - Quality targets



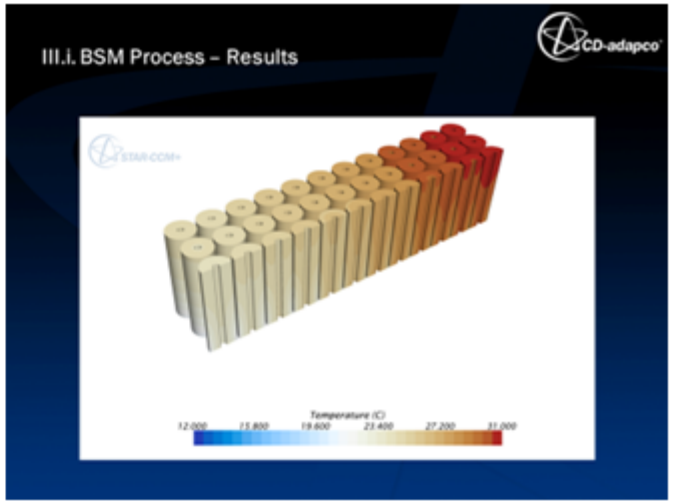
Audi e-tron Battery Pack

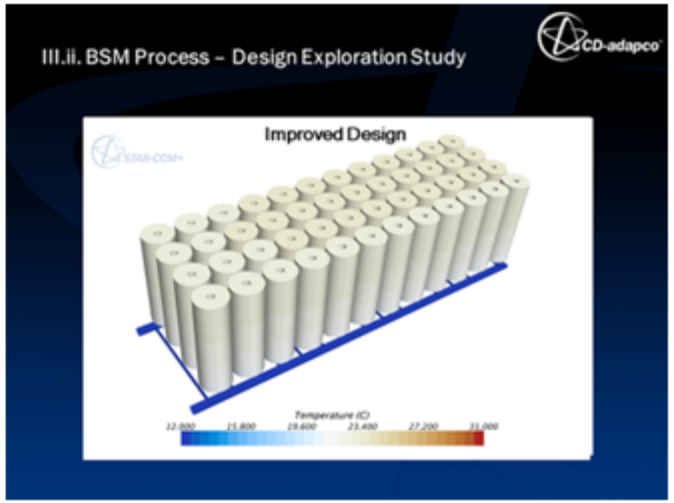
Image by Audi: © Audi reserves all rights

Thermal Subsystem

Thermal System

- **Thermal subsystem removes heat from the battery cells and is measured by 4 key metrics**
  - ***Tmax*** – Maximum cell temperature during drive, charge and rest
  - ***DT pack*** – Delta temperature from highest temperature cell to lowest temperature cell
  - ***DT intracell*** – Delta temperature within a single cell
    - Thermal system can impact, but is limited by, cell design
  - ***Trise*** – Temperature rise in highest cell temperature from coolant media temperature
- **Thermal subsystems may also need to protect the ESS from ambient and external heat sources (based on application and installation environment)**
- **Thermal system should be evaluated w/ the following minimum test conditions**
  - Continuous drive-cycle at nominal application RMS power until thermal steady-state to verify that the system is a controllable system
  - 50th and 90th percentile drive tests
    - Should be run and tmax and DT should be evaluated to verify that the target life is achievable
  - ***Application Example***: Consider multi-segmented drives in cold ambient and the effect on ESS thermal w/ cold ambient on heated ESS



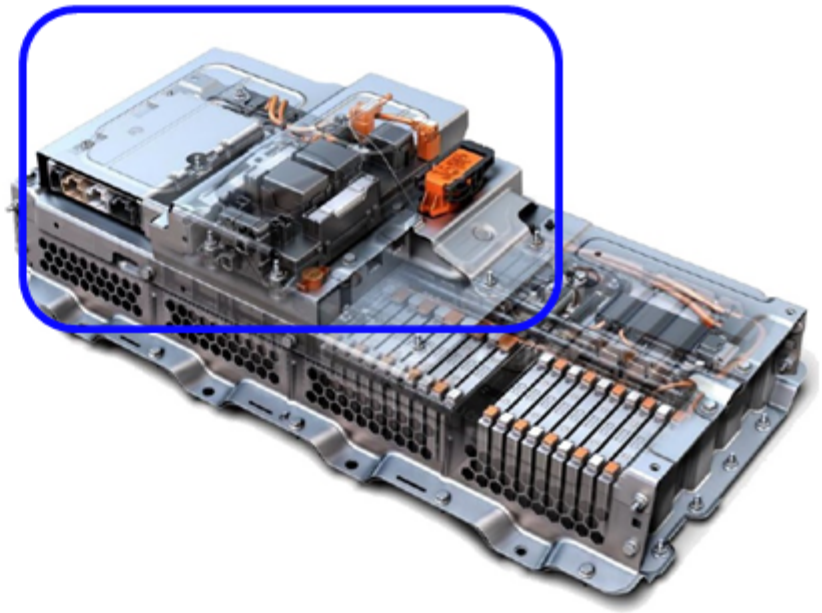


CD-Adapco Simulation Software © CD-Adapco reserves all rights

BMS Subsystem

BMS Subsystem Requirements Drivers Include:

- Vehicle and other controller interface (physical lines and CAN messaging)
- Algorithm targets and accuracy (i.e. SOC/SOH/SOP)
- Cell balancing targets
- Pre-charge and contactor control
- Fusing
- Environmental durability (i.e. shock, vibration, drop, etc.)
- EMI/EMC
- System efficiency and power budget
- NVH (i.e. contactor closure sound)
- Packaging volume (i.e. centralized/distributed; circuit-card size)
- Mechanical system integration (i.e. module mounting for distributed circuit-cards; wire/cable routing)
- Safety/ASIL targets
- Cost targets
- Quality targets



Chevy Malibu Hybrid Battery Pack

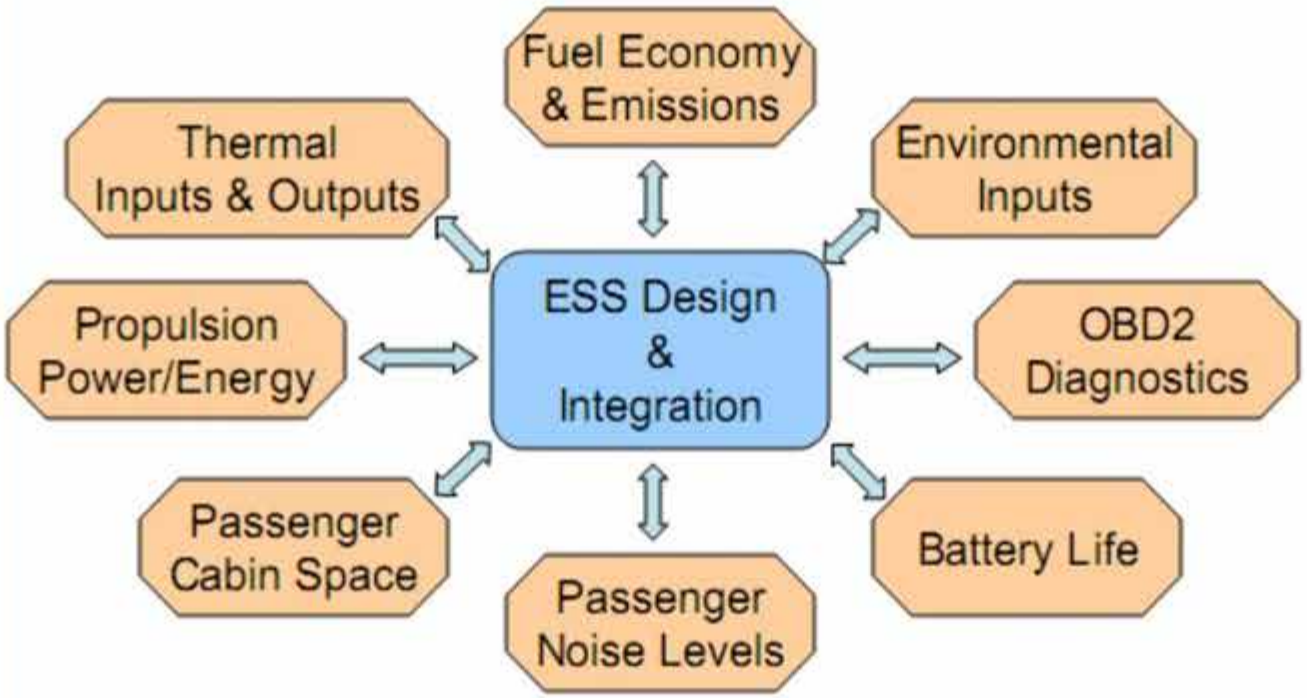
Image by GM: © GM reserves all rights

Thermal Subsystem

BMS Software

- **A typical Battery Management System (BMS) contains a software package that is comprised of the following components**
  - ***Application Software***
    - Main controlling software
    - I/O processing
    - CAN communication
    - Relay control (if included in system)
    - Fault handling
  - ***Algorithm Suite***
    - State-of-charge (SOC) – determination of the remaining capacity of the ESS
    - State-of-health (SOH) – determination of the remaining life of the ESS (required if OBD2, may be optional otherwise – OEM dependent requirement)
    - Power/current available – algorithm to communicate to main controller the ESS's current state and available charge/discharge power
  - ***Diagnostics***
    - OBD2 (US), if required (regulated)
    - Additional diagnostics (unregulated) for operation & service
- **Drivers & low-level software operate below the above**

System Integration



ESS Integration Must Be Achieved While Meeting Multiple Requirements and Balancing Multiple Inputs & Outputs

Image by GM © GM reserves all rights - http://media.gm.com

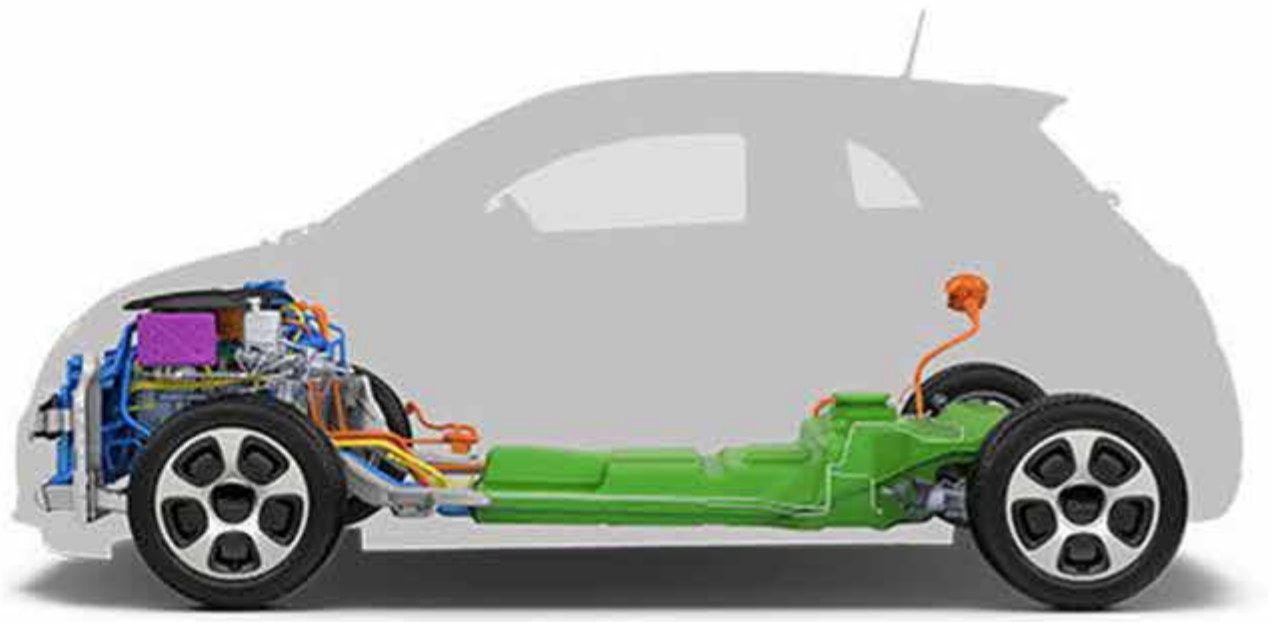


Image by FCA © FCA reserves all rights - http://www.fiatusa.com/en/500e/

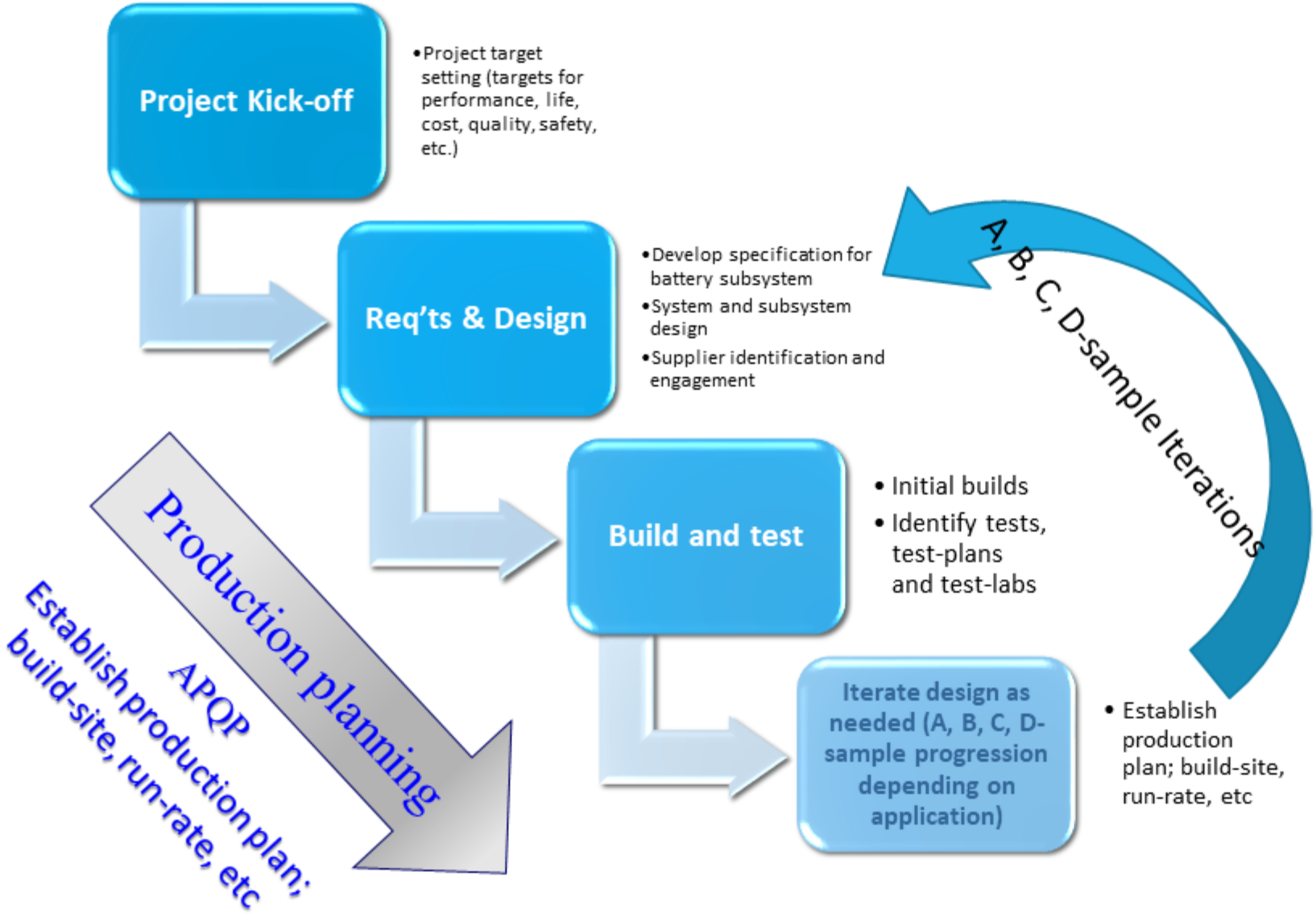
Design Example: EVs

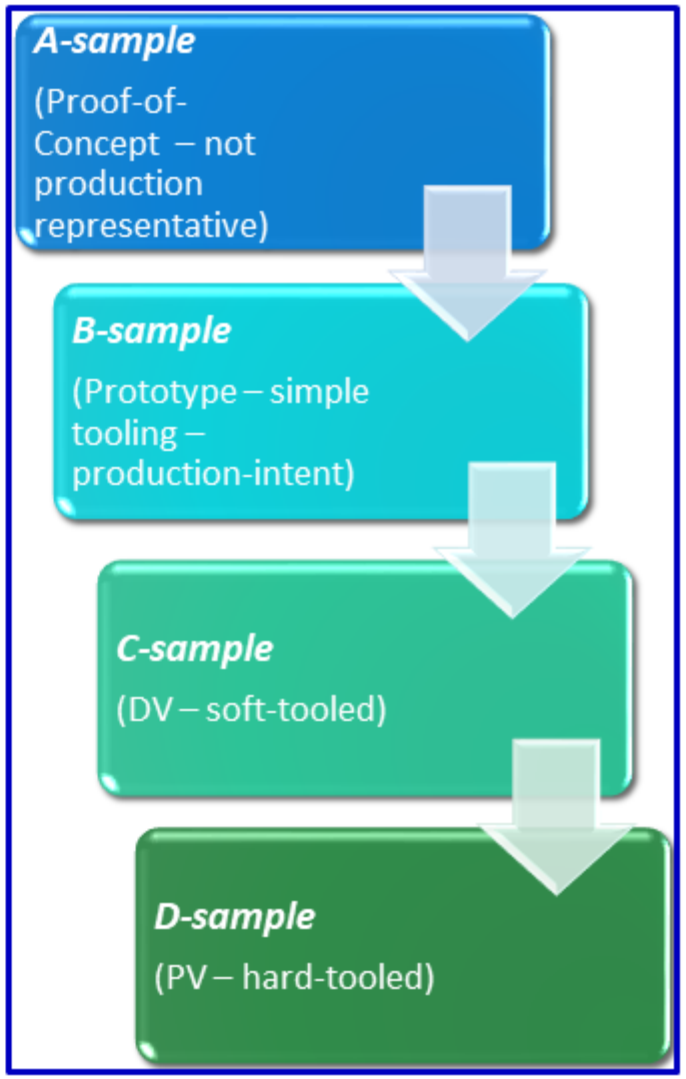
How can safety hazards occur after production starts?

- Manufacturing defect
- Latent design flaw (not present at BOL)
- Aging effects not fully studied/characterized
- Unforeseen or untested usage application
- Improper usage
- Abnormal/abusive usage
  - From poor control systems, algorithm errors or component failure
- Natural disasters (hurricanes, floods, tornados)
- Integration issue

Image by GM © General Motors reserves all rights

Product Development Plan





Report Outline

I. xEV Battery System Key Design Attributes

II. Battery Packs for EVs

III. Battery Packs for PHEVs

IV. Battery Packs for HEVs

V. Charging Systems of EV/PHEVs

EVs DISCUSSED IN THIS SECTION

- 2014-19 BMW i3 BEV
- 2012-15 BYD e6 (60 kWh)
- 2016 BYD e6 (80 kWh)
- 2014-17 Daimler Mercedes B250e
- 2019 Daimler EQC (*)
- 2013-18 Daimler Smart Fortwo
- 2013-19 Fiat 500e EV
- 2012-18 Ford Focus EV
- 2014 Chevrolet Spark EV (A123)
- 2015-16 Chevrolet Spark EV (LG)
- 2017-19 Chevy Bolt
- 2013-14 Honda Fit EV
- 2017-19 Hyundai Ioniq Electric
- 2019 Hyundai Kona Electric (*)
- 2019 Jaguar i-Pace (*)
- 2015-20 Kia Soul EV (*)
- 2019 Kia Niro Electric (*)
- 2012-16 Mitsubishi iMiEV M-grade
- 2012-17 Mitsubishi iMiEV World
- 2011-16 Nissan Leaf (24kWhr)
- 2016-17 Nissan Leaf (30kWhr)
- 2018-19 Nissan Leaf (40kWhr) (*)
- 2011-15 Renault Kangoo EV
- 2012-19 Renault Zoe EV
- 2017-19 Tesla Model 3 (*)
- 2012-19 Tesla Model S
- 2016-19 Tesla Model X
- 2012-14 Toyota RAV4 EV
- 2019 Audi e-Tron (*)
- 2015-19 Volkswagen e-Golf
- 2013-17 Volkswagen e-Up!

(*) *New/updated model in 2019 Battery Packs of Modern xEVs Report*

Battery Pack Capacity Diversity

Large diversity of battery-pack sizes and e-range

- Tesla offers largest battery packs
- Average battery size is 48 kWh
- Note:
  - Tesla Model X packs are not shown as duplicates w/ Model S
  - Kia Niro packs are not shown as duplicates w/ Hyundai Kona

Pack Capacity Distribution (kWh)

Min = 7
Ave = 48
Max = 100
Median = 40

ESS Specific Energy

Battery Pack Specific Energy Diversity

- Large range of 57.5 to 168 Wh/km
- Lowest are packs w/ LTO-based power cells
- Highest are packs w/ NMC (Ni-rich) & NCA energy cells
- Tesla Model 3 pack achieves the highest value

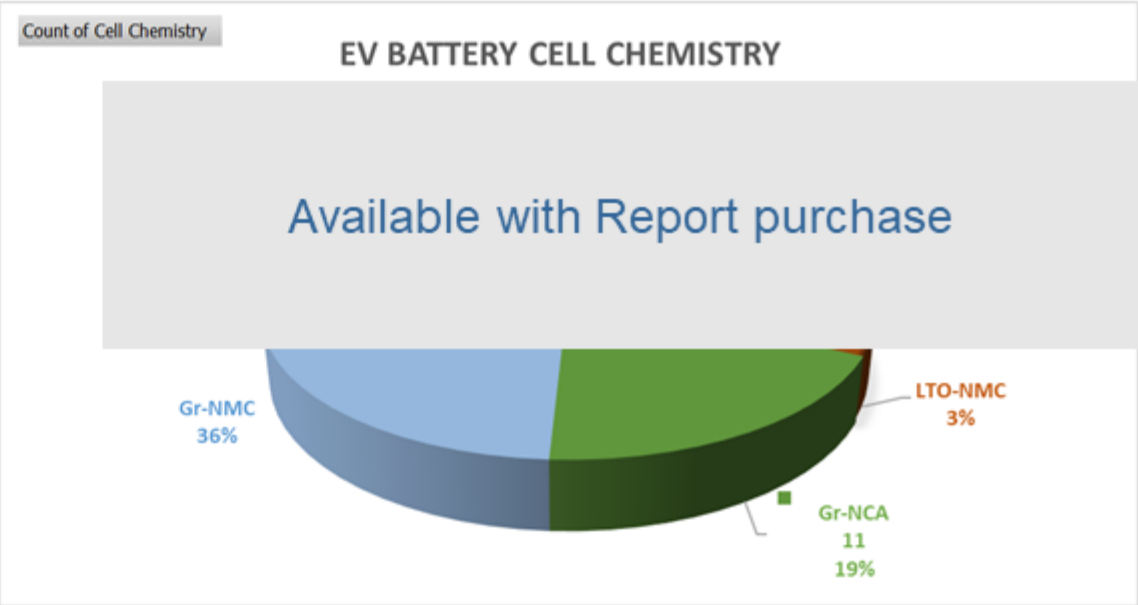
ESS Specific Energy Distribution (Wh/kg)
Min = 57.5
Ave = 113.0
Max = 168.0
Median = 109.0

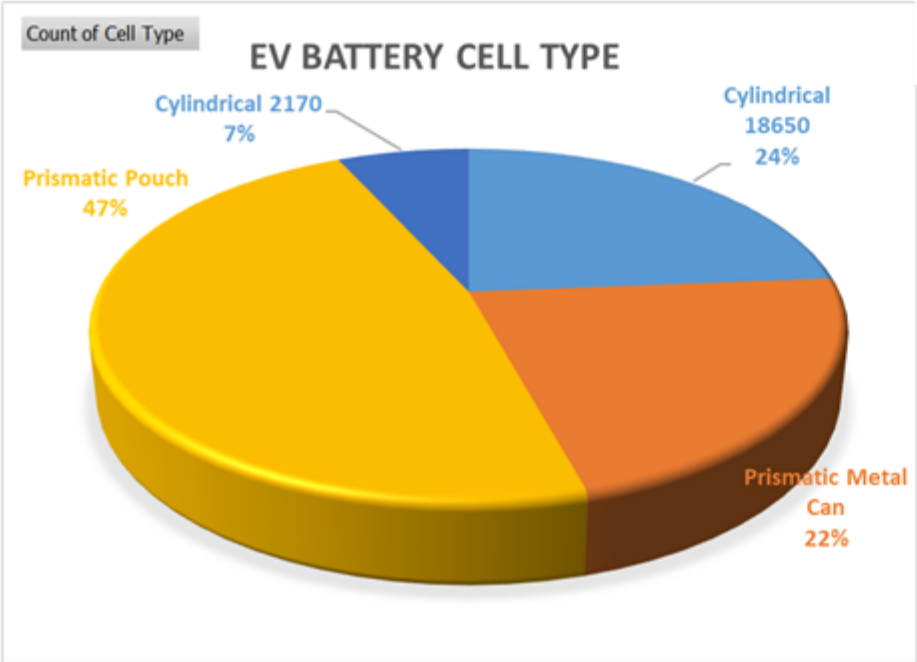
Battery Cell Type & Chemistry

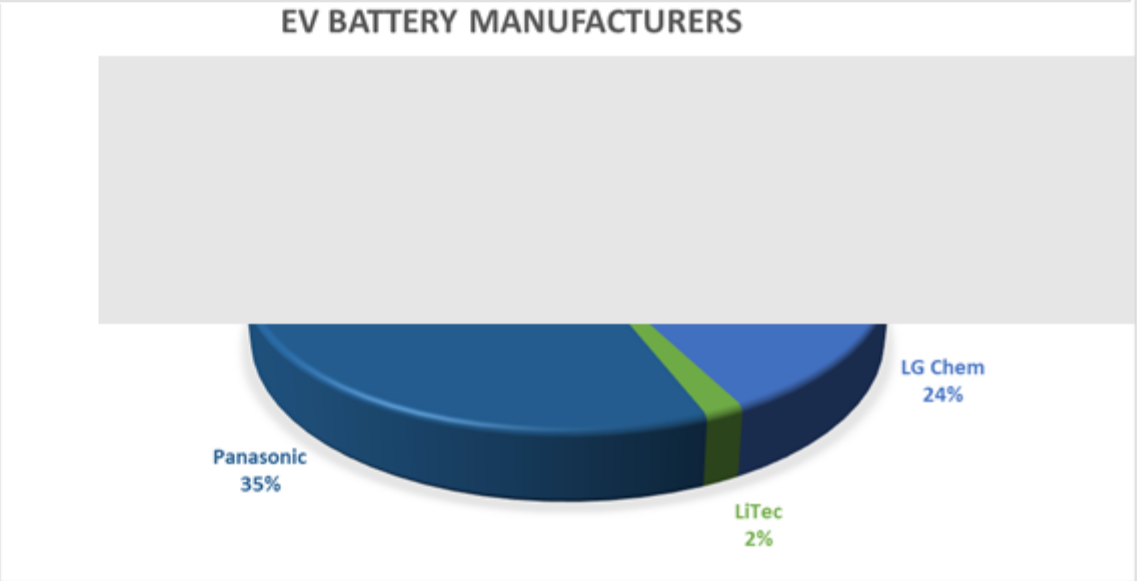
Battery Cells Implemented in Production EVs

- Cell types are split between cylindrical, prismatic pouch, and prismatic metal can
- Battery cell chemistries are split between multiple Li-Ion chemistries
  - NCA is used across the multiple Tesla models and tesla-designed packs (Toyota RAV4 & Daimler partnerships)

Note: Percentages based on vehicle iteration/generation (not sales volume)







Battery Cell Parameters

(not actual cell, but representative type & form factor)
Image by LG Chem © LG Chem reserves all rights

Parameter	Value
Cell Supplier	LG Chem
Cell Type	Prismatic Pouch
Anode Chemistry	Graphite
Cathode Chemistry	NMC (622)
Cell Capacity (Ah)	63
Cell Voltage (V)	3.65
Weight (g)	965
Dimensions (mm)	11.5 x 125 x 325 (est)
Volume (mL)	467
Specific Energy (Wh/kg)	242
Energy Density (Wh/L)	499
Specific Power (W/kg) (10sec. discharge)	n/a

** Estimated and assumed cell parameters*

Battery Pack Parameters

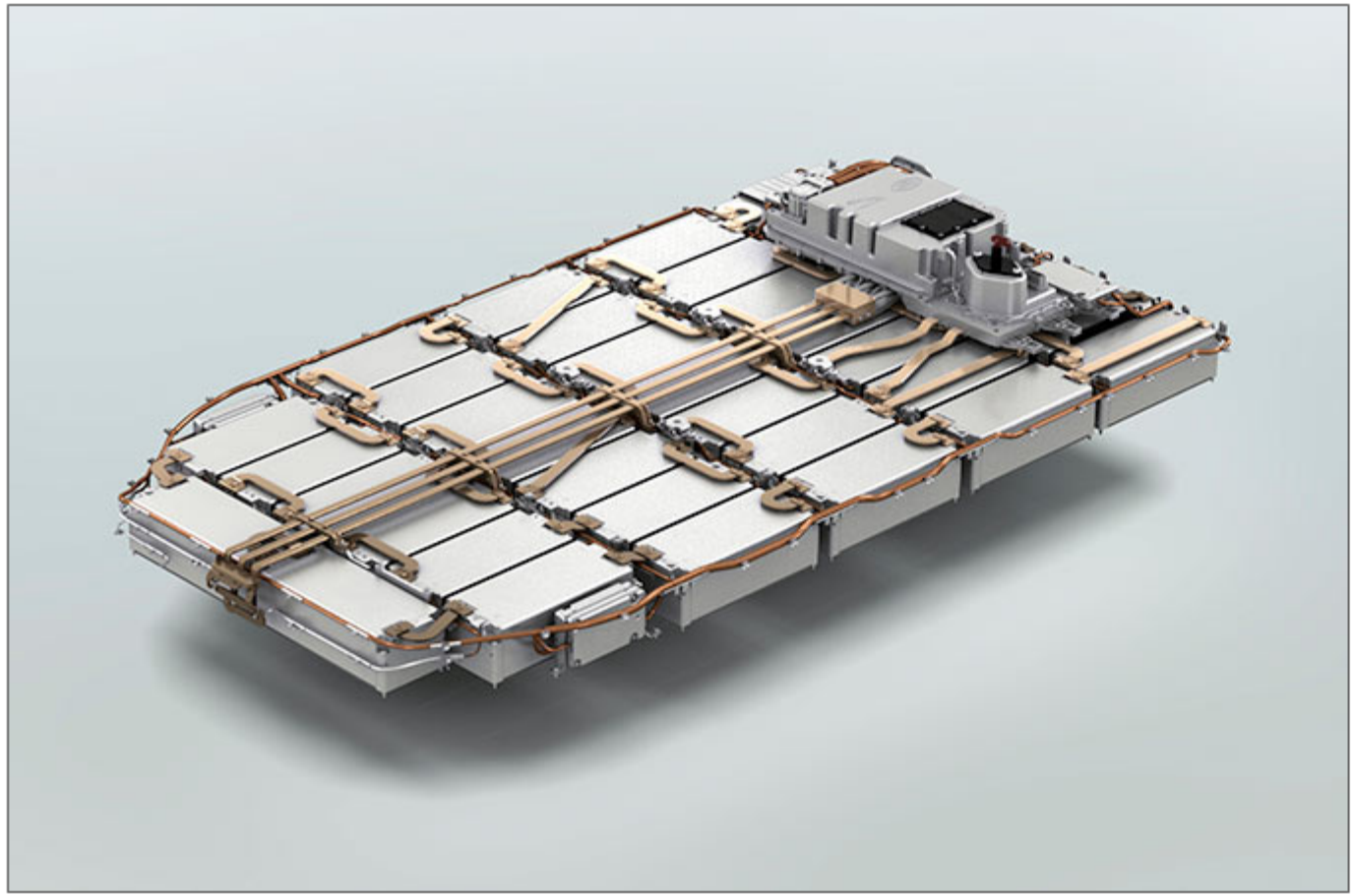
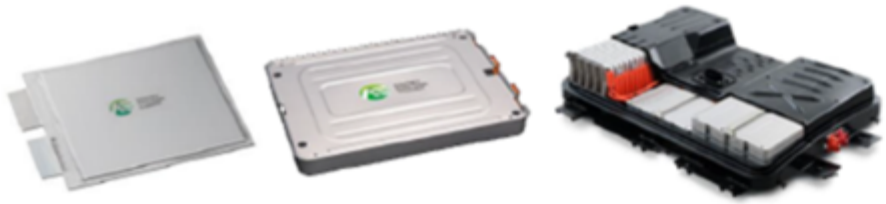


Image by Jaguar © Jaguar reserves all rights

ESS Parameter	Value
Pack Integrator	Jaguar/Williams
Configuration	108s4p
Voltage (V nominal)	396
Peak Power (kW)	294
Energy (kWh)	90
P/E Ratio (kW/kWh)	3.3
Mass (kg)	603
Specific Energy (Whr/kg)	149.3
BMS Type	Distributed
Thermal System	Liquid
Enclosure Material	Metallic

AESC Li-ion Battery for LEAF



40 kWh LEAF

62 kWh LEAF e-Plus

ESS Parameter	2011-16 (24kWh)	2016-17 (30kWh)	2018-19 (40kWhr)	2019 (62kWhr)
Pack Integrator	AESC	AESC	Nissan	Nissan
Configuration	96s2p	96s2p	96s2p	96s3p
Voltage (V nominal)	355	355	360	360
Peak Power (kW)	>90	>90	110	160
Energy (kWh)	24	30	40	62
P/E Ratio (kW/kWh)	3.8	3.0	2.8	2.6
Mass (kg)	273	294	295 (est)	437 (est)
Specific Energy (Wh/kg)	87.9	102	135.6	141.8 (est)
BMS Type	Distributed			
Thermal System	Convection			Air
Enclosure Material	Metallic			

Top: Image by AESC © AESC reserves all rights
Middle: Image by Nissan © Nissan reserves all rights
Bottom: Image by Nissan © Nissan reserves all rights
https://www.youtube.com/watch?v=mcfXiNEfPsM

Battery Pack Parameters

Images by Renault:© Renault reserves all rights

ESS Parameter	12-13	14-16	2017
Pack Integrator	Renault		
Configuration	96s2p		
Voltage (V nominal)	360		
Peak Power (kW)	80		
Energy (kWh)	25.6 (total) 22 (usable)	25.6 (total) 23.3 (usable)	45 (total) 41 (usable)
P/E Ratio (kW/kWh)	3.6	3.4	1.95
Mass (kg)	280	280	300
Specific Energy (Wh/kg)	78.6	83.2	136.7
BMS Type	Distributed		
Thermal System	Air		
Enclosure Material	Metallic		

Battery Pack Parameters

Image by Tesla © Tesla reserves all rights

- *Note: A 40-kWh version was offered to early deposit holders, but was physically a 60-kWh pack software limited to 40 kWh*
- *Original 60-kWh battery option is now obsolete*
- *Newer 60-kWh battery was physically a 75-kWh battery software limited to 60 kWh*

ESS Parameter	60 60D	70 70D	75 75D	85 85D P85D	90D P90D	100D P100D
Pack Integrator	Tesla					
Configuration	84s74p (est)			96s74p		96s86s
Voltage (V nominal)	302.4V (est)				345V	
Peak Power (kW)	235 245			278 311 345	311 345	311 451
Energy (kWh)	60	70	75	85	90	100
P/E Ratio (kW/kWh)	3.4 3.5			3.3 3.7 4.1	3.1 3.3	3.1 4.5
Mass (kg)	570 (est)			618	637 (est)	670 (est)
Specific Energy (Wh/kg)	122.8			138	141.3	149.3
BMS Type	Distributed					
Thermal System	Liquid					
Enclosure Material	Metallic					

Battery Cell Parameters

Image by Panasonic © Panasonic reserves all rights

Image by Tesla © Tesla reserves all rights

Parameter	60-85kWh	90-100 kWh	Model 3
Cell Supplier	Panasonic		Tesla/Panasonic
Cell Type	Cylindrical 18650		Cylindrical 2170
Anode Chemistry	Graphite	Graphite/Silicon	Graphite/Silicon
Cathode Chemistry	NCA		
Cell Capacity (Ah)	3.1	3.4	5
Cell Voltage (V)	3.6		
Weight (g)	45	47	67 (est)
Dimensions (mm)	18D x 65L		21D x 70L
Volume (mL)	16.5		24
Specific Energy (Wh/kg)	248	260	269 (est)
Energy Density (Wh/L)	675	740	742
Specific Power (W/kg) (10sec)	>1080 (based on system pwr)	>1080 (based on system pwr)	>1180 (based on system pwr)

Battery Pack Parameters

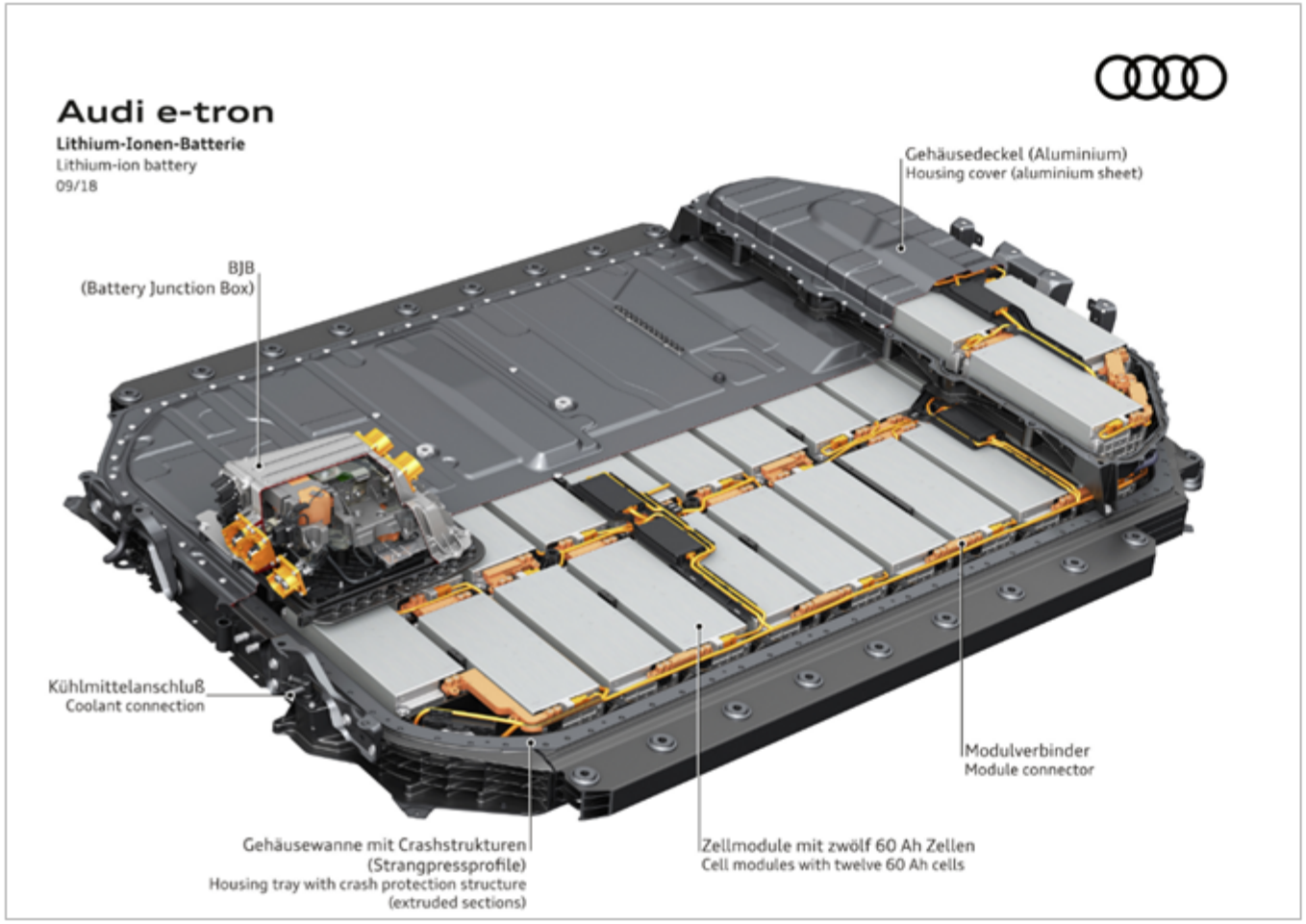


Image by Audi © Audi reserves all rights

ESS Parameter	2019
Pack Integrator	Audi
Configuration	108s4p
Voltage (V nominal)	396
Peak Power (kW)	300 (system)
Energy (kWh)	95
P/E Ratio (kW/kWh)	3.2
Mass (kg)	715
Specific Energy (Wh/kg)	131.9
BMS Type	Distributed
Thermal System	Liquid
Enclosure Material	Metallic

II. Battery Packs for EVs

A. EVs discussed in this section

B. Battery packs for EVs – Analysis

C. Vehicle-specific review for production EVs

- US/EU/JP/KR vehicles
- Chinese OEM vehicles

Special thanks to Guohua Ye for his detailed research and assistance for the Chinese OEM section.

EVs DISCUSSED IN THIS SECTION FROM CHINESE OEMs

- BAIC EC180 : 2016-18
- BAIC EC3 : 2018-19
- BAIC EU260 : 2016-17
- BAIC EU5 : 2018-19
- BAIC EV160 : 2014-16
- BAIC EV200 : 2018-19
- BAIC EV300 : 2018-19
- BAIC EX200 : 2016-18
- BAIC EX260 : 2017-18
- BAIC EX360 : 2018-19
- BAIC EX5 : 2019-19
- BYD e5 : 2015-15
- BYD e5 EV300: 2016-17
- BYD e5 EV450: 2018-18
- BYD Qin EV300: 2017-17
- BYD Qin EV400: 2018-18
- BYD Qin Pro: 2019-19
- BYD Song EV400: 2018-18
- BYD Song EV500: 2018-19
- BYD Tang EV600: 2019-19
- BYD Yuan EV360: 2018-19
- BYD Yuan EV535: 2019-19
- Chery Arrizo 5e : 2017-19
- Chery eQ : 2015-19
- Chery eQ1 300: 2018-18
- Chery eQ1 EV400: 2018-19
- Chery Tiggo 3xe : 2018-19
- Denza : 2014-16
- Denza 400 : 2017-17
- Denza 500 : 2018-19
- Geely Emgrand : 2016-16
- Geely Emgrand EV300: 2017-17
- Geely Emgrand EV450: 2018-19
- Geely Emgrand GSE: 2018-19
- Hawtai EV160B : 2017-19
- Hawtai EV160R : 2017-19
- Hawtai iEV230 : 2016-19
- Hawtai iEV360 : 2018-19
- Hawtai xEV260 : 2016-19
- Hawtai xEV360 : 2016-19
- JAC iEV4 : 2016-19
- JAC iEV6E : 2017-19
- JAC iEV6s : 2016-17
- JAC iEV7 : 2017-19
- JAC iEV7s : 2017-19
- JAC iEVA50 : 2018-19
- JMC E200 : 2017-18
- JMC E400 : 2018-18
- Nio ES6 : 2019-19
- Nio ES8 : 2018-19
- SAIC Roewe Ei5 : 2018-19
- SAIC Roewe ERX5 : 2019-19
- Zhidou D2 : 2016-19
- Zhidou D3 : 2018-19
- Zotye E200 : 2017-19
- Zotye Z500EV : 2018-19

All New Models in the 2019 Battery Packs of Modern xEVs Report

Chinese OEMs

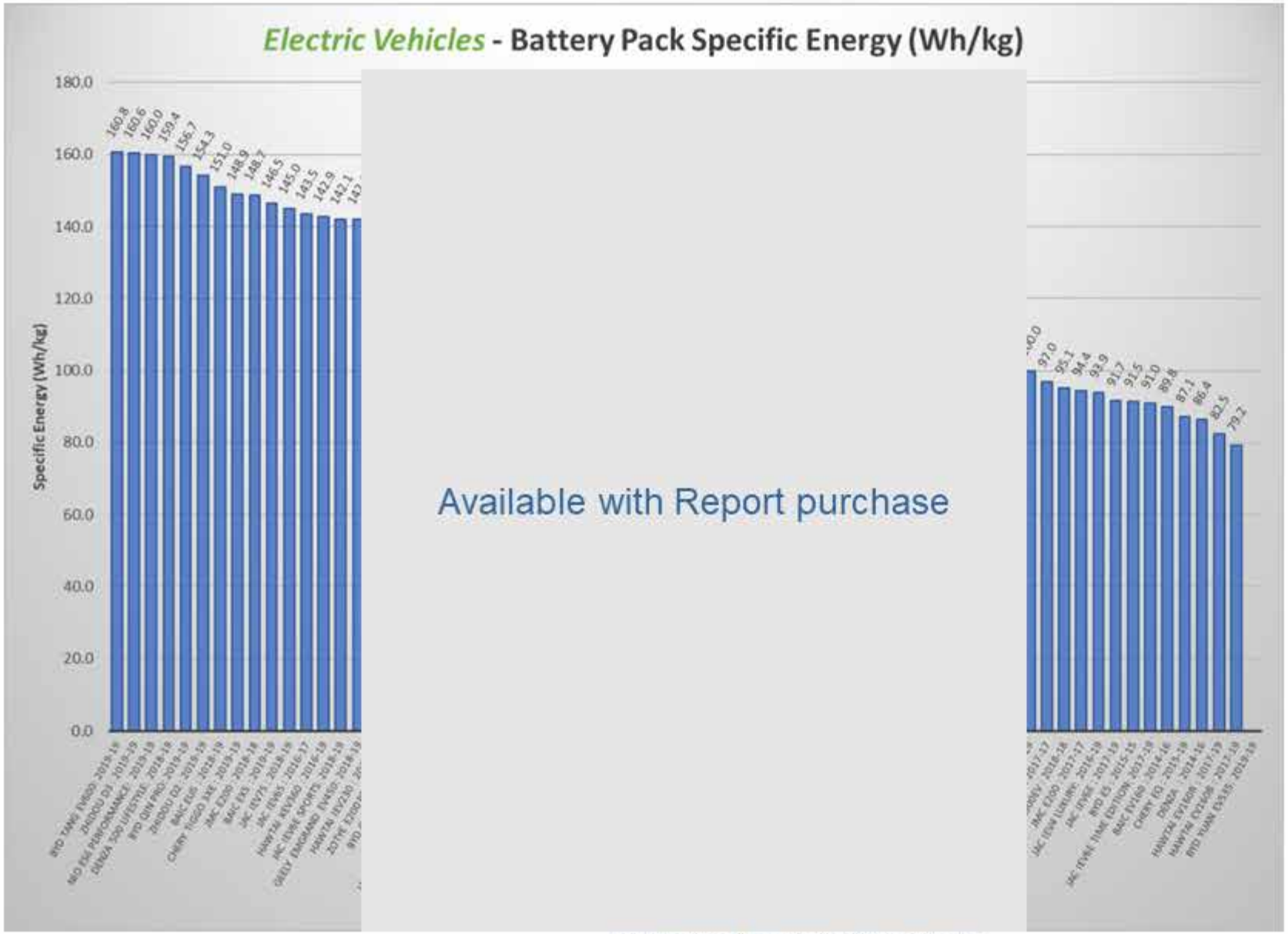
Battery Pack Capacity Diversity

Large diversity of battery-pack sizes and e-range

- Tesla offers largest battery packs
- Average battery size is 42.4 kWh
- Note: Most duplicate packs in additional vehicles from an OEM have been removed for clarity

Pack Capacity Distribution (kWh)

Min = 17
Ave = 42.4
Max = 84
Median = 42

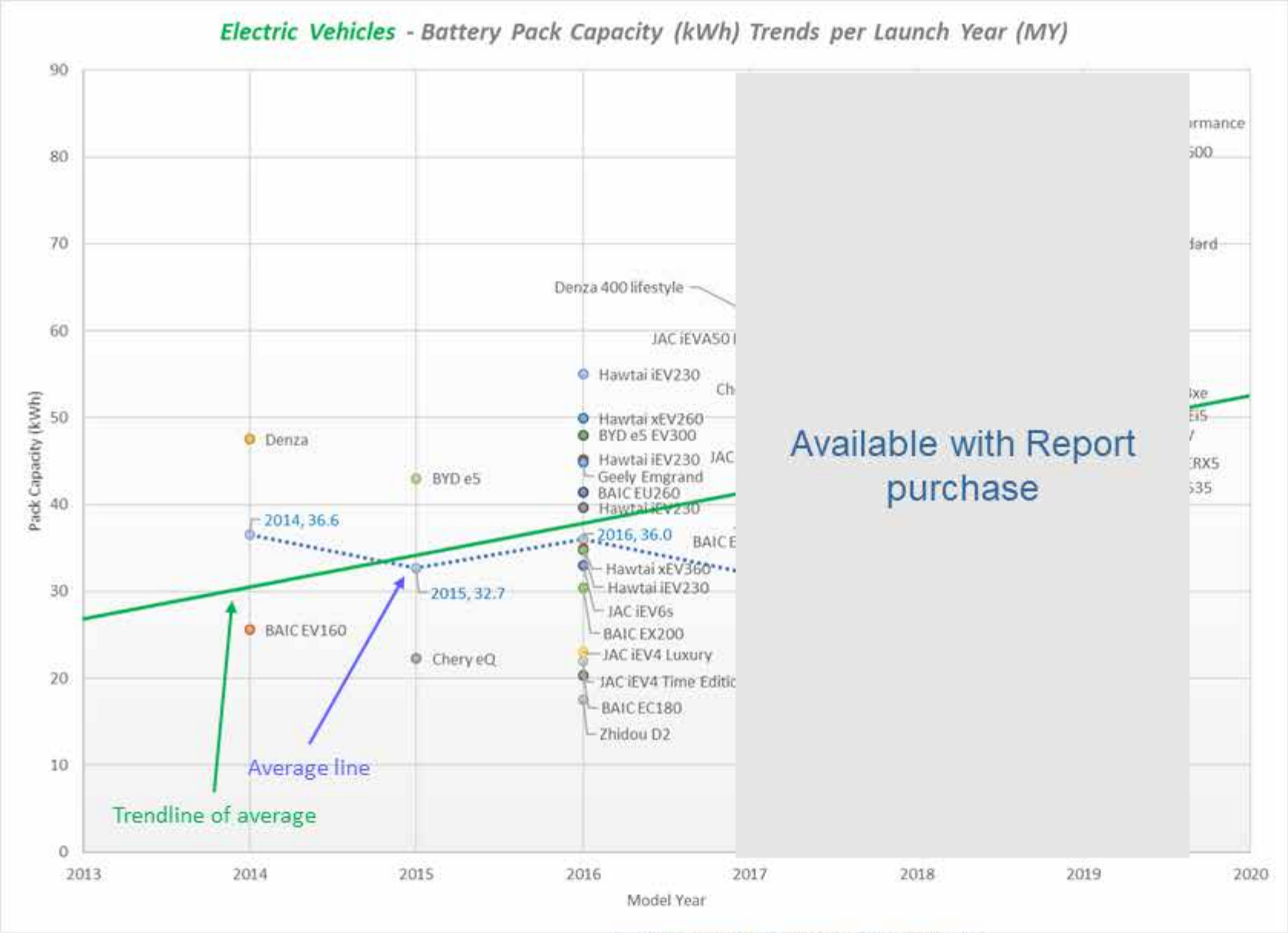


Chinese OEMs

Battery Pack Specific Energy Diversity

- Large range of 57.5 to 168 Wh/km
- Lowest are packs w/ LFP-based power cells
- Highest are packs w/ NMC (Ni-rich) energy cells

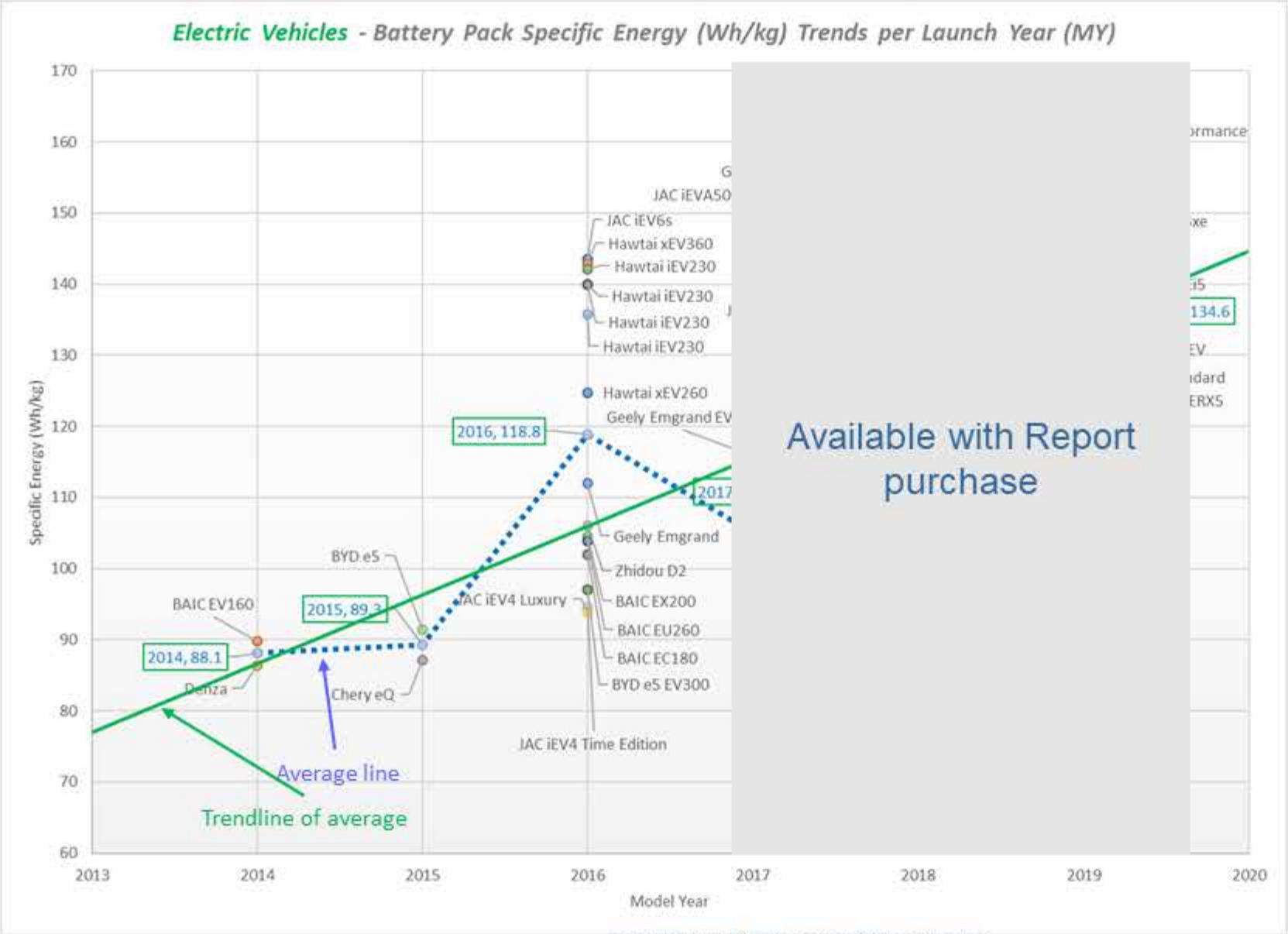
ESS Specific Energy Distribution (Wh/kg)
Min = 79.3
Ave = 125.3
Max = 160.6
Median = 133.3



Chinese OEMs

Pack Capacity vs. Launch Year

- Chart shows battery pack capacity in relation to model year for new model and upgrade launches (MY).



Chinese OEMs

Pack Specific Energy vs Launch Year

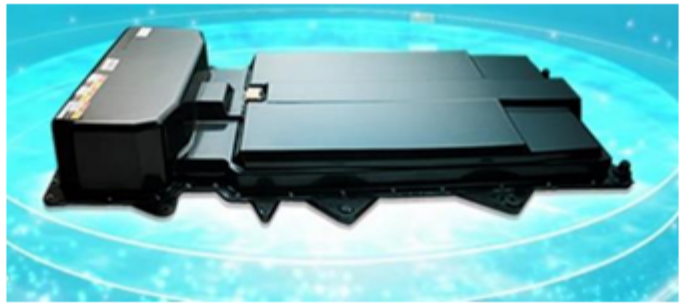
- Chart shows a general increase in battery pack specific energy in relation to model year (MY).

Battery Pack Parameters

Image by CATL © CATL reserves all rights

BAIC EX5 Battery Pack

Image by BAIC-BJEV © BAIC-BJEV reserves all rights



BAIC EX360 Battery Pack

ESS Parameter	2016-18 EX200	2018-19 EX260	2018-19 EX360	2019 EX5
Pack Integrator	BESK*	Beijing Pride	Beijing Pride	Beijing Pride
Peak Power (kW)	53	53	80	160
Energy (kWh)	30.4	38.6	48	61.8
P/E Ratio (kW/kWh)	1.74	1.37	1.67	2.6
Mass (kg)	291	340	395	421.8
Specific Energy (Wh/kg)	96	115	122	146.5
BMS Type	Distributed			
Thermal System	Convection			
Enclosure Material	Metallic			
Cell Supplier	BESK	CATL	CATL	CATL
Cell Chemistry	NMC	NMC	NMC	NMC
Cell Type	Metal Can Prismatic			

* Beijing Electronics Holding & SK Technology Co., Ltd.

Battery Pack Parameters

Image by BYD: © BYD reserves all rights

ESS Parameter	2015 E5 EV220	2017 Qin EV300 E5 EV300	2018 Qin EV450 E5 EV450	2019 Qin Pro
Pack Integrator	BYD			
Peak Power (kW)	160	160	160	120
Energy (kWh)	43	48	60.5	56.4
P/E Ratio (kW/kWh)	3.7	3.3	Available with Report purchase	
Mass (kg)	470	495		
Specific Energy (Wh/kg)	91	97		
BMS Type	Distr			
Thermal System	Liqui			
Enclosure Material	Me			
Cell Supplier	BYD	BYD		
Cell Chemistry	LiFePO4 (36 Ah)	LiFePO4		
Cell Type	Metal Can Prismatic			

Battery Pack Parameters

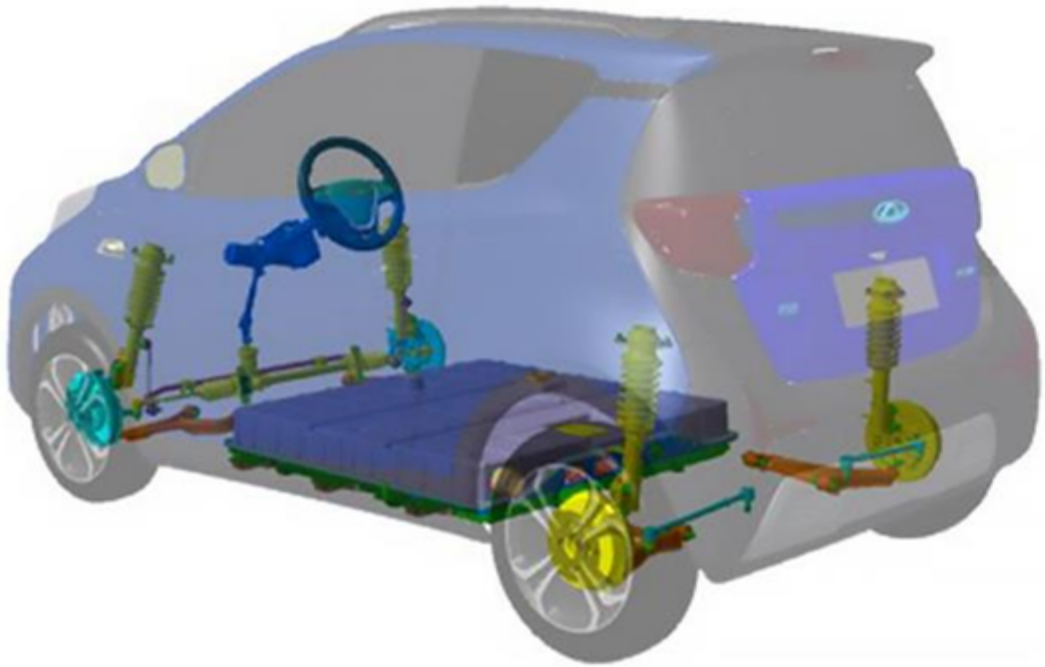


Image by Chery © Chery reserves all rights

ESS Parameter	EQ	EQ1 300	EQ1 400
Pack Integrator	Tianjin EV Energies/DFD New Energy	CATL/Wuhu Qida Power Battery Systems	CATL/Wuhu Qida Power Battery Systems
Voltage (V nom)	310.8	300 (est)	300 (est)
Peak Power (kW)	41.8	Available with Report purchase	
Energy (kWh)	22.3		
P/E Ratio (kW/kWh)	1.9		
Mass (kg)	256		
Specific Energy (Wh/kg)	86		
BMS Type	Distributed		
Thermal System	Convection		
Enclosure Material	Metallic		
Cell Supplier	Wanxiang A123	CATL (est)	CATL (est)
Cell Chemistry	LFP (72 Ah)	NMC	NMC
Cell Type	Prismatic Pouch (est)	Metal Can Prismatic (est)	

Battery Pack Parameters

Daimler/BYD JV Denza
2014-19 Denza 400/500

Images by Denza: © Denza reserves all rights

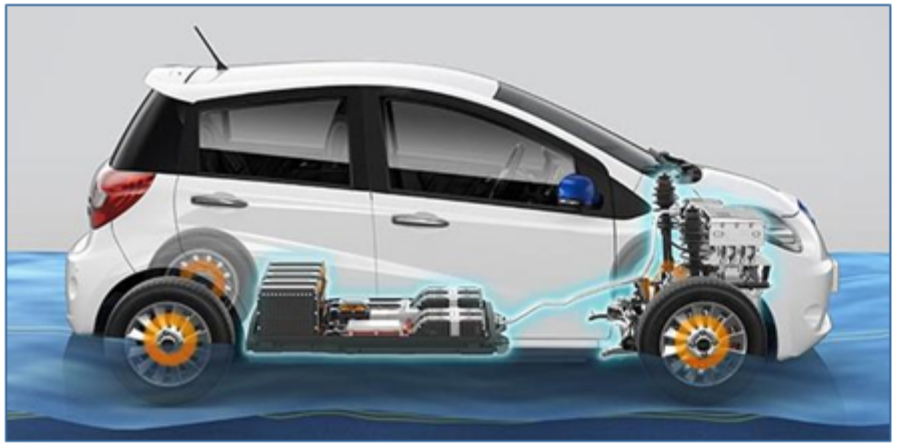
ESS Parameter	2014 Denza 400	2017 Denza 400	2018 Denza 500
Pack Integrator	BYD		
Configuration	144s1p (est)	144s1p (est)	132s3p (est)
Voltage (V nominal)	475.2	Available with Report purchase	
Peak Power (kW)	86		
Energy (kWh)	47.5		
P/E Ratio (kW/kWh)	1.2		
Mass (kg)	550		
Specific Energy (Wh/kg)	86		
BMS Type	Distributed		
Thermal System	Liquid		
Enclosure Material	Metallic		
Cell Supplier	BYD	BYD	BYD
Cell Chemistry	LiFePO4	LiFePO4	NMC
Cell Capacity (Ah)	100	130	50 (est)
Cell Type	Metal Can Prismatic		

Battery Pack Parameters

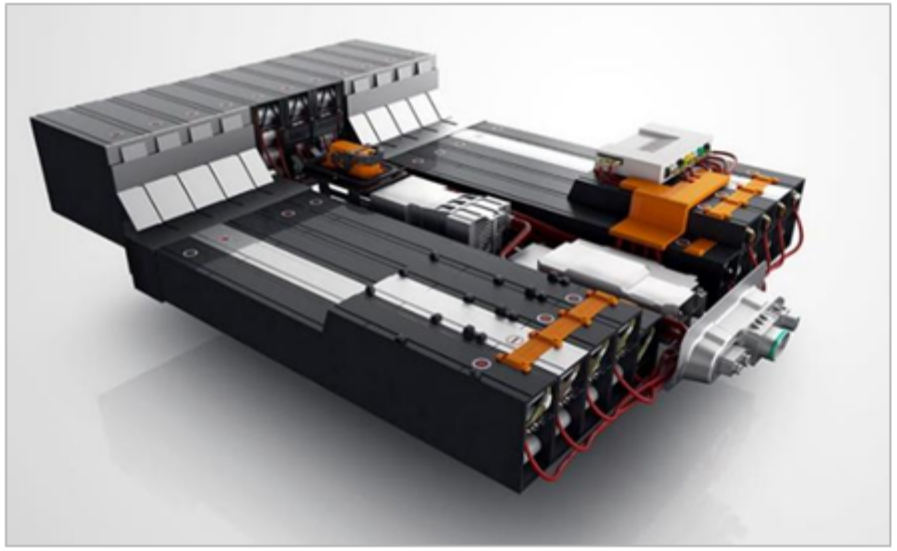
Images by Geely: © Geely reserves all rights

ESS Parameter	2015 Emgrand	2017 Emgrand EV300	2018 Emgrand EV450 2018 Emgrand GSE
Pack Integrator	CATL	CATL	CATL
Voltage (V nominal)	356	350 (est)	350 (est)
Peak Power (kW)	95	95	Available with Report purchase
Energy (kWh)	44.8	41	
P/E Ratio (kW/kWh)	2.12	2.3	
Mass (kg)	400	354	
Specific Energy (Wh/kg)	112	124	
BMS Type	Distributed		
Thermal System	Liquid (est		
Enclosure Material	Metallic		
Cell Supplier	CATL	CATL	
Cell Chemistry	LFP	NMC	
Cell Type	Metal Can Prismatic		

Battery Pack Parameters



JAC iEV6E



JAC iEV7 Battery Pack

Images by JAC: © JAC reserves all rights

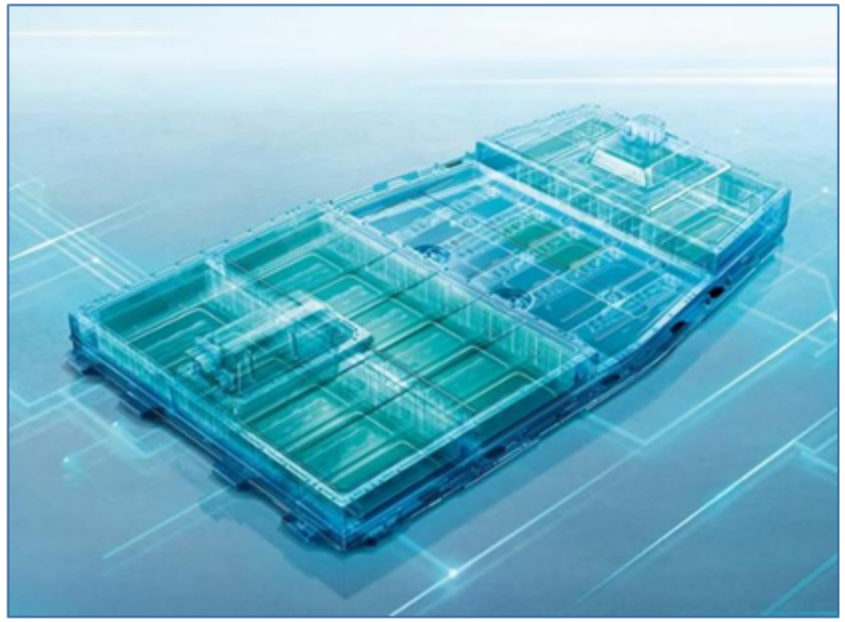
ESS Parameter	iEV4 Luxury	iEV4 Time Edition	iEV7	IEV6E Base/Time Edition		IEV6E Upgrade/Sports	
Pack Integrator	SinoEV/Heifei Guoxuan High-Tech Power Energy	Heifei Guoxuan High-Tech Power Energy	Heifei Guoxuan High-Tech Power Energy	Heifei Guoxuan High-Tech Power Energy	Heifei Guoxuan High-Tech Power Energy	Sino EV	SinoEV
Peak Power (kW)	42	60	50	45	60	55	50
Energy (kWh)	23	Available with Report purchase					
P/E Ratio (kW/kWh)	1.8						
Mass (kg)	245 (est)						
Specific Energy (Wh/kg)	94 (est)						
BMS Type							
Thermal System	Liquid						
Enclosure Material							
Cell Supplier							
Cell Chemistry	LFP						
Cell Type	Cylindrical 18650	Cylindrical 18650				Cylindrical 18650	

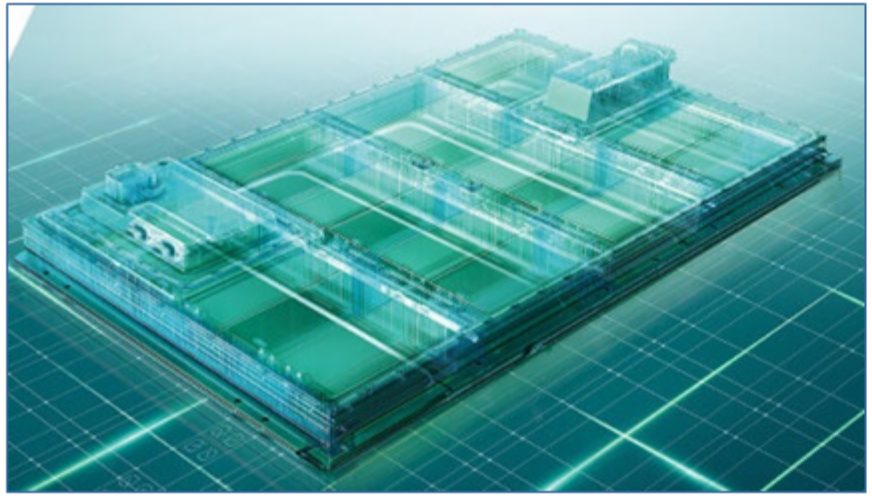
Battery Cell Parameters

Image by CATL © CATL reserves all rights

Parameter	70 kWh Battery Pack	84 kWh Battery Pack
Cell Supplier	CATL	CATL
Cell Type	Metal-can Prismatic	Metal-can Prismatic
Anode Chemistry	Graphite	Graphite
Cathode Chemistry	Available with Report purchase	
Cell Capacity (Ah)		
Cell Voltage (V)		
Weight (g)		
Dimensions (mm)		
Volume (mL)		
Specific Energy (Wh/kg)		
Energy Density (Wh/L)		
Specific Power (W/kg) (10sec discharge)		

Battery Pack Parameters





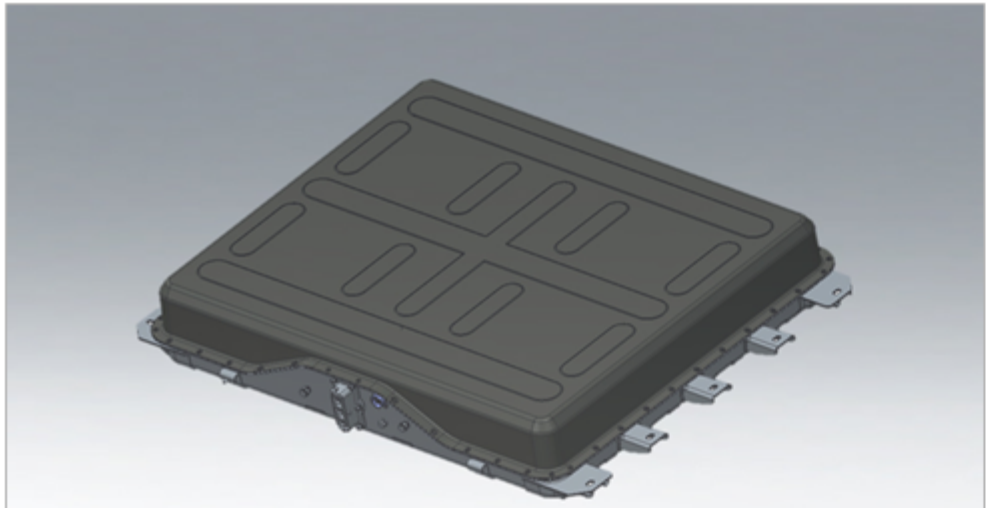
Top: SAIC Roewe Ei5 Battery Pack

Right: SAIC Roewe ERX5 Battery Pack

Images by Roewe: © Roewe reserves all rights

ESS Parameter	2018 Ei5	2019 Ei5	2019 ERX5
Pack Integrator	CATL/Shanghai Advanced Traction Battery Systems	CATL/Shanghai Advanced Traction Battery Systems	CATL/Shanghai Advanced Traction Battery Systems
Configuration	96s2p (est)	96s3p (est)	96s3p (est)
Voltage (V nominal)	Available with Report purchase		
Peak Power (kW)			
Energy (kWh)			
P/E Ratio (kW/kWh)			
Mass (kg)			
Specific Energy (Wh/kg)			
BMS Type	Distributed		
Thermal System	Liquid		
Enclosure Material	Metallic		

Battery Pack Parameters



Zotye E200 Battery System

Image by Zotye: © Zotye reserves all rights

ESS Parameter	2017-18 E200	2018-19 E200 Pro	2018 Z500EV	2019 Z500EV
Pack Integrator	Huizhou EVE Energy	Shenzhen BAK Battery	Tianjin EV Energies	Heifei Guoxuan High-Tech Power Energy
Peak Power (kW)	60	60	95	95
Energy (kWh)	24.5	31.9	39	49.7
P/E Ratio (kW/kWh)	Available with Report purchase			
Mass (kg)				
Specific Energy (Wh/kg)				
BMS Type				
Thermal System	Convection (est)			
Enclosure Material	Metallic			
Cell Supplier	Tenpower, BAK, Wina (est)			
Cell Chemistry	NMC (est)			
Cell Type	Cylindrical 18650 (est)			

Report Outline

III. Battery Packs for PHEVs

A. PHEVs discussed in this section

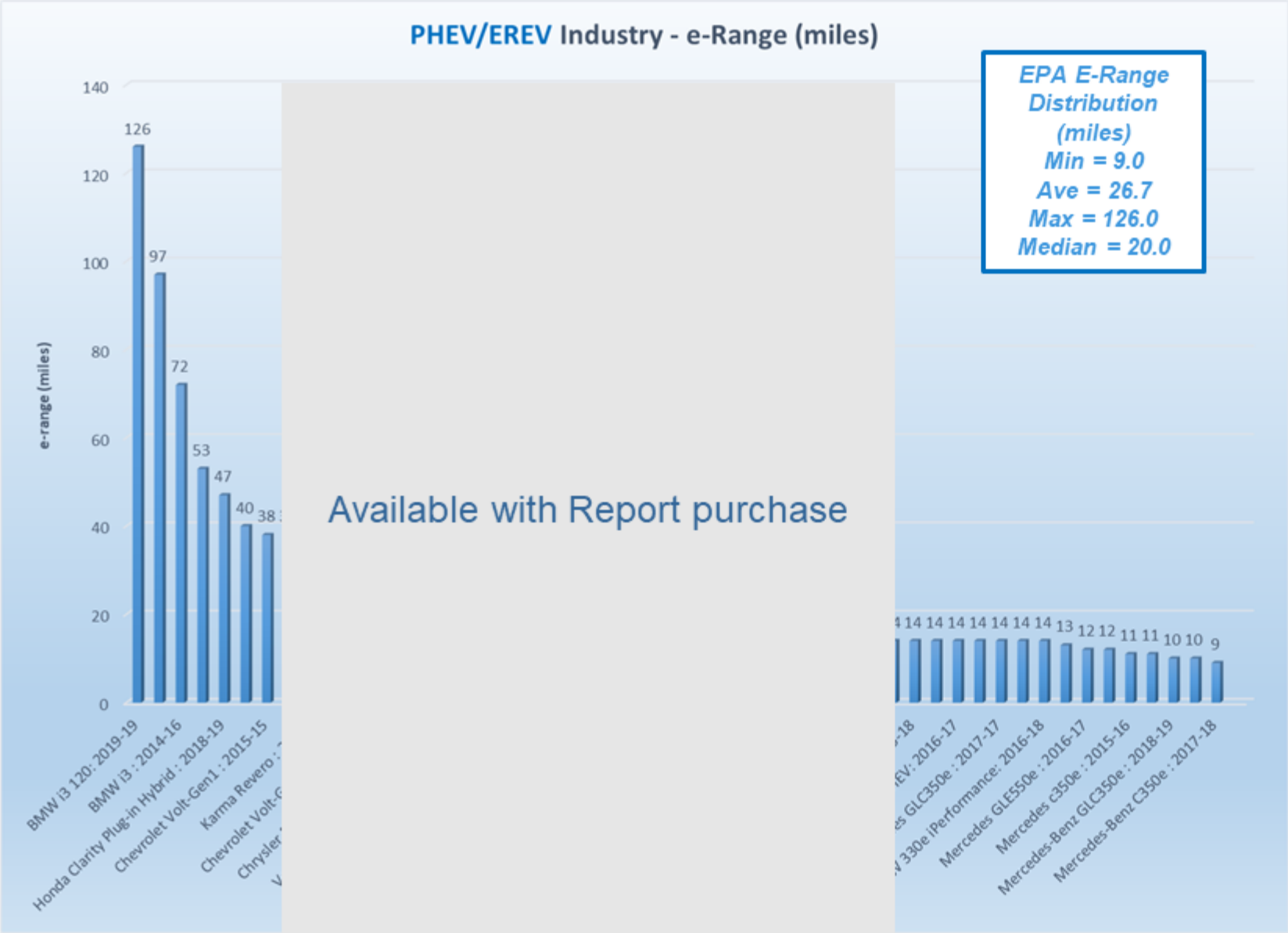
B. Battery packs for PHEVs – Analysis

C. Vehicle-specific review for production PHEVs

THE FOLLOWING PHEVS ARE DISCUSSED IN THIS CHAPTER

- 2014-19 BMW i3/i3s (range-extender) (*)
- 2014-19 BMW i8
- 2016-18 BMW X5
- 2016-18 BMW 225xe iPerformance
- 2016-19 BMW 330e iPerformance
- 2017-18 BMW 530e iPerformance
- 2016-19 BMW 740e iPerformance
- 2017-19 Chrysler Pacifica PHEV
- 2015-17 Daimler Mercedes S550e
- 2015-18 Daimler Mercedes c350e
- 2016-18 Mercedes GLE550e
- 2012-12 Fisker Karma
- 2018 Karma Revero (*)
- 2013-17 Ford C-max Energi
- 2013-19 Ford Fusion Energi (*)
- 2014-16 Cadillac ELR
- 2011-15 Chevrolet Volt-Gen1
- 2017-18 Cadillac CT6
- 2016-19 Chevrolet Volt-Gen2
- 2014 Honda Accord PHEV
- 2018-19 Honda Clarity PHEV (*)
- 2016-19 Hyundai Sonata PHEV
- 2018-19 Hyundai Ioniq PHEV (*)
- 2017-19 Kia Optima PHEV
- 2018-19 Kia Niro PHEV (*)
- 2013-19 Mitsubishi Outlander
- 2012-15 Toyota Prius Plug-in
- 2017-18 Toyota Prius Prime Plug-in
- 2016-18 Audi A3 E-tron
- 2017 Audi Q7 E-tron
- 2015-18 Porsche Cayenne S E-hybrid
- 2014-18 Porsche Panamera S E-hybrid
- 2014-17 Volkswagen Golf GTE
- 2015-17 Volkswagen Passat GTE
- 2013-16 Volvo V60 PHEV
- 2016-17 Volvo XC90 PHEV

(*) New/updated model in 2019 report

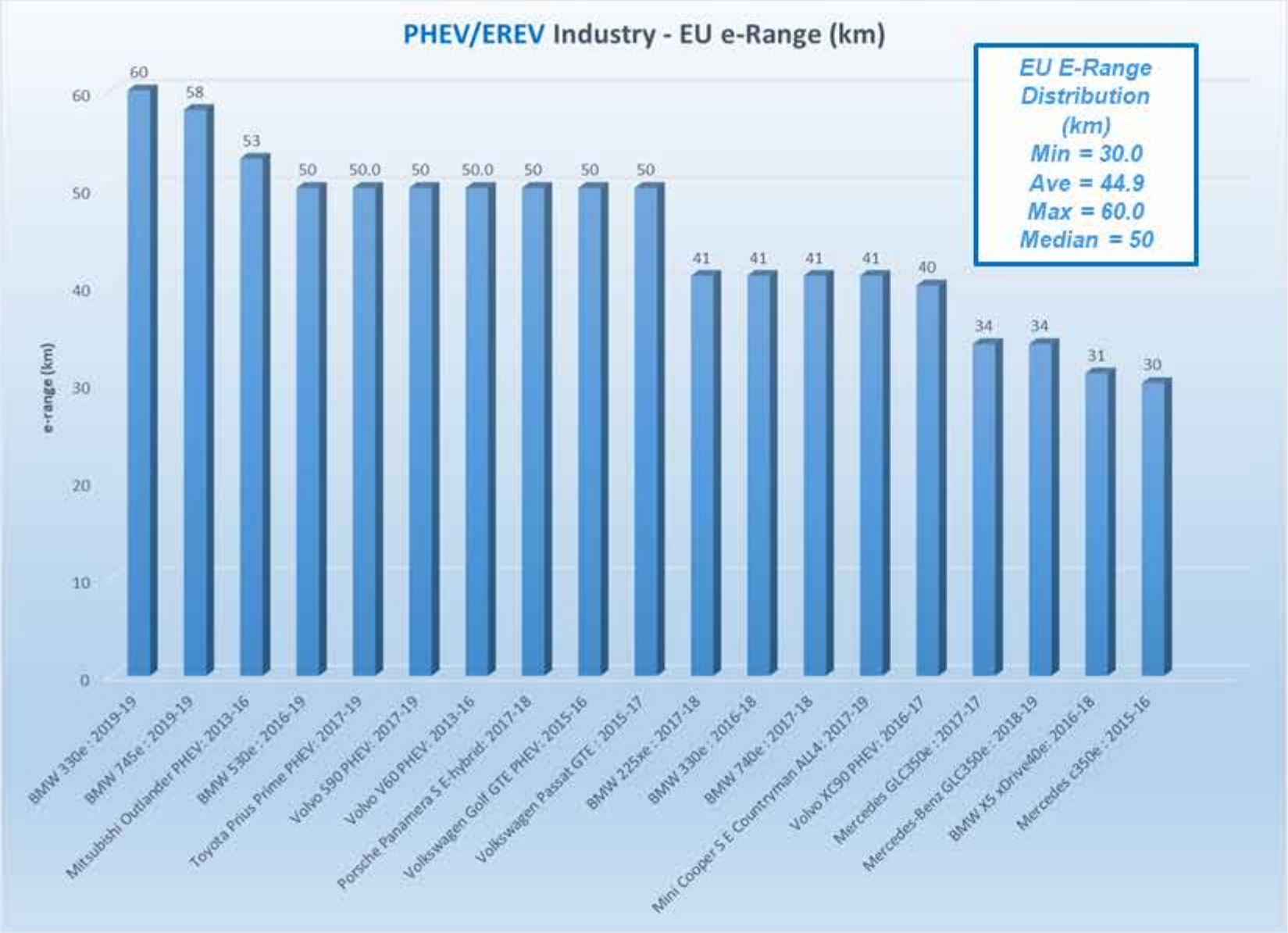


E-Range Diversity

- Large diversity of e-range
  - BMW i3 offers largest range
  - Average e-range is 26.7, and median value is 20 Miles

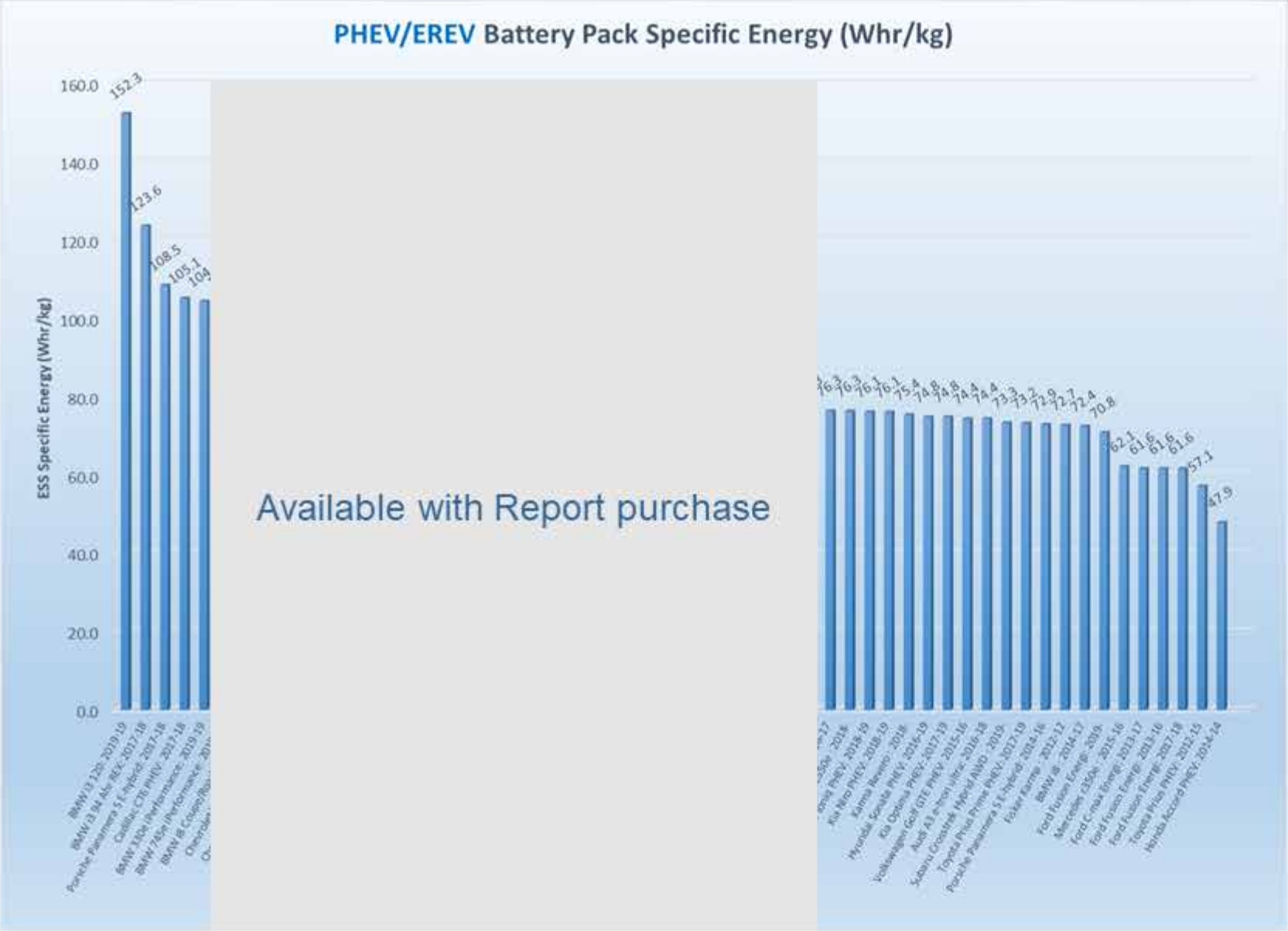
PHEV/EREV Trends

E-Range



E-Range Diversity

- Large diversity of e-range
- EU Market Targeting 50 km e-range prior to WLTP emission standards upgrade

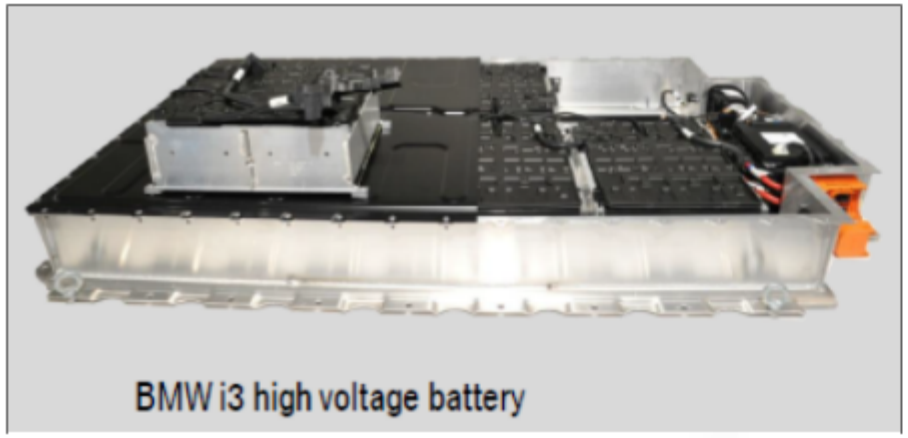


Battery Pack Specific Energy Diversity

- Large range of 47.9 to 152.3
- BMW i3, '17 Panamera, Cadillac CT6, and Chevy Volt represent the highest specific energy

Pack Specific Energy Distribution (Wh/kg)
Min = 47.9
Ave = 82.9
Max = 152.3
Median = 80.0

Battery Pack Parameters



Images by BMW © BMW reserves all rights
https://www.press.bmwgroup.com

ESS Parameter	2014-16	2017-18	2019
Pack Integrator	BMW		
Configuration	96s1p		
Voltage (V nominal)	360		
Peak Power (kW)	125	125 (est)	125/135
Energy (kWh)	22.0	33	42.2
P/E Ratio (kW/kWh)	5.7	3.8	3.0/3.2
Mass (kg)	233	267 (est)	277 (est)
Specific Energy (Wh/kg)	94.4	123.6	152.3
BMS Type	Distributed		
Thermal System	Refrigerant		
Enclosure Material	Metallic		

Vehicle & Battery Unique Attributes

- One of a minority of OEMs using $LiFePO_4$ chemistry
- Battery is packaged above rear axle
- Initial c350e launch in Europe w/ US debut in December 2016 (CY)
- Vehicle rollout plan of these two plug-in systems (6.2kWh & 8.7kWh)
- 3rd Generation PHEV system announced to launch in mid-2019 with a 13.5-kWh battery
  - Battery built by ACCUMOTIVE with 37-Ah NMC cells from SKI

Top: Mercedes s550e

Bottom Left: Mercedes c350e

Bottom Right: Mercedes GLE550e

Images by Mercedes-Benz © Mercedes-Benz reserves all rights

https://www.mercedes-benz.com/en/mercedes-benz/vehicles/passenger-cars/s-class/the-s-500-plug-in-hybrid/

Battery Cell Parameters

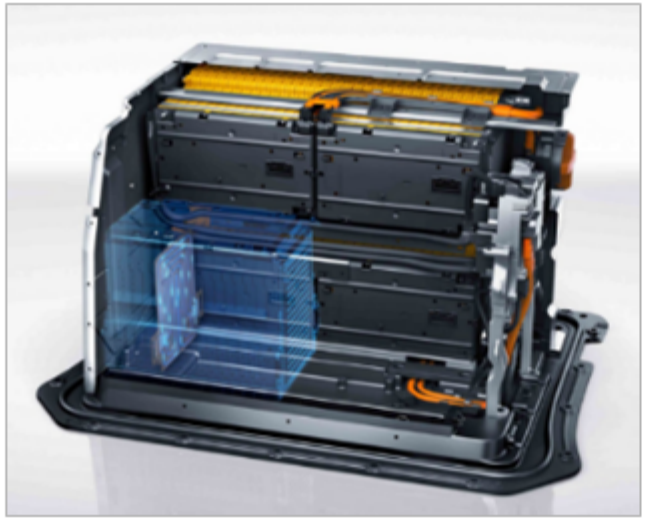
Note: Representative cell pictured, not actual cell

Image by LG: © LG reserves all rights

Parameter	2017-19
Cell Supplier	LG Chem
Cell Type	Prismatic Pouch
Anode Chemistry	Graphite
Cathode Chemistry	NMC (Ni-rich)
Cell Capacity (Ah)	48
Cell Voltage (V)	3.65
Weight (g)	895 (est)
Dimensions (mm)	159x300x10.5
Volume (mL)	498
Specific Energy (Wh/kg)	196 (est)
Energy Density (Wh/L)	350
Specific Power (W/kg) (10sec discharge)	>1000

Battery Pack Parameters

General Motors
2011-19 Chevy Volt
2014-16 Cadillac ELR; 2017-18 Cadillac CT6



Top-left: 2011-15 Volt Battery Pack

Top-right: 2016-17 Volt Battery Pack

Bottom: 2017 CT6 Battery Pack

Images by GM: © GM reserves all rights - http://media.gm.com

ESS Parameter	Volt	ELR	CT6
Pack Integrator	General Motors		
Configuration	96s3p (2011-15 Volt/ELR; 2016 ELR) 96s2p (2016-17 Volt)		96s2p
Voltage (Vnominal)	360		
Peak Power (kW)	110 (2011-15 Volt/ELR; 2016 ELR) 120 (2016-17 Volt)		120
Energy (kWh)	16.0 (2011-12) 16.5 (2013-14) 17.1 (2015) 18.4 (2016-17)	16.5 (2014-15) 17.1 (2016)	18.4
P/E Ratio (kW/kWh)	6.9 (2011-12) 6.7 (2013-14) 6.4 (2015) 6.5 (2016-17)	6.7 (2014-15) 6.4 (2016)	6.5
Mass (kg)	196 (2011-15 Volt/ELR; 2016 ELR) 183 (2016-17 Volt)		175 (est)
Specific Energy (Wh/kg)	81.6 (2011-12) 84.2 (2013-14) 87.2 (2015) 100.5 (2016-17)	84.2 (2014-15) 87.2 (2016)	105 (est)
BMS Type	Distributed		
Thermal System	Liquid-direct		
Enclosure Material	Composite		

Battery Cell Parameters

Top: Image by Blue Energy © Blue Energy reserves all rights
http://www.blue-energy.co.jp/en/newsrelease/pdf/20130711e.pdf

Bottom: Image by Panasonic © Panasonic reserves all rights
http://news.panasonic.com/global/images/01PHEV.jpg

Parameter	2014 Accord PHEV	2018-19 Clarity PHEV
Cell Supplier	Blue Energy	Panasonic
Cell Type	Prismatic Metal Can	Prismatic Metal Can
Anode Chemistry	Graphite	Graphite
Cathode Chemistry	LiFePO4	NMC
Cell Capacity (Ah)	Available with Report purchase	
Cell Voltage (V)		
Weight (g)		
Dimensions (mm)		
Volume (mL)		
Specific Energy (Wh/kg)		
Energy Density (Wh/L)		
Specific Power (W/kg) (10sec discharge)	>788 (based on system power)	1304

Battery Cell Parameters

Image by Panasonic © Panasonic reserves all rights
http://news.panasonic.com/global/images/01PHEV.jpg

Parameter	'12-15	'17-19 Prime
Cell Supplier	Panasonic	
Cell Type	Prismatic Metal-Can	
Anode Chemistry	Graphite	
Cathode Chemistry	NMC	
Cell Capacity (Ah)	21.5	25
Cell Voltage (V)	3.65	3.65
Weight (g)	746	690
Dimensions (mm)	PHEV2: 148x26.5x91	
Volume (mL)	357	
Specific Energy (Wh/kg)	110	134
Energy Density (Wh/L)	223	259
Specific Power (W/kg) (10sec discharge)	n/a	1304

Battery Pack Parameters

Volkswagen Group
2016-18 Audi A3 e-tron
2014-17 VW Golf GTE; 2015-17 VW Passat GTE

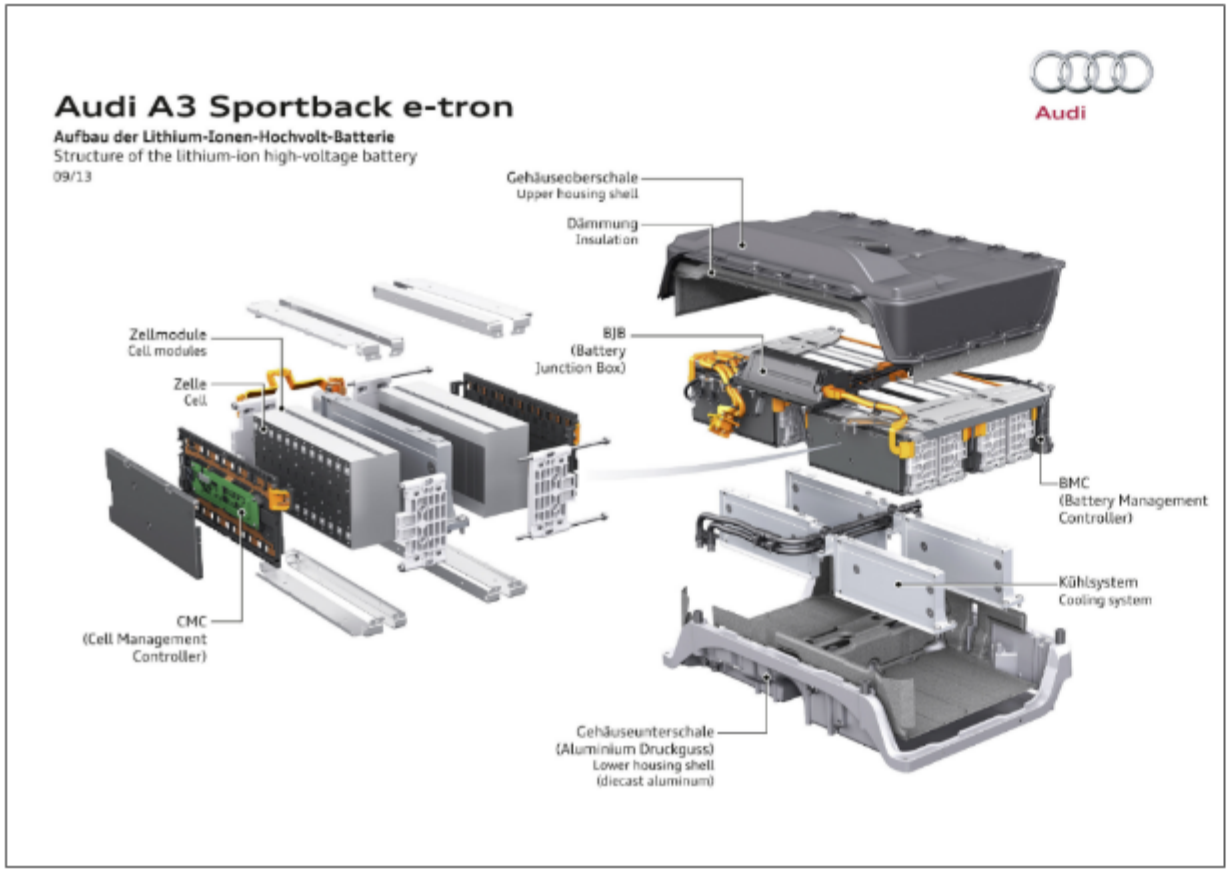


Image by Audi: © Audi reserves all rights - https://www.audi-mediacenter.com/en/photos/album/audi-a3-sportback-e-tron-12

ESS Parameter	A3 e-tron Golf GTE	Passat GTE
Pack Integrator	VW	
Configuration	96s1p	
Voltage (V nominal)	360	
Peak Power (kW)	75 (system power)	85 (system power)
Energy (kWh)	Available with Report purchase	
P/E Ratio (kW/kWh)		
Mass (kg)		
Specific Energy (Wh/kg)		
BMS Type		
Thermal System	Liquid-glycol	
Enclosure Material	Metallic (aluminum)	

Vehicle & Battery Unique Attributes

- Shared powertrain and battery between Audi A3 & VW Golf GTE
- Battery pack mounted below rear seat
- VW Golf GTE only sold in Europe
- Uses liquid cooling system as opposed to the e-Golf which uses convection w/ same battery cell
- Passat GTE shares mechanical structure w/ A3/Golf battery but changes the cell to a higher capacity Samsung 28-Ah cell (still in PHEV2 form factor)
- Passat GTE announced for late 2019 with upgraded battery to 13.0 kWh (from 9.9 kWh)

Top Right: VW Golf GTE
Bottom Right: VW Passat GTE
Bottom Left: Audi A3 e-tron

Image by Audi © Audi reserves all rights
Images by Volkswagen: © Volkswagen reserves all rights

Battery Pack Parameters

Volvo Group
2013-16 V60 PHEV; 2018-19 XC60
2016-19 XC90 PHEV; 2017-19 S90 PHEV

Images by Volvo: © Volvo reserves all rights

https://www.media.volvocars.com/uk/en-gb/media/pressreleases/40462/photos

ESS Parameter	13-16 V60	16-17 XC90	17-19 S90 18-19 XC60 18-19 XC90
Pack Integrator	LG	Volvo/LG	
Configuration	100s2p	96s1p	
Voltage (V nominal)	370	355	
Peak Power (kW)	50	65	
Energy (kWh)	11.2	9.2	10.4
P/E Ratio (kW/kWh)	4.5	7.1	6.25
Mass (kg)	138 (est)	113	114
Specific Energy (Wh/kg)	81.4	81.4	91.2
BMS Type	Distributed		
Thermal System	Liquid-glycol		
Enclosure Material	Metallic (aluminum)		

III. Battery Packs for PHEVs

A. PHEVs discussed in this section

B. Battery packs for PHEVs – Analysis

C. Vehicle-specific review for production PHEVs

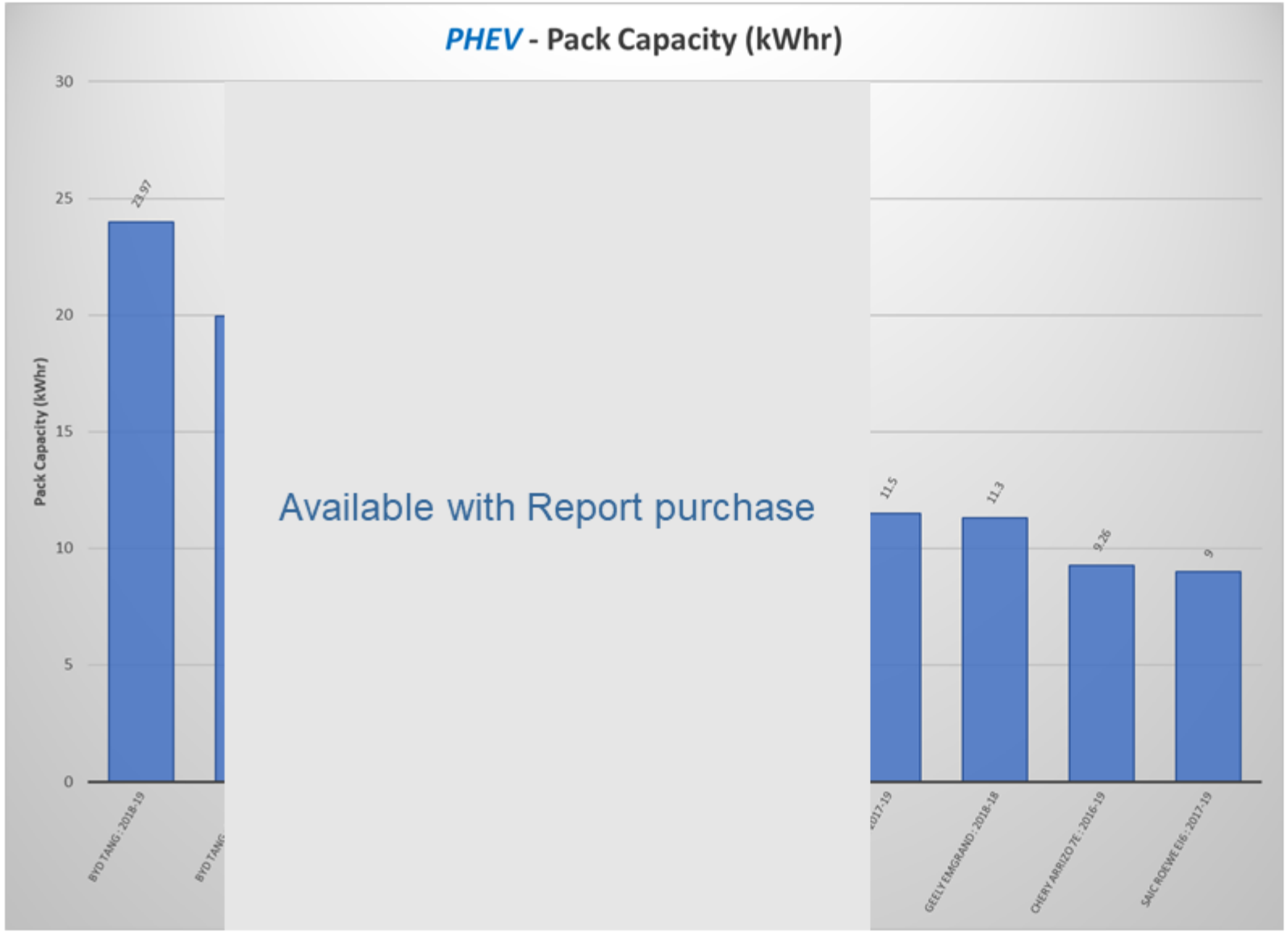
- US/EU/JP/KR PHEVs
- PHEVs made in China

THE FOLLOWING PHEVS ARE DISCUSSED IN THIS CHAPTER

CHINESE OEMs

- BYD Qin Pro DM: 2018-19
- BYD Song DM: 2017-19
- BYD Tang : 2018-19
- BYD Tang : 2018-19
- Chery Arrizo 7e : 2016-19
- Geely Borui PHV: 2017-19
- Geely Emgrand : 2018-18
- SAIC Roewe e550 : 2014-17
- SAIC Roewe e950 : 2016-19
- SAIC Roewe Ei6 : 2017-19
- SAIC Roewe eRX5 : 2016-19

All models are new in 2019 report

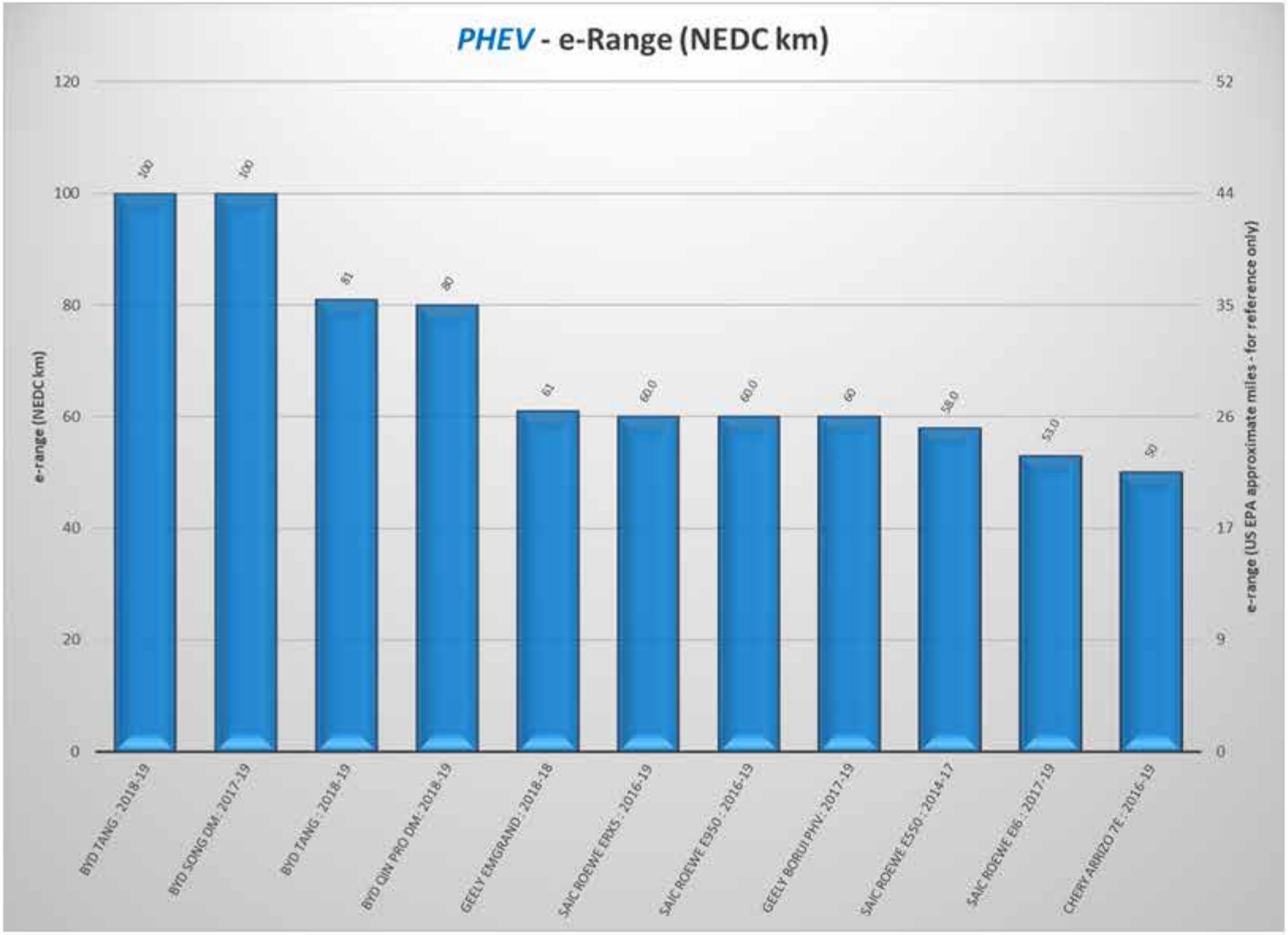


CHINESE OEMs

Battery Pack Capacity Diversity

- Large diversity of battery pack sizes and e-range
  - BYD Tang has largest battery pack

Pack Capacity Distribution (kWh)
Min = 9.0
Ave = 13.8
Max = 24.0
Median = 11.8

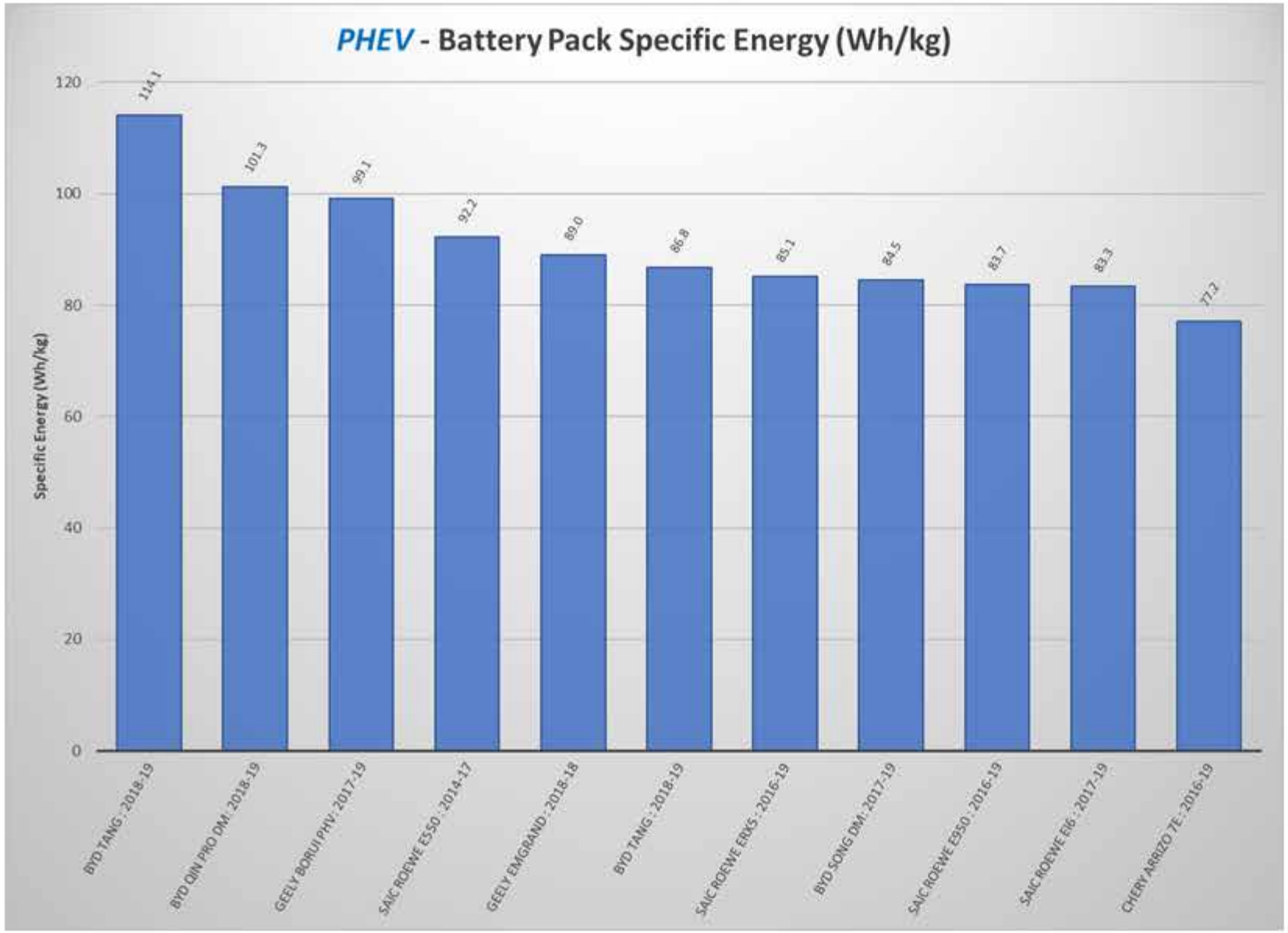


CHINESE OEMs

E-Range Diversity

- Large diversity of e-range
  - BYD Tang offers largest range
  - Average e-range is 69.4 km, and median value is 60 km

E-Range Distribution (NEDC km)
Min = 50.0
Ave = 69.4
Max = 100
Median = 60.0



CHINESE OEMs

Battery Pack Specific Energy Diversity

- BYD Tang represent the highest specific energy

Pack Specific Energy Distribution (Wh/kg)
Min = 77.2
Ave = 90.6
Max = 114.1
Median = 86.8

Battery Pack Parameters

BYD Qin Pro DM

BYD Song DM

Images by BYD © BYD reserves all rights

ESS Parameter	Qin Pro DM	Song DM	Tang DM	
Pack Integrator	BYD	BYD	BYD	
Peak Power (kW)	110 (system)	110 (front motor) 110 (rear motor)	110 (front motor) 180 (rear motor)	
Energy (kWh)	14.38	16.9	19.96	23.97
P/E Ratio (kW/kWh)	7.6	Available with Report purchase		
Mass (kg)	142			
Specific Energy (Wh/kg)	101.3			
BMS Type	Distributed			
Thermal System	Liquid			
Enclosure Material	Metallic			
Cell Supplier	BYD	BYD	BYD	BYD
Cell Chemistry	LFP	LFP	LFP	LFP

Battery Pack Parameters

Image by Geely © Geely reserves all rights

ESS Parameter	Emgrand	Borui
Pack Integrator	CATL	CATL
Peak Power (kW)	114 (system)	80
Energy (kWh)	Available with Report purchase	
P/E Ratio (kW/kWh)		
Mass (kg)		
Specific Energy (Wh/kg)		
BMS Type	Distributed	
Thermal System	Liquid (est)	
Enclosure Material	Metallic	
Cell Supplier	CATL (est)	CATL (est)
Cell Chemistry	NMC (est)	NMC (est)

Overview

- SAIC produces multiple xEVs
- PHEVs include:
  - SAIC Roewe Ei6
  - SAIC Roewe e550
  - SAIC Roewe e950

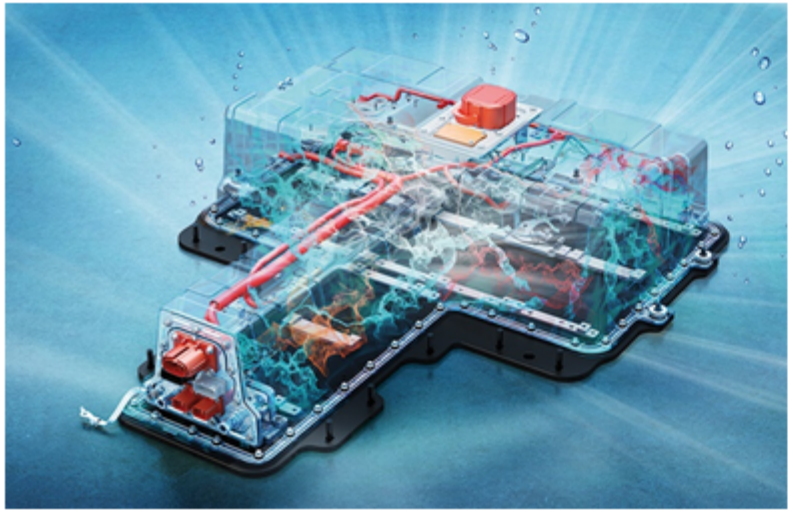
Image by SAIC © SAIC reserves all rights

Battery Pack Parameters

SAIC

2017-19 Roewe Ei6; 2014-17 Roewe e550; 2016-19 e950; 2016-19 Roewe eRX5

Roewe Ei6 Battery



Roewe eRX5 Battery

ESS Parameter	Roewe Ei6	Roewe eRX5	Roewe e550	Roewe e950
Pack Integrator	Wanxiang A123	Wanxiang A123	Wanxiang A123	Wanxiang A123
Peak Power (kW)	60 (sys)	56 (sys)	44 (sys)	60 (sys)
Energy (kWh)	9	Available with Report purchase		
P/E Ratio (kW/kWh)	6.7			
Mass (kg)	108			
Specific Energy (Wh/kg)	83.3			
BMS Type	Distributed (est)			
Thermal System	Liquid (est)			
Enclosure Material	Metallic			
Cell Supplier	Wanxiang A123 (est)	Wanxiang A123	Wanxiang A123	Wanxiang A123
Cell Chemistry	LFP	NMC	LFP	NMC

Images by SAIC © SAIC reserves all rights

IV. Battery Packs for HEVs

A. HEVs discussed in this section

B. Battery packs for HEVs – Analysis

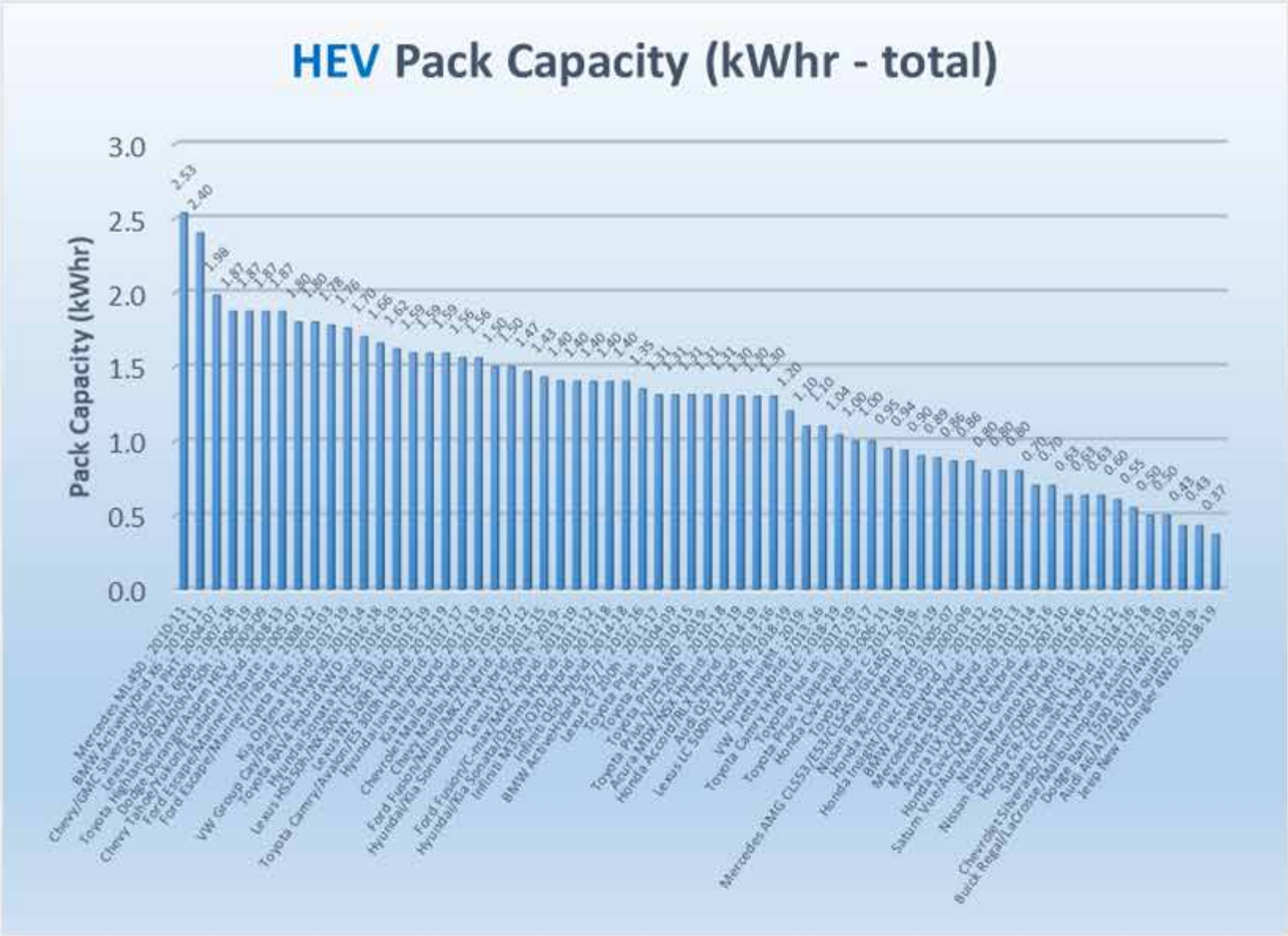
C. Vehicle-specific review for production HEVs

HEVs DISCUSSED IN THIS SECTION

- 2013-15 BMW Activehybrid 3
- 2012-16 BMW Activehybrid 5
- 2011-12 BMW Activehybrid 7
- 2013-15 BMW ActiveHybrid 7
- 2010-11 BMW ActiveHybrid X6 Hybrid
- 2013-15 Mercedes E400 Hybrid
- 2010-11 Mercedes ML450
- 2010-13 Mercedes S400 Hybrid
- 2019 Mercedes AMG CLS53 & E53 (*)
- 2019 Mercedes CLS450 (*)
- 2009-09 Dodge Durango/Aspen HEV
- 2019 Dodge Ram 1500 (*)
- 2018-19 Jeep Wrangler (*)
- 2013-17 Ford C-max Hybrid
- 2005-12 Ford Escape/Mariner/Tribute
- 2010-19 Ford Fusion
- 2011-19 Lincoln MKZ Hybrid
- 2009-13 Cadillac Escalade Hybrid
- 2008-10 Chevy Malibu Eco
- 2016-19 Chevy Malibu Hybrid
- 2013-14 Chevy Malibu eAssist
- 2004-07 Chevy Silverado/Sierra Hybrid
- 2009-13 Chevy Silverado/Sierra Hybrid
- 2017-18 Chevy Silverado/Sierra Hybrid (*)
- 2008-13 Chevy Tahoe/Yukon Hybrid
- 2016 Chevy/GMC Silverado/Sierra
- 2007-09 Saturn Vue/Aura Greenline
- 2012-16 Buick Regal/LaCrosse eAssist
- 2013-14 Acura ILX Hybrid
- 2014-19 Acura RLX Hybrid
- 2017 Acura MDX
- 2017 Acura NSX
- 2005-07 Honda Accord Hybrid
- 2014-15, 17-19 Honda Accord Hybrid
- 2003-15 Honda Civic Hybrid
- 2011-16 Honda CR-Z Hybrid
- 2000-06 Honda Insight
- 2010-14 Honda Insight
- 2019 Honda Insight (*)
- 2012-16 Honda Fit/Jazz Hybrid (Japan)
- 2011-17 Hyundai Sonata Hybrid
- 2017-19 Hyundai Ioniq Hybrid
- 2011-19 Kia Optima Hybrid
- 2017-19 Kia Niro Hybrid
- 2012-16 Mazda Axela Hybrid (Japan)
- 2012-13 Infiniti M35h Hybrid
- 2014-17 Infiniti Q50 Hybrid
- 2014-18 Infiniti Q70 Hybrid
- 2014-17 Infiniti QX60 Hybrid
- 2007-11 Nissan Altima Hybrid
- 2014-14 Nissan Pathfinder Hybrid
- 2010-16 Nissan Fuga Hybrid (Japan)
- 2012-15 Nissan Cima Hybrid (Japan)
- 2014-16 Nissan Skyline Hybrid (Japan)
- 2016 Nissan Murano Hybrid
- 2017-19 Nissan Rogue Hybrid
- 2014-16 Subaru Crosstrek Hybrid
- 2011-17 Lexus CT 200h
- 2013-19 Lexus ES 300h
- 2007-11 Lexus GS 450h
- 2013-18 Lexus GS 450h
- 2010-12 Lexus HS 250h
- 2008-16 Lexus LS 600h
- 2018-19 Lexus LC 500h (*)
- 2018-19 Lexus LS 500h (*)
- 2015-19 Lexus NX 300h
- 2006-08 Lexus RX 400h
- 2010-19 Lexus RX 450h
- 2019 Lexus UX 250h (*)
- 2013-19 Toyota Avalon Hybrid
- 2007-19 Toyota Camry Hybrid
- 2018-19 Toyota Camry LE (*)
- 2006-19 Toyota Highlander Hybrid
- 2001-19 Toyota Prius
- 2012-19 Toyota Prius c
- 2012-17 Toyota Prius v
- 2019 Toyota Prius AWD
- 2016-18 Toyota RAV4 Hybrid
- 2013-16 Audi Q5 Hybrid
- 2019 Audi A6 Hybrid (*)
- 2019 Audi A7 Hybrid (*)
- 2019 Audi A8 L Hybrid (*)
- 2011-14 Porsche Cayenne S Hybrid
- 2012-13 Porsche Panamera S Hybrid
- 2013-16 Volkswagen Jetta Hybrid
- 2011-15 Volkswagen Touareg Hybrid

** New/updated model in 2019 report*

Pack Capacity



Battery Pack Capacity Diversity

- Diversity of battery pack sizes
- Average battery size is 1.25 kWh

Pack Capacity Distribution (kWh)

Min = 0.37
Ave = 1.25
Max = 2.53
Median = 1.3

ESS Specific Energy

Battery Pack Specific Energy Diversity

- Large range of 17 to 42
- Graph does not show clear differentiation between NiMH-based systems and Li Ion
- Note: 42/48V systems are not graphed

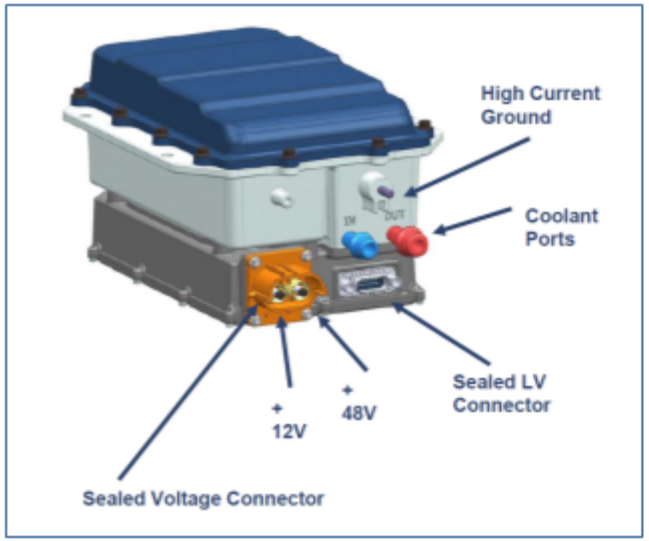
Pack Specific Energy Distribution (Wh/kg)
Min = 17.0
Ave = 30.6
Max = 42.2
Median = 30.4

Battery Pack Parameters

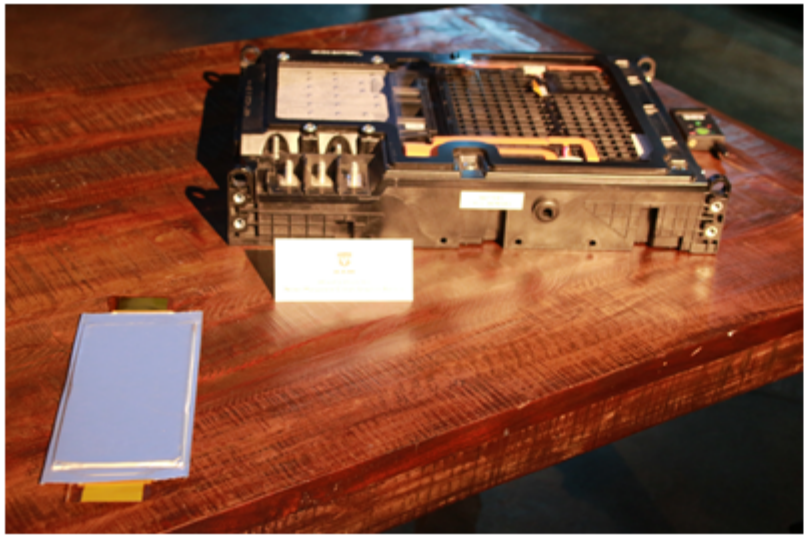
Images by Daimler © Daimler reserves all rights

ESS Parameter	48V EQ Boost Battery
Model Years	2019
Pack Integrator	Accumotive
Chemistry Family	Lithium-Ion
Configuration	12s1p (est)
Voltage (V nom)	42.8
Peak Power (kW)	16
Energy (kWh)	0.9
P/E Ratio (kW/kWh)	17.8
Mass (kg)	15 (est)
Specific Energy (Whr/kg)	60
BMS Type	Centralized
Thermal System	Liquid
Enclosure Material	Metallic

Battery Pack Parameters



Images by FCA © FCA reserves all rights



ESS Parameter	Dodge Ram 48V eTorque Battery	Jeep Wrangler 48V eTorque Battery
Model Years	2019	2019
Pack Integrator	LG	Samsung
Chemistry Family	Lithium-Ion	Lithium-Ion
Configuration	12s1p	12s1p
Voltage (Vnom)	43.8	43.8
Peak Power (kW)	Available with Report purchase	
Energy (kWh)		
P/E Ratio (kW/kWh)		
Mass (kg)	n/a (integrated battery module w/ system)	n/a (integrated battery module w/ system)
Specific Energy (Whr/kg)	n/a	n/a
BMS Type	Centralized	Centralized
Thermal System	Air	Liquid
Enclosure Material	Metallic	Metallic

Source: Forbes https://blogs.forbes.com/samabuelsamid/files/2018/08/2019-Ram-1500-eTorque-first-drive-1280-1-of-8.jpg © Forbes reserves all rights

Ford HEV Family

- ***350V NiMH***
  - 2005-12 Ford Escape Hybrid 2WD/4WD (2012 AWD)
  - 2006-11 Mercury Mariner Hybrid 2WD/4WD
  - 2006-11 Mazda Tribute Hybrid 2WD/4WD
- ***330V NiMH***
  - 2010-12 Ford Fusion Hybrid
  - 2010-11 Mercury Milan
  - 2011-12 Lincoln MKZ Hybrid
- ***275V Li Ion***
  - 2013-19 Ford Fusion Hybrid FWD
  - 2013-17 Ford C-max Hybrid
  - 2013-17 Lincoln MKZ Hybrid FWD

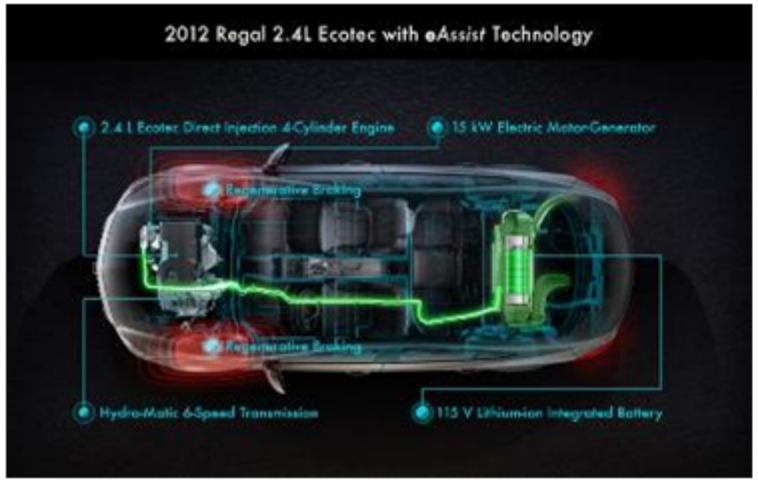
2016 Lincoln MKZ Hybrid

2016 Ford Fusion Hybrid

2005 Ford Escape Hybrid

Images by Ford © Ford reserves all rights - https://media.ford.com/

Cadillac Escalade Hybrid



Images by General Motors © General Motors reserves all rights http://media.gm.com

GM Mild Hybrid Generations

- 2004-07: PHT (Parallel Hybrid Truck)
  - 2004-07 Chevy Silverado
  - 2004-07 GMC Sierra
- 2007-10: BAS (Belted Alternator Starter); Also 'Greenline'
  - 2007-09 Saturn Aura Hybrid Greenline
  - 2007-10 Saturn Vue Hybrid Greenline
  - 2008-10 Chevrolet Malibu Hybrid
- 2012-19: eAssist – 115V BAS System – Also "BAS+"
  - 2012-15 Buick Regal eAssist
  - 2012-19 Buick LaCrosse eAssist
  - 2013-13 Chevrolet Malibu eAssist
  - 2014-14 Chevrolet Impala eAssist
  - 2017-18 Chevy Silverado eAssist

Strong Hybrids

- 2009-13: 2-mode Hybrids (GM & Dodge)
  - 2009-13 Cadillac Escalade Hybrid 2WD & 4WD
  - 2008-13 Chevrolet Tahoe Hybrid 2WD & 4WD
  - 2008-13 GMC Yukon Hybrid 2WD & 4WD
  - 2009-13 Chevrolet Silverado Hybrid 2WD & 4WD
  - 2009-13 GMC Sierra Hybrid 2WD & 4WD
  - 2009 Dodge Durango
  - 2009 Chrysler Aspen
- 2016-19: Gen 2 Strong Hybrid
  - 2016-19 Chevy Malibu Hybrid

Honda Hybrid Generations

- 144V NiMH
  - 2000-06 Honda Insight
  - 2003-05 Honda Civic Hybrid
  - 2005-07 Honda Accord Hybrid
- 158V NiMH
  - 2006-11 Honda Civic Hybrid
- 100.8V NiMH
  - 2011-12 Honda CR-Z Hybrid
  - 2010-14 Honda Insight
- 144V Li-Ion
  - 2012-15 Honda Civic Hybrid
  - 2013-16 Honda CR-Z Hybrid
  - 2013-14 Acura ILX Hybrid
  - 2012-16 Honda Fit/Jazz Hybrid (Japan)
- 260V Li-Ion
  - 2014-15, 17-19 Honda Accord Hybrid
  - 2014-19 Acura RLX Hybrid
  - 2017-19 Acura NSX Hybrid
  - 2017-19 Acura MDX Hybrid

2014 Honda Insight

2016 Acura RLX Hybrid

Images by Honda © Honda reserves all rights - http://automobiles.honda.com/

Battery Pack Parameters

Honda Motor Company
2000-19 Honda HEV Family

Acura NSX Battery Pack

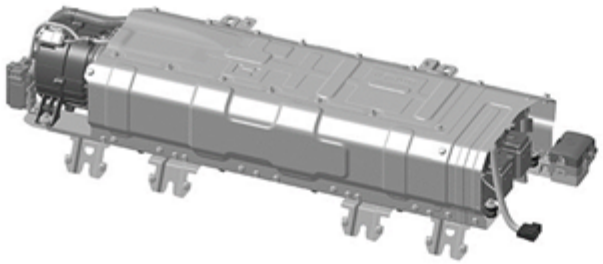
Image by Blue Energy © Blue Energy reserves all rights

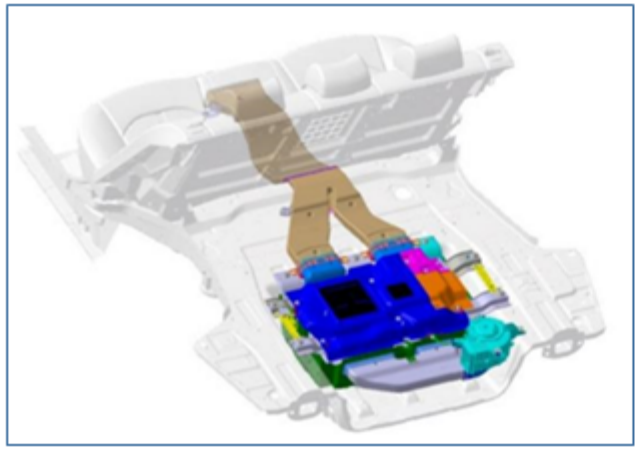
ESS Parameter	Insight Civic Accord	Civic	CR-Z Insight	Civic CR-Z Acura ILX Fit/Jazz	Accord Acura RLX Acura NSX Acura MDX	Honda Insight [1]
Model Years	2000-06 2003-05 2005-07	2006-11	2011-12 2010-14	2012-15 2013-16 2013-14 2012-16	2014-15, 17-19 2014-19 2017-19 2017-19	2019
Pack Integrator	Honda					
Chemistry Family	NiMH			Li Ion		
Configuration	120s1p	132s1p	84s1p	40s1p	72s1p	60s1p
Voltage (V)	144	158	100.8	144	260	216
Peak Power (kW)	13.8	15	12	Available with Report purchase		
Energy (kWh)	0.86	0.95	0.6			
P/E Ratio (kW/kWh)	16	15.8	20			
Mass (kg)	32	35.2	29.5			
Specific Energy (Wh/kg)	27	27	20.5			
BMS Type	Centralized			Centralized		
Thermal System	Air					
Enclosure Material	Metallic					

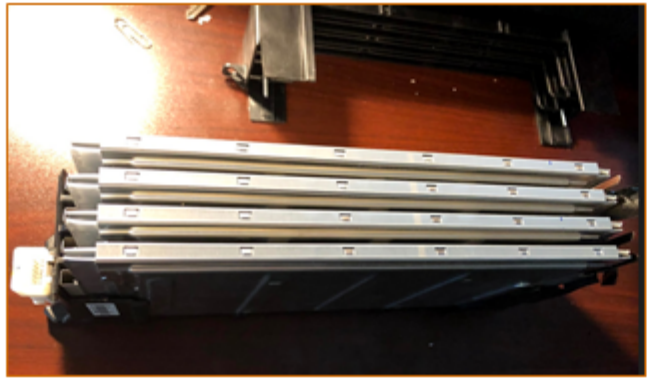
[1] *Estimated values*

Battery Pack Parameters

Hyundai Motor Group
2011-19 Hyundai Sonata & 2017-19 Ioniq
2011-19 Kia Optima & 2017-19 Niro







Top: Ioniq/Niro Battery Pack

Middle : Sonata/Optima Battery Pack

Images by Hyundai © Hyundai reserves all rights

http://www.hyundainews.com/us/en/media/pressreleases/

http://www.hyundai.com/eu/en/Showroom/Eco/IONIQ-Electric/PIP/index.html

ESS Parameter	Sonata/Optima				Ioniq/Niro
Year	2011-12	2013-15	2016	2017 -19	2017-19
Pack Integrator	Hyundai				Hyundai
Chemistry Family	Lithium Ion Pouch				Li-Ion Pouch
Configuration	72s1p				64s1p
Voltage (V nominal)	Available with Report purchase				
Peak Power (kW)	34				
Energy (kWh)	1.43				
P/E Ratio (kW/kWh)	24.3				
Mass (kg)	43.5				
Specific Energy (Whr/kg)	32.2				
BMS Type	Centralized				Centr.
Thermal System	Air				Air
Enclosure Material	Metallic				Metallic

Nissan/Infiniti Hybrid Generations

- **244.8V NiMH**
  - 2007-11 Nissan Altima
- **346V Li-Ion**
  - 2012-13 Infiniti M35h Hybrid
  - 2014-18 Infiniti Q70 Hybrid
  - 2012-18 Infiniti Q50 Hybrid
  - 2010-16 Nissan Fuga Hybrid (Japan)
  - 2012-15 Nissan Cima Hybrid (Japan)
  - 2014-16 Nissan Skyline Hybrid (Japan)
- **144V Li-Ion**
  - 2014 Nissan Pathfinder Hybrid
  - 2012-17 Infiniti QX60 Hybrid
  - 2016 Nissan Murano Hybrid
- **300V**
  - 2015-2019 Nissan e-note
- **202V Li-Ion**
  - 2017-19 Nissan Rogue Hybrid

Images by Infiniti © Infiniti reserves all rights - http://www.infinitiusa.com/content/dam/infiniti/vehicles/

2014 Infiniti QX60 Hybrid

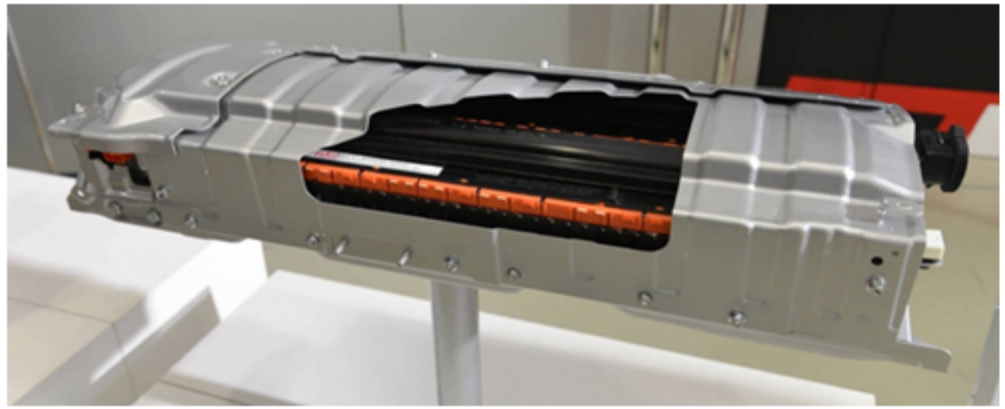
2015 Infiniti Q70 Hybrid

Unique Hybrid Battery Pack Designs

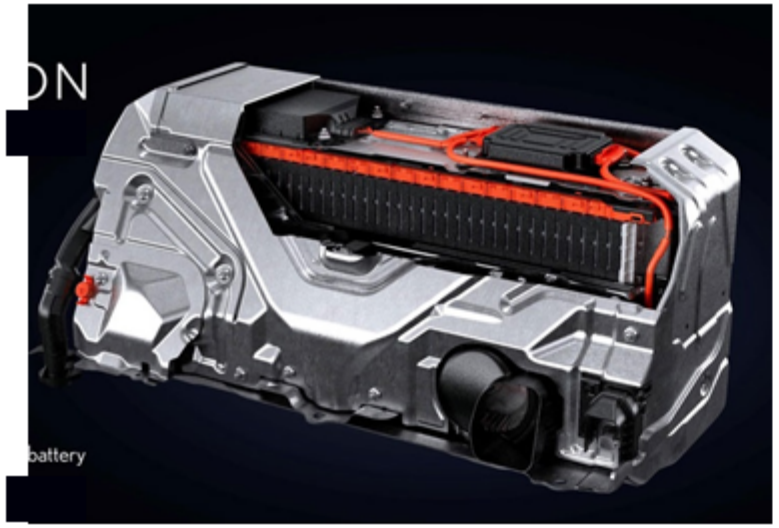
- **144V NiMH**
  - 2012-17 Toyota Prius c
  - 2014-16 Toyota Corolla (Jpn)
- **201.6V NiMH**
  - 2004-09 Toyota Prius Gen 2
  - 2010-15 Toyota Prius Gen 3
  - 2016-19 Toyota Prius Gen 4 (certain models)
  - 2012-17 Toyota Prius v
  - 2011-17 Lexus CT 200h
  - 2014-16 Toyota Voxy/Noah (Jpn)
- **216V NiMH**
  - 2019 Lexus UX 250h
- **230.4 V NiMH**
  - 2014-16 Lexus GS 300h (EU & Jpn)
  - 2015-16 Lexus RC (EU & Jpn)
- **244.8V NiMH**
  - 2007-19 Toyota Camry Hybrid
  - 2013-19 Toyota Avalon Hybrid
  - 2013-19 Lexus ES 300h
  - 2010-12 Lexus HS 250h
  - 2015-19 Lexus NX 300h FWD/AWD
  - 2016-18 Toyota RAV4 Hybrid AWD
  - 2014-16 Toyota Harrier (Jpn)
- **273.6V NiMH**
  - 2001-03 Toyota Prius Gen 1
- **288V NiMH**
  - 2006-19 Toyota Highlander
  - 2006-08 Lexus RX 400h
  - 2010-19 Lexus RX 450h
  - 2007-11 Lexus GS 450h
  - 2013-18 Lexus GS 450h
  - 2008-16 Lexus LS 600h
  - 2014-16 Toyota Majesta (Jpn)

- **207.2V Lilon**
  - 2012-16 Toyota Prius v (Japan)
  - 2016-19 Toyota Prius (certain models)
- **259V Lilon**
  - 2018-19 Toyota Camry LE
- **310.8V Lilon**
  - 2018-19 Lexus LC 500h Hybrid
  - 2018-19 Lexus LS 500h Hybrid

Toyota's Li-Ion HEV Products



Toyota Camry Battery



Lexus LC 500h and LS 500h Battery

Images by Toyota © Toyota reserves all rights

ESS Parameter	Lithium-Ion Battery Packs			
Model Years	2012-16 Prius v (Japan)	2016-19 Prius	2018-19 Camry	2018-19 Lexus LC 500h; LS 500h
Pack Integrator	Panasonic & PEVE	Available with Report purchase		
Chemistry Family				
Configuration	56s			
Voltage (V nom)	207.2			
Peak Power (kW)	60 (system)			
Energy (kWh)	1.03			
P/E Ratio (kW/kWh)	60			
Mass (kg)	34			
Specific Energy (Wh/kg)	29			
BMS Type	Centralized			Distributed
Thermal System	Air			
Enclosure Material	Metallic			

Battery Cell Parameters

Volkswagen Group
2011-16, 2019 VW/Porsche/Audi HEV Family

Parameter	2011-14 Porsche Cayenne S 2012-13 Porsche Panamera S 2011-15 VW Touareg	2013-16 VW Jetta 2013-16 Audi Q5	2019 Audi A6 2019 Audi A7 2019 Audi A8 [1]
Cell Supplier	Panasonic/Sanyo	Panasonic	LG Chem
Cell Type	Cylindrical	Prismatic Metal Can	Prismatic Pouch
Anode Chemistry	Ni Alloy	Graphite	Graphite
Cathode Chemistry	NiO(OH)	LiNCM	NMC
Cell Capacity (Ah)	6	5	9.6
Cell Voltage (V)	1.2	Available with Report purchase	
Weight (g)	180		
Dimensions (mm)	32.3Dx58.5L		
Volume (mL)	48		
Specific Energy (Wh/kg)	40		
Energy Density (Wh/L)	150.2		
Specific Power (W/kg) (10sec disch.)	1055		

Top left – Panasonic NiMH cylindrical cell
Middle – Panasonic LiIon Metal Can Prismatic Cell
Bottom – LG Chem LiIon Prismatic Pouch Cell

[1] Estimated values

Report Outline

I. xEV Battery System Key Design Attributes

II. Battery Packs for EVs

III. Battery Packs for PHEVs

IV. Battery Packs for HEVs

V. Charging Systems of EV/PHEVs

V. Charging Systems of EV/PHEVs

A. **Charging Systems Overview**

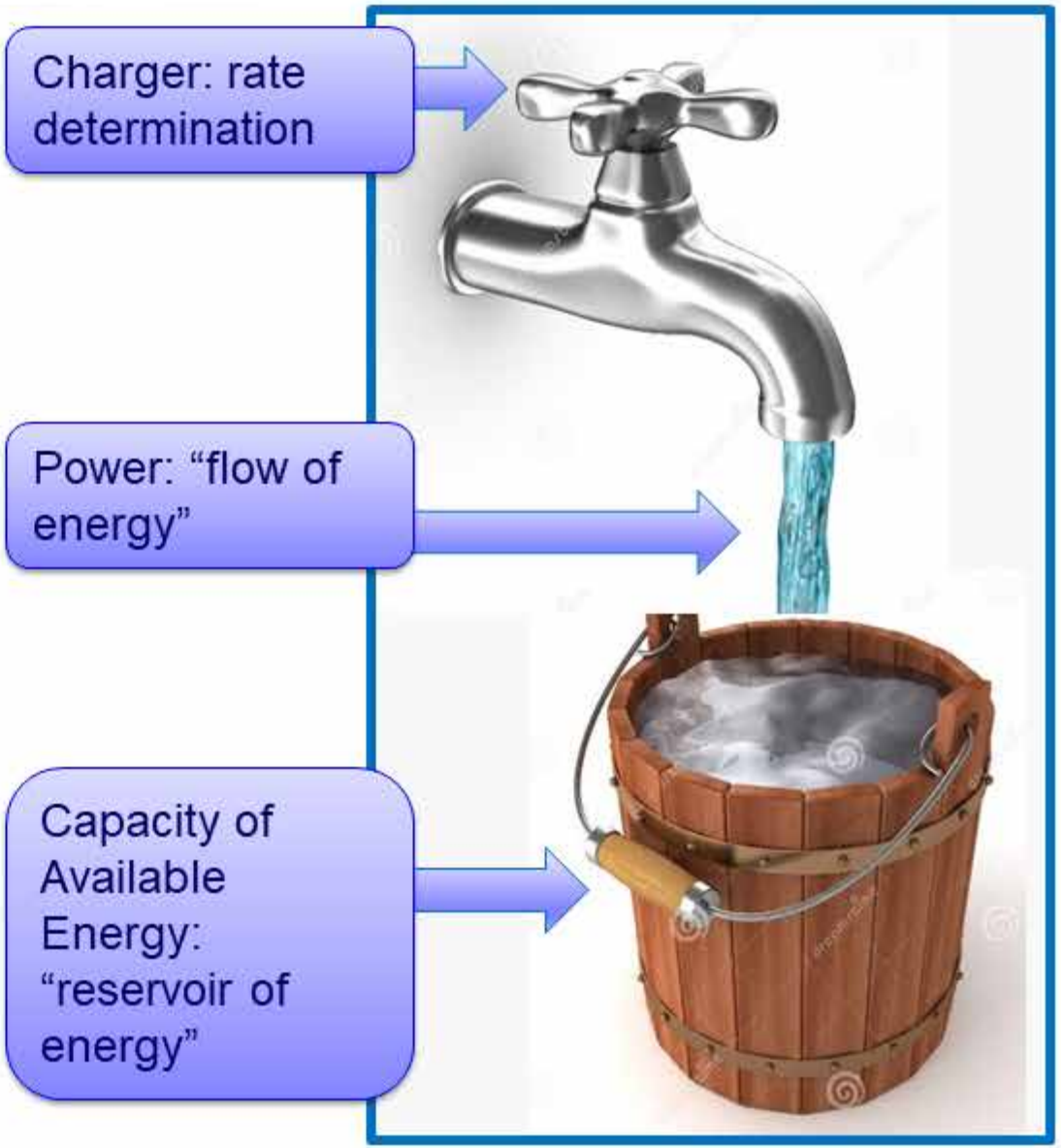
B. Charging Standards

C. Application Usage of Charging

D. Vehicle Trends for Production EVs

Charging Systems

- **Charge power determined by multiple items, including:**
  1. **Battery Cell Capability**
     - Plating Avoidance
     - Impact on Cycle Life
  2. **Battery Cell/Module Condition at Time of Charge**
     - Impedance Degradation
     - Cell Temperature
     - SOC
  3. **Available Utility Power**
  4. **Maximum Charging System Electronics Design**
     - Charger Maximum Power
     - Cabling/Wiring/Bus-Bars
  5. **Battery Thermal System**
     - Capability to Reject Heat to Maintain Peak Power Levels



➢ Charging System Standards

Tesla

- **Electric Vehicle or Plug-in Hybrid-Electric Vehicle**
  - "AC Charging" (typically on-board AC/DC power conversion)
    - Tesla
    - SAE J1772
    - IEC 62196 ("Mennekes")
    - GB/T (China) 20234.2-2015
  - "DC Fast-Charge" (off-board AC/DC power conversion)
    - Tesla
    - CCS1 (SAE J1772)
    - CCS2 (IEC 62196)
    - CHAdeMO
    - GB/T (China) 20234.3-2015

Source: zhangjiagangyouchen

SAE J1772
Source: Delphi

IEC62196
Source: Mennekes

SAE J1772
Source: SAE

IEC62196
Source: Mennekes

CHAdeMO
Source: Yazaki

Charging

- **1. Growth outlook for charging infrastructure**
  - **DC Fast Charging (DCFC) grows in multiple standards**
    - Tesla supercharging
    - CHAdeMO
    - SAE j1772 ('Combo') – newer standard
    - China GB/T charging standard

Chademo (left) and SAE Combo (right)

- **2. Potential difficulties to the roll out of charging infrastructure**
  - Present-day infrastructure is still limiting for long-distance drives; requiring 30-40 minutes for charge every 2-3 hrs of driving
  - Rate is mostly current-limited (i.e. max'd out)
  - Porsche is proposing a high-voltage (~800V) architecture to allow for faster charge times for long-distance drives (targeting ~15 minutes)
- **3. Drivers leading to greater adoption**
  - **Longer-range EVs open up ability to drive long distances**
    - Previously not possible w/ <100 mile EV range compliance cars
  - **More of a driver demand for fast-charging in order to replace ICE cars**
    - Otherwise, expectation is to keep an ICE car for convenience
      - This is removed with longer-range EVs and short charge-times

AC Charge Standards

Ratings	SAE J1772-2017 (US/Global)	IEC62196 – Type 2 "Mennekes" (Europe) (1-phase)	(3-phase)	GB/T (China) 20234.2-2015
Level/Mode 1	120 V 12 A 16 A **1.4 kW 1.9 kW**	16 A **3.7 kW**	16 A **11.0 kW**	16A, 32A 250V/400V **4 kW 12.8 kW**
Level/Mode 2	240 V 80 A **19.2 kW**	32 A **7.4 kW**	32 A **22.0 kW**	n/a
Level/Mode 3	n/a	63 A **14.5 kW**	63 A **43.5 kW**	n/a

Chademo (left) and SAE Combo (right)

DCFC Standards

Ratings	Tesla (in use in 2018)	CCS (SAE J1772-2017) DC Level 1	DC Level 2	CHAdeMO	GB/T (China) 20234.3-2015
Voltage (rated)	**400 V**	50-1000 V	50-1000 V	500 V	400-1000 V
Current (rated)	**300 A**	80 A	400 A	125 A	80-250 A
Power (max rated)	**120 kW**	80 kW	400 kW	62.5 kW	32-187.5 kW
Power (application @ Vmax = 400Vdc)	**120 kW**	32 kW	160 kW	45 kW	90 kW
Power (application @ Vmax = 800Vdc)	**n/a**	64 kW	320 kW	n/a	180 kW

- **Long-distance driving example**

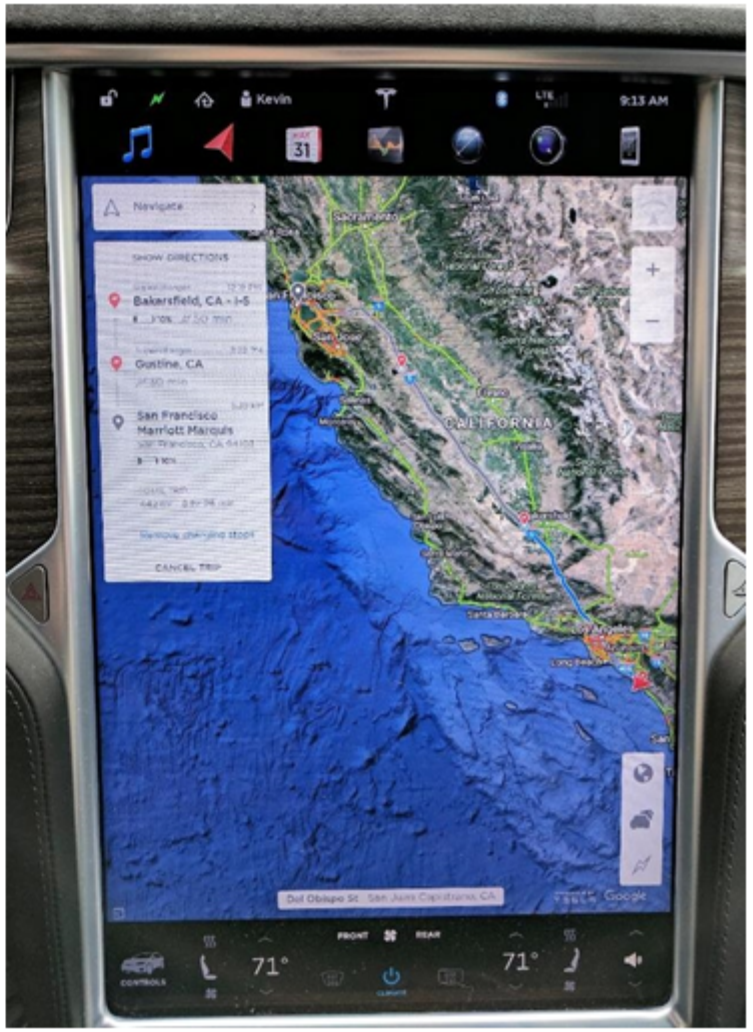
Initial drive
100 -> 10% SOC

Charge
10 -> TBD% SOC
(30min lim)

2nd drive
< 80% -> 10% SOC

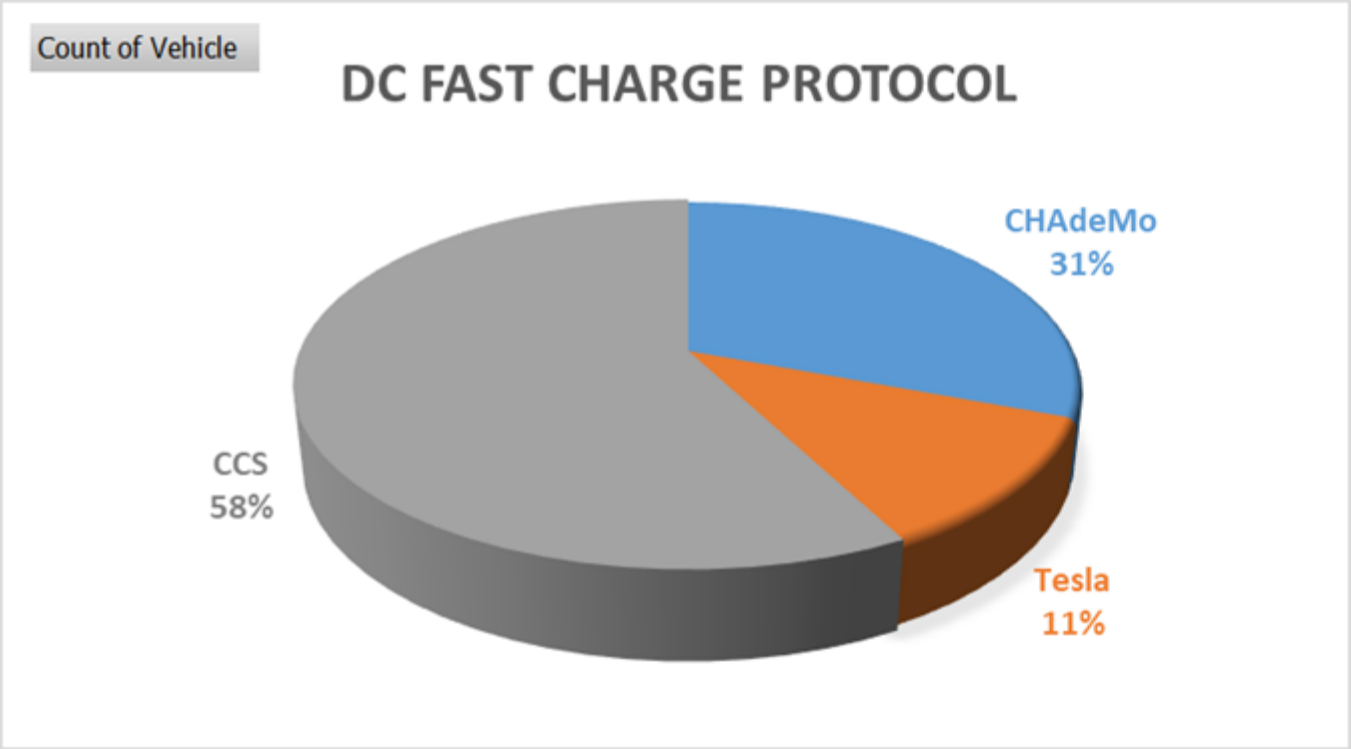
Charge
10 -> TBD% SOC
(30min lim)

Example Vehicle	Charge Power Peak (kW)	Charge Power 30-min Ave (kW)	Real-World Miles Added Per 30-min Charge	Driving To Next Charge @ 70mph (hrs)
Tesla Model 3 Long-Range	120	95	175.0	2.50
Tesla Model S 100D	120	86	129.0	1.84
Chevy Bolt EV	50	45	75.9	1.08
Example Vehicle	**MPG (real-world)**	**Fuel added per refill (<30 min; 85% capacity)**	**Real-world Miles Added per Refill (mi)**	**Driving To Next Refill @ 70mph ave (hrs)**
Toyota Prius	50.0	9.6	480.3	6.86
Ford Explorer (AWD V6)	17.5	15.8	276.7	3.95

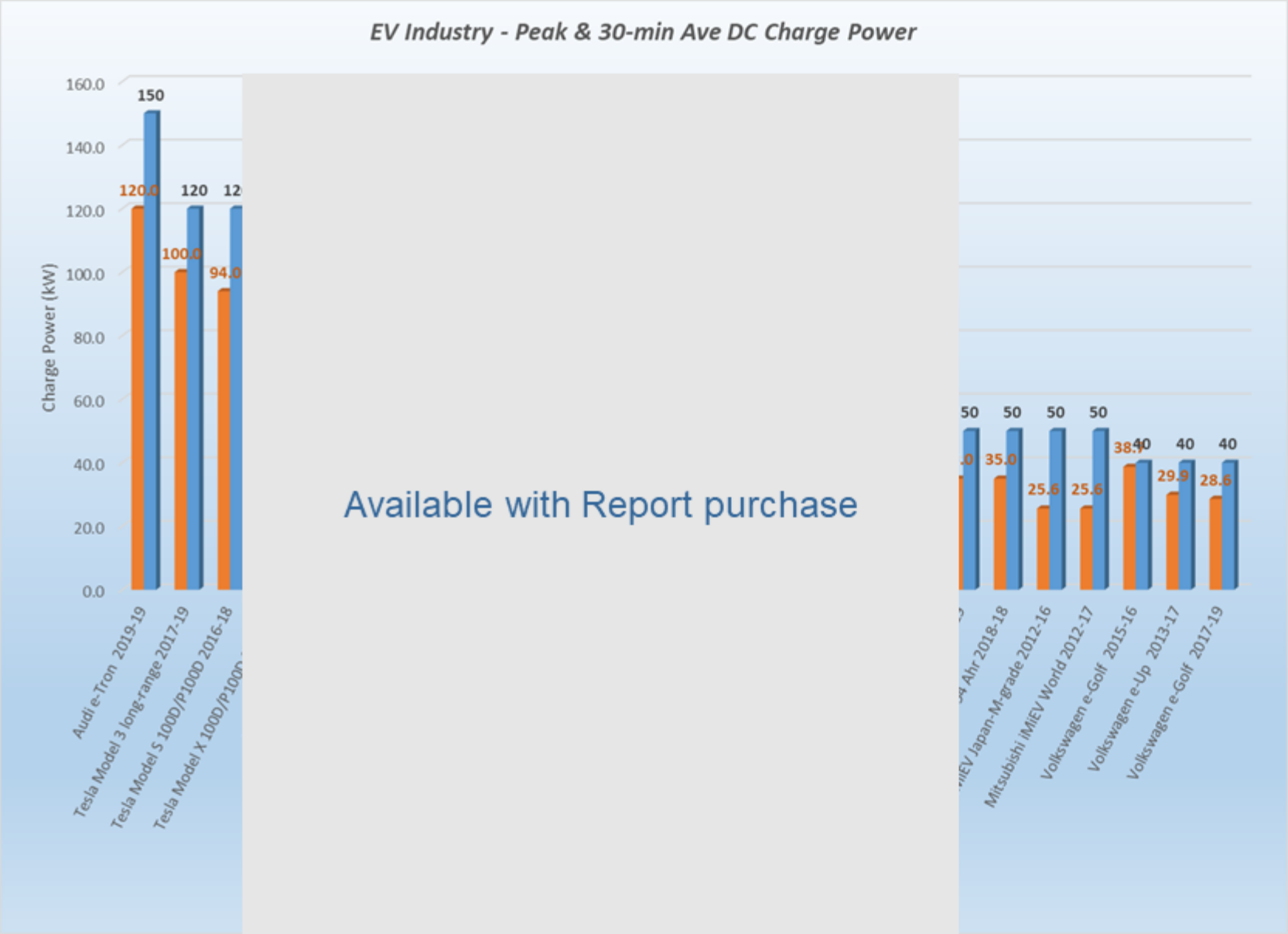


DC Fast Charge Trends

- CCS is more prevalent for DC fast charging in vehicle design



Vehicle	DCFC Protocol
Audi e-Tron 2019-19	CCS
BMW i3 BEV 120 Ahr 2019-19	CCS
BMW i3 BEV 60 Ahr 2014-17	CCS
BMW i3s BEV 120 Ahr 2019-19	CCS
BMW i3s BEV 94 Ahr 2018-18	CCS
Chevrolet Bolt EV 2017-19	CCS
Ford Focus EV 2017-18	CCS
Hyundai Ioniq Electric 2017-19	CCS
Hyundai Kona Electric Long-Range 2019-19	CCS
Jaguar I-Pace 2019-19	CCS
Kia Niro Electric Long-Range 2019-19	CCS
Kia Soul EV 2015-17	CHAdeMo
Kia Soul EV 2018-19	CHAdeMo
Mercedes EQC 2019-	CCS
Mitsubishi iMiEV Japan-M-grade 2012-16	CHAdeMo
Mitsubishi iMiEV World 2012-17	CHAdeMo
Nissan Leaf 2011-13	CHAdeMo
Nissan Leaf 2014-16	CHAdeMo
Nissan Leaf 2018-19	CHAdeMo
Nissan Leaf (30kWh) 2016-17	CHAdeMo
Tesla Model 3 long-range 2017-19	Tesla
Tesla Model S 100D/P100D 2016-18	Tesla
Tesla Model X 100D/P100D 2016-18	Tesla
Volkswagen e-Golf 2015-16	CCS
Volkswagen e-Golf 2017-19	CCS
Volkswagen e-Up 2013-17	CCS



DC Fast Charge Power

- Audi offers highest DC fast-charging capability based on preliminary specifications
  - Note: All values In this chart (except Tesla Model 3) are advertised/rated
  - Real-world/tested values are used elsewhere in this report and are noted as such