Modeling Power in Electric Vehicles

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October 15, 2014

Transportation Electrification

Motivation

- Improve efficiency: reduce energy consumption
- Displace petroleum as primary energy source
- Reduce impact on environment
- Reduce cost

EIA:

- Transportation accounts for 28% of total U.S. energy use
- Transportation accounts for 33% of CO2 emissions
- Petroleum comprises 93% of US transportation energy use

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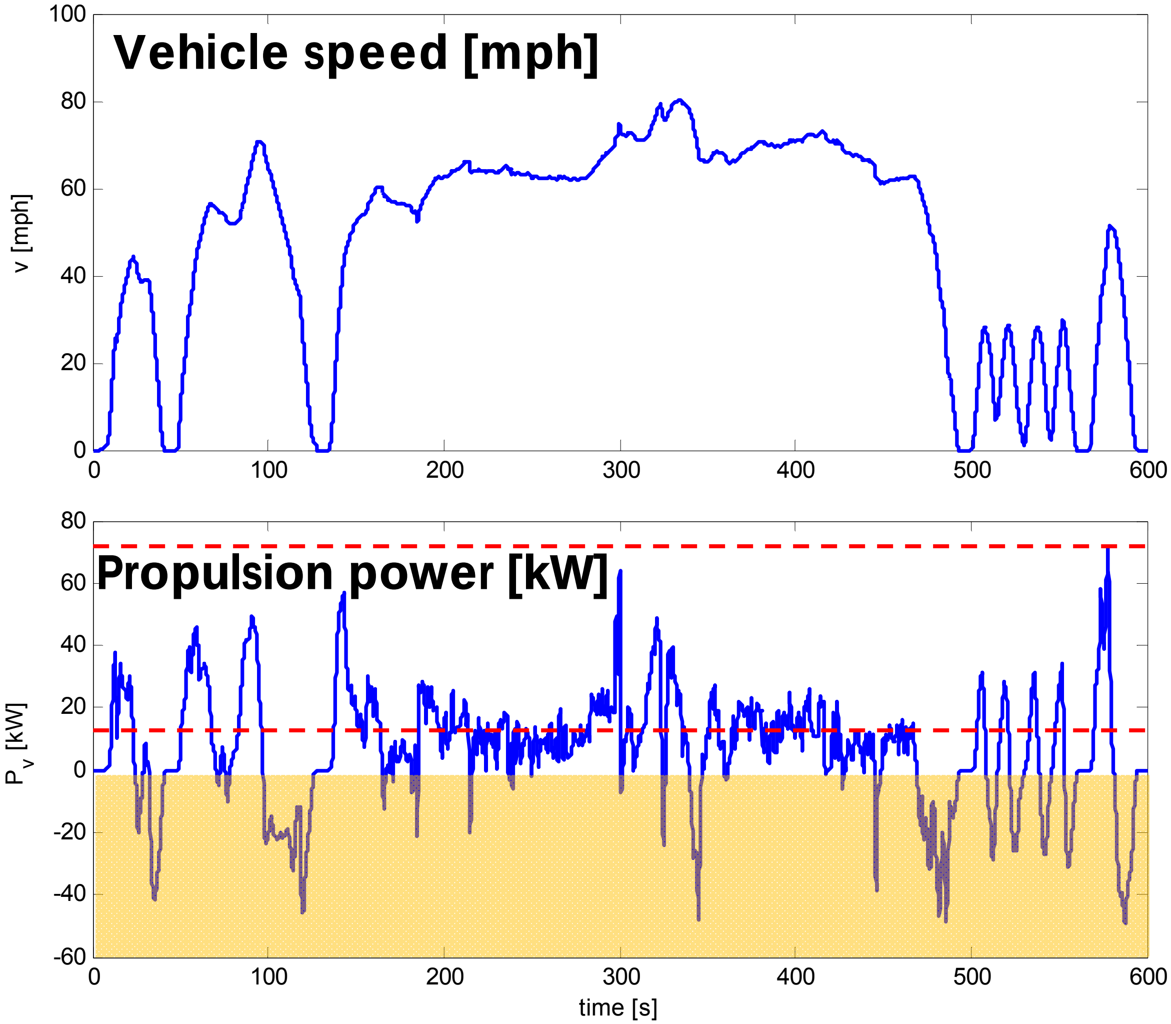
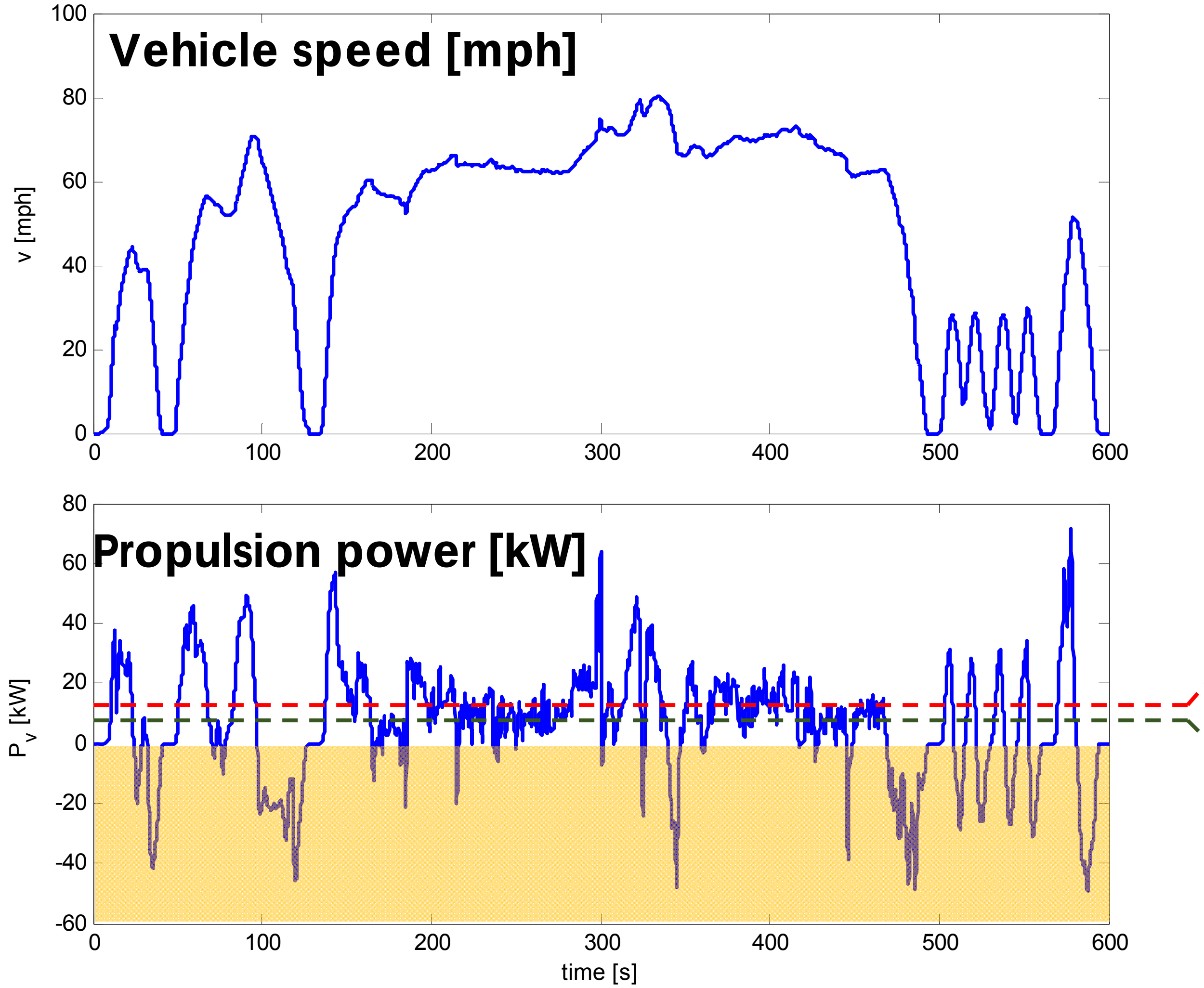
Example: US06 driving cycle



10-min
8 miles

Example:
Prius-sized
vehicle

Average power and energy



Prius-sized vehicle

Dissipative braking

P_{vavg} = 11.3 kW

235 Wh/mile

Regenerative braking

P_{vavg} = 7.0 kW

146 Wh/mile

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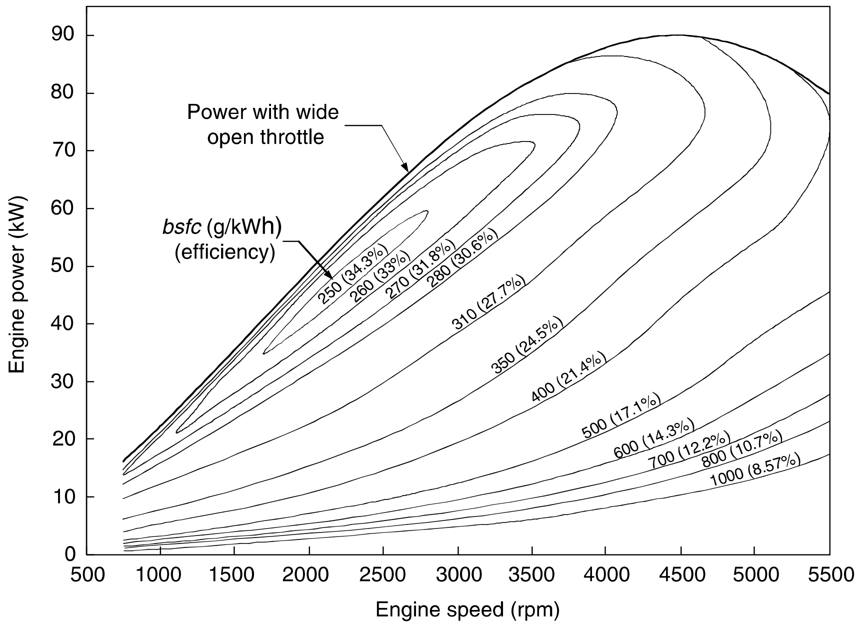
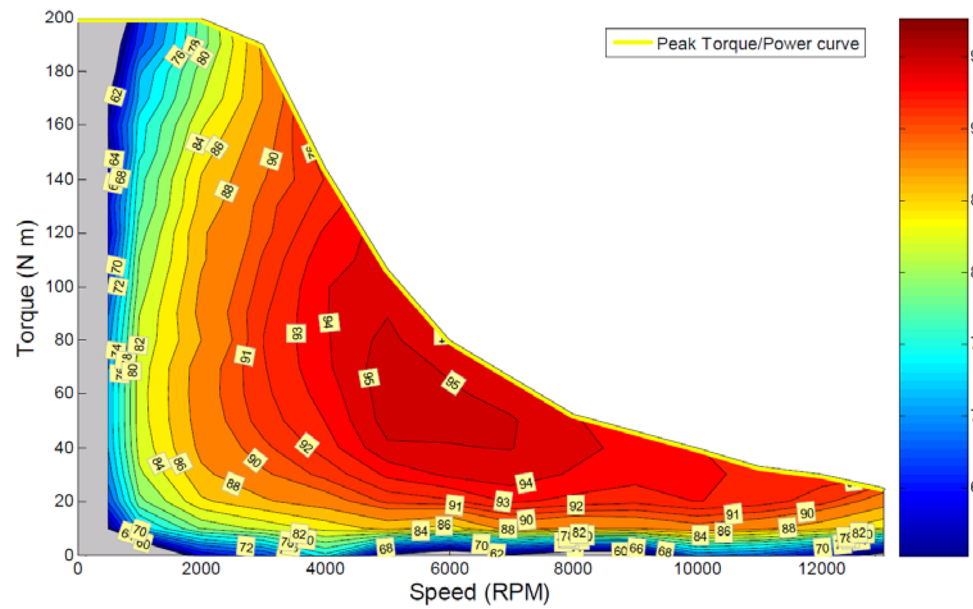
ICE vs. ED



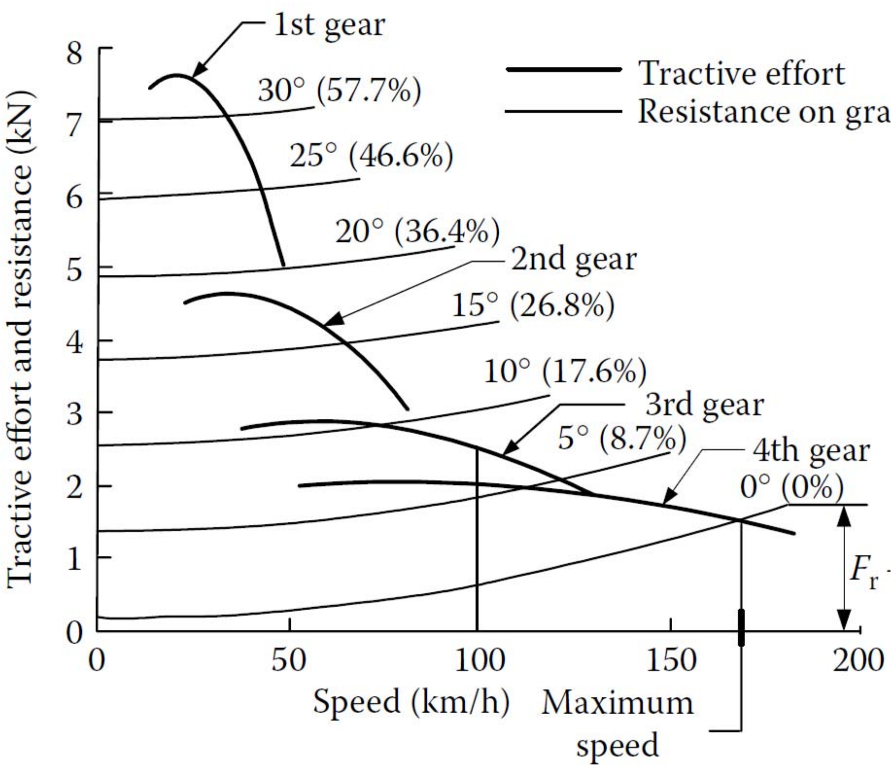
Internal Combustion Engine (ICE)



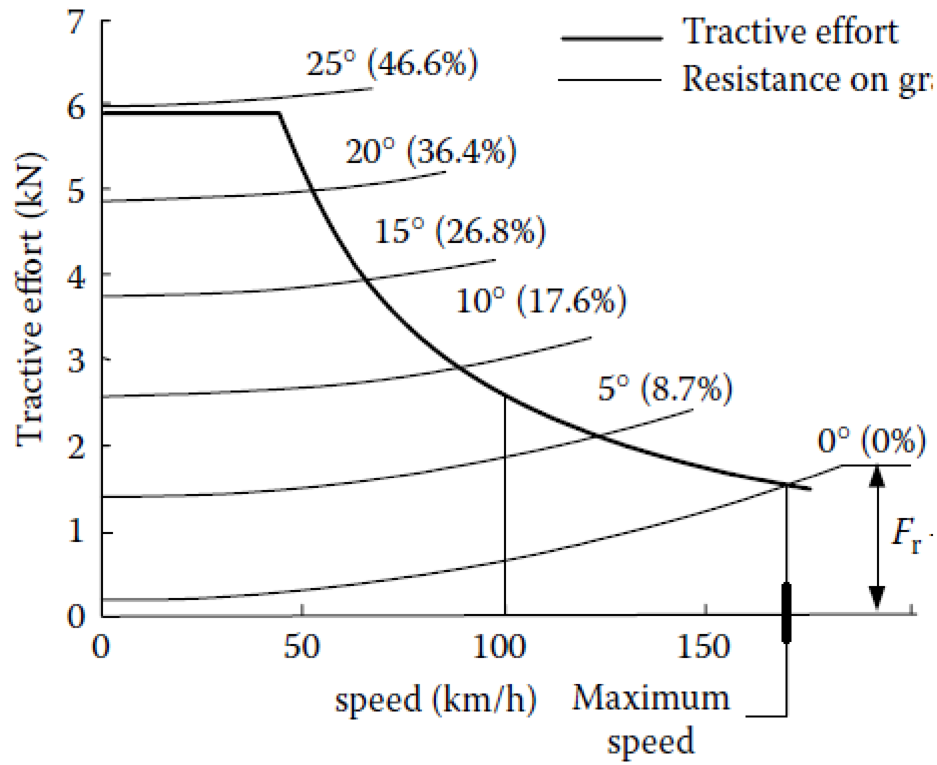
Electric Drive (ED)

- ED offers full torque at zero speed
- $\eta_{ED,pk} \approx 95\%$; $\eta_{ICE,pk} \approx 35\%$

Transmissions in Conventional Vehicles



ICE with multi-gear transmission



Electric motor with single gear

Conventional Vs. Electric Vehicle

(Prius-sized vehicle example)

	Tank + Internal Combustion Engine	Electric Vehicle (EV) Battery + Inverter + AC machine
Regenerative braking	NO	YES
Tank-to-wheel efficiency	≈ 20% 1.2 kWh/mile, 28 mpg	≈ 85% 0.17 kWh/mile, 200 mpg equiv.
Energy storage	Gasoline energy content **12.3 kWh/kg, 36.4 kWh/gallon**	$LiFePO_4$ battery 0.1 kWh/kg, 0.8 kWh/gallon
Refueling	5 gallons/minute **11 MW**, 140 miles/minute	Level I (120Vac): 1.5 kW, <8 miles/hour Level II (240Vac): 6 kW, <32 miles/hour Level III (DC): 100 kW, <9 miles/minute
Cost	12 ¢/mile [$3.50/gallon]	2 ¢/mile [$0.12/kWh]
CO_2 emissions (tailpipe, total)	≈ (300, 350) g CO_2/mile	(0, ≈120) g CO_2/mile [current U.S. electricity mix]

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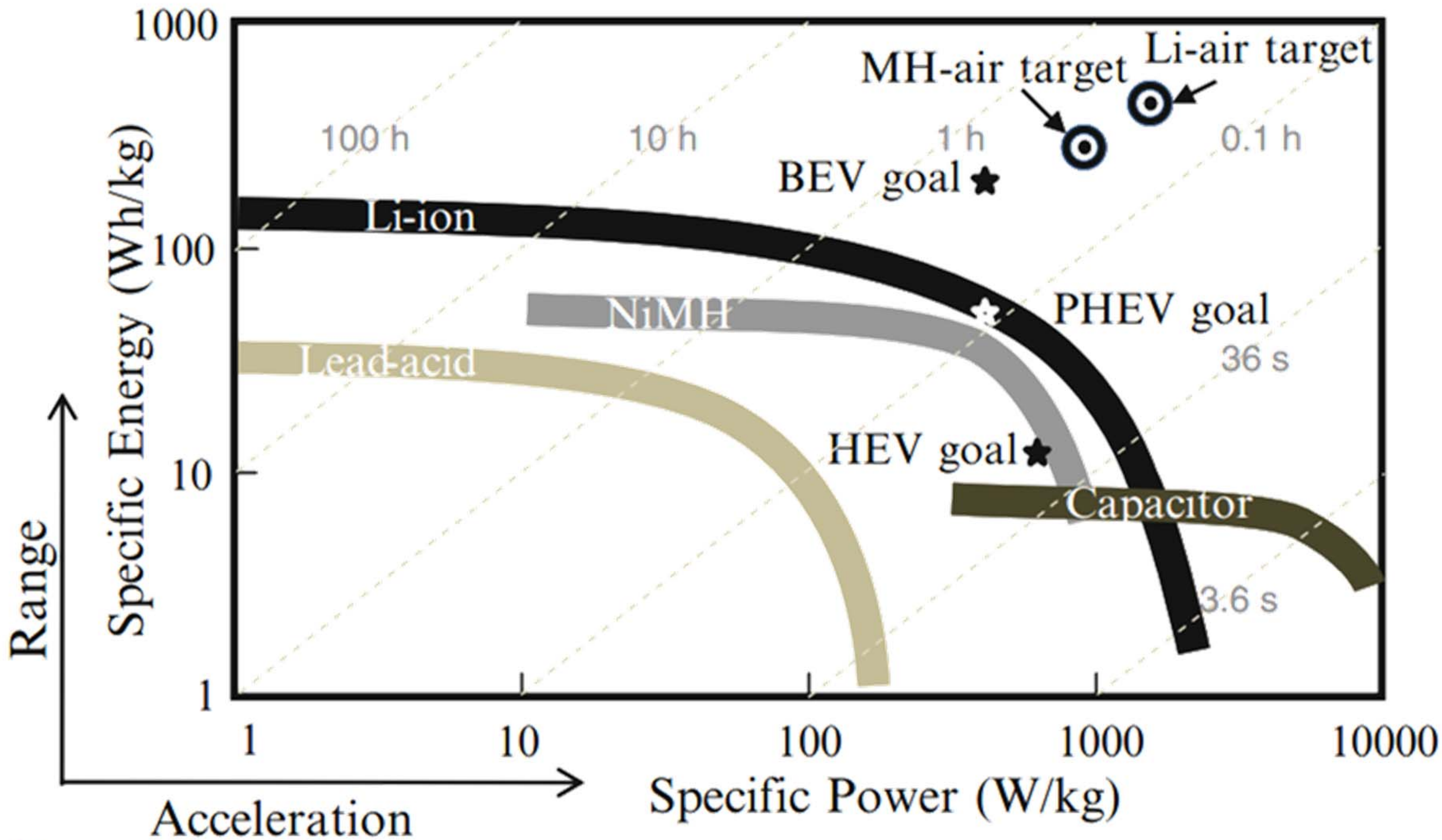
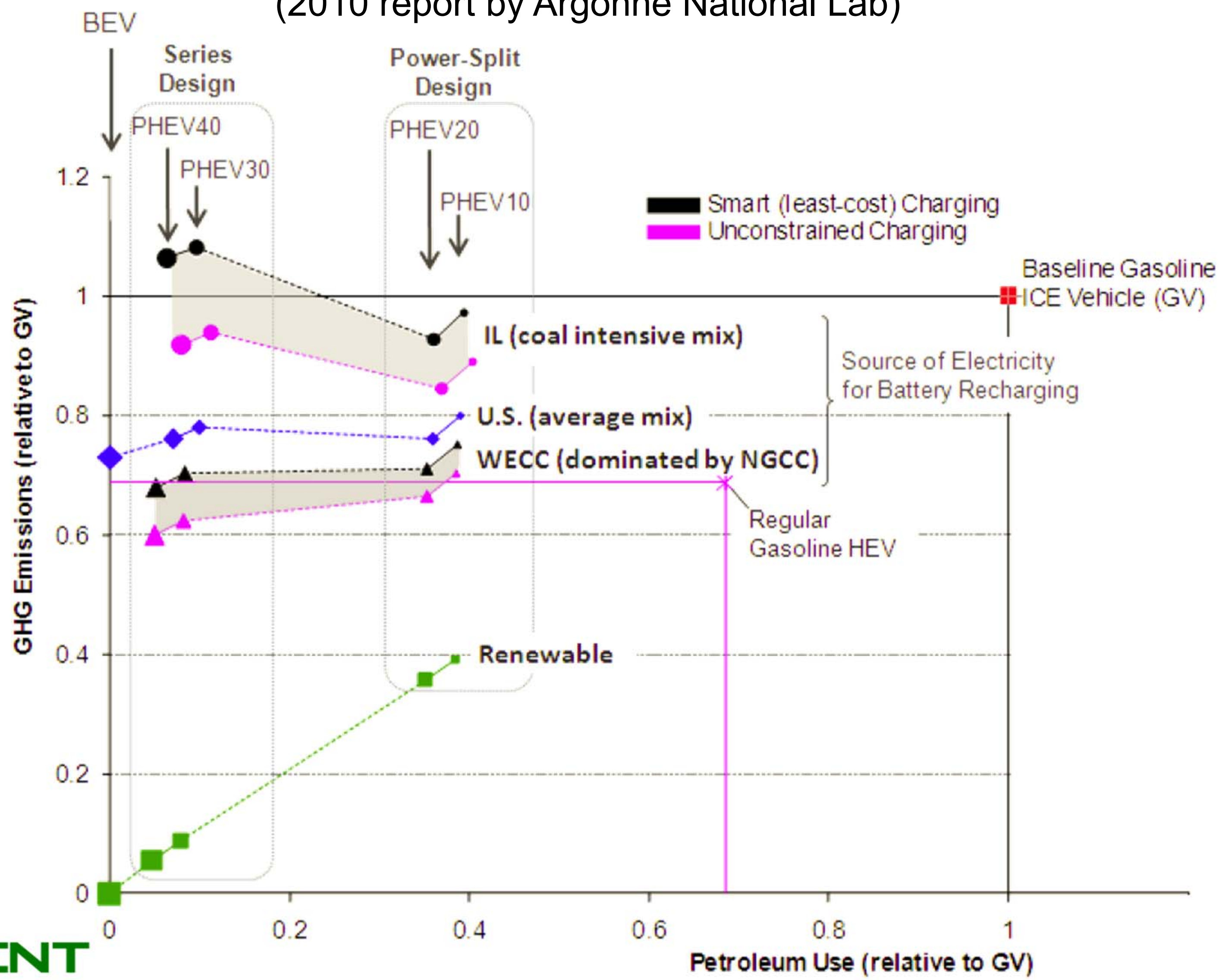
Energy and Power Density of Storage

12000



CO_2 emissions and oil displacement study

Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of PHEVs
(2010 report by Argonne National Lab)



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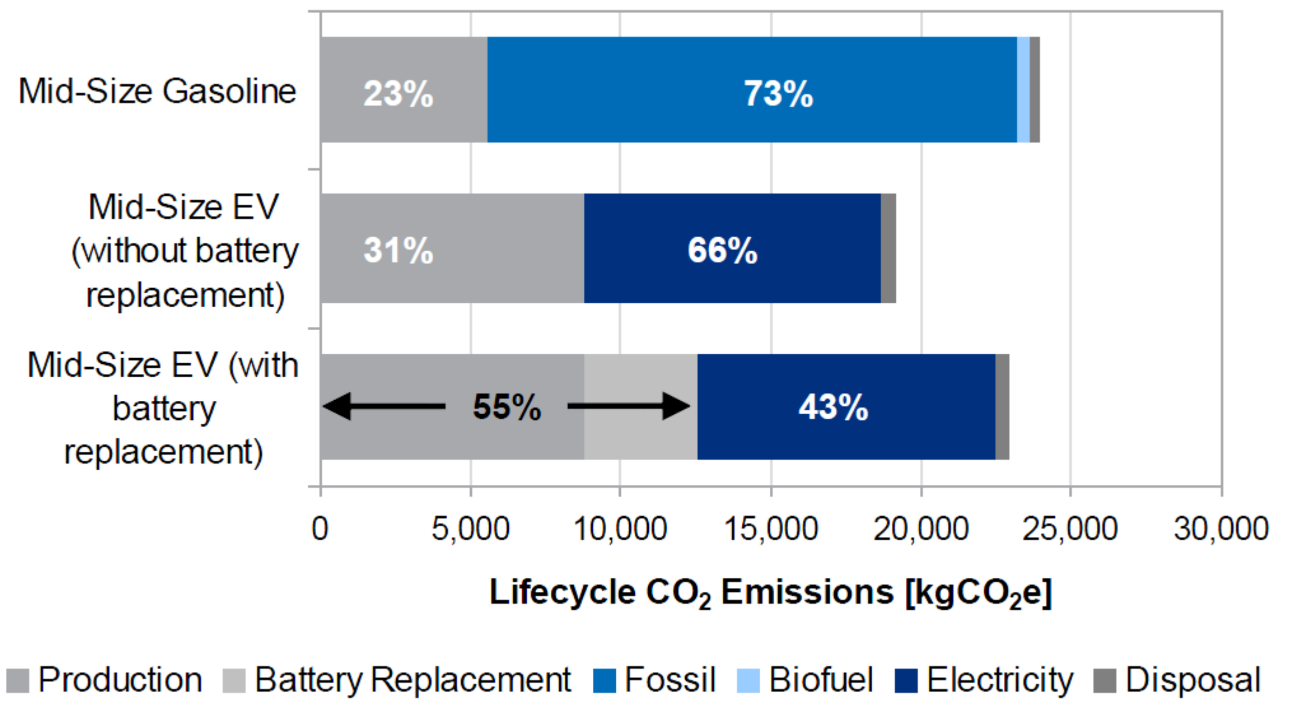
CO_2 emissions Over Full Lifetime

Preparing for a Life Cycle CO_2 Measure (2011 report by Ricardo)



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Conventional Vs. Electric Vehicle

(Ford Focus comparison)

	Tank + Internal Combustion Engine (Ford Focus ST)	Electric Vehicle (EV) Battery + Inverter + AC machine (Ford Focus Electric)
Purchase Price	$24,495	$39,995
Significant Maintenance	$5,000 (Major Engine Repair)	$0 - 13,500 (Battery Pack Replacement)
Energy Costs (10-year, 15k mi/yr)	$18,000	$3,000
Range	> 350 mi	< 100 mi
Performance	160 hp @ 6500 rpm 0-60 mph : 8.7 sec ¼ mile: (16.4 sec @ 85.4 mph)	123 hp, 2000-12000 rpm 0-60 mph: 9.6 sec ¼ mile: (17.2 sec @ 82.1 mph)
Curb Weight	3,000 lb	3,700 lb

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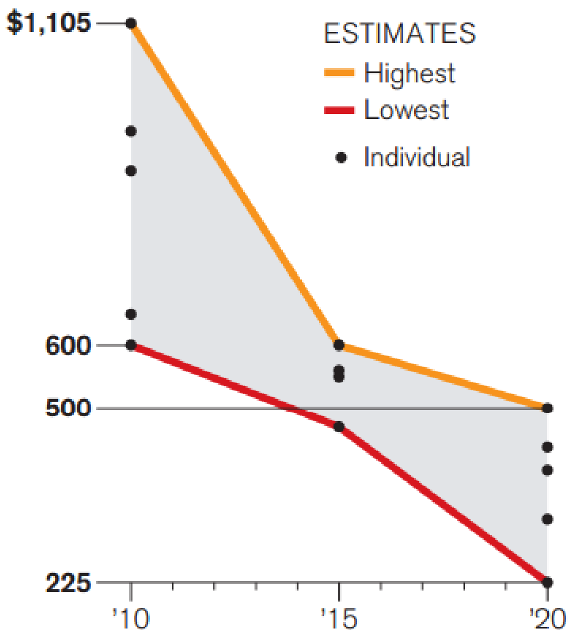
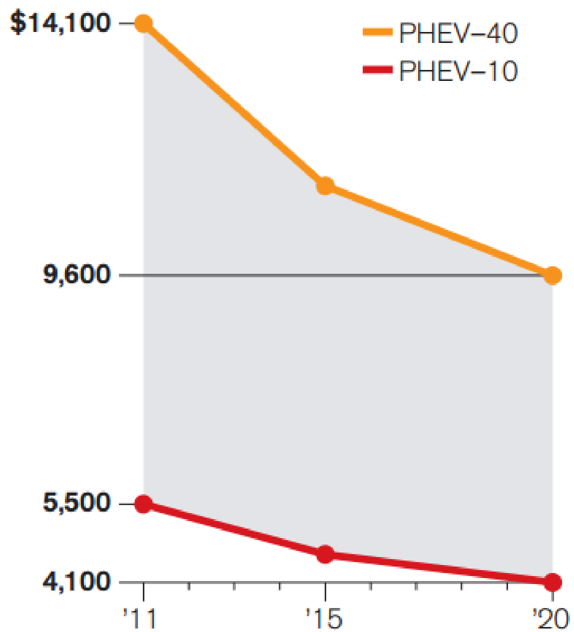
The Price of Batteries

Estimates of electric-vehicle battery costs
$ per kilowatt-hour



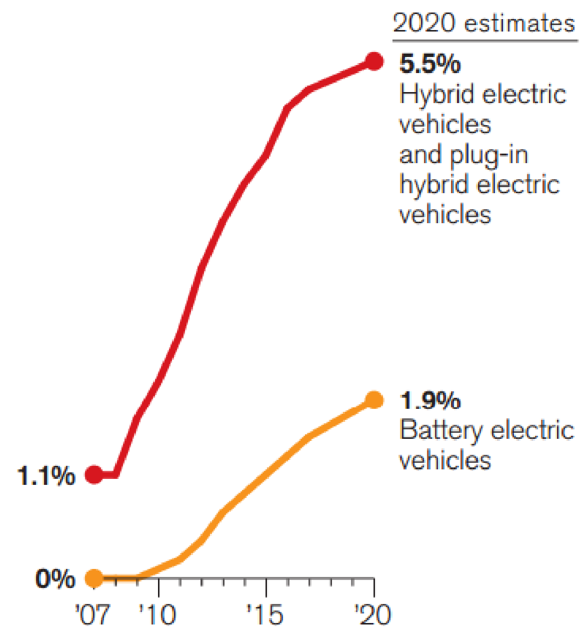
Sources: Advanced Automotive Batteries, Boston Consulting Group, Deutsche Bank, Electrification Coalition, National Research Council, and Pike Research

Additional cost of a plug-in hybrid electric vehicle (PHEV) over a conventional vehicle*



*Note: *Low estimates for cars with 40- or 10-mile electric range. Source: National Research Council*

Market share of hybrid and electric vehicles
2007–2020, estimated



Source: J. D. Power & Associates

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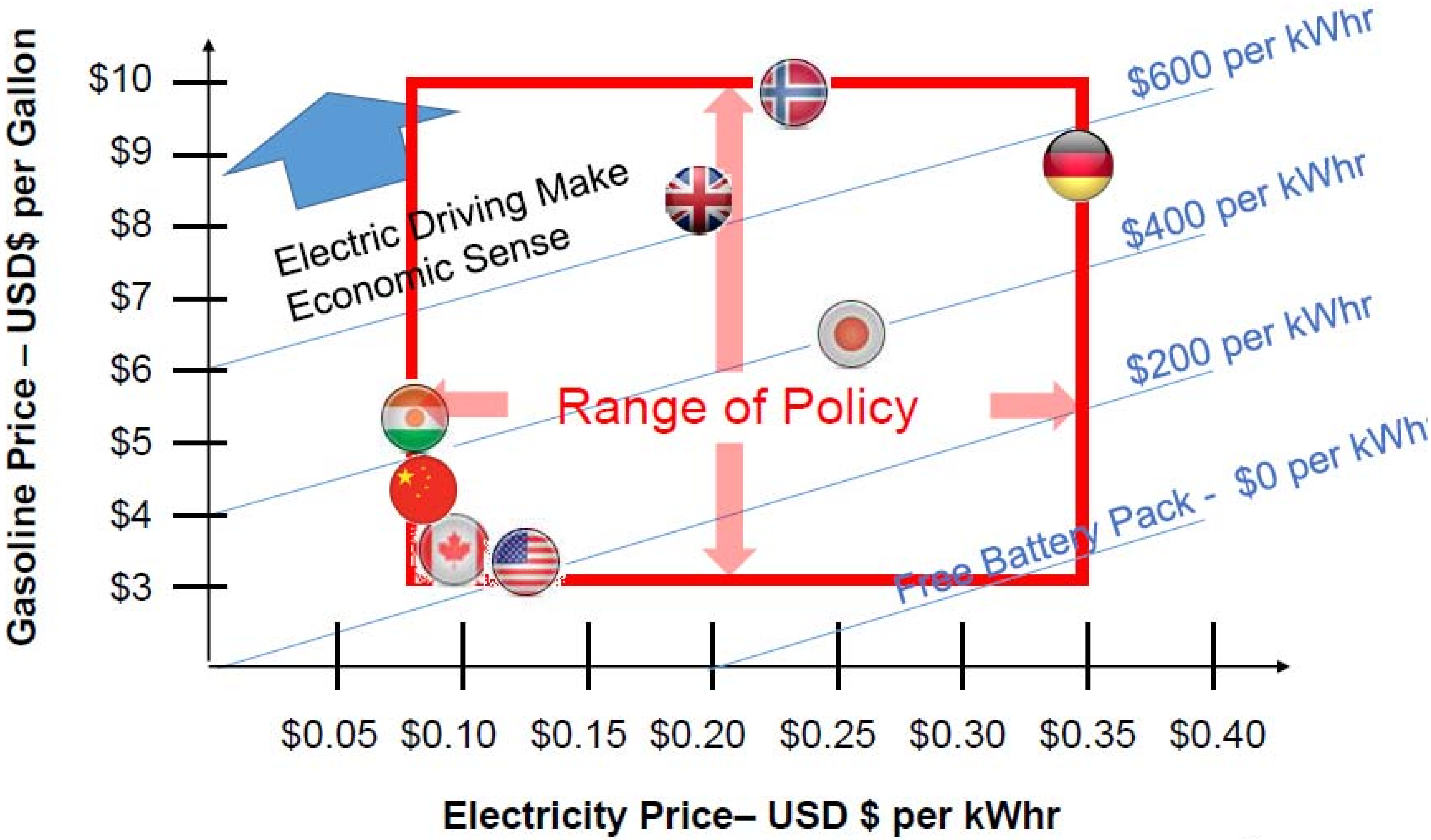
The Impact of Policy



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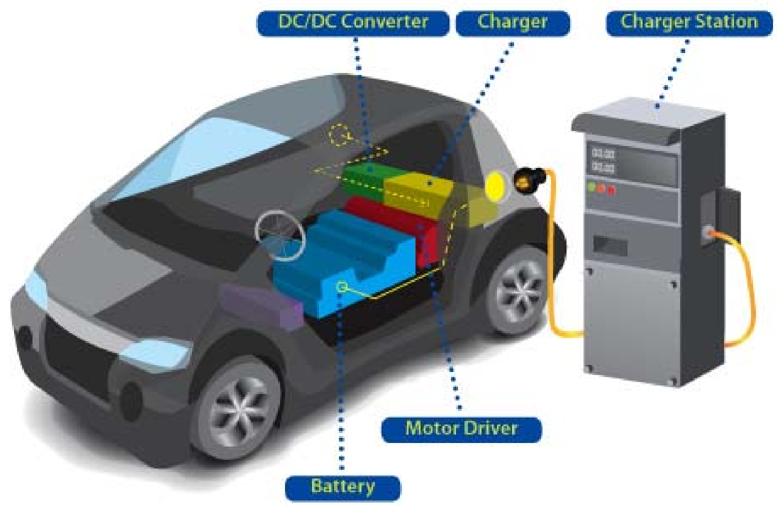
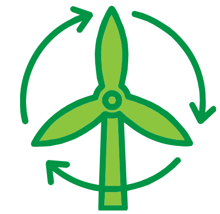
Peter Savagian, “Barriers to the Electrification of the Automobile,” Plenary session, ECCE 2014

A Vision: Renewable Sources + Battery Electric Vehicles





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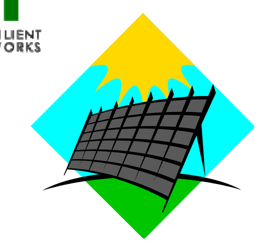
CENTER FOR ULTRA-WIDE-AREA RESILIENT ELECTRIC ENERGY TRANSMISSION NETWORKS



- Zero GHG emissions, no petroleum
- High efficiencies are feasible: 80% grid-to-wheel
- Challenges
  - Battery technology: cost, cycle life, power and energy density
  - Efficient, reliably and cost-effective drivetrain components
  - Need for charging infrastructure
  - Limited charging power, long charge-up times

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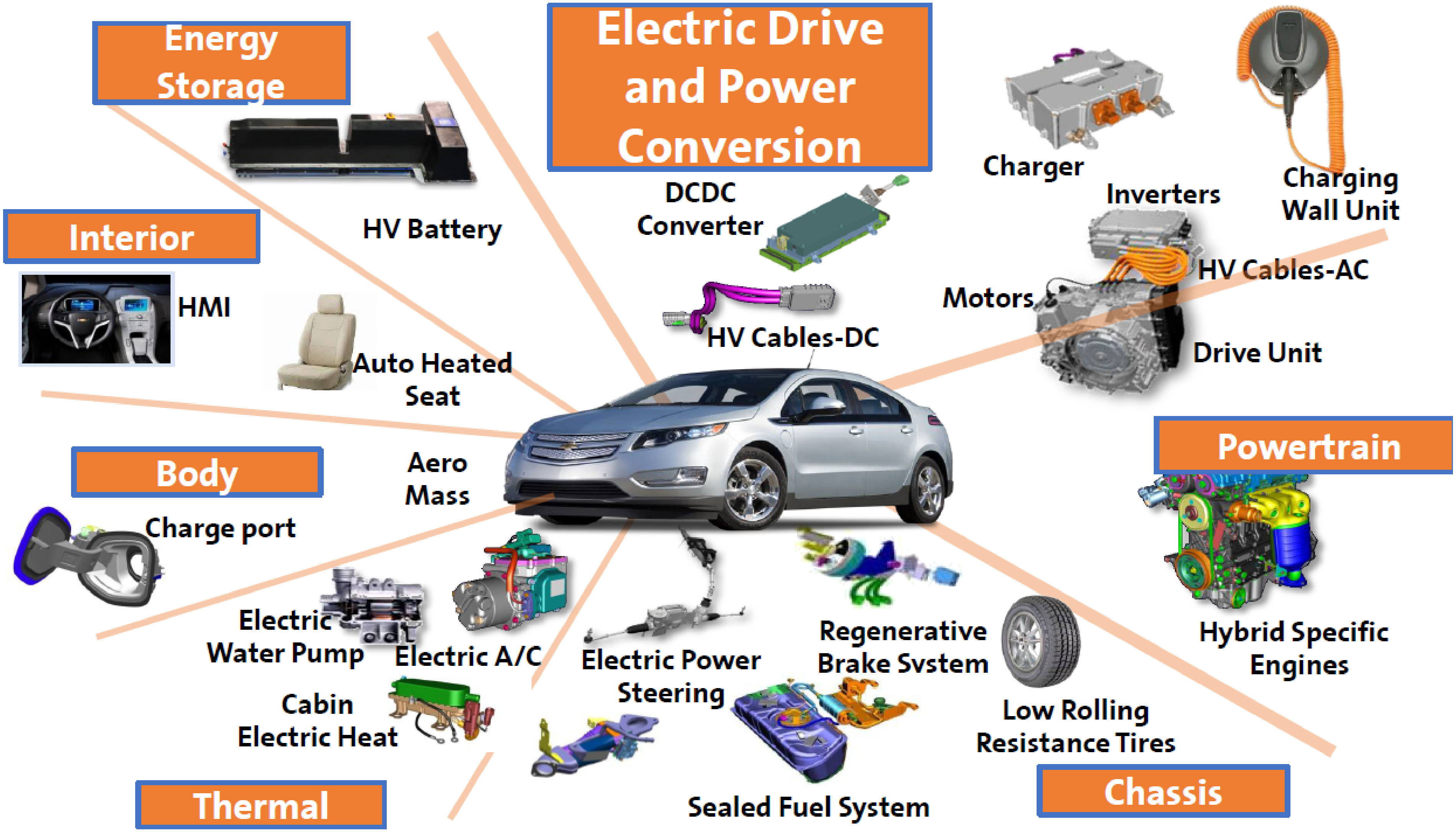
Power Electronics in Electric Vehicles



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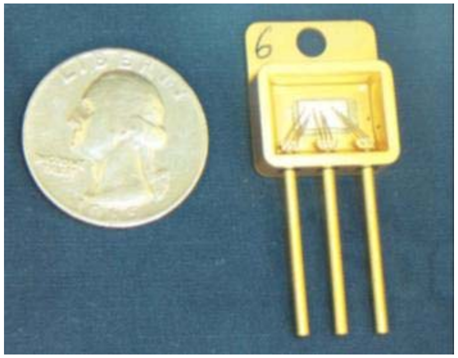
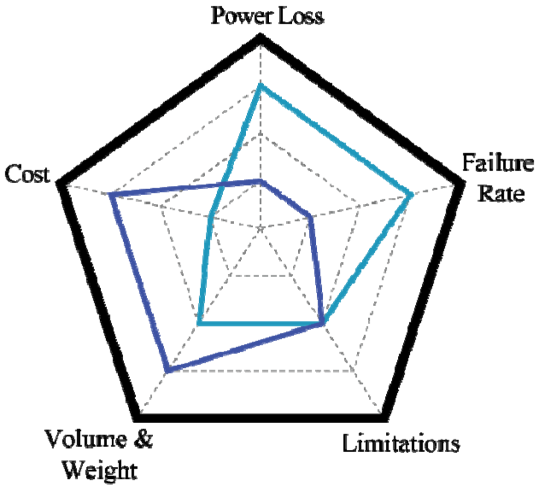
Peter Savagian, "Barriers to the Electrification of the Automobile," Plenary session, ECCE 2014

Power Electronics Research Focus Areas

Power Electronics at UTK and ORNL	
Focus Area	**Benefits**
New Topologies for Inverters and Converters *(Decrease size, cost, and improve reliability)*	Avenue to achieve significant reductions in PE weight, volume, and cost and improve performance . • Reduce capacitance need by 50% to 90% yielding inverter volume reduction of 20% to 35% and cost reduction. • Reduce part count by integrating functionality thus reducing inverter size and cost and increasing reliability. • Reduce inductance, minimize electromagnetic interference (EMI) and ripple, reduce current through switches all result in reducing cost.
WBG Semiconductors *(Temperature-tolerant devices)*	Produces higher reliability, higher efficiency, and enables high-temperature operation.
Packaging *(Greatly reduced PE size, cost, and weight with higher reliability)*	Provides opportunity for greatly decreased size and cost • Module packaging can reduce inverter size by 50% or more, cost by 40%, enable Si devices to be used with high-temp coolant for cost savings of 25%, and enable use of air cooling. • Device packaging to reduce stray inductance, improve reliability and enable module packaging options. When coupled with heat transfer improvements gains are enhanced.
Capacitors *(Reduced inverter volume)*	Improved performance can reduce capacitor size by 25% reducing inverter size by 10% and increase temperature limit.
Vehicle Charging *(Provide function at minimum cost)*	Provide the vehicle charging function in a policy neutral manner at virtually no additional cost with bi-directional capability.





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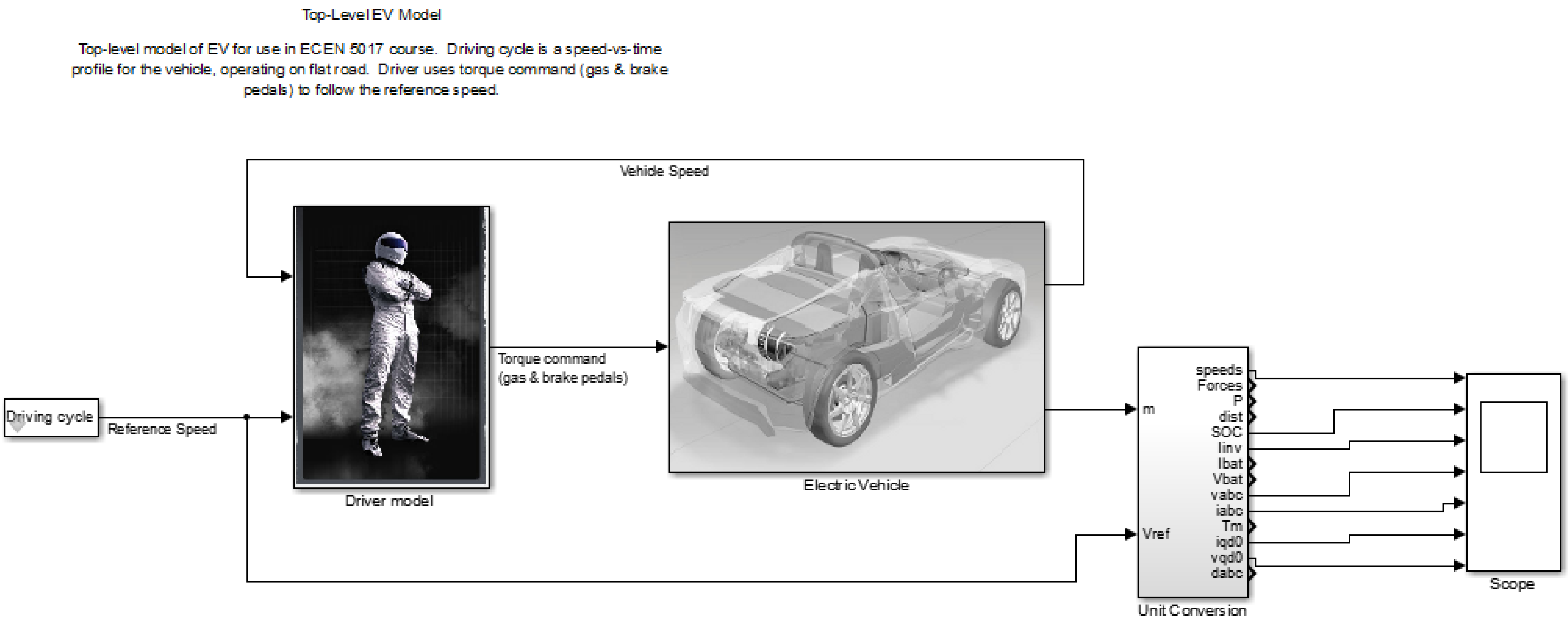
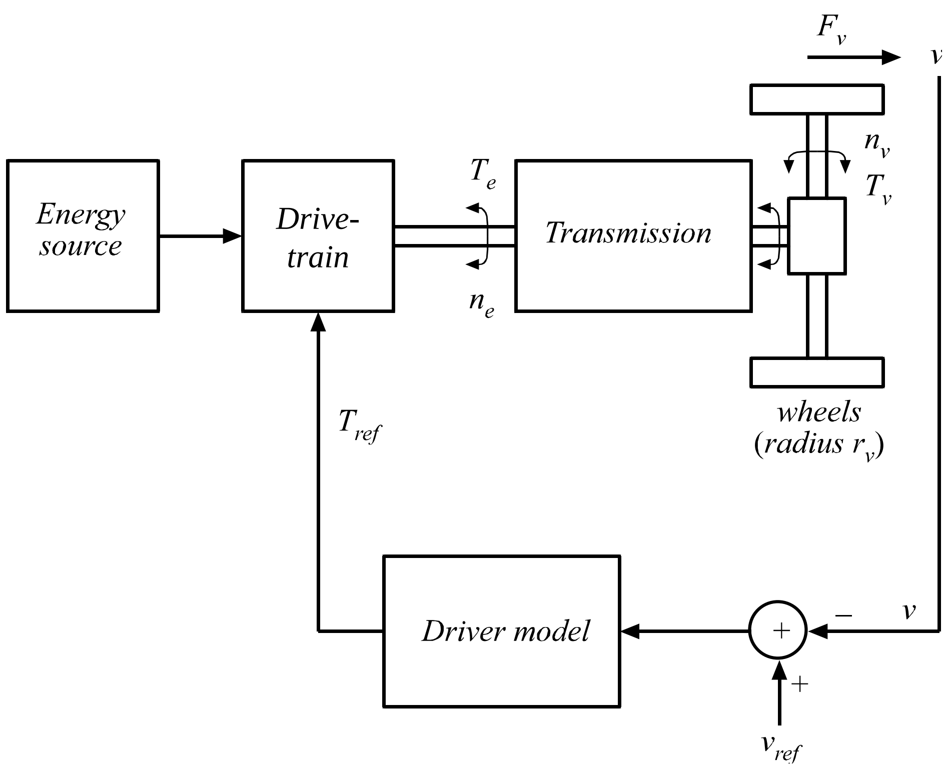
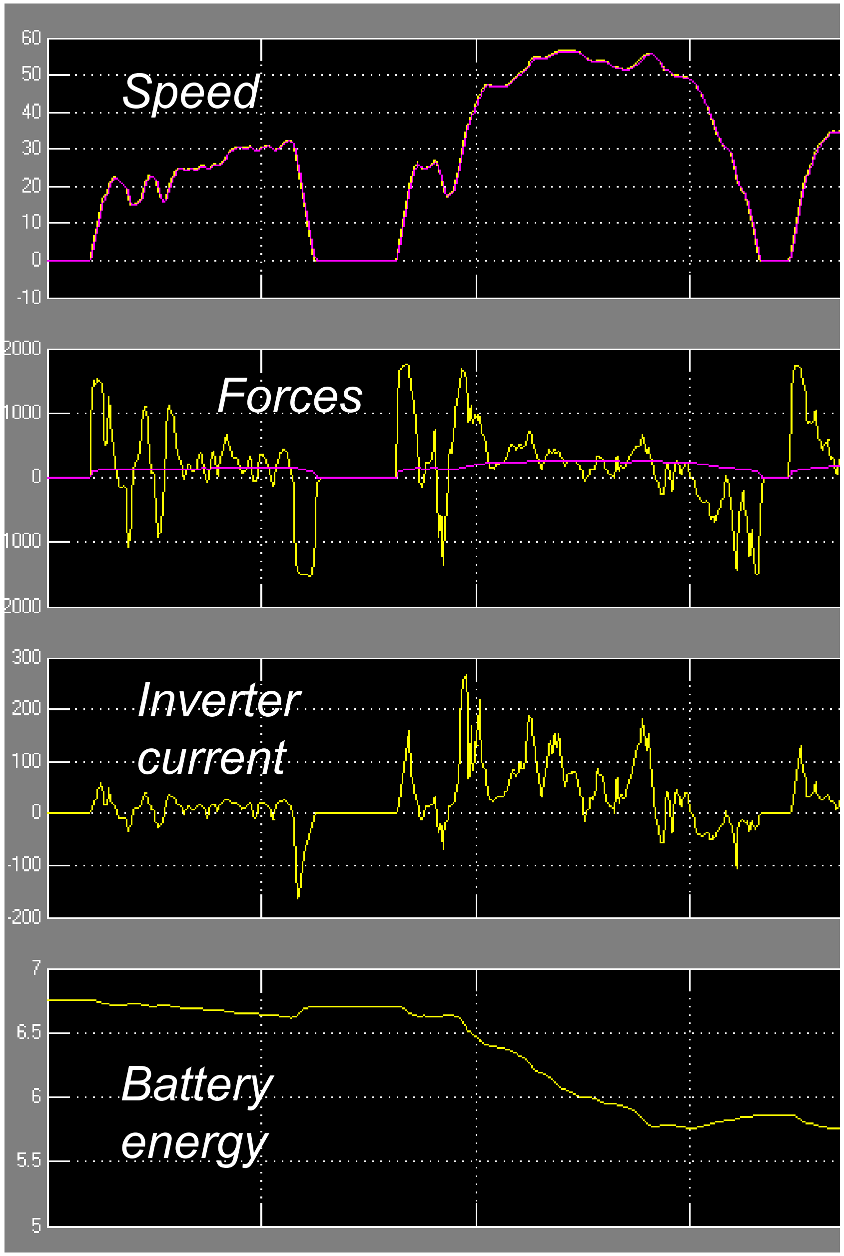
Modeling EV Performance

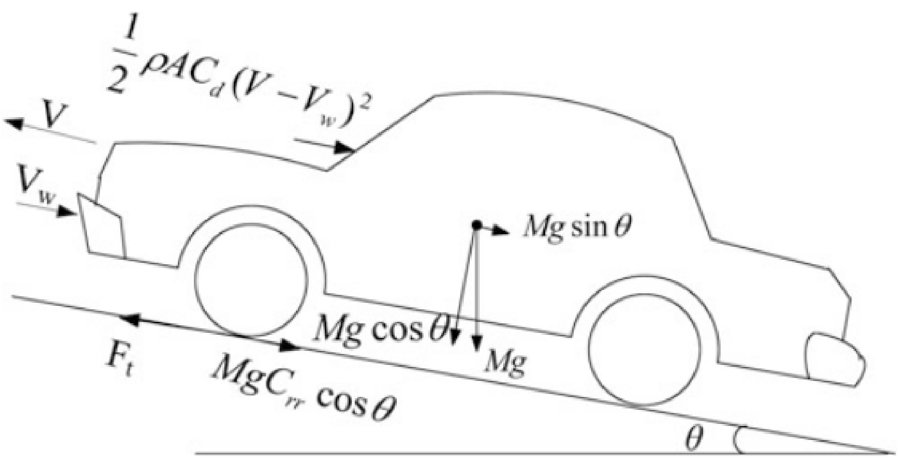


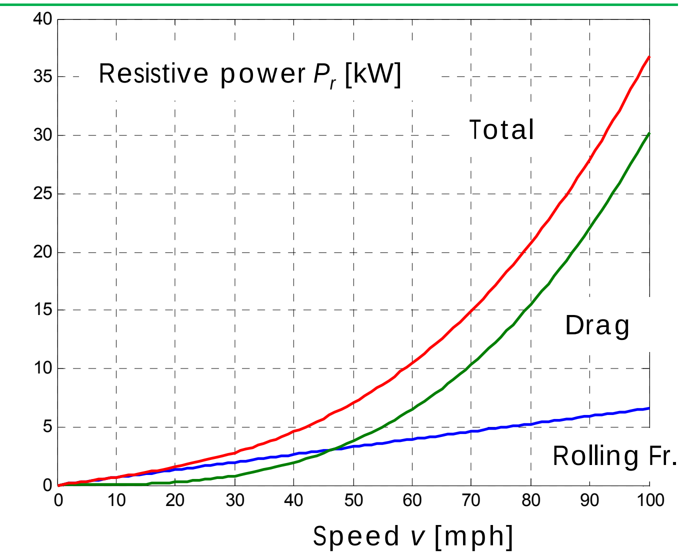
Simulink Vehicle Simulation Model

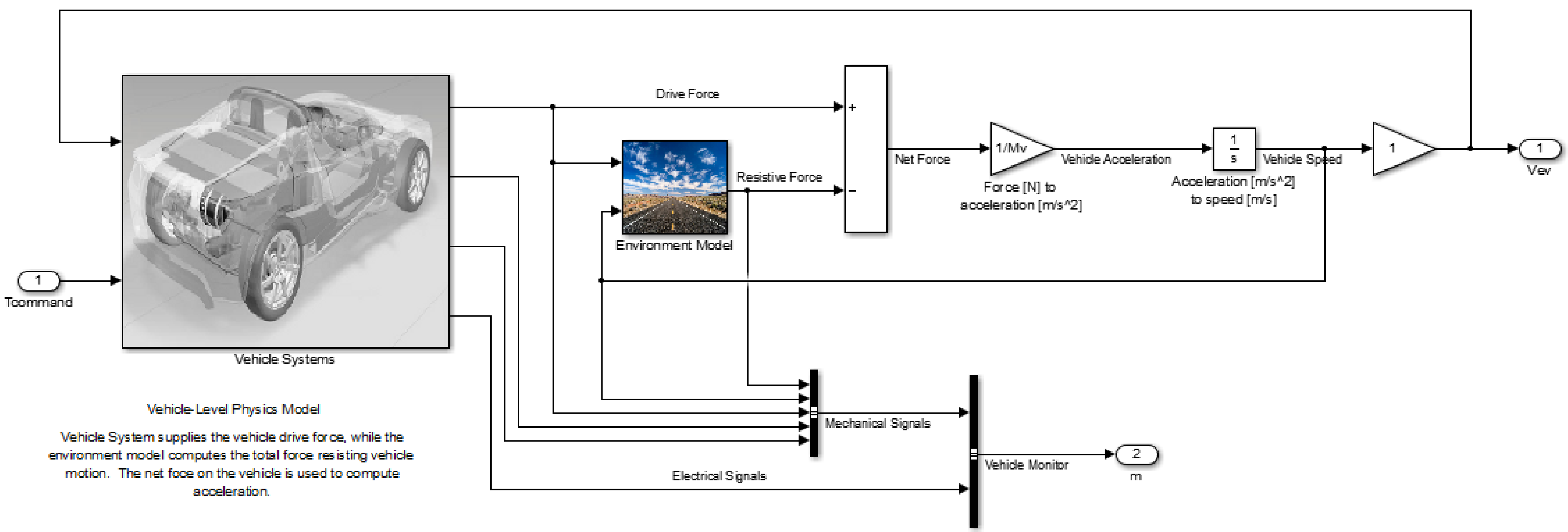




Vehicle Kinematics





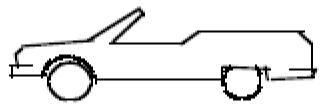
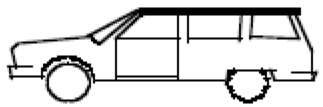
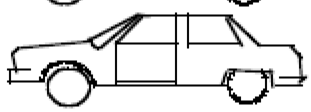
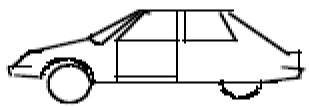
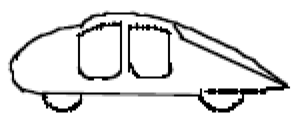
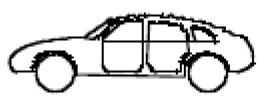
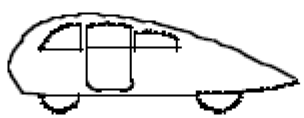


Rolling resistance coefficient C_r

Rolling Resistance Coefficients

Conditions	Rolling resistance coefficient
Car tires on concrete or asphalt	0.013
Car tires on rolled gravel	0.02
Tar macadam	0.025
Unpaved road	0.05
Field	0.1–0.35
Truck tires on concrete or asphalt	0.006–0.01
Wheels on rail	0.001–0.002

Aerodynamic drag coefficient C_d

Vehicle Type	Coefficient of Aerodymanic Resistance
 Open convertible	0.5–0.7
 Van body	0.5–0.7
 Ponton body	0.4–0.55
 Wedge-shaped body; headlamps and bumpers are integrated into the body, covered underbody, optimized cooling air flow	0.3–0.4
 Headlamp and all wheels in body, covered underbody	0.2–0.25
 K-shaped (small breakway section)	0.23
 Optimum streamlined design	0.15–0.20
Trucks, road trains	0.8–1.5
Buses	0.6–0.7
Streamlined buses	0.3–0.4
Motorcycles	0.6–0.7

Reference: Mehrdad Ehsani, Yimin Gao, Sebastien E .Gay, and Ali Emadi, Modern Electric, Hybrid Electric, and Fuel Cell Vehicles, CRC Press 2004. Chapter 2

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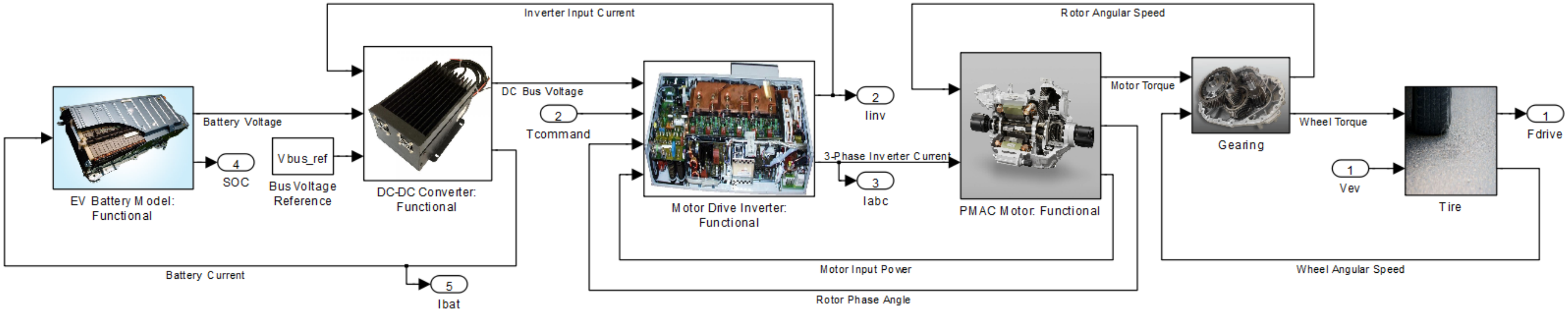
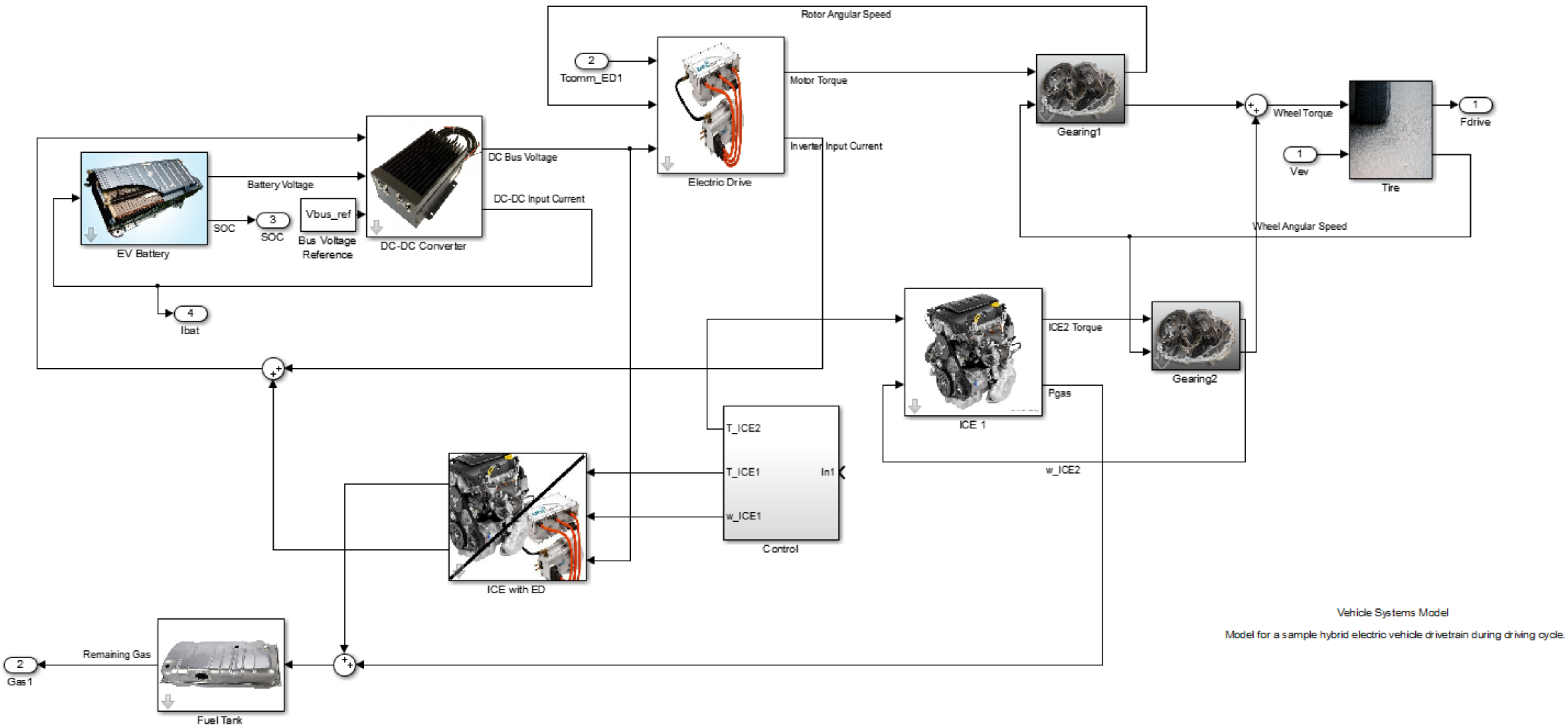
Modeling the EV Drivetrain



Modeling HEV Drivetrain



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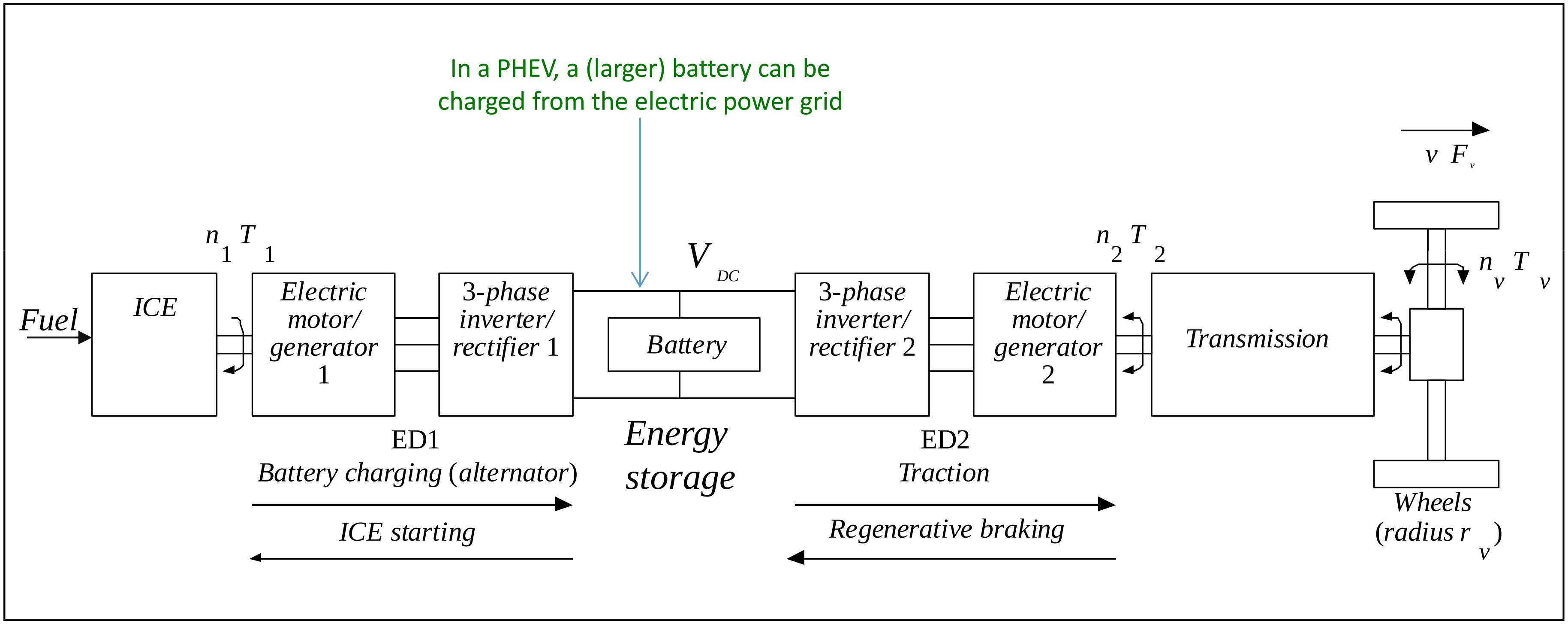
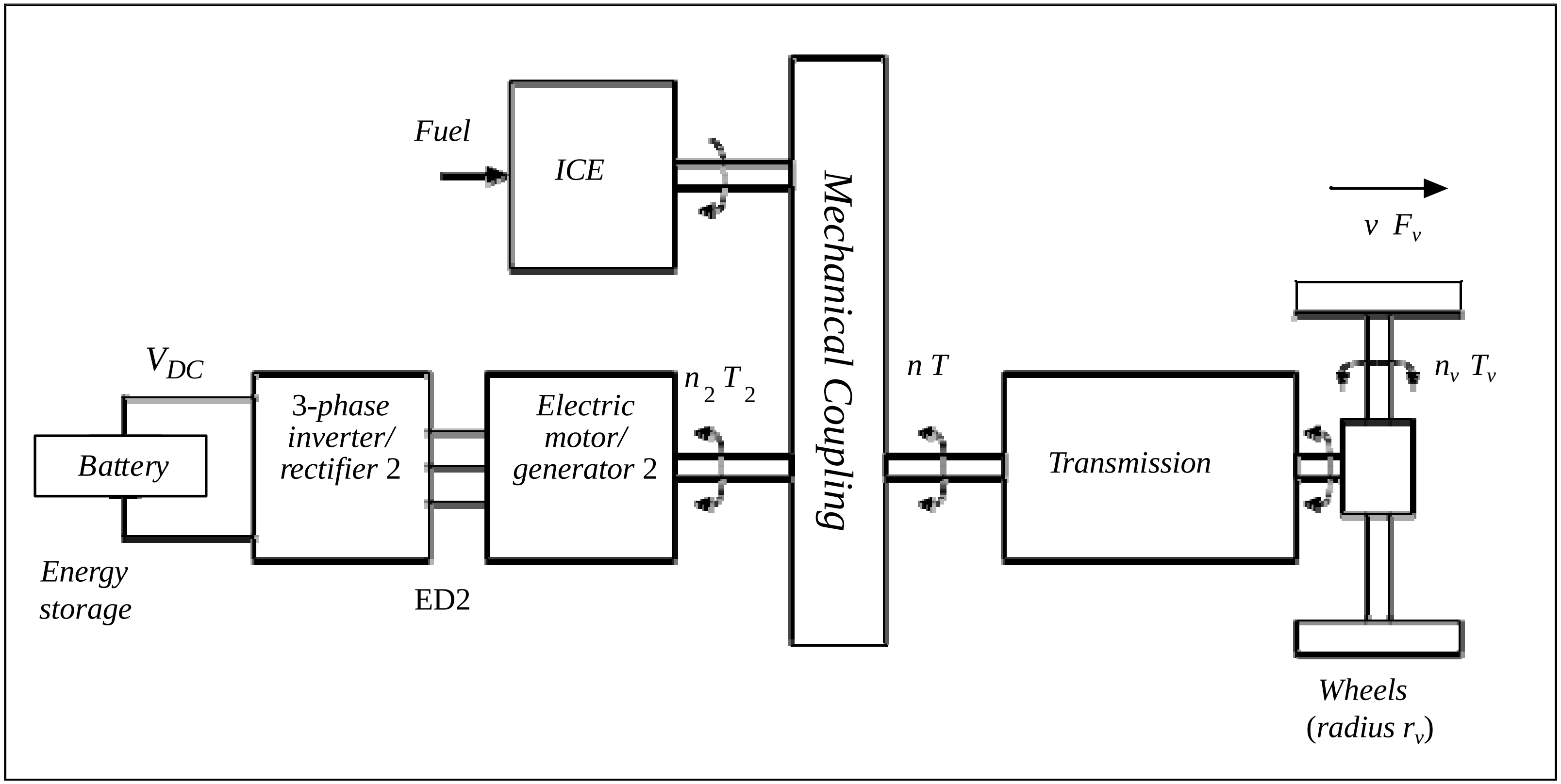
Series HEV Architecture



Example: Chevy Volt, a PHEV with a drive-train based on the series architecture:

- 62 kW (83 hp, 1.4 L) ICE
- 55 kW electric drive ED1
- 111 kW (149 hp) electric drive ED2

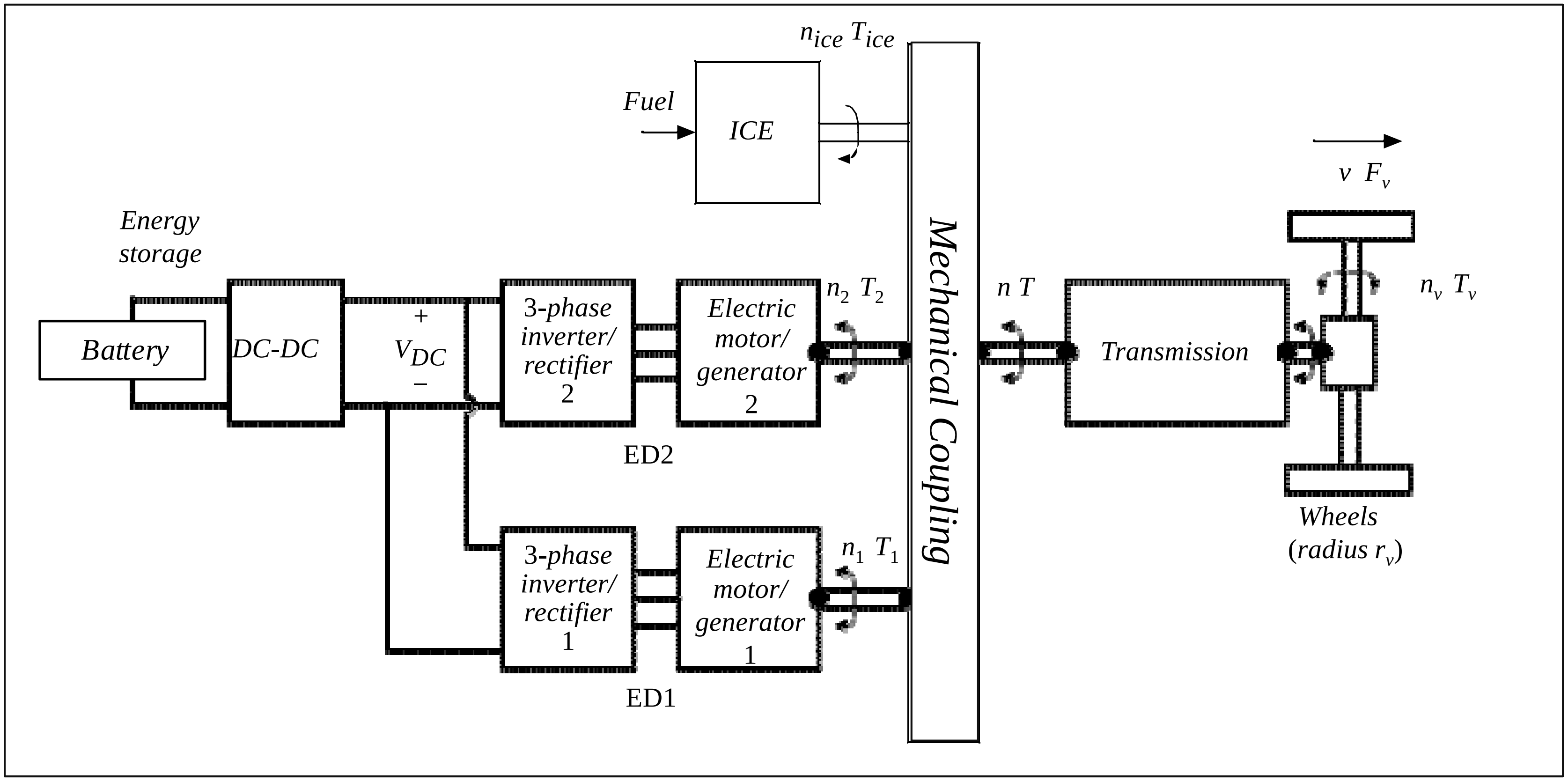
Parallel HEV



Example: 2011 Sonata HEV with a drive-train based on the parallel architecture:

- 121 kW (163 hp, 2.0 L) ICE
- 30 kW electric drive ED1
    - 8.5 kW hybrid starter/generator connected to crankshaft

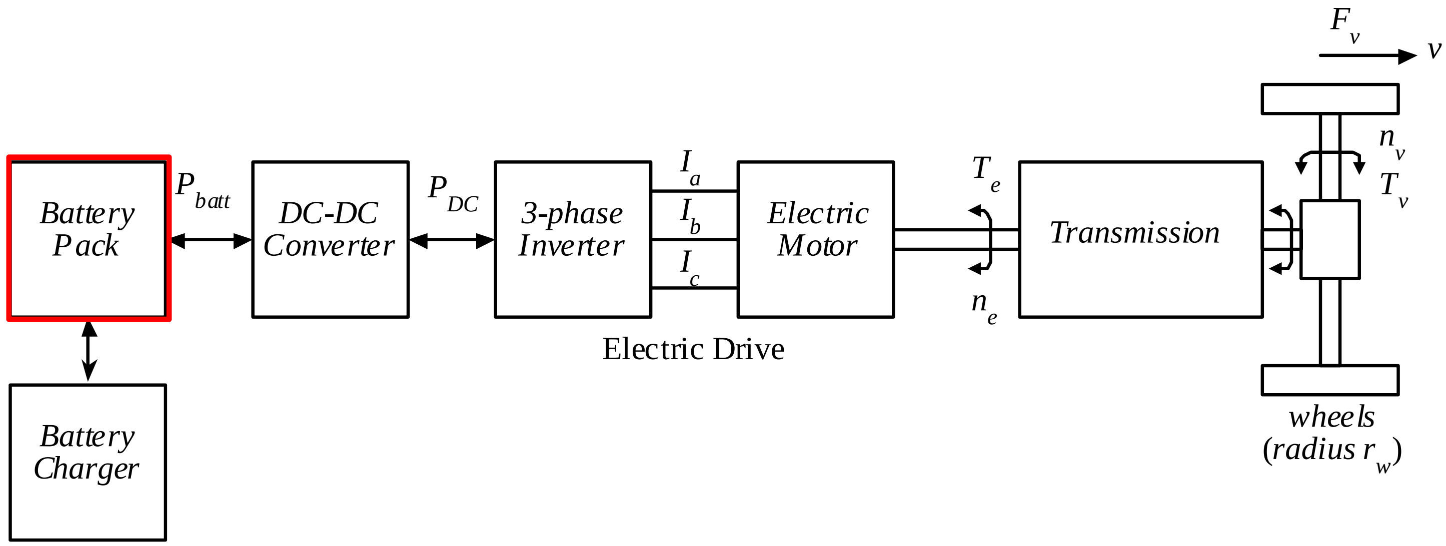
Series/Parallel HEV



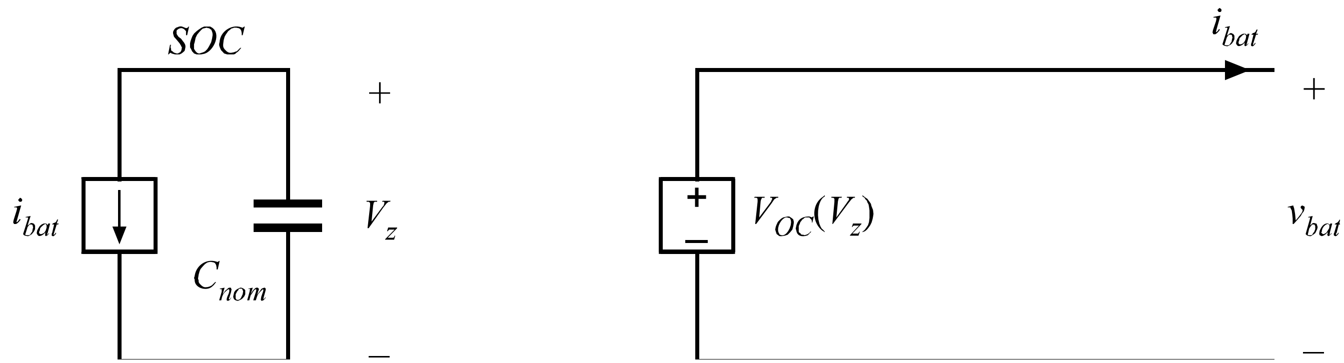
Example: 2010 Prius HEV with a drive-train based on the series/parallel architecture :

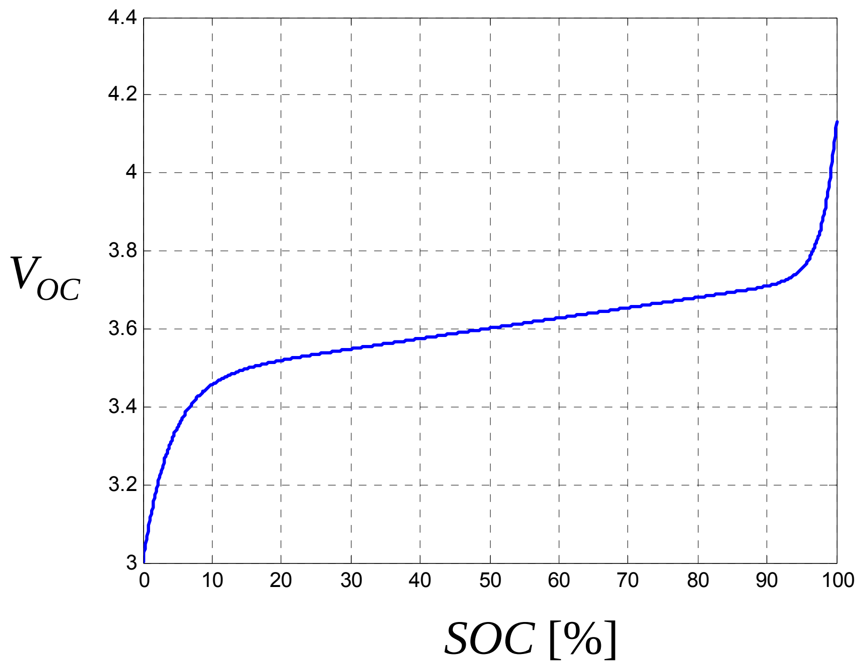
- 73 kW (98 hp, 1.8 L) ICE
- 60 kW electric drive ED2
  - 100 kW total power
  - 42 kW (149 hp) electric drive ED1

Electric Drive Realization

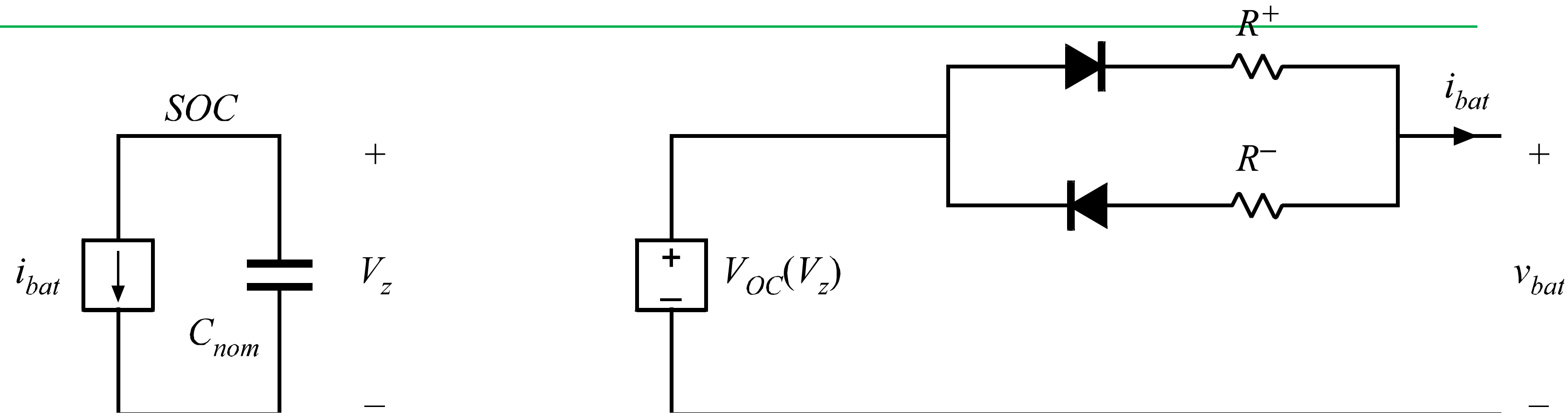


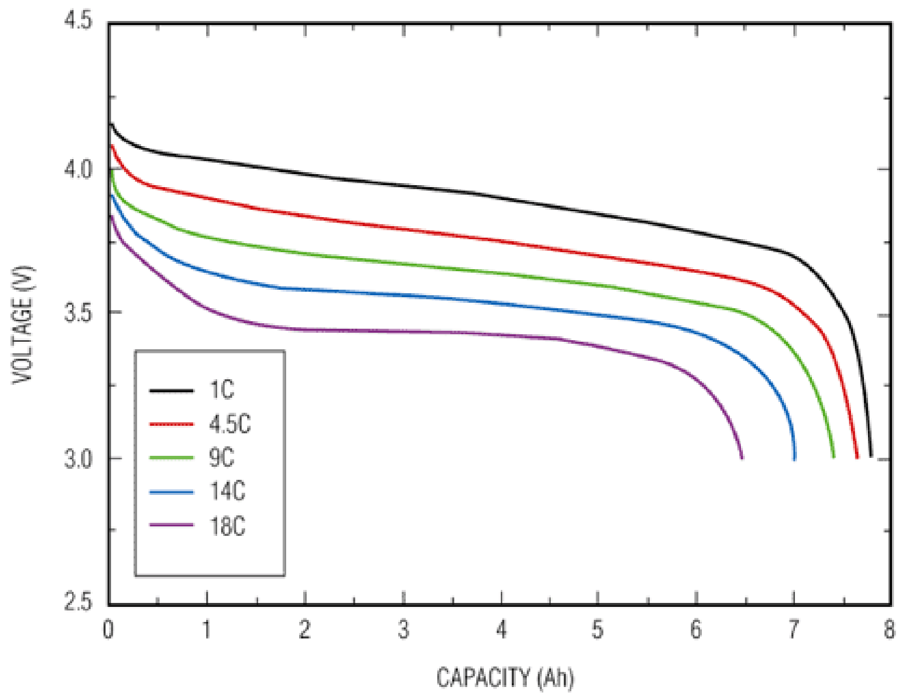
Battery Pack Modeling





Series Resistance





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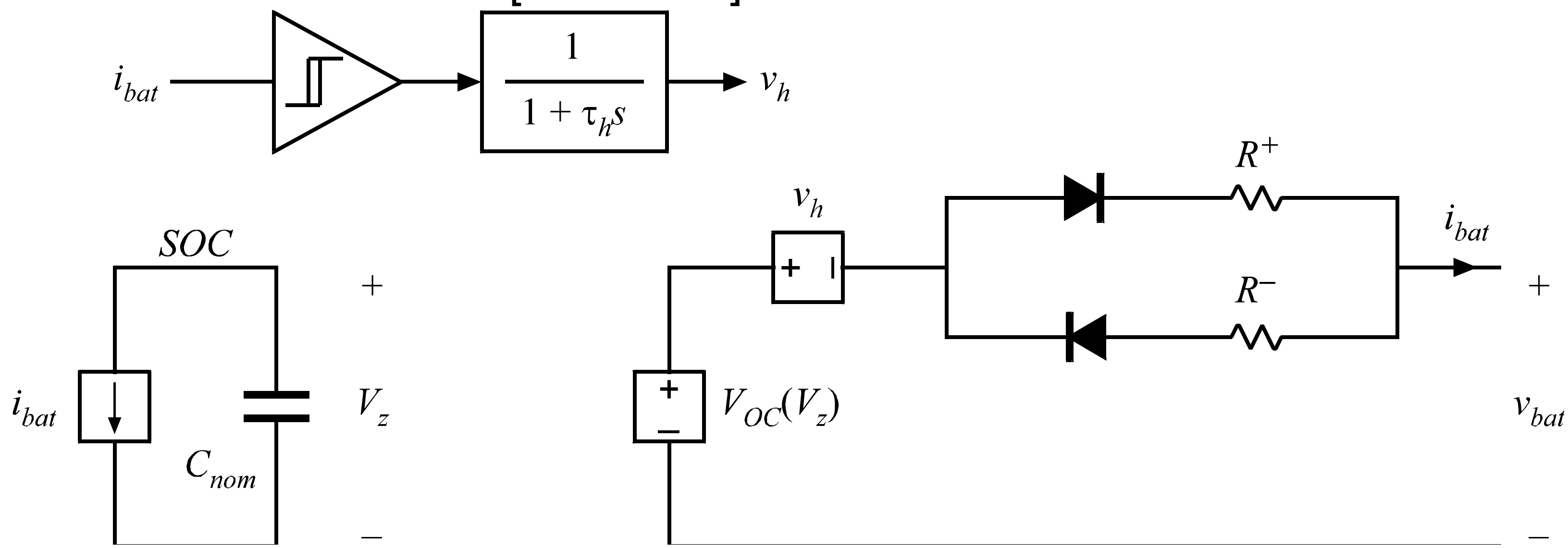
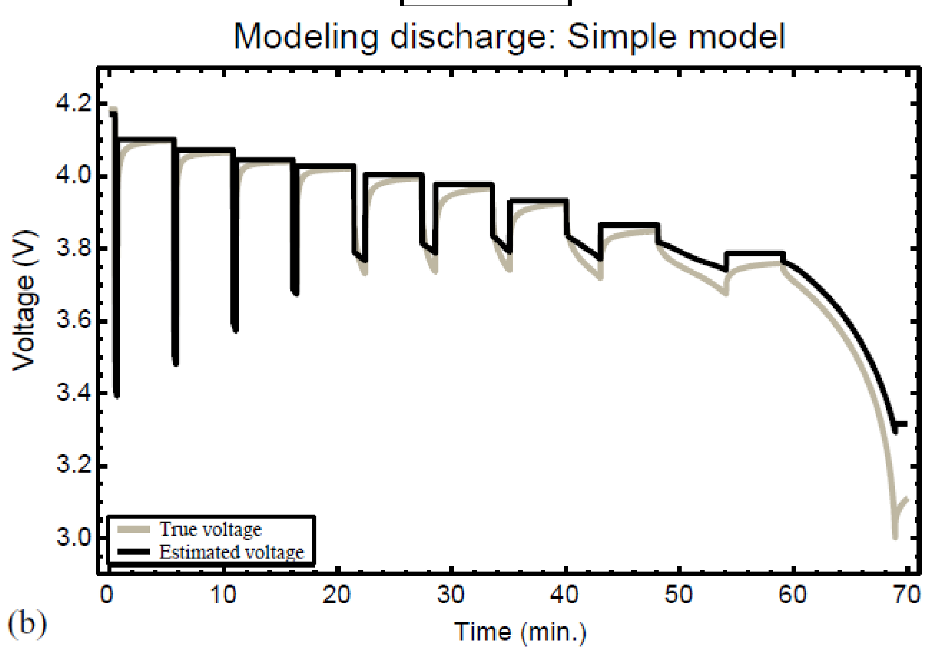
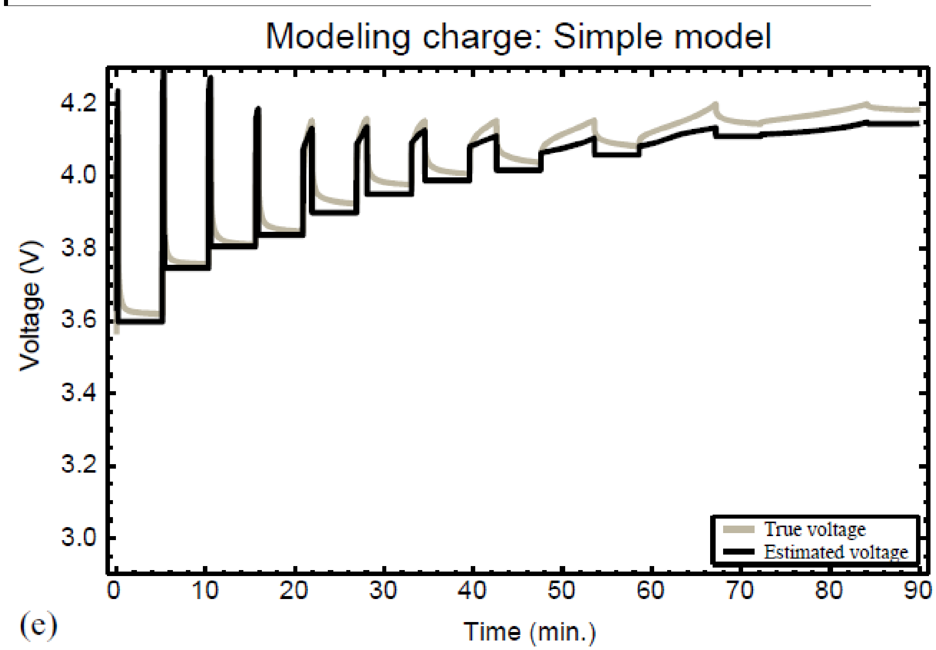
Battery Hysteresis

[Plett 2004]





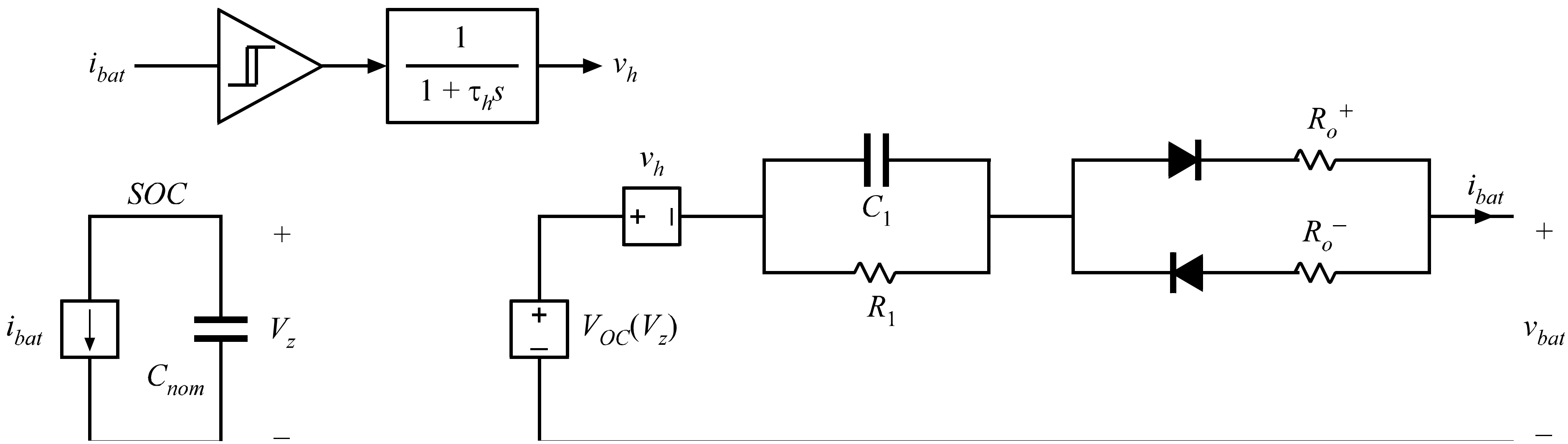
(b)

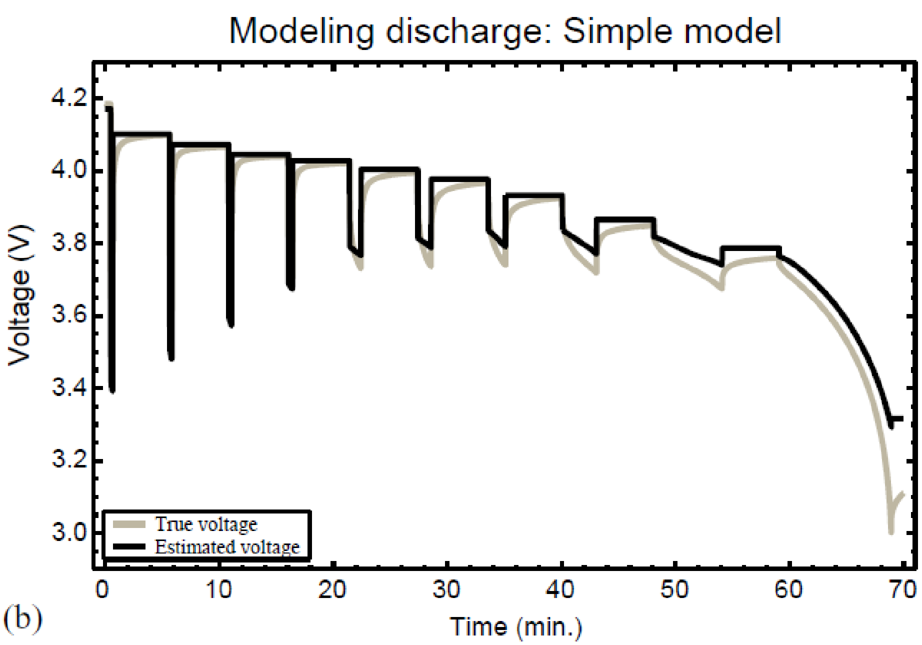


(e)

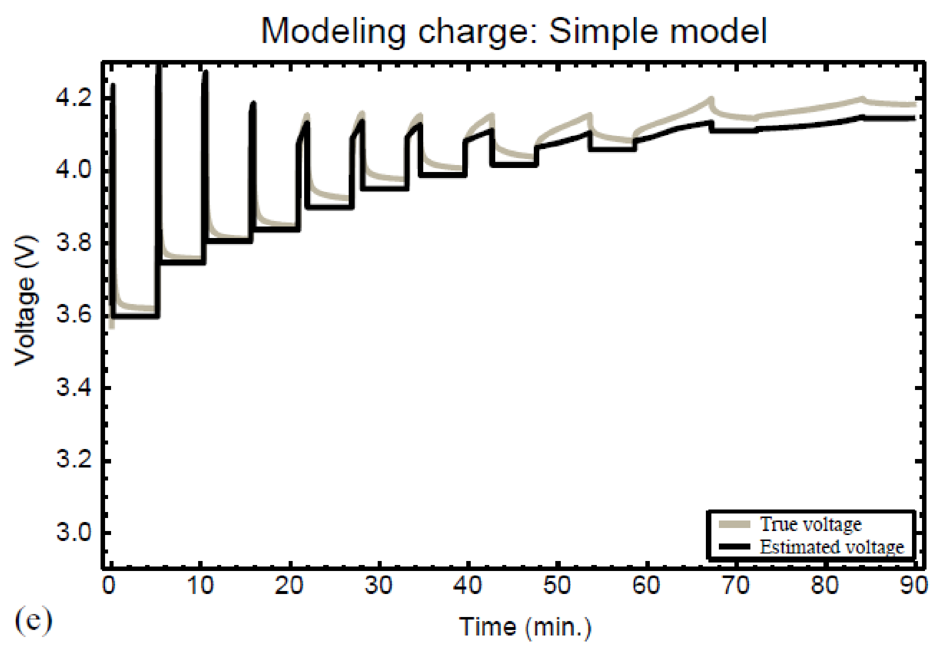
Battery Diffusion Dynamics

[Plett 2004]





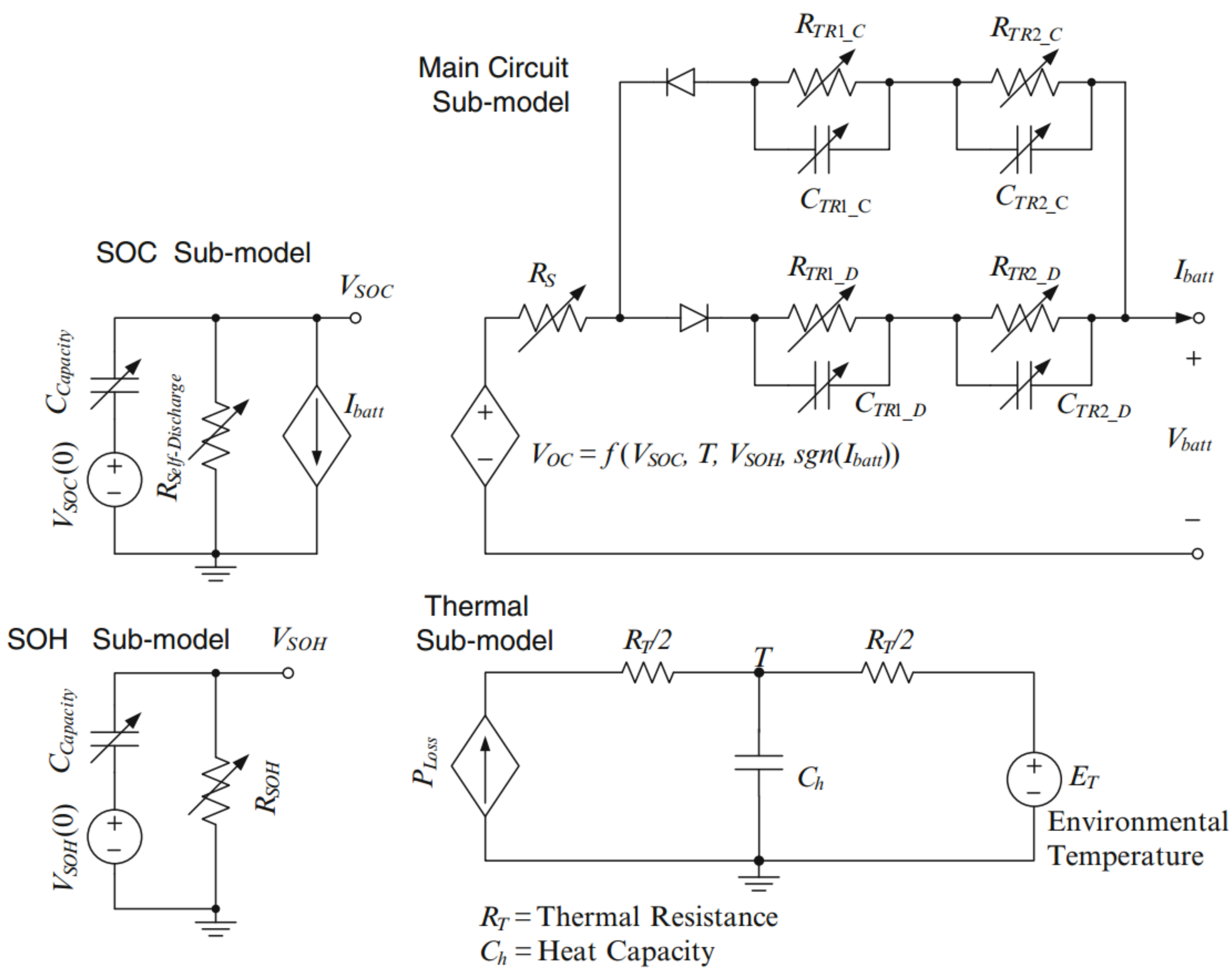
(b)



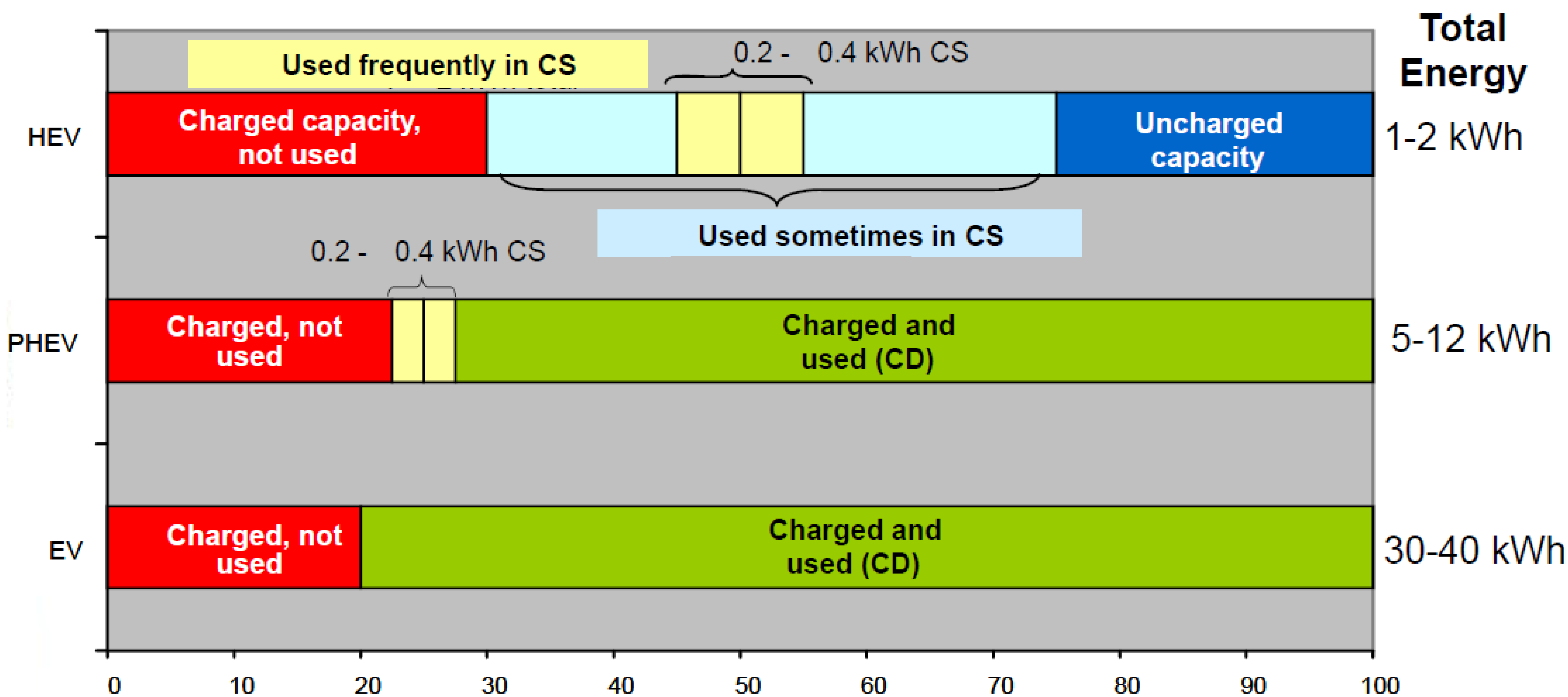
(e)

Lifetime Degradation

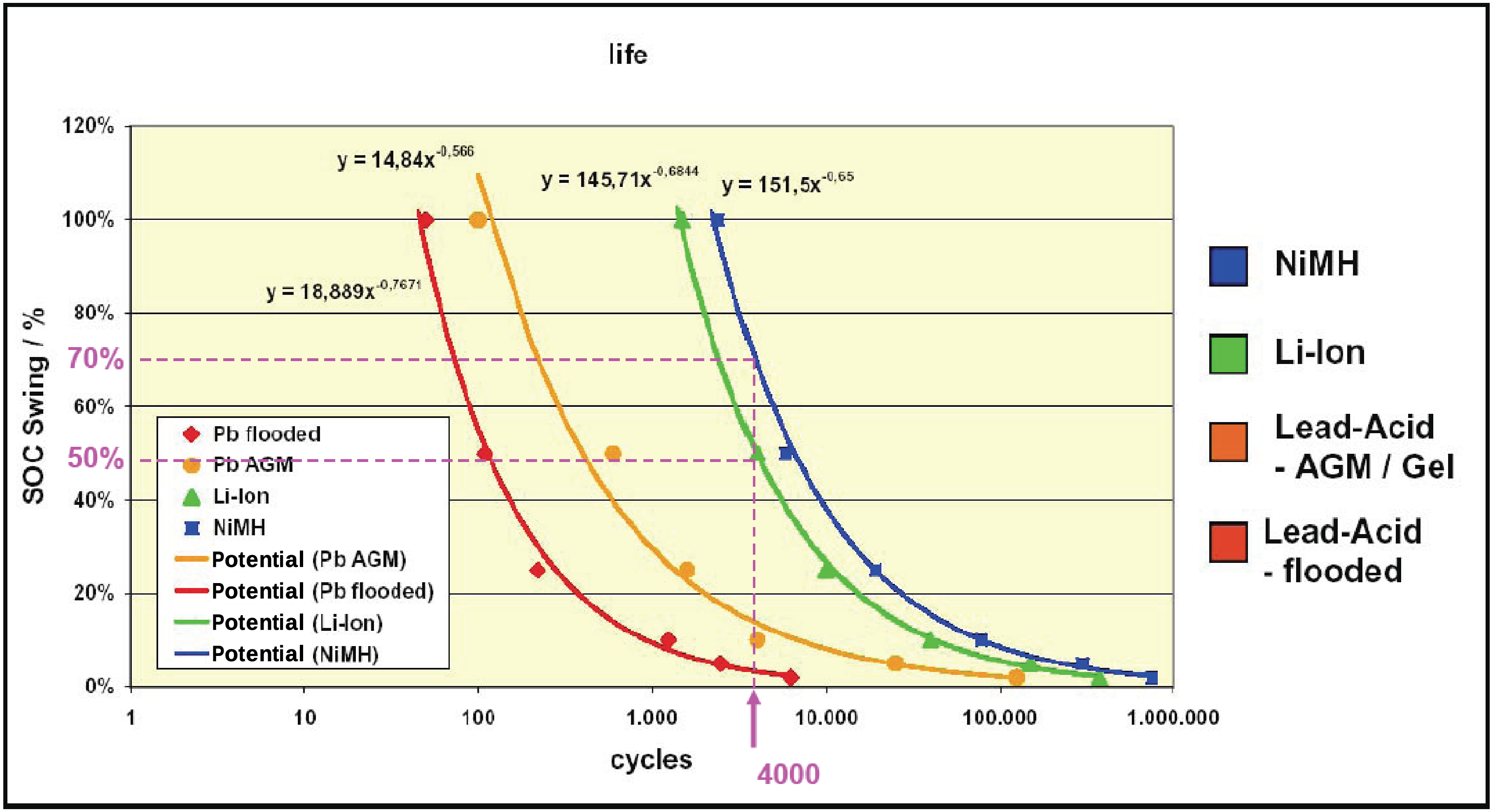
K. Young et al, “Chapter 2: Electric Vehicle Battery Technologies”



Battery Pack Usage



Cycle Life of EV Battery Packs



Data presented by Christian Rosenkranz (Johnson Controls) at EVS 20

Example EV Batteries

Cutaway battery of Nissan Leaf electric vehicle. The Leaf includes a 24kWh lithium-ion battery with a city driving range of 160km (100 miles). The battery fits under the floor of the car, weighs 272kg (600lb) and is estimated to cost $15,600 (2010).

Tesla Model S frame-integrated battery. The Model S includes a 60-85kWh lithium-ion battery with a city driving range of 480km (300miles). The battery weighs 544kg (1200lb) and is estimated to cost $24-34,000.

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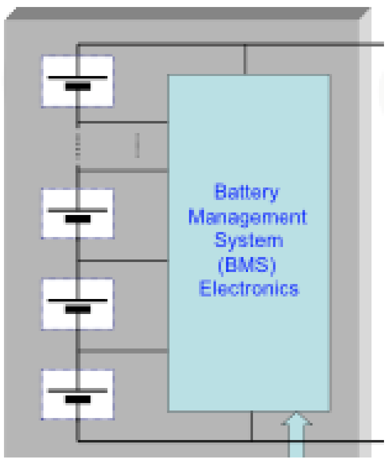
Additional EV Batteries

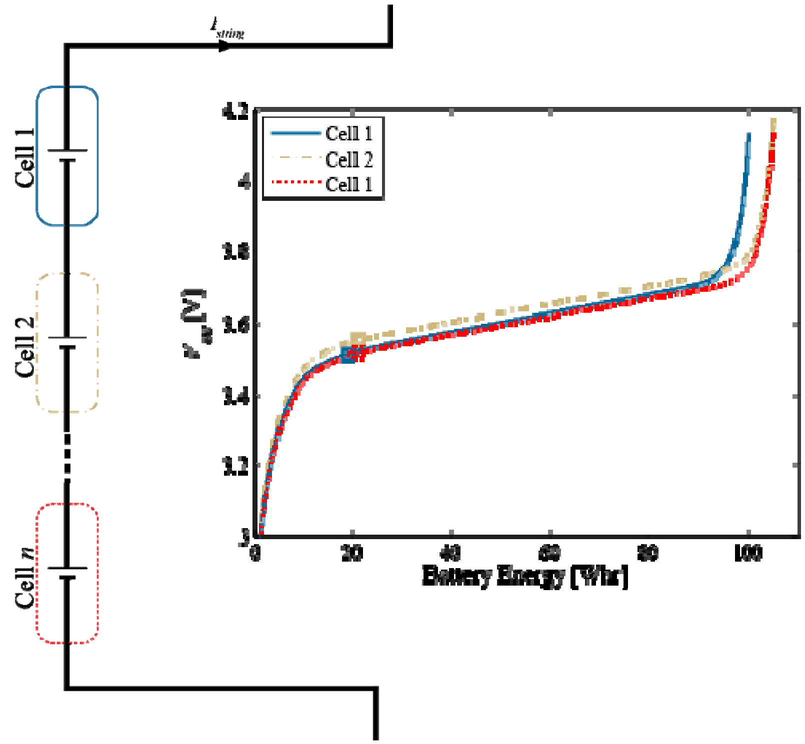
Battery University

Electric vehicle	Battery	Range advertised	Range in real world	Charge times
BMW Mini E	35kWh, air cooled; 18650 cells; NMC 355V, 96s53p	250km, 156 miles	153km, 96 miles; 112km, 70 miles below freezing	26h at 115VAC; 4.5h at 230V, 32A
Chevy Volt	16kWh, liquid cooled Li-manganese, 181kg (400lb)	64km, 40 miles	45km, 28 miles; 149hp electric & 1.4 liter IC engine	10h at 115VAC; 4h at 230VAC
Toyota plug-in Prius	3 Li-ion packs, one for hybrid; two for EV, 42 temp sensors	20km, 13 miles	N/A; 80hp electric & 98hp IC engine	3h at 115VAC; 1.5h min 230VAC
Mitsubishi iMiEV	16kWh; 88 cells, 4-cell modules; Li-ion; 109Wh/kg; 330V	128km, 80 miles	88km, 55 miles; highway speed, mountain pass	13h at 115VAC; 7h at 230VAC
Nissan LEAF	24kWh; Li-manganese, 192 cells; 80Wh/kg, air cooled; 272kg (600lb)	160km, 100 miles	100km, 62 miles at highway speed with heater on	8h at 230VAC; 30 min high ampere
Tesla Roadster	56kWh, 6,831 Li-cobalt computer cells; liquid cooled	352km, 220 miles	224km, 140 miles; 172km, 108 miles driven sports car	3.5h at 230VAC high ampere
Think City	24.5kW, Li-ion or sodium-based	160km, 100 miles	N/A. Sodium-type has few problems	8h at 115VAC
Smart Fortwo ED	16.5kWh; cylindrical Li-ion (computer cells), made by Tesla Motors	136km, 85 miles	Less than predicted	8h at 115VAC 3.5H at 230VAC

Battery Management System

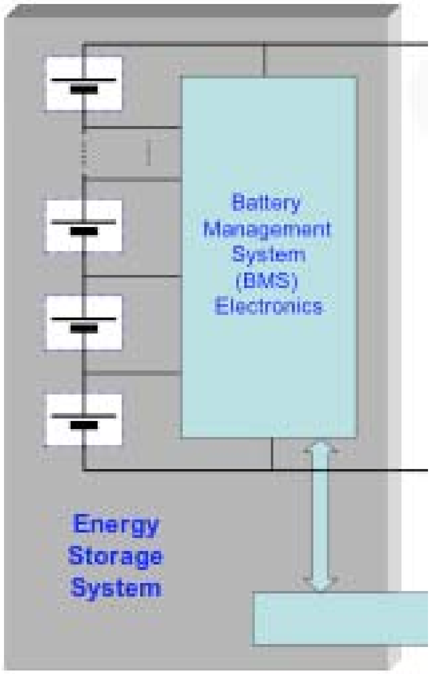


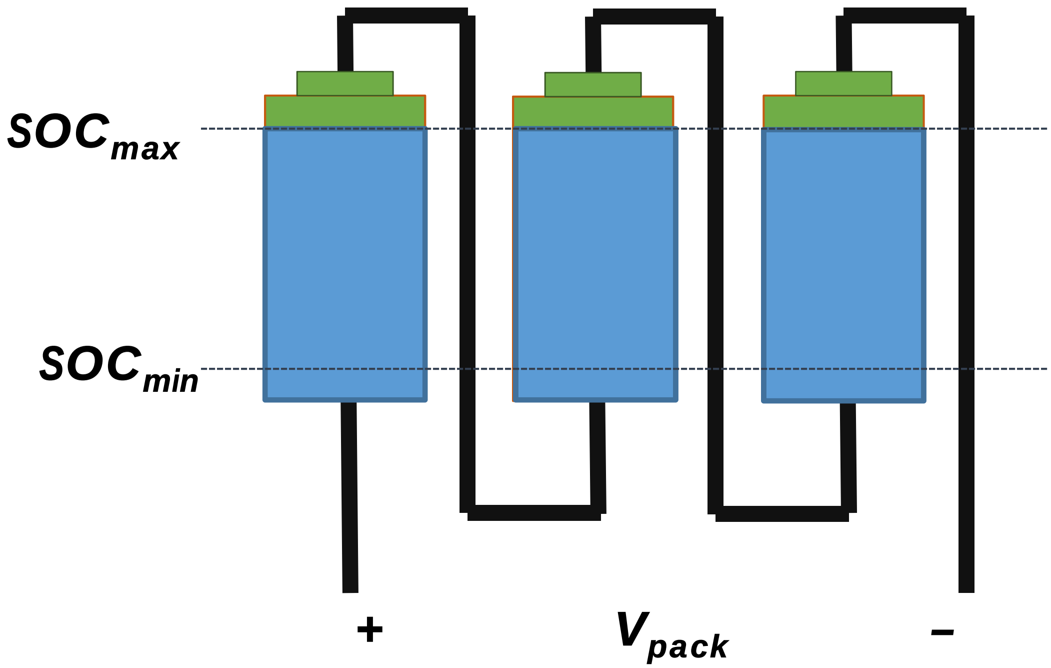
Battery Management System



- EV battery consists of many (100’s) series battery cells (LFP, Li-ion, NiMH)
- Cells share a charging and discharging current, but may have mismatches in series resistance, capacity, operating temperature, health, or dynamics
- Cells binned by manufacturer to limit mismatch at beginning-of-life

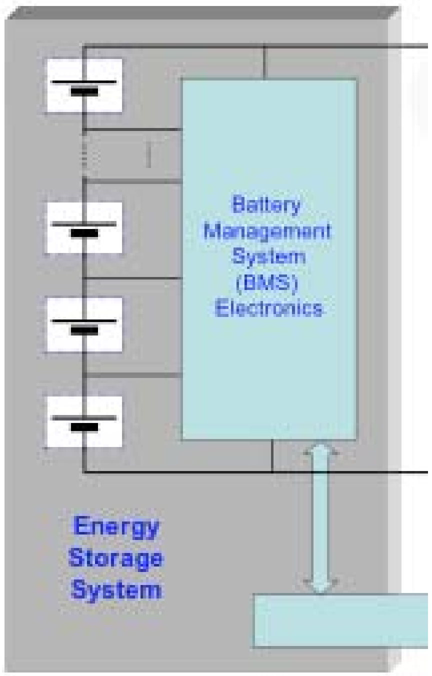
Cell Balancing

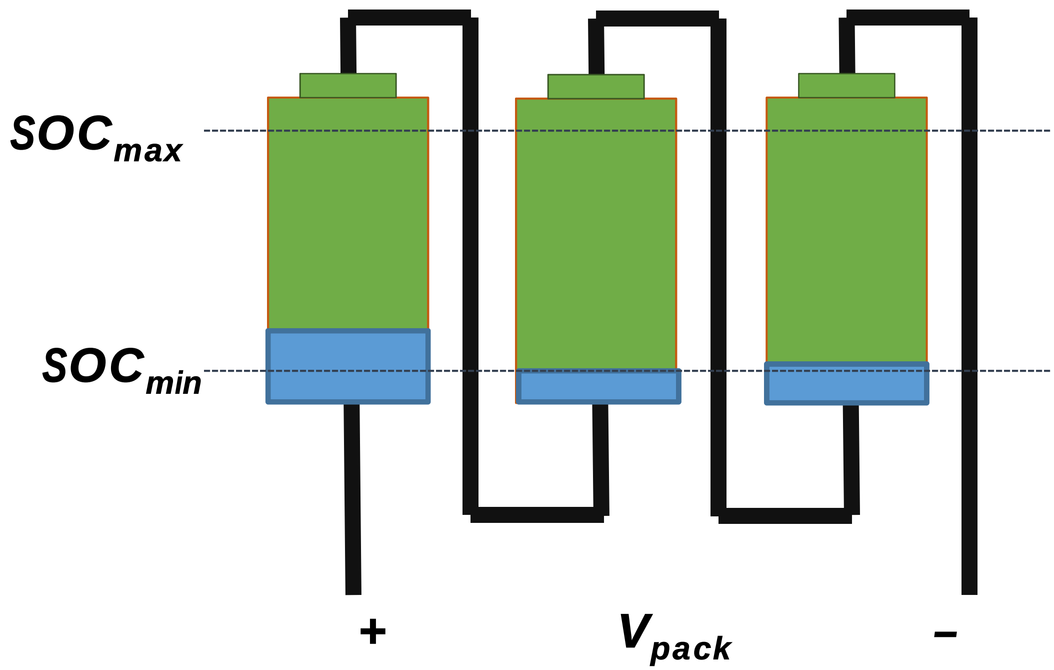




- Small differences in cell characteristics are exacerbated over multiple charge and discharge cycles due to their series connection

Cell Balancing





- Discharge is limited by the first cell to reach the minimum allowable State-of-Charge (SOC).

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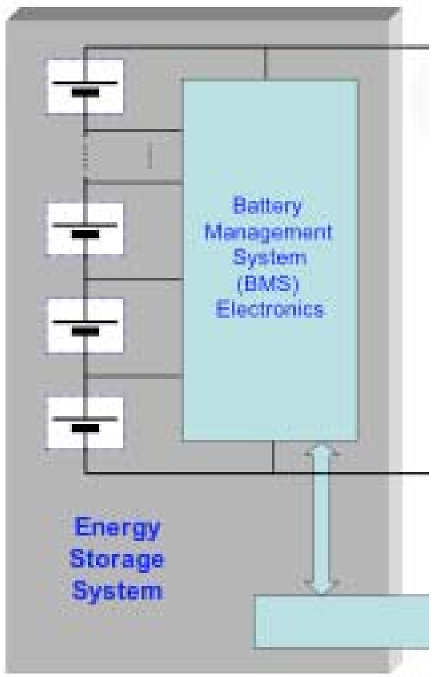
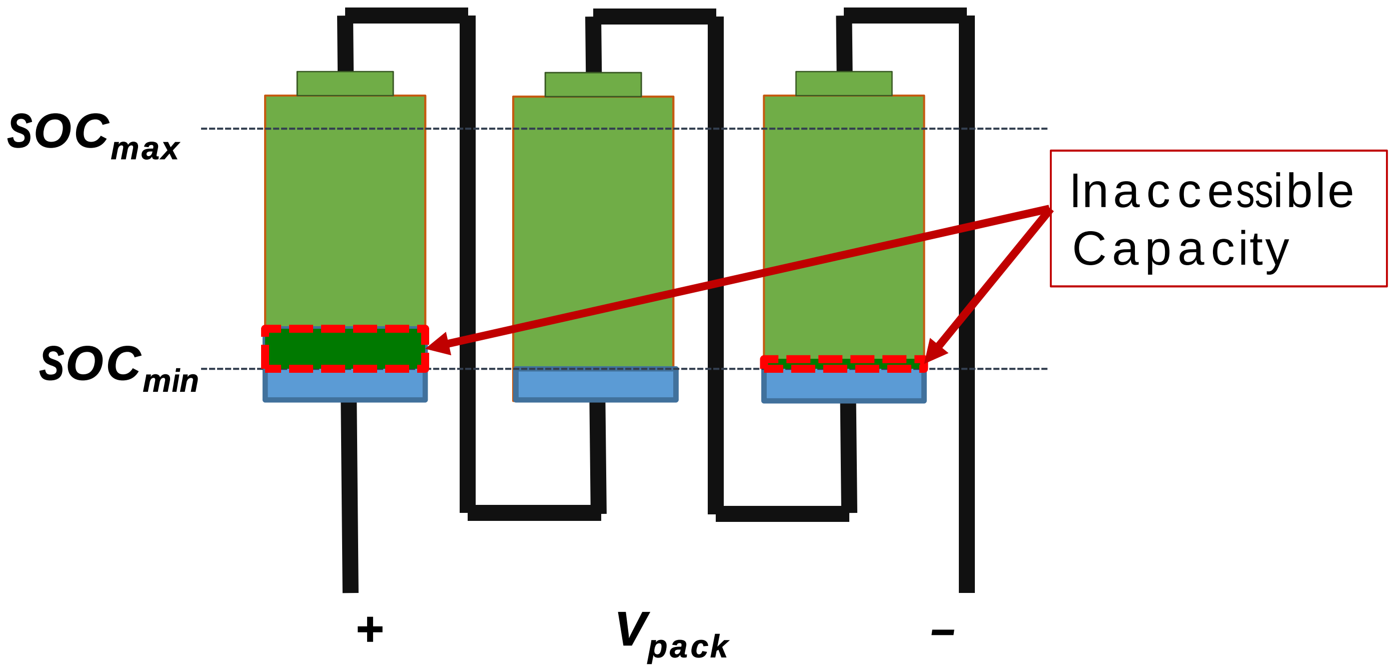
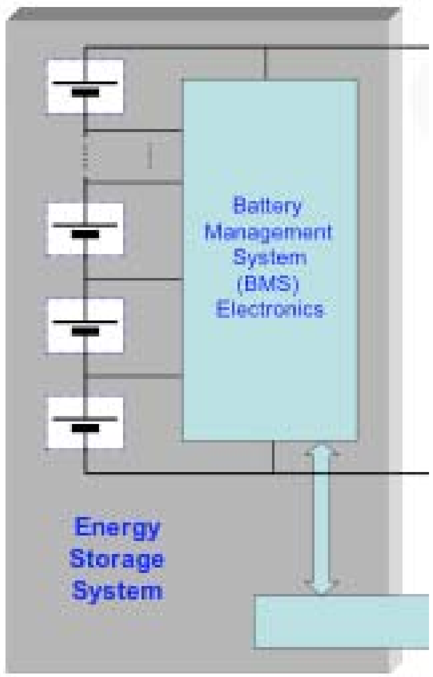
Cell Balancing

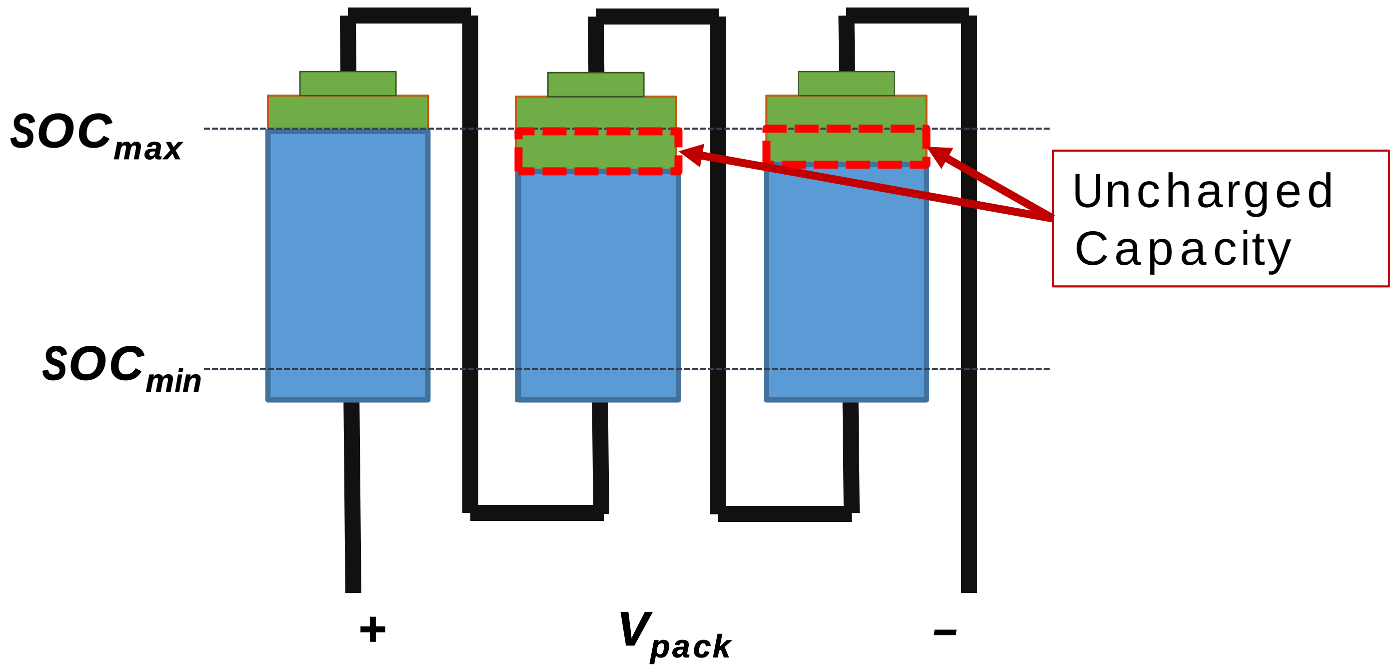




- Discharge is limited by the first cell to reach the minimum allowable State-of-Charge (SOC).
- Effective pack capacity limited to the capacity of the lowest cell (in Amp-hours)

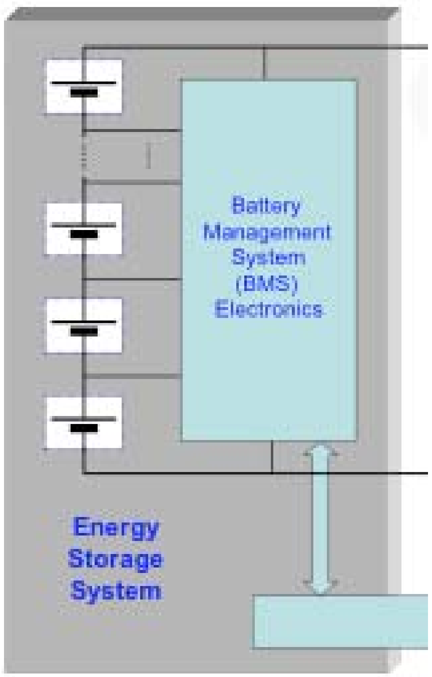
Cell Balancing

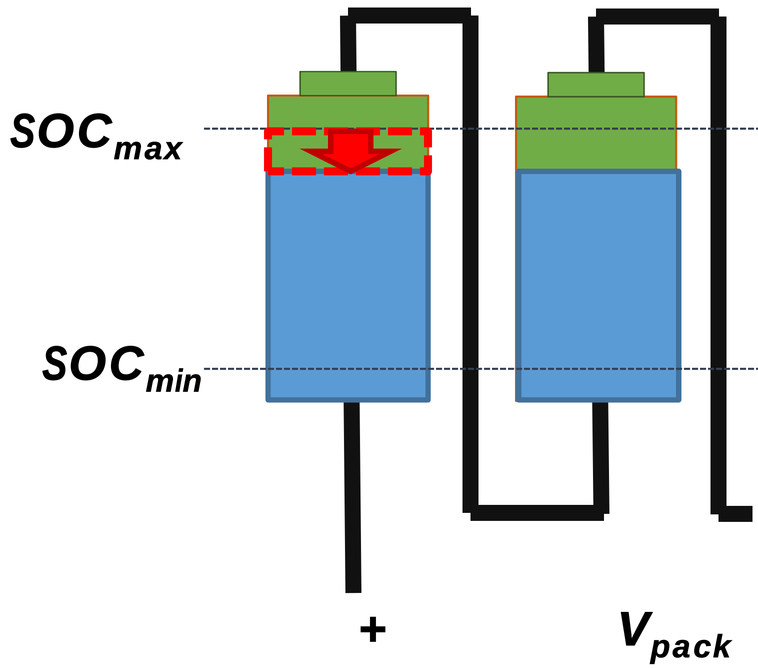




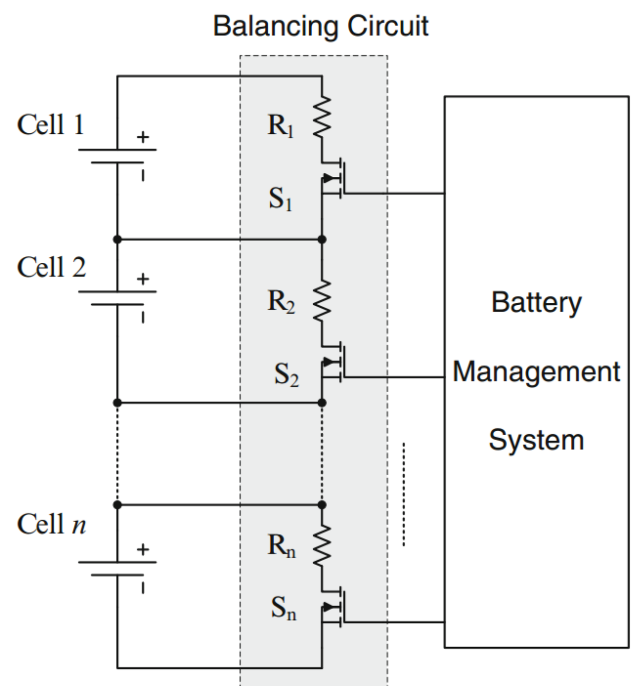
- When recharged, charging is stopped when the first cell reaches maximum capacity, leading to incomplete charging of some cells and lower total pack capacity

Passive Dissipative Balancing

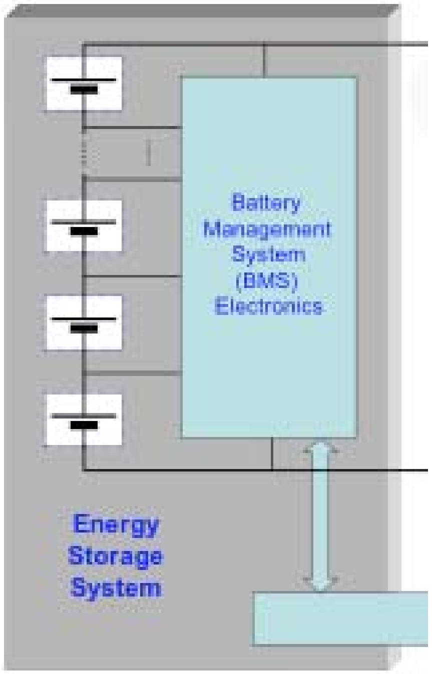


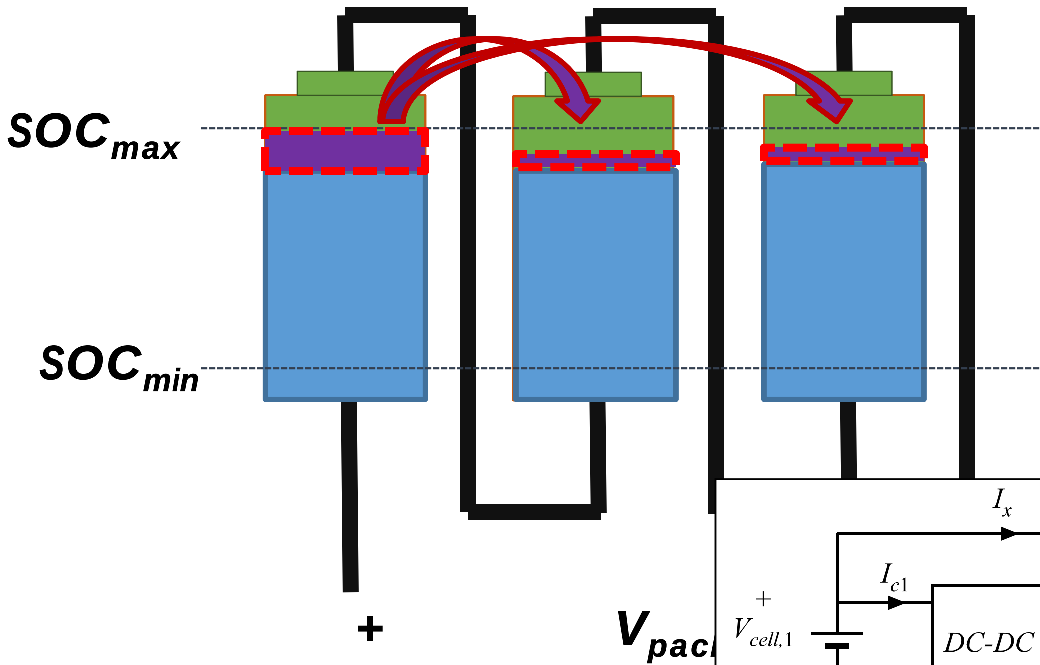


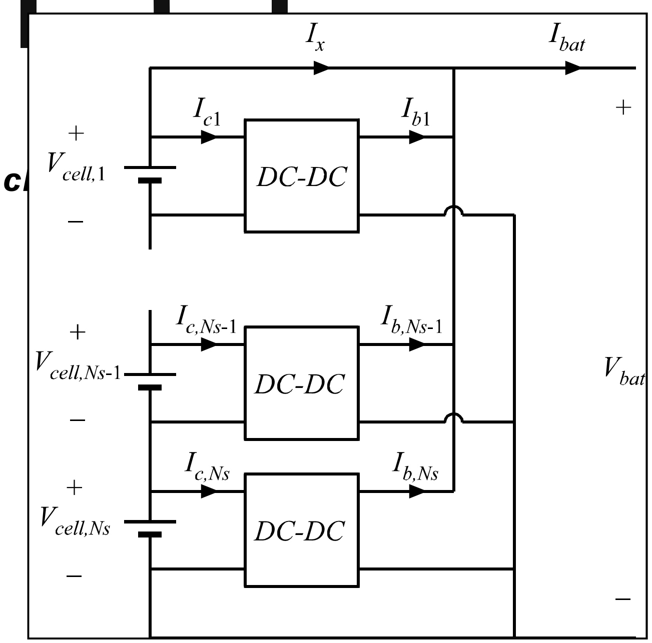
- Option 1: Dissipate, then recharge
  - Repeat a number of cycles to balance all cells at full charge



Active Balancing

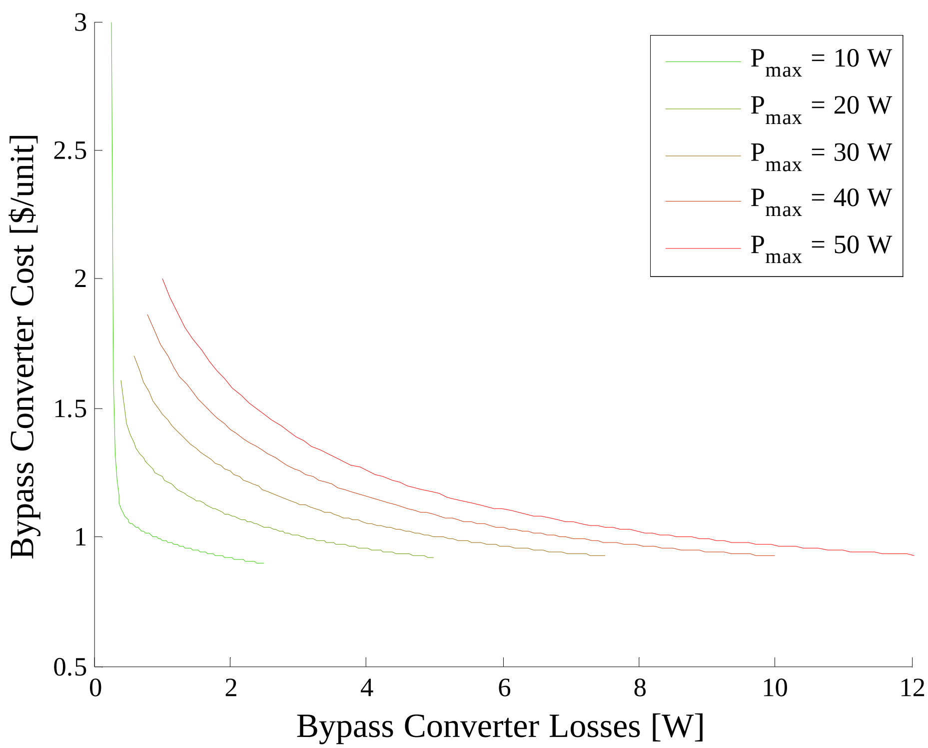


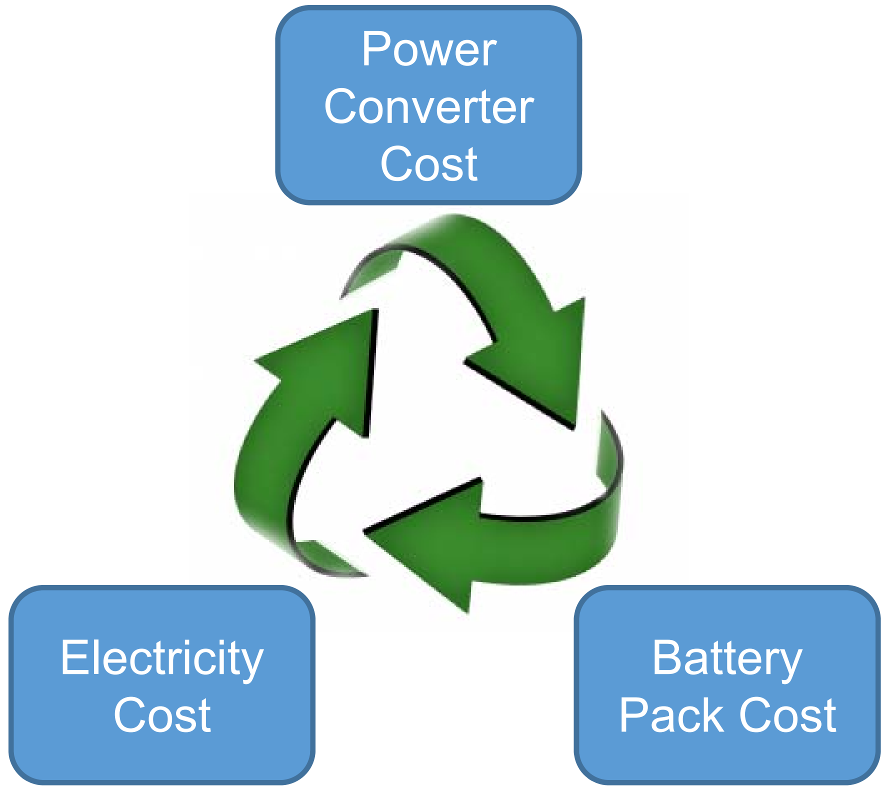




- Option 2: Redistribute
  - Requires more advanced circuits
  - Can be run continuously, during runtime

Cost-Only Design of BMS Converters





- Multidisciplinary approach can determine the minimum lifetime cost. Need accurate modeling of:
  - Power electronics cost
  - Battery cell degradation
  - Vehicle lifetime usage
  - Consumer demand
  - Market value
  - Electricity pricing

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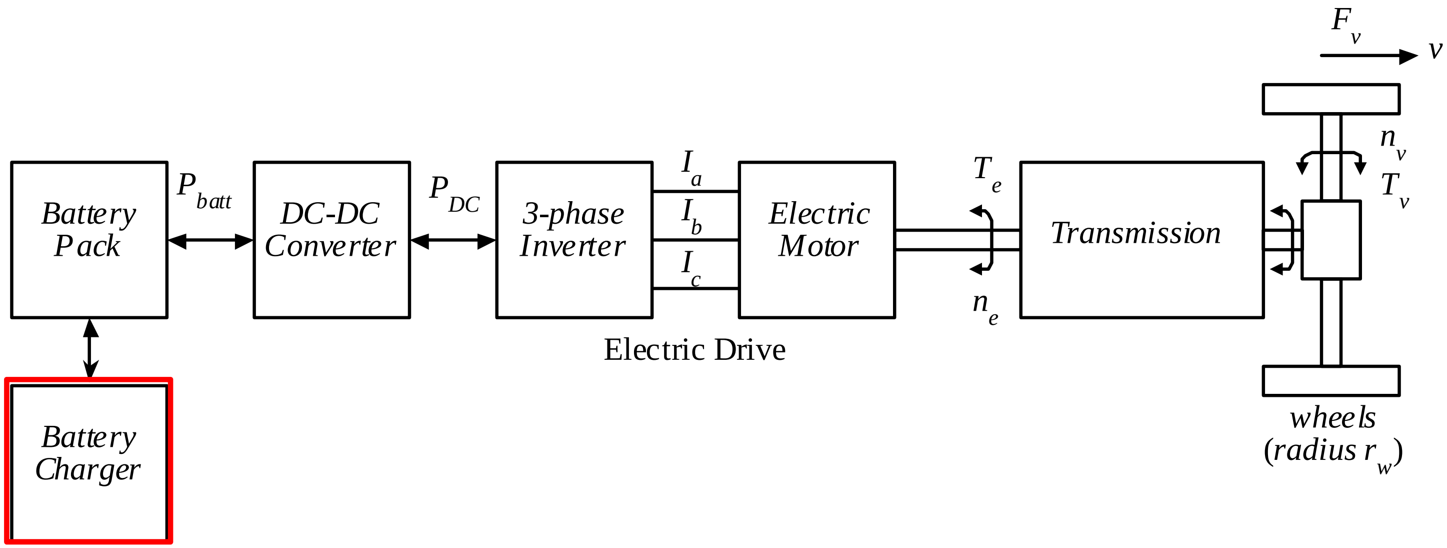
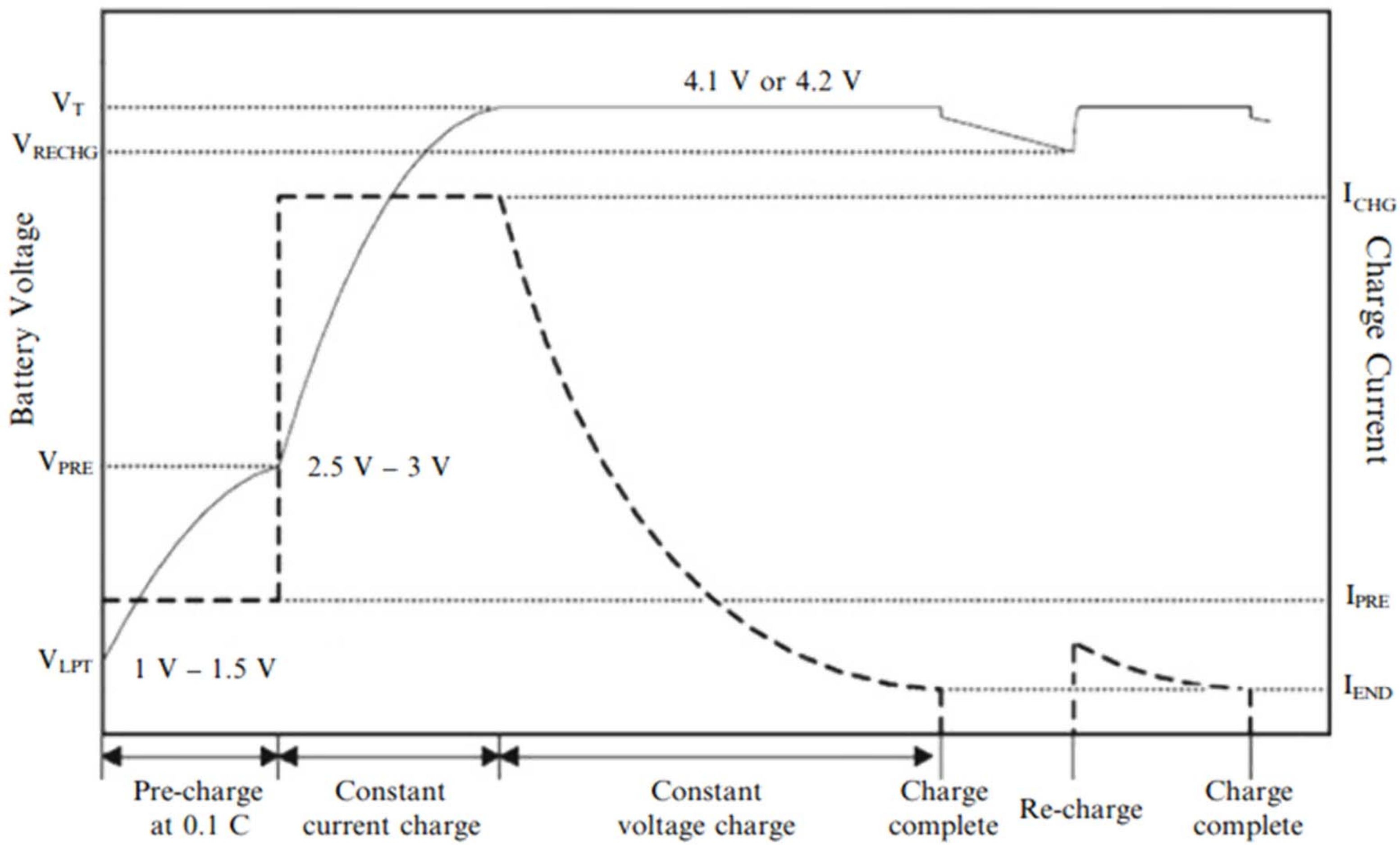
Electric Drive Realization



Li-ion Cell Charge Profile

K. Young et al, "Chapter 2: Electric Vehicle Battery Technologies"



I_{CHG}:	Charge current. 0.5C-1C can be considered as fast charge.	V_T:	Battery terminal voltage.
I_{PRE}:	Pre-charge current, e.g. 0.1 C.	V_{RECHG}:	Threshold voltage to start recharge.
I_{END}:	Ending charge current, e.g. 0.02 C.	V_{PRE}:	Voltage when pre-charge finished.
		V_{LPT}:	Low protection threshold voltage.

Charge Time Optimization

Anderson Hoke et. al., "Electric Vehicle Charge Optimization Including Effects of Lithium-Ion Battery Degradation"

$$c_{x,T} = c_{bat} \cdot \left(\underbrace{\int_{t_{ch}} \frac{1}{8760 \cdot L_x\left(T_{amb} + R_{th} \cdot \left|P(t)\right|\right)} dt}_{\Delta L/L \text{ due to charging}} + \underbrace{\frac{t_{max} - t_{ch}}{8760 \cdot L_x\left(T_{amb}\right)}}_{\Delta L/L \text{ while plugged in but not charging}} - \underbrace{\frac{t_{max}}{8760 \cdot L_x\left(P_{min} \cdot R_{th} + T_{amb}\right)}}_{\text{Baseline } \Delta L/L \text{ that would be expended by slow charging}} \right)$$

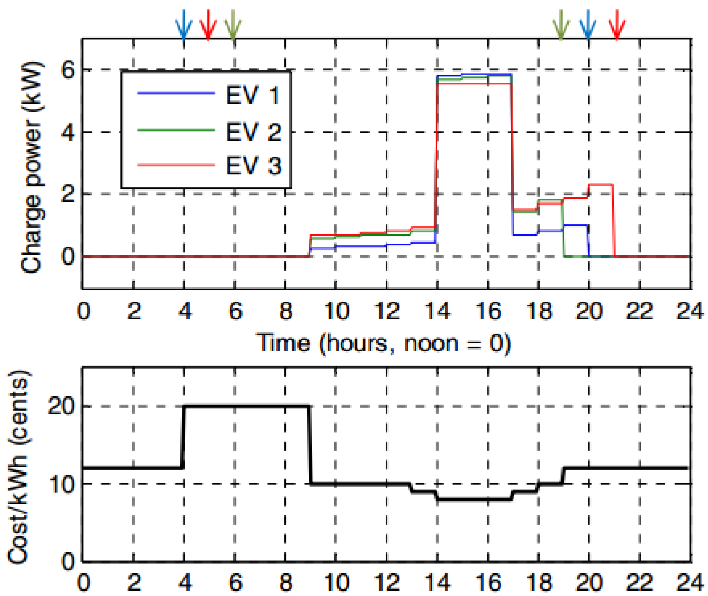


Fig. 8. Optimized charging of 3 EVs with multi-level cost of energy

- Battery lifetime degradation due to
  - SOC
  - DOD
  - Temperature
- Can optimize cost of battery over lifetime vs. instantaneous cost of energy

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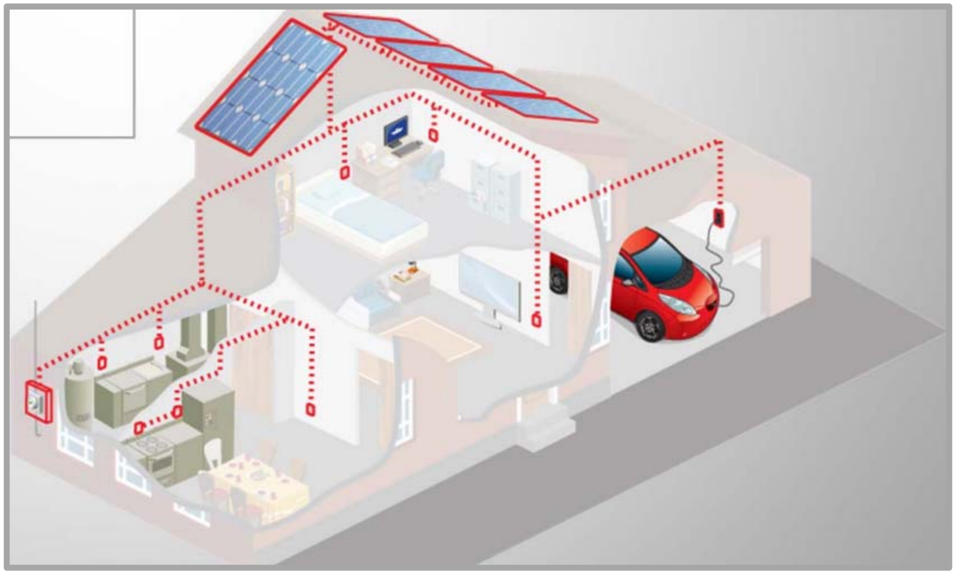
Vehicle-Grid Interactions

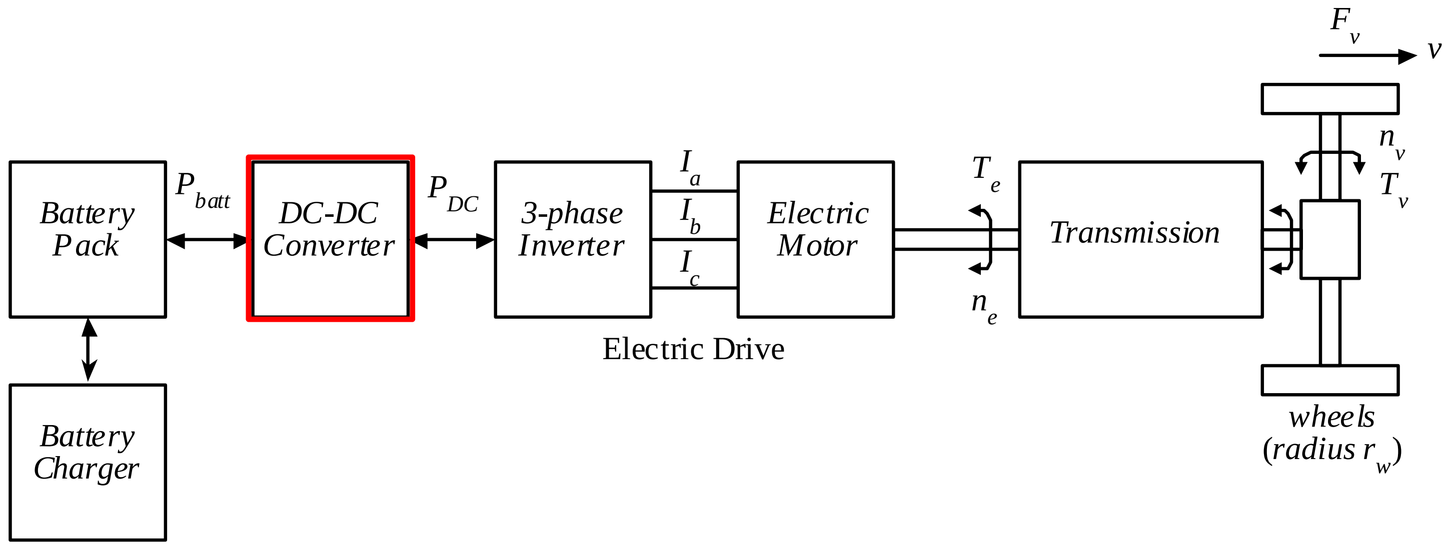
SAE Ground Vehicle Standards SmartGrid

- EV batteries used as energy storage for grid
- Intermittency mitigation coupled to renewables
- Load shifting
- Power compensation

Features	V0G	V1G	V2G	V2B
Real-time communication		√	√	√
Communication with grid		√	√	
Timed charging		√	√	√
Backup source			√	√
Controllable load		√	√	√
Bidirectional grid ancillary service			√	
Load shifting for renewables			√	√

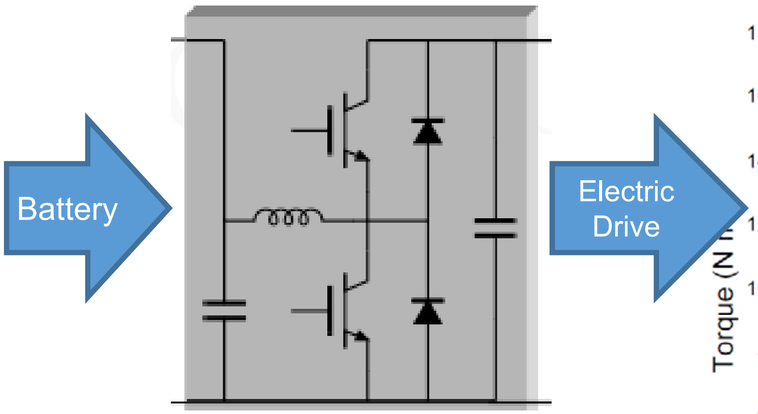


Electric Drive Realization

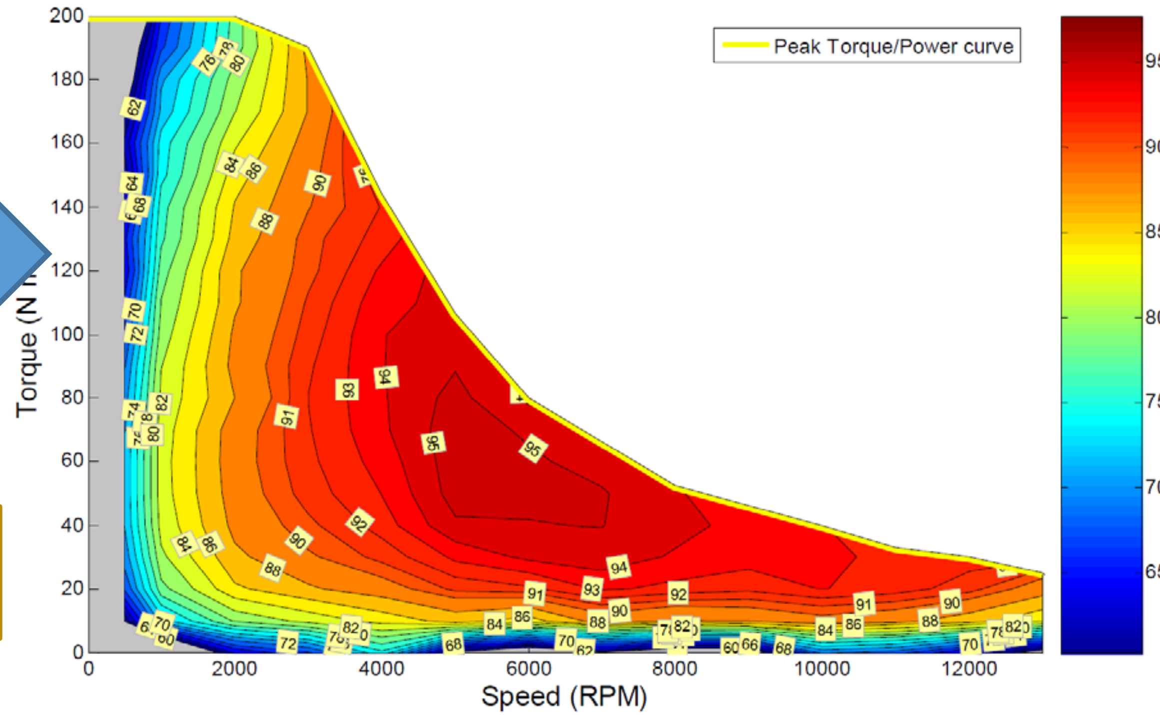


Drivetrain DC-DC Converter

Oak Ridge National Lab, "Benchmarking of Competitive Technologies"



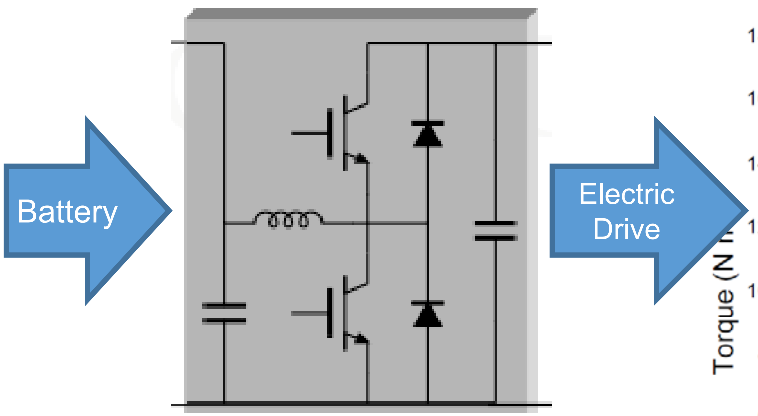
Bidirectional DC-DC Converter



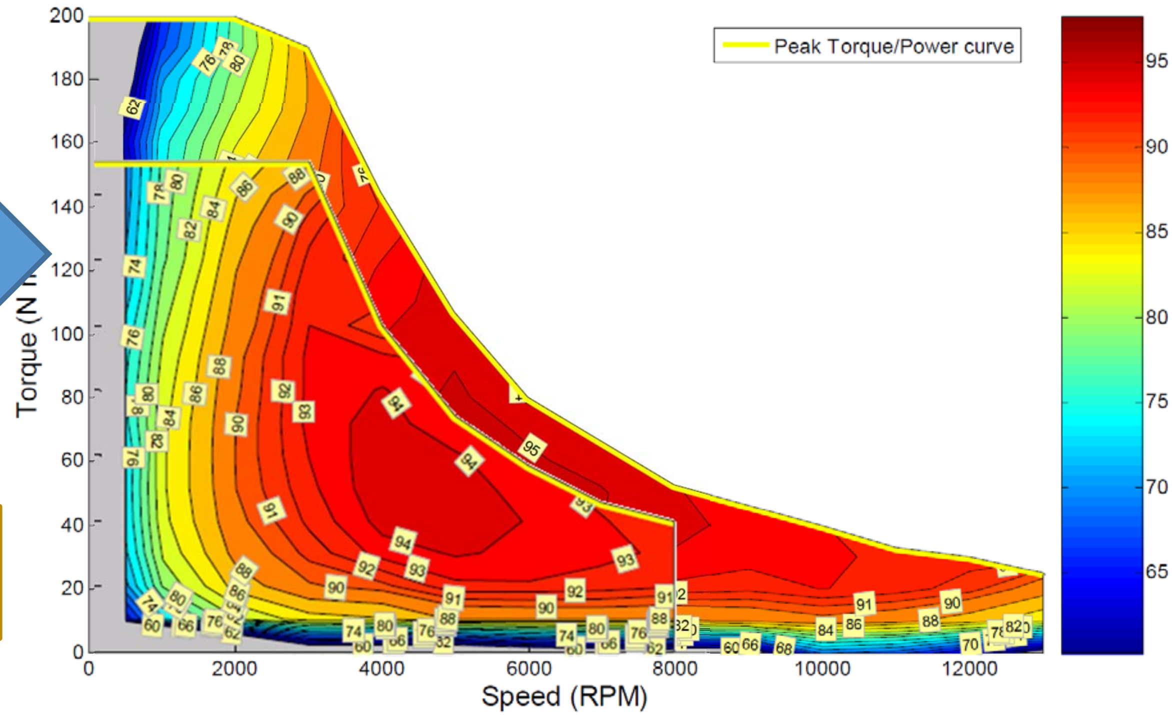
- A DC-DC converter to boost battery voltage is included in many Evs
  - Allows higher efficiency operation of ED
  - Wider operating range
  - Lower pack voltage

Drivetrain DC-DC Converter

Oak Ridge National Lab, "Benchmarking of Competitive Technologies"



Bidirectional DC-DC Converter



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Drivetrain DC-DC Converter

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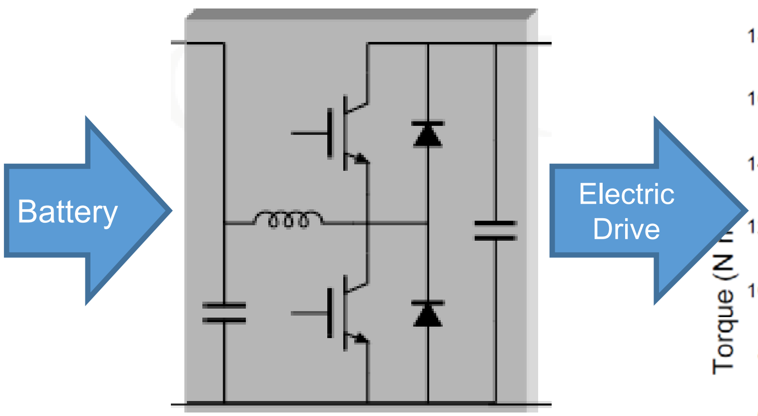
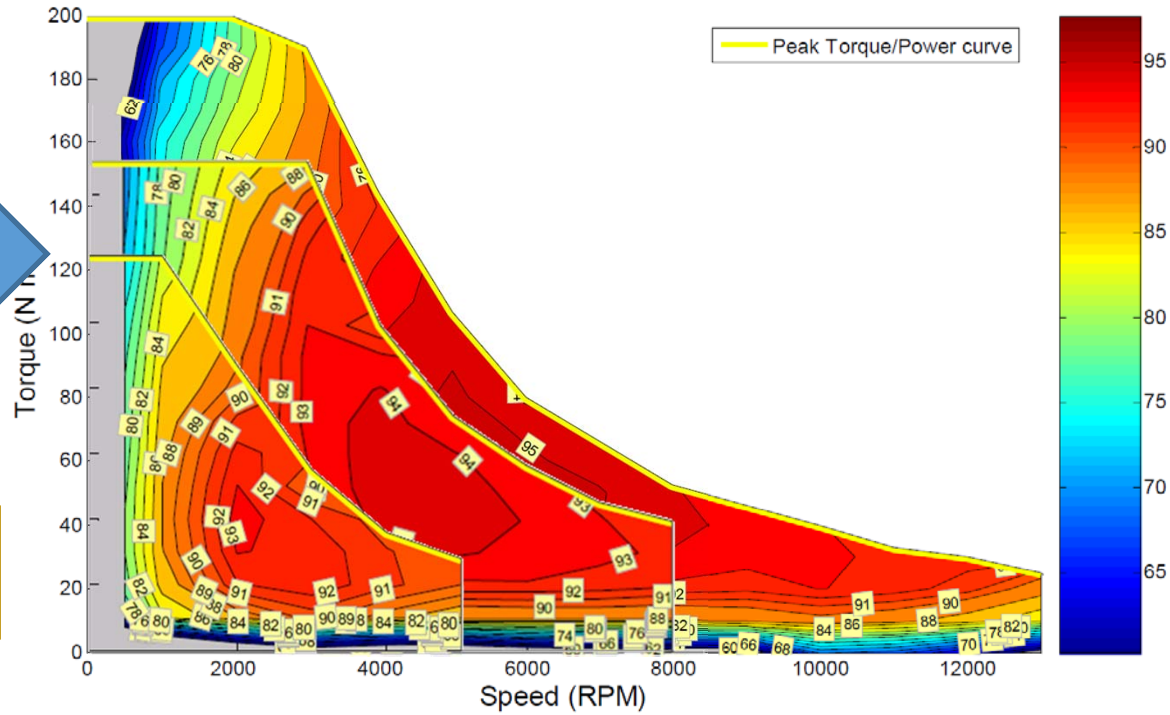
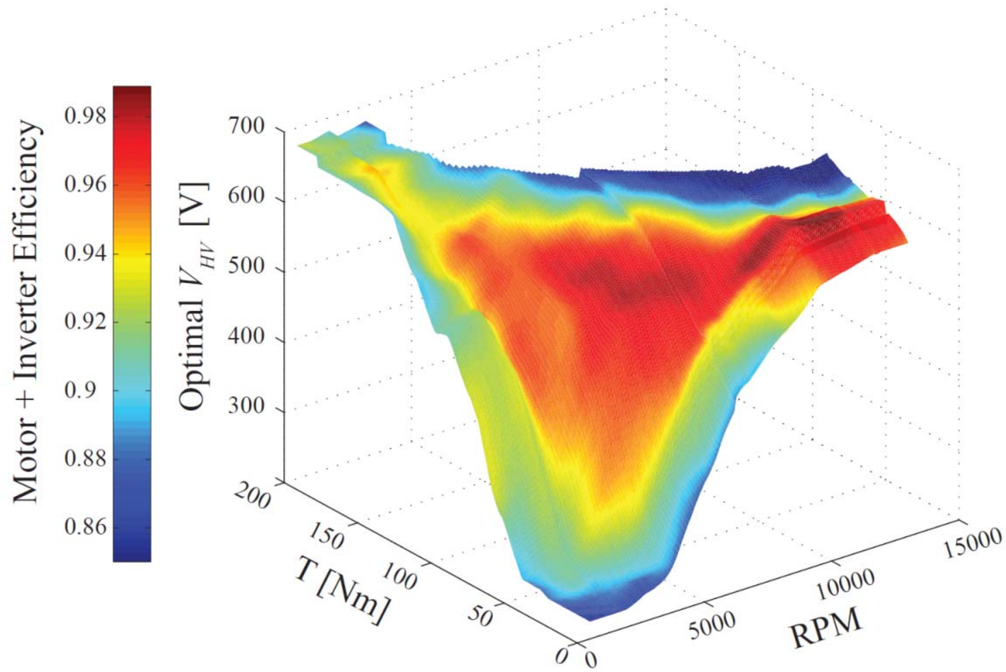




Bidirectional DC-DC Converter

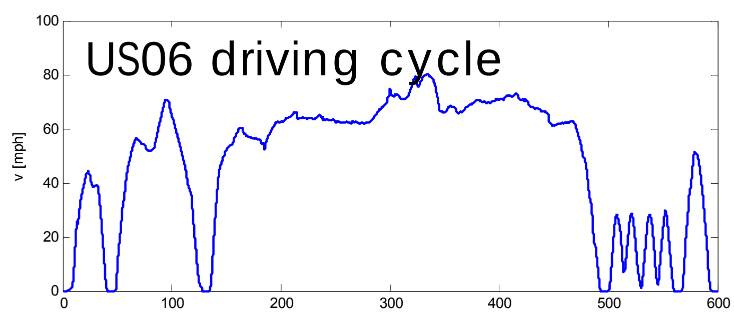
- A DC-DC converter to boost battery voltage is included in many Evs
    - Allows higher efficiency operation of ED
    - Wider operating range
    - Lower pack voltage

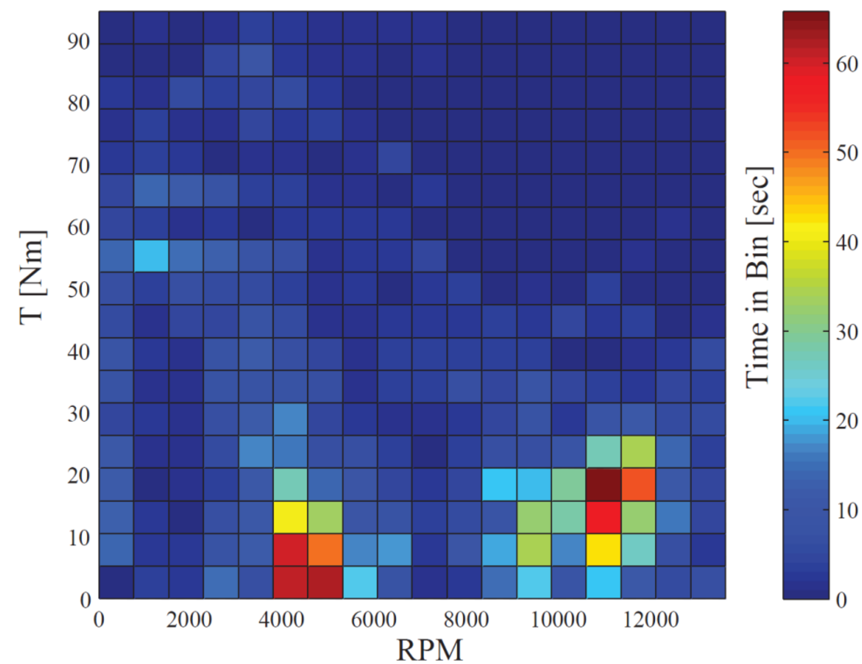
Optimal Bus Voltage



- Bus voltage for maximum efficiency of electric drive varies with speed and torque
- Maximum ED efficiency only obtained when power electronics vary bus voltage dynamically
- Often, only high power operating points are considered in design, but…

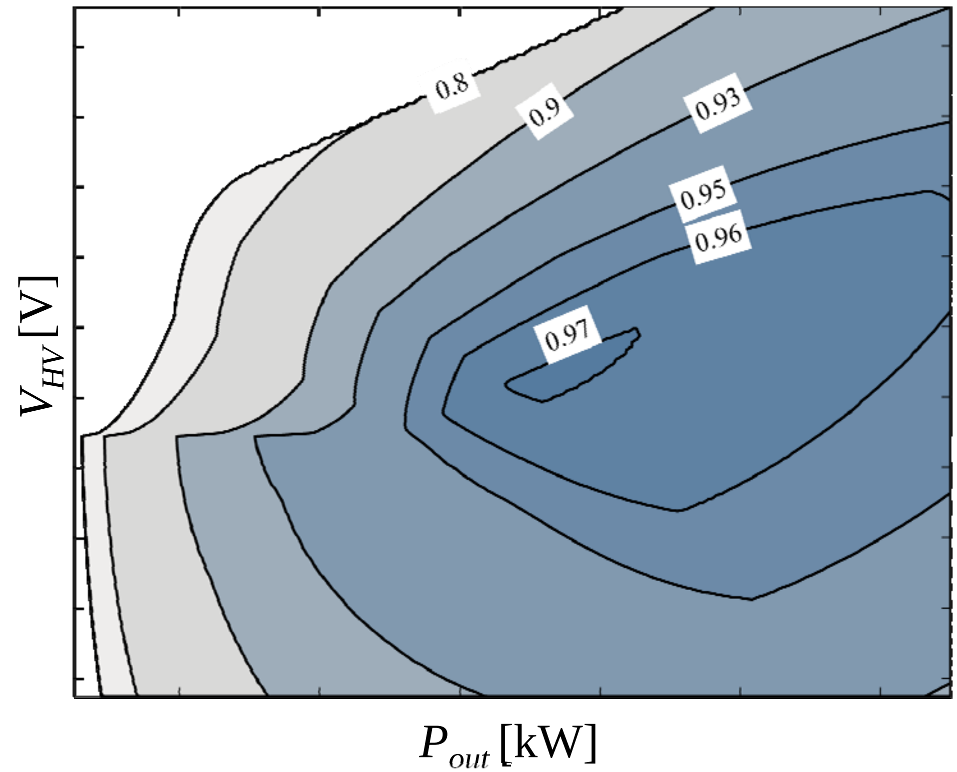
- … under normal driving conditions, ED operates predominately at low power

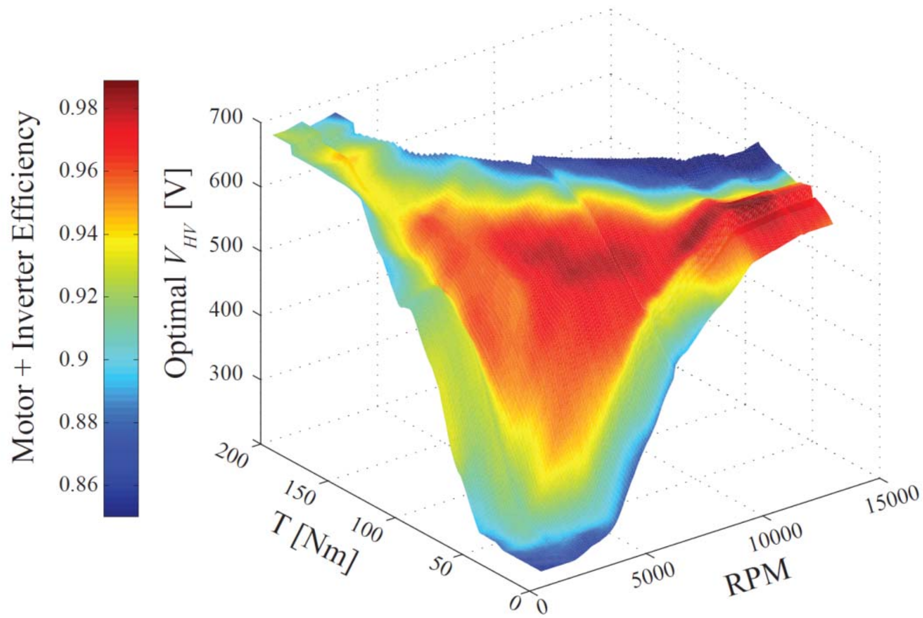


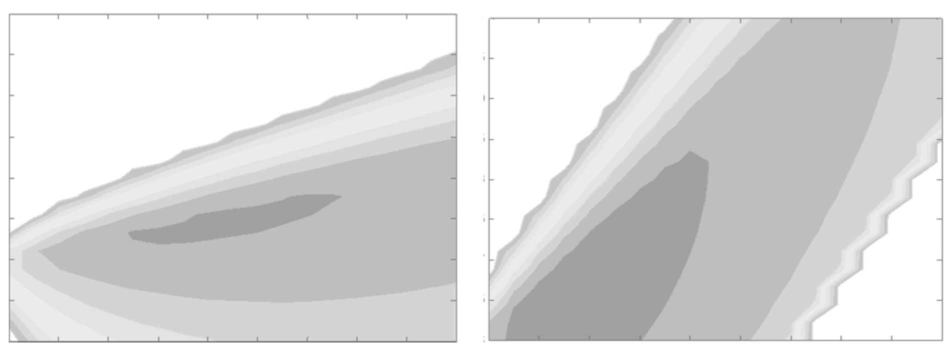


Efficiency of DC-DC Converter

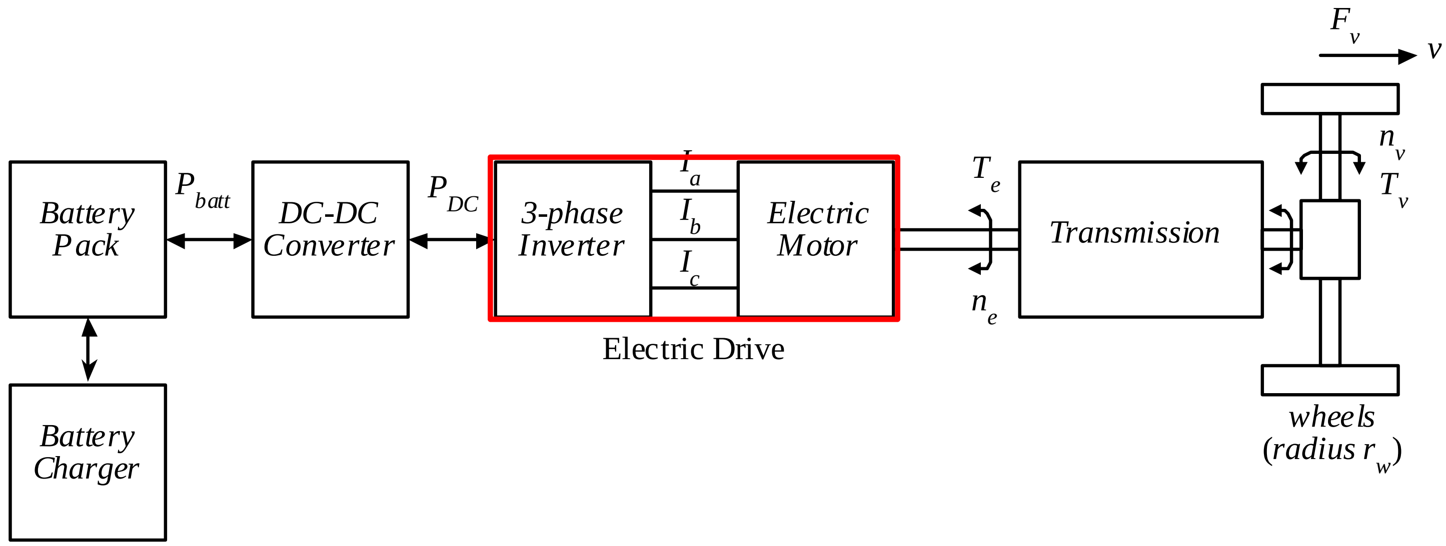
- DC-DC converter efficiency also varies with voltage and power
- Converter needs to be *codesigned* with electric drive for minimum loss under real operating conditions



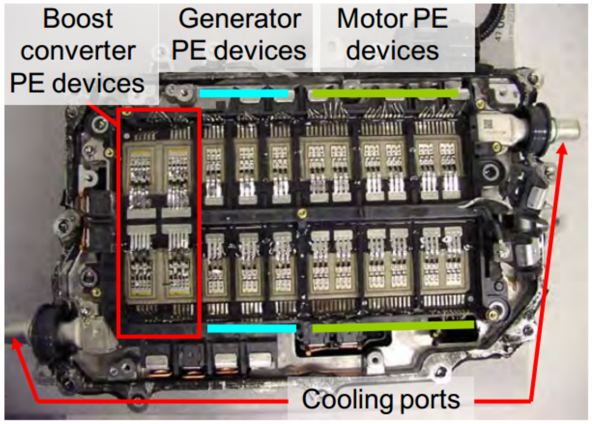




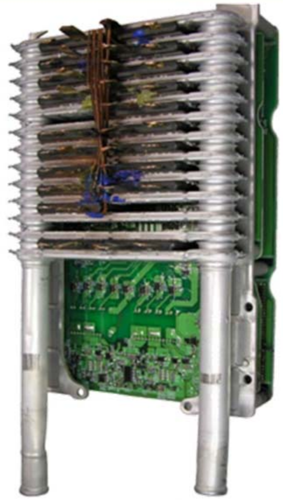
Electric Drive Realization

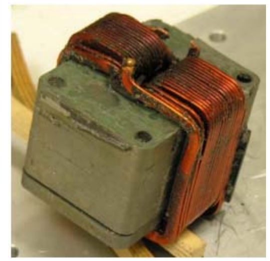


Example EV Power Electronics Converters



2010 Prius PEM





Design Feature	2010 Prius*	2008 LS 600h	2007 Camry	2006 Accord	2004 Prius
Motor-related Technology					
Motor peak power rating	**60 kW**	**110 kW**	**70kW**	**12.4 kW**	**50 kW**
Motor peak torque rating	**207 Newton meters (Nm)**	**300 Nm**	**270 Nm**	**136 Nm**	**400 Nm**
Rotational speed rating	**13,500 rpm**	**10,230 rpm**	**14,000 rpm**	**6,000 rpm**	**6,000 rpm**
Power electronics-related Technology					
IPM Cooling	**Direct cooled, single side water/glycol loop**	**Double-sided infrastructure, water/glycol loop**	**Heat sink with water/glycol loop**	**Air-cooled heat sink**	**Same as Camry**
Bi-directional DC-DC converter output voltage	**200-650 Vdc**	**~288-650 Vdc**	**250–650 Vdc**	**N/A**	**200–500 Vdc**
High-voltage (HV) Ni-MH battery	**201.6 V, 6.5 Ah**	**288 V, 6.5 Ah,**	**244.8 V, 6.5 Ah,**	**144V, 6.5 Ah**	**201.6 V, 6.5 Ah,**
	27 kW	**36.5 kW**	**30 kW**	**13.8 kW**	**20 kW**

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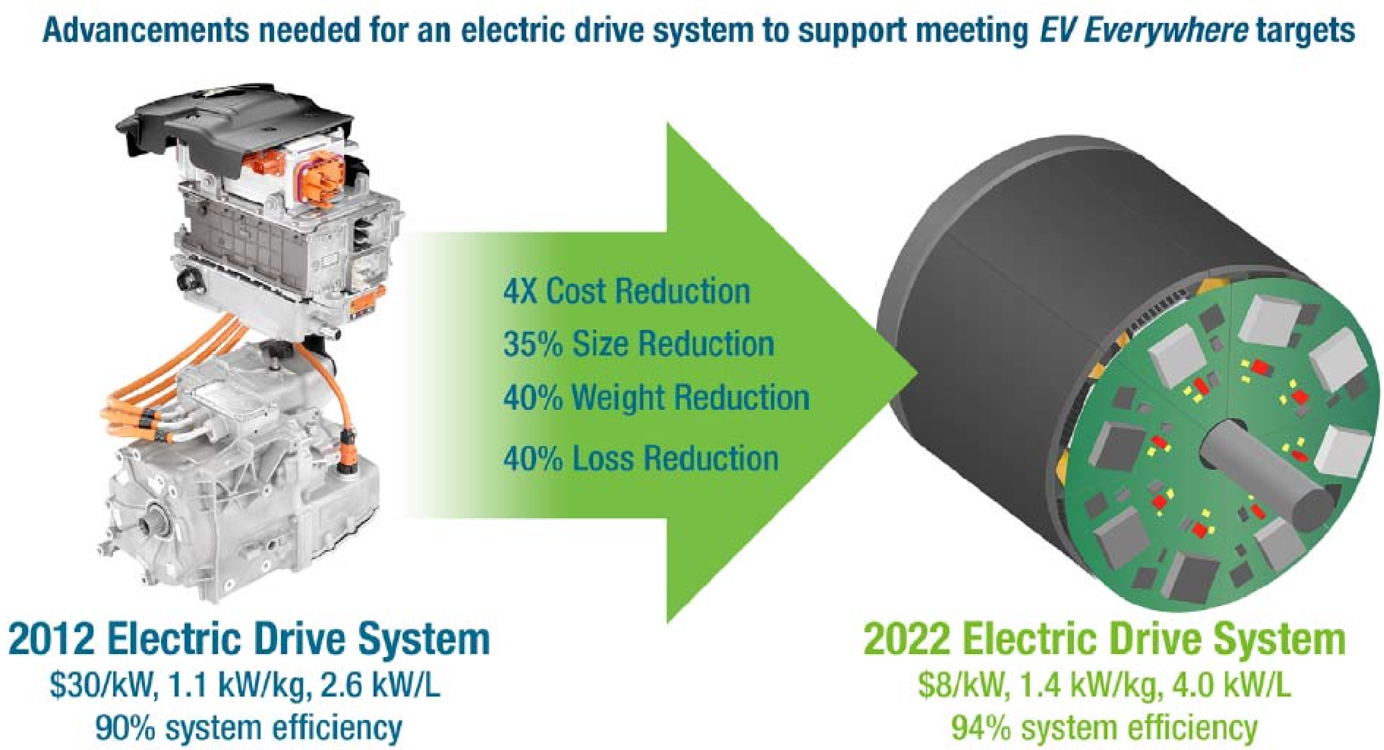
Tim Burress, "Benchmarking of Competitive Technologies" 2011

EV Everywhere Grand Challenge



Research efforts focus on:

- Wide bandgap (WBG) devices for power electronics
- Novel packaging for power electronics
- Improvements in thermal management and reliability
- Integration of power electronics functions

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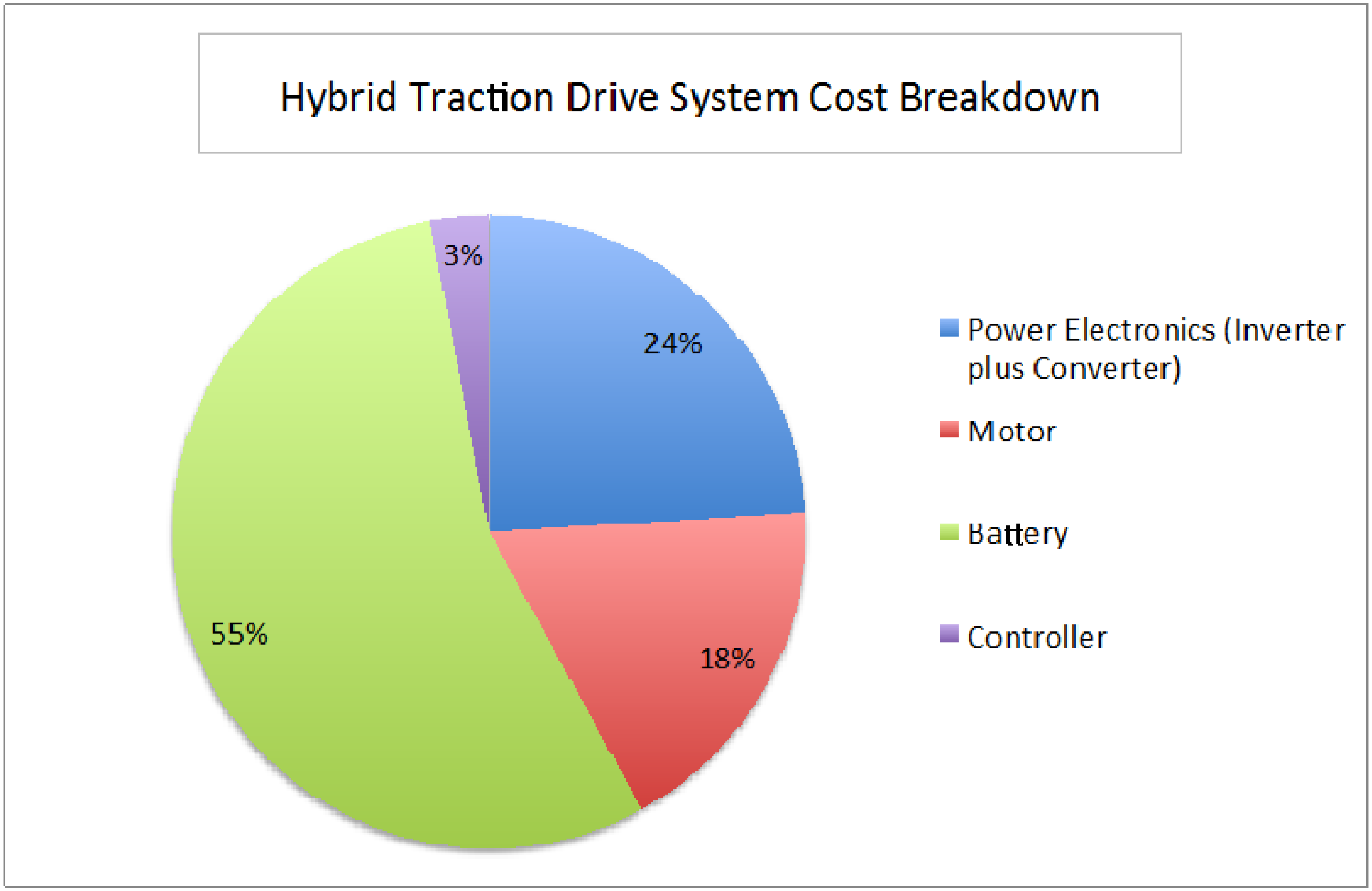
Cost of Powertrain



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Conclusions

- Electrification of transportation is an enabling technology for safe, reliable, and environmental future
- Issues:
  - Battery energy storage and charging times inadequate for consumer expectations
  - 33% of total cost of an HEV is due to power electronics
  - Weight and volume miniaturization required; Thermal management and packaging increase weight and require overdesign
  - Materials (semiconductor, inductor, capacitor) materials not cost-effective
- Intelligent and comprehensive design of power electronics is necessary to continue development of electric vehicles.

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CENTER FOR ULTRA-WIDE-AREA RESILIENT ELECTRIC ENERGY TRANSMISSION NETWORKS

Questions