Transportation Electrification
Land and Air

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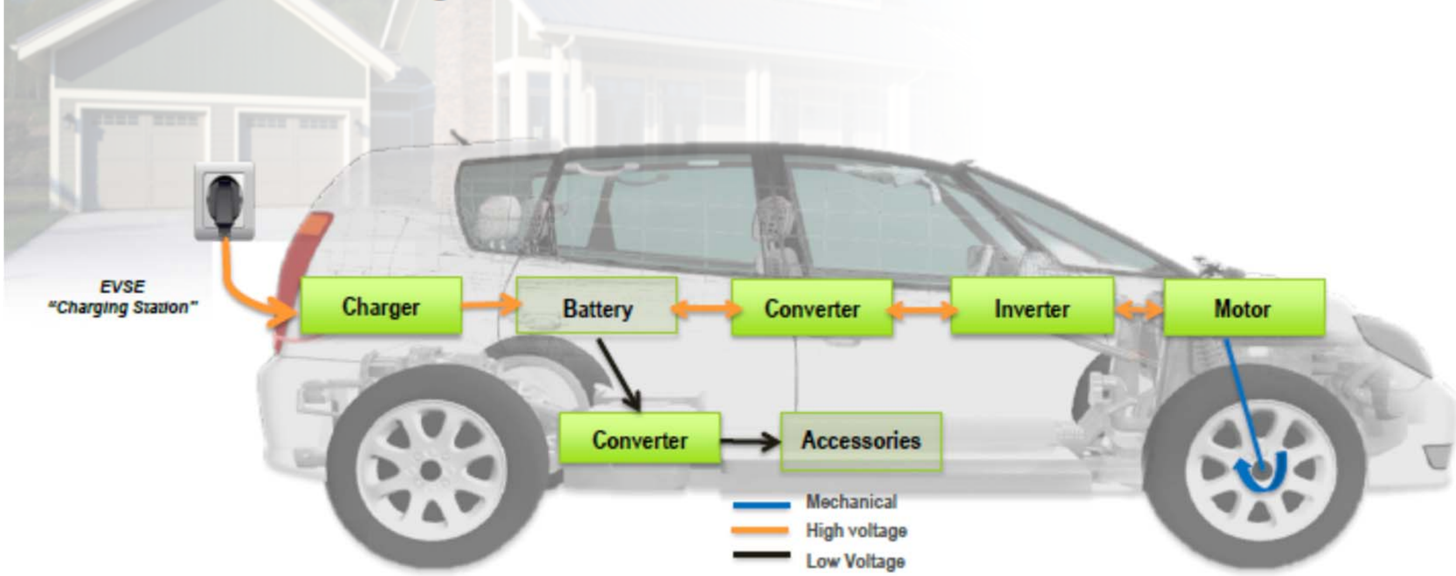
EV to PHEV to EV

Electric Drive System Components

Electric Drive System Components

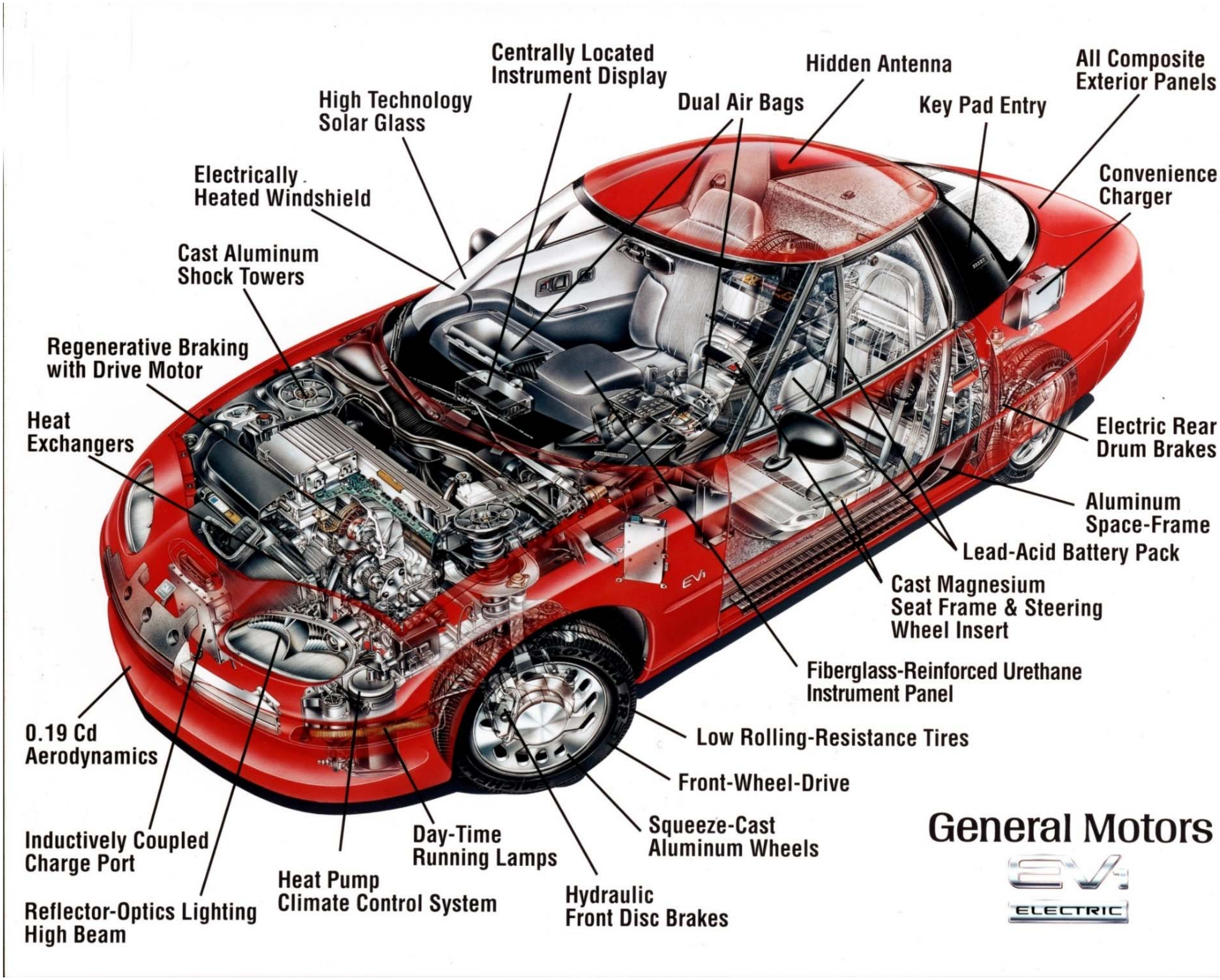
- **Electric motor** – converts electrical energy to mechanical power for motive power
- **Inverter** – converts high voltage direct current to varying pulses that control and power the electric motor
- **Charger** – modifies and controls electrical energy to re-energize the battery
- **Converter(s)** – increases the battery voltage for the traction drive system and decreases the voltage for the accessories



Integration of components will reduce electric drive system cost and improve efficiency

GM Impact 1990

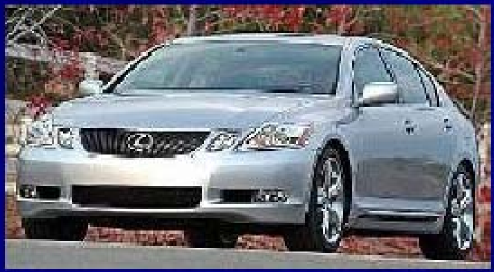
- The Impact prototype was powered by two induction motors, one driving each front wheel. The battery pack consists of 32 compact 10-volt Delco Remy lead-acid batteries, connected in series. The inverter for converting the battery voltage to ac has 288 MOSFETs, each leg consisting of 24 parallel connected devices, switching at about 20 KHz. The slip frequency of the AC current was varied to maintain the highest possible efficiency throughout the RPM range. Each motor's output is transmitted to the tires via a 10.5:1 planetary gear unit.
  - Motor Type — Three phase induction motor
  - Max. motor output — 57 bhp @ 0 to 6600 rpm (per motor)
  - Motor speed at 60 mph — 9500 rpm
  - Top speed — 100 mph (rev.limited to 75 mph)
  - Torque — 47 lb-ft @ 0 to 6600 rpm (per motor)
  - Inverter type — Dual MOSFET inverter
  - Frequency range — 0-500 Hz
  - Battery type — Lead acid, 32, ten volt batteries in series.
  - Capacity — 42.5 amp. hour,13.6 KWh
  - Battery weight — 395 Kg
  - Battery charger — Integral with dual inverter package
  - Recharge Time — 2 hrs (80%)
  - Range — 120 miles @ 55 mph
  - Acceleration(0 to 60 mph) — 8 seconds
  - Vehicle weight — 1000 Kg
- GM's Impact was the first production intent EV announced by a major car manufacturer. Impact technology led to the production of EV1 electric vehicles.


Centrally Located
Instrument Display
Hidden Antenna
All Composite
Exterior Panels
High Technology
Solar Glass
Dual Air Bags
Key Pad Entry
Electrically
Heated Windshield
Convenience
Charger
Cast Aluminum
Shock Towers
Regenerative Braking
with Drive Motor
Heat
Exchangers
Electric Rear
Drum Brakes
Aluminum
Space-Frame
Lead-Acid Battery Pack
Cast Magnesium
Seat Frame & Steering
Wheel Insert
Fiberglass-Reinforced Urethane
Instrument Panel
Low Rolling-Resistance Tires
0.19 Cd
Aerodynamics
Front-Wheel-Drive
Squeeze-Cast
Aluminum Wheels
Inductively Coupled
Charge Port
Day-Time
Running Lamps
Heat Pump
Climate Control System
Hydraulic
Front Disc Brakes
Reflector-Optics Lighting
High Beam
General Motors
EV1
ELECTRIC

TOYOTA

Today - Hybrids

Toyota Prius



Lexus GS 450h

Camry Hybrid

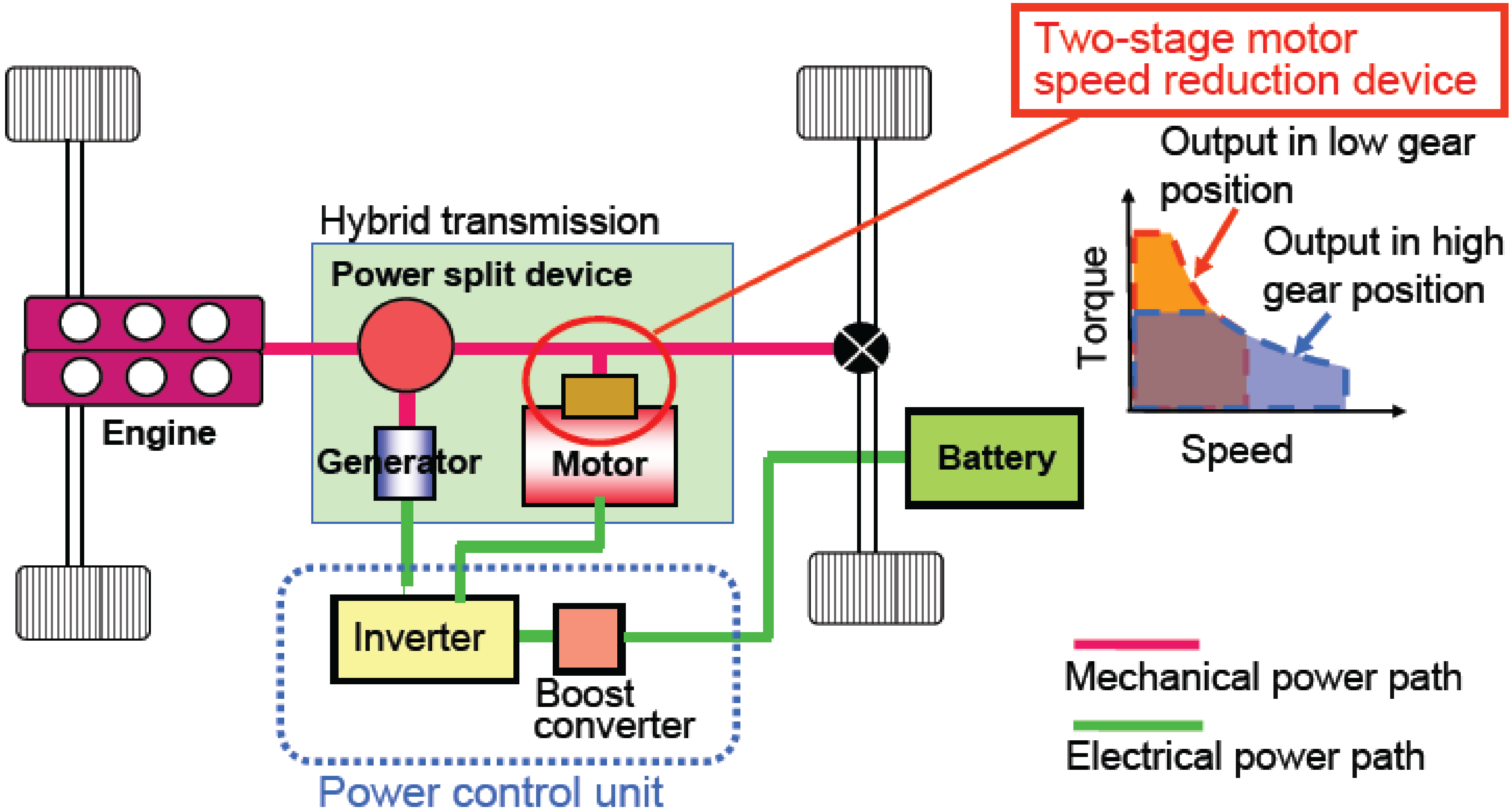
Highlander Hybrid

Lexus RX400h

Hybrid targets for early next decade: 10 models & 1.0 million/year sales

Toyota Hybrid System II

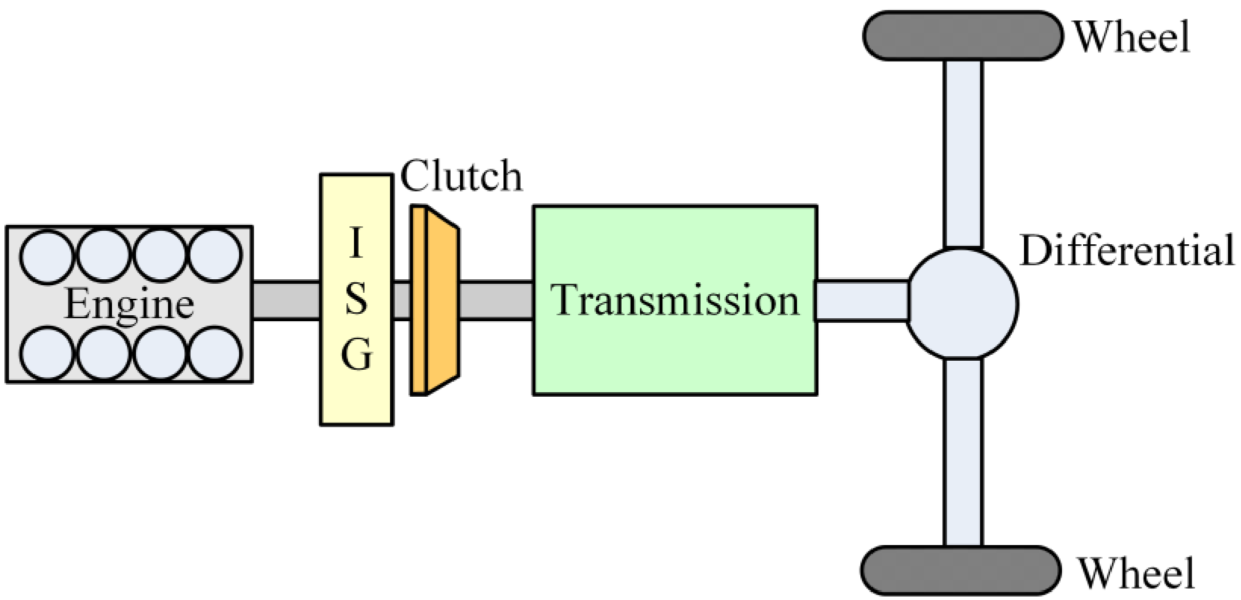
With two-stage motor speed reduction device



Toyota Prius Hybrid Synergy Drive Control

Integrated Starter Generator (ISG) Architecture

- Features
  - Engine stop at vehicle stop; Engine cutout at coast and deceleration
  - 10 to 20% fuel economy gain in urban driving cycles
- Impact
  - Removal starter motor,
  - Requires energy management system
  - Increases length of the power train



Tesla Roadster

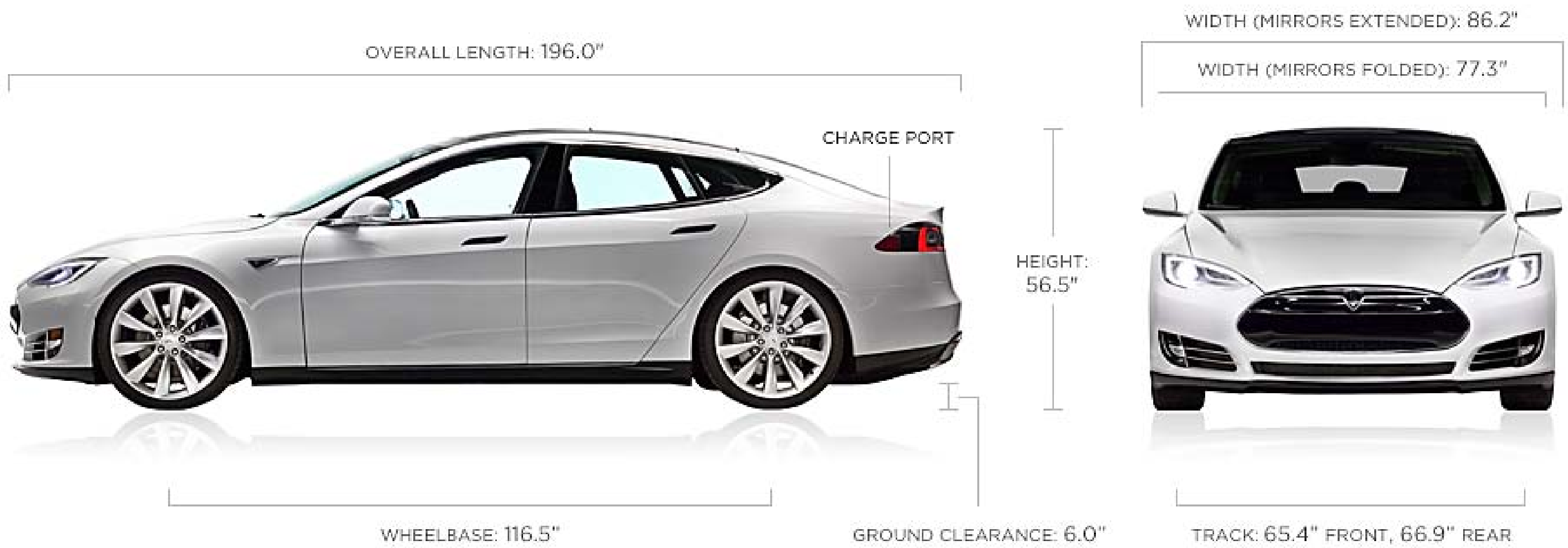
- Top Speed – 125 mph
- 2 Speed Transmission
- Range – 220 miles
- Full charge in 3.5 hrs (with 70 amp home charging station)
- Shaft Drive
- Weight – 2690 lbs
- 6,831 Lithium Ion batteries (laptop)
- Each cell is independent
- 100,000 mile life expectancy
- 3-phase, 4-pole electric induction motor, 215 kW
- Propels car 0 – 60 mph in under 4 seconds
- 85% – 95% efficient

Discontinued

Tesla Model - S

Powertrain:

Model S is a rear wheel drive electric vehicle. The liquid-cooled powertrain includes the battery, motor, drive inverter, and gear box. Microprocessor controlled, 60 kWh lithium-ion battery (230 miles range, It is 300 miles with 85 kWh), Three phase four pole induction motor with copper rotor (310 kW, 600 N·m), Inverter with variable frequency drive and regenerative braking system , and Single speed fixed gear with 9.73:1 reduction ratio.



Charging:

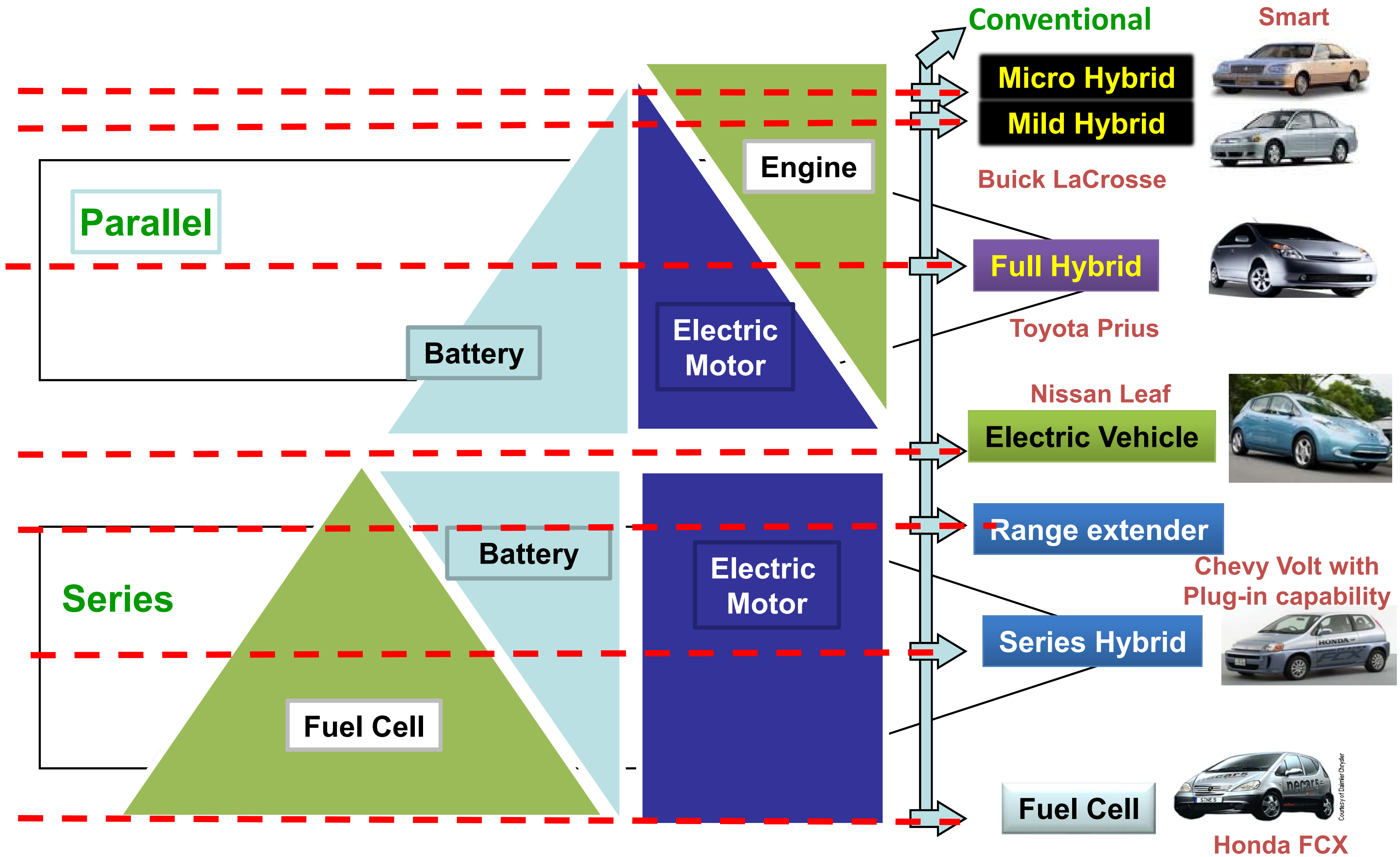
* 10 kW capable on-board charger with the following input compatibility: 85-265 V, 45-65 Hz, 1-40 A (Optional 20 kW capable Twin Chargers increases input compatibility to 80 A)
* Peak charger efficiency of 92%
* 10 kW capable Universal Mobile Connector with 110 V, 240 V, and J1772 adapters

2017 BMW i3 EV (Range Extender)

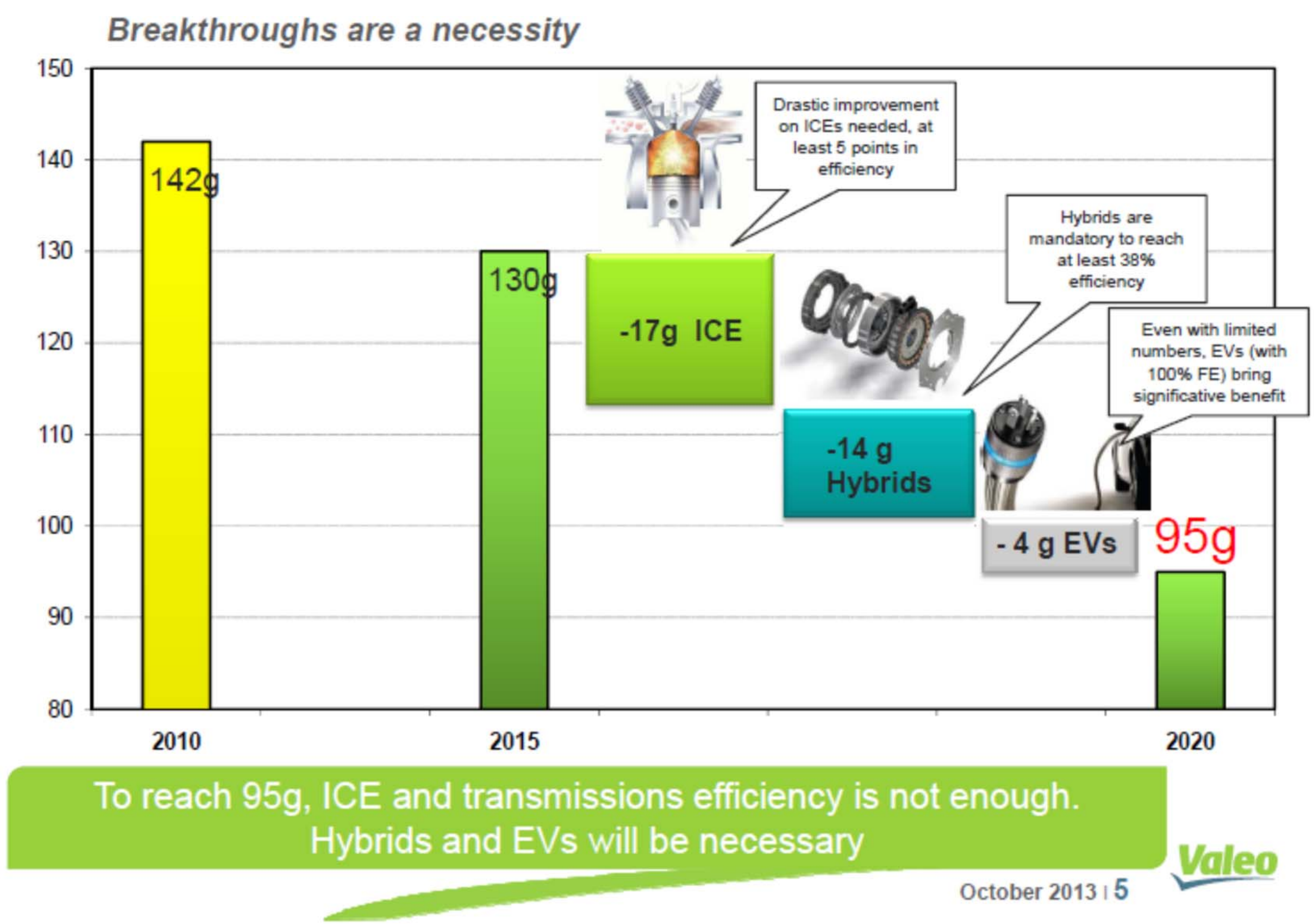
 

Motor type	Hybrid synchronous motor	Range	231-240miles
Motor power output	125kW	Battery Type	Li ion
Motor torque	250Nm	Battery Energy	27.2kWh
Top Speed	150 kmph	Charging time @ 125A 50kW DC	<40min
Acceleration (0-100kmph)	8.1s	Charging time @ 16A	7.5 hrs

Hybrid Power train Topology



2020 European 'CAFE' Prospective



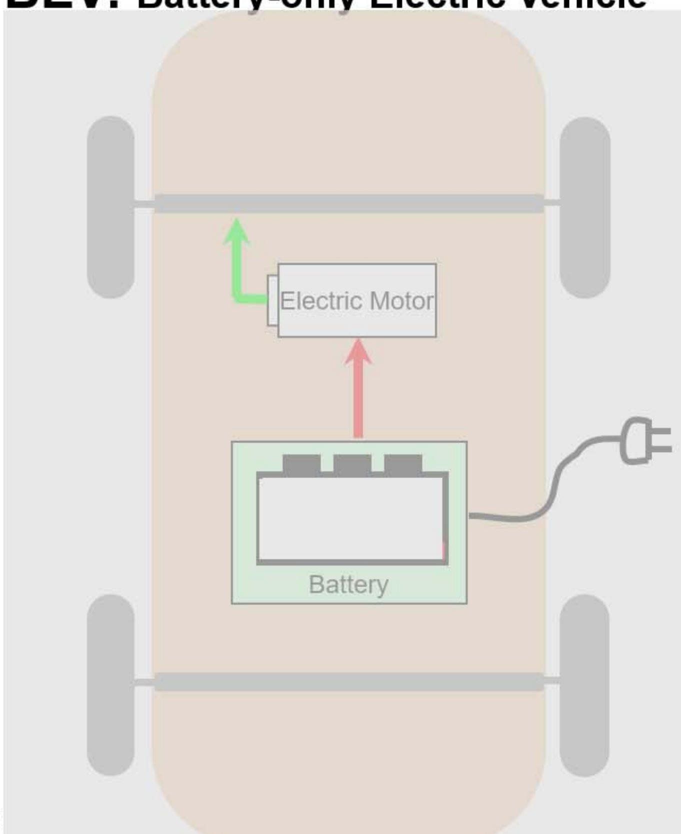
48/12 Volt Architectures

- There are 2 basic Architectures for 48/12 Volt Systems, which can be functionally identical within the power range of an accessory belt drive
  - Belt-Alternator-Starter
    - Advantageous when other powertrains are used on the same vehicle since the basic engine & transmission configuration is common.
  - Integrated Starter-Alternator
    - Does not have large starter-alternator external to the powertrain
    - Can transmit more power since it is not limited by belt drive.
    - Packaging tradeoff at the expense of serviceability

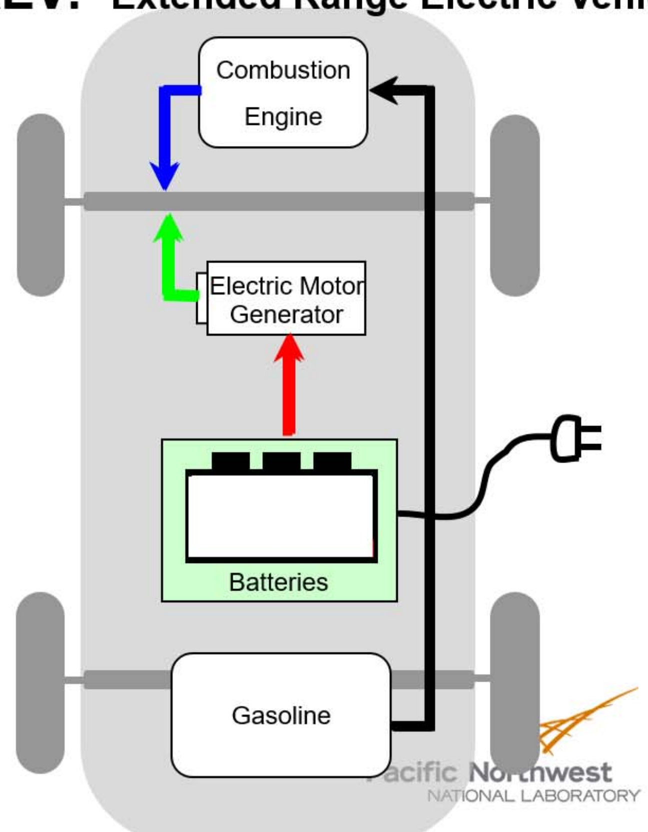
Plug-in Hybrid Vehicle

PEV: **Plug-in Electric Vehicle**

EV: **Electric Vehicle**
BEV: **Battery-only Electric Vehicle**

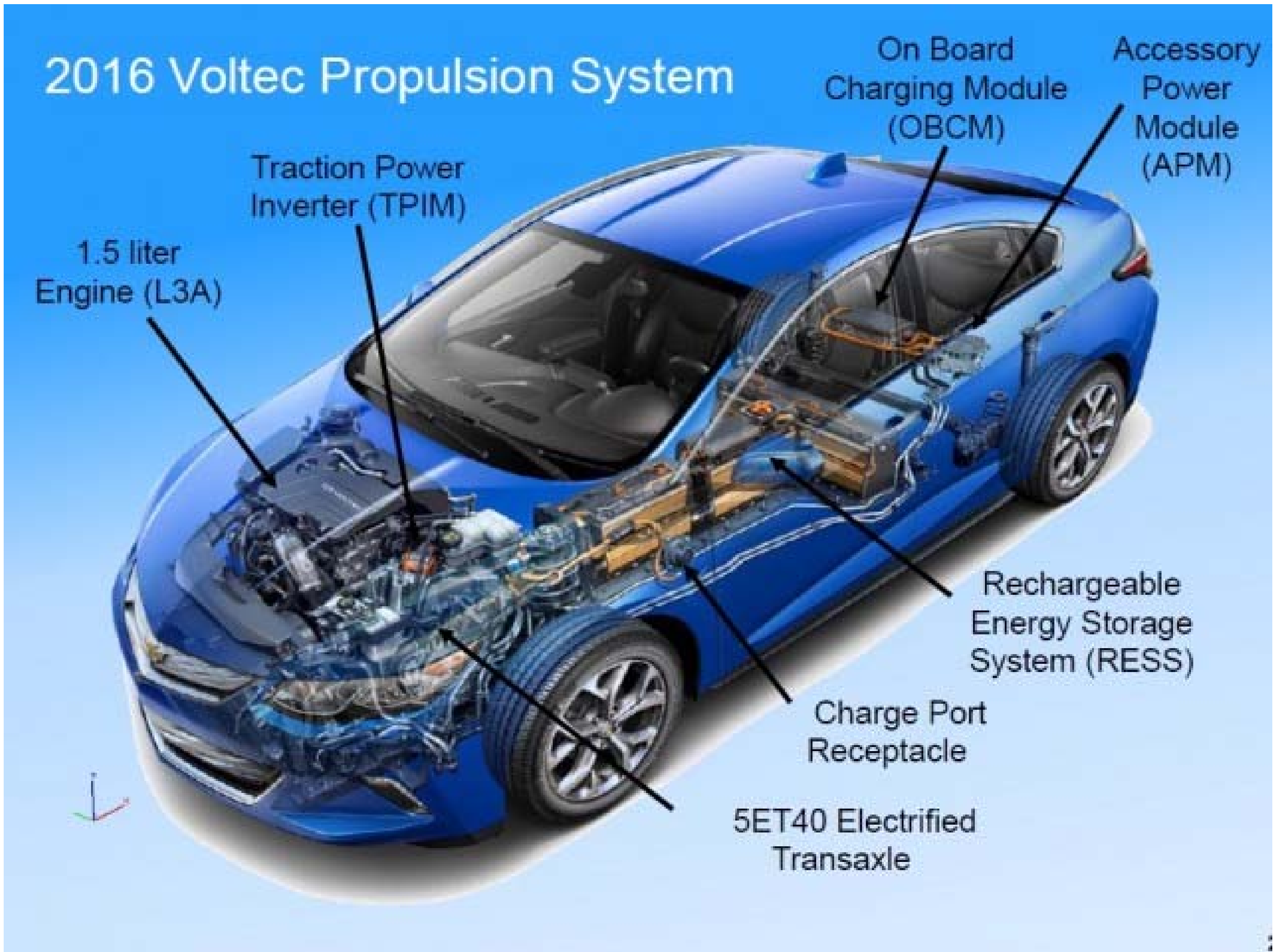


PHEV: **Plug-in Hybrid Electric Vehicle**
EREV: **Extended Range Electric Vehicle**



CHEVROLET VOLT

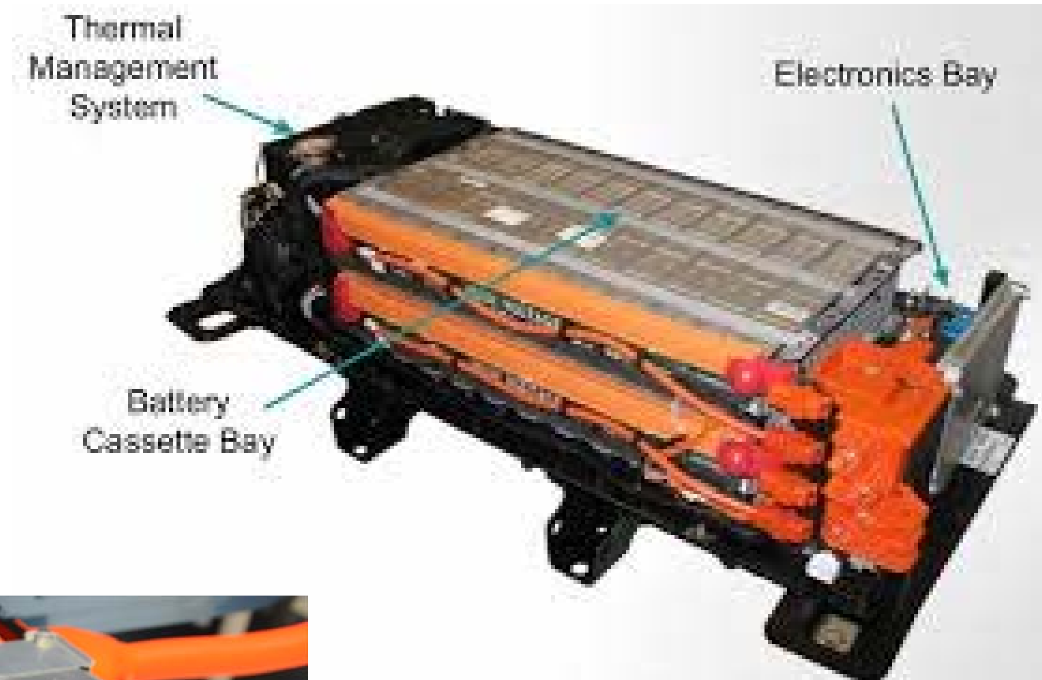
YEAR: First introduced in January 2011



Specifications	
Battery(KWh)	17.5 (2015 Models) 18.4 (2017 Models) (192 cells)
Type	Lithium Ion 360V Nominal
Battery pack weight Total Energy	183 kg 18.4kWh
All Electric Range	40 miles (2015 model) 53 miles (2017 model)
Gasoline Engine (Opel's Family)	1.4L 4-cylinder engine
Power	80hp (60KW)
Fuel Tank Capacity	9.3 US Gallons
Generator/Motor 2	48kW (Ferrite)
Maximum Speed	100 miles per hour (160 km/h
Motor 1 Type	Permanent Magnet
Motor Power (Peak)	87kW
Torque	370Nm
Range	Range with a full tank of gasoline and a fully charged battery is 379 miles (609.9 km)

Energy and Power Needs

Storage technology	Energy density
Lead-acid batteries	100 kJ/kg (30 W-h/kg)
Lithium-ion batteries	600 kJ/kg
Compressed air, 10 MPa	80 kJ/kg (not including tank)
Conventional capacitors	0.2 kJ/kg
Ultracapacitors	20 kJ/kg
Flywheels	100 kJ/kg
Gasoline	43000 kJ/kg



Nissan Leaf battery pack

Lithium ion batteries

Li-ion systems get their name from their unique cathode materials. The lithium-ion family is divided into three major battery types, so named by their cathode oxides, which are cobalt, manganese and phosphate. The characteristics of these Li-ion systems are as follows.

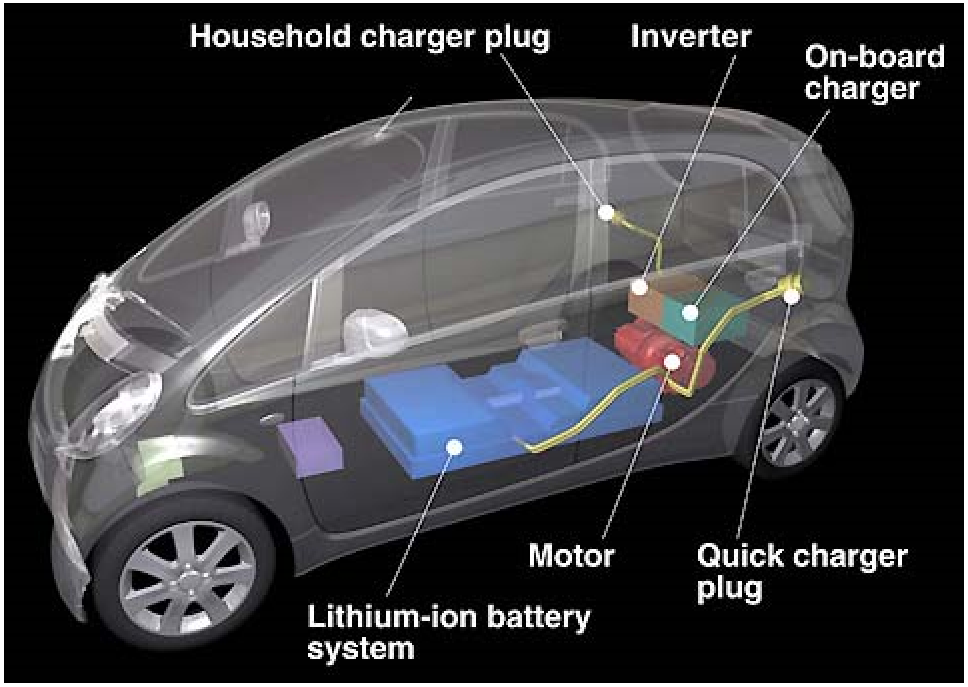
- **Lithium-ion-cobalt** or *lithium-cobalt* (LiCoO2): Has high specific energy with moderate load capabilities and modest service life. Applications include cell phones, laptops, digital cameras and wearable products.
- **Lithium-ion-manganese** or *lithium-manganese* (LiMn2O4): Is capable of high charge and discharge currents but has low specific energy and modest service life; used for power tools, medical instruments and electric powertrains.
- **Lithium-ion-phosphate** or *lithium-phosphate* (LiFePO4): Is similar to lithium-manganese; nominal voltage is 3.3V/cell; offers long cycle life, has a good safe record but exhibits higher self-discharge than other Li-ion systems.

Figures of Merit of Advanced batteries

		Lead-Acid		Nickel-Metal Hydride		Lithium-Ion	
		SLI	Advanced	HEV	BEV	HEV	PHEV-BEV
Nominal Cell Voltage	V	2.0	2.0	1.2	1.2	3.3-3.8	3.3-3.8
Energy Density	Wh/l	60	75	100	250	150	200-400
Specific Energy	Wh/kg	25	40	50	100	90	120-200
Power Density	W/l	1200	600	2000 - 2500	500-800	3500-9000	800-2200
Specific Power	W/kg	500	250	1000-1300	200-400	2000-4000	500-1200

- Values are shown for cells.
- System values can be reduced by as much as half (more for HEV).

Electric Vehicle



No engine
Only battery, power electronics, and electric motor

PHEV Fast Charging

- DC-fast charging (DCFC) enables a direct connection to the DC leads to the vehicle battery for the very fastest rate charging.
- DCFC is typically most useful for battery electric vehicles (BEVs) that have no gasoline engine backup for intercity travel
- DCFC is most often associated with the fastest charging rates possible in an attempt to approach the rapid energy transfer rate of gasoline refueling.
- DCFC charge rates of 100kW+ require grid connections that are only typically available in commercial or industrial sites (and not homes).
- While DCFC still delivers slower than the energy transfer at the gas pump, DCFC can get the electric vehicle driver back on the road conveniently to provide a substantial amount of range.
- For an intercity trip, a rough estimate is that a large battery BEV (such as an 85kWh Tesla Model S) can acquire enough charge for about 2.5 hours of highway driving in 30 minutes at the fastest Tesla Supercharger DCFC station.

http://tec.ieee.org/newsletter/january-february-2015/plug-in-hybrid-electric-vehicle-dc-fast-charging-the-future-just-got-more-interesting

DC Fast Charging

Miles per 30 minutes of charging

Level 1 = 1.7 kW	0.5hr*1.7kWHr*4mi/kWHr = 3.4 miles
Level 2 = 6 kW	0.5hr*6.0kWHr*4mi/kWHr = 12 miles
Level 3 = 50 kW	0.5hr*50.0kWHr*4mi/kWHr = 100 miles

DC Fast Charging

The Fleet solution: Sarge

Product Overview

Sarge - 50 kW Networked Fast Charge Station

Power Requirements: Max Draw 67A 480/3 Phase

Designed, Engineered & Manufactured in VA, USA

CHAdeMO certified (December 2010)

UL certification (January 2011)

Future Proof – SAE 1772 DC Coupler

Touch Screen Interface

Tamper-proof enclosure

Vertical cable to avoid tipping hazards

CHAdeMO

DC Fast Charging- Fuji Electric

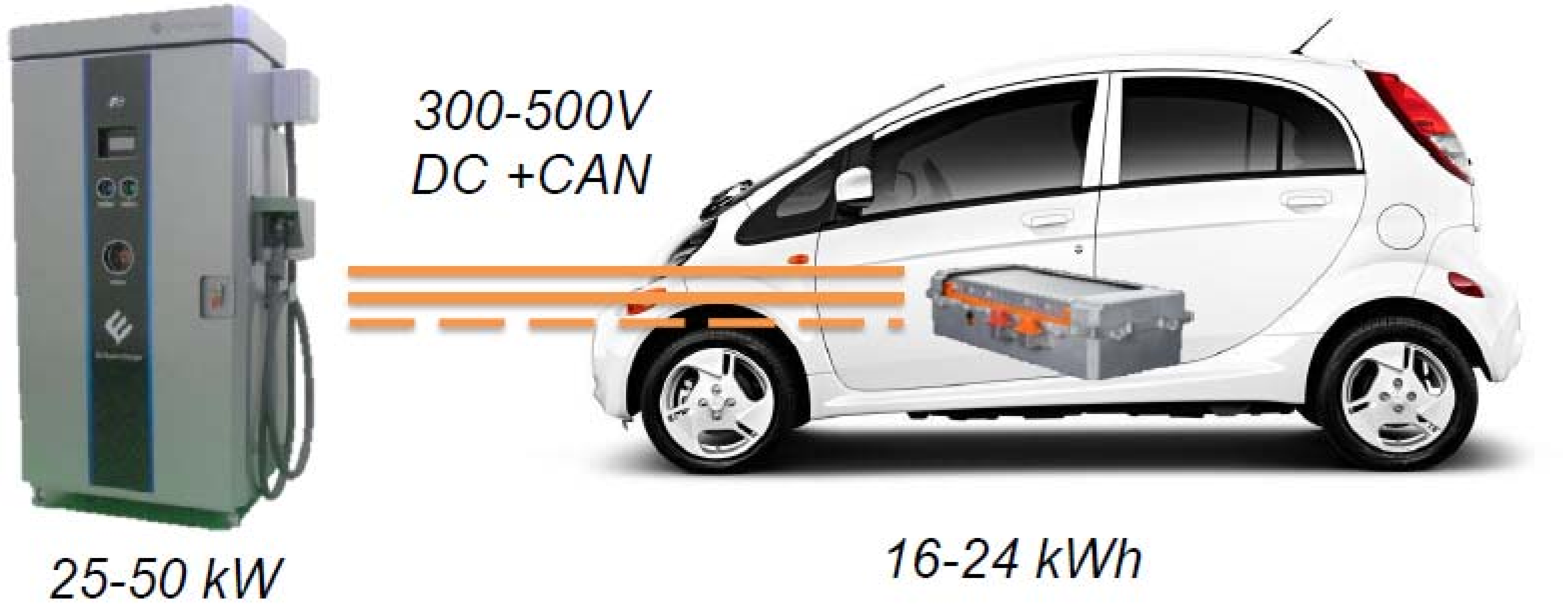
DC Quick Charging

- 3 phase 208V AC is Converted to DC.
- DC is sent directly to the EV Battery.
- BMS commands charging current via CAN

Level 2 AC Charging

- 208V AC is sent through the charger to the Vehicle
- The On-Board Charger converts the AC to DC
- DC Charging is limited to the Power of the On-Board Charger

Fast Charging Management



How CHAdeMO Quick Charging Works…

- BMS Decides the Charging Rate Based on Battery Conditions
- The Charger is Given the Proper Voltage and Rate to Charge via CAN
- The Charger Pre-charges the Circuit to the Voltage given by the BMS and Limits Charging to the Specified Rate
- Improvements in battery technology can be implemented without a change to the charger. The BMS can specify a higher charging rate to the existing infrastructure.

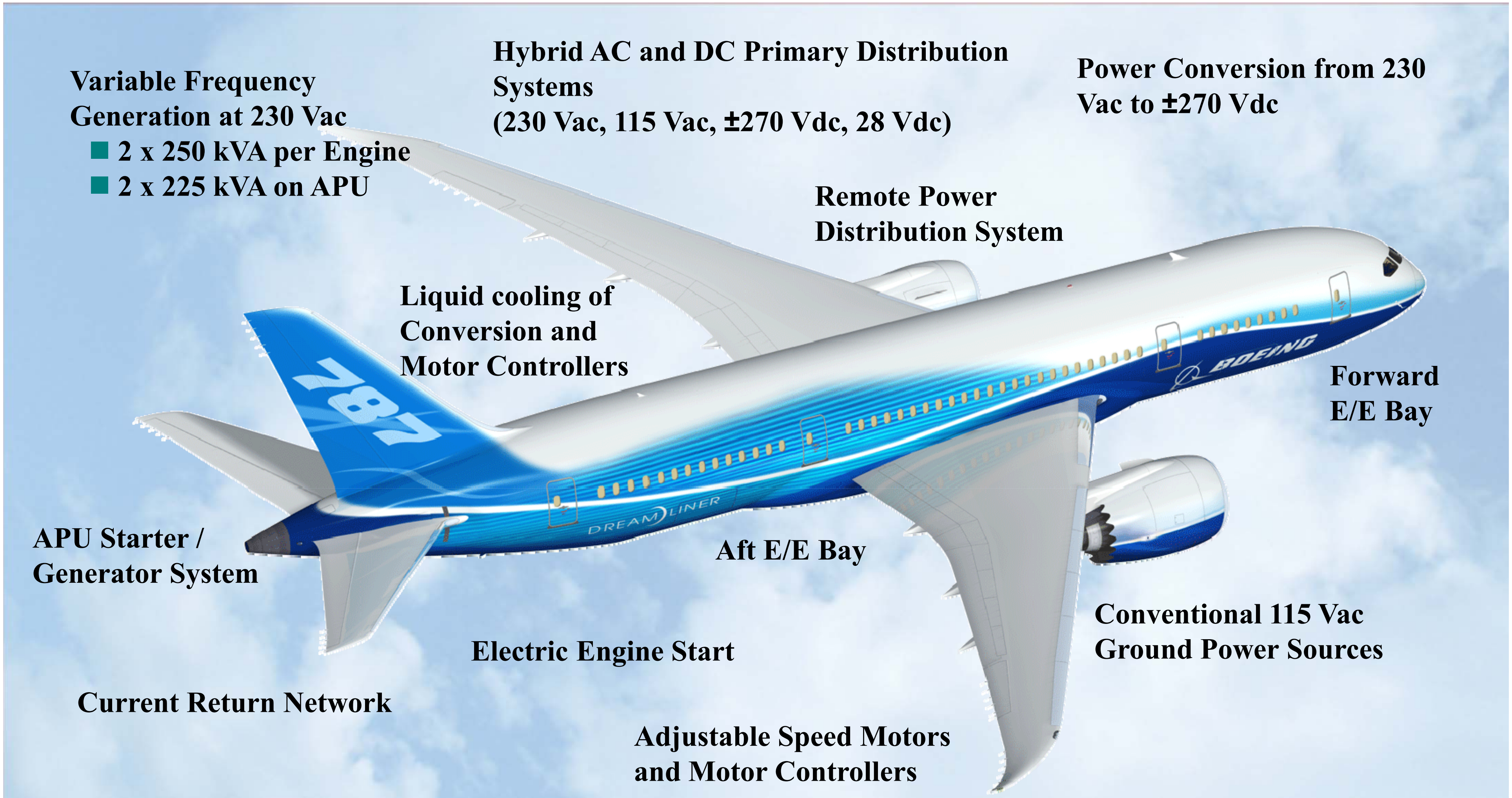

POWEREX
Phase Control SCR
4500V/3300A
POWEREX
Dual Fast Diode
600V/300A, 400A
1200V/300A, 400A
POWEREX
Phase Control SCR
4500V/2800A
POWEREX
Dual Diode
1800V/160A
POWEREX
General Purpose Diode

Bombardier ZEFIRO Very High Speed Trains

- The ZEFIRO is the latest class of very high speed (VHS) trains from Bombardier.
- It is one of the fastest sleeper trains in the world and is currently being operated in China. Operating speed of 250kmph to 380kmph

- The ZEFIRO features sustainable technologies and an aerodynamic design that generates 20% energy savings.
- It requires the lowest energy consumption per seat in its segment. It also offers the highest service speed among the ZEFIRO class of trains
- Power:
  - Voltage/frequency nom.: 25 kV-50 Hz; min. 17.5 kV; Max 30 kV,
  - Asynchronous motors, forced cooling
  - Distributed drives
  - 20 MW (16 cars, 380 kph)

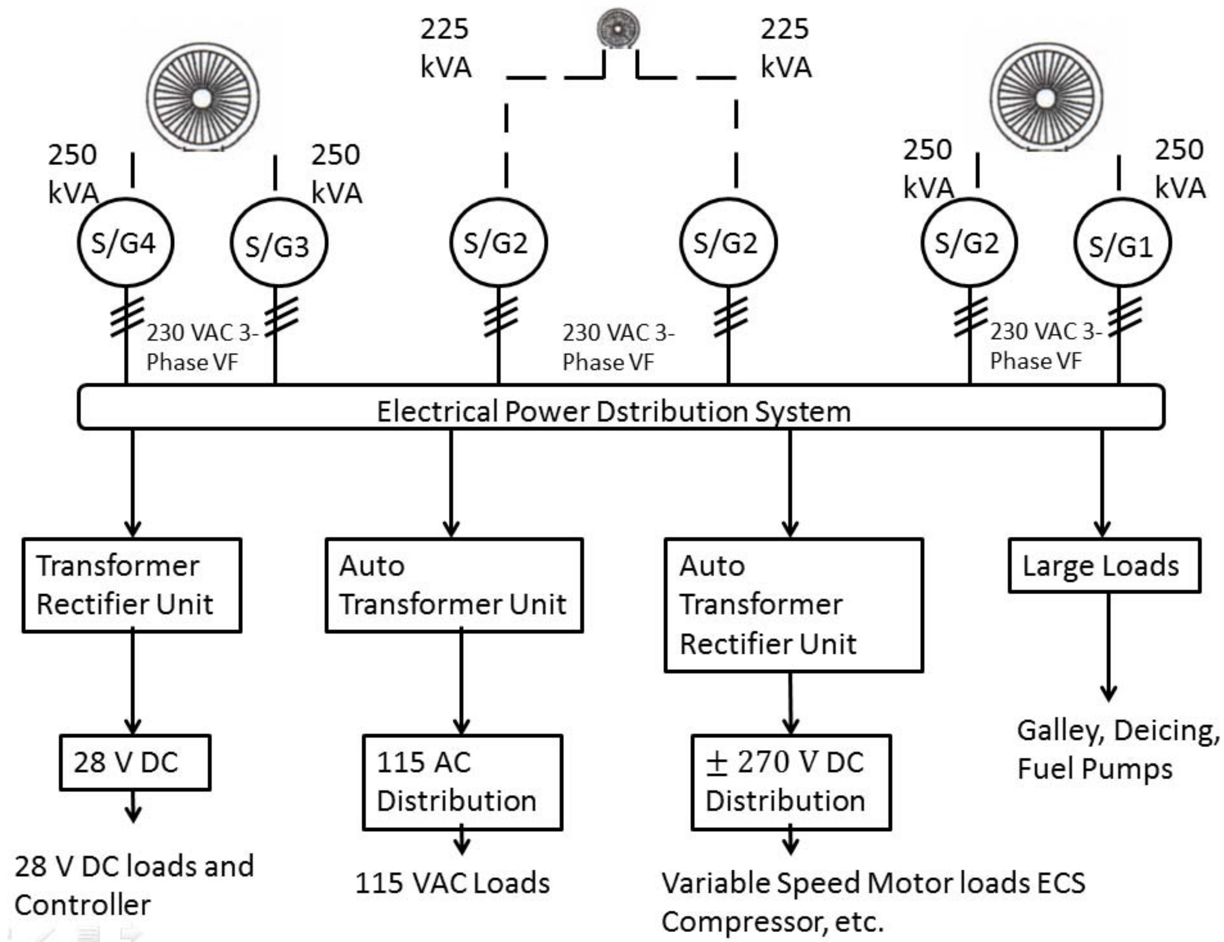
Boeing 787



787 Systems and Performance by Tim Nelson

http://myhres.com/Boeing-787-Systems-and-Performance.pdf/

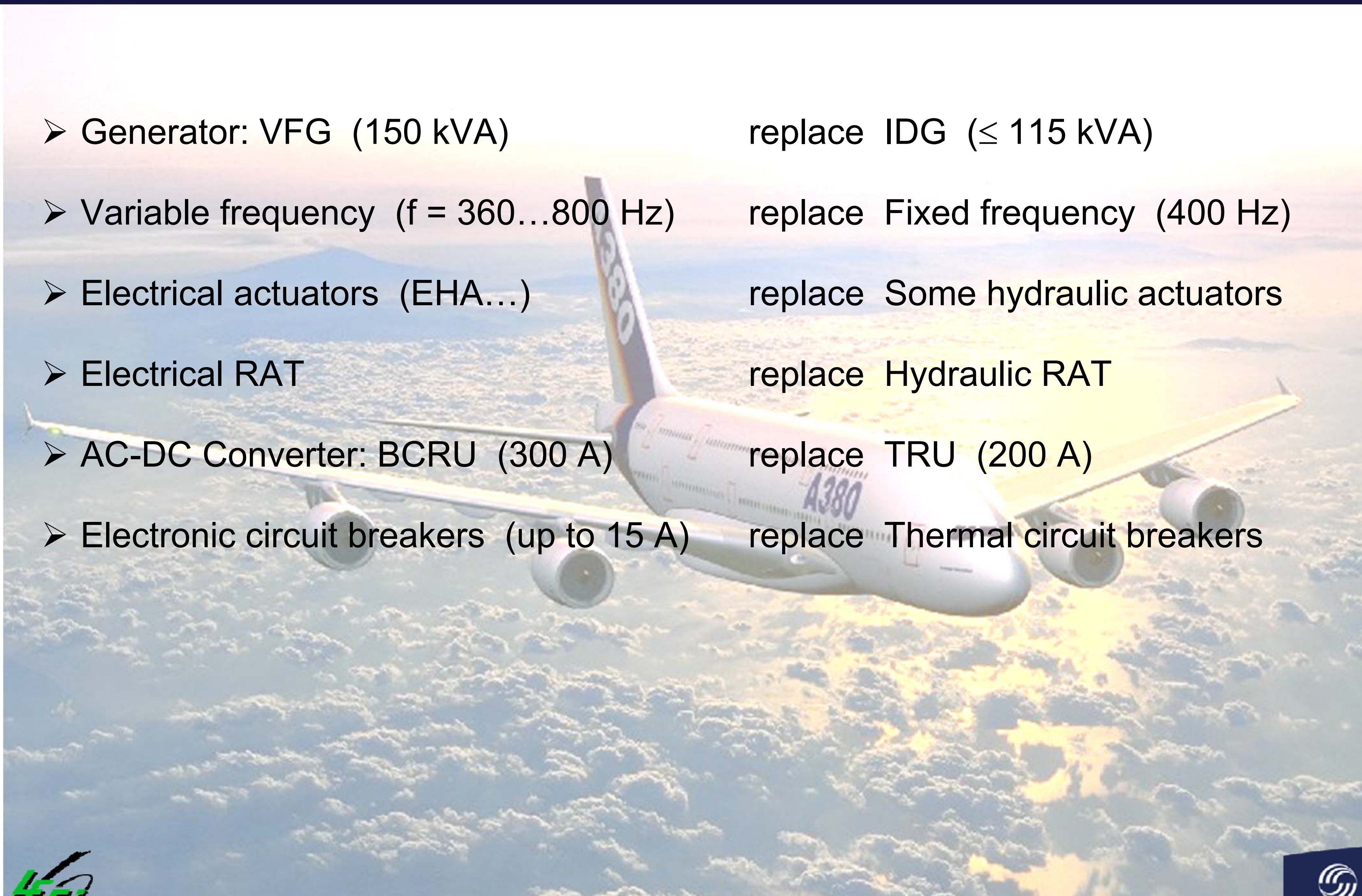
Boeing 787 electrical distribution system



With this no-bleed airframe, the ECS, cabin pressurization system, wing anti-icing system, and other conventionally air-powered subsystems are all electrically powered.

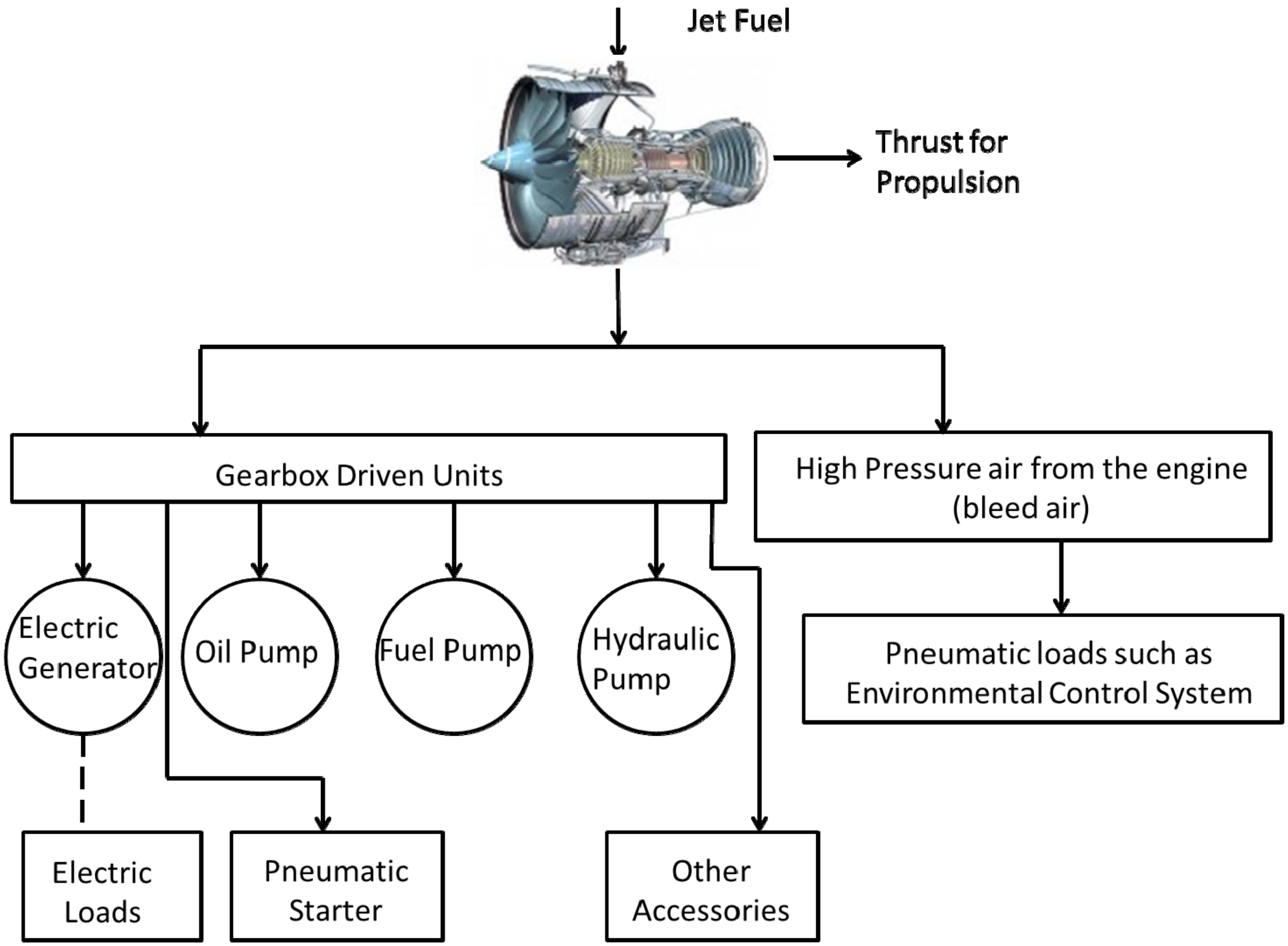
Ian Moir and Allan Seabridge, "Aircraft Systems: Mechanical, Electrical and Avionics Subsystems Integration," 3rd Edition, Wiley, 2008

A380 System



- Generator: VFG (150 kVA) replace IDG (≤ 115 kVA)
- Variable frequency (f = 360…800 Hz) replace Fixed frequency (400 Hz)
- Electrical actuators (EHA…) replace Some hydraulic actuators
- Electrical RAT replace Hydraulic RAT
- AC-DC Converter: BCRU (300 A) replace TRU (200 A)
- Electronic circuit breakers (up to 15 A) replace Thermal circuit breakers

Traditional Aircraft System



In a traditional airplane, the jet engine is designed to produce thrust and to power the pneumatic, hydraulic and electrical systems.

Airbus 330 Engine off take loads

Example: Power used on A330

Electrical power
- Avionics
- Commercial
- Pumps
- De-icing
- Lights
- ……

115VAC-230kVA

Hydraulic power
- Flight Controls
- Landing gear
- Braking
- Reverse
- Doors

240kW-206bars

Mechanical power
- Engine Fuel Pump
- Engine Oil Pump

- Engine start

200kW (peak)

100kW (local)

Pneumatic power
- Air conditioning
- Pressurisation
- Ice Protection

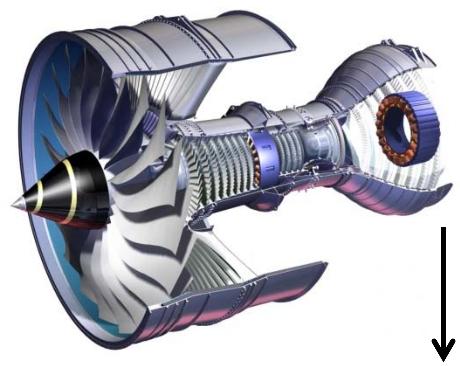
- Engine start

From some bars up to 20bars-1200kW

More Electric Engine (MEA)

Jet Fuel

Thrust for Propulsion



Generator can be mounted to the shaft (as embedded generator or on the gearbox)

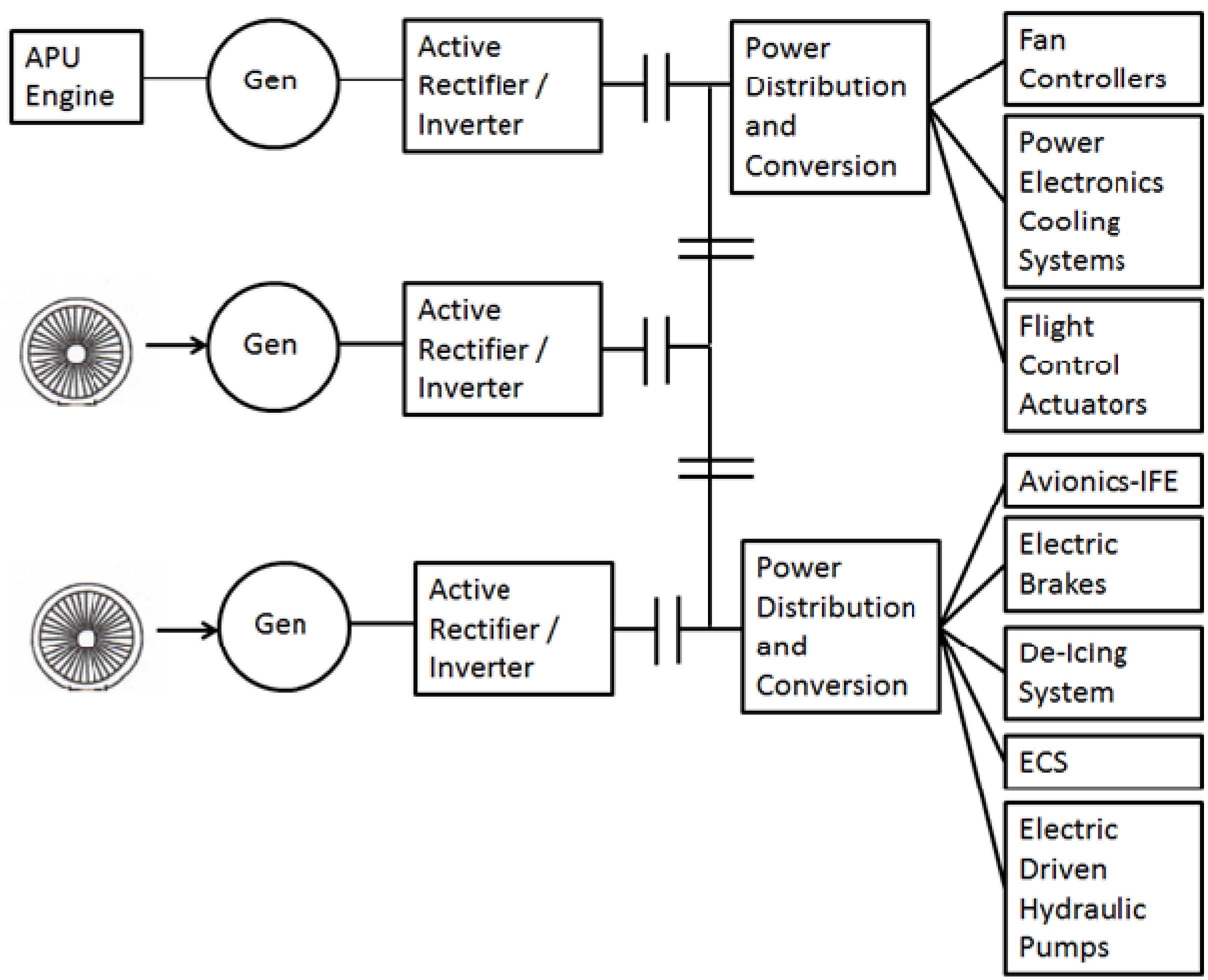
Generator

- Traditional Aircraft Electric Load
- Electric de-icing, galley loads
- Environment Control System
- Oil, Hydraulic and Fuel Pump Motors
- Other Access Loads

In a More Electric Aircraft (MEA) system, the jet engine is optimized to produce the thrust and the electric power.

Power Electronics and Power Conversion

Typical power conversion system with various loads



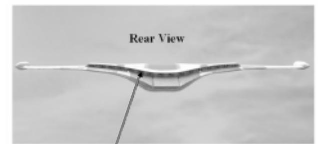
Hybrid Electric Aircraft

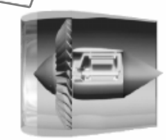
N3-X Concept Description by NASA

- TeDP-HWB: Turboelectric Distributed Propulsion– Hybrid Wing Body
- Decoupled propulsive producing device from power producing device
- Two wingtip mounted turboshaft engines driving superconducting generators
- Superconducting electrical transmissions
- Fifteen superconducting motor driven propulsors embedded in fuselage
- Two cooling schemes, cryo-cooled and LH2-cooled

Turboelectric Distributed Propulsion Engine Cycle Analysis for Hybrid Wing Body Aircraft – (AIAA) 2009-1132

Hybrid Electric Distributed Propulsion (HEDP) Aircraft

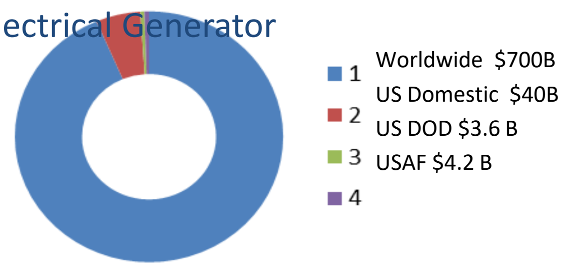




30 MW Superconductor Power Transmission

6 MW Superconductor Electrical Motor Turbo Fans

30 MW Superconductor Electrical Generator



Superconductor Applications Needed	Class
Generators	30-40 MW
Motors	4-6 MW
Power Transmission Cables	5-70 MW DC ±270
Power Inverters	1-30 MW
Power Electronics	30-40 MW

Fuel Efficiency + 70%
Potential World-Market Pull :
$400/yr saving

T.J. Haugan, "Design of SMES Devices for Air and Space Applications," http://www.cvent.com/events/tenth-epri-superconductivity-conference/custom-18-0ac856fa88e84a97ac2058094d0a4629.aspx, October 2011

N3-X Turboelectric Distributed Propulsion (TeDP) Vehicle Concept

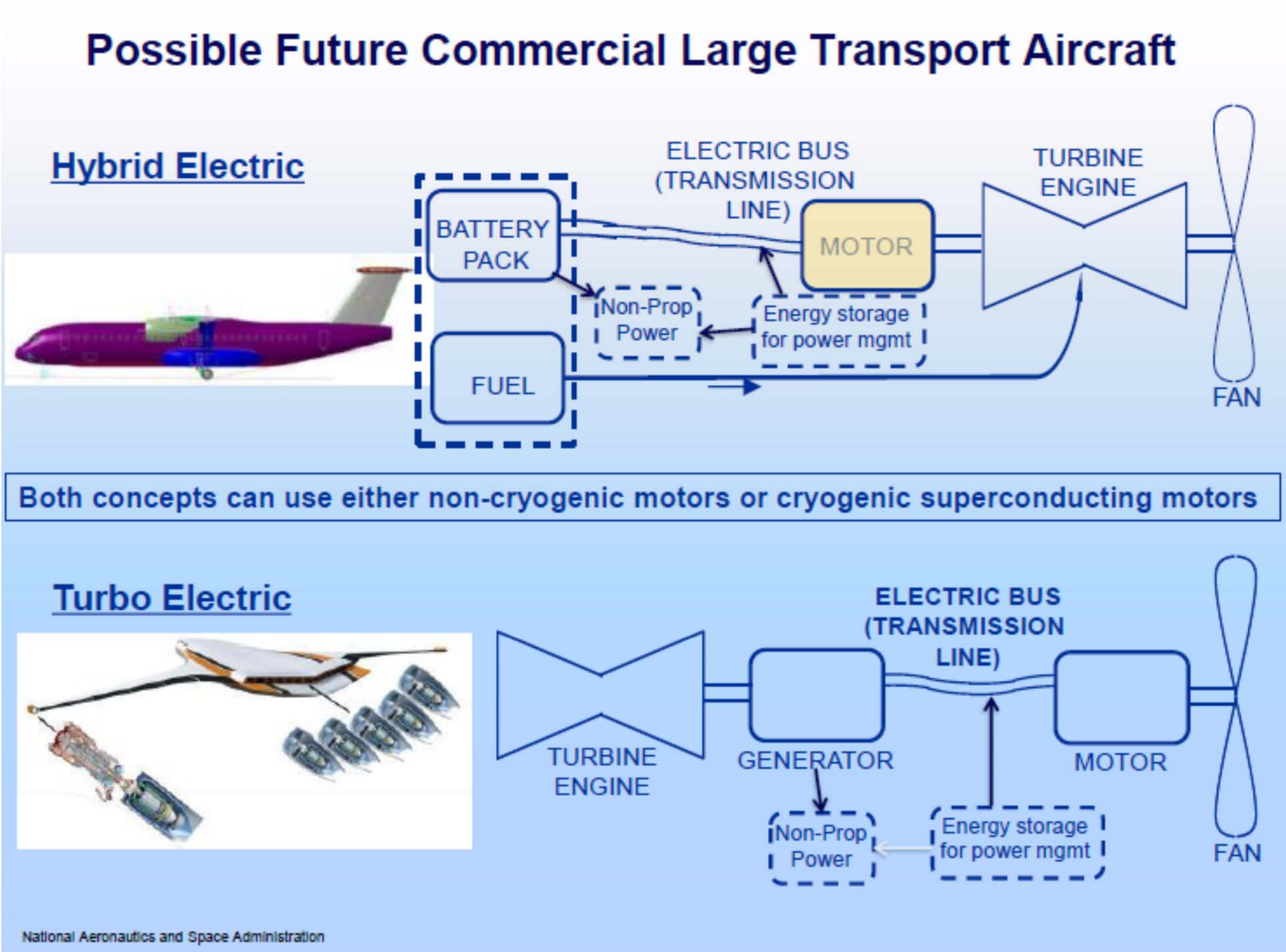
Aircraft Attributes		
Range	7500nm	
Payload	118100 lbm	
M_{cruise}	>0.8	
Cruise alt	35,000 ft	
	Takeoff	Cruise
Thrust/Engine	54888 lbf	19293 lbf
Empty Weight (Baseline B777-200LR)	267400 lbm (Δ73,400)	
Number of Propulsors	14 or 15 (function of aircraft width, FPR, and net thrust)	
Generator/engine	30,000 hp (22.4 MW)	
Motor/propulsor	4000 hp (3 MW)	

Turboelectric Distributed Propulsion Engine Cycle Analysis for Hybrid Wing Body Aircraft – (AIAA) 2009-1132

Turboelectric Distributed Propulsion in a Hybrid Wing Body Aircraft – (AIAA) ISABE-2011-1340

- Increased Aerodynamic Efficiency
  - Hybrid Wing Body Concept Aircraft
    - Blended wing body (BWB) aircraft have higher aerodynamic efficiency
    - Additional 3-7% fuel burn reduction
- Increased Propulsive Efficiency
  - Decouple fan and engine speeds
  - Operation at optimal fan speed
  - Effective bypass ratio > 30
- Cryogenically Cooled Superconducting Electrical System
  - Tasked with providing aircraft propulsion and some level of differential thrust for yaw control

48


Possible Future Commercial Large Transport Aircraft
Hybrid Electric
BATTERY PACK
FUEL
ELECTRIC BUS (TRANSMISSION LINE)
MOTOR
Non-Prop Power
Energy storage for power mgmt
TURBINE ENGINE
FAN
Both concepts can use either non-cryogenic motors or cryogenic superconducting motors
Turbo Electric
TURBINE ENGINE
GENERATOR
ELECTRIC BUS (TRANSMISSION LINE)
MOTOR
Non-Prop Power
Energy storage for power mgmt
FAN
National Aeronautics and Space Administration

Aircraft Turboelectric Propulsion

Projected Timeframe for Achieving Technology Readiness Level (TRL) 6

Spinoff Technologies Benefit More/All Electric Architectures:

- High-power density electric motors replacing hydraulic actuation
- Electrical component and transmission system weight reduction

>10 MW
- Turboelectric and hybrid electric distributed propulsion 300 PAX

5 to 10 MW
- Hybrid electric 737–150 PAX
- Turboelectric 737–150 PAX

2 to 5 MW class
- Hybrid electric 100 PAX regional
- Turboelectric distributed propulsion 150 PAX

1 to 2 MW class
- Hybrid electric 50 PAX regional
- Turboelectric distributed propulsion 100 PAX regional

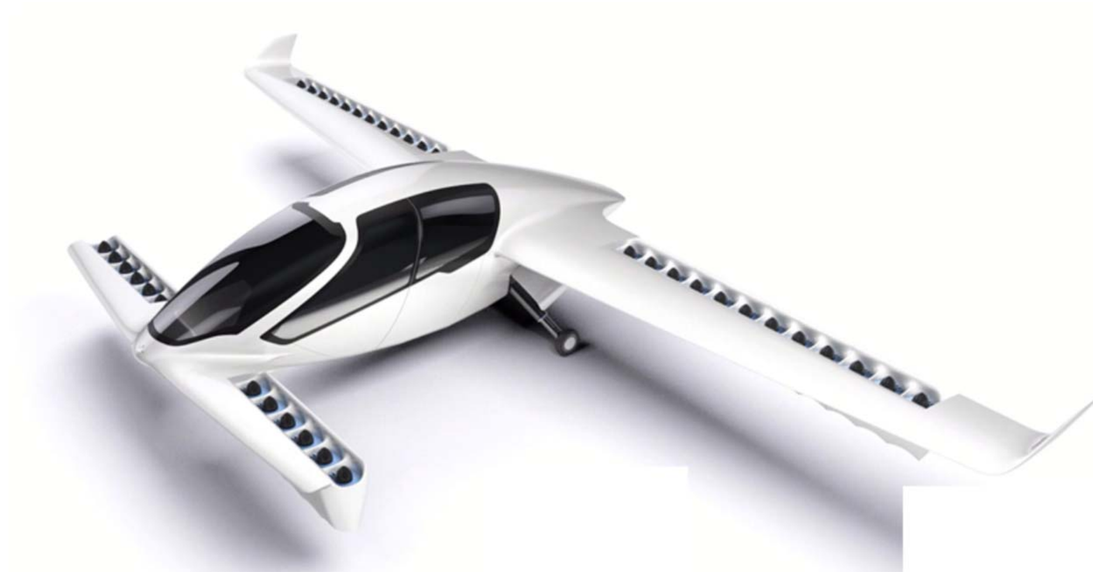
kW class
- All-electric and hybrid-electric general aviation

(Power level for single engine)

Power Level for Electrical Propulsion System

Today | 10 Year | 20 Year | 30 Year | 40 Year

Lilian VTOL Electric Aircraft

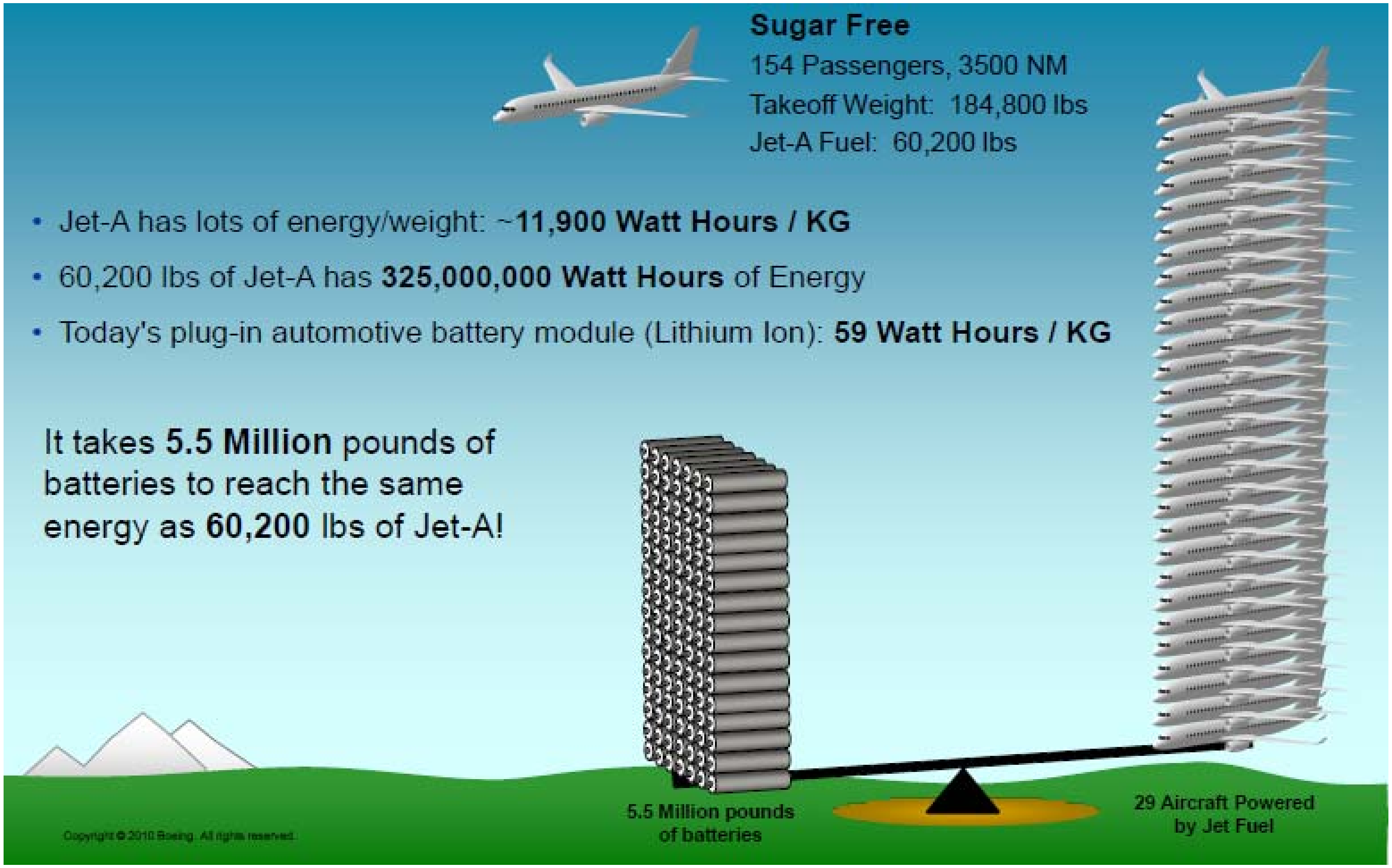


The Lilium Jet consists of a rigid winged body with 12 flaps. Each one carries three electric jet engines. Depending on the flight mode, the flaps tilt from a vertical into a horizontal position. At take-off, all flaps are tilted vertical, so that the engines can lift the aircraft. Once airborne, the flaps gradually tilt into a horizontal position, leading the aircraft to accelerate. When they have reached complete horizontal position, all lift necessary to stay aloft is provided by the wings as in a conventional airplane.

Boeing 777 to electric?

- An airplane like 777-ER uses two Trent 800 series engines, each producing about 70,000 lbs of thrust. To achieve the same capability, you need electric motors each of 45MW. This is a very big motor even if it is a superconducting motor. You need to consider the cooling system weight and volume.
- Even for regional airplanes, we need about 5-10MW of power.
- If you take about 10 kW/kg (Optimistic value), still the weight of the motor would be very high value
- The power electronics would be complicated. Again , if you consider 15kW/kg and 20kW/liter(optimistic value), the weight and volume will be very large
- <u>Voltage</u>
- In the Aerospace area, the maximum dc voltage is 270V. In Boeing 787, they use +/-270VDC. Higher dc voltages are not being used because of the corona effect. With this dc voltage, the current will be of the order of several thousands of amperes. This would require busbars, not cables.
- The fuel capacity of 777 is 31,000 gallons and that of 777-200 ER is 45,000 gallons. Even with 3000 Whr/kg (lithium-air) battery, it needs 69,000 kg of batteries. What about the volume?

Electric Airline challenges



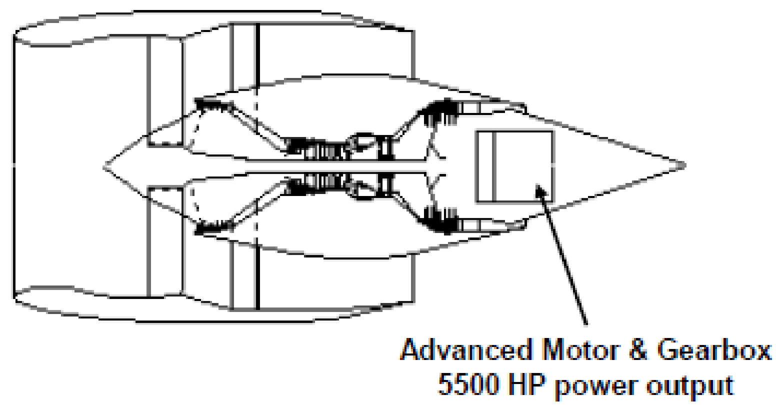
Zach Hoisington, Airliners with Electric Propulsion, 4thAnnual CAFE Foundation Electric Aircraft Symposium, Sonoma, CA April 23, 2010

NASA's X-57 Electric Research Plane (Pure Electric)

With 14 electric motors turning propellers and all of them integrated into a uniquely-designed wing, NASA will test new propulsion technology using an experimental airplane now designated the X-57 and nicknamed “Maxwell.” The X-57’s electric propulsion technology is expected to significantly decrease aircraft noise, making it less annoying to the public.

Hybrid Electric Airplane

- Hybrid Propulsion (Energy is stored in Batteries and Jet Fuel)
  - Long ranges can still be flown using jet fuel
  - Shorter ranges can be flown mostly with batteries
- Average range of a 737 is only 900 NM, allowing for significant fuel savings on most missions
- Reserve fuel can be stored as jet fuel to reduce weight
- Weight of electric propulsion system is low if it drives the same fan or open rotor as the gas turbine



Zach Hoisington, Airliners with Electric Propulsion, 4th Annual CAFE Foundation Electric Aircraft Symposium, Sonoma, CA April 23, 2010

Conclusions

- There will be an exponential growth in electrical power demands in aircraft
- More Electric Architecture and hybrid aircraft are expected to play a significant role in the future of overall airplane system design, operation, and performance
- "More Electric" is a technology enabler for power generation, energy storage, conversion systems, and other technologies
- Power electronics plays a significant role in the advancement of MEA technologies in terms of improving system efficiency, architecture, size, etc
- The main objectives are to obtain high power and volume density, high efficiency, reliability, and the ability to withstand harsh environments.
- Achieving lower weight and volume are very critical in More Electric and Hybrid Electric Aircraft systems.