Promising Electric Aircraft Drive Systems

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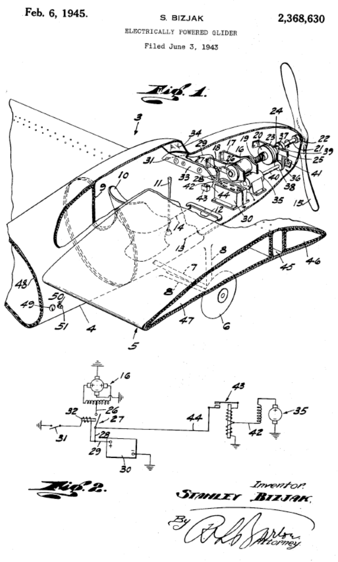
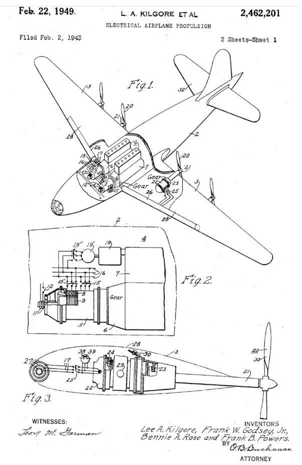
Outline

- Background
- Critical Technologies for Electric Aircraft
- Power-system configuration options
- Comparing Electric Aircraft Power-systems
- Analytical approach
- Typical component subsystem performance
  - **Energy Storage**
  - **Energy Conversion**
- Power-system weight comparisons
- Electric power systems performance targets
- Summary

Background

- The idea to power aircraft with electric motors has been around a long time
  - **Patents filed in 1943 for both battery and piston-engine hybrid electric airplanes**
  - **Progress limited by key technology barriers**
    - A source of electricity with power and energy densities suitable for aircraft
    - Electric motors with high power/weight ratios

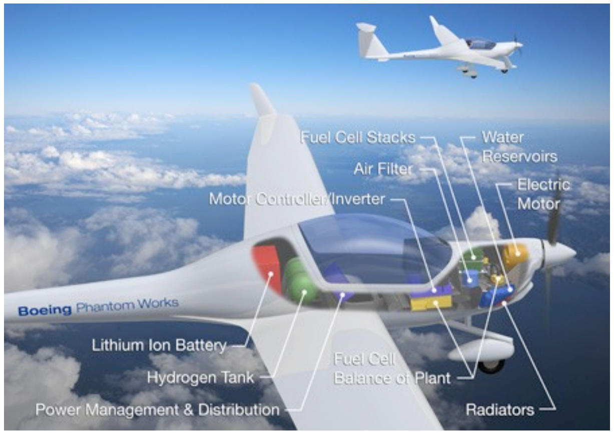




- What has changed
  - **Environmental concerns are accelerating development of electric power-system technologies that have the potential to overcome the historical barriers**

Worldwide Interest in Piloted Electric Aircraft

Pipistrel Taurus – 2007
Li-Polymer battery
65 mph 1.0 hr



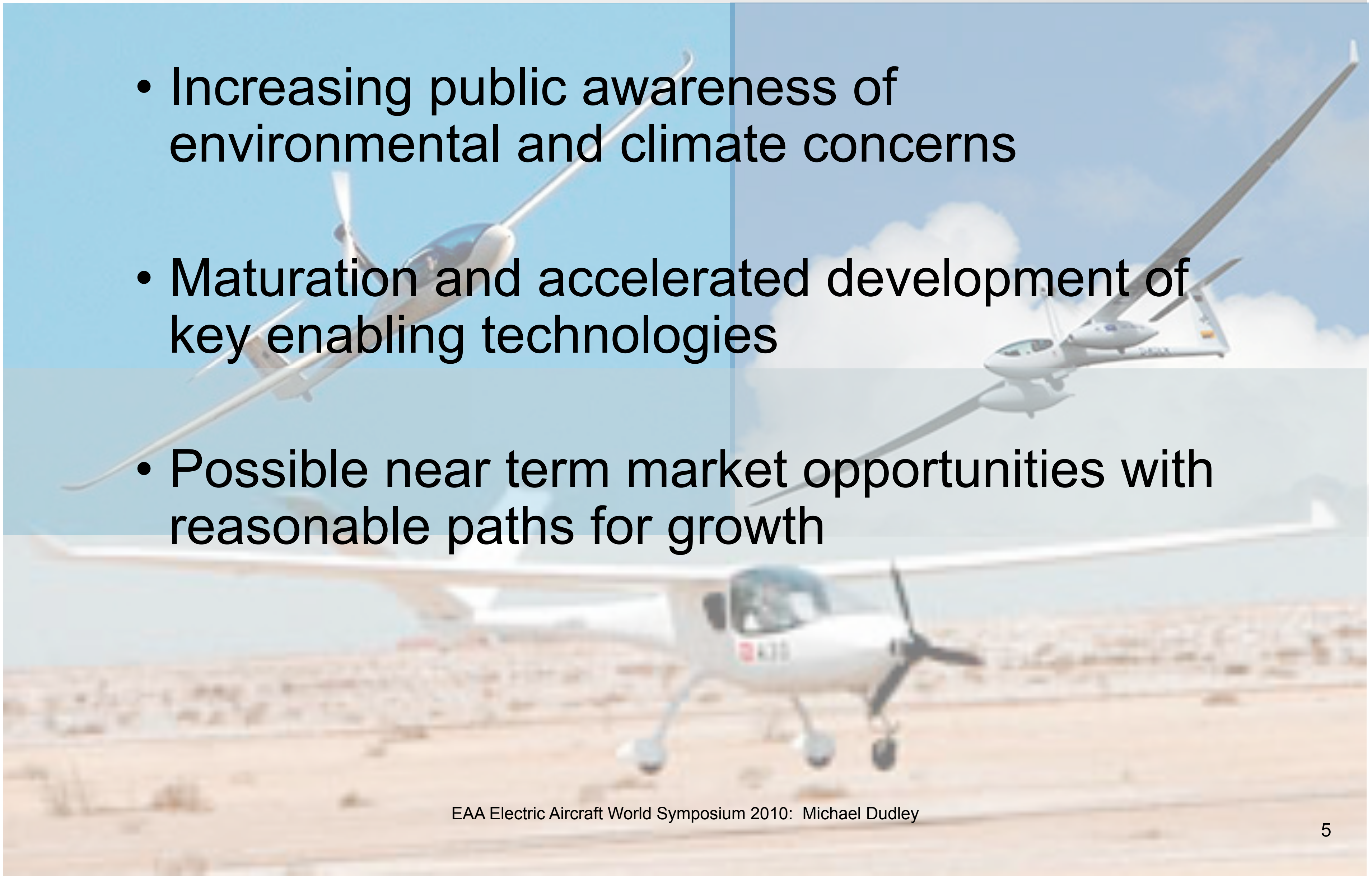
Boeing Dimona – 2008
PEM fuel cell + Li-ion battery
62 mph for 20 min

Antares DLR-H2 – 2008
PEM fuel cell + battery
106 mph, 10 min flight, 465 mi range

DigiSky SkySpark – 2009
Li-Polymer battery
155 mph, 8 minute flight

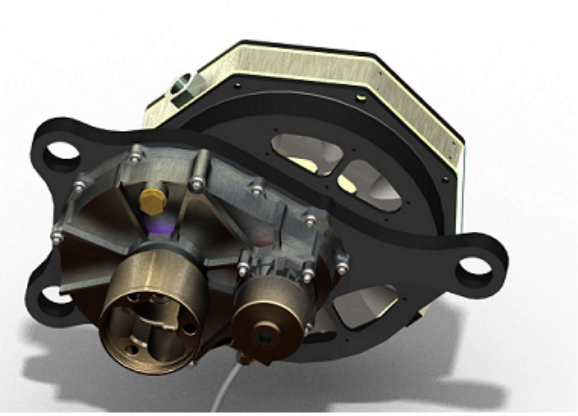
Yuneec E430 – 2009
Li-ion battery
~1.5-2 hr with 60 mph cruise

Why Now

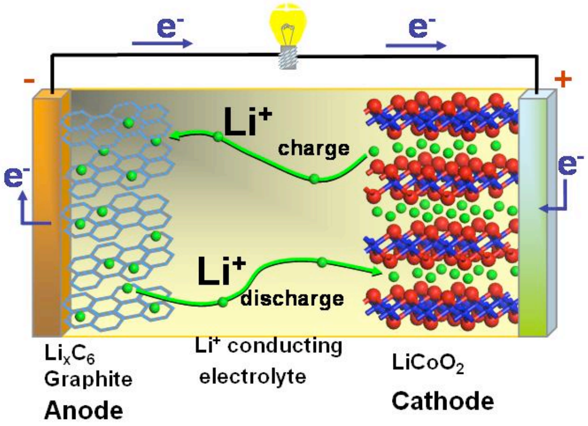


- Increasing public awareness of environmental and climate concerns
- Maturation and accelerated development of key enabling technologies
- Possible near term market opportunities with reasonable paths for growth

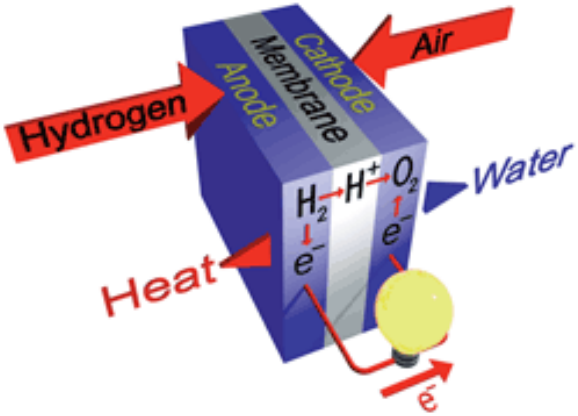
Critical Technologies for Electric Aircraft



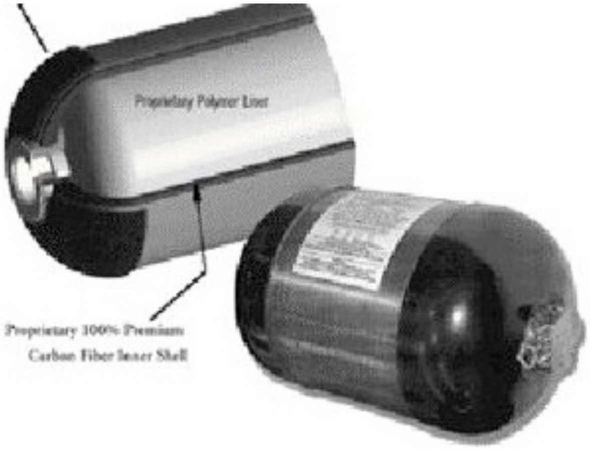
Electric Motor



Battery/Energy Storage

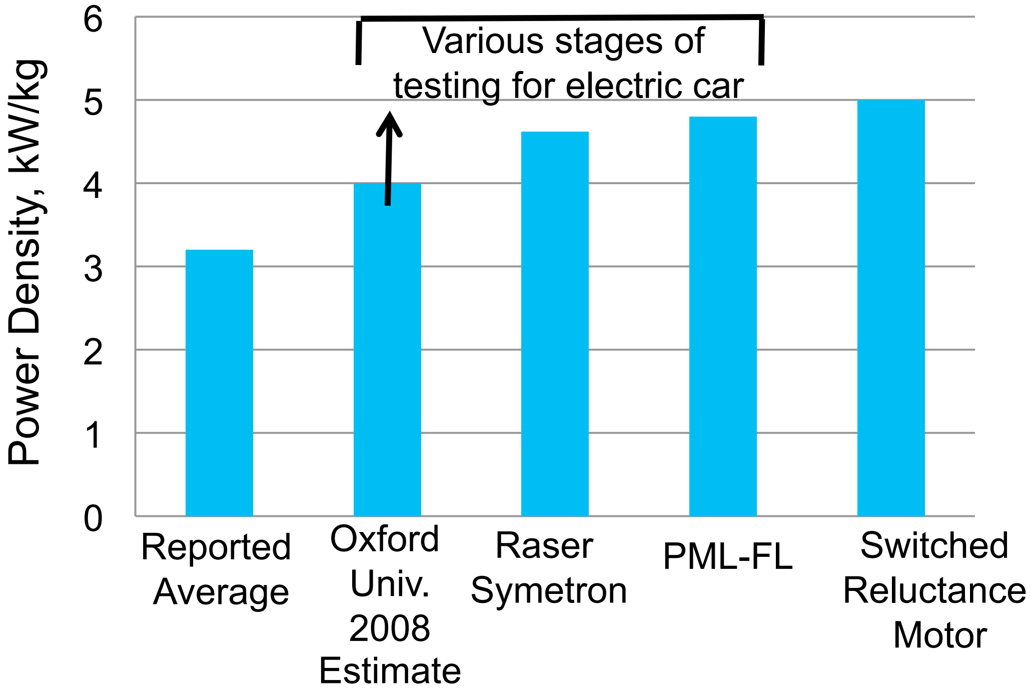


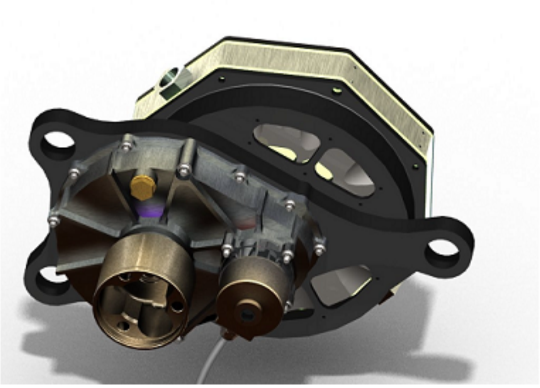
Fuel-cell



Hydrogen Storage

Non-Cryogenic Electric Motors



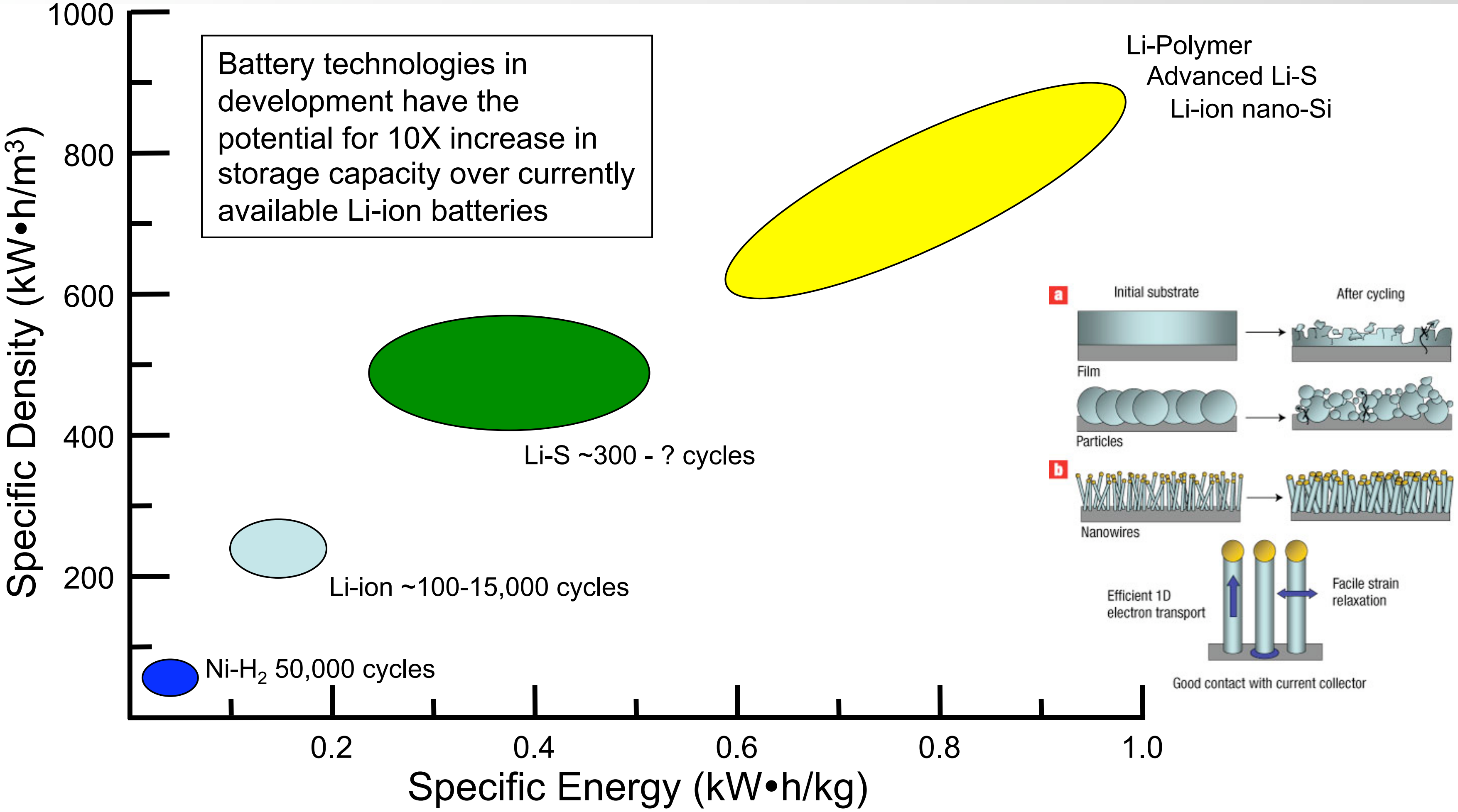


Recently developed lightweight motor by University of Oxford claims to have high power density

- Power density of non-cryogenic motor will continuously increase with the growth in electric car market (> 6 kW/kg motors can be expected in future).

- > 20 kW/kg power density can be achieved for cryogenic motors

Battery Energy Storage

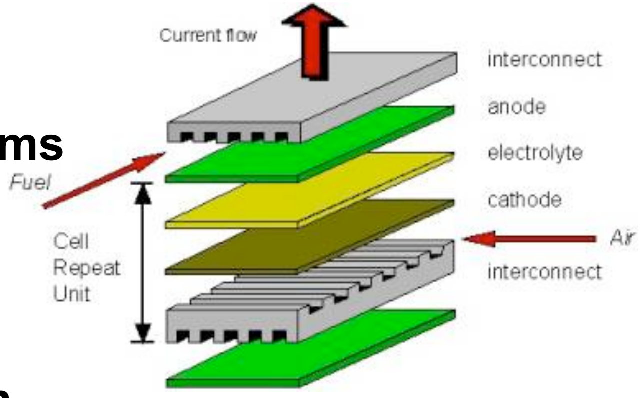


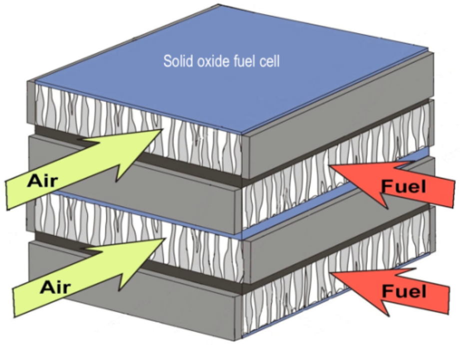
Battery technologies in development have the potential for 10X increase in storage capacity over currently available Li-ion batteries

Fuel-cell power-systems will require some battery storage to balance power demands

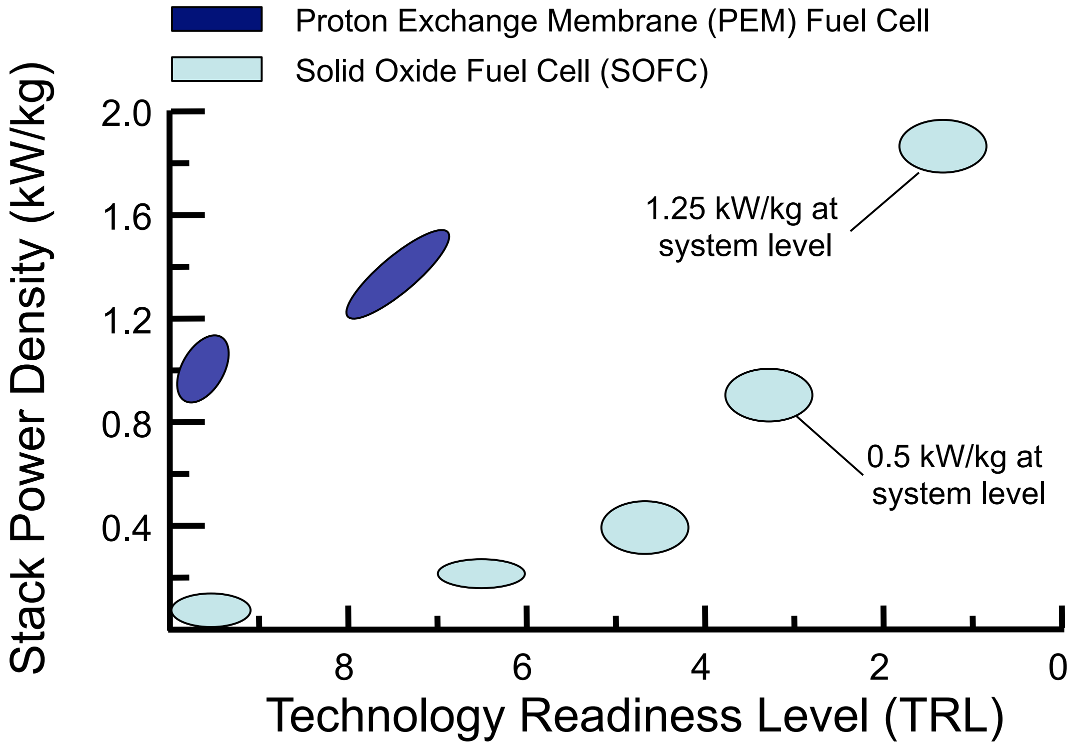
Fuel Cell Systems - Advantages / Disadvantages

- Proton Exchange Membrane (PEM) Fuel-cell:
  - **More mature, operational in cars, high power density demonstrated**
  - **Need pure H_2, availability and storage challenge**
  - **Lower operating temperature (low quality heat released) needs larger heavier heat exchanger**
- Solid Oxide Fuel-Cell (SOFC)
  - **Less mature, currently low power density systems**
  - **30-45 minute startup warm-up**
    - > Battery startup operations could reduce impact
  - **Can use hydrocarbon fuels**
  - **Efficiencies greater than 60 % for hybrid system**
    - > Fuel-cell with gas turbine bottoming cycle
  - **Higher power density needed for mobile systems**
    - > Pathway exists to achieve higher power density but will require significant technology development



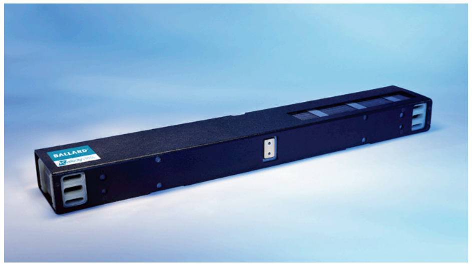


State of Fuel-cell Technology

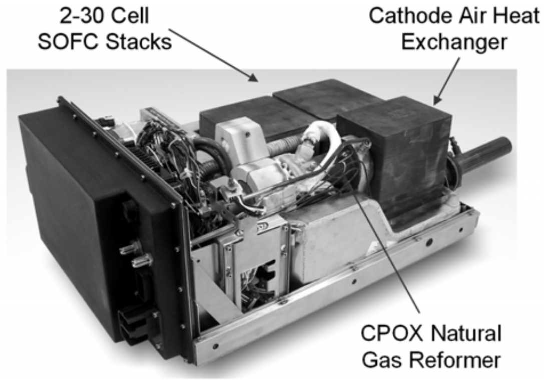


- Significant opportunity exists to reduce weight of balance of plant through use of lightweight materials and composite materials (~50% weight reduction possible) – 1 kW/kg stack would correspond to 0.66 kW/kg at system level

- Effective system integration may yield further weight reductions



Commercial PEM Fuel Cell

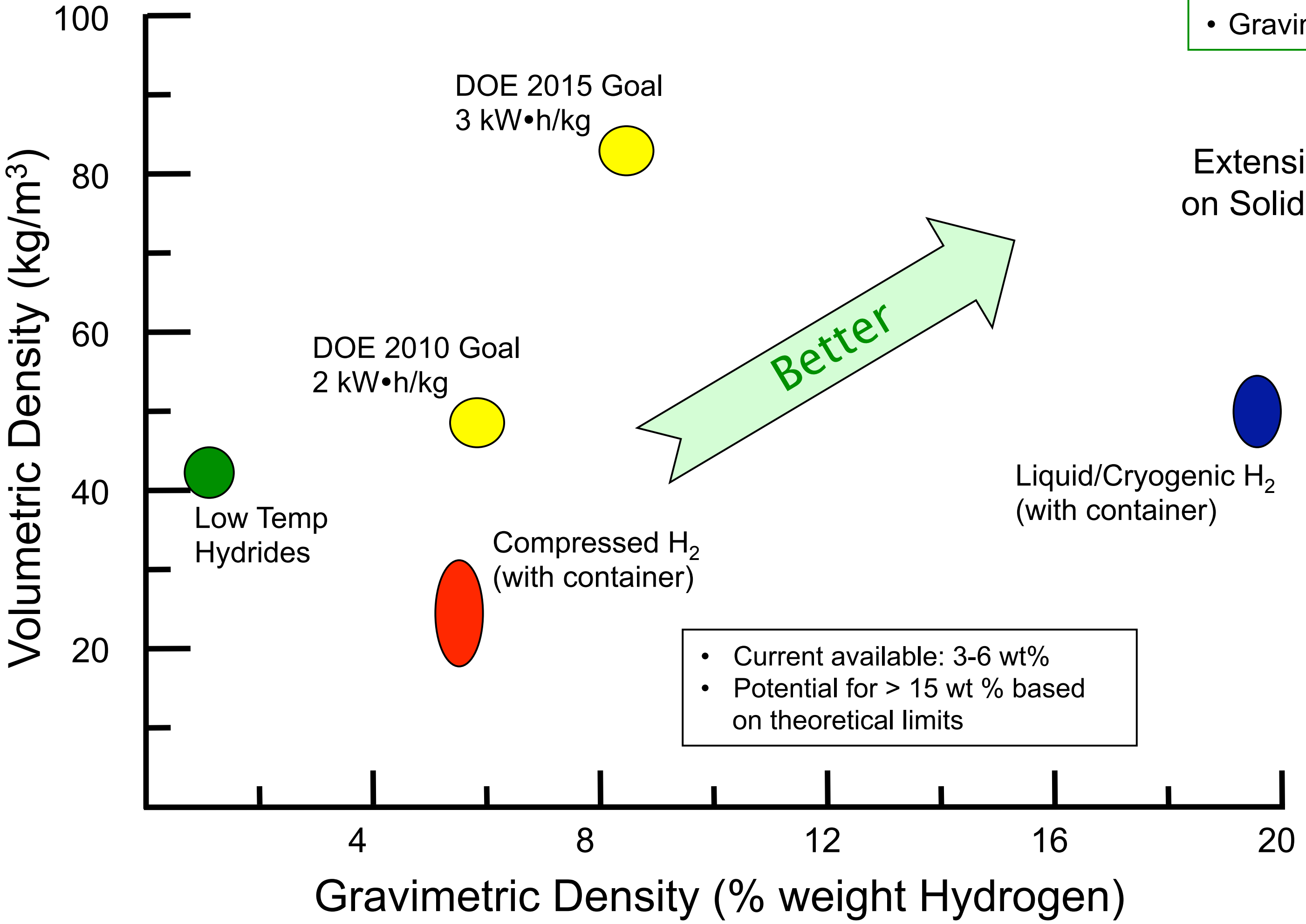


Developmental SOFC

Balance of Plant Contributes Significant Weight (~50%)

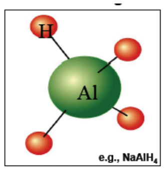
Hydrogen Storage

H_2 content of Reformed kerosene
- Volumetric Density: 320 kg/m^3
- Gravimetric Density: 33%

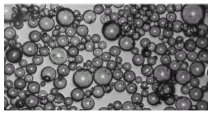


- Current available: 3-6 wt%
- Potential for > 15 wt % based on theoretical limits

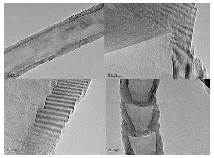
Extensive Research Underway
on Solid State Hydrogen Storage



Complex hydrides

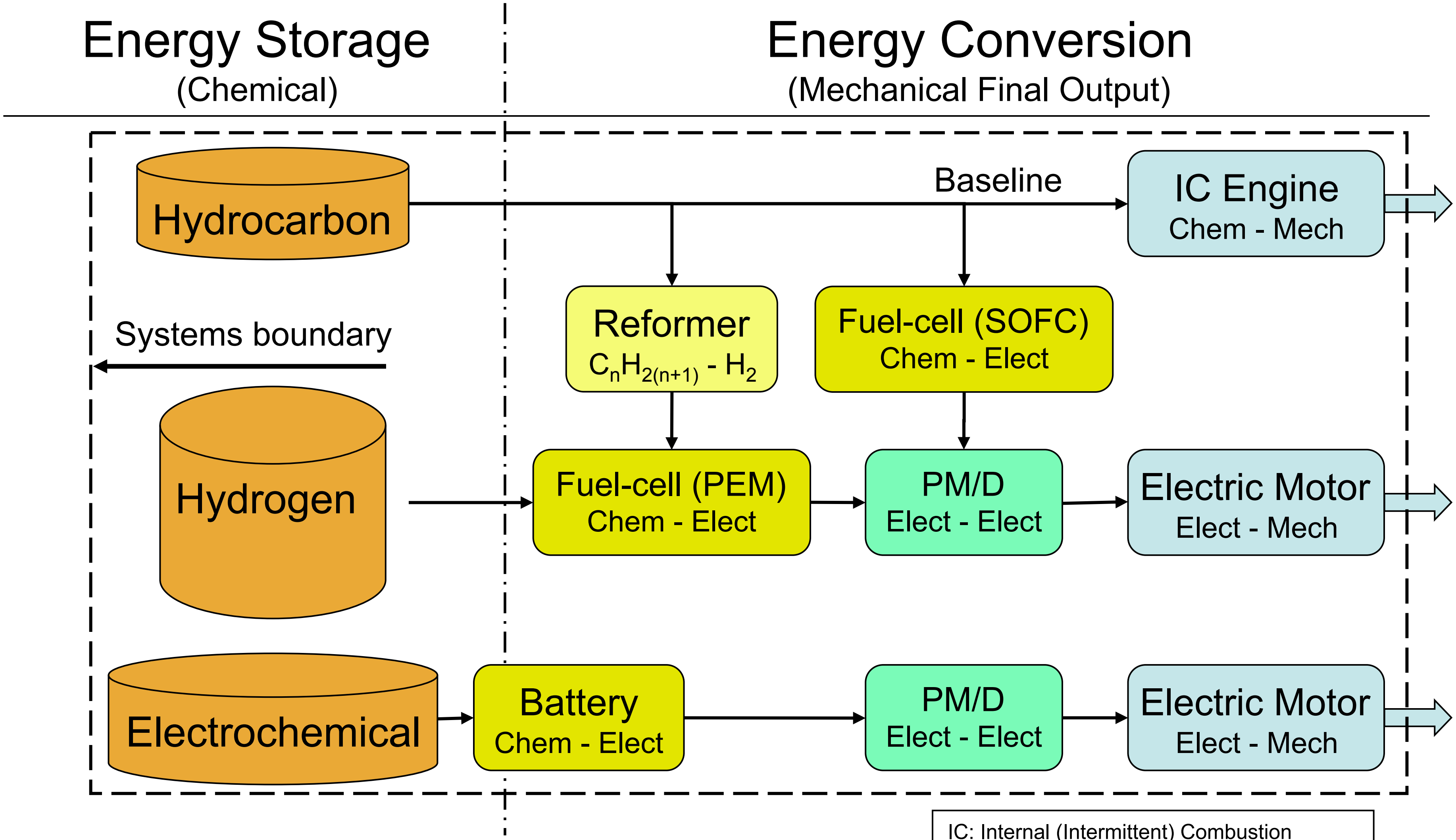


Microspheres



Nanotubes

Power-system configuration options



Energy Storage
(Chemical)

Energy Conversion
(Mechanical Final Output)

Hydrocarbon

Baseline

IC Engine
Chem - Mech

Systems boundary

Reformer
$C_nH_{2(n+1)}$ - H_2

Fuel-cell (SOFC)
Chem - Elect

Hydrogen

Fuel-cell (PEM)
Chem - Elect

PM/D
Elect - Elect

Electric Motor
Elect - Mech

Electrochemical

Battery
Chem - Elect

PM/D
Elect - Elect

Electric Motor
Elect - Mech

IC: Internal (Intermittent) Combustion
PEM: Proton Exchange Membrane
SOFC: Solid Oxide Fuel-Cell
PM/D: Power Management/Distribution

Comparing Electric Aircraft Power-systems

- Power-systems are normalized by maximum power and total available energy
- System weight is used as a figure of merit
- Two reference mission used as a basis for comparison
  - **Light Utility General Aviation (GA)**
    - > 3525 lb GTOW
    - > 170 Knts
    - > 300 HP
    - > 4.75 hr endurance
  - **Light Primary Trainer**
    - > 1100 lb GTOW
    - > 85 Knts
    - > 67 HP
    - > 1.5 hr endurance
- Electric aircraft synergistic advantages not considered

Analytical Approach

- Vehicle Power-systems are decomposed into energy *storage* and energy *conversion* subsystem components
  - **Energy storage components**
    - Fuel: *Hydrocarbons,* H_2*, electrochemical…*
    - Containers: *tanks, pressure vessels, batteries…*
  - **Energy conversions components**
    - Chemical to mechanical: *Combustion Engines*
    - Chemical to electric: *Fuel-cells, Batteries*
    - Electric to electric: *Power Management*
    - Electric to mechanical: *Electric Motors*
- Storage component weights scale to *energy* requirement
- Conversion component weights scale to *power* requirement
- Weight of Power-systems providing equivalent mechanical energy (Power delivered over time) is the primary figure of merit

Power-system Energy Model

- E_R: Energy Requirement

$$E_R = \sum_n^m (P_n)(t_n)$$

Where: P_n is power level for interval n
t_n is time at interval n

- E_S: Total stored energy

$$E_S = \frac{E_R}{(\eta_1)(\eta_2)(\eta_3)(\eta_4)}$$

Where: η_n is efficiency of energy conversion component n

Reference Missions:

Light Utility GA	E_R = 800 kW∗hr
	P_{max} = 225 kW
Light Trainer	E_R = 60 kW∗hr
	P_{max} = 50 kW

Power-system Weight Model

- W_S: Total system weight

$$W_S = W_{ES} + W_{EC}$$

- W_{ES}: Sum of energy storage component weights

$$W_{ES} = \sum_n (E_S)(\gamma_n)$$

- W_{EC}: Sum of energy conversion component weights

$$W_{EC} = \sum_n^m (P_{\max})(\theta_n)$$

Where: P_{max} is Maximum power
γ_n is the weight scaling factor for energy storage component n
θ_n is weight scaling factor for energy conversion component n

Energy Storage

Typical and Projected Performance Parameters

Energy Storage weight factors: γ (energy density)

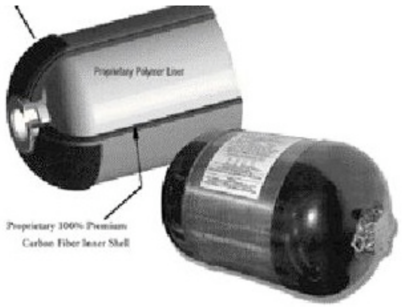
- Fuels

– **Hydrogen (H_2)**	**33.5**	**kW∗hr/kg**
– **Kerosene ($C_{12}H_{26}$)**	**14.3**	**kW∗hr/kg**

- Batteries (η = .98)

– **Li-S (2010)**	**0.25**	**kW∗hr/kg**
– **Li-ion/Li-S (2015)**	**0.65**	**kW∗hr/kg**

• Tanks	Fuel/Tank wt ratio
– **Liquid HC**	**10.0**
– **$H_{2(gas)}$ (2010)**	**0.06**
– **$H_{2(gas)}$ (2015)**	**0.10**



Chemical and Electrical Energy Conversion

Typical and Projected Performance Parameters

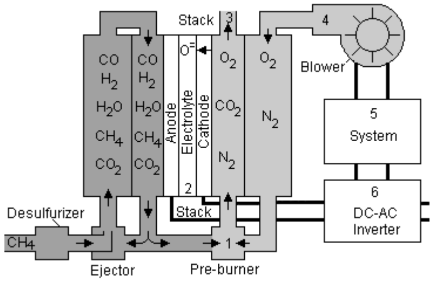
Energy Conversion weight factors; θ (power density)

- Fuel-cells (η = 50%)
  - **Proton Exchange Membrane (PEM)**

> 2010: Automotive systems	0.9 kW/kg
> 2015	1.5 kW/kg

  - **Solid Oxide Fuel-Cell (SOFC)**

> 2010	0.25 kW/kg
> 2015	0.50 kW/kg



- Power management/distribution (η = 97%)

> 2010: Automotive systems	5.0 kW/kg
> 2015	8.0 kW/kg

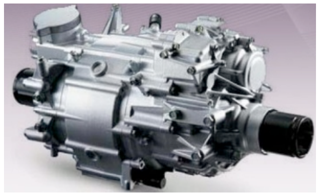
Mechanical Energy Conversion

Typical Performance Parameters

Energy Conversion weight factors; θ (power density)

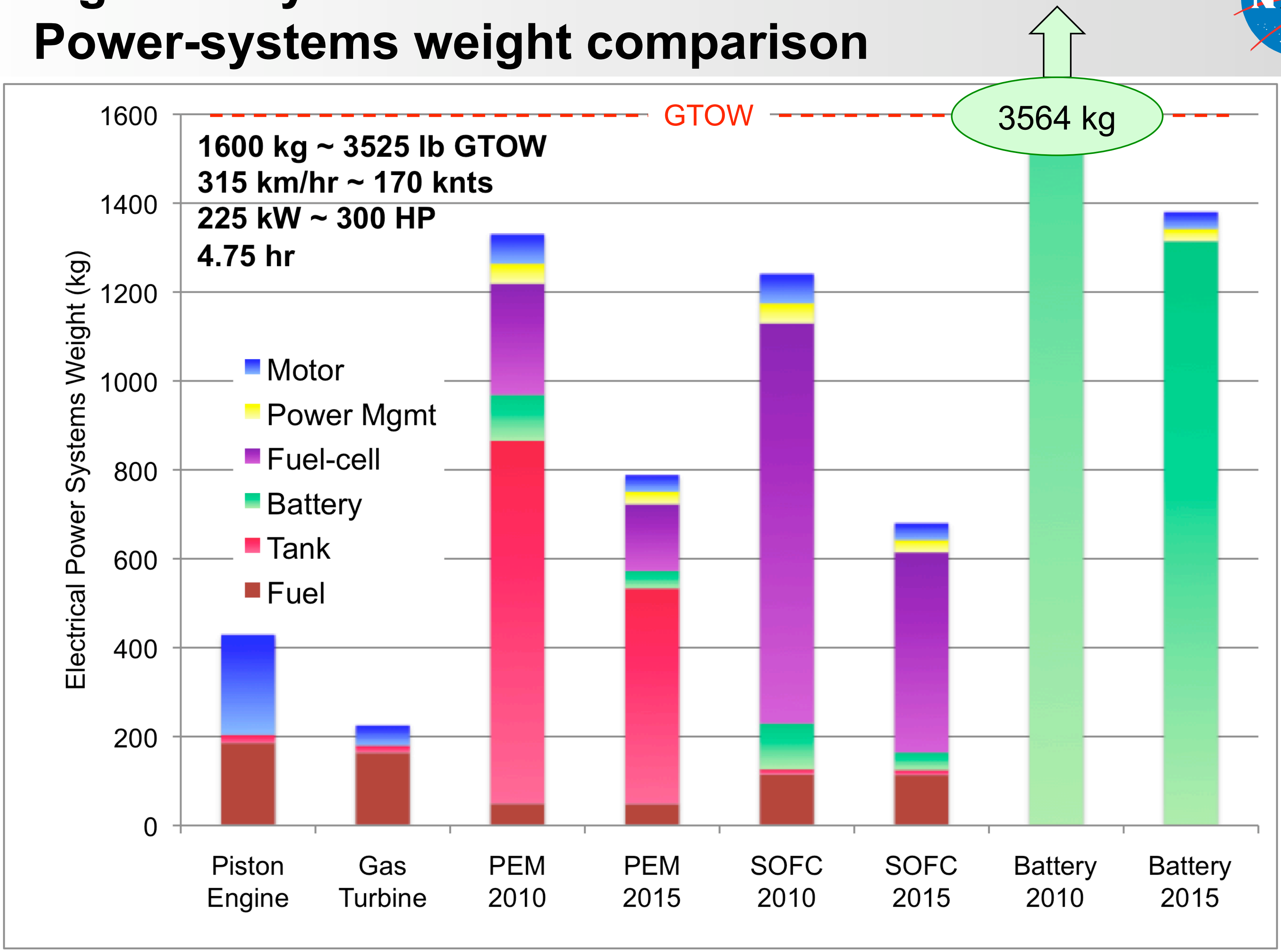
- Internal Combustion Engine (η = 30%) — 1.0 kW/g
  - **Continental IO-550 (300 HP)** — **0.984 kW/kg**
    - Power = 224 kW
    - Weight = 227 kg
  - **Rotax 912S (100HP)** — **1.10 kW/kg**
    - Power = 74.6 kW
    - Weight = 68 kg

- Electric Motors (η = 95%) — 3.4 kW/kg
  - **Tesla Automobile (244 HP)** — **3.49 kW/kg**
    - Power = 182 kW
    - Weight = 52.2 kg
  - **Honda FCX (134 HP)** — **2.96 kW/kg**
    - Power = 100 kW
    - Weight = 33.8 kg

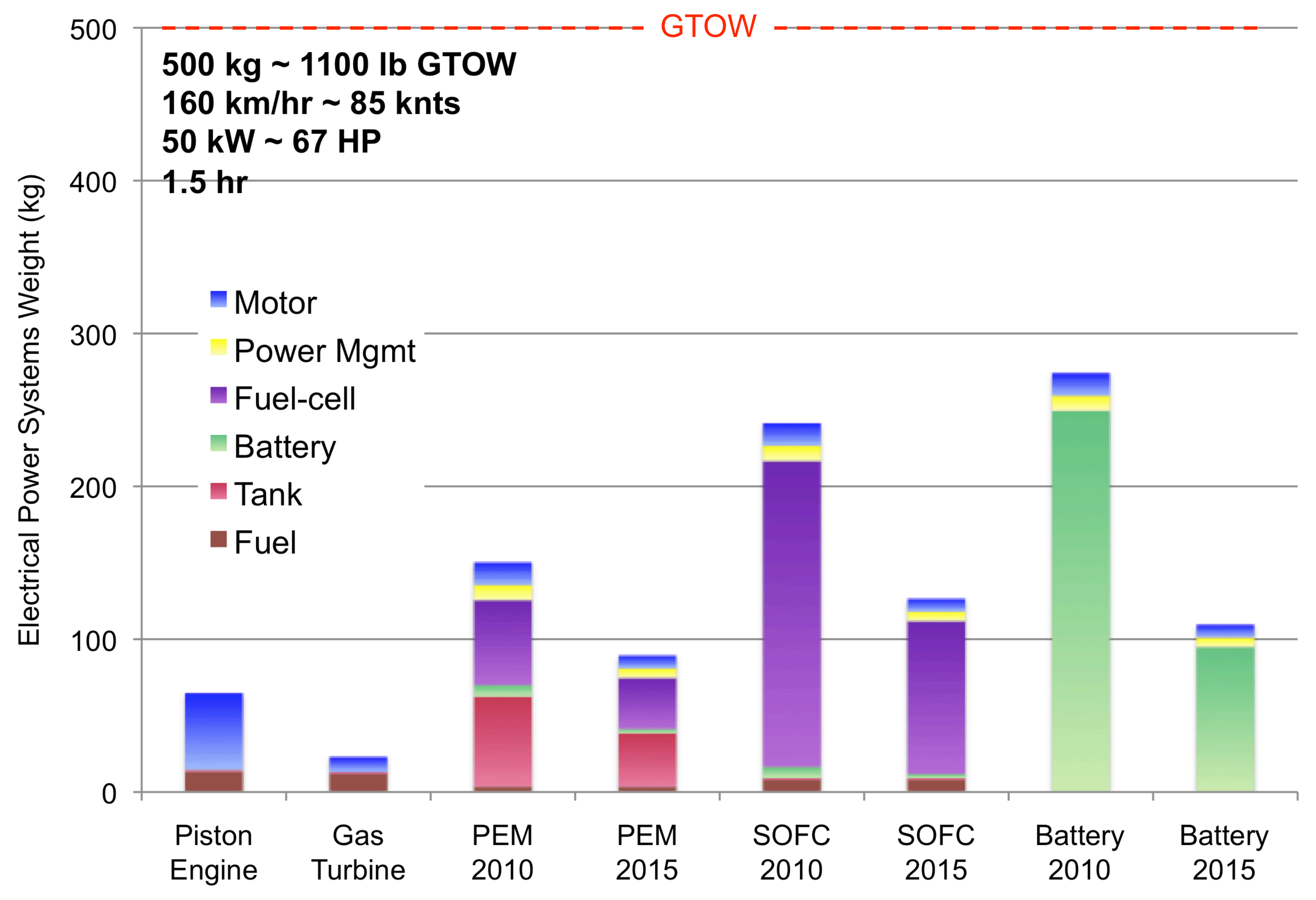


- Gas Turbine (η = 34%) — 5.1 kW/kg
  - **P&W PT6A (1500 HP)**
    - Power = 1125 kW
    - Weight = 220 kg

Light Utility Aircraft
Power-systems weight comparison



Light Primary Trainer
Power-systems weight comparison



Electric power-systems performance targets to match a piston engine Light Utility GA Aircraft

	Current	Piston Equivalent
•PEM		
– **Efficiency; η**	**50%**	**60%**
– **Power density; θ**	**0.9** kW/kg	**2.5** kW/kg
– **Battery energy density; γ**	**0.25** kW∗hr/kg	**0.75** kW∗hr/kg
– **Fuel/Tank weight ratio; ρ**	**0.06**	**0.20**
•SOFC		
– **Efficiency; η**	**50%**	**65%**
– **Power density; θ**	**0.25** kW/kg	**0.90** kW/kg
– **Battery energy density; γ**	**0.25** kW∗hr/kg	**0.75** kW∗hr/kg
•Pure Battery		
– **Battery energy density; γ**	**0.25** kW∗hr/kg	**2.35** kW∗hr/kg

Summary

- Available electric motor and power-management systems are adequate, however significant technology challenges remain in the development of batteries, fuel-cells, and light weight H_2 tanks
- Battery powered aircraft will require a 10X energy density increase to match Light Utility GA piston performance, but looks like a viable option for Light Primary Trainer aircraft in the near future
- Several potentially viable approaches exist for electric propulsion-systems and targets for component performance have been identified, but significant development work remains before the best solution is known
- The rate Electric Aircraft Propulsion technologies are advancing is encouraging and holds the promise of new more capable aircraft in the near future.