Electric Airplane Power-system Performance Requirements

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Michael Dudley: NASA Ames Research Center
Ajay Misra: NASA Glen Research Center

Outline

- Introduction
- Basic premises
- Power-system configuration options
- Power-system modeling
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  - **Weights**
- Current fuel-cell technology and projections
- Performance parameters
  - **Energy Storage**
  - **Energy Conversion**
    - Chemical and Electrical
    - Mechanical
- Power-system weight comparisons
- Performance parameter targets for competitive power-systems
- Observations

Introduction

- 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**
  - **Historical technology barriers:**
    - > Electric motors with high power/weight
    - > An electricity source with power and energy densities suitable for aircraft applications

- What has changed
  - **Environmental concerns are accelerating electric ground vehicle technology development, which in turn is stimulating interest in airborne applications**

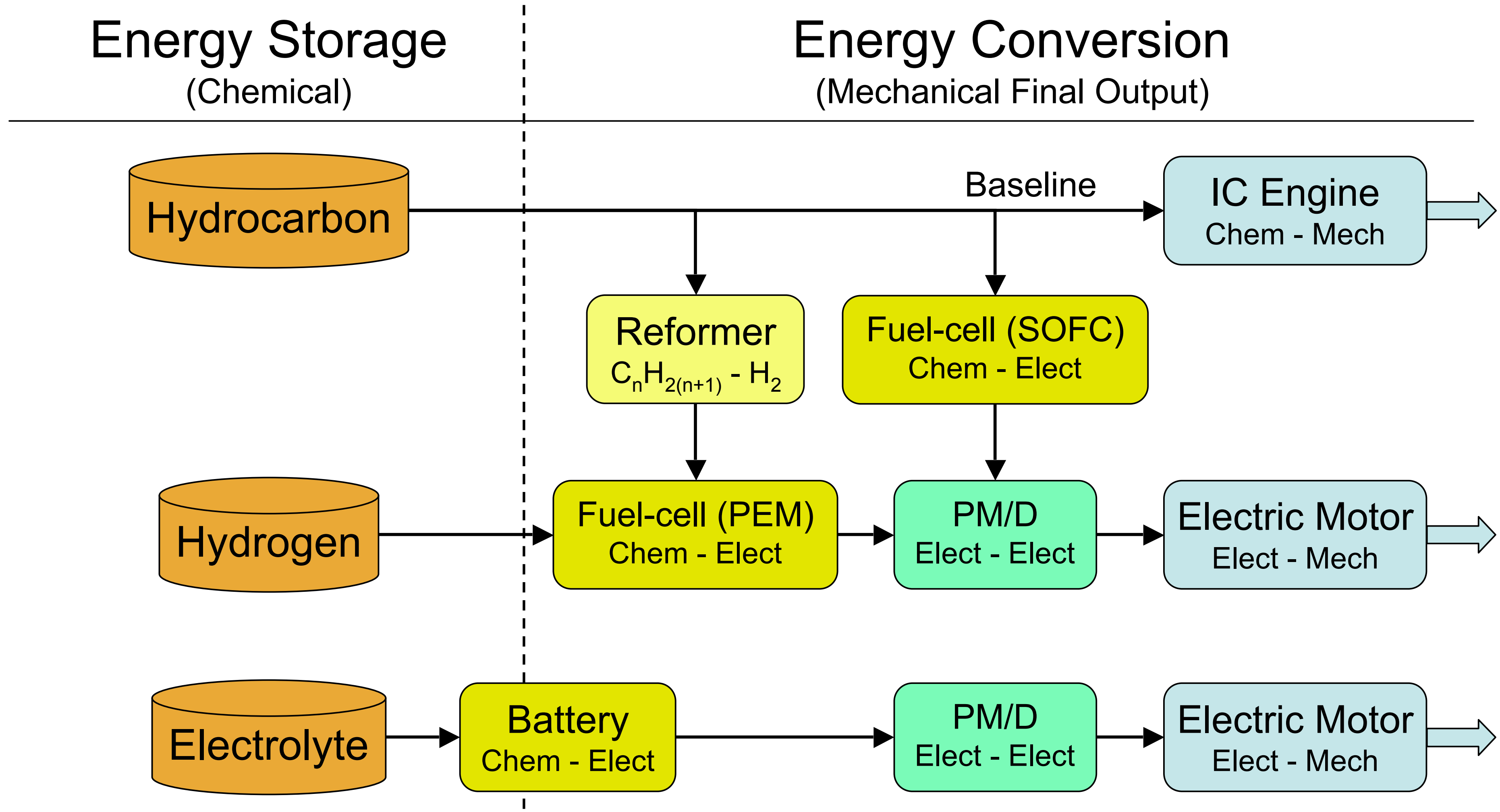
Basic Premises

- Power-systems can be decomposed into two major subsystems
  - **Energy storage components**
    - > Fuel: Hydrocarbons, H_2, electrolytes…
    - > 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

- Aircraft Power-system performance will determine if Electric Propulsion is competitive with existing systems
  - **Advances in Airframe technologies that provide the same benefit to conventionally powered aircraft will not give electric propulsion an advantage**

- Electric Aircraft should have the potential to penetrate at least a billion dollar market in order to generate National interest

Power-system configuration options



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

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

- Reference mission
  - **Max Power for 0.5 hr** **$P_1 * t_1$**
  - **75% Power for 3.5 hr** **$P_2 * t_2$**
  - **55% Power for 0.75 hr** **$P_3 * t_3$**

P_1 = 225 kW

E_R = 796 kw∗hr

- E_S; Total stored energy

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

Where: η_n is efficiency of energy conversion component n

Power-system Weight Model

- W_S: Total system weight

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

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

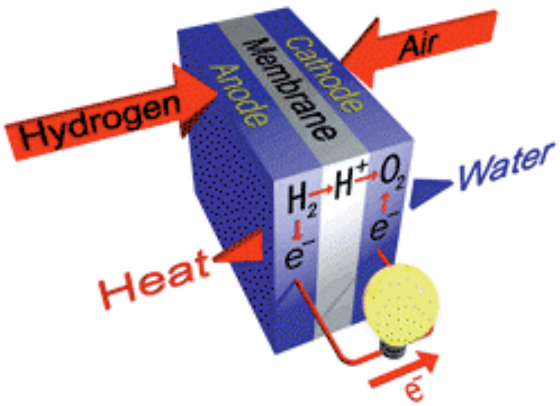
$$W_{ES} = \sum_n (E_S)(\gamma_n)$$

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

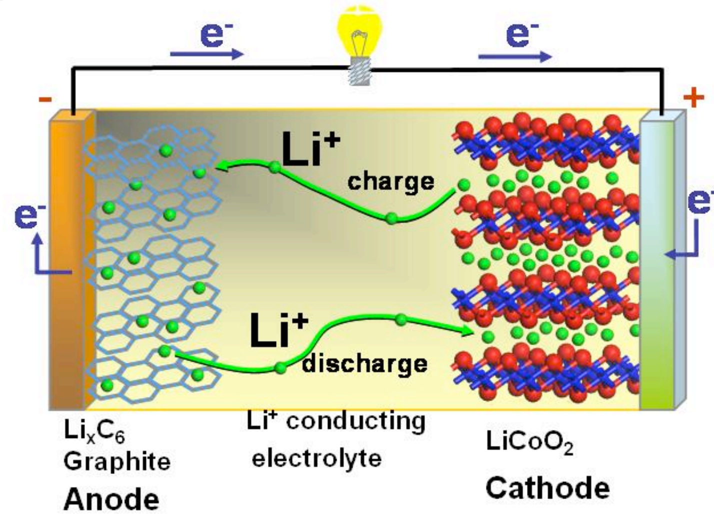
$$W_{EC} = \sum_n^m (P_1)(\theta_n)$$

Where: P_1 is Maximum power
γ_n is energy storage component n weight factor
θ_n is energy conversion component n weight factor

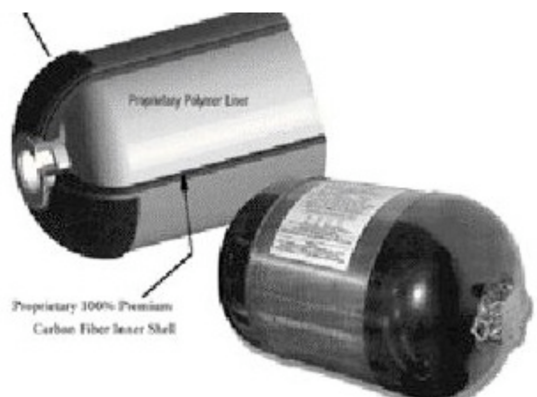
Critical Technologies For All Electric Airplane



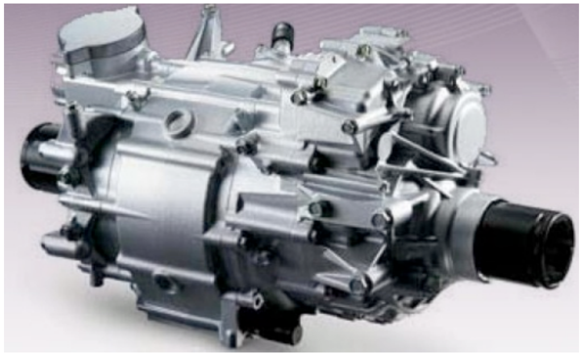
Fuel Cell



Battery/Energy Storage



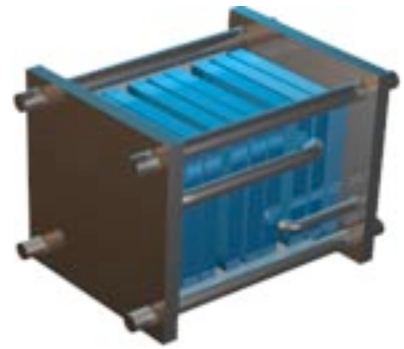
Hydrogen Storage

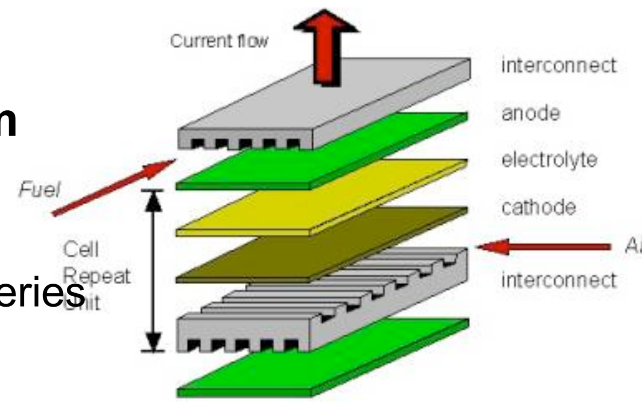


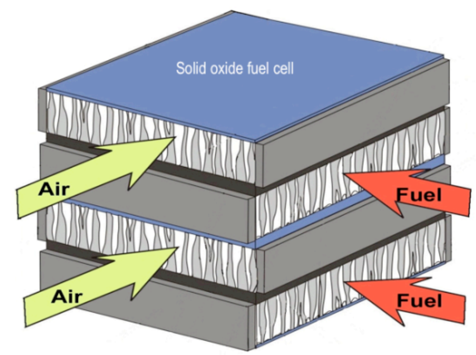
Electric Motor

Fuel Cell Systems - Advantages / Disadvantages

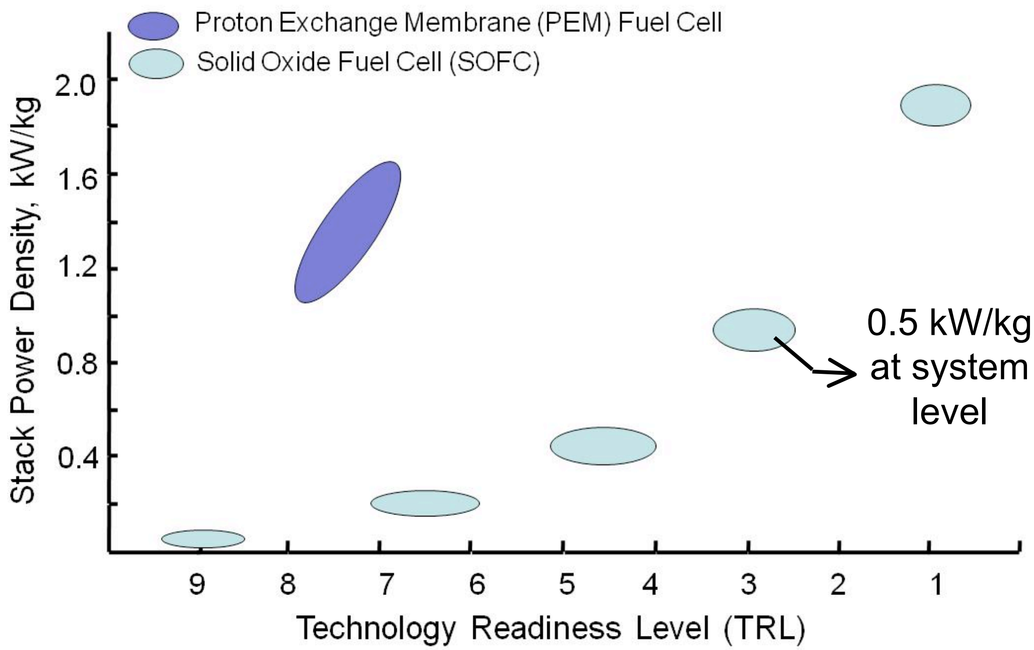
- Proton Exchange Membrane (PEM) Fuel-cell:
  - **More mature, operational in cars, high power density demonstrated**
  - **Need pure H_2, cannot accommodate CO from reformed jet fuel**
  - **Lower operating temperature (low quality heat released) needs larger heavier heat exchanger**
- Solid Oxide Fuel-Cell (SOFC)
  - **Less mature, low power density for SOA system**
  - **30-45 minute startup warm-up**
    - > Jet fuel combustion hybrid cycle may reduce time
    - > Impact to mobile operations can be reduced with batteries
  - **Potential to directly use liquid fuel without reforming**
  - **Efficiencies greater than 60 % for hybrid system**
    - > Fuel-cell with gas turbine bottoming cycle
  - **Higher power density required**
    - > Pathway exists to achieve higher power density but will require significant technology development





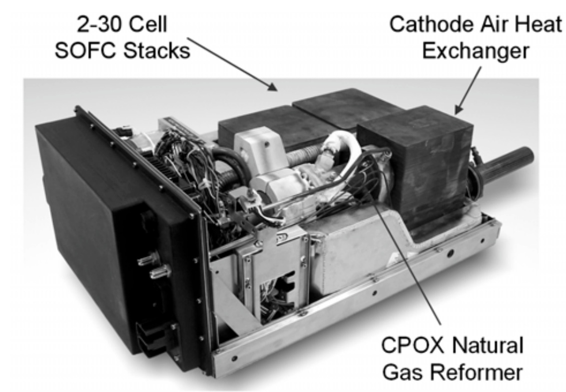


State of Fuel Cell Technology



Balance of Plant Contributes to Significant Weight (~50%)

Commercial PEM Fuel Cell

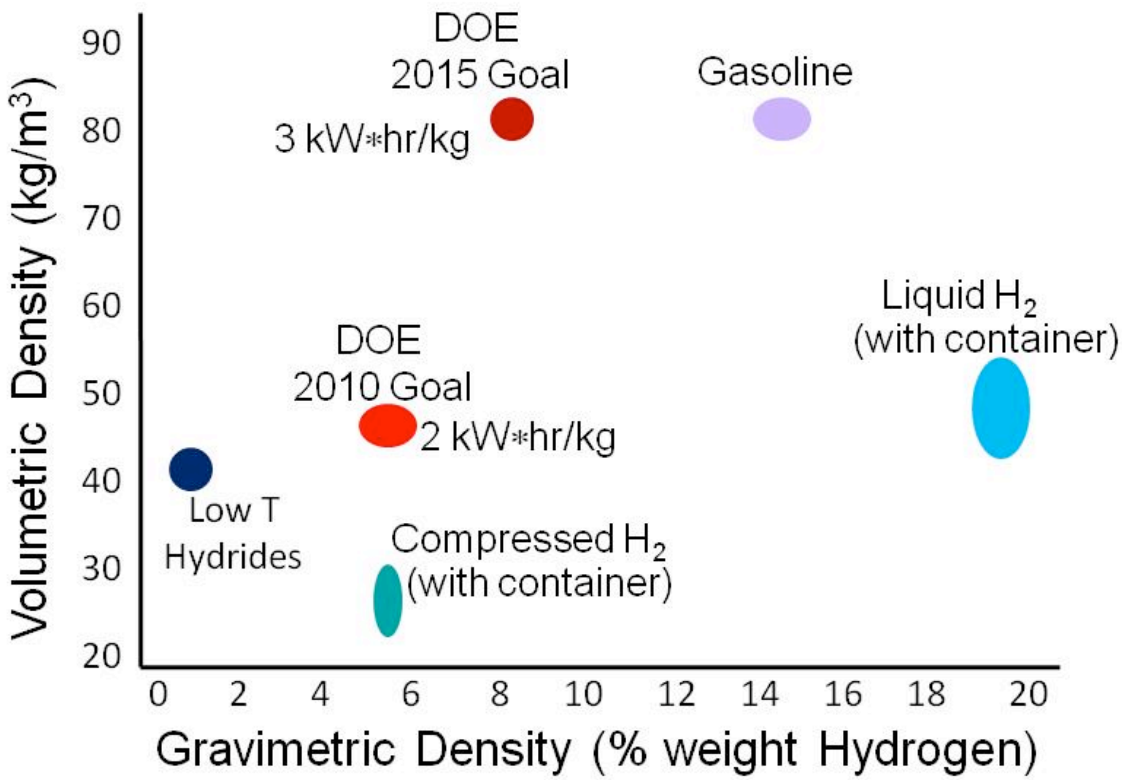


Developmental SOFC

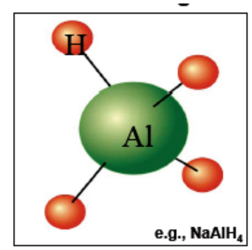
- Significant opportunity exists to reduce weight of balance of plant through use of lightweight materials and composite materials (~50% weight reduction possible) – 1 kW/kg stack would correspond to 0.66 kW/kg at system level

- Effective system integration may yield further weight reductions

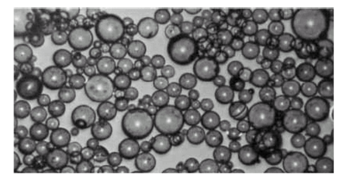
Hydrogen Storage



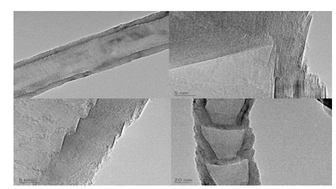
Extensive Research Underway on Solid State Hydrogen Storage



Complex hydrides



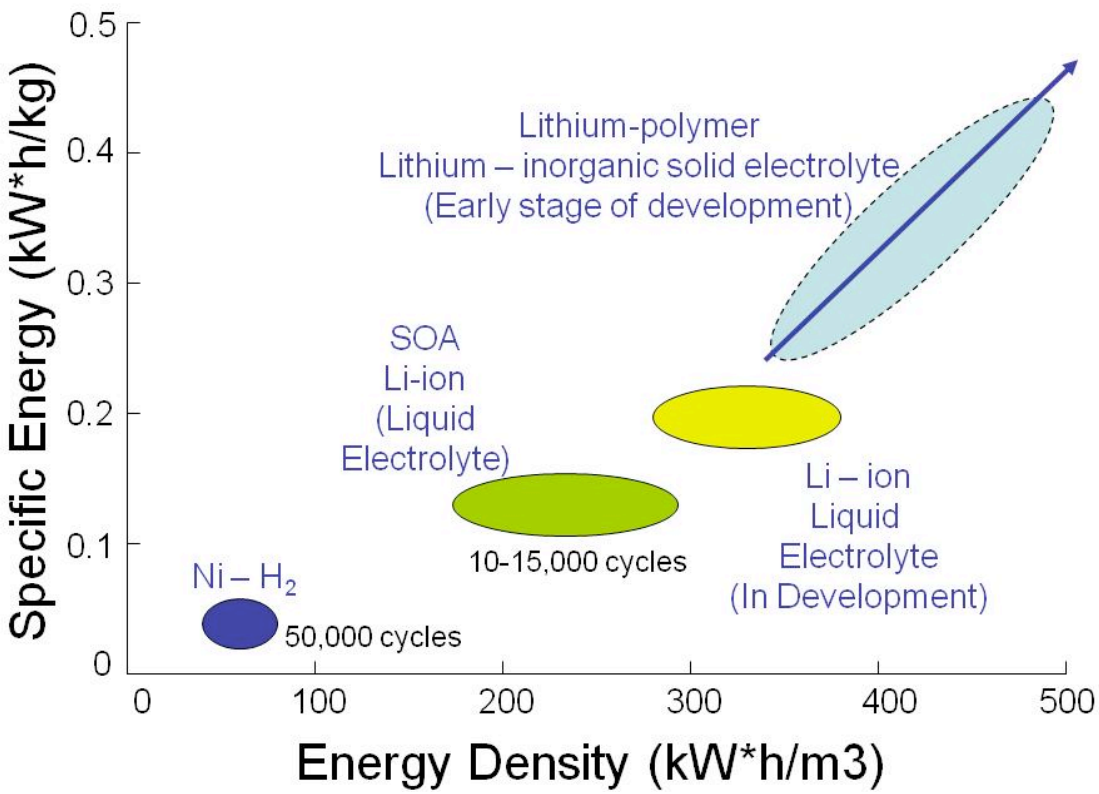
Microspheres

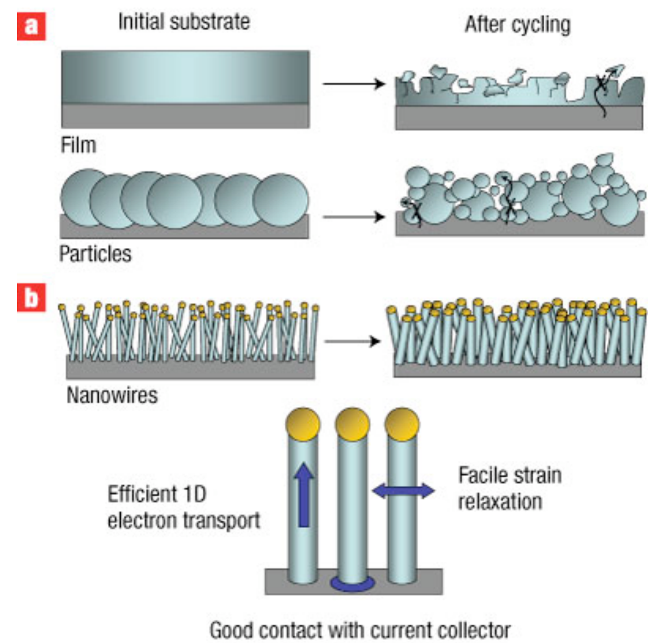


Nanotubes

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

Li-Ion Battery for Energy Storage





Li-ion batteries with nano-Si wire electrodes offer potential for 10X increase in storage capacity

Some battery storage will be required in addition to fuel-cell to balance power demands

Performance Parameters Used In This Study
Energy Storage

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**
  - **Propane (C_3H_8)** — **13.9 kw∗hr/kg**
  - **H_2 gas reformed from $C_nH_{2(n+1)}$**
    - Methane - CH_4 — 11.2 $kW{*}hr/kg_{HC}$ — (0.33 kg H_2 per kg HC fuel)
    - Propane - C_3H_8 — 6.09 $kW{*}hr/kg_{HC}$ — (0.18 kg H_2 per kg HC fuel)
    - Kerosene - $C_{12}H_{26}$ — 5.12 $kW{*}hr/kg_{HC}$ — (0.15 kg H_2 per kg HC fuel)

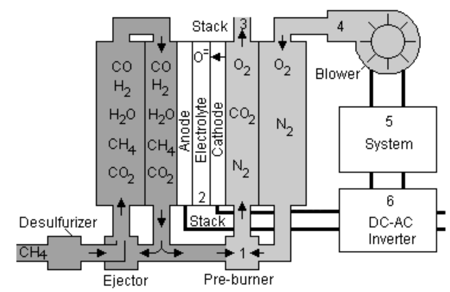
- Tanks
  - **Liquid HC** — **82.0 kW∗hr/kg**
  - **Propane** — **15.0 kW∗hr/kg**
  - **$H_{2(liquid)}$ (H_2 20% fuel wt: 2010)** — **8.38 kW∗hr/kg**
  - **$H_{2(gas)}$ (H_2 9% fuel wt: 2015)** — **3.31 kW∗hr/kg**
  - **$H_{2(gas)}$ (H_2 6% fuel wt: 2010)** — **2.14 kW∗hr/kg**

- Batteries (η = .98)
  - **Li-ion (2010: Tesla car)** — **0.12 kW∗hr/kg**
  - **Li-ion (2015)** — **0.20 kW∗hr/kg**
  - **Nano-wire (advanced)** — **0.75 kW∗hr/kg**

Performance Parameters Used In This Study
Chemical and Electrical Energy Conversion

Energy Conversion weight factors; θ (power density)

- Fuel-cells (η = 50%)
  - **Proton Exchange Membrane (PEM)**
    - > 2010: Automotive systems — 0.73 kW/kg
    - > 2015 — 1.5 kW/kg
  - **Solid Oxide Fuel-Cell (SOFC)**
    - > 2010 — 0.25 kW/kg
    - > 2015 — 1.0 kW/kg



- Fuel Reformer ($C_nH_{2(n+1)}$ - H_2)
    - > 2010 (η = 80%) — 0.75 kW/kg
    - > 2015 (η = 85%) — 1.60 kW/kg

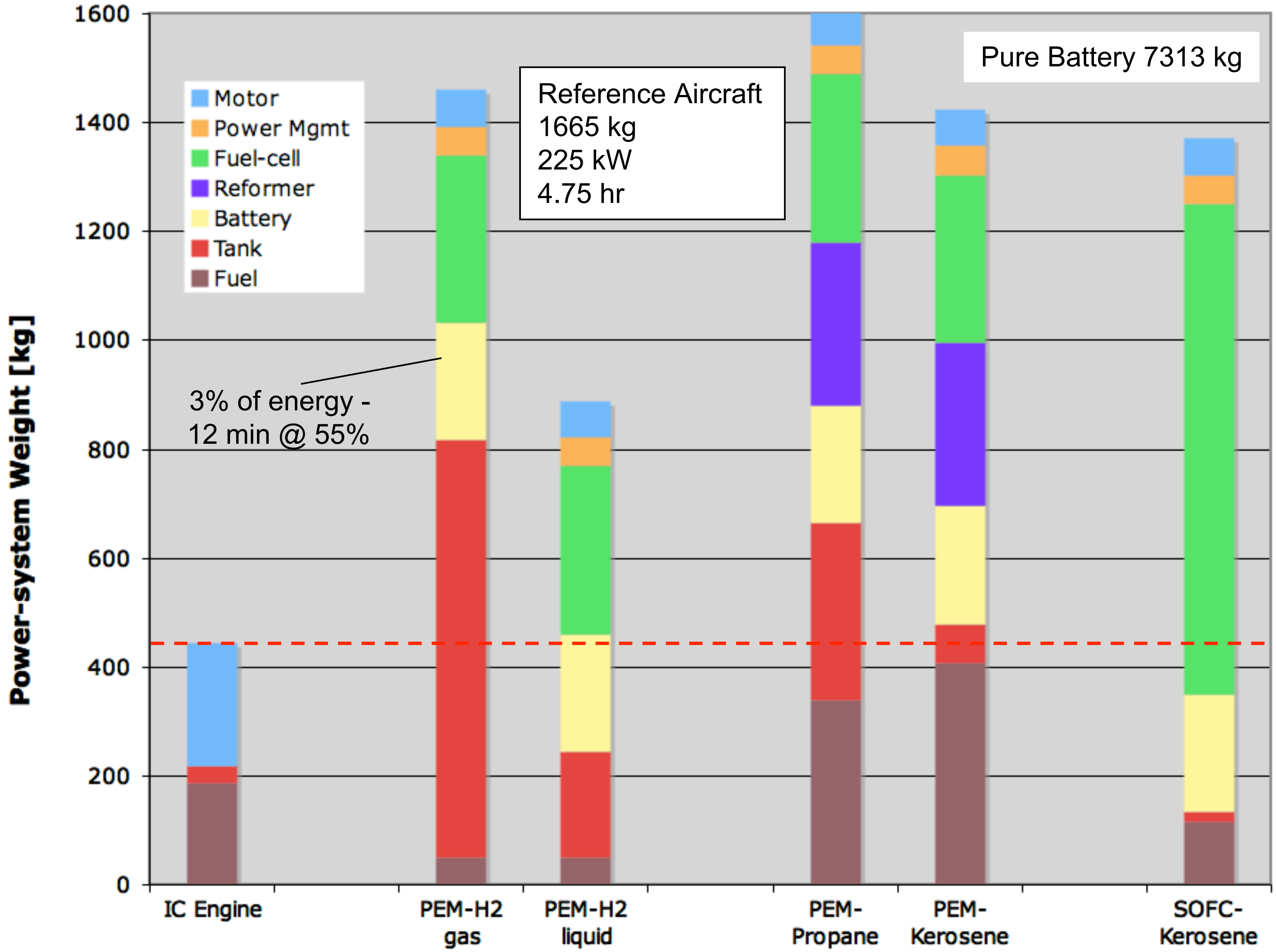
- Power management/distribution (η = 97%)
    - > 2010: automotive (Tesla, EcoStar) — 4.2 kW/kg
    - > 2015 — 6.0 kW/kg

Performance Parameters Used In This Study
Mechanical Energy Conversion

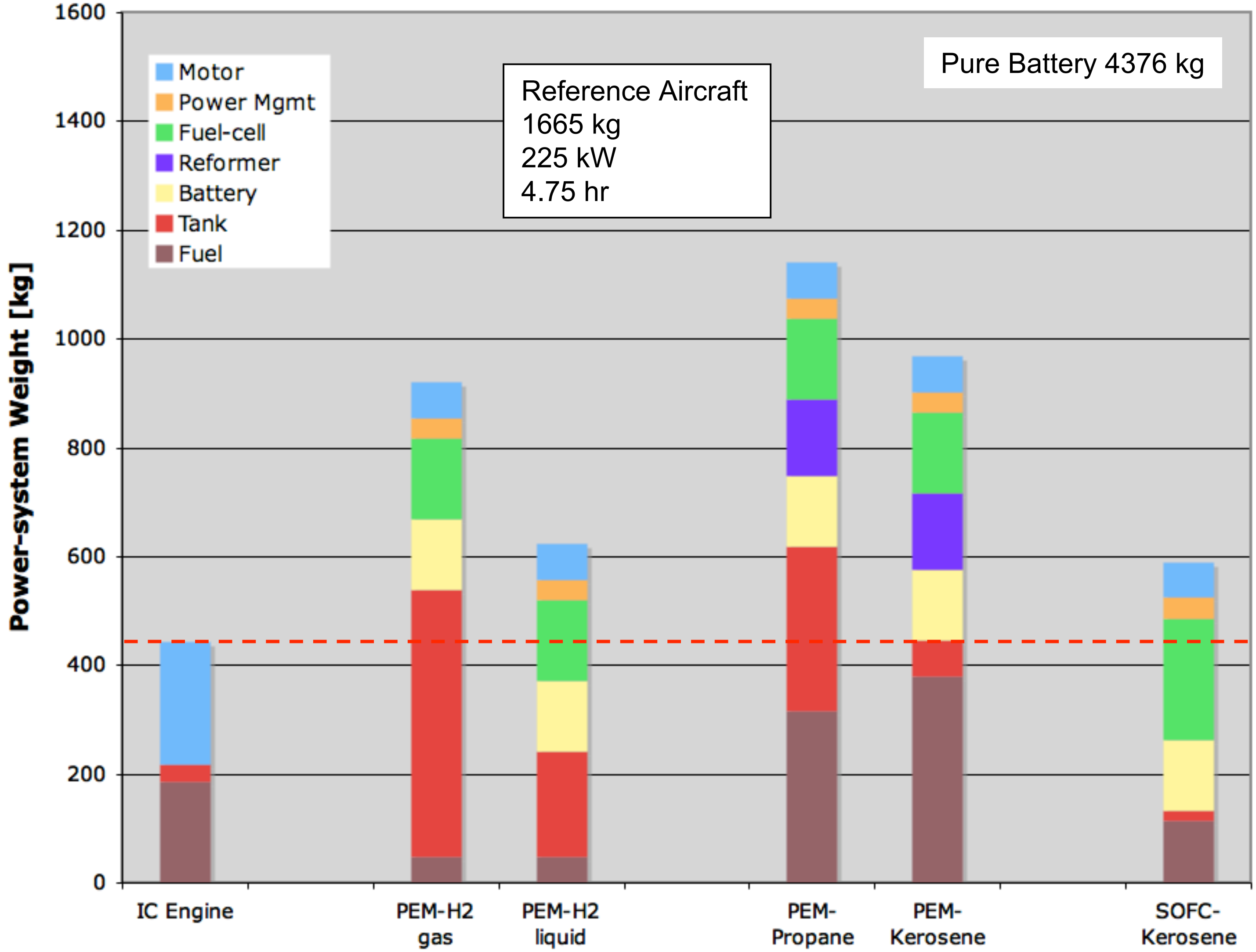
Energy Conversion weight factors; θ (power density)

- Internal Combustion Engine (η = 30%) — 1.0 kW/kg
  - **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 = 97%) — 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

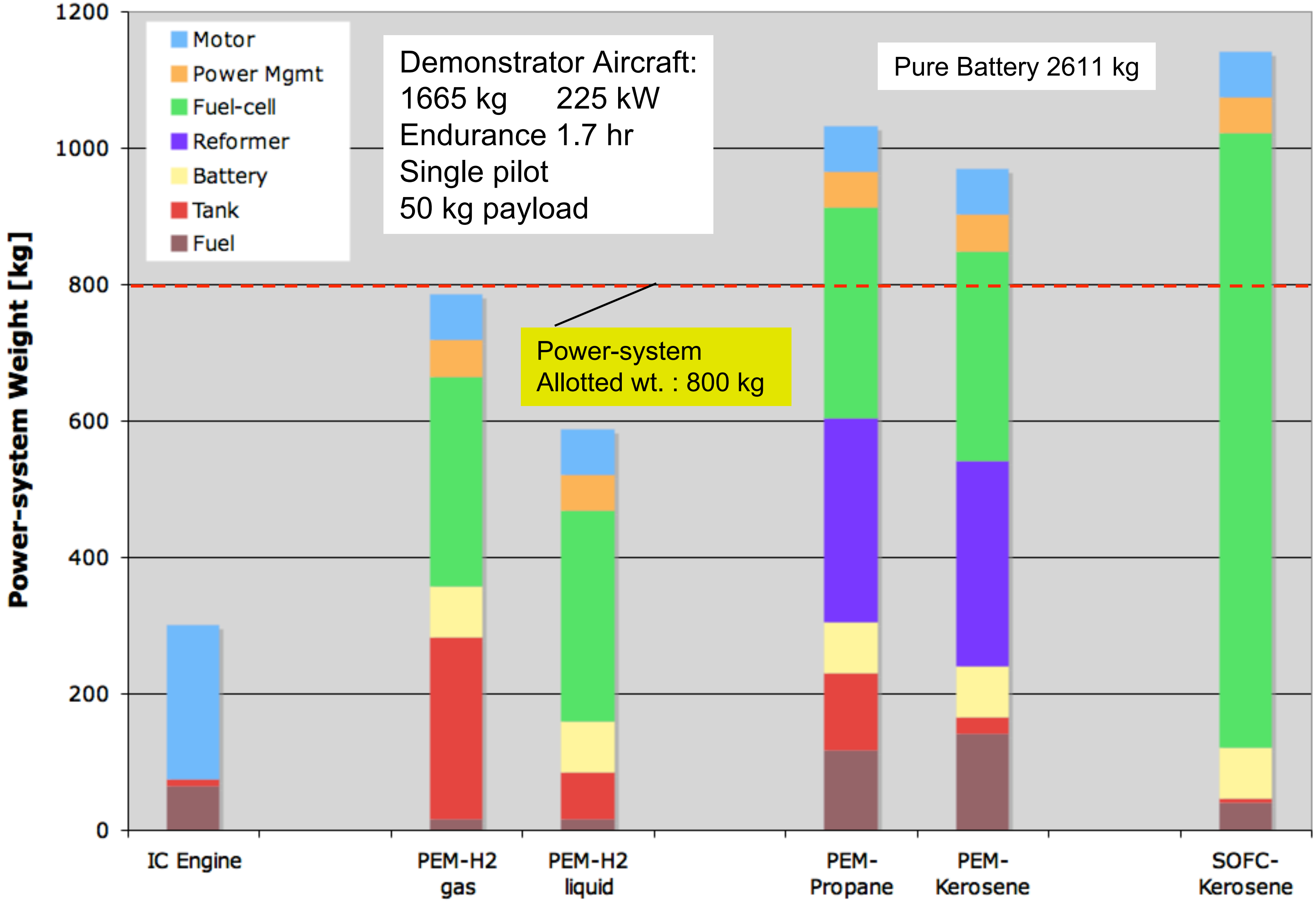
Power-systems weight comparison (2010)



Power-systems weight comparison (2015)



Demonstrator Power-system weight comparison



Performance parameter targets for competitive power-systems

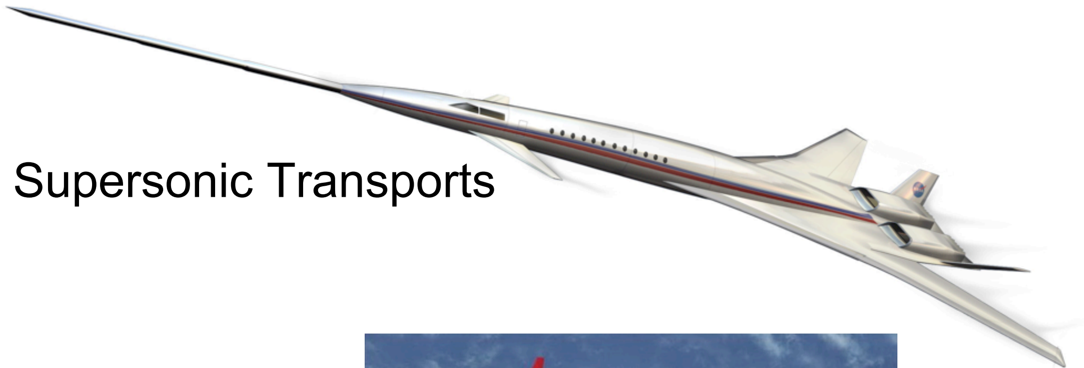
Electric Propulsion Component's required performance to be competitive with combustion engines

	Current	Comparable to IC
• PEM with H_2 fuel		
– **Fuel-cell efficiency**	η **= 50%**	η **= 50%**
– **Fuel-cell power density**	θ **= 0.73** kW/kg	θ **= 2.5** kW/kg
– **Battery energy density**	γ **= 0.12** kW∗hr/kg	γ **= 0.75** kW∗hr/kg
– **Fuel/Tank + Fuel weight ratio**	ρ **= 0.05**	ρ **= 0.22**
• SOFC with liquid HC fuel		
– **Fuel-cell efficiency**	η **= 50%**	η **= 60%**
– **Fuel-cell power density**	θ **= 0.25** kW/kg	θ **= 1.3** kW/kg
– **Battery energy density**	γ **= 0.12** kW∗hr/kg	γ **= 0.75** kW∗hr/kg
• Pure Battery		
– **Battery energy density**	γ **= 0.12** kW∗hr/kg	γ **= 2.5** kW∗hr/kg

Observations

- Significant improvements in lightweight H_2 pressure tanks are needed to make compressed gas fed PEM Fuel-cell systems feasible
- Reformatted Hydrocarbon fuels to supply H_2 to PEM fed Fuel-cells releases more CO_2 than combustion engines
- A factor of 20 improvement over Li-ion battery technology is needed for competitive electric propulsion transportation aircraft
- While current electric motor and power-management systems are adequate, significant technology challenges remain in the development of batteries, fuel-cells, and composite high-pressure tanks
- Solid Oxide Fuel-Cells with liquid hydrocarbon fuels show the most promise (assuming > 1 kW/kg stack power density can be achieved), but will need effective component system integration to reduce balance-of-plant weight

Something to think about…



Supersonic Transports

Scalable Electric Propulsion-systems will offer the potential for greener aviation across all classes of vehicles

Future Subsonic Transports

General Aviation

Technology Demonstrators

Boeing Concept