



High-Efficiency Hybrid-Electric Power Delivery

Nick Borer

NASA Langley Research Center

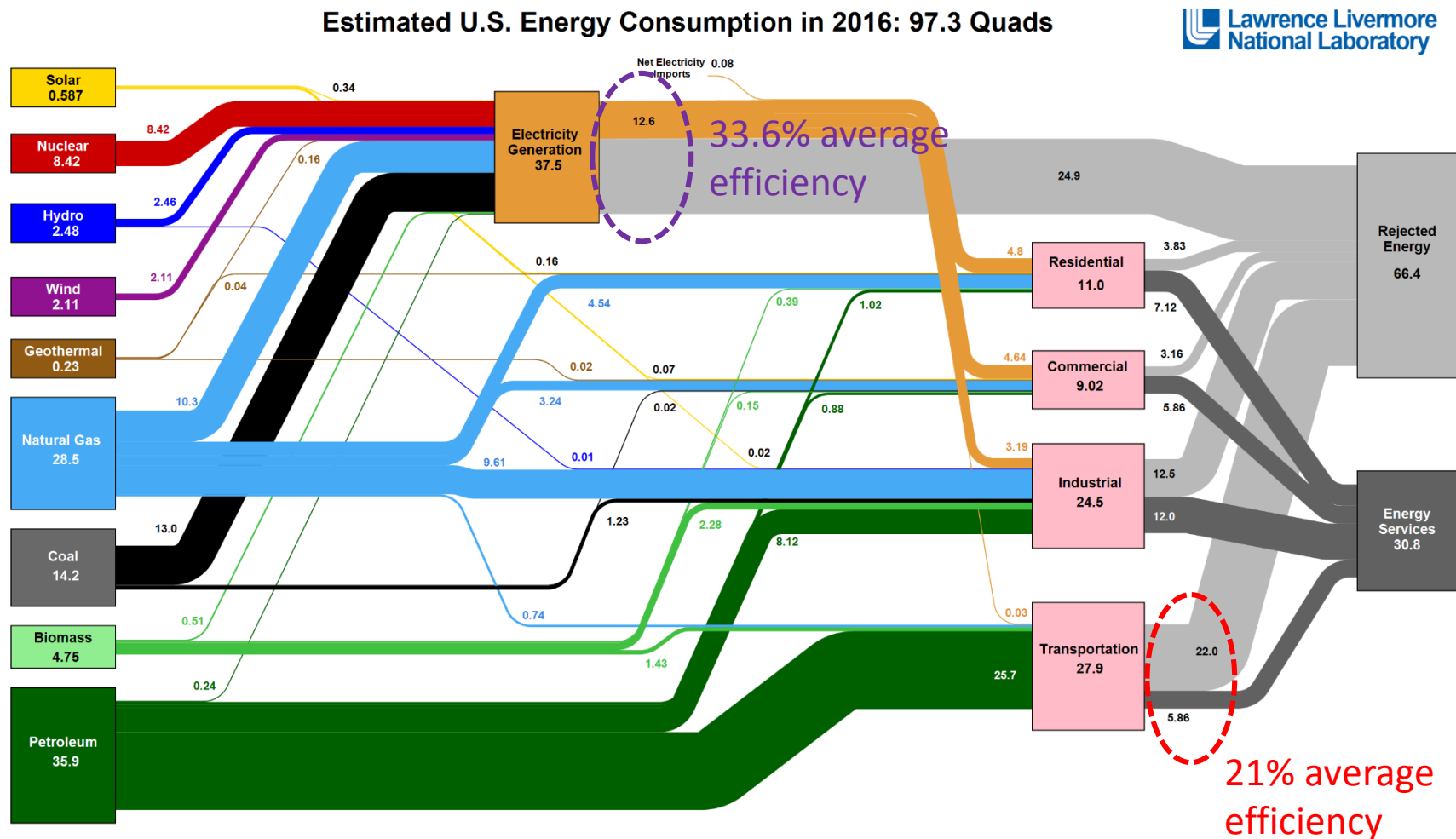
Systems Analysis & Concepts Directorate

Aeronautics Systems Analysis Branch

Disclaimer

- The views and opinions expressed in this presentation are those of the author and do not necessarily reflect the official policy or position of any agency of the U.S. government.

U.S. Energy Consumption & Waste, 2016



1.6x difference, but...

- Transmission/local storage
- Electrical storage system charging
- Electrical storage -> mechanical motion
- Mechanical -> propulsive work

However...

Electric propulsion can still be a winner

Sources: LLNL, March, 2017. Data is based on DOE/EIA MER (2016). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. This chart was revised in 2017 to reflect changes made in mid-2016 to the Energy Information Administration's analysis methodology and reporting. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector, and 49% for the industrial sector which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Challenge: Specific Energy of Onboard Storage

- Batteries are typical energy storage mechanism for electric propulsion concepts
 - Specific energy: chemical vs. pack
 - Certification: runaway, venting
 - Cycle life, amount of charge available
- Hydrocarbon fuels are significantly more energy-rich
 - Blunted by difference in efficiency
 - Growth in specific energy
- Mass parity not necessarily goal
 - EP -> aero/propulsive integration
 - Emissions, operating costs, reliability

Challenge: Energy Distribution Infrastructure

- Where does energy come from?
 - Distributed (commuting) vs. concentrated (station-to-station) operations
 - Power for rec/industrial use vs. power for transportation
 - Operations in high-energy demand locations -> surge power generation
- Rapid recharge – limiting to “surge” ops tempo
 - Charge rates vs. pumping fuel
 - Cooling

Urban Air Taxi Requirements

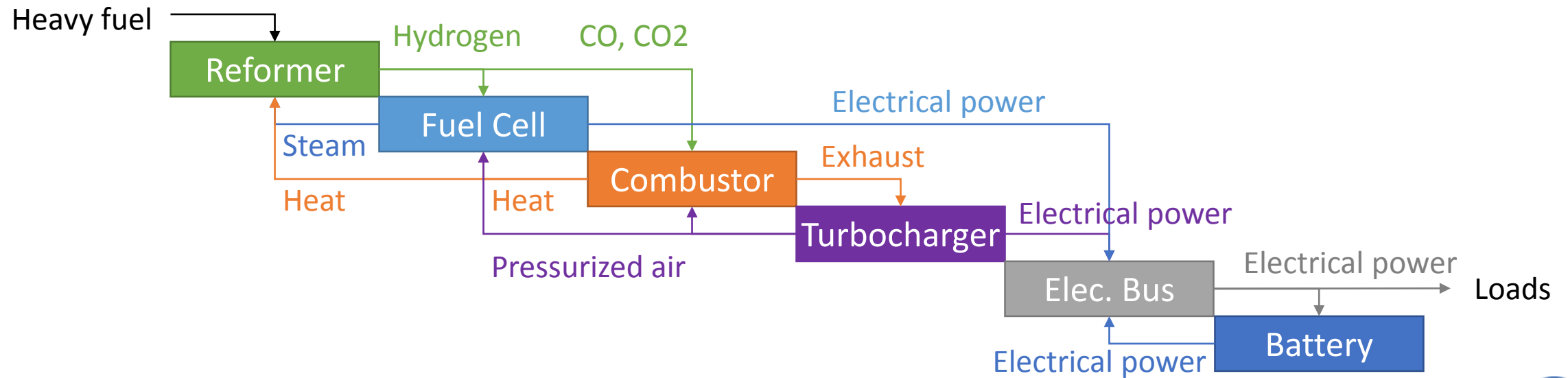
- Uber Elevate Dallas market (McDonald & German)
 - 24mi nominal trip, 55mi max
 - 200-500kW cruise, 300-1000kW hover
 - Average C-rate 1.2-1.6
 - 300Wh/kg energy storage
 - 400kW charge rate yields peak ops tempo of ~10-12 trips/rush (3 hours)
- Derived: 30-50kWh of energy required per trip
 - 1.4-2.3 gallons of diesel @60%
 - Stored fuel vs. stored energy at vertiport

What About Hybrid Architectures?

- Or, “charge the battery in the air, not on the ground”
- Primary power system sized for average, rather than peak, power
- Secondary power system sized for peak “surge” loads
- Key: efficiency, specific power of primary power system

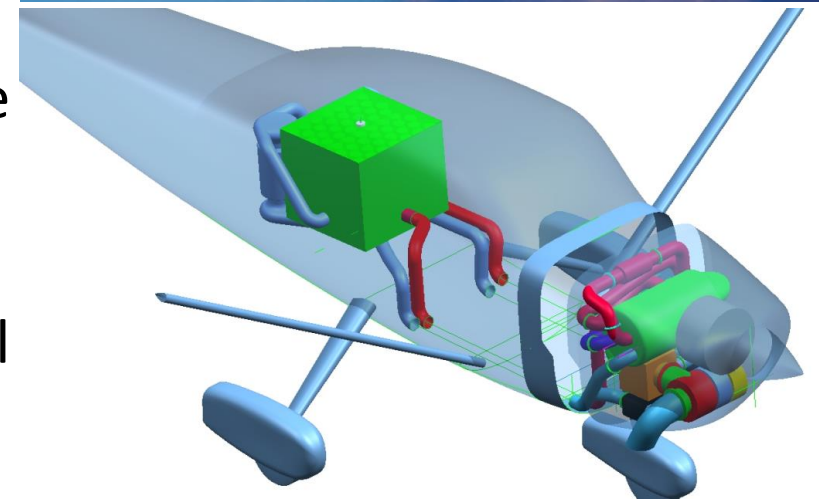
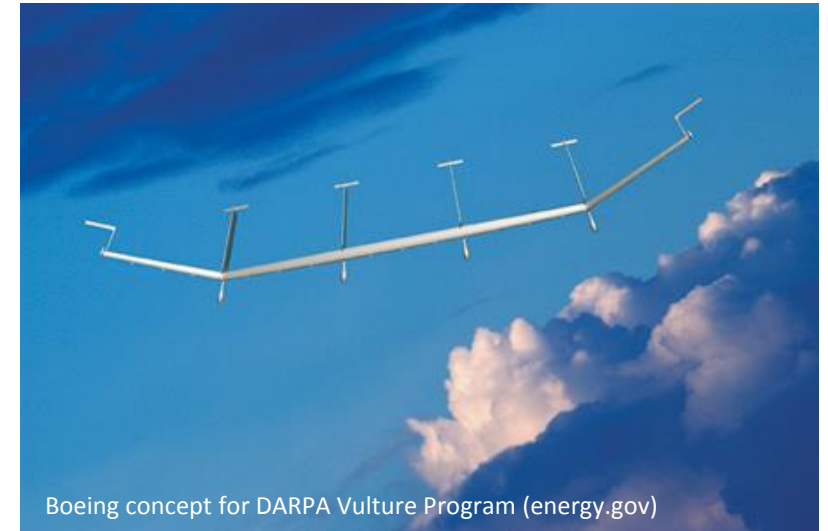
How? Heavy Fuel Hybrid-Electric SOFC

- Convergence in critical power generation technologies
 - High-efficiency Solid Oxide Fuel Cells (SOFC)
 - High-yield steam reformation of fuel for hydrogen harvesting
 - Hybrid architectures allow sizing to average power
 - Tight integration to make judicious use of “waste” products



Relevant Research Programs

- DARPA, Vulture II (2010-2015, ultra-long endurance aircraft with 5 years on station)
 - Boeing concept included regenerative solar power system with fuel cells to power aircraft through night
- NASA, “Overcoming the Adoption Barrier to Electric Flight” (2015-2016)
 - Investigated hybrid-electric SOFC for airborne primary propulsion outside of ultra-long endurance
- NASA, Fostering Ultra-Efficient, Low-Emitting Aviation Power (FUELEAP, 2016-2018)
 - Development of primary power system for notional flight demonstrator as well as APU concept
 - SOFC testing & risk reduction



FUELEAP Feasibility Objectives

- **Power output >75kW (100hp)** – necessary for primary power on light aircraft and secondary/auxiliary power for large aircraft
- **Installed specific power >300W/kg for entire system (0.18 hp/lb)** – otherwise too heavy for most aviation applications
- **Fuel-to-electrical efficiency of >60% using “pump gas”** – reduces carbon emissions by ~50% compared to today’s combustion engines while using existing fuel distribution infrastructure

Powerplant	P _{cont} (hp)	W (lb)	BSFC (lb/hp/hr)	Eff. (% LHV)	P/W (hp/lb)
HTS900-2	891	338	0.52	26.2%	2.63
PT6A-67D	1214	515	0.53	25.9%	2.36
CT7-9B	1750	805	0.45	30.5%	2.17
IO-550N	310	450	0.49	27.9%	0.69
R912S	100	135	0.43	31.9%	0.74
DH180A4	180	315	0.40	34.6%	0.57
AE300	168	408	0.37	37.1%	0.41
SR305-230	227	455	0.36	38.1%	0.5
Siemens 260+FC	344/261	1565	0.25	55.2%	0.22
Siemens 80+FC	106/80	470	0.25	55.2%	0.23
JM57+FC (X-57)	97/73	474	0.25	55.2%	0.20
JM57 (X-57)	97	77/502	14.69**	92.0%*	1.25/0.19

Turboshaft
 Turboprop
 Gasoline piston
 Turbodiesel piston
 Proposed fuel cell system
 Pure battery-electric

**“BSFC” is Battery that must be added per hp-hr; *Assumes 92% motor/controller efficiency



FUELEAP Flight Demonstrator Baseline

- Selected X-57 “Mod II” platform for FUELEAP baseline
 - NASA airworthiness established prior to end of FUELEAP CAS project
 - Lower mismatch between takeoff and cruise power requirements -> load-leveling hybrid
 - No significant difference in mass or volume available for power system between Mod II and Mod III/IV
 - Allows for independent demonstration of FUELEAP from SCEPTOR with low cost
 - 14 CFR Part 23/EASA CS-23 Certified wing design without life limits (Tecnam P2006T)

NASA X-57 Mod II “Maxwell” Flight Demonstrator



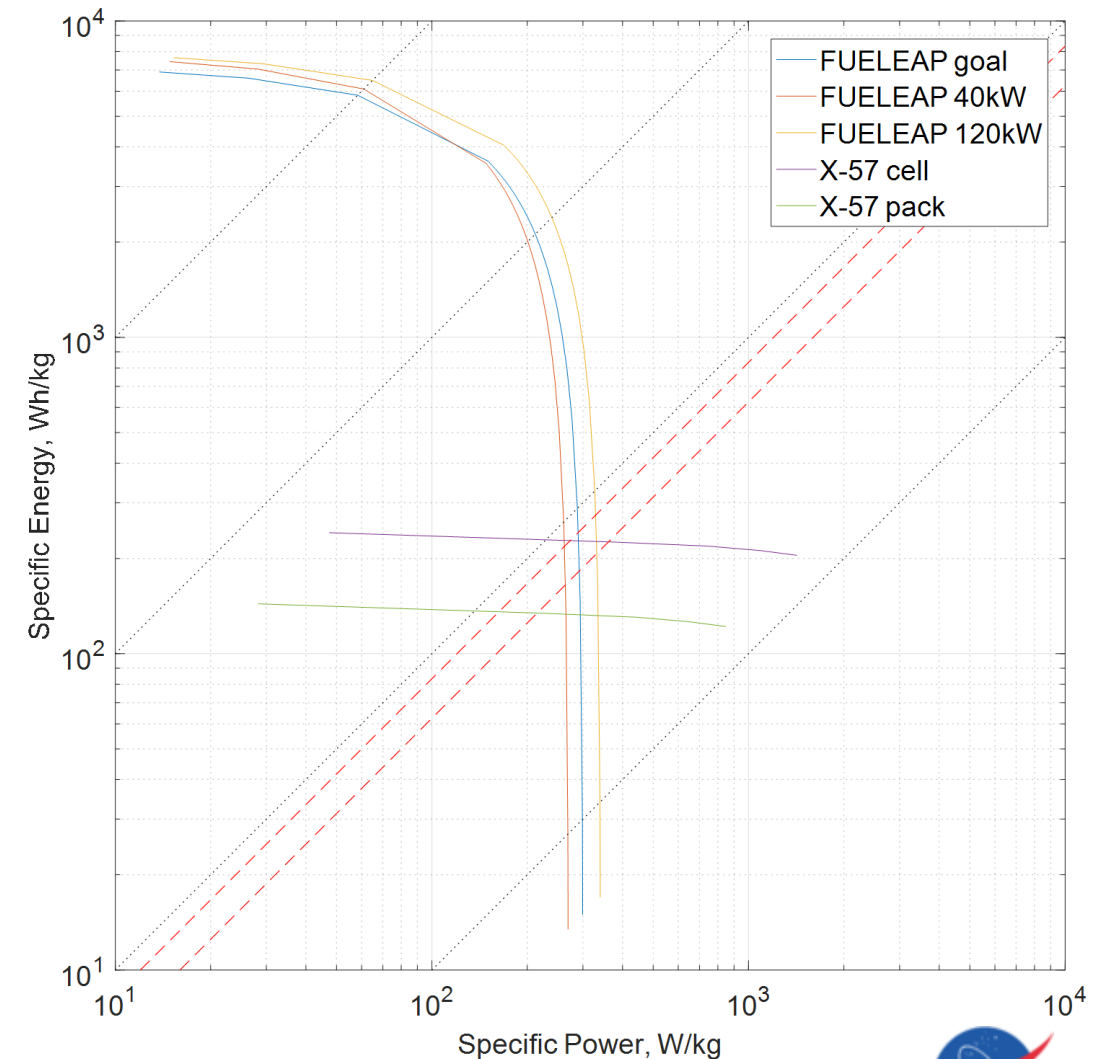
Aircraft	Motor/Energy/Fuel Weight (lbs)	Cruise Time* (hrs)
P2006T	335/--/317	5.80*
X-57 Mod II	163/850**/--	0.47
X-57-F (mass parity)	163/838/12	0.44
X-57-F (½ fuel mass)	163/838/158.5	5.76
X-57-F (½ fuel vol.)	163/838/172	6.25

*Nominal cruise ~9k ft, ~91 kW shaft power (~100kWe)

**Current X-57 design goal

FUELEAP System Performance

- From a system mass perspective, FUELEAP provides distinct advantage for long endurance
- Competitive with modern batteries for Uber Elevate C-rates
 - Current 120kW system: 329 W/kg, 274 Wh/kg with fuel for $C = 1.2$, ~65% efficient
 - Some weight reduction with increased power level, better technology
 - Balance peak loads with battery to enable competitive system w/ fast turnaround times, great “legs” for longer missions



Takeaways/Discussion Topics

- Electric propulsion is compelling, but challenges remain related to specific energy and infrastructure
- Concentrated air taxi ops require significant surge grid energy – why not charge battery in the air, and not the ground?
- High-efficiency hybrid-electric fuel cell architectures, which use hydrocarbon fuels, may be competitive in this space... and certainly are for longer-range missions
- Same technology growth fueling battery mass reduction can fuel hybrid-electric mass reduction

Acknowledgements

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Thank You!

Questions?