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HybriDrive® Propulsion System

Cleaner, smarter power for transit

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DOE/FTA Fuel Cell Research Priorities Workshop

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Overview

- BAE Systems FC Experience / Deployments
- Technology gaps/barriers to ***full commercialization*** of fuel cell buses
  - Well-to-wheels energy efficiency and emissions
  - Cost metrics
  - Bus integration issues
- Fuel cell bus R&D needs
- Future plans

BAE Systems FC Experience / Deployments

- 1998 - Georgetown/FTA/DOE Fuel Cell Bus #1 (still serviceable)
  - UTC 100 kW Phosphoric Acid FC using on-board Methanol Reformate, Hybrid propulsion & Electric accessories
- 2000 - Georgetown/FTA/DOE Fuel Cell Bus #2 (retired)
  - Ballard 120 kW PEM FC on-board Methanol Reformate, Hybrid propulsion & Electric accessories
- 2008 - CalStart/FTA Fuel Cell APU Demonstration (this Summer)
  - Hydrogenics 2 x 12 kW FC APU units using compressed H_2, supplementing ICE-Hybrid propulsion & Electric accessories
- 2010 - Sunline/FTA American Fuel Cell Bus (initial Design phase)
  - Ballard 130 kW PEM FC using compressed H_2, Hybrid propulsion & Electric accessories

Technology Gaps & Barriers to

Full Commercialization of

Fuel Cell Buses

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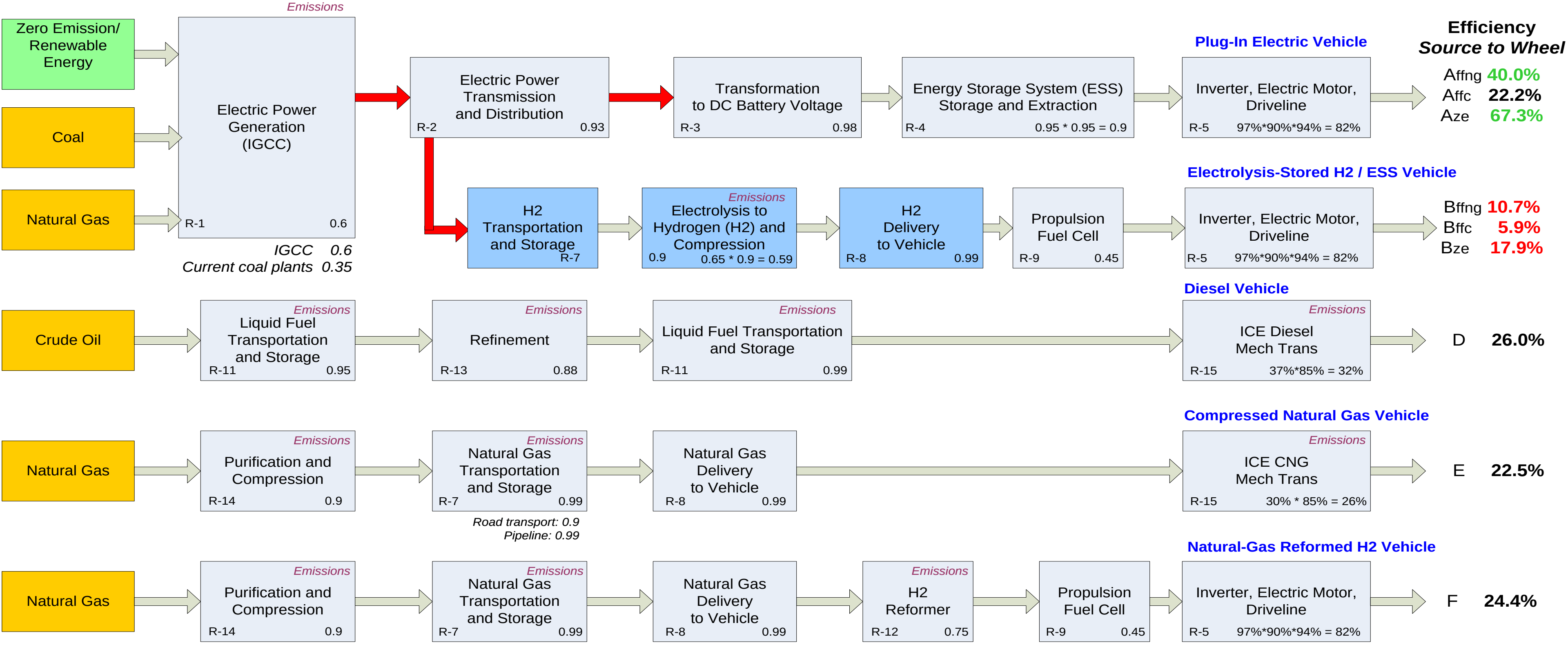
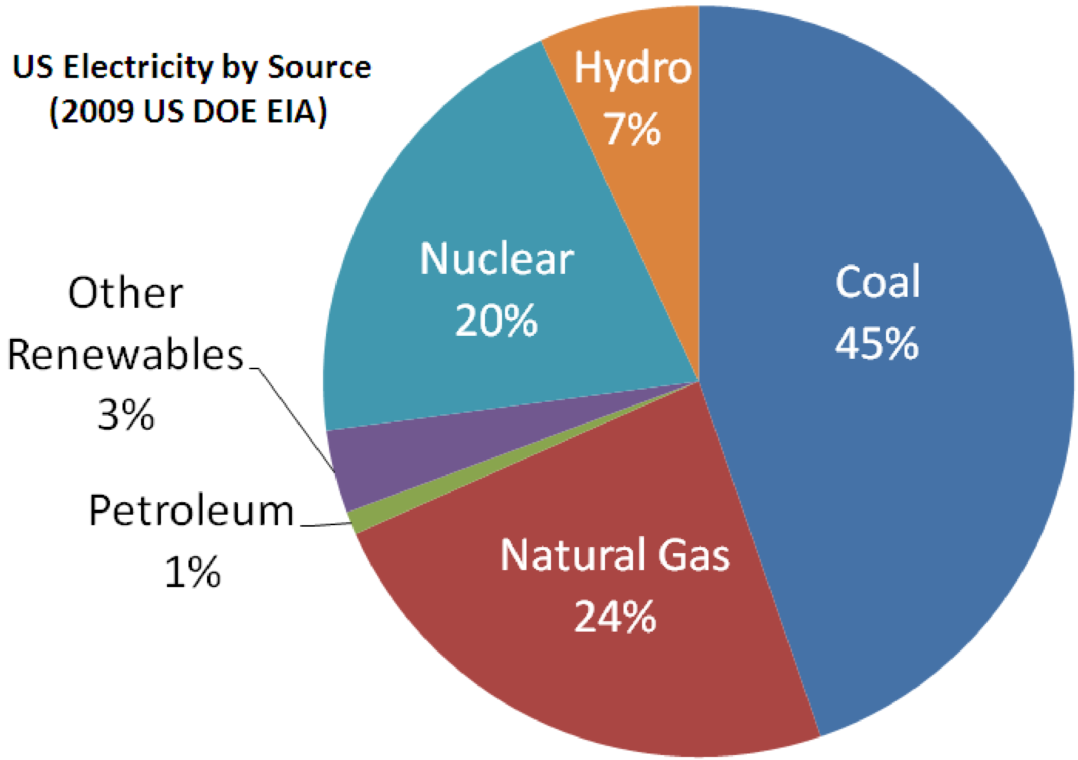
Well-to-Wheels Efficiency

- **Battery EV is best at 40% from NG or 22% from Coal**
- **Diesel ICE is best fuel burner at 26%**
- **Fuel Cell with H_2 from reformed NG 24%**
- **CNG ICE is 22%**
- **Fuel Cell with H_2 from electrolysis has efficiency at 6%-11%**



What Does Zero Emission Vehicle Really Mean?

- True ZEV only if Hydrogen is industrial "waste product" (relatively insignificant amount) or if electric energy source for electrolysis is "clean" Zero Emission.
  - 30% US electricity is "clean": Nuclear, Hydro, Wind, Solar, Geothermal, etc.
    - Only 10% if Nuclear is not considered "clean"
- Otherwise, emissions same as electric generation fuel source or reformate fuel source
- Electrolysis will need to be conducted at off-peak times and stored so as not to over tax an already stressed daytime power generation network



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Cost Metrics

Architecture	Vehicle CO_2 Reduction	Bus Premium** Δ to $325k Dsl	$ per % CO_2 Reduction	Infrastructure Requirement
Propulsion Fuel Cell	100%	$1,475k	$14.8k /%	H_2
Battery EV	100%	$575k	$5.8k /%	Electric
FC APU [Dsl (CNG)]	50% (68%)	$375k ($425k)	$7.5k/% ($6.3k/%)	H2 (H2 & CNG)
Hybrid /EA [Dsl (CNG)]	33% (48%)	$225k ($275k)	$6.8k/% ($5.7k/%)	No (CNG)
Conv / EA [Dsl (CNG)]	15% (33%)	$50k ($100k)	$3.3k/% ($3.0k/%)	No (CNG)
CNG Conventional	18%	$50k	$2.8k /%	CNG

** Bus Only, Not including H_2/CNG fueling or battery charging infrastructure, or battery/FC replacements

- Hybrid/EA w/CNG is optimal for carbon reduction & fueling infrastructure maturity
- FC-APU provides substantial CO_2 reductions at affordable (capital) & sustainable (O&M) costs
- Conventional w/Electric Accessories and/or CNG fuel most cost effective approaches
- Battery EV looks good, but range & performance is still too limited to be broadly viable
- Propulsion FC, high initial cost plus significant O&M (FC replacements over 12 yr /50khr life)

FC- APU Architectures are currently Most Economically Viable Path to Emission Reductions and Mass FC Commercialization

Propulsion Fuel Cell Vehicle Integration Challanges

- Weight / Passenger Capacity & Cost
  - Hydrogen Storage
    - Long Range, High Endurance, sub-optimal accessory systems and sub-optimal propulsion power path drive large and heavy fuel capacity
  - Cooling System
    - Low FC coolant temps dictate large / heavy and higher power consumption cooling systems
  - FC / including Balance of Plant
    - Go-Anywhere capability, sustained highway speeds, high-speed gradeability drive larger heavier fuel cells, more cooling & air handling
- Efficiency and Power Processing
  - DC-Buss voltage dynamics & management
    - Propulsion fuel cell voltage is same as hybrid propulsion 600 Vdc typ.
    - They cannot co-exist on same DC-Link without powerful, heavy & costly conversion/regulation devices in-between, hampering efficiency
  - Slow FC time constant limits regen energy recovery potential & efficiency

Summary of Gaps / Barriers to Full Commercialization

- FC Buses need to have a lower procurement cost to support purchase in commercial quantities.
  - Example: Hybrid buses currently pose acquisition challenges at ~$500k-$600k.
- Lifetime FC planned stack replacement costs need to be reduced
  - Example: Hybrid buses currently have a planned mid-life (6-year) battery replacement at ~$40k that is taxing TAs O&M budgets.
- FC Bus weight reductions need to be addressed (thru efficiency & less tankage)
  - FC & balance of plant is good, about equivalent to diesel engine
  - Propulsion power arrangement optimization & FC response
  - Accessory loads, including balance of plant, optimization
- Unless above challenges are addressed, realizing acquisition & operation of FC buses in full commercial scale will remain a difficult challenge.

FC- APU Architectures are currently Most Viable Path: Economically, Technically, and Operationally to Mass FC Commercialization

R&D Needs – Architectural & Organizational

- Develop optimized design guidelines for "Cost Effective" propulsion architectures
  - Appropriate sizing & proper application of power sources "Prime" and "APU" will make FC buses more cost-effective and commercially viable
    - Transit Bus average/intermittent power ~40 kW / 200 kW (160 kW delta)
    - $/kW for power source: ICE ~$75/kW, Fuel Cell ~$5,000 to $8,000/kW
- Develop Fleet Management guidelines for Fuel Cell and other Advanced Propulsion technologies to maximize benefit of investment
  - Procurement and O&M cost savings can be realized if buses are designed for 2-3 specific broad duty-cycle categories vs. the current "one size fits all" approach
    - Example: European "city/urban" buses with 45 mph top speed and lesser gradeability result in significantly smaller, lighter more efficient engines and higher fuel efficiency

"Remember, advanced technology cannot overcome the laws of physics" FoMoCo

R&D Needs – Vehicle Technical

- Top-down systems approach to define & optimize vehicle & component requirements
- Optimization of vehicle accessory systems, including balance of plant
  - At 40 kW average power, 1 kW reduction in accessory load results in a 2.5% efficiency improvement
- Optimized self-contained fuel cell APU at 20-60 kW net power output class
  - Requires only hydrogen supply, single cooling loop, and 28V power
- Increase fuel cell operating temperature by 5-10C
  - Will reduce heat exchanger size by 20% to 40%
- Ensure all “balance of plant” thermal requirements are consistent: same or escalating (serial) cooling temperature
- Reconfigure FC stack of higher power FCs so that voltage is ***always*** below DC-Link of hybrid propulsion system
  - Eliminate one DC/DC converter and its losses, improving cost weight and efficiency proposition - - allows implementation of simple FC boost converter
- Life - - Increase operational life of FC to minimum 6-years, 25k hrs

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