High Efficiency Hybrids Workshop

October 12-13, 2017

Chris Atkinson, Sc.D., Fellow ASME
Grigorii Soloveichik, D.Sc.
Program Directors
ARPA-E

ARPA-E Personnel

- Hosts – Grigorii Soloveichik and Chris Atkinson, Program Directors
- Assistant Director – Patrick McGrath
- Program Directors – Paul Albertus and David Tew
- Technology Commercialization – John Jennings
- Technical Assistants – Julian Sculley, Gokul Vishwanathan, Laura Demetrion, Dawson Cagle, Rosemary Cox-Galhotra, Russel Ross
- Fellows – Fadl Saadi and Addison Stark
- Workshop Coordinator – Nancy Hicks

What is this Workshop about?

1. Next generation high efficiency hybrid vehicles (all)

2. Advanced engines for next generation high efficiency hybrids (Chris)

3. Advanced fuel cells for next generation high efficiency hybrids (Grigorii)

What is the purpose of this Workshop?

1. To gauge the interest of the community in these topic areas.

2. To evaluate the state of the art in the topic areas.

3. To evaluate where the technology is heading in these areas.

4. Determine sizing of battery and fuel cell/engine for different applications.

5. To establish goals and targets for a potential future funding program(s).

The problems

Low transportation efficiency of conventional vehicles

- Undesirable dependence on oil

- High carbon emissions

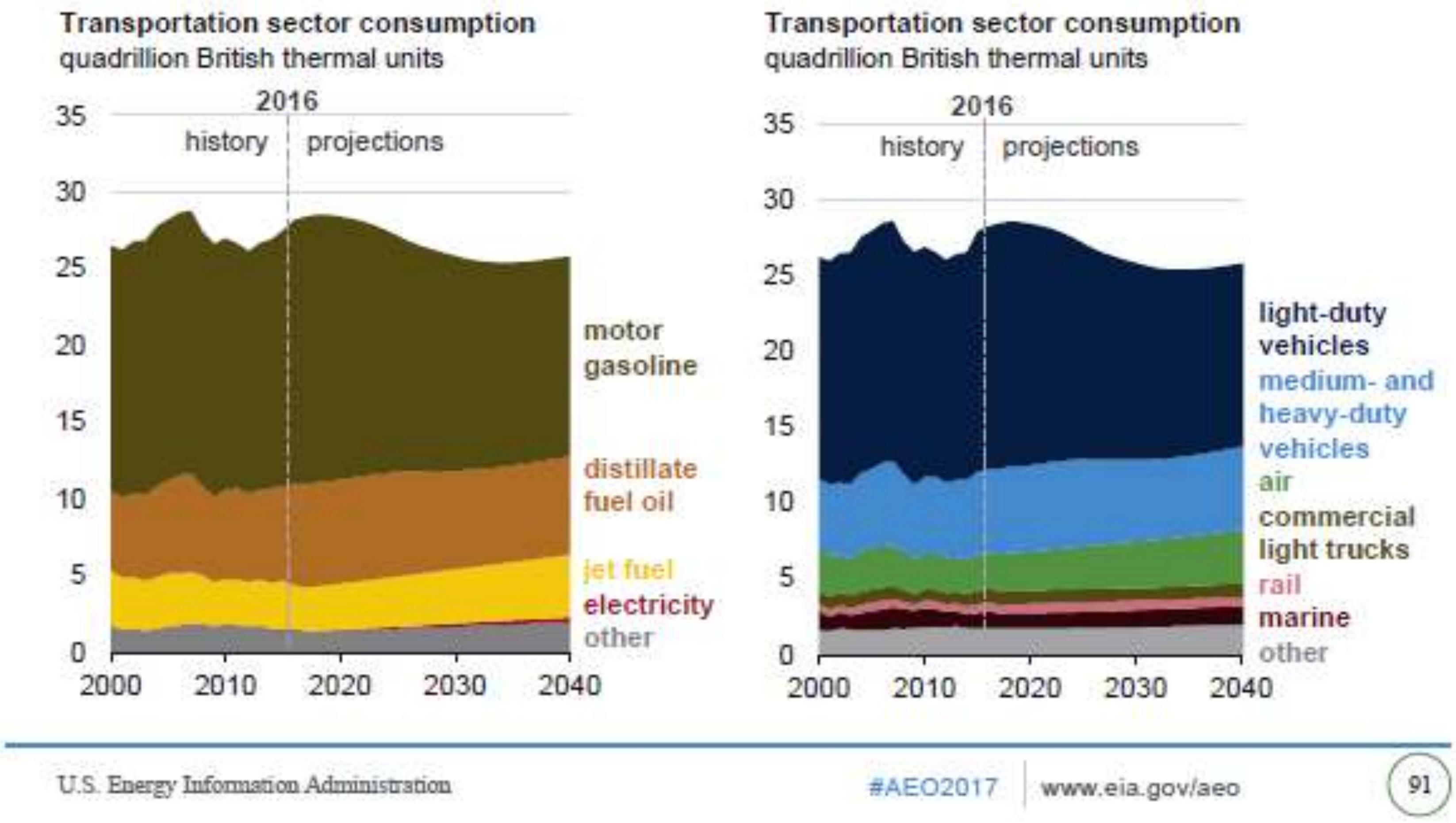
- Average fuel efficiency of light duty vehicles 22 mpg (CAFÉ standard 54.5 mpg by 2025)
- Transportation sector consumes 13.5 million barrels of oil (385 million GGE) per day
- Improvements in fuel use are often tempered by increases in travel stimulated by better fuel economy (“rebound effect”)

Low customer acceptance of electrical vehicles/alternative fuels

- High cost
- Insufficient infrastructure
- Direct correlation with driving range
- Alternative fuels (NG, E85, propane, electricity, and hydrogen) consist 0.35% of total fuel use

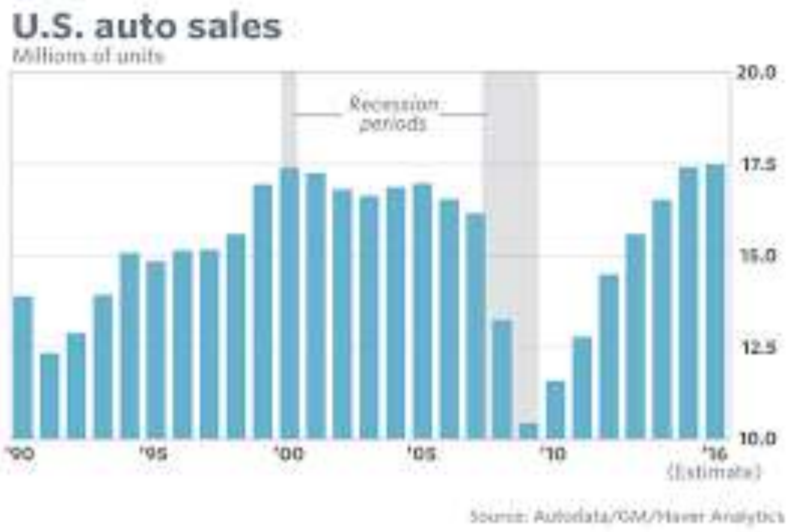
Source: US Department of Transportation

Transportation Energy Usage in the US

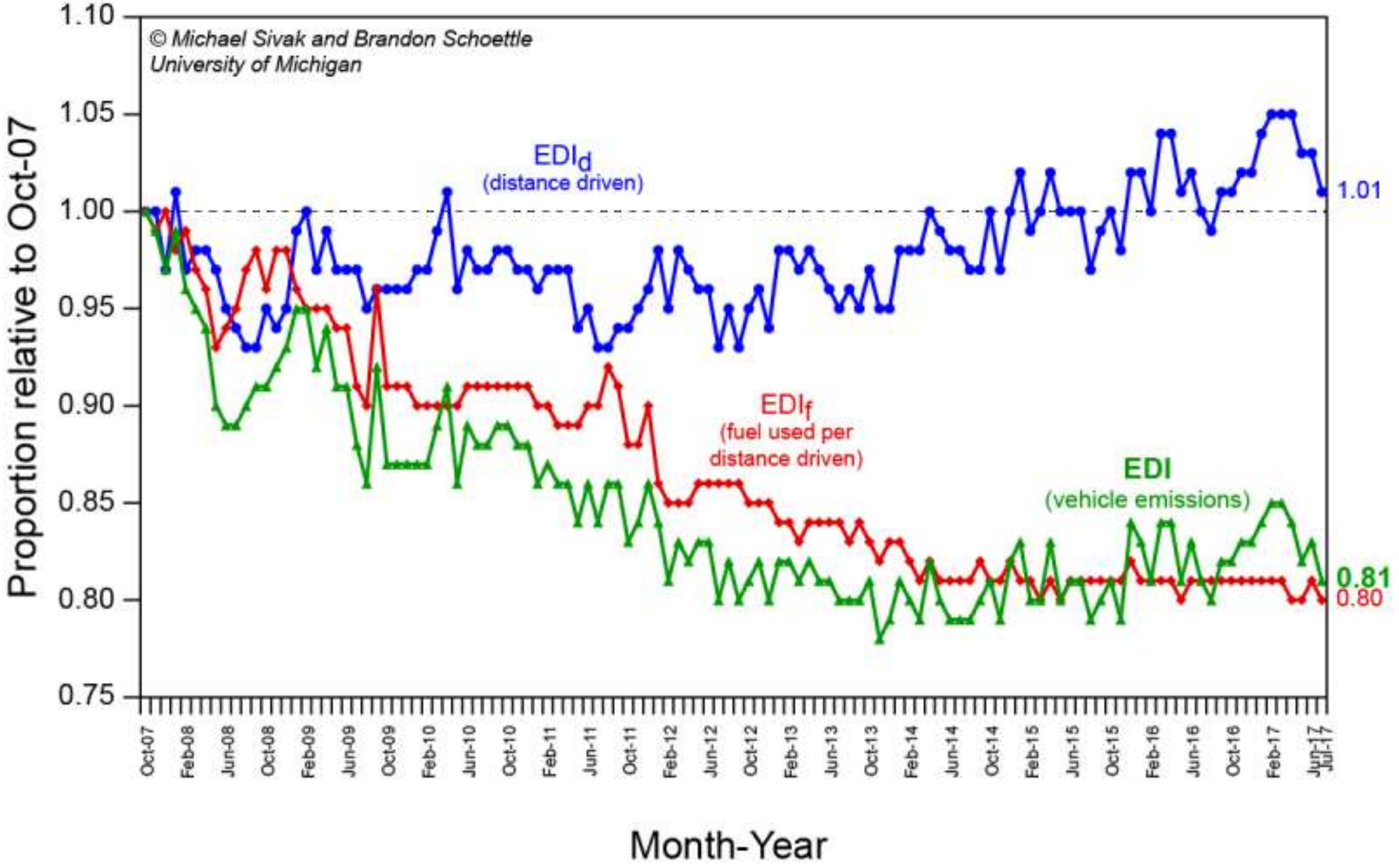


The State of the Automotive Industry Today

- **Total light-duty vehicle sales** in 2016 were ~17.5 million (at $34k average)
- **Total vehicle fleet** in the US: 190 million cars, 50 million pickup trucks, 12 million heavy-duty (HD) vehicles (trucks, buses).
- **57% of sales** are now pickup trucks, SUVs, crossovers and minivans.
- Average LD vehicle age is now **11.4 years** (Polk).
- LD vehicle fleet takes **10-15+ years** to turn over.
- xEV sales (US, 2016): 0.7% BEVs, 2.7% HEVs (including PHEVs)
- Average costs of personal vehicle ownership and operation are **~$0.60/mile**.
- **Heavy-duty** truck sales in 2016 were 270,000 (truck costs are **$3.00+/mile**).

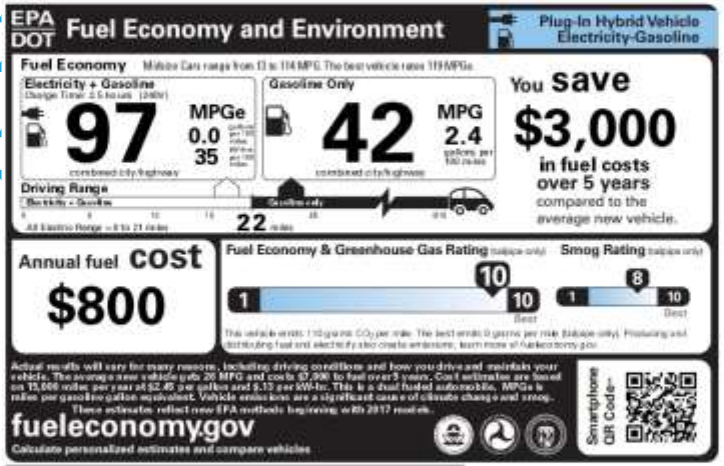


VMT increasing, fuel efficiency stagnant



3 Dominant Trends in Automotive Transportation

1. Fuel economy (or energy efficiency)

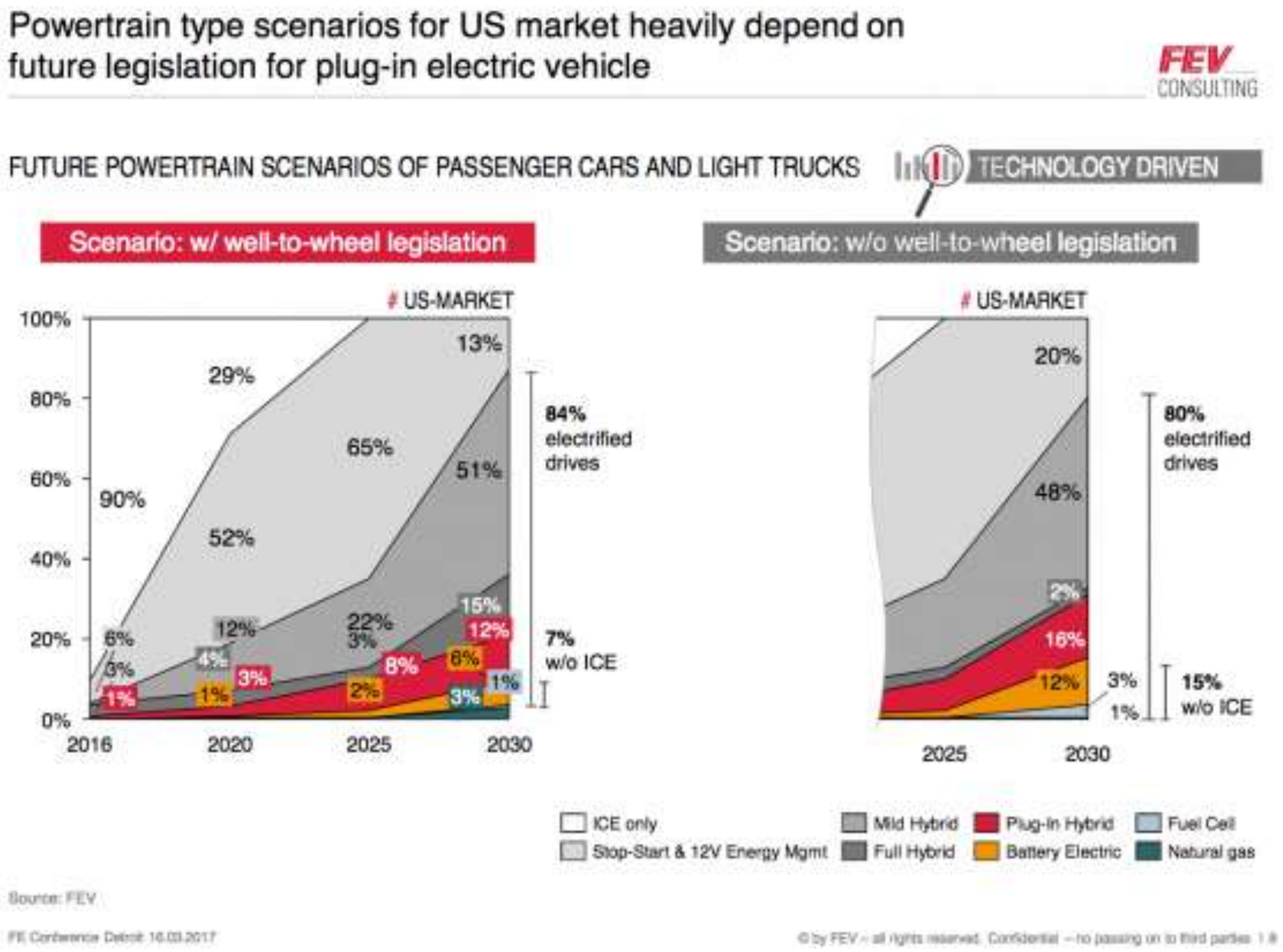


- **Light-duty** fuel economy standards increased (54.5 mpg CAFE by 2025).
- **Heavy-duty** fuel economy regulated by EPA/NHTSA Phase 2 GHG rules.

Fuel efficiency improvements will be achieved by **vehicle light-weighting, reducing aerodynamic drag and tire rolling losses, engine downsizing, boosting, improved transmissions (multispeed 9-12 speeds, CVT), increased electrification, hybridization, waste energy recovery, and reductions in friction and parasitic losses.**

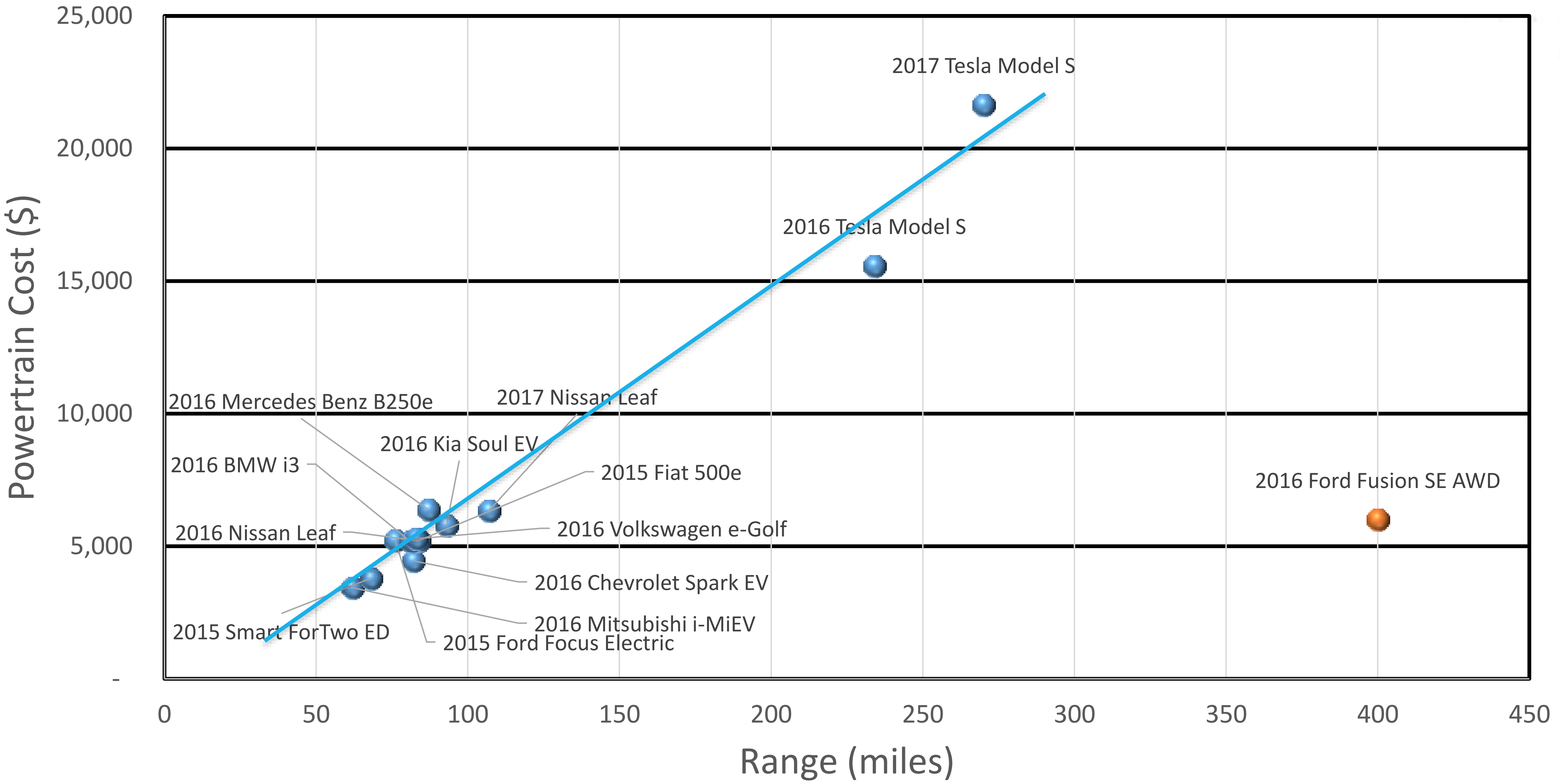
arpa·e
CHANGING WHAT'S POSSIBLE

Trend 1 – Fuel Economy (or Energy Efficiency)



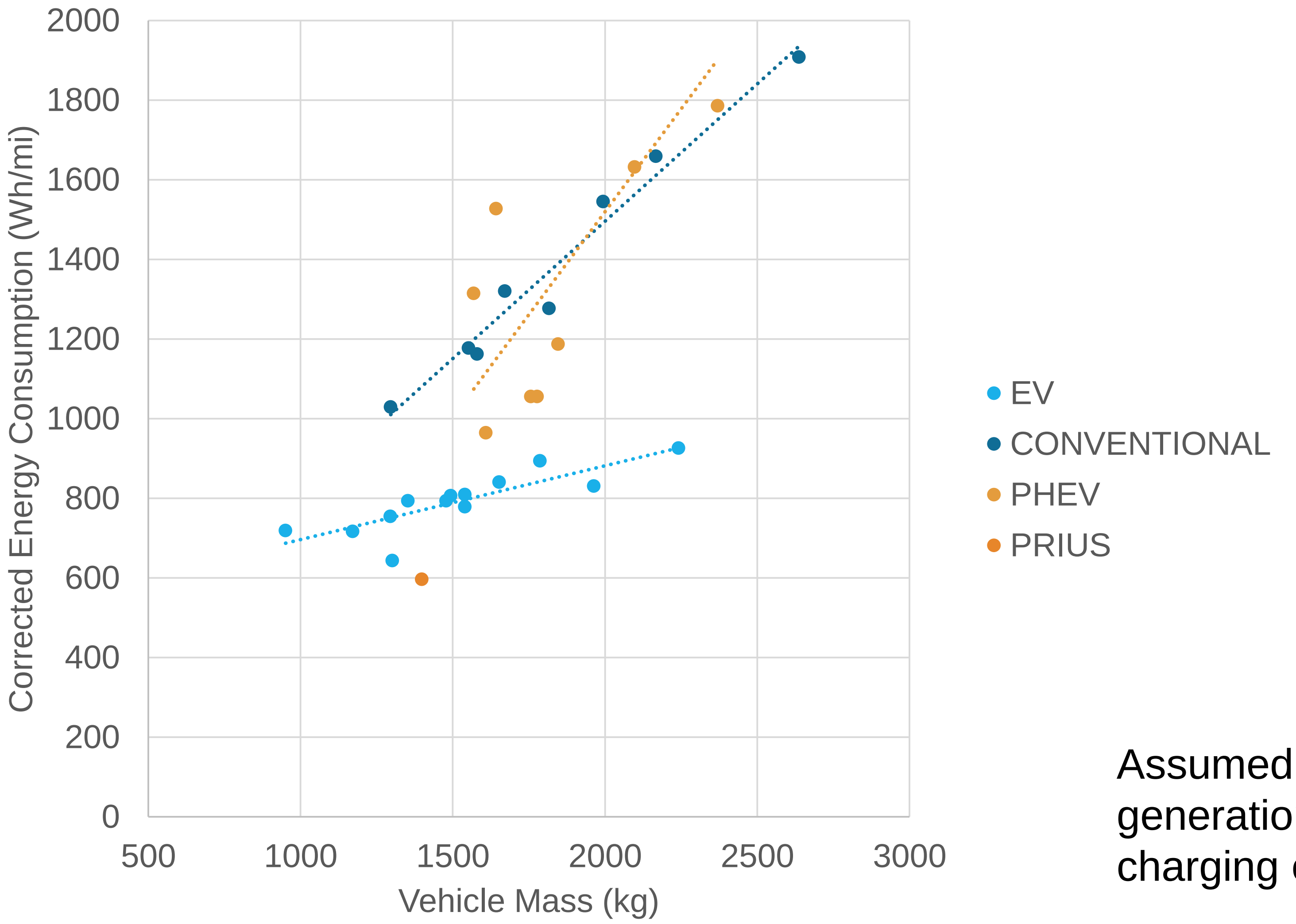
2016: HEVs – 2.7%, BEVs – 0.7%

Powertrain Cost (Battery Pack cost $190/kWh, Motor and Power Electronics $8/kW)



CHANGING WHAT'S POSSIBLE

Corrected energy consumption (Wh/mi) (tank-to-wheels)



Assumed 40% fossil energy generation efficiency, 90% charging efficiency

What are the implications for future energy usage?

- Liquid hydrocarbon fuels (petroleum, biofuels) will persist due to large legacy fleet, cost, energy density, range, refueling infrastructure, ease of refueling
  - Potential for halving fuel use with constant VMT is real
- BEVs will make inroads – currently 0.7% of new vehicle sales; 10-20% quite reasonable by 2030 or beyond (average daily driving range is <60 miles; 99th percentile is 400 miles)
  - Li-ion to 2030 – what is beyond Li-ion?
  - Present $250/kWh at 75 kWh per vehicle is $18,750 (compared to a conventional powertrain cost of ~$5,000)
  - 2 million BEVs per year (~12% of 2016 sales) requires 4 Gigafactories' output.
  - At $150/kWh, 1 GF = $5.6B per year
  - If whole US vehicle fleet was BEV, 3.2T miles would take ~30% of US annual electricity production
  - A Class 8 tractor-trailer (SuperTruck) would travel 50 miles on 100 kWh (typical travel duration can be 400-500 mi/day) – would need 1,000 kWh of storage.
- Replacing dependence on imported oil with imported minerals?

What powertrain technologies will drive the future?

- Hybrid architectures – regenerative braking energy capture; series hybrids; parallel hybrids; multi-mode hybrids
- xEVs
- FCEVs
- High efficiency engines – 50% brake thermal efficiency engines exist – compression ignition, waste energy recovery
- *New engine architectures – free piston, linear engines; split-cycle engines…..*
- *New combustion modes – low temperature combustion; reactivity controlled combustion; ultra-lean; knock resistant……*

How do we best reduce energy in the "inefficient interim" term?

Clearly one answer is more efficient hybrids, and engines or fuel cells.

Current ARPA-E program portfolio focusing on efficiency improvements in stationary and transportation engines/vehicles

Program

GENSETS – High efficiency residential CHP

ICE – Aerodyne, Air Squared, Mahle, Tour, WERC and WVU
Stirling – ITC, Sunpower and WVU
Brayton – Brayton Energy and Metis

NEXTCAR – Leveraging connectivity and automation for improving powertrain efficiency

LD– GM, MTU (GM), OSU (Delphi, Tula), SwRI (Toyota, UM), UCB (Hyundai), Udel (Bosch, BU) and Umich (PNNL)
MD– UCR (US Hybrid) and UMinn (Workhorse)
HD– Penn State (Volvo Trucks) and Purdue (Cummins, Peterbilt, Peloton, NREL)

OPEN-2015

Achates, Cummins and UMich

Requirements for commercial success

Any new powertrain technology should be comparable to or better than the baseline in:

Criterion	Explanation
Safety	FMVSS, NHTSA crashworthiness
Power	Power density (or energy density including the fuel/energy storage capacity) ⇒ Customer acceptance
Efficiency	Fuel economy (over real-world dynamic driving) ⇒ Regulation Energy efficiency (EPA/NHTSA)
Emissions	Regulated criteria pollutants (and CO_2) ⇒ Regulations (EPA)
Cost	Total cost of ownership (including capex and energy cost)
Reliability	Mean time between failures, maintainability
Utility	Acceleration, driveability, NVH, cold or off-cycle operation, ease of use, transparency to the user, refueling, and acceptable range
Fuel acceptability	Use a readily available fuel or energy source.

Huge Foundational Shifts in the Automotive Industry

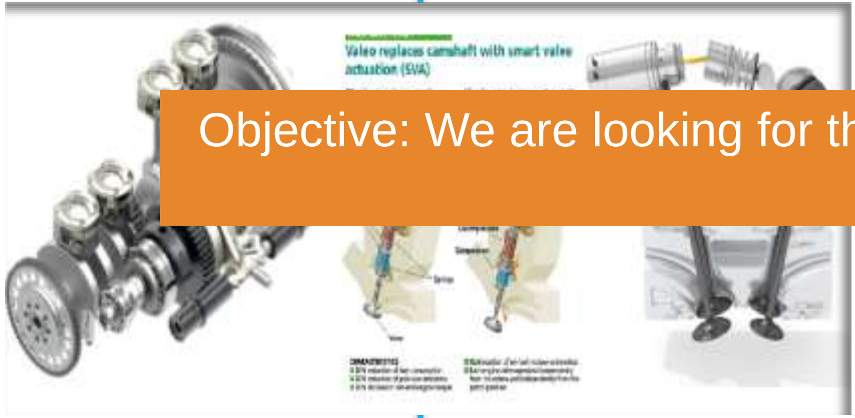
- **Old Model**
- Vehicle hardware as the differentiating factor
- Complex powertrain
- Long development cycles
- Human operator, stand-alone
- Single vehicle with a single user
- Owner is driver and user
- OEMs are foremost
- Tightly controlled supply chain
- “One sale, once”
- OEM profitability required or at least desired

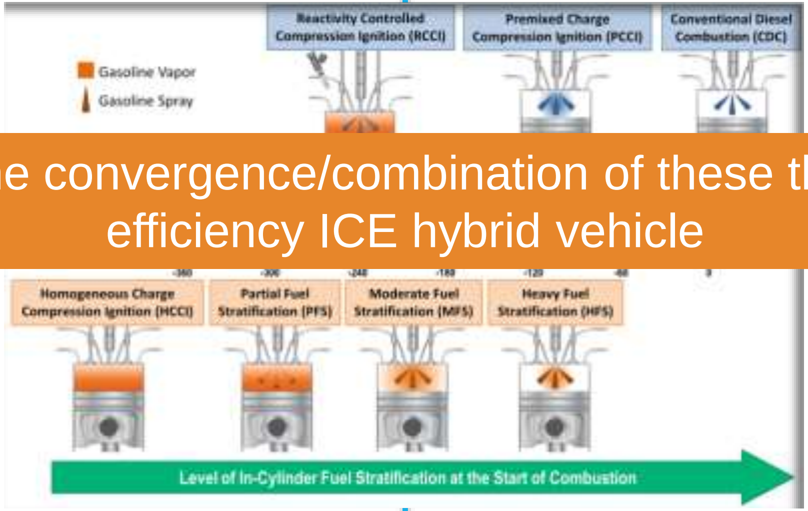
- **New Paradigm**
- Software as the differentiating factor
- Complex powertrain
- Short development cycles
- Automated operation, connected
- New models of usage – ridesharing
- New models of ownership
- Suppliers now hold more sway
- New models of monetization
- No requirement for immediate profitability

Food for thought themes for ICE hybrid…

Themes for Discussion

Engine and accessory architecture | **Advanced Combustion** | **Hybrid architectures**





Objective: We are looking for the convergence/combination of these themes to result in a future high-efficiency ICE hybrid vehicle

High-Efficiency ICE Hybrid

Source: Dempsey et al. IJER, 2016, Malikopoulos, A.A. IEEE Transactions on Intelligent Transportation Systems (2014), IAV, Valeo, FIAT, Cummins

The current electrification options: pros and cons

Battery Electric Vehicle (BEV)

85 kWh battery
~265 mi.

Fuel Cell Vehicle (FCEV)

113 kW FC
1.6 kWh battery
~312 mi.

	BEV	FCEV
Strengths	• **High round trip efficiency** • **High power** • Grid connected infrastructure • Short range, fleet operations	• **High energy density – large driving range** • **Fast charging time comparable to ICE** • Power and energy separated • Long range, heavy duty
Weaknesses	• **Limited range (range anxiety)** • **Long recharging time** • **Lithium battery safety** • Infrastructure (urban) • **Battery cost**	• **Infrastructure** • **Less mature technology** • **Lower round trip efficiency** • Hydrogen safety • **Fuel cell cost**

Power and energy coupled: range requirements lead to unused power

Power and energy decoupled: power mostly underused

arpa·e CHANGING WHAT'S POSSIBLE

Solution: hybridization with highly efficient liquid fuel cells or thermal engines

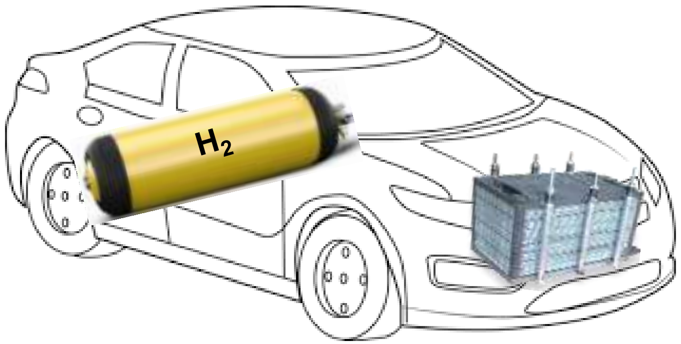
Combination of a plug-in EV with fuel cell or ICE range extender could be the optimal solution

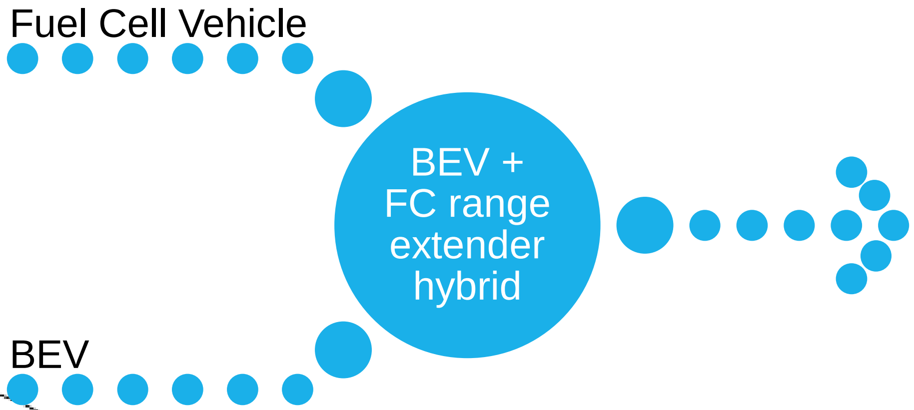
- Smaller battery provides power for acceleration at low cost, weight and space
- Smaller fuel cell stack or thermal engine provides energy for desirable driving range
- Liquid fuels allows for smaller tank sizes and using existing infrastructure

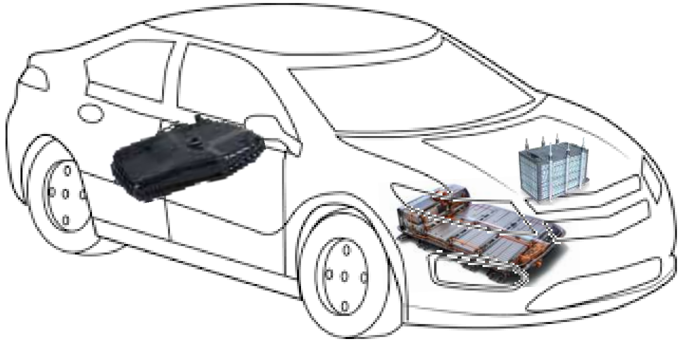
Critical needs

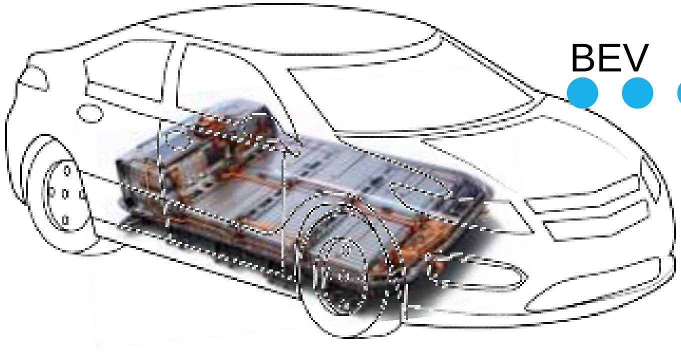
- **Fast**: short time for start-up/shut down
- **Furious**: high power density
- **Flexible**: capable to use a variety of sustainable liquid fuels

Battery/fuel cell hybrid concept









Common parts (power electronics, electric motors, inverters)

Potential fuels for direct liquid FCHEVs

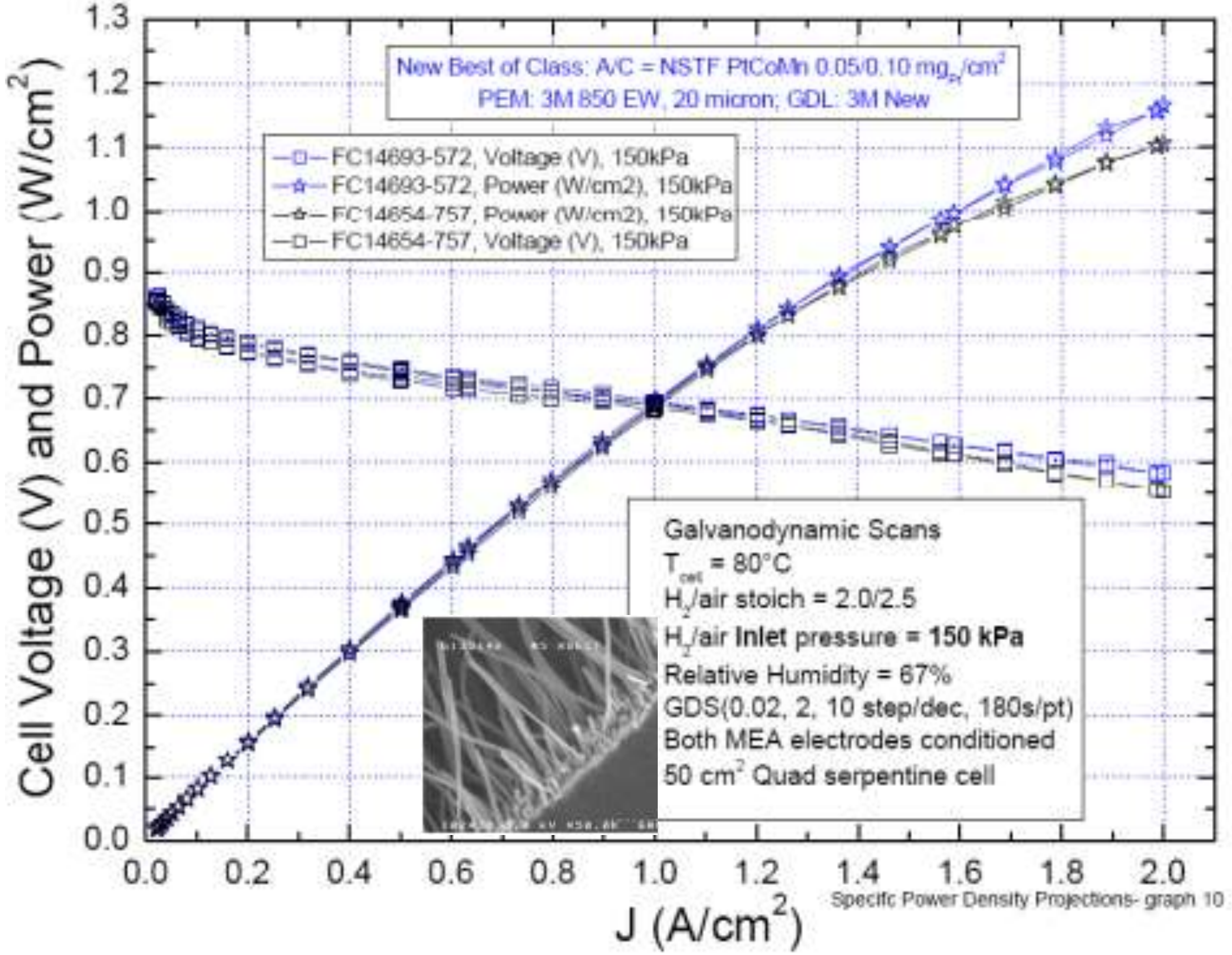
Fuel	B.p., deg C	Energy density, kWh/L	Driving range (miles)*	
			Primary (16 gal)	Extender (8 gal)
Synthetic gasoline	69-200	9.7	682	307
Biodiesel	340-375	9.2	581	291
Methanol	64.7	4.67	554	249
Dimethyl ether (DME)	-24	5.36	**632**	**284**
Ethanol	78.4	6.30	**750**	**338**
Glycerol	**290**	6.21	**736**	**330**
Formic acid (88%)	100	2.10	272	123
Ammonia	-33.3	4.32	**470**	**212**
Hydrazine hydrate	114	3.40	418	188
Liquid hydrogen	-252.9	2.54	259	116
Compressed hydrogen (700 bar)	gas	1.55	158	71

* - Fuel cell efficiency 55%, battery round trip efficiency 90%, energy consumption 0.3 kWh/mile

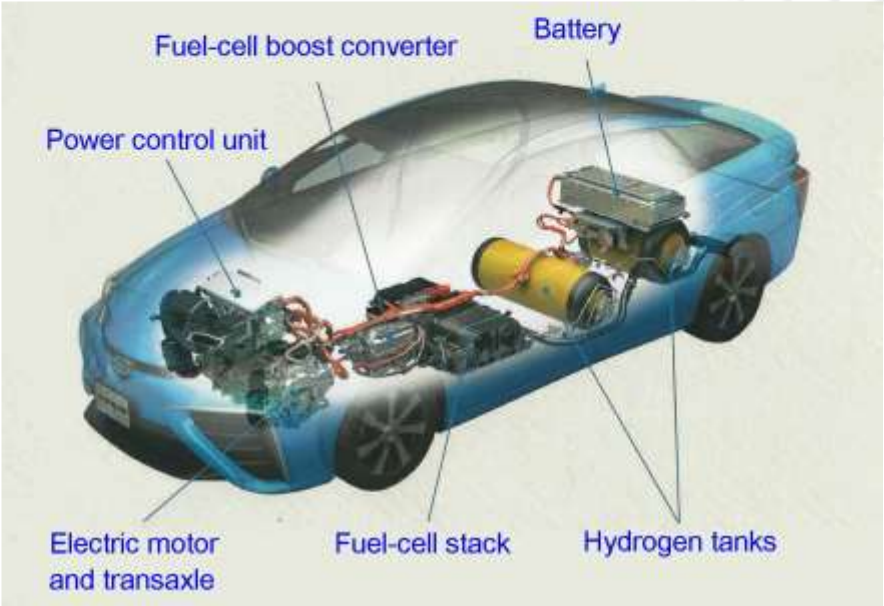
arpa·e
CHANGING WHAT'S POSSIBLE

FCEV state of the art: proton exchange membranes (PEM)

3M's NSTF shows high power at low PGM loading (<0.2g/kW) and is stable for >5000 hours



Toyota Mirai

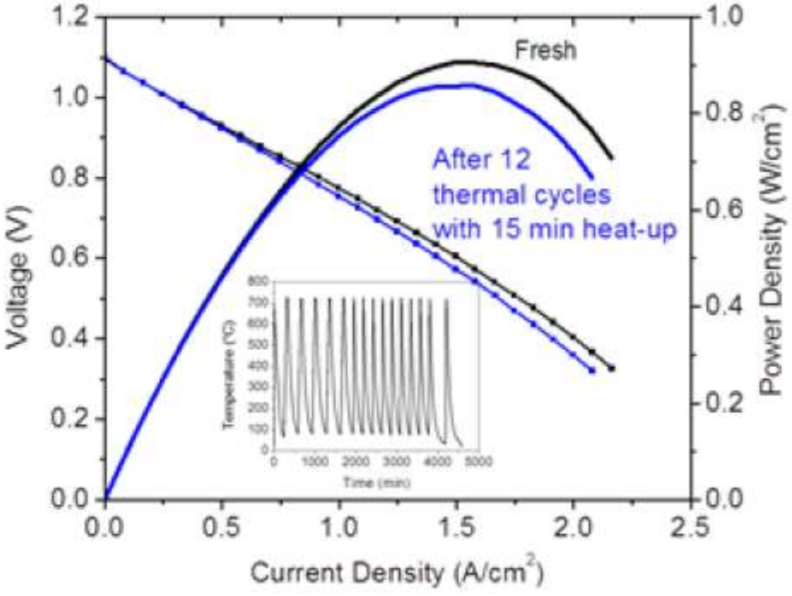


- Fuel: H2
- Battery Capacity: 1.6 kWh NiMH
- Tank Capacity: 122L+deadspace
- PEM Output: 114kW
- Driving Range: 312 miles

* Honda Clarity has very similar specs

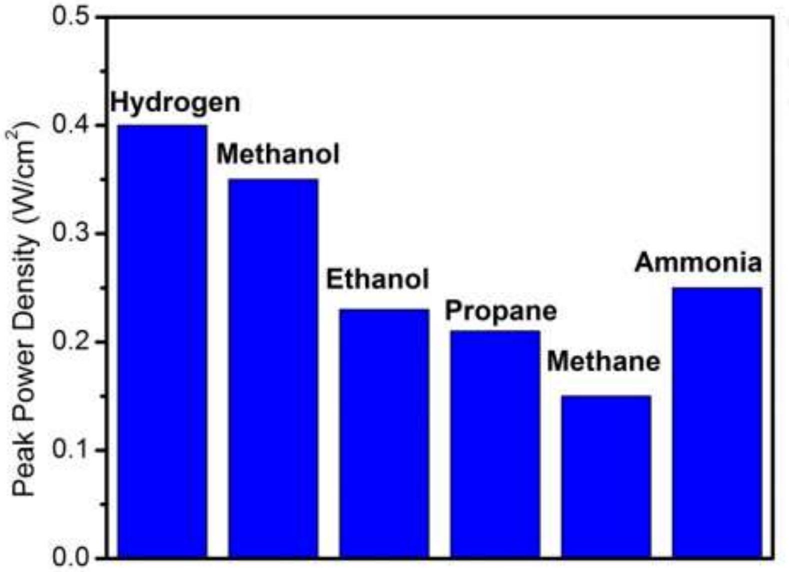
State of the art: solid oxide fuel cells (SOFCs)

LBNL metal-supported
polarization curve, 700 C



8 sec start time,
multiple thermal
cycles demonstrated

Colorado School of Mines
Peak power density, 500 C



FuelCell Energy

T (C)	Pk pwr density (W/cm2)
600	0.45
700	1.41
800	2.34

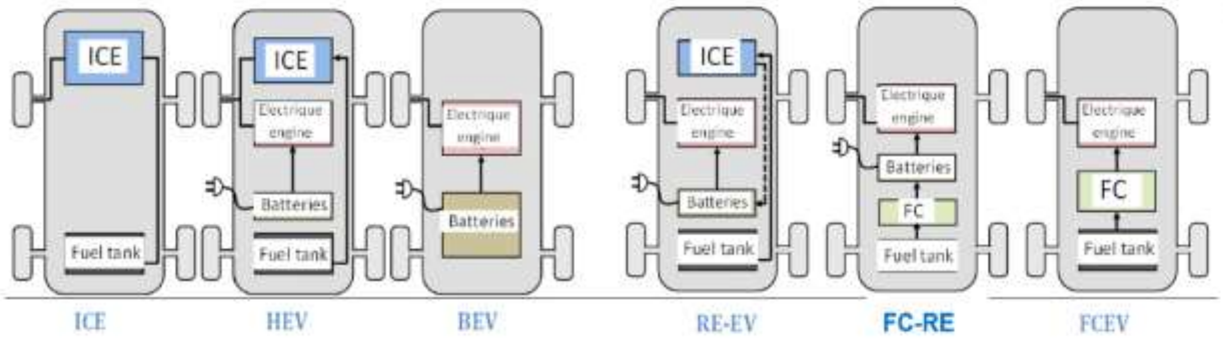
Nissan SOFC vehicle

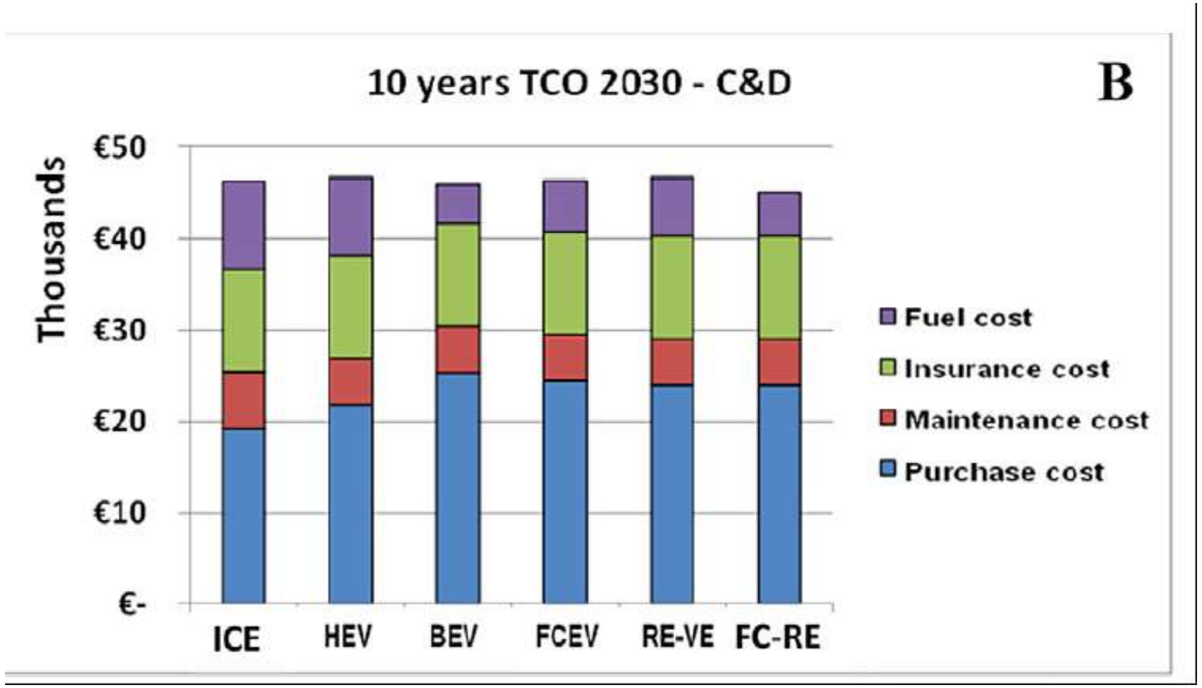
- Fuel: ethanol
- Battery Capacity: 24kWh
- Tank Capacity: 30L
- SOFC Output: 5kW
- Driving Range: 372 miles

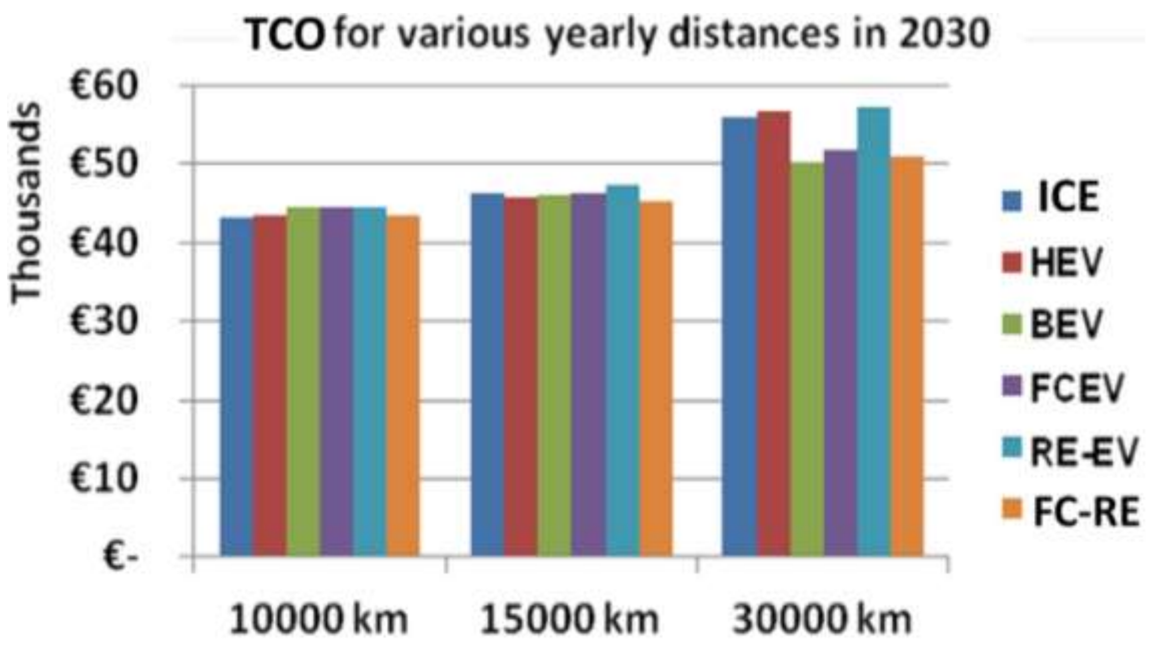
arpa·e
CHANGING WHAT'S POSSIBLE

Total cost of ownership for different vehicle configurations

- Total cost of ownership (TCO) for [standard U.S. 10k miles/yr] FC-RE is cheaper than ICE, but about the same as BEV.
- Highly dependent on H2 prices and COE







A. Le Duigou, *IJHE*, 39 (2014) 17873

FC hybrids competitive, especially at higher gasoline prices

	Generator			Tank		
	Size (kW)	Weight (kg)	Cost ($)	Size (kWh)	Weight (kg)	Cost ($)
Volt-FC10	10	29	550	82.5	46	1403
Volt-FC30	30	86	1650	82.5	46	1403
Volt-FC50	50	143	2750	82.5	46	1403
Volt-FC30L	30	86	1650	163	92	2805
Volt-ICE	62	194	1430	313	32	22

- Assumptions include $4/kgH2, $0.12/kWh COE

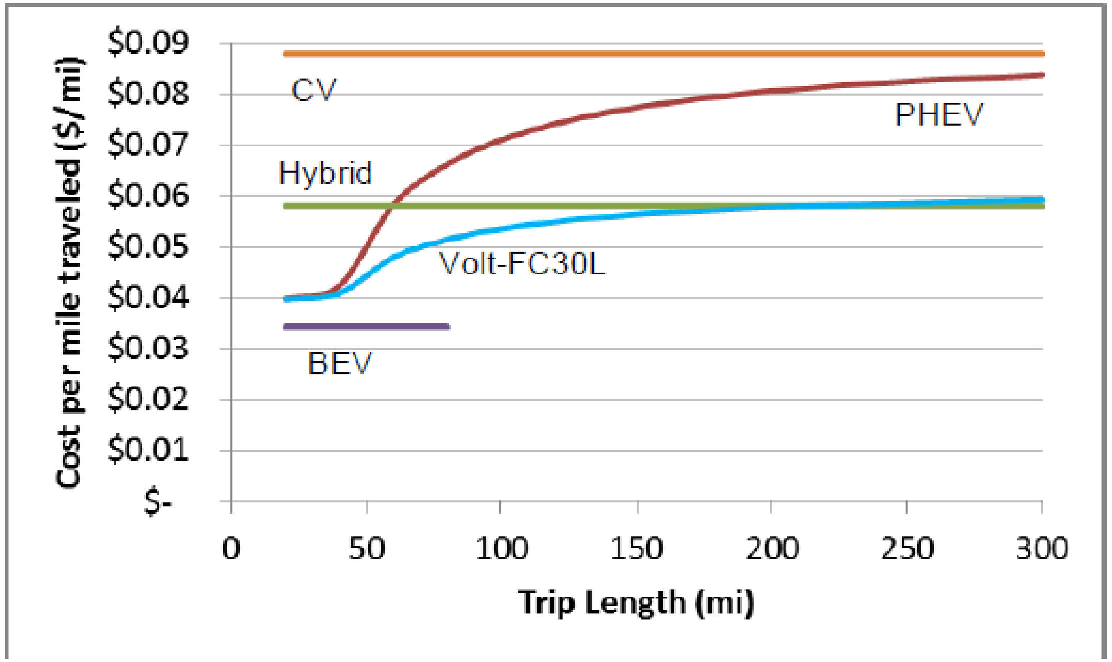
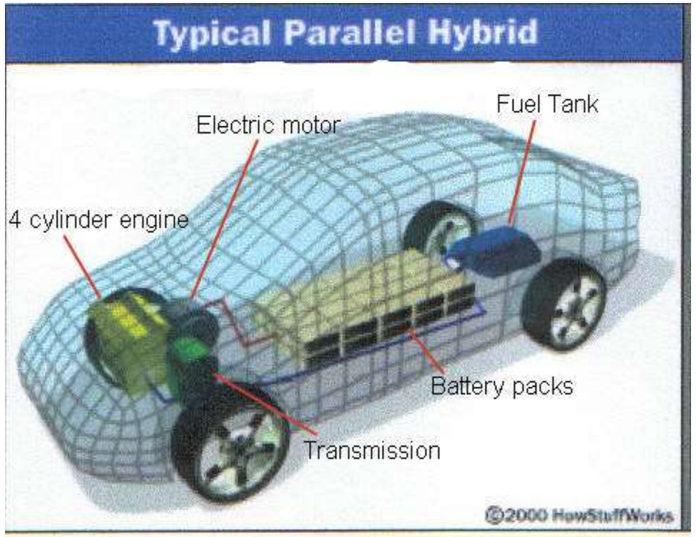
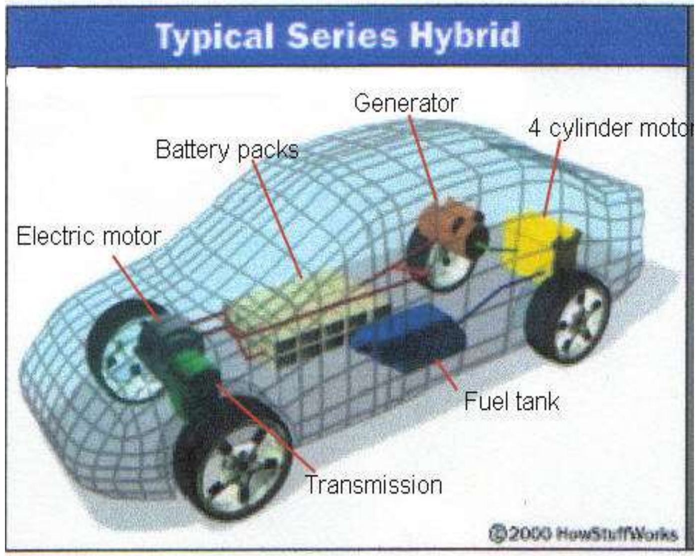


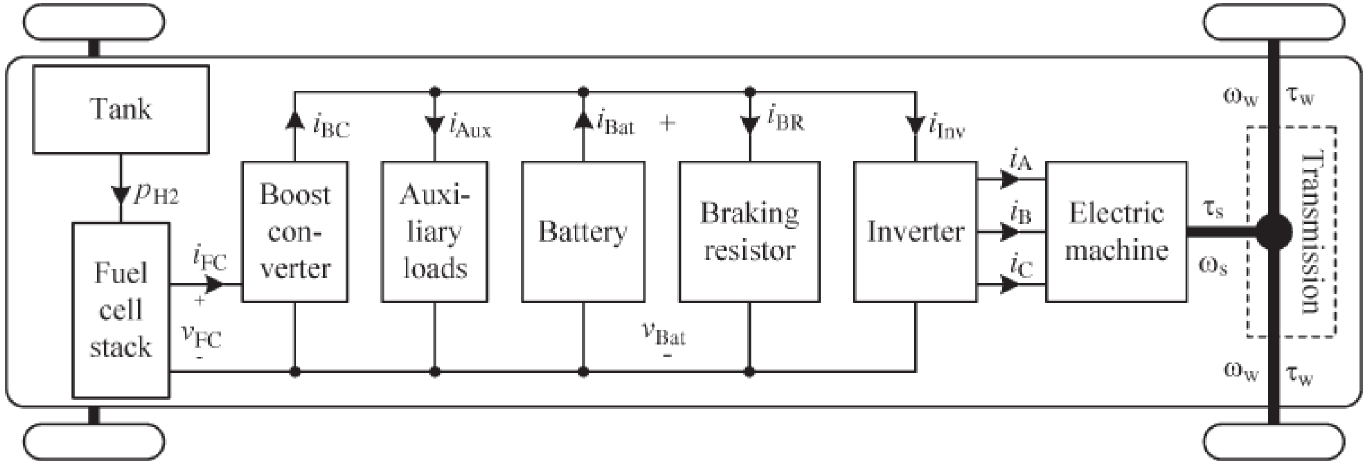
Figure 7. Cost per mile traveled for different vehicles, with gasoline at $2.90/gal

P. Brooker, U Central Florida, FSEC Report Number: FSEC-CR-1995-14 (2015)

FC direct drive vs. range extender







DESIGNED EV SETUPS USED FOR SIMULATION. MOTOR SIZE IS SPECIFIED IN CONTINUOUS POWER

Set-up	Vehicle Mass [kg]	Drive System [L]	Battery [Wh]
Range Extender	1349	121	17371
90 FCHEV	1452	344	14476
110 FCHEV	1508	397	17371
130 FCHEV	1623	496	23161
Set-up	**Fuel Cell [W]**	**Motor [W]**	**Methanol Tank [L]**
Range Extender	6021	90829	8
90 FCHEV	47514	107776	93
110 FCHEV	62043	109611	81
130 FCHEV	85014	114184	73

- FC direct drive has longer range
- FC range extender has higher efficiency, fewer Wh/mi, smaller drivetrain mass & volume

H-C B. Jensen, et al, *IEEE Trans. on Vehicular Tech.* 62, 50-60 (2013)

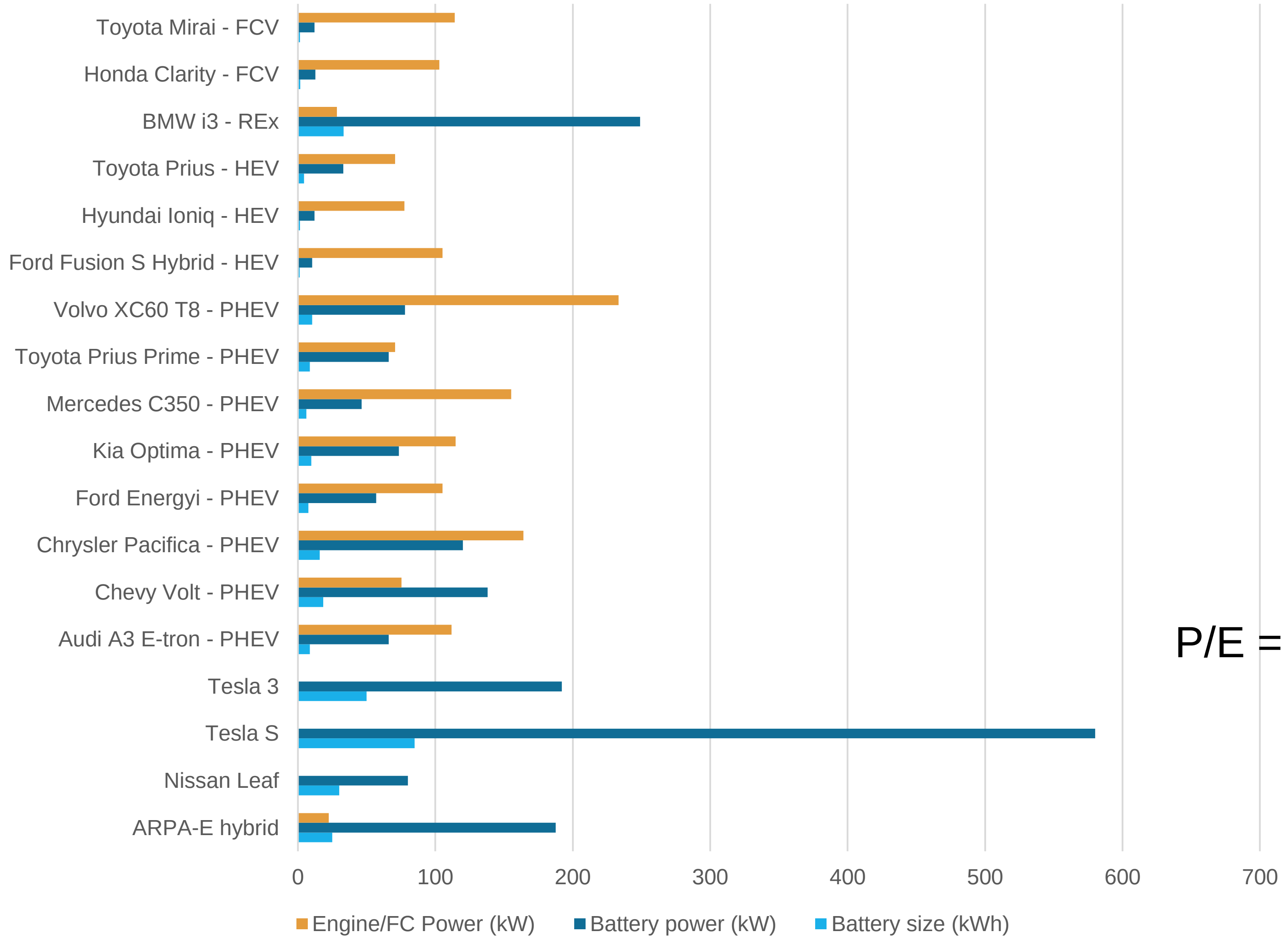
Comparison of proposed concept with BEV and FCEV

		Tesla S85	Toyota Mirai	H_2 FC hybrid	LFC hybrid	H_2 FC hybrid light	LFC hybrid light
Size of battery	kWh	85	1.6*	20	20	15	15
Size of FC stack	kW	0	114	30	30	20	20
Size of fuel tank	kWh	0	197	99	250	215	250
Battery cost	$/kWh	200		200	200	200	200
FC stack cost	$/kW		155	155	220	155	220
OUTPUT							
System mass	kg	650	144	225	192	230	146
System vol	L	1000	159	346	337	246	265
Fuel tank vol	L	-	122.4 (H2)	62.1 (H2)	51.6 (MeOH)	133.4 (H2)	51.6 (MeOH)
System cost	$	17000	25361	6624	8133	6893	5350
'Trip' Range	mi	265	312	226	466	393	449
Cost per mile	c/mi	20.3	30.2	10.4	12.1	11.3	9.4
Infrastructure							

All system level power electronics to integrate the battery and FC components are assumed to be based on FCV and not included.
*Toyota Mirai1.6 kWh NiMH battery was not included in system level costs.
Cost assumptions: H_2 tank=13$/kWh. MeOH 13 gal tank = 200$; PEM hybrid are based on scaled assumptions of S60/Mirai components.
Cost per mile assumptions: COE = 5c/kWh; $3/kg$H_2$; 0.44$/kg MeOH; 100k miles lifetime; each 'trip' was a full recharge on FC and battery.

arpa·e
CHANGING WHAT'S POSSIBLE

Engine and battery power



P/E = 7.5 assumed for PHEVs

Technical challenges

- Power density
  - Areal power density >1 W/cm^2 demonstrated, 2.3 W/cm^2 within reach
  - Volumetric energy density requires thin cells
- Start/stop cycles
  - Avoiding thermal shock requires symmetrical cells and novel stack design with internal (ohmic or combustion) heating
  - Reducing operation temperatures would reduce thermal stress and allow for using less expensive materials
- Direct liquid fuel cells
  - Sustainable fuels with high energy density (REFUEL)
  - Oxygenated fuels have less coking issues (none for ammonia)

Likely requirements

Component Requirements

- Power density comparable with hydrogen fuel cells
- Combining electrocatalysis and fuel reforming catalysis working below 550 C with no coking issues
- Non- or extremely low Pt catalysts adaptable to different liquid fuels
- No membrane crossover

System Requirements

- Power output
- Start up time
- 1000s thermal cycles with degradation less 5%
- Fuel flexibility
- Projected cost based on 30 kW stack

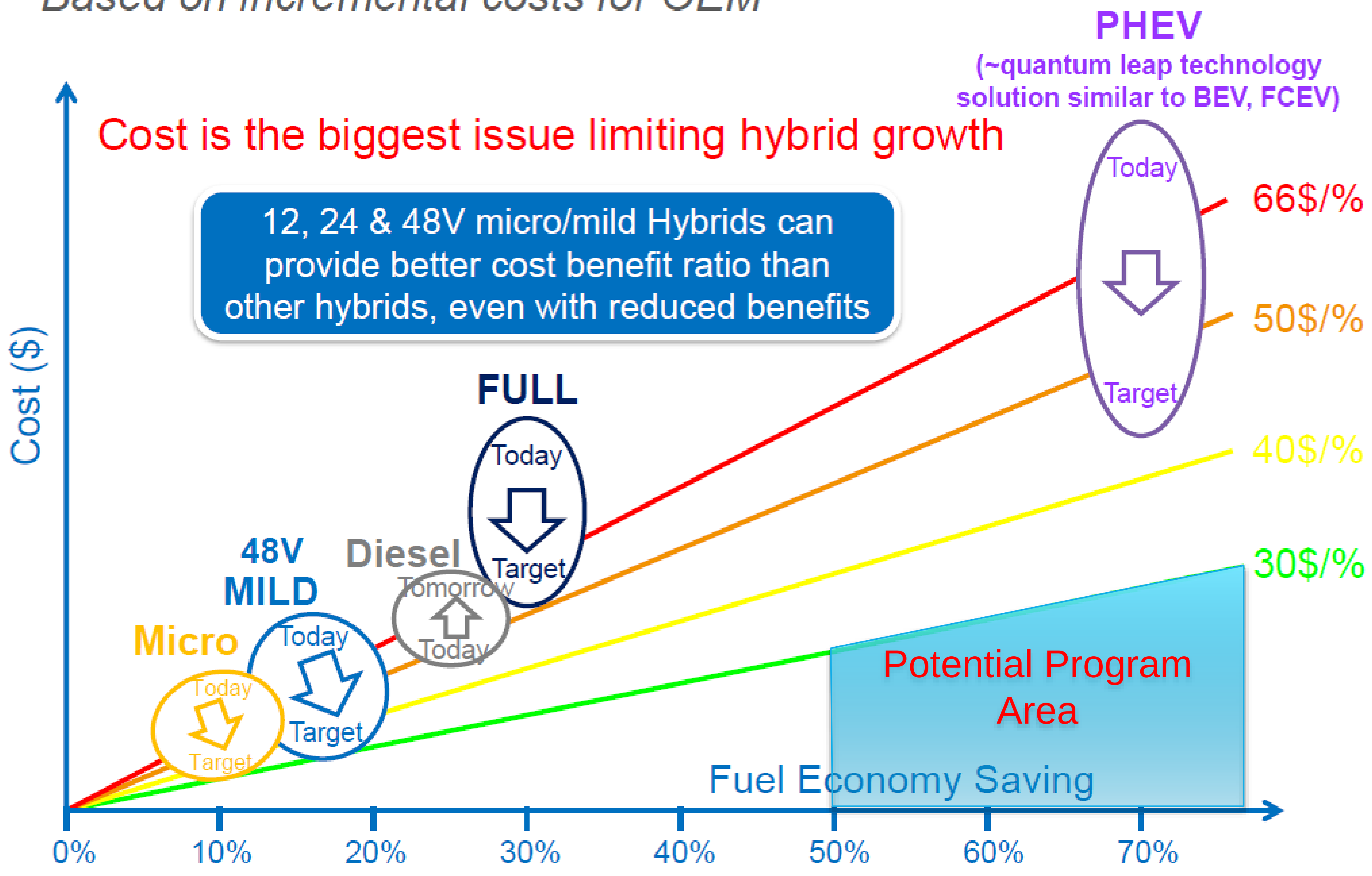
Benefits of Battery/Fuel Cell Hybridization

- Eliminates major hurdles in wide implementation of zero-emission electric vehicles
  - High cost
  - Range anxiety
  - Long charging time
  - Lack of fueling infrastructure
- Expands application space
  - Heavy- and medium-duty vehicles
  - Marine transportation
  - UAV, UUV
  - Aviation APU
- Enables shared and autonomous driving
  - More steering and computing power available

Saves 2.5 Quad energy and avoids emission of 446 MMT of CO_2 at 25% market penetration

6 Cost Benefit Ratio Challenge for Hybrids

Based on incremental costs for OEM



Current best Fuel efficiency ~ 42%

Tank-to-wheels efficiency ~ 34%

Tank-to-wheels eff. target >50%

Improvement ~ 50%

What is the purpose of this Workshop?

1. To gauge the interest of the community in these topic areas.

2. To evaluate the state of the art in the topic areas.

3. To evaluate where the technology is heading in these areas.

4. Determine sizing of battery and fuel cell/engine for different applications.

5. To establish goals and targets for a potential future funding program(s).

Workshop Objectives

- Please **<u>DO NOT</u>** discuss the following:
  - Battery Electric Vehicles (BEVs)
  - Connectivity and vehicle automation unless pertinent to range of hybrid vehicles and/or fuel storage
  - Battery development and battery chemistries
  - Development of control algorithms unless as an enabler for HEVs and PHEVs
  - CAFE and GHG emission regulations
  - Engines and fuel cells operated by gaseous fuels (i.e. CNG, Hydrogen etc.)
- Please **<u>DO NOT</u>** advertise your own technology
- For the next 2 days, this Workshop will be a BUDGET-Free and POLITICS-Free zone
- We will share the challenges of High-Efficiency Hybrid Vehicles, Fuel Cells and Engines from a purely technical point of view