Sustainable Personal Electric Transportation: EVs, PHEVs, and FCVs

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Outline of the presentation

1. Sustainable in personal transportation
2. Battery-powered vehicles EVs
3. Plug-in vehicles PHEVs
4. Fuel cell-powered vehicles FCVs
5. Comparisons of the technologies
6. Summary and conclusions

Sustainable Personal Electric Transportation

- Replaces light-duty vehicles used by individuals and families
- Driveline utilizes electric drive components
- Fuels and electricity from renewable sources

Vehicle technologies considered

- **Battery-powered EVs**
- **Plug-in hybrids PHEVs**
- **Fuel cell-powered FCVs**

Summary of the performance characteristics of lithium-ion batteries of various chemistries

Battery Developer/ Cell type	Electrode chemistry	Voltage range	Ah	Resist. mOhm	Wh/kg	W/kg 90% effic.*	W/kg Match. Imped.	Wgt. (kg)	Density gm/cm3
Enerdel HEV	Graphite/ NiMnO2	4.1-2.5	15	1.4	115	2010	6420	.445	----
Enerdel EV/PHEV	Graphite/ NiMnO2	4.1-2.5	15	2.7	127	1076	3494	.424	----
Kokam prismatic	Graphite/ NiCoMnO2	4.1-3.2	30	1.5	140	1220	3388	.787	2.4
Saft Cylind.	Graphite/ NiCoAl	4.0-2.5	6.5	3.2	63	1225	3571	.35	2.1
GAIA Cylind.	Graphite/ NiCoMnO2	4.1-2.5	40 7	.48 3.6	96 78	2063	5446 3472	1.53 .32	3.22 ---
A123 Cylind.	Graphite/Iron Phosph.	3.6-2.0	2.2	12	90	1393	3857	.07	2.2
Altairnano prismatic	LiTiO/ NiMnO2	2.8-1.5	11	2.2	70	990	2620	.34	1.83
Altairnano prismatic	LiTiO/ NiMnO2	2.8-1.5	3.8	1.15	35	2460	6555	.26	1.91
Quallion Cylind.	Graphite/ NiCo	4.2-2.7	1.8	60	144	577	1550	.043	2.6
Quallion Cylind.	Graphite/ NiCo	4.2-2.7	2.3	72	170	445	1182	.047	2.8
EIG prismatic	Graphite/ NiCoMnO2	4.2-3.0	20	3.1	165	1278	3147	.41	----
EIG prismatic	Graphite/Iron Phosph.	3.65-2.0	15	2.5	113	1100	3085	.42	---
Panasonic EV prismatic	Ni Metal hydride	7.2-5.4	6.5	11.4	46	395	1093	1.04	1.8

* power density $P = \text{Eff.}*(1-\text{Eff.})\ V_{oc}^2/R$, $P_{\text{match. imped.}} = V^2/4R$

Characteristics of lithium-ion batteries using various chemistries

Chemistry Anode/cathode	Cell voltage Max/nom.	Ah/gm Anode/cathode	Energy density Wh/kg	Cycle life (deep)	Thermal stability
Graphite/ $NiCoMnO_2$	4.2/3.6	.36/.18	100-170	2000-3000	fairly stable
Graphite/ Mn spinel	4.0/3.6	.36/.11	100-120	1000	fairly stable
Graphite/ $NiCoAlO_2$	4.2/3.6	.36/.18	100-150	2000-3000	least stable
Graphite/ iron phosphate	3.65/ 3.25	.36/.16	90-115	>3000	Stable
Lithium titanate/ Mn spinel	2.8/2.4	.18/.11	60-75	>5000	most stable

Sustainable energy for transportation

Electricity

- PV
- Wind
- Solar thermal

Bio-fuels

- Wastes
- Energy crops

Hydrogen

- Renewable electricity
- Bio-materials
- Direct solar conversion

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Battery-powered vehicles EVs

Characteristics of battery electric vehicles (EV) of various types

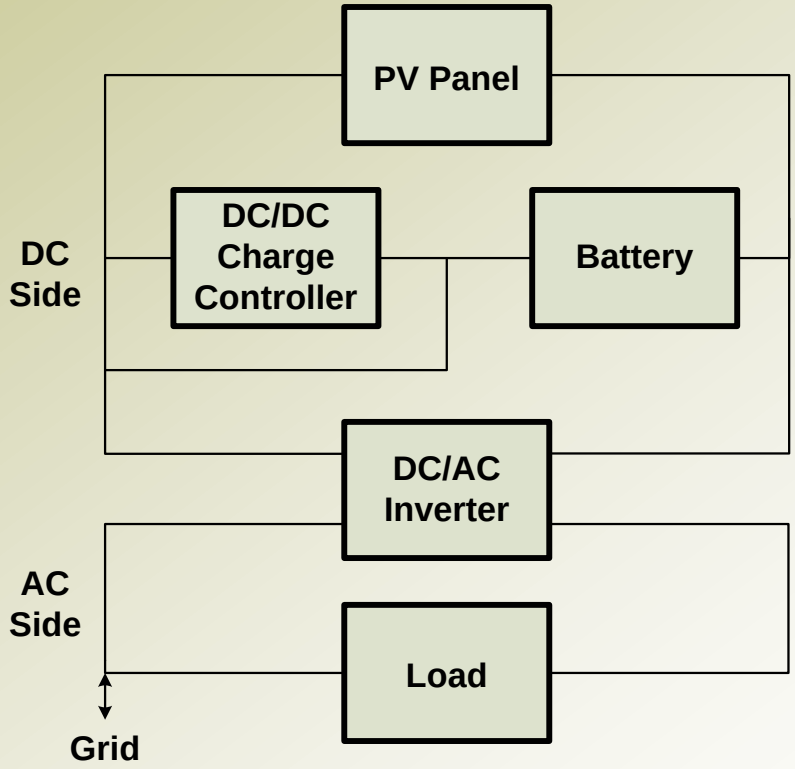
Vehicle type	Vehicle test weight kg	Battery Wgt. kg (1)	Battery kWh stored (2)	Electric motor kW (3)	Required Battery pulse power W/kg (4)	Wh/mi from battery (5)	0-60 mph Sec
Cars							
Compact	1373	168	20.2	65	387	202	11.3
Mid-size	1695	208	24.9	102	490	249	8.9
Full	1949	238	28.5	122	513	285	8.6
SUV							
Small	2103	266	31.9	128	481	319	9.6
Mid-size	2243	278	33.3	143	514	333	9.3
Full	2701	317	38.0	160	501	380	9.6

(1) Lithium-ion battery with an energy density of 120 Wh/kg
(2) All vehicles have a range of 100 miles
(3) Peak motor power
(4) Peak pulsed power required from the battery at 90% efficiency
(5) Average energy consumption on the FUDS and FHWAY drive cycles

Energy requirements of EVs

		kWh required			
Vehicle type	Wh/mi Wall-plug	Range 75 mi	Range 100 mi	Range 150 mi	Daily use 30 mi
Compact car	225	17	22	34	7
Mid-size car	280	21	28	42	9
Small SUV	350	26	35	52	10
Mid-size SUV	375	28	38	56	11

PV systems with battery energy storage



Plug-in Hybrids

- **Use both liquid fuel and wall-plug electricity**
- **Ratio of two energies depends on the all-electric range and the use pattern of the vehicle**

Battery sizing and power density for plug-in hybrid vehicles for various all-electric range and electric motor power (mid-size passenger car)

Range miles	Electric motor kW	Engine power kW	Battery kWh *needed	Battery kWh** stored	Battery kg***	Battery kW/kg
10	50	100	2.52	3.6	30	1.66
15	55	100	3.78	5.4	45	1.22
20	60	75	5.04	7.2	60	1.0
30	75	60	7.56	10.8	90	.83
40	100	50	10.1	14.4	120	.83

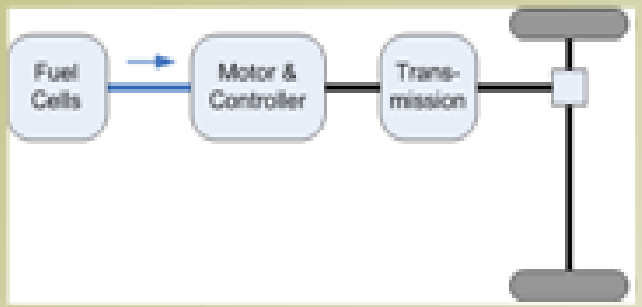
*** Vehicle energy useage from the battery: 250 Wh/mi**
**** Useable state-of-charge for batteries: 70%, weights shown are for cells only**
***** battery energy density 120Wh/kg**

For home PV would want to generate kWh needed to recharge the battery

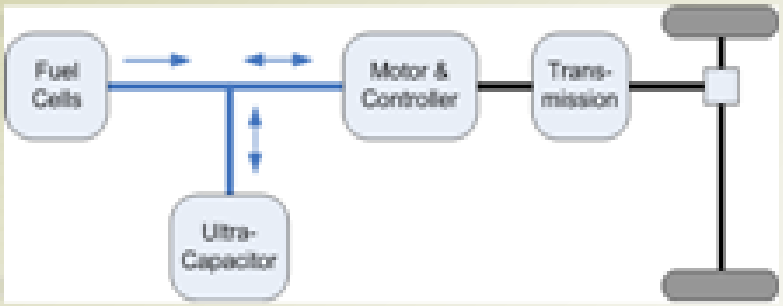
Fuel cell-powered vehicles (mid-size car)

- Hydrogen fueled – high pressure gas storage onboard the vehicle 3-4 kg H2
- PEM fuel cell 75-100 kW
- Small lithium-ion battery or ultracapacitor
- 100-125 kW electric motor
- 75-100 mpg fuel economy equivalent

Powertrain configurations for fuel cell vehicles



(a)



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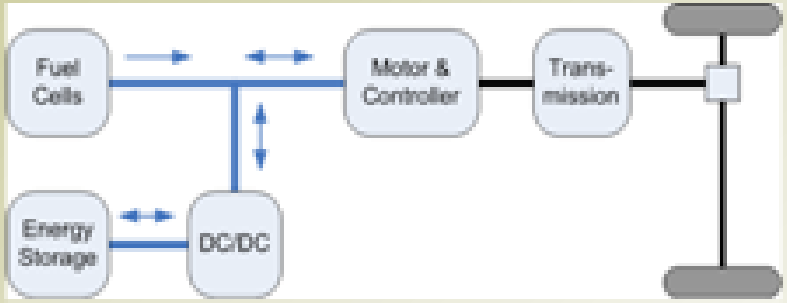

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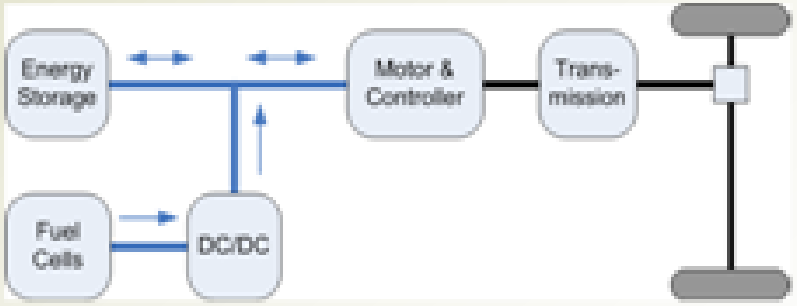
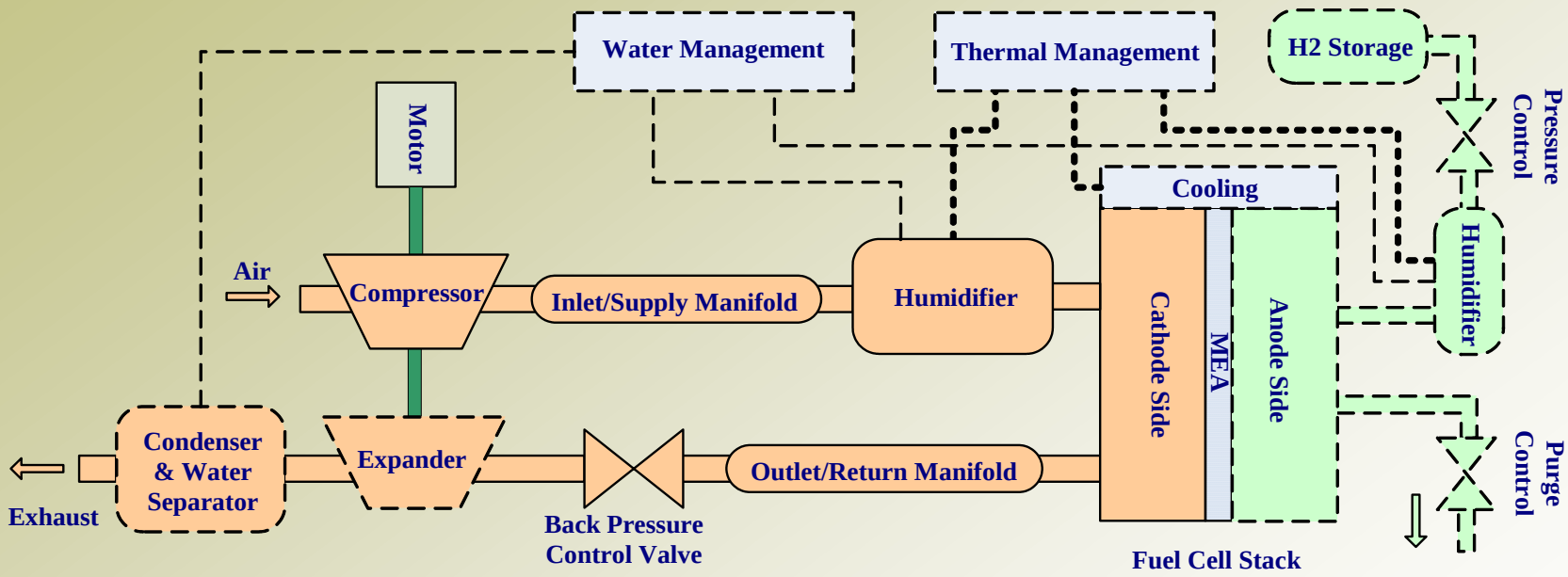


(d)

Direct hydrogen fuel cell system schematic diagram



Fuel Economy projections for fuel cell-battery vehicles

Compact SUVs

mpg

	2015		2030		2045	
	UCD	DOE	UCD	DOE	UCD	DOE
UDDS	61.2	62	74.7	73	80.8	82
HWY	60.6	59	73.0	68	78.7	77
US06	40.5	--	48.8	--	52.9	--
Vehicle Configuration	2015		2030		2045	
C_D	.37		.35		.33	
A_F (m^2)	2.9		2.94		2.94	
Fr	.0075		.007		.007	
FC (kW)	102.6		95.4		92.6	
Motor (kW)	129		110		116	
Batter (kWh)	1.15		1.05		1.05	
Vehicle Test Weight (kg)	1875		1705		1683	
Elec. Acc Load (W)	250		250		250	

SUMMARY OF COST RESULTS FOR A MIDSIZE PASSENGER CAR IN 2030

Component cost assumptions (changes in retail price of the vehicle):

Added vehicle cost to reduce drag and weight, $1,600
Advanced engine/transmission, $45/kW
Standard engine/transmission, $32/kW
Electric motor and electronics, $467 + $27.6/kW
Batteries $/kg = $/kWh x Wh/kg /1000
Fuel cell, $30/kW–$75/kW

Vehicle Configuration	Real-World mpg	Battery Inputs			Energy Saved	Vehicle Cost Differential	Discounted Break-even Gas Price
		$/kWh	Wh/kg	$/kg			
Baseline vehicle 2007	27.1						
Adv. ICE	47.8				.43	$3095	$3.62/gal[1]
HEV	71.1	1000	70	70	.62	$3204	$2.61/gal[1]
		800	70	56		$3003	$2.45/gal[1]
		600	70	42		$2802	$2.29/gal[1]
PHEV-20	75.3[4]	800	100	80	.65	$6409	$5.03/gal[1]
							$3.64/gal[2]
		600	100	60		$5605	$4.40/gal[1]
							$3.19/gal[2]
		400	100	40		$4801	$3.77/gal[1]
							$2.73/gal[2]
PHEV-40	127[5]	700	150	105	.79	$10,228	$6.58/gal[1]
							$4.77/gal[2]
		500	150	75		$8218	$5.29/gal[1]
							$3.83/gal[2]
		300	150	45		$6208	$3.99/gal[1]
							$2.89/gal[2]
FCHEV	89.8						
$75/kW FC		800	70	56	.70	$7549	$5.47/gal[1]
							$3.31/gal[3]
$50/kW FC		800	70	56		$5549	$4.02/gal[1]
							$2.43/gal[3]
$30/kW FC		800	70	56		$3949	$2.86/gal[1]
							$1.73/gal[3]
Battery electric BEV	Equiv. 176						
Range 100 mi.		$700	170	119	.77 wallplug	20294	10.72 (1) 8.09 (3)
		$500	170	85		14694	7.90 (1) 6.04 (3)
		$300	170	47		9094	5.06 (1) 3.99 (3)

Notes:
1. 5 years and 4% discount rate, 12,000 miles/yr
2. 10 years and 10% discount rate, 12,000 miles/yr
3. 10 years and 6% discount rate, 12,000 miles/yr

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2030 Breakeven fuel price $/gal gasoline equiv.

Vehicle design	2007 ICE baseline		Adv. ICE baseline		HEV baseline	
Battery electric *						
5 yr at 4% disc						
. battery cost $/kWh	**w/o disc.**	**with disc**	**w/o disc.**	**with disc**	**w/o disc.**	**with disc**
700	9.57	10.72	14.43	16.16	21.50	24.08
500	7.05	7.90	9.97	11.17	14.91	16.70
300	4.52	5.06	5.50	6.17	8.28	9.27
10 yr at 10% disc						
. battery cost $/kWh	**w/o disc.**	**with disc**	**w/o disc.**	**with disc**	**w/o disc.**	**with disc**
700	4.99	8.09	7.58	12.28	11.31	18.30
500	3.72	6.04	5.35	8.67	7.99	12.94
300	2.46	3.99	3.12	5.05	4.63	7.50
PHEV large battery **						
5 yr at 4% disc						
battery cost $/kWh	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**
700	5.6	6.27	8.07	9.04	14.1	15.79
500	4.55	5.10	6.0	6.72	10.45	11.70
300	3.51	3.93	3.9	4.37	6.8	7.62
10 yr at 10% disc						
battery cost $/kWh	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**
700	2.94	4.76	4.32	7.00	7.54	12.22
500	2.42	3.92	3.27	5.30	5.71	9.25
300	1.89	3.06	2.22	3.60	3.88	6.29
Fuel cell HEV***						
5 yr at 4% disc						
fuel cell cost $/kW	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc**
75	5.07	5.68	6.48	7.26	9.62	10.77
50	4.16	4.66	4.88	5.47	7.25	8.12
30	3.44	3.85	3.61	4.04	5.36	6.00
10 yr at 10% disc						
fuel cell cost $/kW	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**	**w/o disc.**	**with disc.**
75	3.06	4.96	4.17	6.76	6.19	10.02
50	2.61	4.23	3.37	5.46	5.00	8.10
30	2.25	3.64	2.73	4.42	4.06	6.58

*** electric cost 8¢/kWh; 12000 miles/yr.**

**** 65% of miles on electricity, 12,000 miles/yr.**

***** fuel cell cost includes hydrogen storage at $10/kWh, 4 kg H2; $3.5/kg H2**

Summary and conclusions

- **Sustainability is feasible using electrified powertrains**
- **Battery-powered EVs and distributed PV are the most near-term technologies for sustainability**
- **Plug-in vehicles (PHEVs) with all-electric range of 30-40 miles and distributed PV are an alternative**
- **Battery costs of $200-300/kWh are needed for market competitiveness with ICE and HEVs**
- **Fuel cell vehicles are a long term option and offer sustainability if the hydrogen is produced using renewable sources**

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