

Well-to-Wheels Energy Use and Greenhouse Gas Emissions of Plug-In Hybrid Electric Vehicles

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Scope of Argonne's PHEV WTW Analysis: Vehicle Powertrain Systems and Fuel Pathways

- Vehicle powertrain systems:
 - Conventional international combustion engine vehicles (ICEVs)
 - Regular hybrid electric vehicles (HEVs)
 - ➤ Plug-in hybrid electric vehicles (PHEVs) with all electric range (AER) of 10-40
 - ✓ Internal combustion engines (ICEs)
 - ✓ Fuel cells (FCs)
 - Electric vehicles (EVs)
- ☐ Fuel options:
 - > Petroleum
 - √ Gasoline
 - ✓ Diesel
 - > E85 with ethanol from
 - ✓ Corn
 - ✓ Switchgrass
 - > Electricity:
 - ✓ Marginal generation mixes in four regions
 - ✓ Average generation mixes of the U.S., CA, and Northeast U.S.
 - > Hydrogen
 - ✓ Distributed production from NG-SMR
 - ✓ Central production from switchgrass

Argonne's WTW Analysis Addresses PHEV Key Issues in Details

- PHEV performance evaluation
 - > Split design for PHEV10 and 20; series design for PHEV30 and 40
 - On-road adjusted fuel economy for each mode of operation
 - On-road adjusted electric range (AER)
- ☐ In-house simulations of electricity generation mixes in different utility regions to charge PHEVs
 - Distributed EIA's national vehicle stock projections to states
 - > Analyzed distribution of vehicles by last trip ending time for each region
 - Generated PHEVs load profiles in each region for three charging scenarios
- ☐ PHEV mileage shares by power source
 - > Determined VMT shares by grid power and on-board power from on-road AER



Fuel and Electricity Consumption of PHEVs



PSAT Simulation Results Were Processed for This Analysis

- PSAT fuel economy simulations results for these vehicle types were used
 - > ICEV: Gasoline, E85, Diesel
 - ➤ HEV: Gasoline, E85, Diesel; Hydrogen FC (250 mi on UDDS)
 - > PHEV: Gasoline, E85, Diesel; Hydrogen FC
 - > EV (150 mi on UDDS)
- PHEV configuration options
 - Power-Split configuration for AER of 10 and 20 miles (FC-PHEVs are series hybrids)
 - ➤ <u>Series</u> configuration for AER of 30 and 40 miles
- MY 2015 midsize car for 10% PHEV penetration by 2020
- Lab-based fuel economy values from PSAT were adjusted to on-road values for this analysis
- ☐ PHEV miles driven by grid electricity and on-board power
 - On-road AER, instead of design AER, was used
 - ➤ Data from the 2001 National Household Travel Survey was employed to estimate daily VMT share of PHEVs in CD mode (utility factor)



PSAT <u>Lab-Based</u> Fuel Economy Results (Miles of Gasoline Equivalent Gallon, Wh/Mile for Electric Operation)

Unadjusted Wh/mi and mpgge		AER 0	AER 10 Split Design			AER 20 Split Design			AER 30 Series Design			AER 40 Series Design		
		_		CD Engine	CS Engine	CD Electric	CD Engine	CS Engine	CD Electric	CD Engine	CS Engine	CD Electric	CD Engine	CS Engine
UDDS	30.5	55.2	191	222	60.7	193	206	60.25	244	250	41.2	254	555	40.5
HWFET	44.9	49.1	212	98.6	53.7	211	132	53.21	262	850	42.1	264	1030	41.6
UDDS		51.4	191	208	56.6	192	192	56.2	244	232	38.2	254	512	37.5
HWFET		45.7	212	91.5	49.8	211	123	49.5	262	796	39.5	264	974	39.0
UDDS		57.9	198	238	60.8	202	203	60.5	248	274	43.9	256	577	43.2
HWFET		51.1	223	101	53.1	214	135	52.9	267	1100	43.0	266	1150	42.6
UDDS		72.8	210	211	75.4	214	196	74.4	244	457	72.8	248	877	71.6
HWFET		75.9	248	139	75.8	255	645	75.0	262	1510	73.3	264	1290	72.5
	UDDS HWFET UDDS HWFET UDDS	UDDS 30.5 HWFET 44.9 UDDS HWFET UDDS HWFET	mpgge Regular Hybrid UDDS 30.5 55.2 HWFET 44.9 49.1 UDDS 51.4 HWFET 45.7 UDDS 57.9 HWFET 51.1 UDDS 72.8	mpgge Regular Hybrid CD Electric UDDS 30.5 55.2 191 HWFET 44.9 49.1 212 UDDS 51.4 191 HWFET 45.7 212 UDDS 57.9 198 HWFET 51.1 223 UDDS 72.8 210	mpgge Split Design Regular Hybrid CD Electric Engine UDDS 30.5 55.2 191 222 HWFET 44.9 49.1 212 98.6 UDDS 51.4 191 208 HWFET 45.7 212 91.5 UDDS 57.9 198 238 HWFET 51.1 223 101 UDDS 72.8 210 211	mpgge Split Design Regular Hybrid CD Electric Engine Engine Engine UDDS 30.5 55.2 191 222 60.7 HWFET 44.9 49.1 212 98.6 53.7 UDDS 51.4 191 208 56.6 HWFET 45.7 212 91.5 49.8 UDDS 57.9 198 238 60.8 HWFET 51.1 223 101 53.1 UDDS 72.8 210 211 75.4	mpgge Split Design Segular Regular Hybrid CD Electric Engine Engine Electric CD Engine Engine Electric CD Engine Engine Electric CD Electric CD Engine Engine Electric CD Electric CD Electric CD Engine Engine Electric CD Electric CD Engine Electric CD Electric CD Engine Electric CD Electric CD Electric CD Engine Engine Electric CD E	mpgge Split Design Split Design Split Design Regular Hybrid CD CD Electric Engine Engine Engine Electric Engine CD Electric Engine Engine Electric Engine UDDS 30.5 55.2 191 222 60.7 193 206 HWFET 44.9 49.1 212 98.6 53.7 211 132 UDDS 51.4 191 208 56.6 192 192 HWFET 45.7 212 91.5 49.8 211 123 UDDS 57.9 198 238 60.8 202 203 HWFET 51.1 223 101 53.1 214 135 UDDS 72.8 210 211 75.4 214 196	Split Design Split Design Regular Hybrid CD Electric Electric Engine Electric CD Engine Engine Engine Engine CD Electric Engine Engine Engine CD Electric Engine Engine CD Engine Engine Engine UDDS 30.5 55.2 191 222 60.7 193 206 60.25 HWFET 44.9 49.1 212 98.6 53.7 211 132 53.21 UDDS 51.4 191 208 56.6 192 192 56.2 HWFET 45.7 212 91.5 49.8 211 123 49.5 UDDS 57.9 198 238 60.8 202 203 60.5 HWFET 51.1 223 101 53.1 214 135 52.9 UDDS 72.8 210 211 75.4 214 196 74.4	Impage Split Design Split Design Set Regular Hybrid CD Electric Engine Electric Engine Electric Engine Electric Engine Electric CD Engine Electric Engine Electric CD Engine Engine Electric CD Engine Engine Electric UDDS 30.5 55.2 191 222 60.7 193 206 60.25 244 HWFET 44.9 49.1 212 98.6 53.7 211 132 53.21 262 UDDS 51.4 191 208 56.6 192 192 56.2 244 HWFET 45.7 212 91.5 49.8 211 123 49.5 262 UDDS 57.9 198 238 60.8 202 203 60.5 248 HWFET 51.1 223 101 53.1 214 135 52.9 267 UDDS 72.8 210 211 75.4 214 196 74.4 244	Impgge Split Design Split Design Series Design Regular Hybrid CD CD Electric Engine Engine Electric Elect	Impgge Split Design Split Design Series Design Regular Hybrid CD CD Engine Engine CD Engine Engi	Regular CD CD CS CD CD CS CD CD	Regular CD CD CS CD CD Electric Engine Electric

CD Electric = charge depleting operation with grid electricity



UDDS

HWFET

ΕV

267

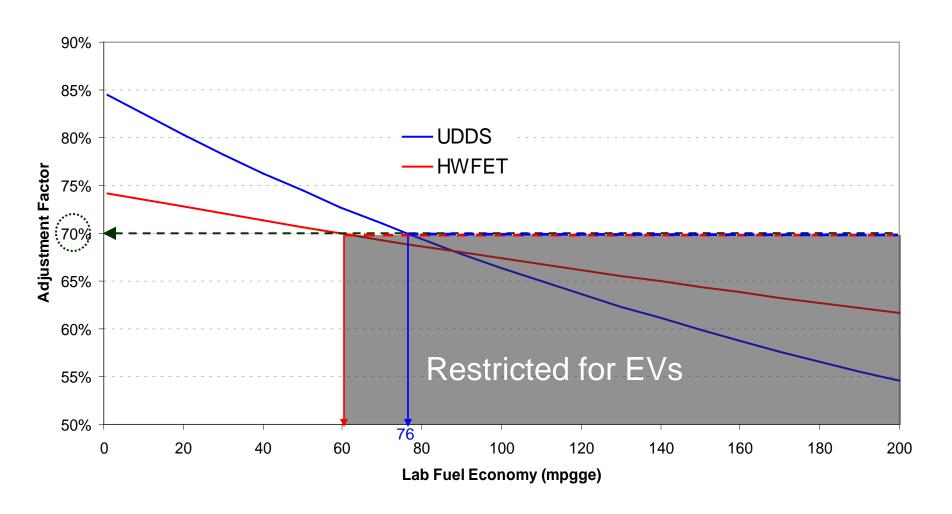
[•] CD Engine = charging depleting operation with on-board power systems (ICE Engine or Fuel Cell)

[•] CS = charge sustaining operation with on-board power systems

UDDS = Urban Dynamometer Driving Schedule; HWFET = Highway Fuel Economy Test

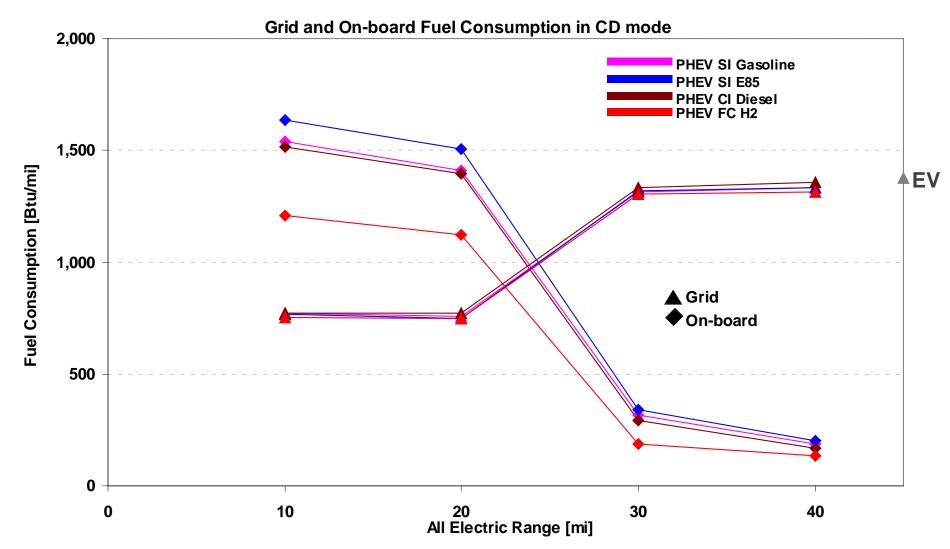
On-Road Adjustment Factor for Lab Fuel Economy: EPA's MPG-Based Formulae

On-road Adjustment Factor as a Function of Fuel Economy



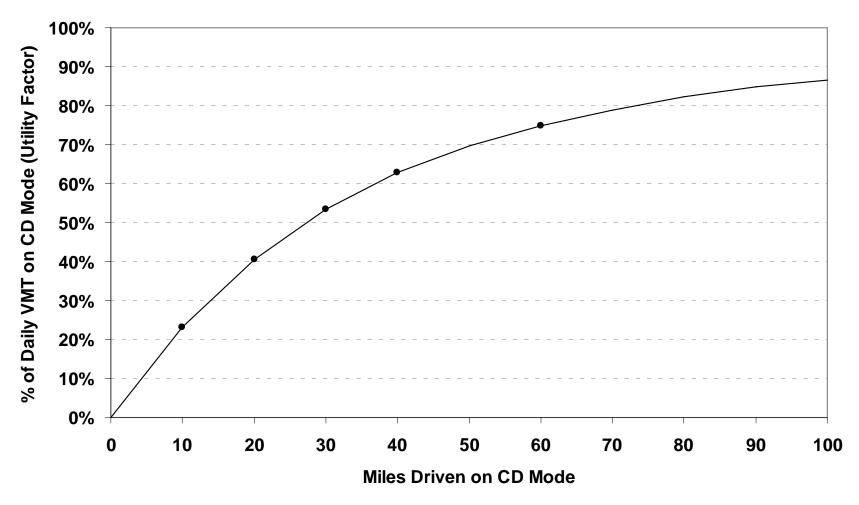


On-road Fuel Consumption by Technology and AER: Grid and On-board Energy Use Under the <u>CD Operation</u>



Note: the two energy sources are combined to serve a given mile.

PHEVs with 20-Mile on CD Mode Account (on the average) For 40% of Daily VMT, PHEVs with 40-Mile More than 60%

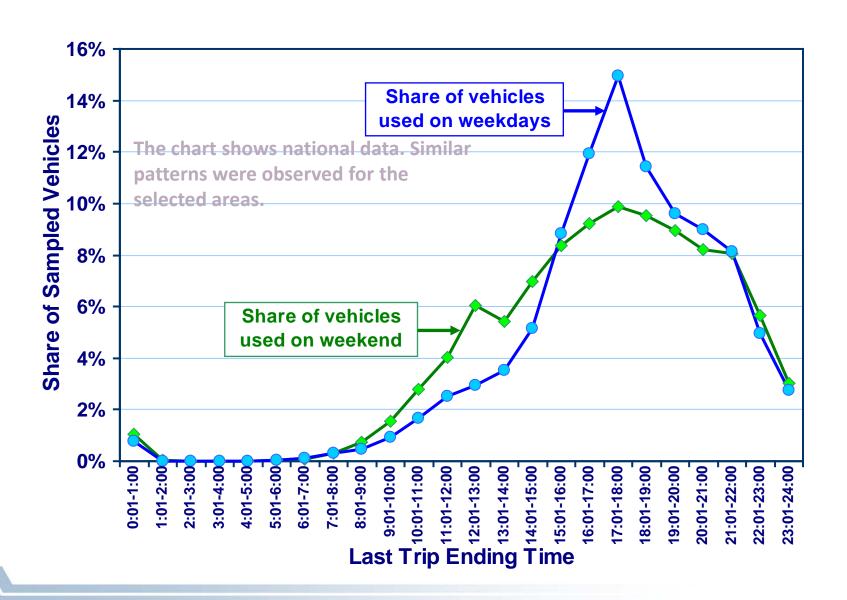


fuel consumption for charge depleting and charge sustaining operations were combined using the utility factor (UF)

$$\rightarrow$$
 (FC_{CDGrid} + FC_{CDICE})* UF + FC_{CS} * (1-UF)

Electric Load Profiles with and without PHEVs

Weekday Last Vehicle Trip Ending Time Shows a Peak At 5-6 PM

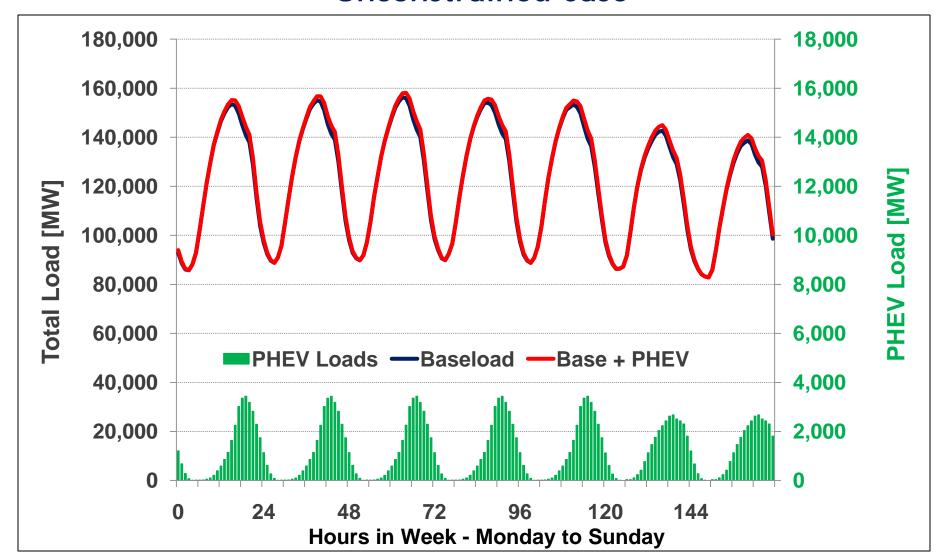


Key Factors Determining Electricity Generation Mix to Charge PHEVs Are Considered in Argonne's Analysis

- ☐ What is the total electric load from PHEVs?
 - > PHEV market penetration: 10% on-road fleet for 2020
 - > Distribution of AER and vehicle class of PHEVs (battery useable energy)
 - One full charge per day per PHEV
- What time of the day are PHEVs being charged?
 - > Three charging scenarios were developed
 - ✓ Unconstrained charging: charging begins at the last trip ending time
 - ✓ Alternative charging scenarios
 - Smart charging (filling valley of load during off-peak hours)
 - Delaying PHEV charging by 3 hours
- ☐ Implications of electric generation capacity in a given region
 - ✓ NE-ISO*, NY-ISO, IL, WECC, CA, WECC excluding CA
- ☐ Specific generating units to be dispatched for PHEV charging to determine marginal generation mix for PHEVs



WECC Load Profile for a Typical Summer Week in 2020 Unconstrained Case



2020 Generation Mixes for PHEV Recharge - Unconstrained Charging (with Added Capacity to Cover PHEV Load)

		NE-I	ISO			NY-I	SO		IL			
	Baseline w/o	with PHEV	Difference		Baseline w/o	with PHEV	Difference		Baseline w/o	with PHEV	Difference	
	PHEV Load	Load	by PHEV	Marginal	PHEV Load	Load	by PHEV	Marginal	PHEV Load	Load	by PHEV	Marginal
	(GWh)	(GWh)	Load (GWh)	Mix	(GWh)	(GWh)	Load (GWh)	Mix	(GWh)	(GWh)	Load (GWh)	Mix
Coal												
Utility Boiler / IGCC	21,147	21,147	0	0.0%	20,980	20,980	0	0.0%	95,213	97,237	2,023	67.2%
Natural Gas			1	4000								Section 2
Utility Boiler	190	179	-11	-0.5%	20,359	20,092	-266	-12.7%	156	177	20	0.7%
Combined Cycle	68,502	70,770	2,268	102.0%	58,781	61,183	2,401	114.5%	3,087	3,768	680	22.6%
Simple Gas Turbine	3,716	4,230	514	23.1%	4,649	4,576	-73	-3.5%	4,249	4,512	264	8.8%
Residual Oil				James .				"Property"				
Utility Boiler	5,552	5,020	-532	-23.9%	2,422	2,445	23	1.1%	195	231	36	1.2%
Nuclear	31,787	31,787	0	•0.0%	42,835	42,835	0	0.0%	74,658	74,672	13	0.4%
Biomass												
Utility Boiler / IGCC	7,646	7,644	-2	-0.1%	25,553	25,552	0	0.0%			0	0.0%
Other												
Renewable	6,756	6,744	-12	-0.6%	25,976	25,987	12	0.6%	37,082	37,054	-28	-0.9%
Total	145,298	147,521	2,224	100.0%	201,554	203,651	2,097	100.0%	214,641	217,650	3,009	100.0%
		CA + I				WECC v	w/o CA			WECC	Total	
	Baseline w/o		Difference		Baseline w/o	with PHEV	Difference		Baseline w/o		Difference	
	PHEV Load	with PHEV Load		Marginal	Baseline w/o PHEV Load	with PHEV Load		Marginal	Baseline w/o PHEV Load	with PHEV Load		Marginal
		with PHEV	Difference	_		with PHEV	Difference	Marginal Mix		with PHEV	Difference	Marginal Mix
Coal	PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	Mix	PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	Mix	PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	Mix
Utility Boiler / IGCC	PHEV Load (GWh)	with PHEV Load	Difference by PHEV	_	PHEV Load	with PHEV Load	Difference by PHEV	Mix 42.0%	PHEV Load	with PHEV Load	Difference by PHEV	_
Utility Boiler / IGCC Natural Gas	PHEV Load (GWh) 21,890	with PHEV Load (GWh) 20,141	Difference by PHEV Load (GWh) -1,749	Mix -27.6%	PHEV Load (GWh) 302,633	with PHEV Load (GWh) 304,458	Difference by PHEV Load (GWh) 1,826	Mix 42.0%	PHEV Load (GWh) 324,522	with PHEV Load (GWh) 324,599	Difference by PHEV Load (GWh)	Mix 0.7%
Utility Boiler / IGCC Natural Gas Utility Boiler	PHEV Load (GWh) 21,890 40,886	with PHEV Load (GWh) 20,141 41,641	Difference by PHEV Load (GWh) -1,749 755	Mix -27.6%	PHEV Load (GWh) 302,633 4,597	with PHEV Load (GWh) 304,458 4,601	Difference by PHEV Load (GWh) 1,826	Mix 42.0%	PHEV Load (GWh) 324,522 45,483	with PHEV Load (GWh) 324,599 46,242	Difference by PHEV Load (GWh) 77 759	0.7%
Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle	PHEV Load (GWh) 21,890 40,886 129,989	with PHEV Load (GWh) 20,141 41,641 136,819	Difference by PHEV Load (GWh) -1,749 755 6,830	Mix -27.6% -11.9% 107.7%	PHEV Load (GWh) 302,633 4,597 11,303	with PHEV Load (GWh) 304,458 4,601 13,793	Difference by PHEV Load (GWh) 1,826 4 2,490	Mix 42.0% 9.1% 57.3%	PHEV Load (GWh) 324,522 45,483 141,292	with PHEV Load (GWh) 324,599 46,242 150,612	Difference by PHEV Load (GWh) 77 759 9,320	0.7% 7.1% 87.2%
Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle Simple Gas Turbine	PHEV Load (GWh) 21,890 40,886 129,989	with PHEV Load (GWh) 20,141 41,641	Difference by PHEV Load (GWh) -1,749 755	Mix -27.6%	PHEV Load (GWh) 302,633 4,597	with PHEV Load (GWh) 304,458 4,601	Difference by PHEV Load (GWh) 1,826	Mix 42.0%	PHEV Load (GWh) 324,522 45,483	with PHEV Load (GWh) 324,599 46,242	Difference by PHEV Load (GWh) 77 759	0.7% 7.1% 87.2%
Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle Simple Gas Turbine Residual Oil	PHEV Load (GWh) 21,890 40,886 129,989 7,471	with PHEV Load (GWh) 20,141 41,641 136,819 8,019	Difference by PHEV Load (GWh) -1,749 755 6,830 548	Mix -27.6% -11.9% 107.7% 8.6%	PHEV Load (GWh) 302,633 4,597 11,303 1,049	with PHEV Load (GWh) 304,458 4,601 13,793 1,072	Difference by PHEV Load (GWh) 1,826 4 2,490 23	Mix 42.0% 0.1% 57.3%	PHEV Load (GWh) 324,522 45,483 141,292 8,521	with PHEV Load (GWh) 324,599 46,242 150,612 9,091	Difference by PHEV Load (GWh) 77 759 9,320 571	Mix 0.7% 7.1% 87.2% 5.3%
Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle Simple Gas Turbine Residual Oil Utility Boiler	PHEV Load (GWh) 21,890 40,886 129,989 7,471 0	with PHEV Load (GWh) 20,141 41,641 136,819 8,019	Difference by PHEV Load (GWh) -1,749 755 6,830 548 0	Mix -27.6% -11.9% 107.7% 8.6%	PHEV Load (GWh) 302,633 4,597 11,303 1,049	with PHEV Load (GWh) 304,458 4,601 13,793 1,072	Difference by PHEV Load (GWh) 1,826 4 2,490 23 0	Mix 42.0% 6.1% 57.3% 0.5%	PHEV Load (GWh) 324,522 45,483 141,292 8,521 0	with PHEV Load (GWh) 324,599 46,242 150,612 9,091	Difference by PHEV Load (GWh) 77 759 9,320 571	Mix 0.7% 7.1% 87.2% 5.3% 0.0%
Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle Simple Gas Turbine Residual Oil Utility Boiler Nuclear	PHEV Load (GWh) 21,890 40,886 129,989 7,471	with PHEV Load (GWh) 20,141 41,641 136,819 8,019	Difference by PHEV Load (GWh) -1,749 755 6,830 548	Mix -27.6% -11.9% 107.7% 8.6%	PHEV Load (GWh) 302,633 4,597 11,303 1,049	with PHEV Load (GWh) 304,458 4,601 13,793 1,072	Difference by PHEV Load (GWh) 1,826 4 2,490 23	Mix 42.0% 0.1% 57.3%	PHEV Load (GWh) 324,522 45,483 141,292 8,521	with PHEV Load (GWh) 324,599 46,242 150,612 9,091	Difference by PHEV Load (GWh) 77 759 9,320 571	Mix 0.7% 7.1% 87.2% 5.3%
Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle Simple Gas Turbine Residual Oil Utility Boiler Nuclear Biomass	PHEV Load (GWh) 21,890 40,886 129,989 7,471 0 37,719	with PHEV Load (GWh) 20,141 41,641 136,819 8,019 0 37,701	Difference by PHEV Load (GWh) -1,749 755 6,830 548 0 -18	Mix -27.6% -11.9% 107.7% 8.6% -0.0% -0.3%	PHEV Load (GWh) 302,633 4,597 11,303 1,049 0 40,375	with PHEV Load (GWh) 304,458 4,601 13,793 1,072 0 40,375	Difference by PHEV Load (GWh) 1,826 4 2,490 23 0	Mix 42.0% 57.3% 0.5% 0.0%	PHEV Load (GWh) 324,522 45,483 141,292 8,521 0 78,094	with PHEV Load (GWh) 324,599 46,242 150,612 9,091 0 78,076	Difference by PHEV Load (GWh) 77 759 9,320 571 0 -18	Mix 0.7% 7.1% 87.2% 5.3% 0.0% -0.2%
Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle Simple Gas Turbine Residual Oil Utility Boiler Nuclear Biomass Utility Boiler / IGCC	PHEV Load (GWh) 21,890 40,886 129,989 7,471 0 37,719	with PHEV Load (GWh) 20,141 41,641 136,819 8,019	Difference by PHEV Load (GWh) -1,749 755 6,830 548 0	Mix -27.6% -11.9% 107.7% 8.6%	PHEV Load (GWh) 302,633 4,597 11,303 1,049	with PHEV Load (GWh) 304,458 4,601 13,793 1,072	Difference by PHEV Load (GWh) 1,826 4 2,490 23 0	Mix 42.0% 6.1% 57.3% 0.5%	PHEV Load (GWh) 324,522 45,483 141,292 8,521 0	with PHEV Load (GWh) 324,599 46,242 150,612 9,091	Difference by PHEV Load (GWh) 77 759 9,320 571	Mix 0.7% 7.1% 87.2% 5.3% 0.0%
Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle Simple Gas Turbine Residual Oil Utility Boiler Nuclear Biomass Utility Boiler / IGCC Other	PHEV Load (GWh) 21,890 40,886 129,989 7,471 0 37,719 3,594	with PHEV Load (GWh) 20,141 41,641 136,819 8,019 0 37,701 3,571	Difference by PHEV Load (GWh) -1,749 755 6,830 548 0 -18	Mix -27.6% -11.9% 107.7% 8.6% -0.3% -0.4%	PHEV Load (GWh) 302,633 4,597 11,303 1,049 0 40,375 245	with PHEV Load (GWh) 304,458 4,601 13,793 1,072 0 40,375	Difference by PHEV Load (GWh) 1,826 4 2,490 23 0 0	Mix 42.0% 57.3% 0.5% 0.0% 0.0%	PHEV Load (GWh) 324,522 45,483 141,292 8,521 0 78,094 3,839	with PHEV Load (GWh) 324,599 46,242 150,612 9,091 0 78,076 3,816	Difference by PHEV Load (GWh) 77 759 9,320 571 0 -18	Mix 0.7% 7.1% 87.2% 5.3% 0.0% -0.2%
Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle Simple Gas Turbine Residual Oil Utility Boiler Nuclear Biomass Utility Boiler / IGCC	PHEV Load (GWh) 21,890 40,886 129,989 7,471 0 37,719	with PHEV Load (GWh) 20,141 41,641 136,819 8,019 0 37,701	Difference by PHEV Load (GWh) -1,749 755 6,830 548 0 -18	Mix -27.6% -11.9% 107.7% 8.6% -0.0% -0.3%	PHEV Load (GWh) 302,633 4,597 11,303 1,049 0 40,375	with PHEV Load (GWh) 304,458 4,601 13,793 1,072 0 40,375	Difference by PHEV Load (GWh) 1,826 4 2,490 23 0	Mix 42.0% 57.3% 0.5% 0.0%	PHEV Load (GWh) 324,522 45,483 141,292 8,521 0 78,094	with PHEV Load (GWh) 324,599 46,242 150,612 9,091 0 78,076	Difference by PHEV Load (GWh) 77 759 9,320 571 0 -18	Mix 0.7% 7.1% 87.2% 5.3% 0.0% -0.2%



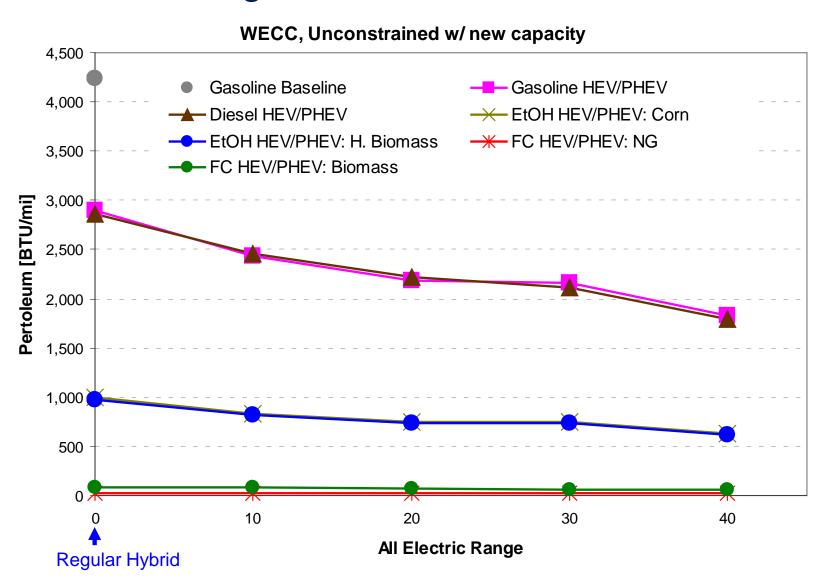
2020 Generation Mixes for PHEV Recharge - Smart Charging (Filling the Valley)

		NE-			NY-ISO				IL			
	Baseline w/o	with PHEV	Difference		Baseline w/o	with PHEV	Difference		Baseline w/o	with PHEV	Difference	
	PHEV Load	Load	by PHEV	Marginal	PHEV Load	Load	by PHEV	Marginal	PHEV Load	Load	by PHEV	Marginal
	(GWh)	(GWh)	Load (GWh)	Mix	(GWh)	(GWh)	Load (GWh)	Mix	(GWh)	(GWh)	Load (GWh)	Mix
Coal												
Utility Boiler / IGCC	21,147	21,147	0	0.0%	20,980	20,980	0	0.0%	95,213	96,325	1,112	99.5%
Natural Gas				4000	1	l						A comment
Utility Boiler		194	3	0.1%	20,359	20,973	615	29.5%	156	156	0	0.0%
Combined Cycle	· '	70,608	2,106	94.7%	58,781	59,965	1,184	56.8%	3,087	3,087	0	0.0%
Simple Gas Turbine	3,716	3,798	81	3.7%	4,649	4,927	278	.13.3%	4,249	4,249	0	0.0%
Residual Oil				"Parat"	1	l		"Property				
Utility Boiler		5,581	29	1.3%	2,422	2,431	9	0.4%	195	195	0	0.0%
Nuclear	31,787	31,787	0	0.0%	42,835	42,835	0	0.0%	74,658	74,658	0	0.0%
Biomass					1							
Utility Boiler / IGCC	7,646	7,651	5	0.2%	25,553	25,553	0	0.0%			0	0.0%
Other					1	l l			Į i			
Renewable		6,756	0	0.0%	25,988	25,988	0	0.0%	37,082	37,088	6	0.5%
T-1-1	145,298	147,521	2,224	100.0%	201,566	203,651	2,085	100.0%	214,641	215,759	1,118	100.0%
Total	0,200	1 17 ,02 1	_,	100.070	201,000			1001070	211,011	·		1001070
I otai	·	CA + I	mport	100.070	·	WECC v	w/o CA	1001070	,	WECC	Total	100.070
I otal	Baseline w/o	CA + I	mport Difference		Baseline w/o	WECC with PHEV	w/o CA Difference		Baseline w/o	WECC	Total Difference	
I otal	Baseline w/o PHEV Load	CA + II with PHEV Load	mport Difference by PHEV	Marginal	Baseline w/o PHEV Load	WECC with PHEV Load	w/o CA Difference by PHEV	Marginal	Baseline w/o PHEV Load	WECC with PHEV Load	Total Difference by PHEV	Marginal
	Baseline w/o	CA + I	mport Difference	Marginal	Baseline w/o	WECC with PHEV	w/o CA Difference	Marginal	Baseline w/o	WECC	Total Difference	Marginal
Coal	Baseline w/o PHEV Load (GWh)	CA + In with PHEV Load (GWh)	mport Difference by PHEV Load (GWh)	Marginal Mix	Baseline w/o PHEV Load (GWh)	WECC with PHEV Load (GWh)	w/o CA Difference by PHEV Load (GWh)	Marginal Mix	Baseline w/o PHEV Load (GWh)	WECC with PHEV Load (GWh)	Difference by PHEV Load (GWh)	Marginal Mix
Coal Utility Boiler / IGCC	Baseline w/o PHEV Load (GWh)	CA + II with PHEV Load	mport Difference by PHEV	Marginal	Baseline w/o PHEV Load	WECC with PHEV Load	w/o CA Difference by PHEV	Marginal Mix	Baseline w/o PHEV Load	WECC with PHEV Load	Total Difference by PHEV	Marginal
Coal Utility Boiler / IGCC Natural Gas	Baseline w/o PHEV Load (GWh) 21,890	CA + In with PHEV Load (GWh)	Difference by PHEV Load (GWh)	Marginal Mix	Baseline w/o PHEV Load (GWh) 302,633	wecc with PHEV Load (GWh)	w/o CA Difference by PHEV Load (GWh) 4,006	Marginal Mix	Baseline w/o PHEV Load (GWh) 324,522	WECC with PHEV Load (GWh) 325,991	Difference by PHEV Load (GWh)	Marginal Mix 13.7%
Coal Utility Boiler / IGCC Natural Gas Utility Boiler	Baseline w/o PHEV Load (GWh) 21,890 40,886	CA + II with PHEV Load (GWh) 19,353 41,524	Difference by PHEV Load (GWh) -2,537	Marginal Mix -40.0%	Baseline w/o PHEV Load (GWh) 302,633 4,597	wecc with PHEV Load (GWh) 306,638	w/o CA Difference by PHEV Load (GWh) 4,006	Marginal Mix 92.3%	Baseline w/o PHEV Load (GWh) 324,522 45,483	WECC with PHEV Load (GWh) 325,991 46,119	Difference by PHEV Load (GWh) 1,468	Marginal Mix 13.7%
Coal Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle	Baseline w/o PHEV Load (GWh) 21,890 40,886 129,989	CA + II with PHEV Load (GWh) 19,353 41,524 137,682	Difference by PHEV Load (GWh) -2,537 638 7,693	Marginal Mix -40.0% -10.1%	Baseline w/o PHEV Load (GWh) 302,633 4,597 11,303	wecc with PHEV Load (GWh) 306,638 4,595 11,685	w/o CA Difference by PHEV Load (GWh) 4,006 -2 382	Marginal Mix 92.3%: -0.1% 8.8%	Baseline w/o PHEV Load (GWh) 324,522 45,483 141,292	WECC with PHEV Load (GWh) 325,991 46,119 149,368	Difference by PHEV Load (GWh) 1,468 635 8,075	Marginal Mix 13.7% 5.9% 75.6%
Coal Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle Simple Gas Turbine	Baseline w/o PHEV Load (GWh) 21,890 40,886 129,989	CA + II with PHEV Load (GWh) 19,353 41,524	Difference by PHEV Load (GWh) -2,537	Marginal Mix -40.0%	Baseline w/o PHEV Load (GWh) 302,633 4,597	wecc with PHEV Load (GWh) 306,638	w/o CA Difference by PHEV Load (GWh) 4,006	Marginal Mix 92.3%	Baseline w/o PHEV Load (GWh) 324,522 45,483	WECC with PHEV Load (GWh) 325,991 46,119	Difference by PHEV Load (GWh) 1,468	Marginal Mix 13.7% 5.9% 75.6%
Coal Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle Simple Gas Turbine Residual Oil	Baseline w/o PHEV Load (GWh) 21,890 40,886 129,989 7,471	CA + In with PHEV Load (GWh) 19,353 41,524 137,682 7,959	Difference by PHEV Load (GWh) -2,537 638 7,693 488	Marginal Mix -40.0% -10.1% 121.3%	Baseline w/o PHEV Load (GWh) 302,633 4,597 11,303 1,049	wecc with PHEV Load (GWh) 306,638 4,595 11,685 1,006	w/o CA Difference by PHEV Load (GWh) 4,006 -2 382 -44	Marginal Mix :92.3%: -0.1% 8.8% -1.0%	Baseline w/o PHEV Load (GWh) 324,522 45,483 141,292 8,521	WECC with PHEV Load (GWh) 325,991 46,119 149,368 8,965	Difference by PHEV Load (GWh) 1,468 635 8,075 444	Marginal Mix 13.7% 5.9% 75.6% 4.2%
Coal Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle Simple Gas Turbine Residual Oil Utility Boiler	Baseline w/o PHEV Load (GWh) 21,890 40,886 129,989 7,471	CA + II with PHEV Load (GWh) 19,353 41,524 137,682 7,959 0	Difference by PHEV Load (GWh) -2,537 638 7,693 488	Marginal Mix -40.0% -10.1% 121.3% 7.7%	Baseline w/o PHEV Load (GWh) 302,633 4,597 11,303 1,049	wecc with PHEV Load (GWh) 306,638 4,595 11,685 1,006	w/o CA Difference by PHEV Load (GWh) 4,006 -2 382 -44 0	Marginal Mix 92.3% -0.1% 8.8% -1.0%	Baseline w/o PHEV Load (GWh) 324,522 45,483 141,292 8,521	WECC with PHEV Load (GWh) 325,991 46,119 149,368 8,965	Difference by PHEV Load (GWh) 1,468 635 8,075 444	Marginal Mix 13.7% 5.9% 75.6% 4.2%
Coal Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle Simple Gas Turbine Residual Oil Utility Boiler Nuclear	Baseline w/o PHEV Load (GWh) 21,890 40,886 129,989 7,471	CA + In with PHEV Load (GWh) 19,353 41,524 137,682 7,959	Difference by PHEV Load (GWh) -2,537 638 7,693 488	Marginal Mix -40.0% -10.1% 121.3%	Baseline w/o PHEV Load (GWh) 302,633 4,597 11,303 1,049	wecc with PHEV Load (GWh) 306,638 4,595 11,685 1,006	w/o CA Difference by PHEV Load (GWh) 4,006 -2 382 -44	Marginal Mix :92.3%: -0.1% 8.8% -1.0%	Baseline w/o PHEV Load (GWh) 324,522 45,483 141,292 8,521	WECC with PHEV Load (GWh) 325,991 46,119 149,368 8,965	Difference by PHEV Load (GWh) 1,468 635 8,075 444	Marginal Mix 13.7% 5.9% 75.6% 4.2%
Coal Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle Simple Gas Turbine Residual Oil Utility Boiler Nuclear Biomass	Baseline w/o PHEV Load (GWh) 21,890 40,886 129,989 7,471 0 37,719	CA + II with PHEV Load (GWh) 19,353 41,524 137,682 7,959 0 37,775	Difference by PHEV Load (GWh) -2,537 638 7,693 488 0 56	Marginal Mix -40.0% 10.1% 121.3% 7.7%	Baseline w/o PHEV Load (GWh) 302,633 4,597 11,303 1,049 0 40,375	wecc with PHEV Load (GWh) 306,638 4,595 11,685 1,006 0 40,375	w/o CA Difference by PHEV Load (GWh) 4,006 -2 382 -44 0 0	Marginal Mix 92.3% -0.1% 8.8% -1.0% 0.0%	Baseline w/o PHEV Load (GWh) 324,522 45,483 141,292 8,521 0 78,094	WECC with PHEV Load (GWh) 325,991 46,119 149,368 8,965 0 78,149	Difference by PHEV Load (GWh) 1,468 635 8,075 444 0 56	Marginal Mix 13.7% 5.9% 75.6% 4.2% 0.0% 0.5%
Coal Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle Simple Gas Turbine Residual Oil Utility Boiler Nuclear Biomass Utility Boiler / IGCC	Baseline w/o PHEV Load (GWh) 21,890 40,886 129,989 7,471 0 37,719	CA + II with PHEV Load (GWh) 19,353 41,524 137,682 7,959 0	Difference by PHEV Load (GWh) -2,537 638 7,693 488	Marginal Mix -40.0% -10.1% 121.3% 7.7%	Baseline w/o PHEV Load (GWh) 302,633 4,597 11,303 1,049	wecc with PHEV Load (GWh) 306,638 4,595 11,685 1,006	w/o CA Difference by PHEV Load (GWh) 4,006 -2 382 -44 0	Marginal Mix 92.3% -0.1% 8.8% -1.0%	Baseline w/o PHEV Load (GWh) 324,522 45,483 141,292 8,521	WECC with PHEV Load (GWh) 325,991 46,119 149,368 8,965	Difference by PHEV Load (GWh) 1,468 635 8,075 444	Marginal Mix 13.7% 5.9% 75.6% 4.2%
Coal Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle Simple Gas Turbine Residual Oil Utility Boiler Nuclear Biomass Utility Boiler / IGCC Other	Baseline w/o PHEV Load (GWh) 21,890 40,886 129,989 7,471 0 37,719 3,594	CA + II with PHEV Load (GWh) 19,353 41,524 137,682 7,959 0 37,775 3,600	Difference by PHEV Load (GWh) -2,537 638 7,693 488 0 56	Marginal Mix -40.0% -10.1% -121.3% -7.7% -0.0% 0.9% -0.1%	Baseline w/o PHEV Load (GWh) 302,633 4,597 11,303 1,049 0 40,375 245	wecc with PHEV Load (GWh) 306,638 4,595 11,685 1,006 0 40,375 245	w/o CA Difference by PHEV Load (GWh) 4,006 -2 382 -44 0 0 0	Marginal Mix 92.3%: -0.1% 8.8% -1.0% 0.0% 0.0%	Baseline w/o PHEV Load (GWh) 324,522 45,483 141,292 8,521 0 78,094 3,839	WECC with PHEV Load (GWh) 325,991 46,119 149,368 8,965 0 78,149 3,846	Difference by PHEV Load (GWh) 1,468 635 8,075 444 0 56	Marginal Mix 13.7% 5.9% 75.6% 4.2% 0.0% 0.5% 0.1%
Coal Utility Boiler / IGCC Natural Gas Utility Boiler Combined Cycle Simple Gas Turbine Residual Oil Utility Boiler Nuclear Biomass Utility Boiler / IGCC	Baseline w/o PHEV Load (GWh) 21,890 40,886 129,989 7,471 0 37,719 3,594	CA + II with PHEV Load (GWh) 19,353 41,524 137,682 7,959 0 37,775	Difference by PHEV Load (GWh) -2,537 638 7,693 488 0 56	Marginal Mix -40.0% 10.1% 121.3% 7.7%	Baseline w/o PHEV Load (GWh) 302,633 4,597 11,303 1,049 0 40,375	wecc with PHEV Load (GWh) 306,638 4,595 11,685 1,006 0 40,375	w/o CA Difference by PHEV Load (GWh) 4,006 -2 382 -44 0 0	Marginal Mix 92.3% -0.1% 8.8% -1.0% 0.0%	Baseline w/o PHEV Load (GWh) 324,522 45,483 141,292 8,521 0 78,094	WECC with PHEV Load (GWh) 325,991 46,119 149,368 8,965 0 78,149	Difference by PHEV Load (GWh) 1,468 635 8,075 444 0 56	Marginal Mix 13.7% 5.9% 75.6% 4.2% 0.0% 0.5%

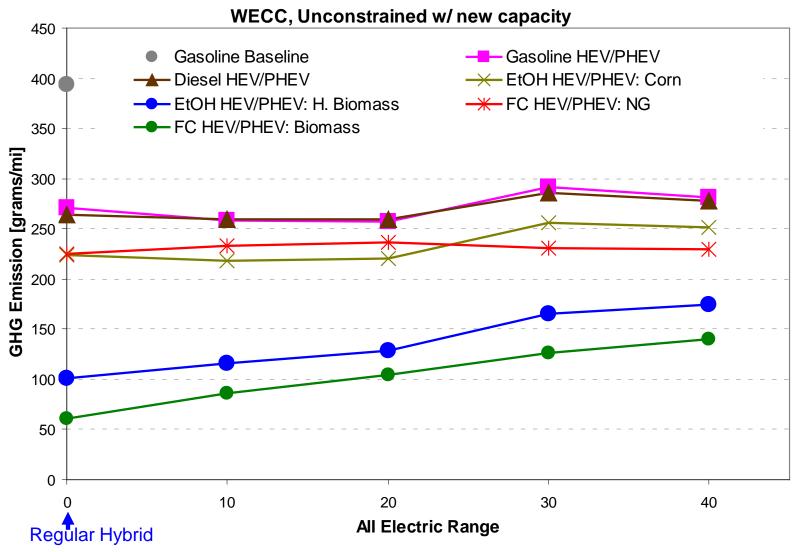


WTW Results: Combined CD and CS Operation For All AERs

WTW <u>Petroleum Energy Use</u>: Comparison of Technology and All Electric Range

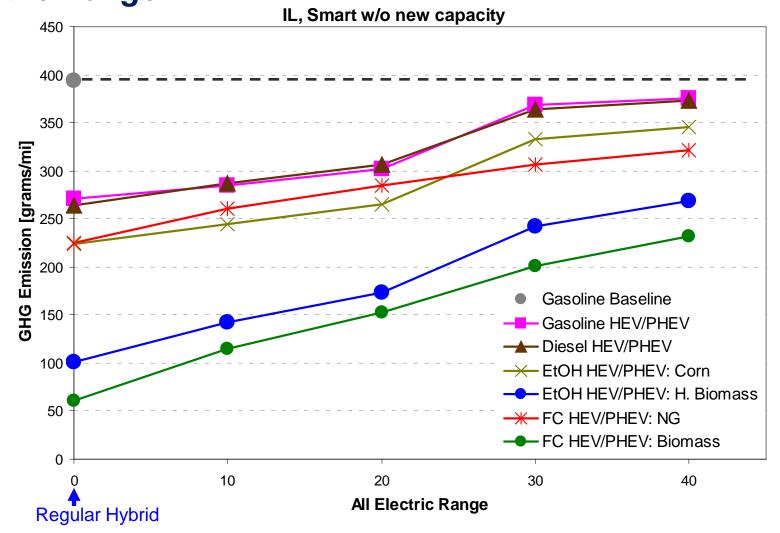


WTW <u>GHG Emissions</u>: Comparison of Technology and All Electric Range



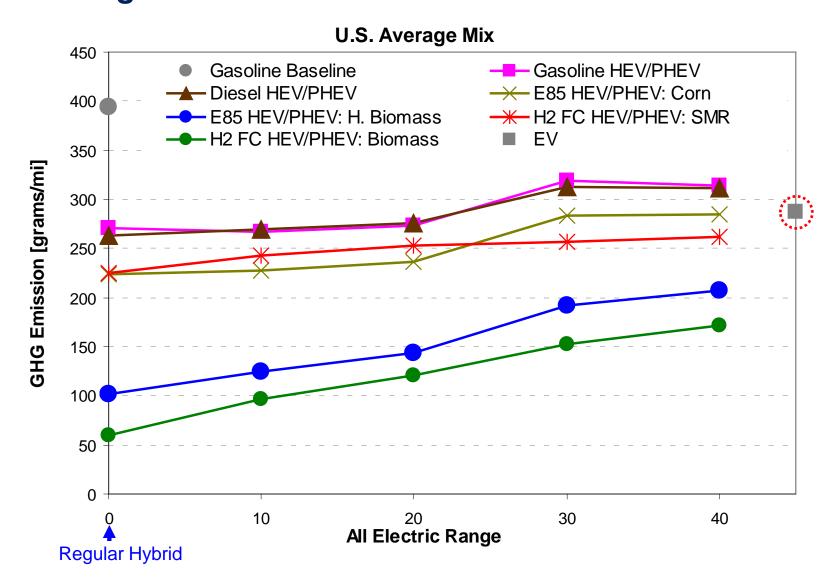
Note: The generation mix for the aggregate load of all PHEVs (with different AERs) is used to characterize the performance of individual AER of PHEVs

WTW <u>GHG Emissions</u>: Comparison of Technology and All Electric Range



Note: The generation mix for the aggregate load of all PHEVs (with different AERs) is used to characterize the performance of individual AER of PHEVs

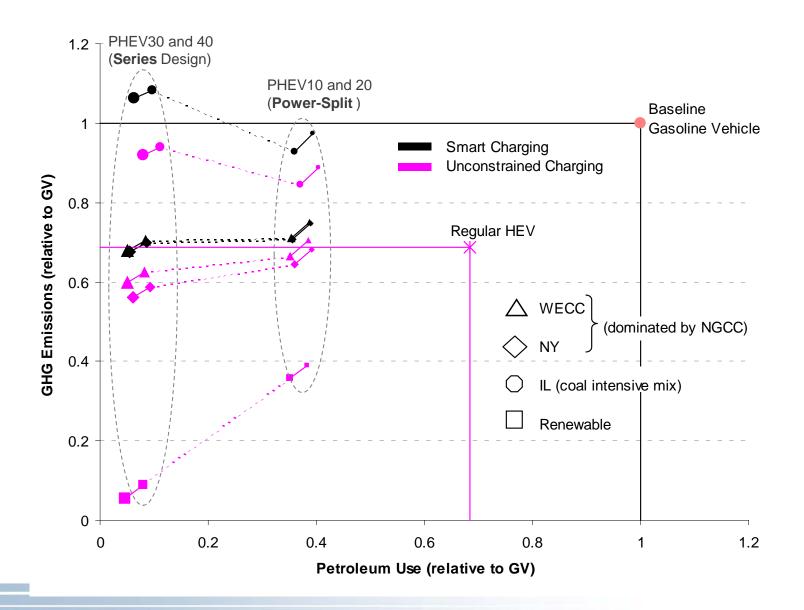
WTW <u>GHG Emissions</u>: Comparison of Technology and All Electric Range



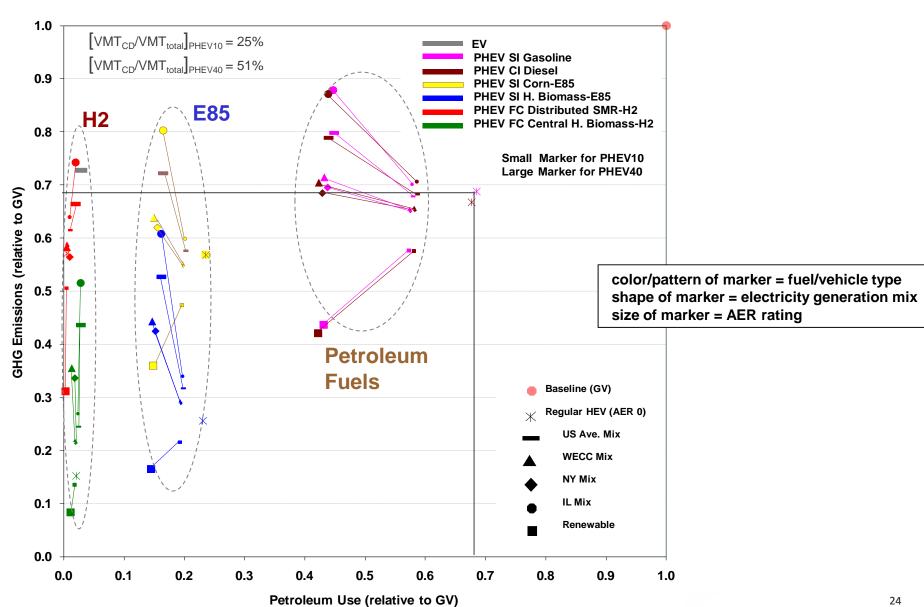
WTW Results Summary



Summary of Petroleum Energy and GHG Effects of Gasoline ICEV, HEV, and CD operation of PHEVs



Summary of Petroleum Energy and GHG Effects of All Evaluated Options: Unconstrained Charging Scenario



Acknowledgment

This work has been sponsored by Fred Joseck, Office of Fuel Cells and Hydrogen Infrastructure Technologies, DOE. We are thankful for his continued support.



Questions/Comments??

aelgowainy@anl.gov

Report available at:

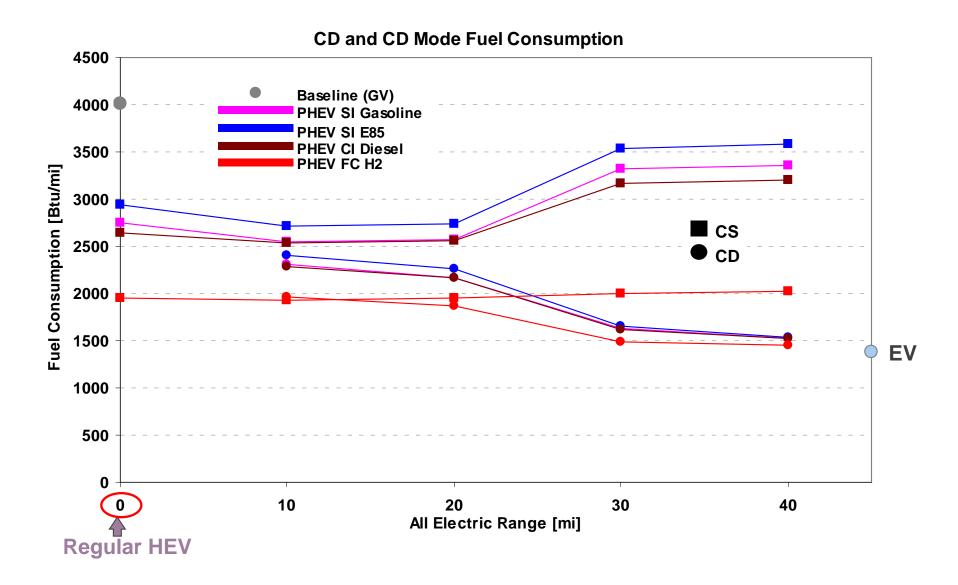
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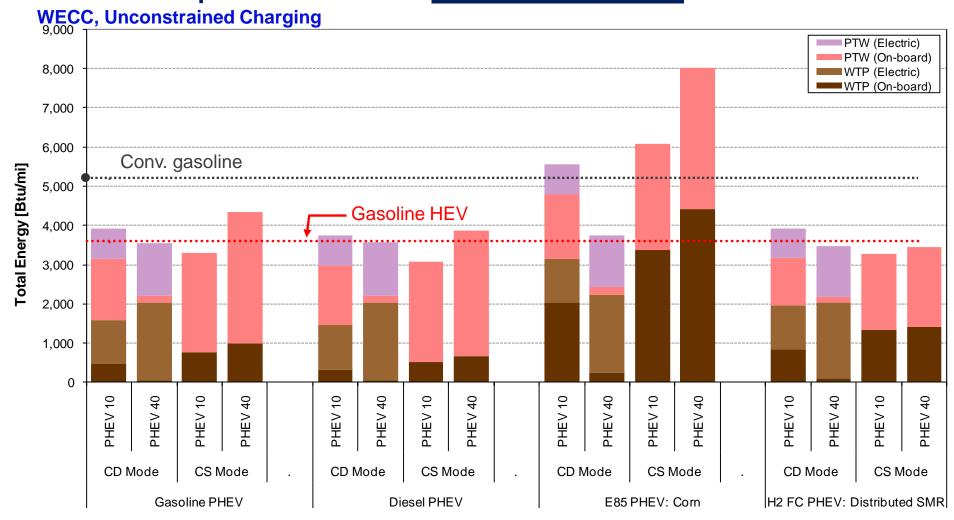
Backup Slides



On-road Fuel Consumption by Technology, Mode, and AER



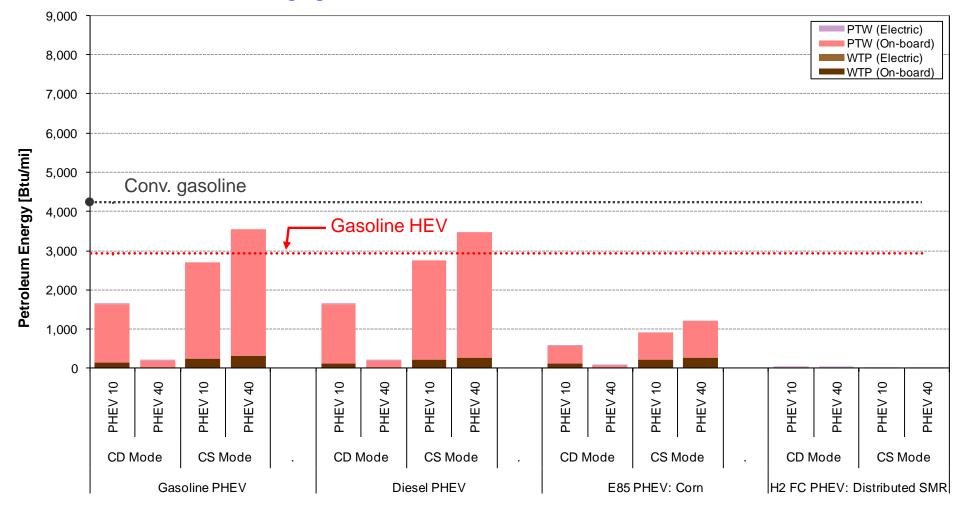
CD vs. CS Operation: WTW Total Energy Use



- ➢ Higher WTW efficiency in CD mode for series design (PHEV 40) compared to split design (PHEV10)
- ➤ Lower WTW efficiency in CS mode for series design (PHEV 40) compared to split design (PHEV10)

CD vs. CS Operation: WTW Petroleum Energy Use

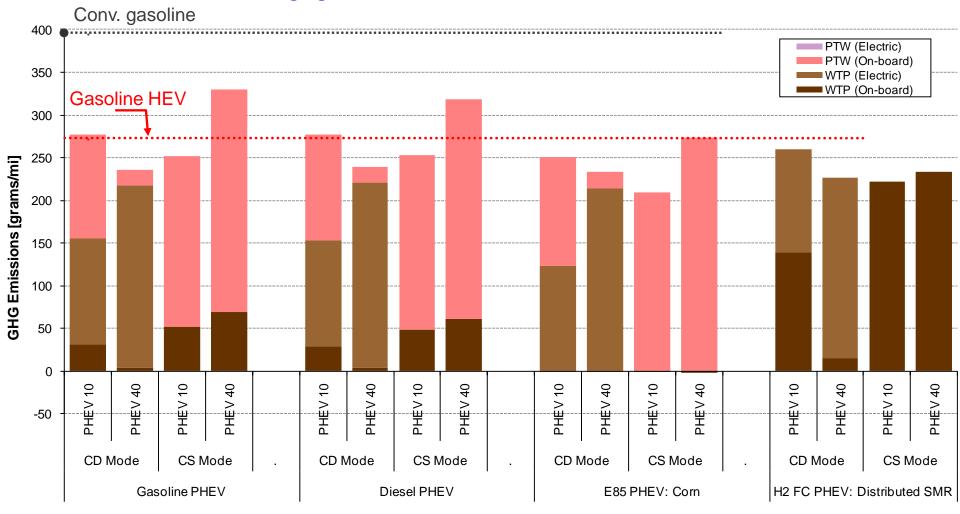
WECC, Unconstrained Charging





CD vs. CS Operation: WTW GHG Emissions

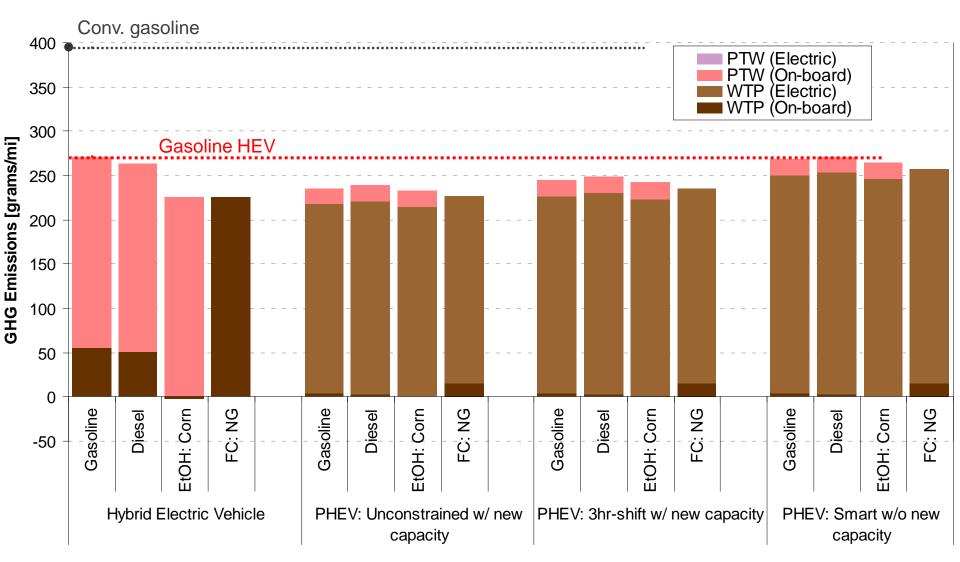
WECC, Unconstrained Charging



Less GHG emissions in CD mode and higher GHG emissions in CS mode for PHEV40 compared to PHEV10

CD Operation Under Three Charging Scenarios: WTW GHG Emissions

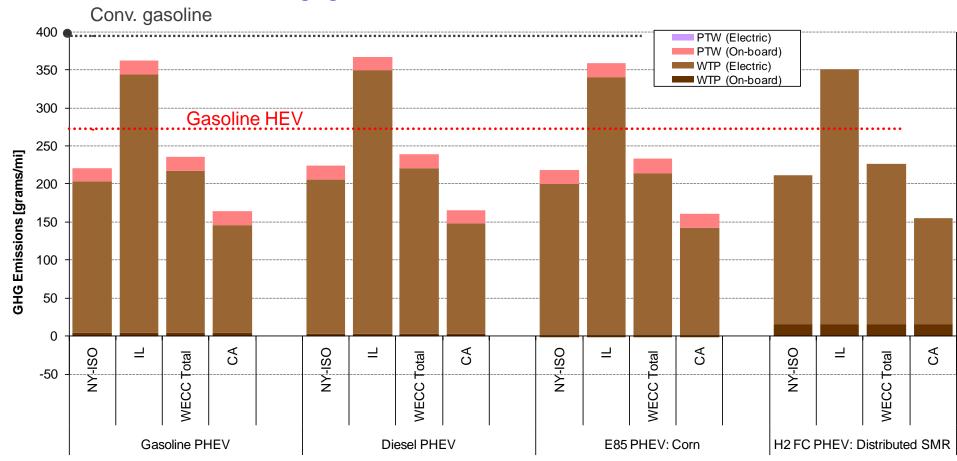
PHEV 40, WECC Total



More GHG emissions from smart charging compared to unconstrained case

CD Operation Among Regions: WTW GHG Emissions

PHEV40, Unconstrained Charging



- Marginal generation mix is key for GHG emissions
- > Impact of higher generation efficiency in WECC compared to NY is shown