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

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LDV Workshop

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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)
  - Series 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)

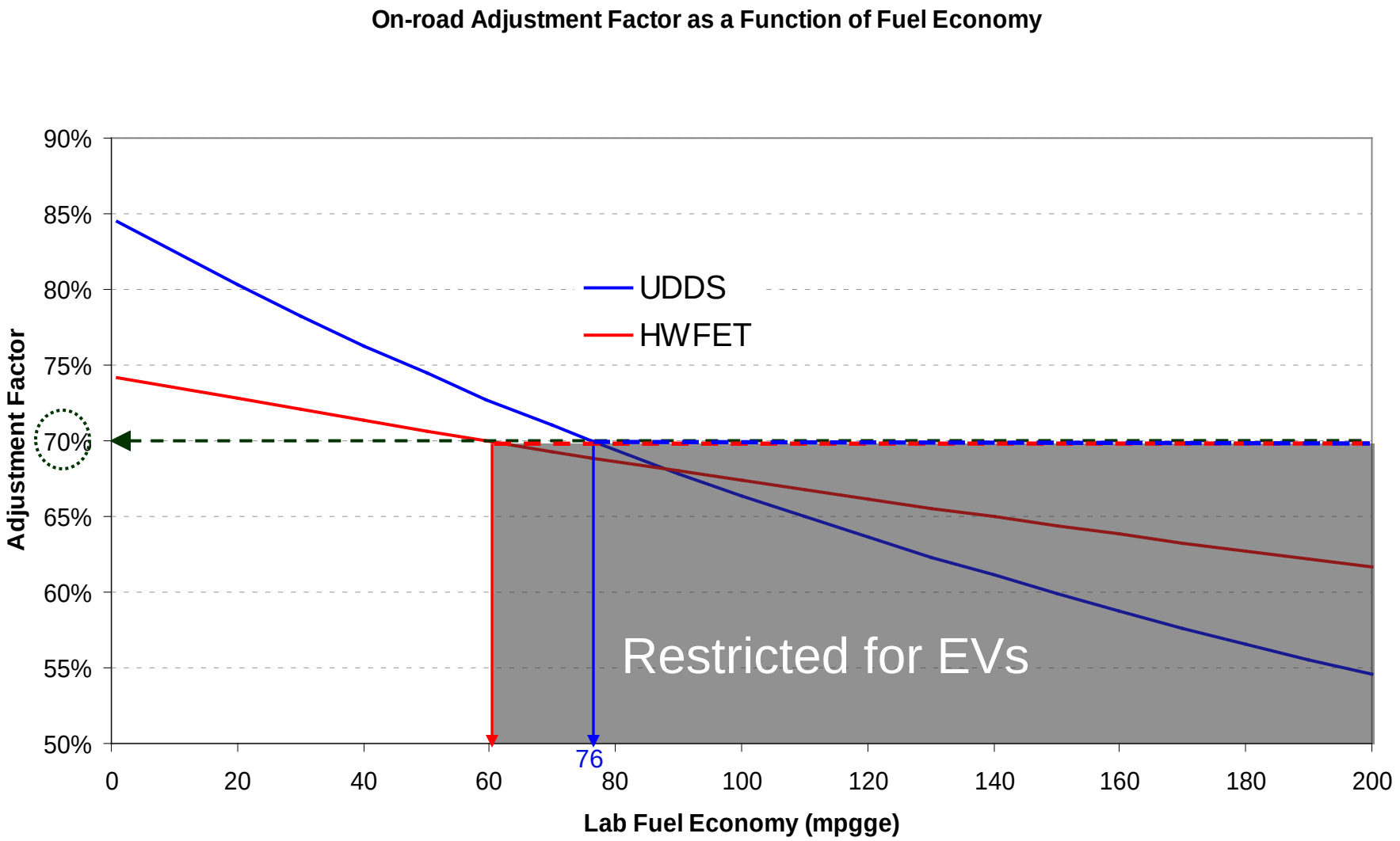
PSAT Lab-Based Fuel Economy Results (Miles of Gasoline Equivalent Gallon, Wh/Mile for Electric Operation)

Unadjusted Wh/mi and mpgge			AER 0	AER 10 Split Design			AER 20 Split Design			AER 30 Series Design			AER 40 Series Design		
			Regular Hybrid	CD Electric	CD Engine	CS Engine	CD Electric	CD Engine	CS Engine	CD Electric	CD Engine	CS Engine	CD Electric	CD Engine	CS Engine
Gasoline ICE	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
E85 ICE	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
Diesel ICE	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
H_2 FC	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
EV	UDDS	267													
	HWFET	274													

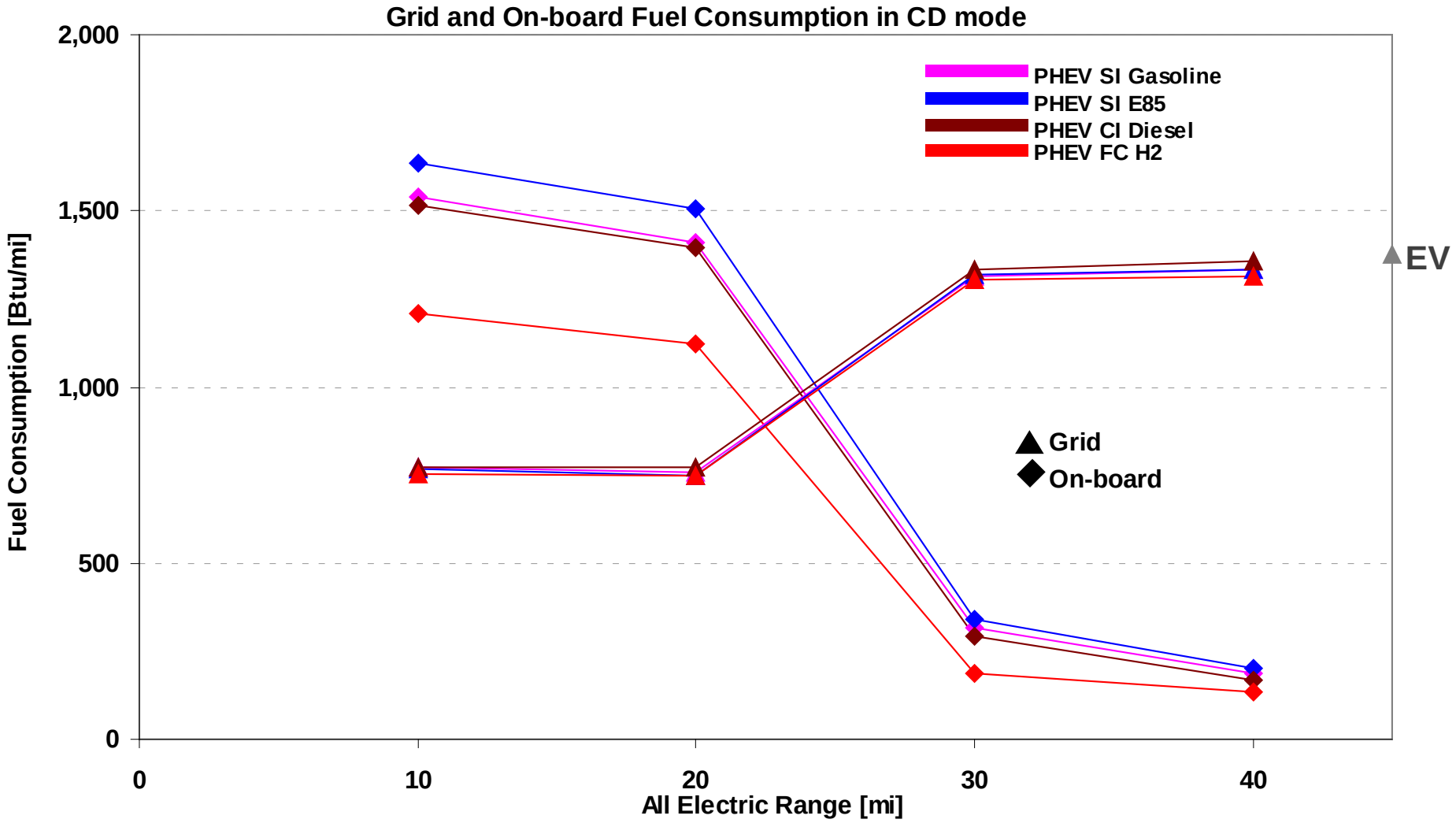
- CD Electric = charge depleting operation with grid electricity
- CD Engine = charging depleting operation with on-board power systems (ICE Engine or Fuel Cell)
- CS = charge sustaining operation with on-board power systems
- UDDS = Urban Dynamometer Driving Schedule; HWFET = Highway Fuel Economy Test

Note: PSAT included after-treatment thermal efficiency penalty to the diesel fuel economy

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

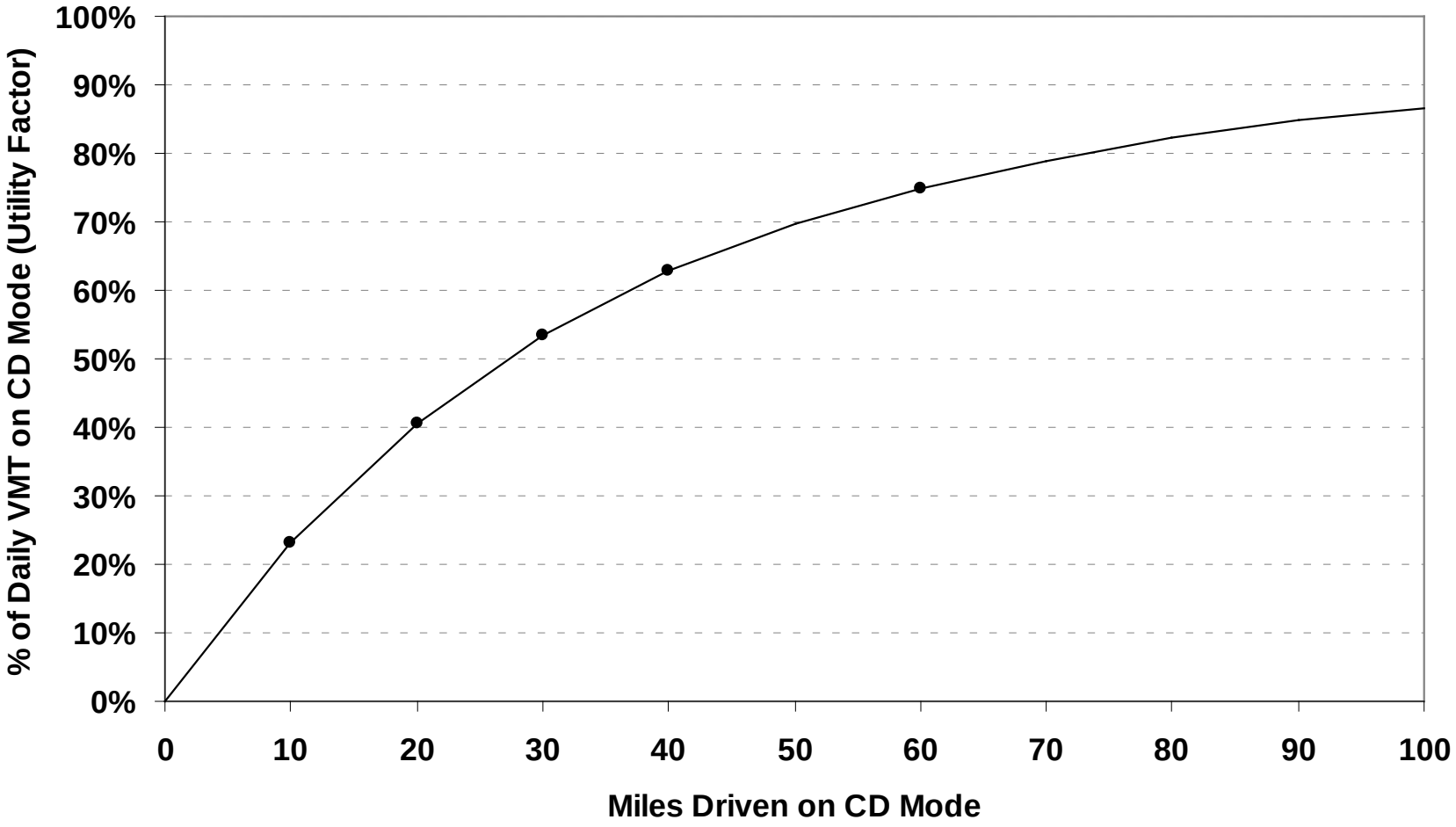


On-road Fuel Consumption by Technology and AER: Grid and On-board Energy Use Under the CD Operation



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%

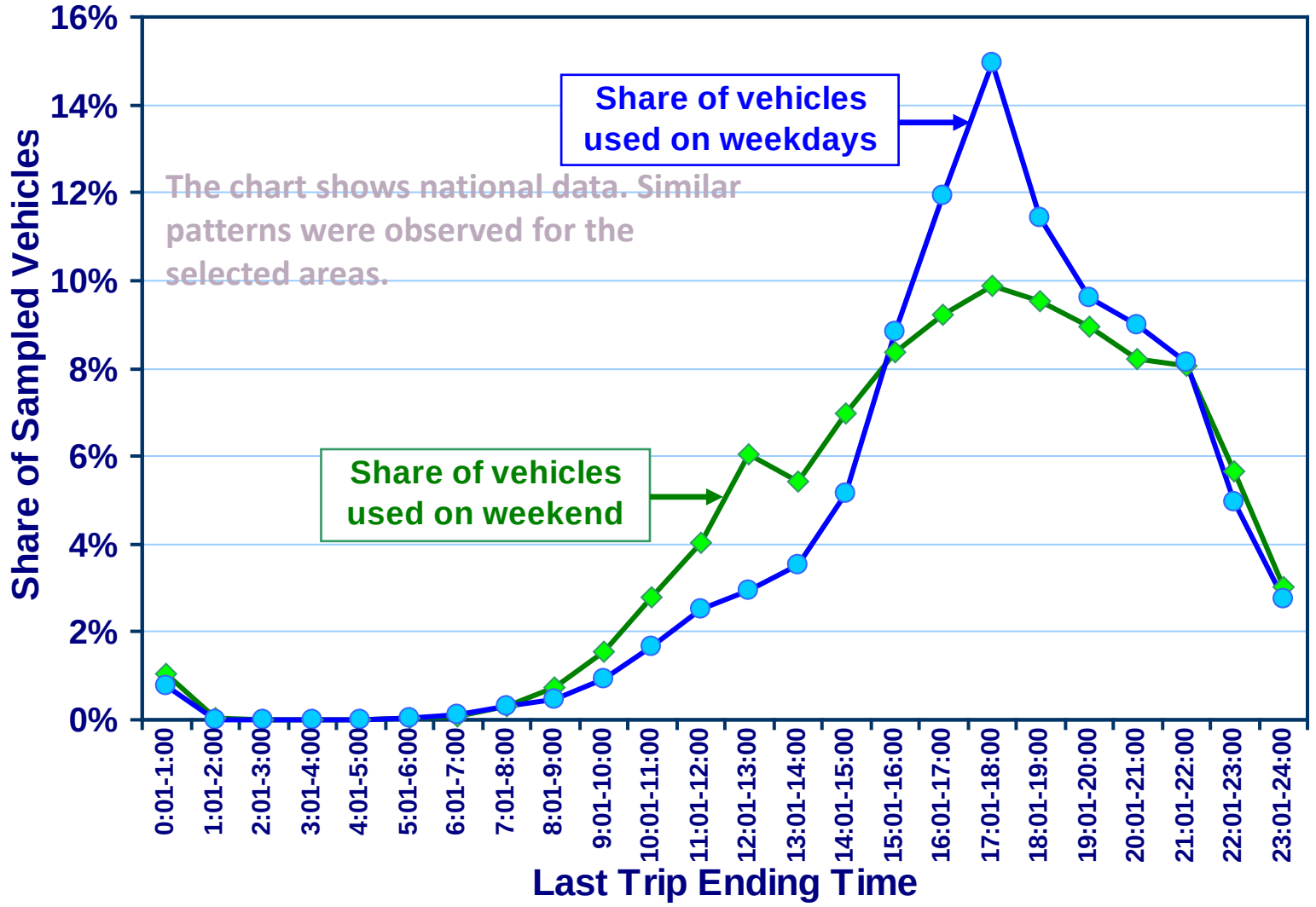


fuel consumption for charge depleting and charge sustaining operations were combined using the utility factor (UF)

- $(FC_{CDGrid} + FC_{CD_{ICE}})* UF + FC_{CS} * (1-UF)$

Electric Load Profiles with and without PHEVs

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

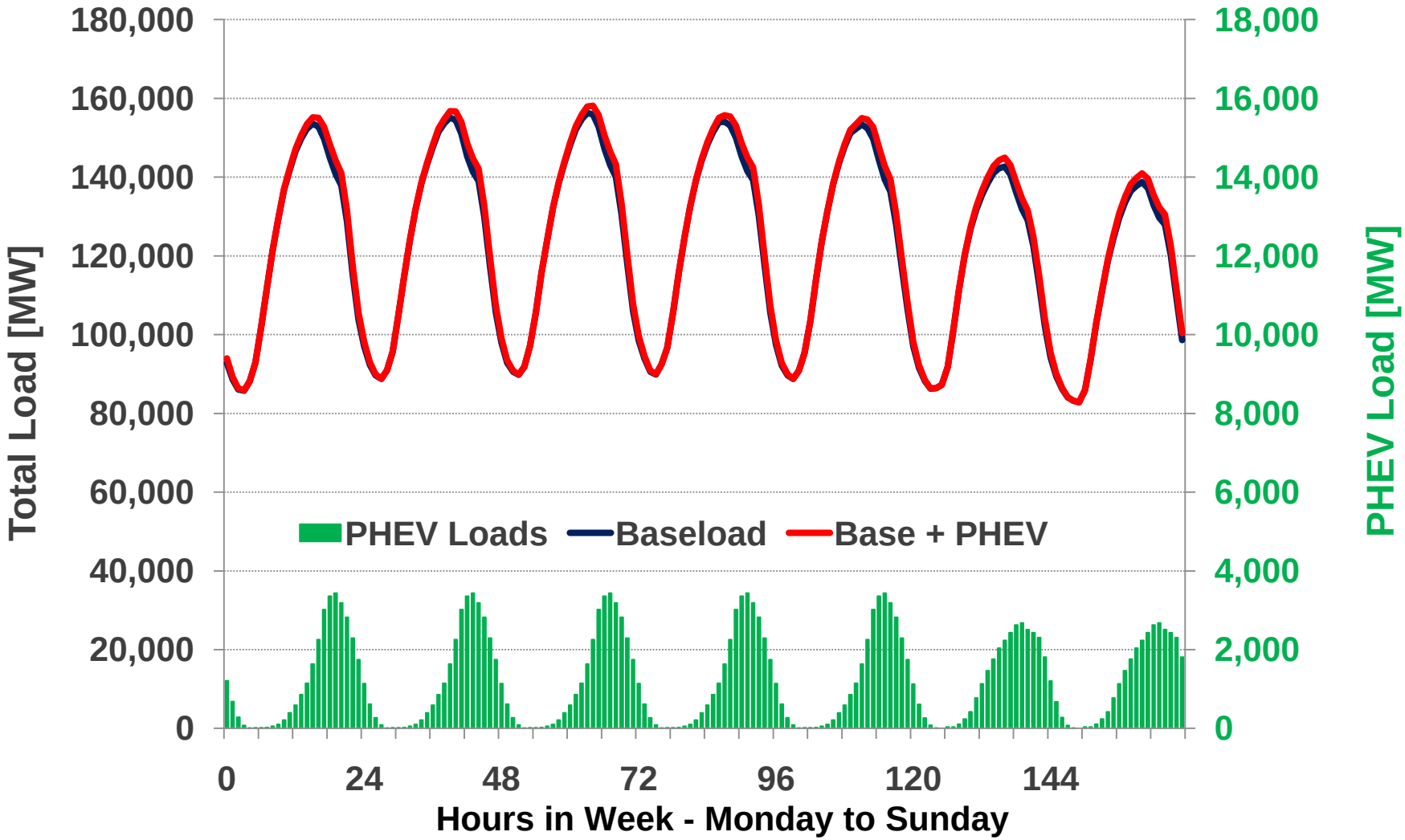


Key Factors Determining Electricity Generation Mix to Charge PHEVs Are Considered in Argonne's Analysis

- 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

*ISO=Independent System Operator (coordinates, controls and monitors the operation of the electrical power grid)

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-ISO				NY-ISO				IL			
	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal 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												
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												
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 + Import				WECC w/o CA				WECC Total			
	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**
Coal												
Utility Boiler / IGCC	21,890	20,141	-1,749	**-27.6%**	302,633	304,458	1,826	**42.0%**	324,522	324,599	77	**0.7%**
Natural Gas												
Utility Boiler	40,886	41,641	755	**11.9%**	4,597	4,601	4	**0.1%**	45,483	46,242	759	**7.1%**
Combined Cycle	129,989	136,819	6,830	**107.7%**	11,303	13,793	2,490	**57.3%**	141,292	150,612	9,320	**87.2%**
Simple Gas Turbine	7,471	8,019	548	**8.6%**	1,049	1,072	23	**0.5%**	8,521	9,091	571	**5.3%**
Residual Oil												
Utility Boiler	0	0	0	**0.0%**	0	0	0	**0.0%**	0	0	0	**0.0%**
Nuclear	37,719	37,701	-18	**-0.3%**	40,375	40,375	0	**0.0%**	78,094	78,076	-18	**-0.2%**
Biomass												
Utility Boiler / IGCC	3,594	3,571	-23	**-0.4%**	245	245	0	**0.0%**	3,839	3,816	-23	**-0.2%**
Other												
Renewable	99,677	99,677	0	**0.0%**	207,661	207,661	0	**0.0%**	307,338	307,338	0	**0.0%**
Total	341,226	347,570	6,345	**100.0%**	567,863	572,205	4,342	**100.0%**	909,089	919,776	10,686	**100.0%**

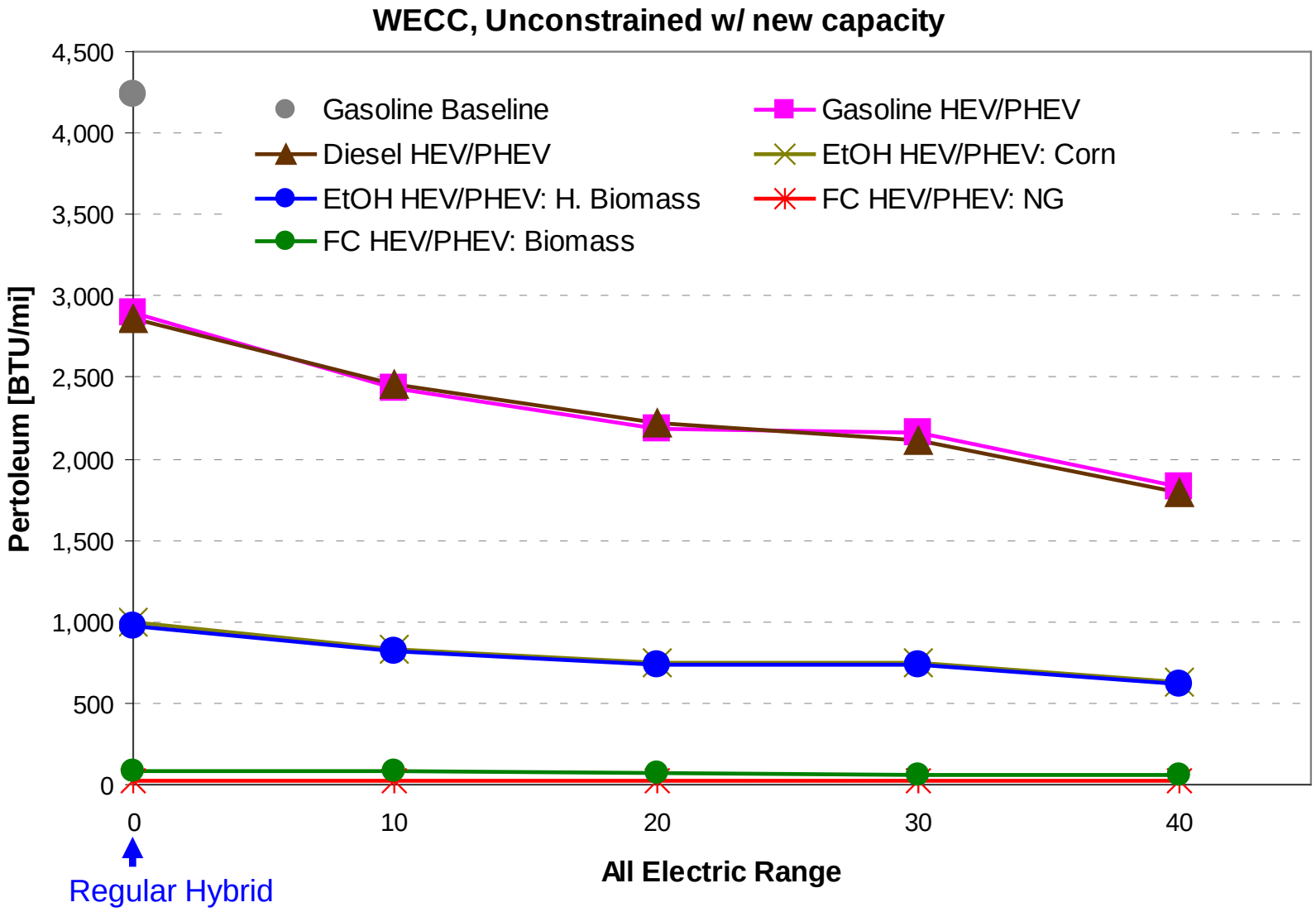
2020 Generation Mixes for PHEV Recharge - Smart Charging (Filling the Valley)

	NE-ISO				NY-ISO				IL			
	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal 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												
Utility Boiler	190	194	3	**0.1%**	20,359	20,973	615	**29.5%**	156	156	0	**0.0%**
Combined Cycle	68,502	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												
Utility Boiler	5,552	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												
Utility Boiler / IGCC	7,646	7,651	5	**0.2%**	25,553	25,553	0	**0.0%**			0	**0.0%**
Other												
Renewable	6,756	6,756	0	**0.0%**	25,988	25,988	0	**0.0%**	37,082	37,088	6	**0.5%**
Total	145,298	147,521	2,224	**100.0%**	201,566	203,651	2,085	**100.0%**	214,641	215,759	1,118	**100.0%**

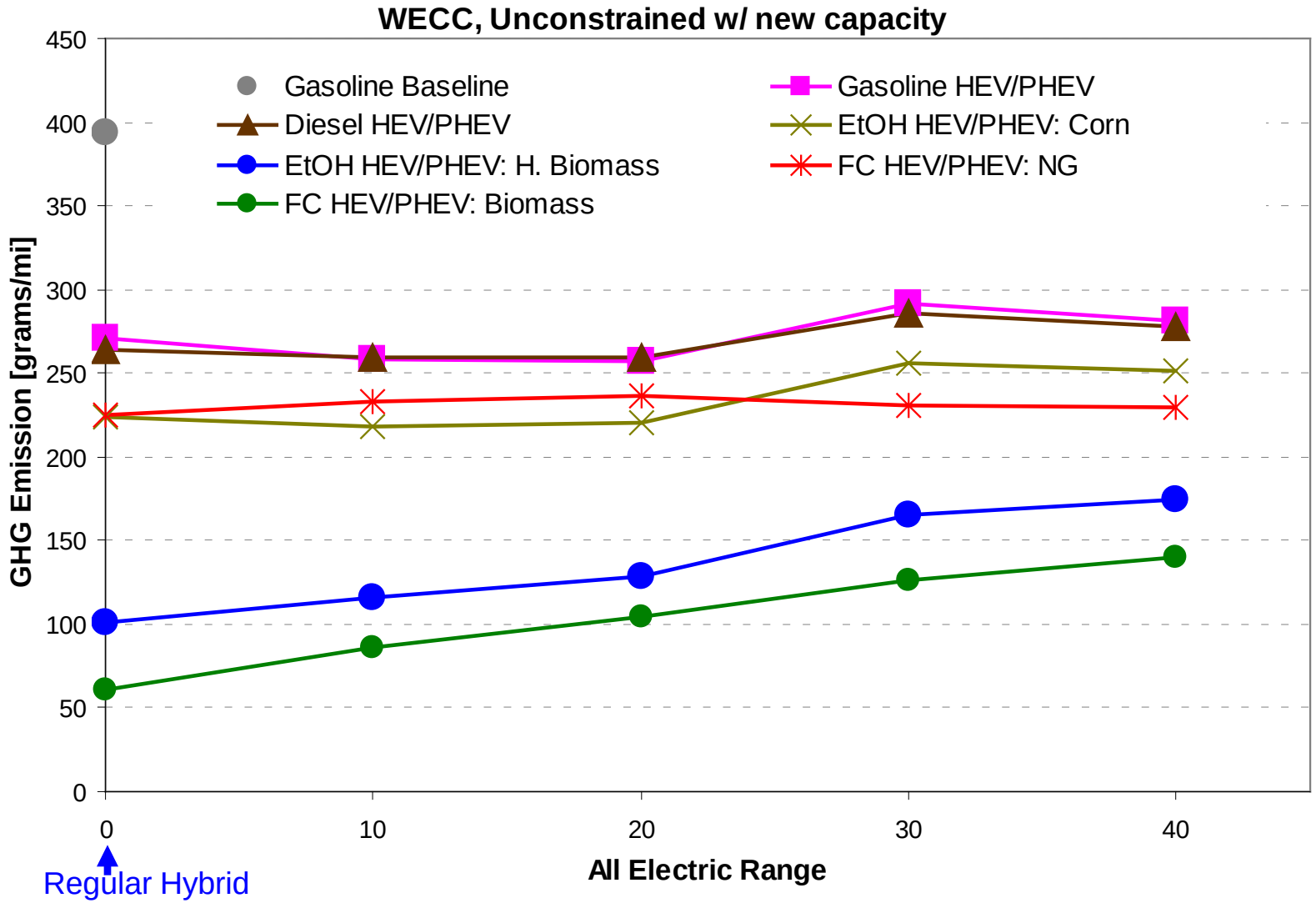
	CA + Import				WECC w/o CA				WECC Total			
	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**	Baseline w/o PHEV Load (GWh)	with PHEV Load (GWh)	Difference by PHEV Load (GWh)	**Marginal Mix**
Coal												
Utility Boiler / IGCC	21,890	19,353	-2,537	**-40.0%**	302,633	306,638	4,006	**92.3%**	324,522	325,991	1,468	**13.7%**
Natural Gas												
Utility Boiler	40,886	41,524	638	**10.1%**	4,597	4,595	-2	**-0.1%**	45,483	46,119	635	**5.9%**
Combined Cycle	129,989	137,682	7,693	**121.3%**	11,303	11,685	382	**8.8%**	141,292	149,368	8,075	**75.6%**
Simple Gas Turbine	7,471	7,959	488	**7.7%**	1,049	1,006	-44	**-1.0%**	8,521	8,965	444	**4.2%**
Residual Oil												
Utility Boiler	0	0	0	**0.0%**	0	0	0	**0.0%**	0	0	0	**0.0%**
Nuclear	37,719	37,775	56	**0.9%**	40,375	40,375	0	**0.0%**	78,094	78,149	56	**0.5%**
Biomass												
Utility Boiler / IGCC	3,594	3,600	7	**0.1%**	245	245	0	**0.0%**	3,839	3,846	7	**0.1%**
Other												
Renewable	99,677	99,677	0	**0.0%**	207,661	207,661	0	**0.0%**	307,338	307,338	0	**0.0%**
Total	341,226	347,570	6,345	**100.0%**	567,863	572,205	4,342	**100.0%**	909,089	919,776	10,686	**100.0%**

WTW Results: Combined CD and CS Operation For All AERs

WTW Petroleum Energy Use: Comparison of Technology and All Electric Range

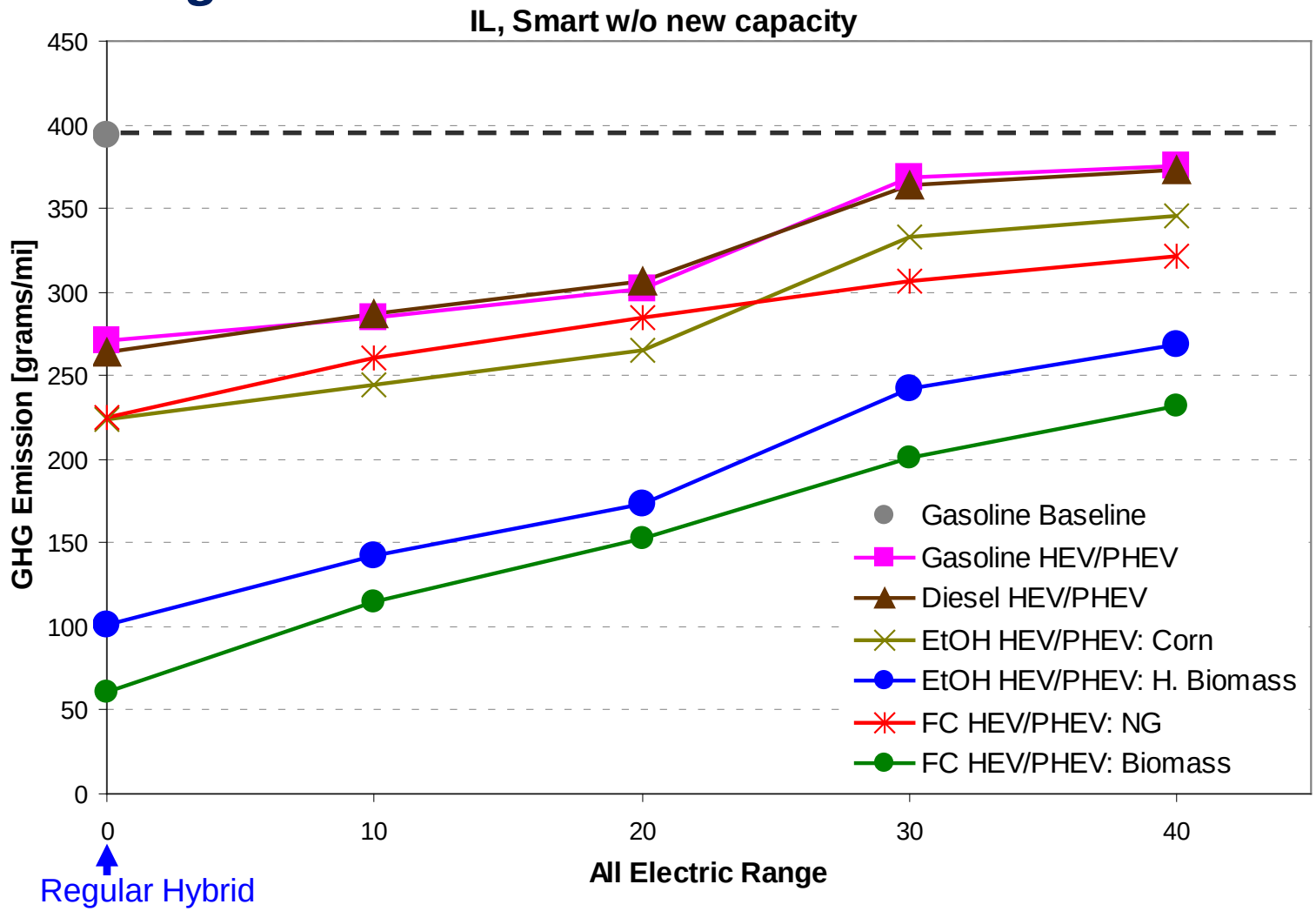


WTW GHG Emissions: Comparison of Technology and All Electric Range



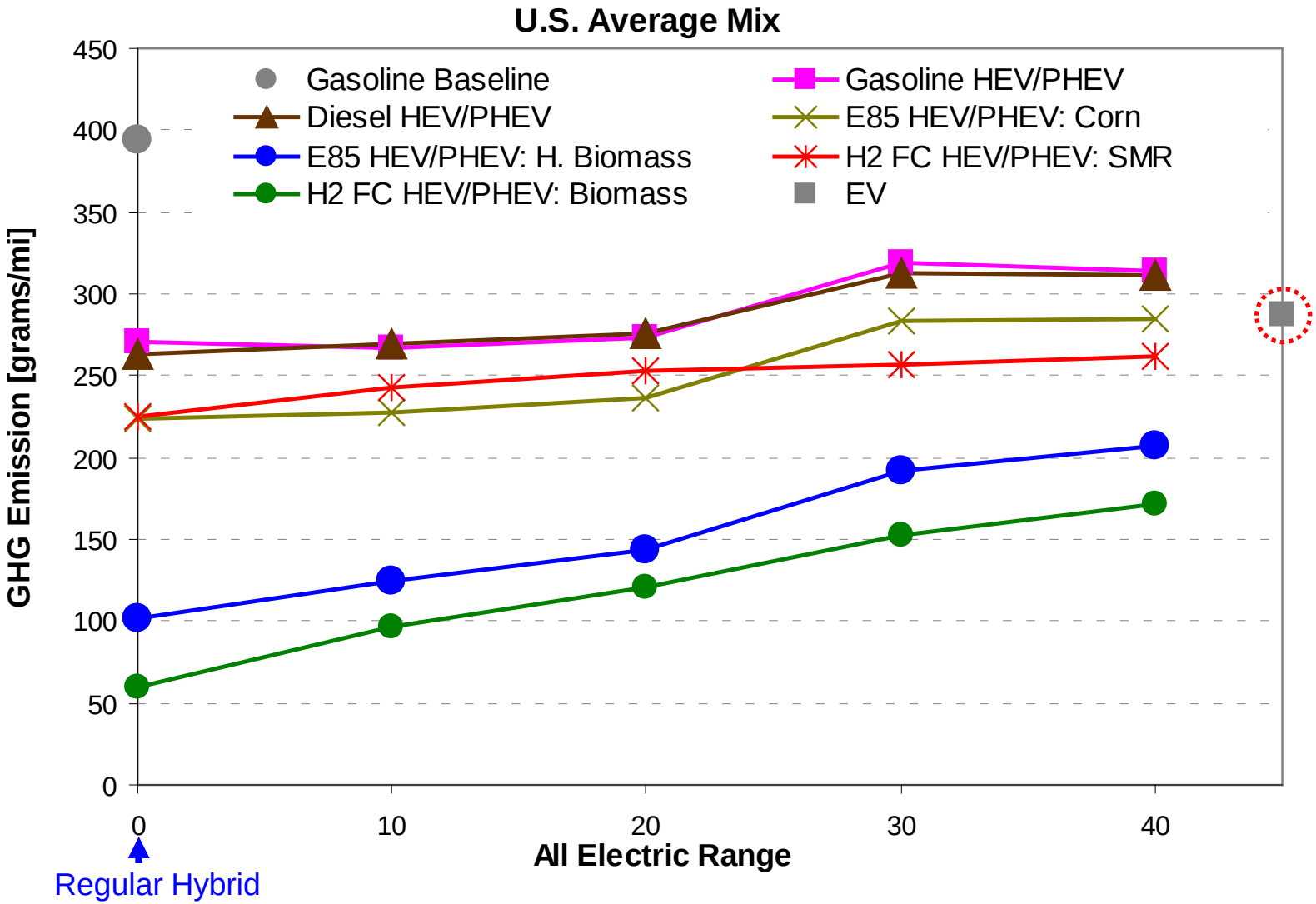
***Note**: The generation mix for the aggregate load of all PHEVs (with different AERs) is used to characterize the performance of individual AER of PHEVs*

WTW GHG Emissions: Comparison of Technology and All Electric Range



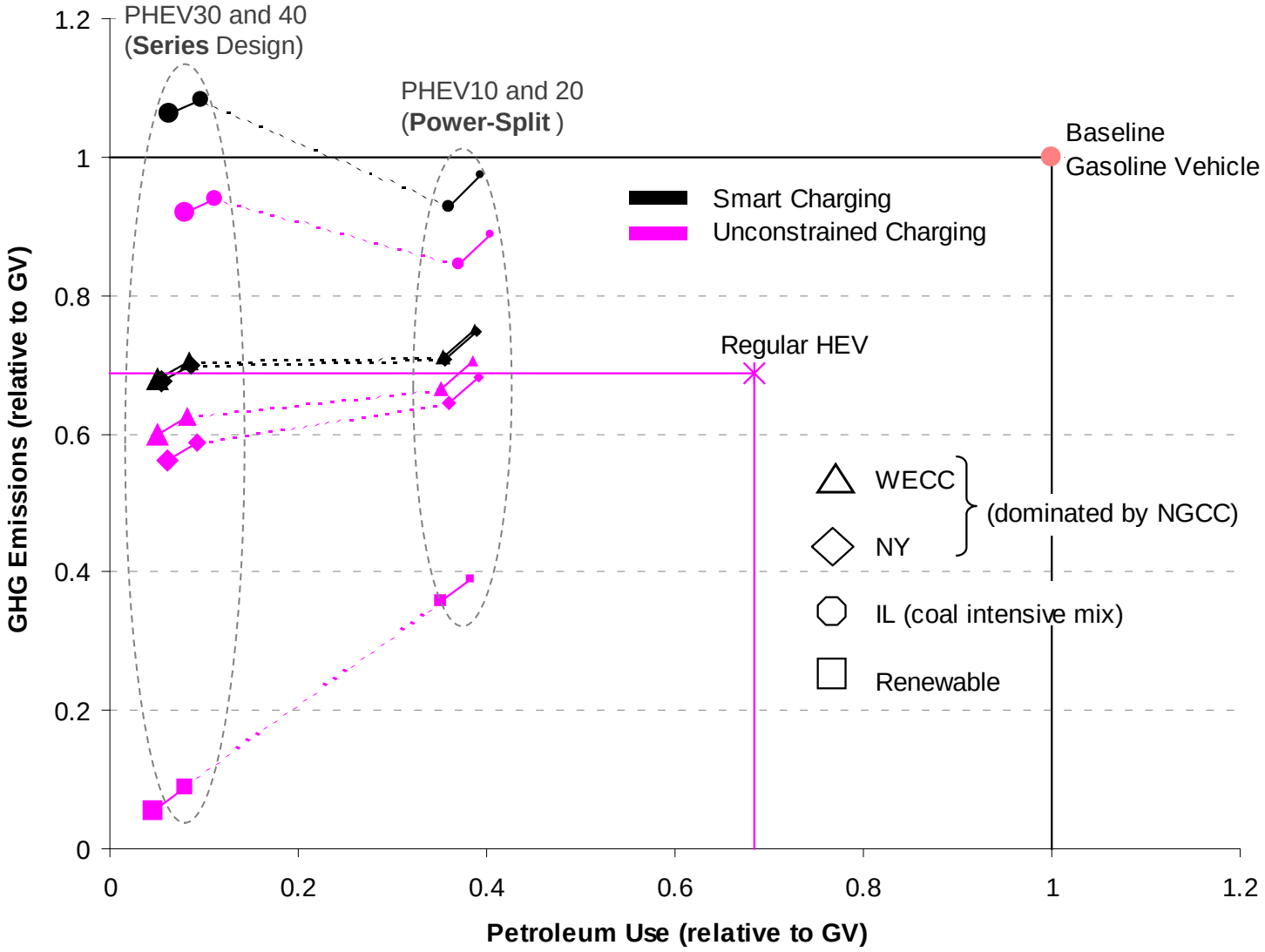
Note: The generation mix for the aggregate load of all PHEVs (with different AERs) is used to characterize the performance of individual AER of PHEVs

WTW GHG Emissions: Comparison of Technology and All Electric Range

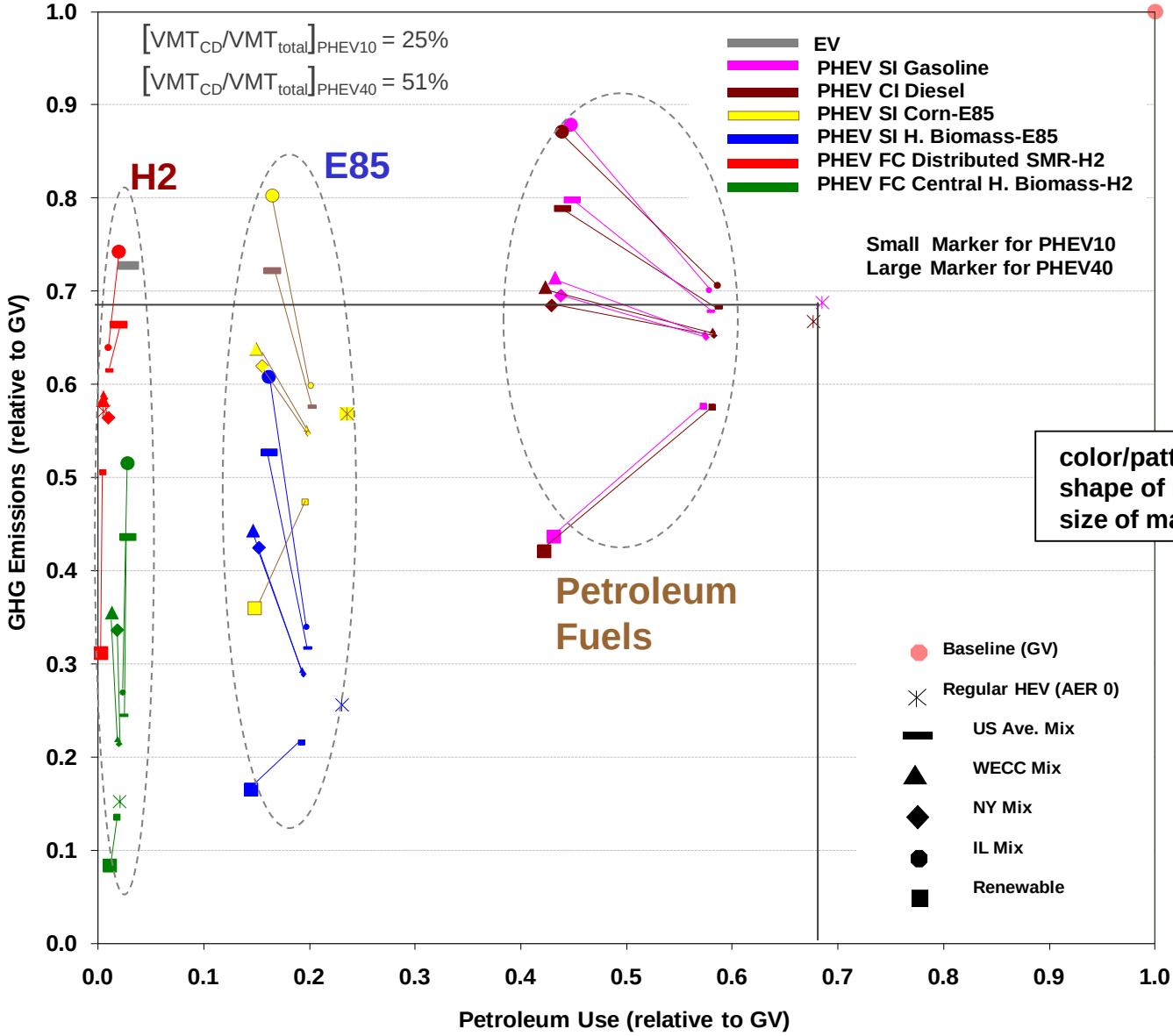


WTW Results Summary

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



color/pattern of marker = fuel/vehicle type
shape of marker = electricity generation mix
size of marker = AER rating

Acknowledgment

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Questions/Comments??

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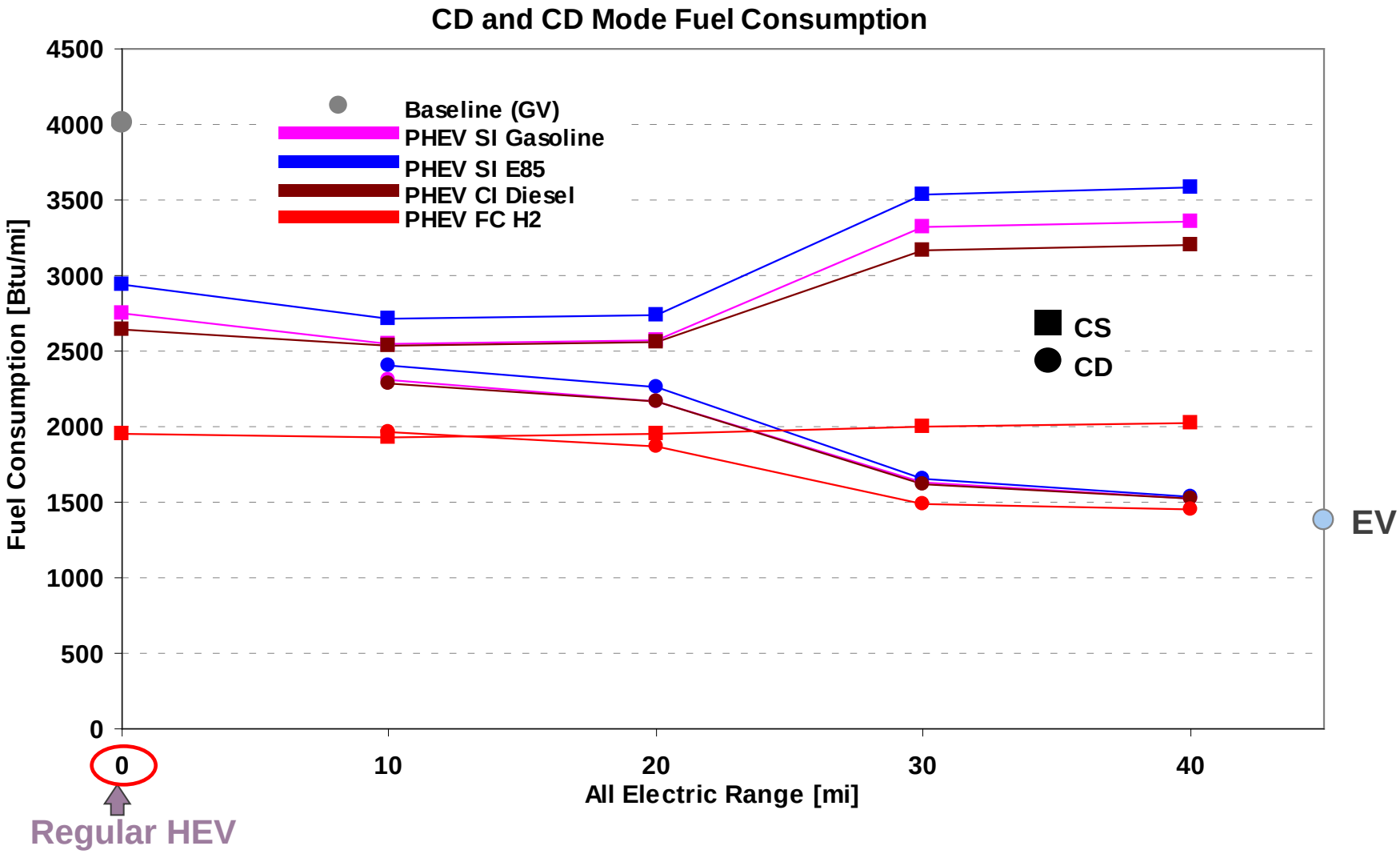
Report available at:
http://www.transportation.anl.gov/pdfs/TA/629.PDF

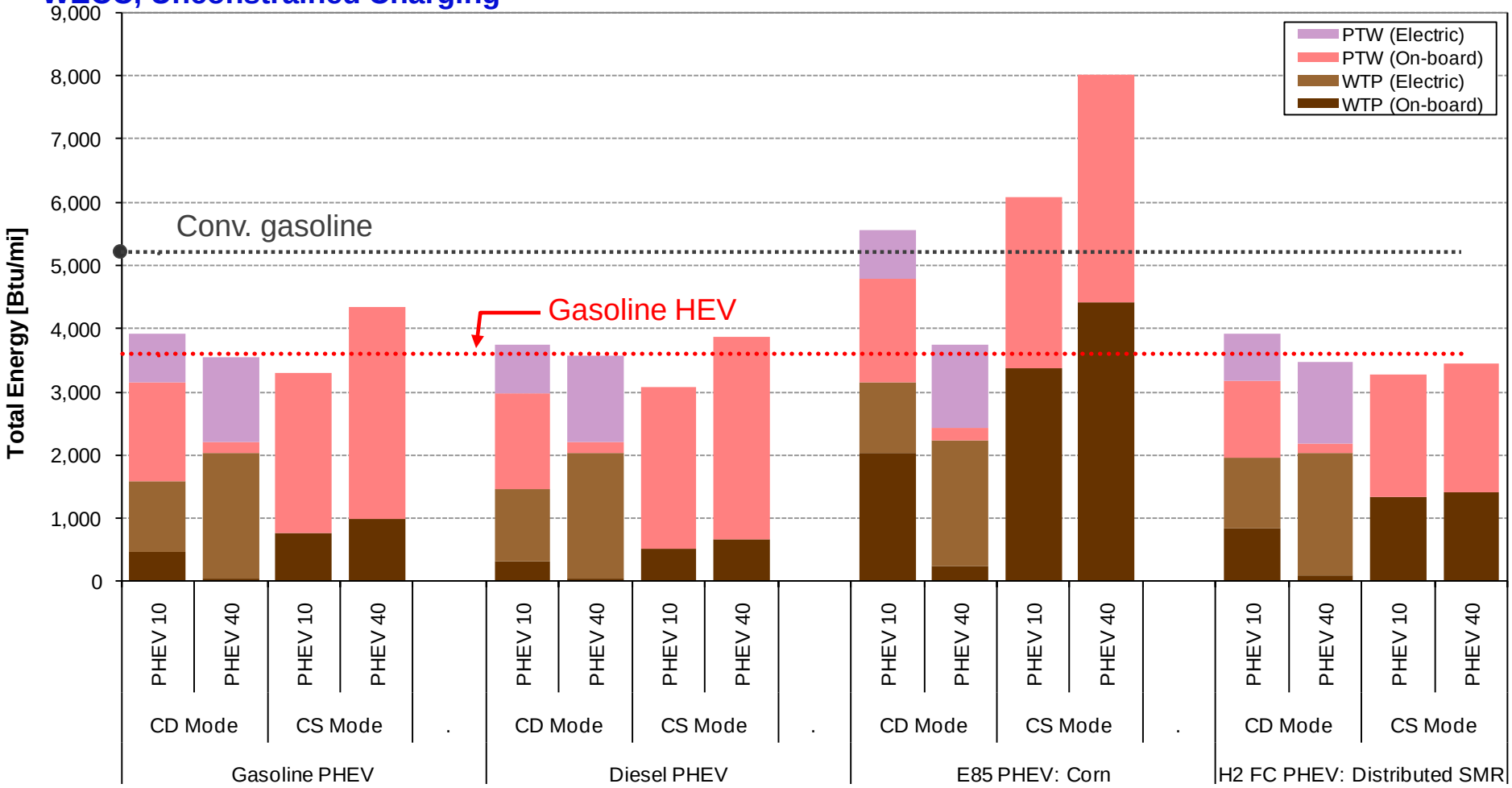
Backup Slides

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



CD vs. CS Operation: WTW Total Energy Use

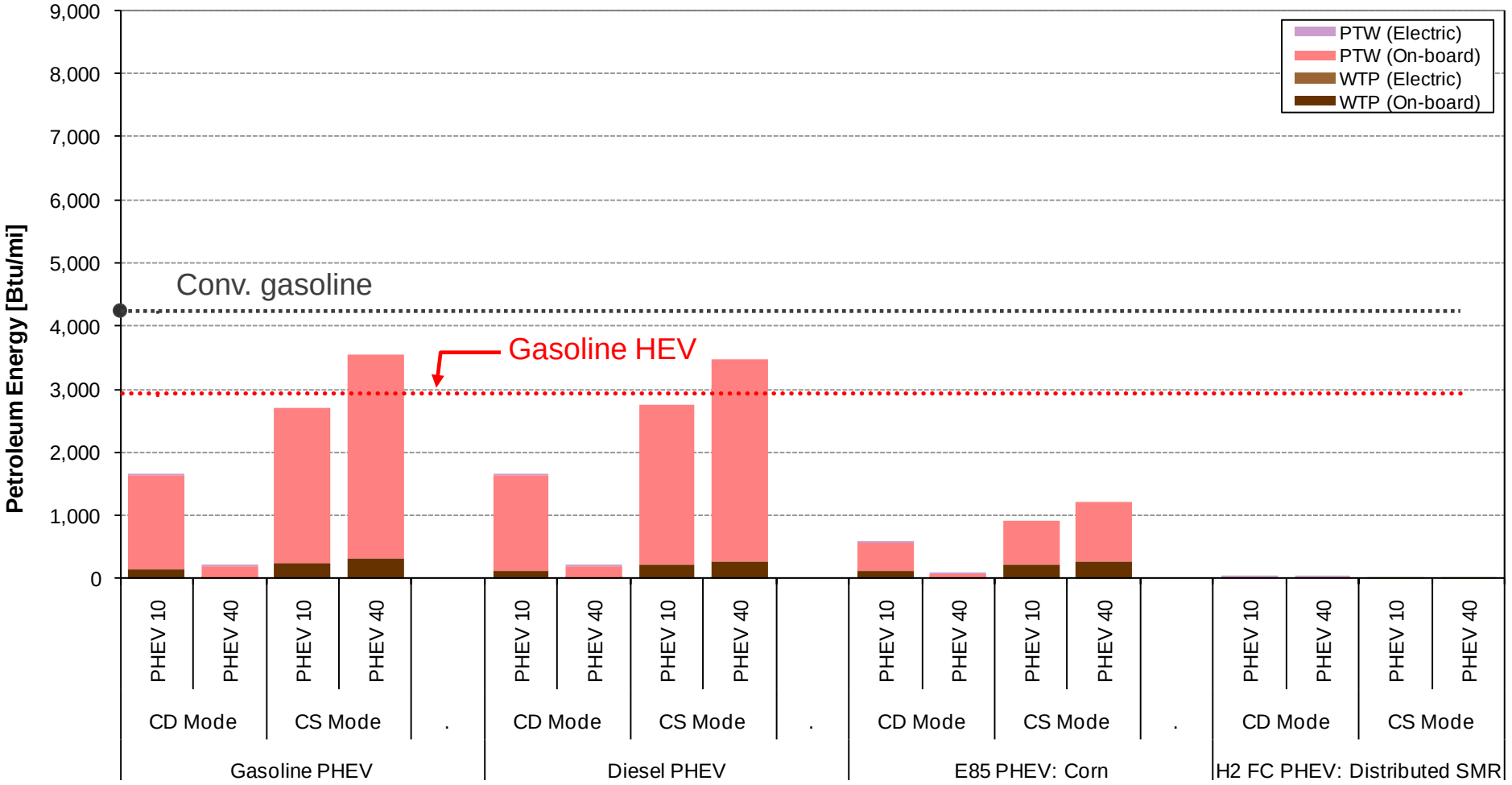
WECC, Unconstrained Charging



- 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)

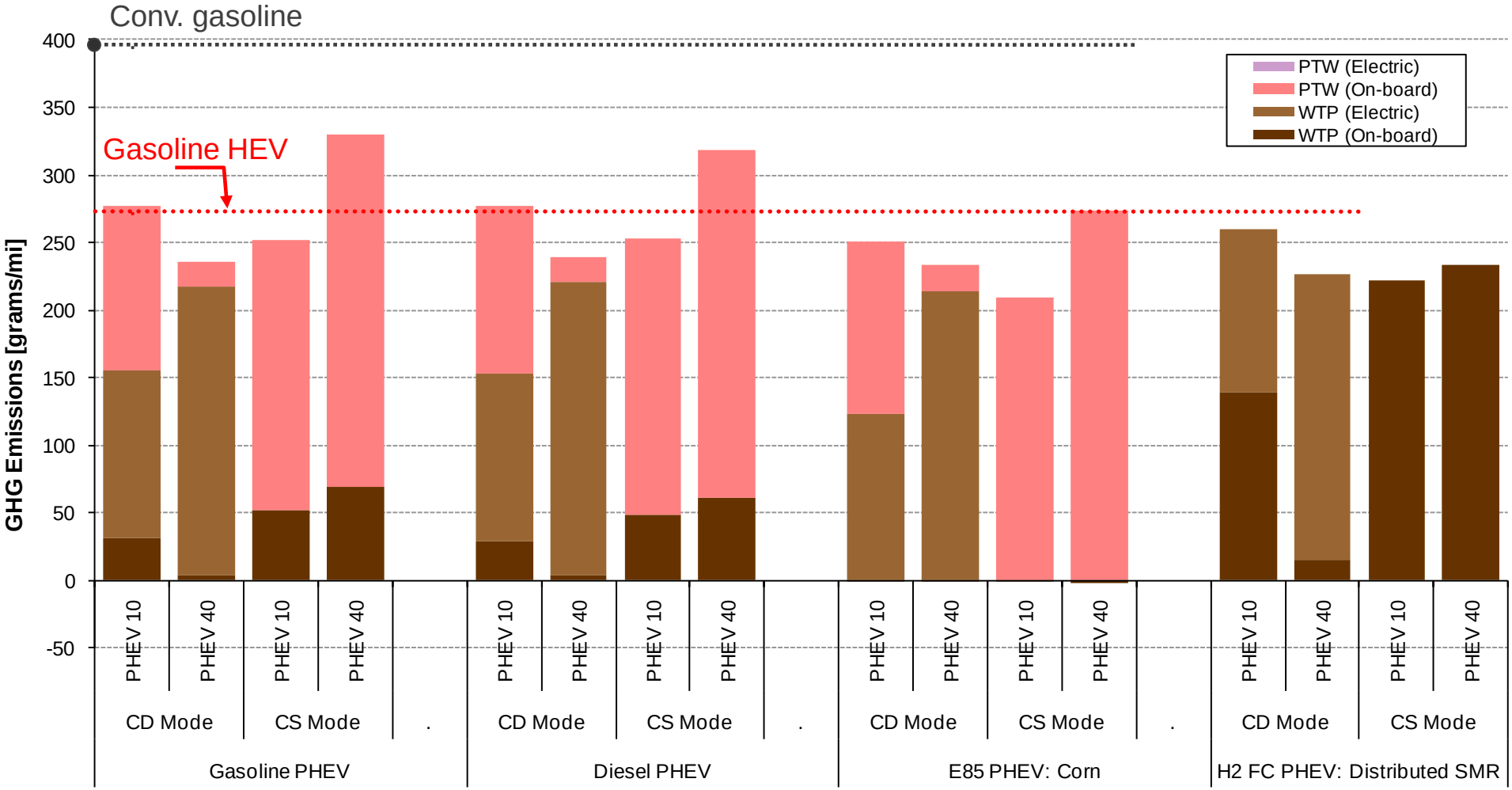
CD vs. CS Operation: WTW Petroleum Energy Use

WECC, Unconstrained Charging



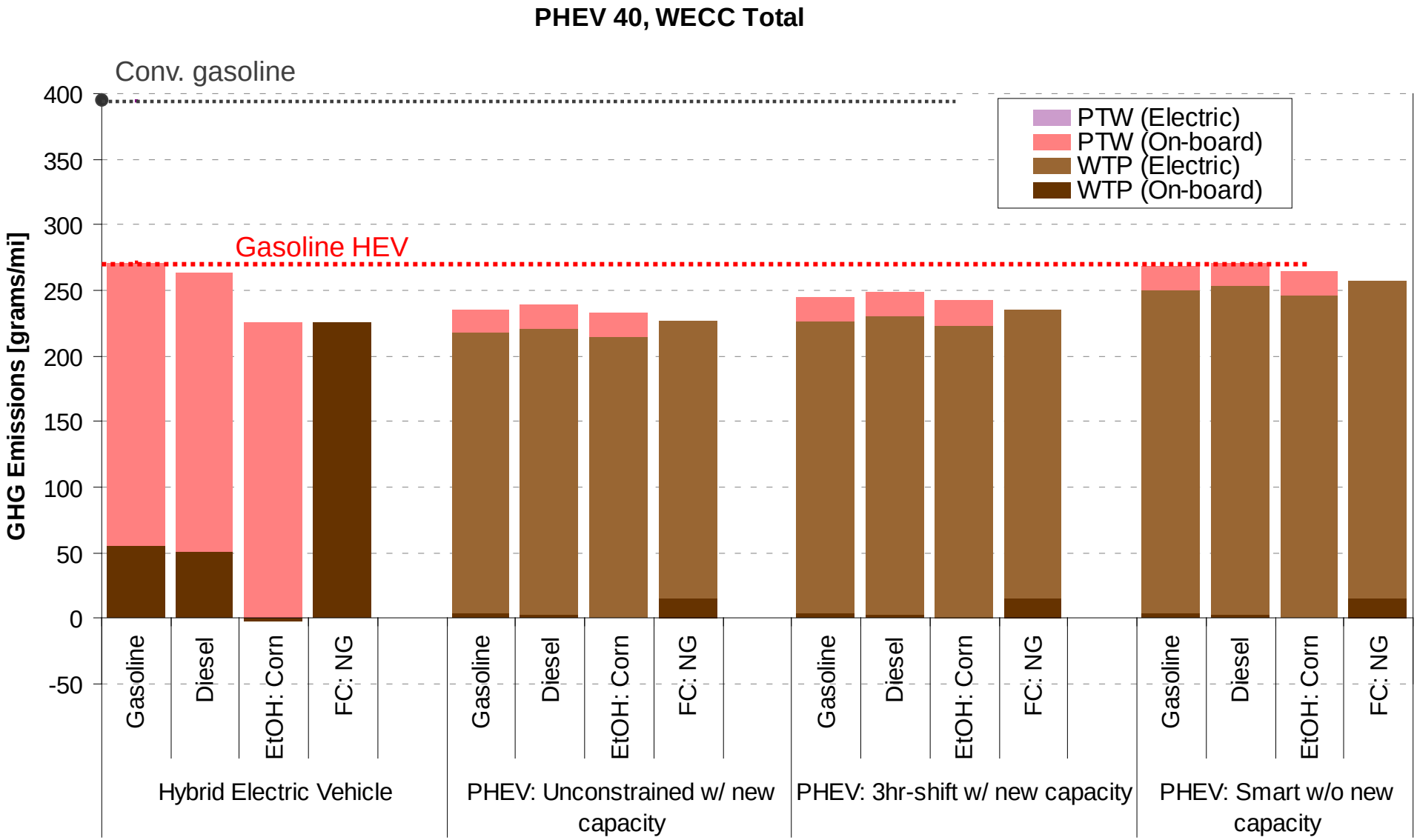
CD vs. CS Operation: WTW GHG Emissions

WECC, Unconstrained Charging



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

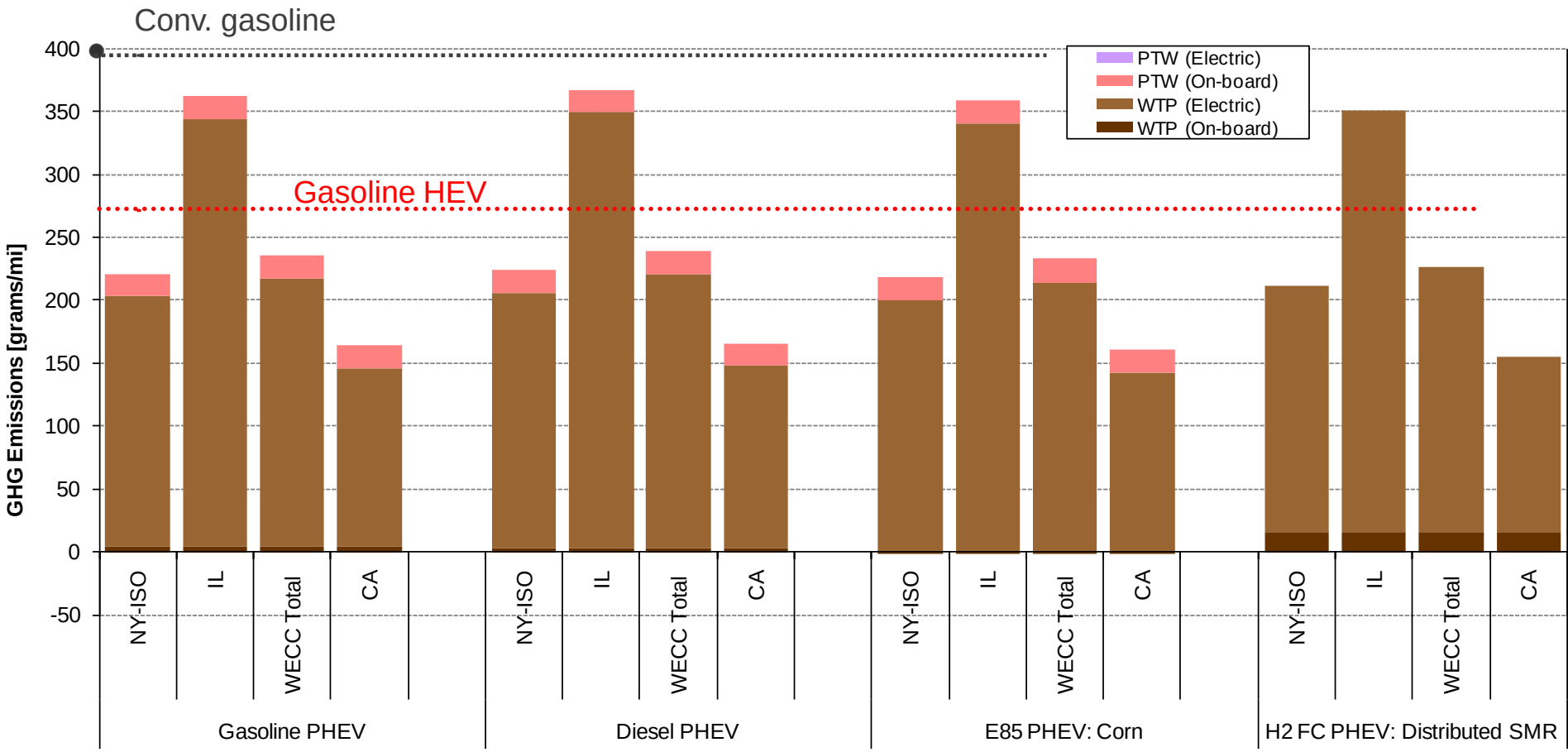
CD Operation Under Three Charging Scenarios: WTW GHG Emissions



- 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