Well-to-Wheels GHG Emissions of Natural Gas Use in Transportation: CNGVs, LNGVs, EVs, and FCVs

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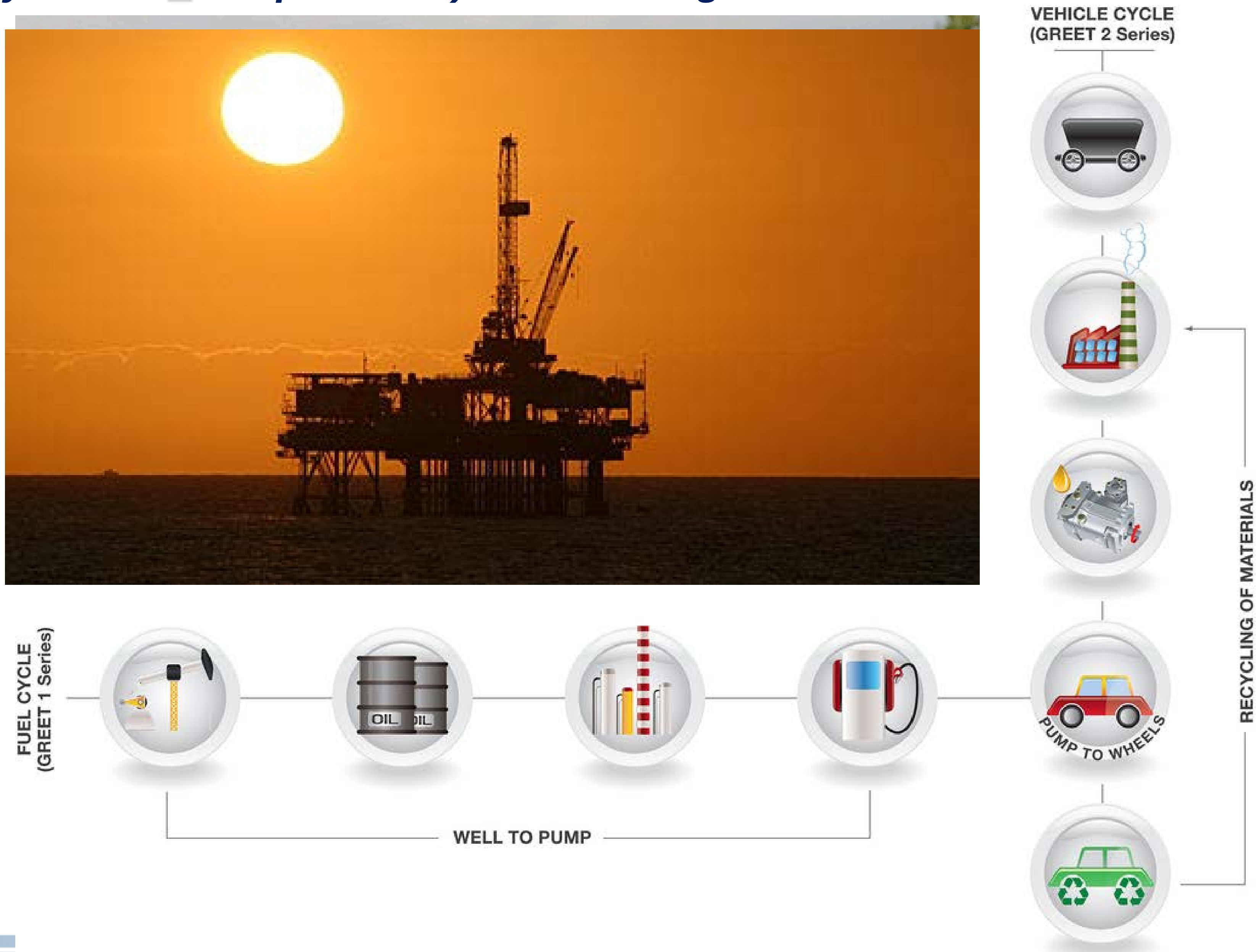
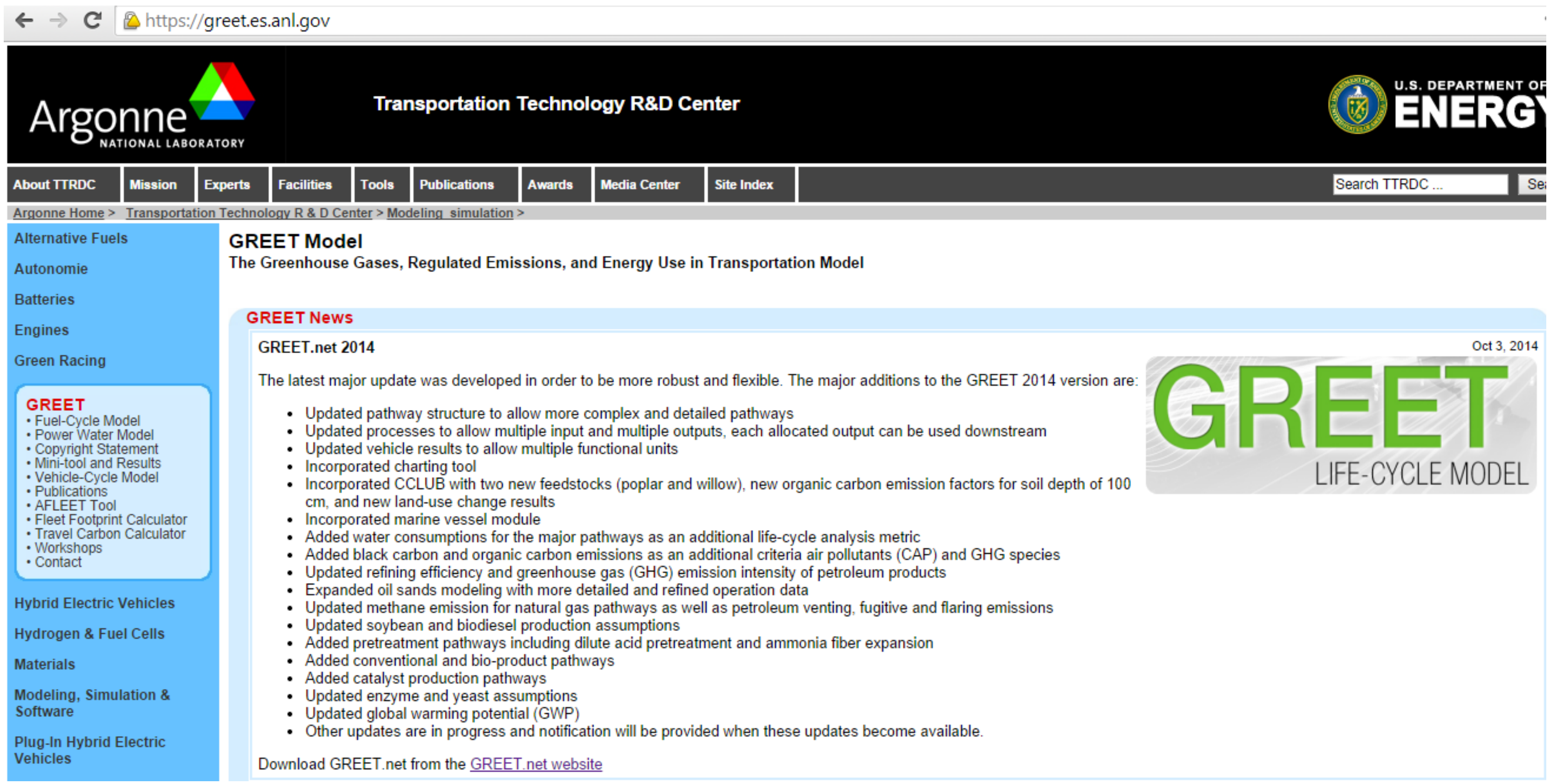
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model at Argonne National Lab



GREET and Its Documents Are Available at Argonne's GREET Website (http://greet.es.anl.gov/)

- Several DOE EERE programs have been sponsoring GREET development and applications since 1995
  - Vehicle Technology Office
  - Bioenergy Technology Office
  - Fuel Cell Technology Office
  - Geothermal Technology Office (previously)
- The current GREET version (GREET1_2014) was released in October 2014



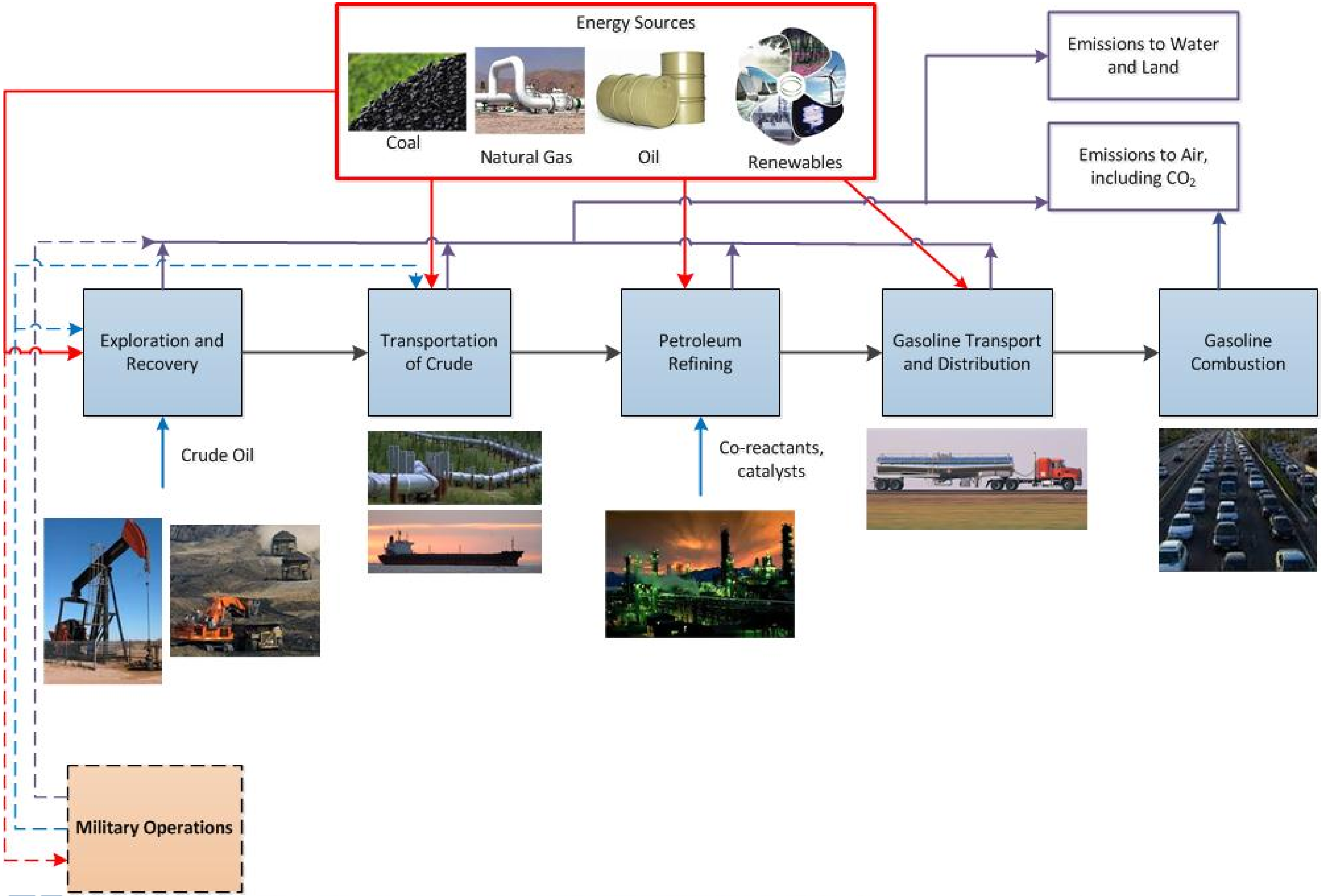
GREET Outputs Include Energy Use, Greenhouse Gases, and Criteria Pollutants for Vehicle/Fuel Systems

- Energy use
  - Total energy: fossil energy and renewable energy
    - Fossil energy: petroleum, natural gas, and coal (they are estimated separately)
    - Renewable energy: biomass, nuclear energy, hydro-power, wind power, and solar energy
- Greenhouse gases (GHGs)
  - CO_2, CH_4, N_2O, and black carbon (in 2014 release)
  - CO_2e of the three (with their global warming potentials)
- Criteria pollutants
  - VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, and SO_x
  - They are estimated separately for
    - Total (emissions everywhere)
    - Urban (a subset of the total)
  - Water consumption (in 2014 release)
- GREET LCA functional units
  - Per mile driven
  - Per unit of energy (million Btu, MJ, gasoline gallon equivalent)
  - Other units (such as per ton of biomass)

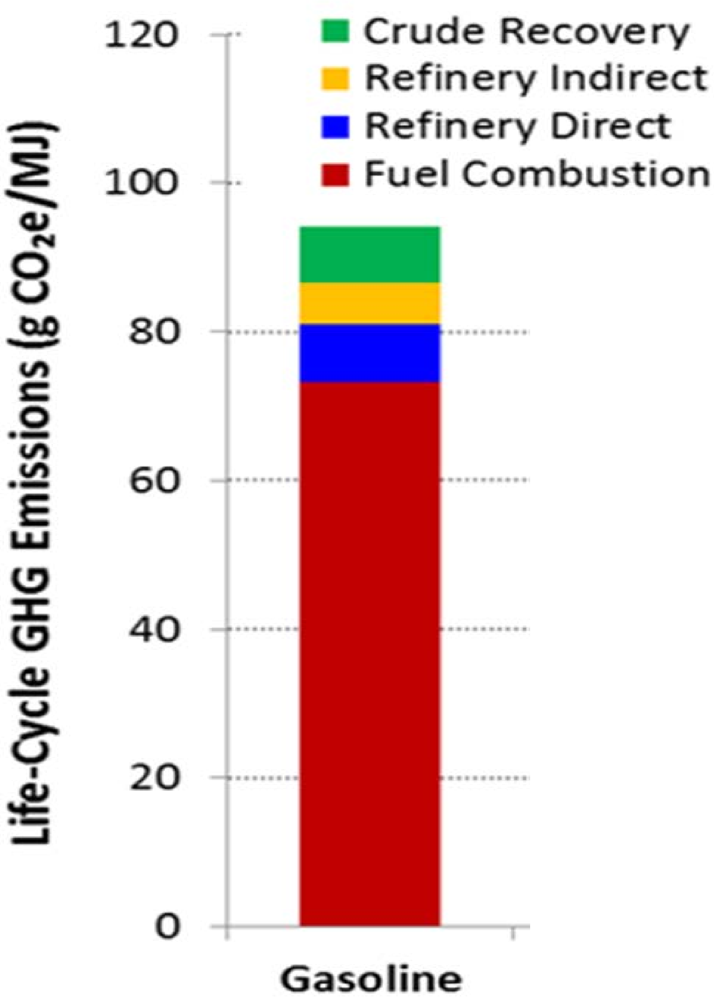
GREET Includes More Than 100 Fuel Production Pathways from Various Energy Feedstock Sources

Feedstock	Fuel
Petroleum Conventional Oil Sands	Gasoline Diesel Jet Fuel Liquefied Petroleum Gas Naphtha Residual Oil
Coal	Hydrogen Fischer-Tropsch Diesel Fischer-Tropsch Jet Methanol Dimethyl Ether
Natural Gas North American Non-North American Shale gas **Renewable Natural Gas** Landfill Gas Animal Waste Waste water treatment	Compressed Natural Gas Liquefied Natural Gas Liquefied Petroleum Gas Methanol Dimethyl Ether Fischer-Tropsch Diesel Fischer-Tropsch Jet Fischer-Tropsch Naphtha Hydrogen
Coke Oven Gas Petroleum Coke Nuclear Energy	Hydrogen
Corn	Ethanol Butanol
Sugarcane	Ethanol
Soybeans Palm Rapeseed Jatropha Camelina Algae	Biodiesel Renewable Diesel Renewable Gasoline Hydroprocessed Renewable Jet
Cellulosic Biomass Switchgrass Willow/Poplar Crop Residues Forest Residues Miscanthus	Ethanol Hydrogen Methanol Dimethyl Ether Fischer-Tropsch Diesel Fischer-Tropsch Jet Pyro Gasoline/Diesel/Jet
Residual Oil Coal Natural Gas Biomass Other Renewables	Electricity

LCA System Boundary: Petroleum to Gasoline

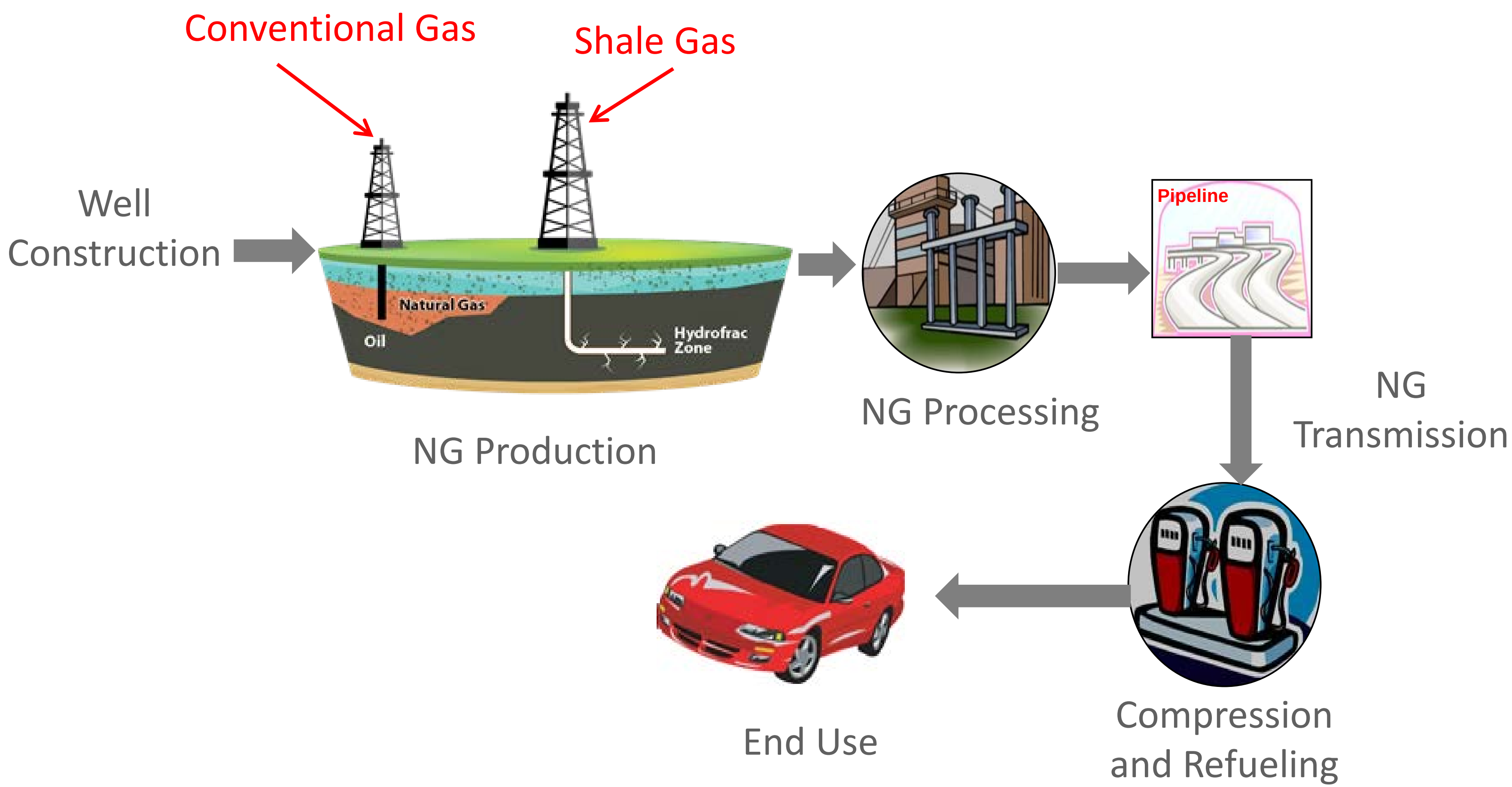


Gasoline GHG emissions: grams/MJ



http://pubs.acs.org/doi/abs/10.1021/es5010347
http://pubs.acs.org/doi/abs/10.1021/es501035a

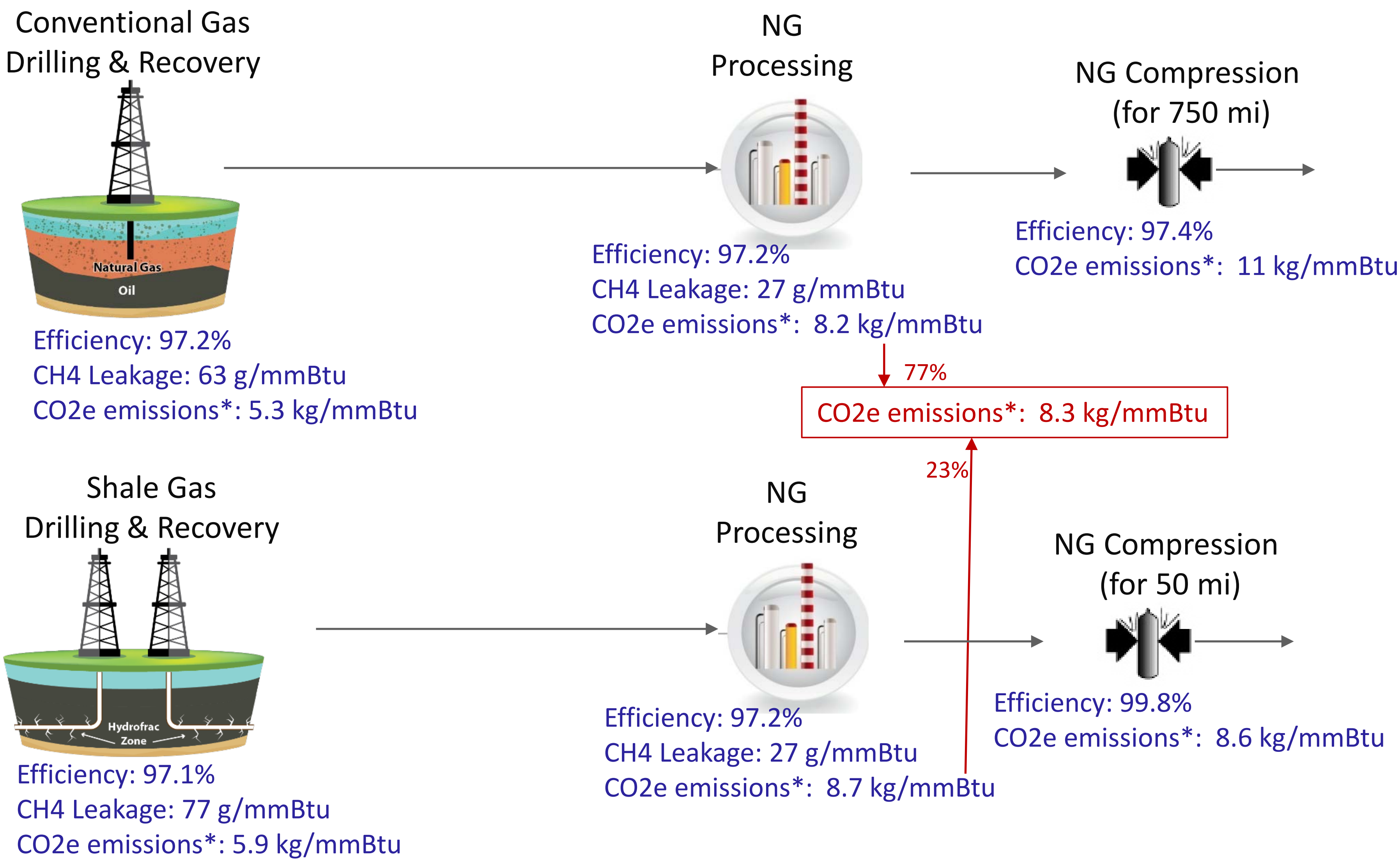
LCA System Boundary: Compressed Natural Gas



- CH_4 leakage during the entire supply chain
- Emissions from process fuels for recovery, transportation, and compression; and NG combustion
- Infrastructure-related emissions are usually small

CNG cars and LNG trucks

Key Upstream Stages for Natural Gas Recovery and Processing

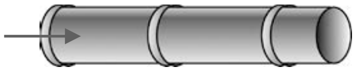


*Includes all upstream emissions

Key Parameters and Emissions for CNG and LNG Pathways

CNG Car

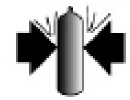
NG Transportation
(750 mi)



Efficiency: 99.6%
CH4 Leakage: 89 g/mmBtu
CO2e emissions*: 14 kg/mmBtu

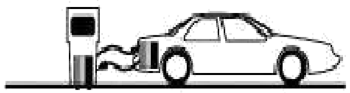
NG
Distribution

Efficiency: 99.7%
CH4 Leakage: 64 g/mmBtu
CO2e emissions*: 16 kg/mmBtu



NG
Compression

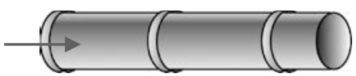
Efficiency: 97.9%
CO2e emissions*:
19.4 kg/mmBtu



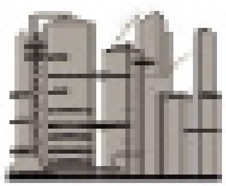
CNGV
TTW Efficiency: 16%
CO2e emissions*:
80 kg/mmBtu

LNG Heavy Trucks

NG Transportation
(50 mi)

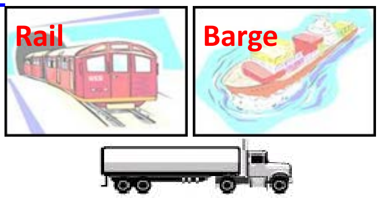


Efficiency: 99.98%
CH4 Leakage: 6 g/mmBtu
CO2e emissions*: 11.2 kg/mmBtu



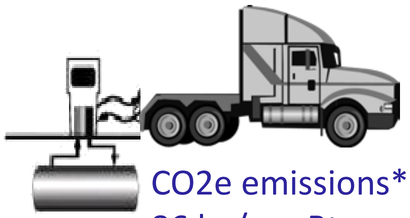
LNG Plant

Efficiency: 91%
CH4 Leakage: 34 g/mmBtu
CO2e emissions*: 16.5
kg/mmBtu



Distribution
and Storage

Efficiency: 99%
CH4 Boiloff loss: 48 g/mmBtu
CO2e emissions*: 18.7
kg/mmBtu

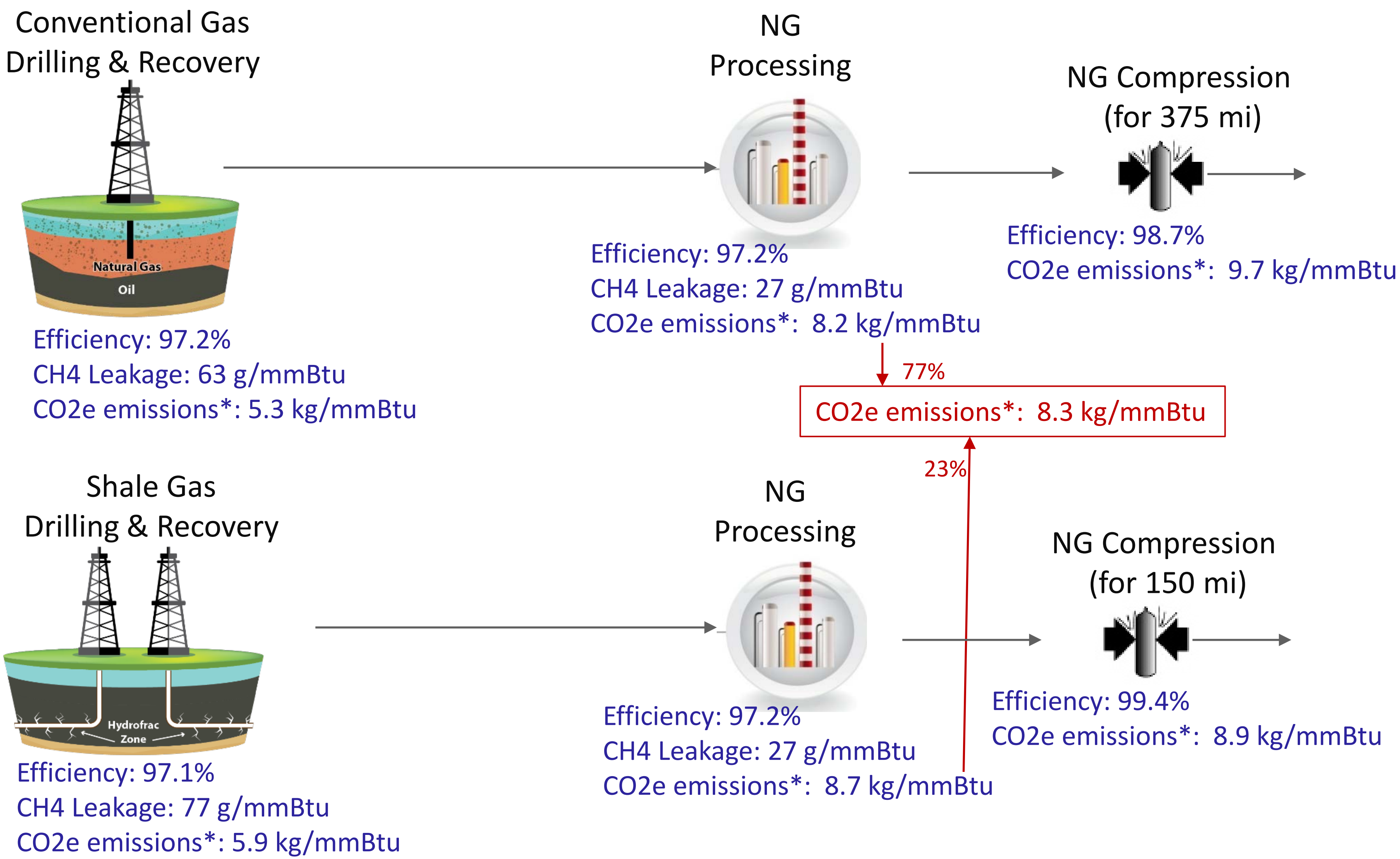


CO2e emissions*:
86 kg/mmBtu

*Includes all upstream emissions

BEVs and FCEVs

Key Upstream Stages for Natural Gas Recovery and Processing

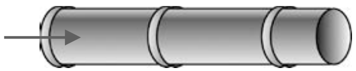


*Includes all upstream emissions

Key Parameters and Emissions for NG-Based Electricity in Electric Vehicles and Hydrogen in Fuel Cell Electric vehicles

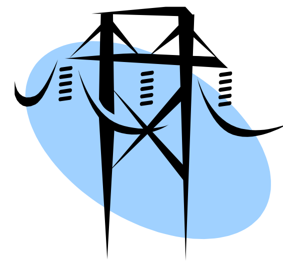
Electric Car

NG Transportation
(375 mi)



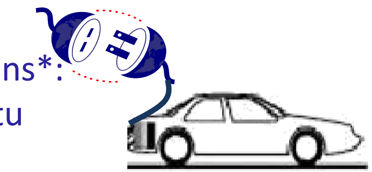
Efficiency: 99.8%
CH_4 Leakage: 45 g/mmBtu
CO_2e emissions*: 10.8 kg/mmBtu

NG Power Plants
Efficiency: 50%
CO_2e emissions*:
140 kg/mmBtu



Electricity
T&D
Efficiency: 93.5%
CO_2e emissions*:
150 kg/mmBtu

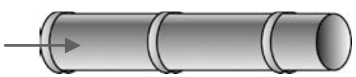
Efficiency: 85%
Charging
CO_2e emissions*:
175 kg/mmBtu



BEV
TTW Efficiency: 67%
CO_2e emissions*:
175 kg/mmBtu

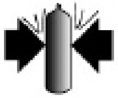
Fuel Cell Car

NG Transportation
(150 mi)



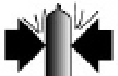
Efficiency: 99.9%
CH_4 Leakage: 18 g/mmBtu
CO_2e emissions*: 9.3 kg/mmBtu

NG SMR Plant
Efficiency: 72%
CO_2e emissions*:
97 kg/mmBtu

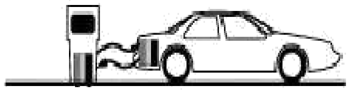


H_2
Compression
Efficiency: 97%
CO_2e emissions*:
103 kg/mmBtu

H_2 T&D
(750 mi)



H_2
Compression
Efficiency: 91.5%
CO_2e emissions*:
120 kg/mmBtu



FCEV
TTW Efficiency: 35%
CO_2e emissions*:
120 kg/mmBtu

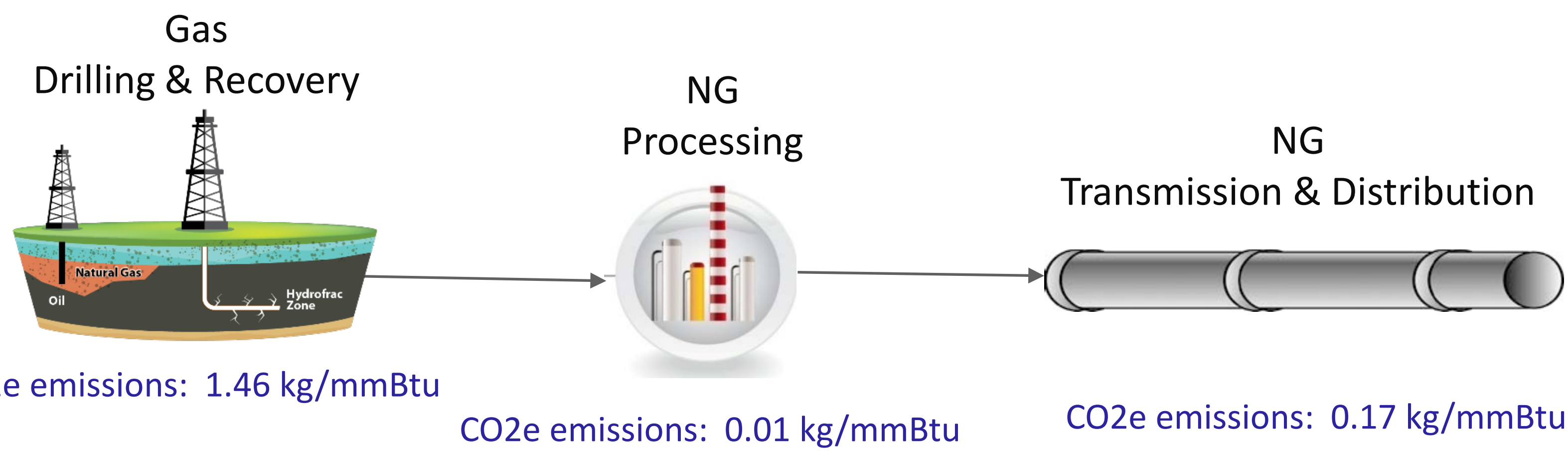
*Includes all upstream emissions

Comparison of pathway efficiency with ORNL paper

	Gasoline ICEV	Diesel ICEV	CNGV	BEV [excluding charging losses]	H2 FCEV
ANL Fuel Economy [MPGGE]ǂ	25	30	23	99	52
ANL TTW (vehicle) efficiency	17%	20%	16%	67%	35%
ORNL TTW (vehicle) efficiency	Did not provide	N/A	14%-26%	79%-91%	N/A

Vehicle Technology		ProductionxPower generation (by deduction)	Compression /T&D	Charging/fueling efficiency	WTT efficiency	TTW (vehicle) efficiency	WTW efficiency
CNGV	ANL	94.5%	96.7%	97.9%	89.46%	16%	**14%**
	ORNL	80% - 89.5% (by deduction)	95%	Lumped w/ compression	76%-85%	14%-26%	**11%-22%**
BEV	ANL	93.06% x 50%	93.5%	85%	36.98%	67%	**25%**
	ORNL	51%	92%	95%	28%-45%	79%-91%	**22%-35%**
FCEV	ANL	93.8% x 72%	97%	91.5%	60%	35%	**21%**

Infrastructure Steel Impact is Small but not Negligible



Shares	Gas	Oil
Onshore	87.1%	73.8%
Offshore	12.9%	26.2%

	Gas	Oil
	(g GHG/MJ)	(g GHG/MJ)
Onshore	1.22	0.55
Offshore	2.57	2.34
Total	1.39	1.02

https://greet.es.anl.gov/publication-oil-gas-prod-infra

Methane Leakage Estimates in GREET

- Methane leakage has been one of the hotly debated issues in the past several years
- First major revision was Argonne’s 2011 analysis
  - Based on EPA’s 2011 GHG inventory
  - Examined methane leakage of coal, NG and petroleum sectors
- GREET1_2014 uses EPA’s 2014 inventory data
  - Liquid unloading emissions
  - Shale gas completion/workover frequency and emissions
  - Well equipment emissions
  - Estimated Ultimate Recovery (EUR) per gas well

Methane Leakage of Natural Gas Production, Transmission, and Distribution Varies Significantly Among Studies

Sector	CH_4 Emissions: Percent of Volumetric NG Produced (Gross)									
	EPA - Inventory 5 yr avg (2011)	CMU - Marcellus Shale (2011)	NREL - Barnett Shale (2012)	API/ ANGA Survey (2012)	NOAA - DJ Basin (2012)	NOAA - Uintah Basin (2013)	Exxon Mobil (2013)	EPA - Inventory 5 yr avg (2013)	EPA - Inventory 2011 data (2013)	Univ. Texas (2013)
Gas Field	**1.18**		**0.9**	**0.75**	**2.3-7.7**	**6.2-11.7**	**0.6**	**0.59**	**0.44**	**0.42**
Completion/ Workover			0.7					0.22	0.17	0.03
Unloading			0					0.08	0.04	0.05
Other Sources			0.2					0.29	0.23	0.34
Processing	**0.16**		**0**				**0.17**	**0.15**	**0.16**	
Transmission	**0.38**		**0.4**				**0.42**	**0.36**	**0.34**	
Distribution	**0.26**							**0.26**	**0.23**	
Total	**1.98**	**2.2**						**1.36**	**1.17**	

Stage *Throughput-Based Methane Leakage* Rates Are More Accurate for LCA Applications

Sector	CH_4 Emissions: Percent of Volumetric NG Stage Throughput				
	EPA - Inventory 5 yr avg (2011)	EPA - Inventory 5 yr avg (2013)	EPA - Inventory 2011 data (2013)	GREET Shale Gas (2013)	GREET Conv. Gas (2013)
Gas Field	**1.32**	**0.67**	**0.49**	**0.58**	**0.34**
Completion/ Workover				0.25	0.003
Unloading				0.05	0.05
Other Sources				0.29	0.29
Processing	**0.17**	**0.17**	**0.18**	**0.18**	**0.18**
Transmission	**0.49**	**0.45**	**0.42**	**0.42**	**0.42**
Distribution	**0.57**	**0.52**	**0.46**	**0.46**	**0.46**
Total	**2.55**	**1.81**	**1.55**	**1.64**	**1.40**

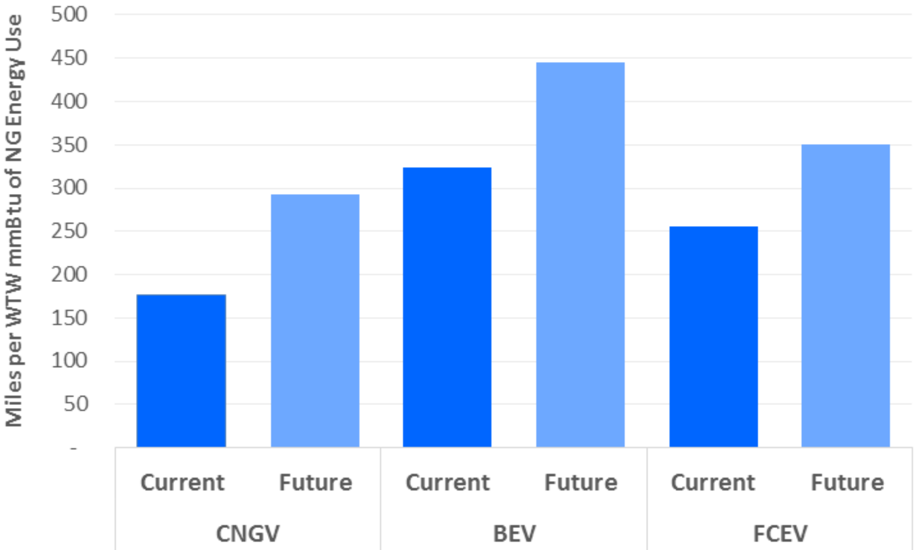
- Gross withdrawal includes NG used in enhanced oil recovery, flared NG, vented NG, and NGLs
  - LCA of NG requires to look at amount of NG leaked per NG at the end use
- On average, leak rates are 1.3x when using stage throughput approach
  - Distribution leak rates are 2x

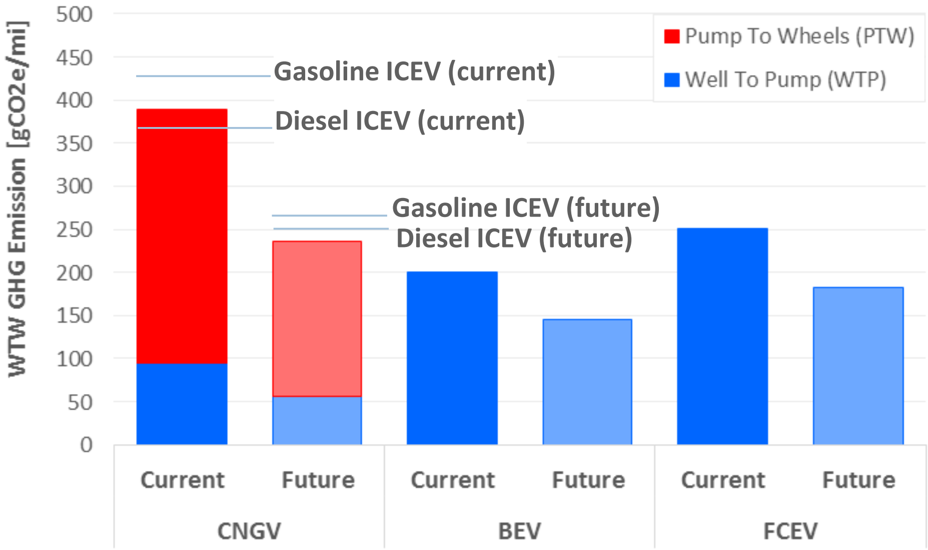
Summary of Differences in Results between GREET1_2013 and GREET1_2014

Sector	Process	Unit	Shale 2013	Conventional 2013	Shale 2014	Conventional 2014	Shale % Change	Conventional % Change
Production	Completion	g CH4/million Btu NG	42.8	0.5	12.4	0.5	-71%	-1%
	Workover		8.6	0.0	2.5	0.0	-71%	-1%
	Liquid Unloading		10.2	10.2	10.4	10.4	2%	2%
	Well Equipment		59.1	59.1	51.3	51.3	-13%	-13%
Processing	Processing	g CH4/million Btu NG	37.0	37.0	26.7	26.7	-28%	-28%
Transmission	Transmission and Storage	g CH4/million Btu NG	87.4	87.4	81.2	81.2	-7%	-7%
Distribution	Distribution (station pathway)	g CH4/million Btu NG	70.7	70.7	63.6	63.6	-10%	-10%
Total		g CH4/million Btu NG	315.7	264.9	248.1	233.8	-21%	-12%

https://greet.es.anl.gov/publication-emissions-ng-2014

*Natural Gas Energy Use and GHG Emissions For Various Pathways**





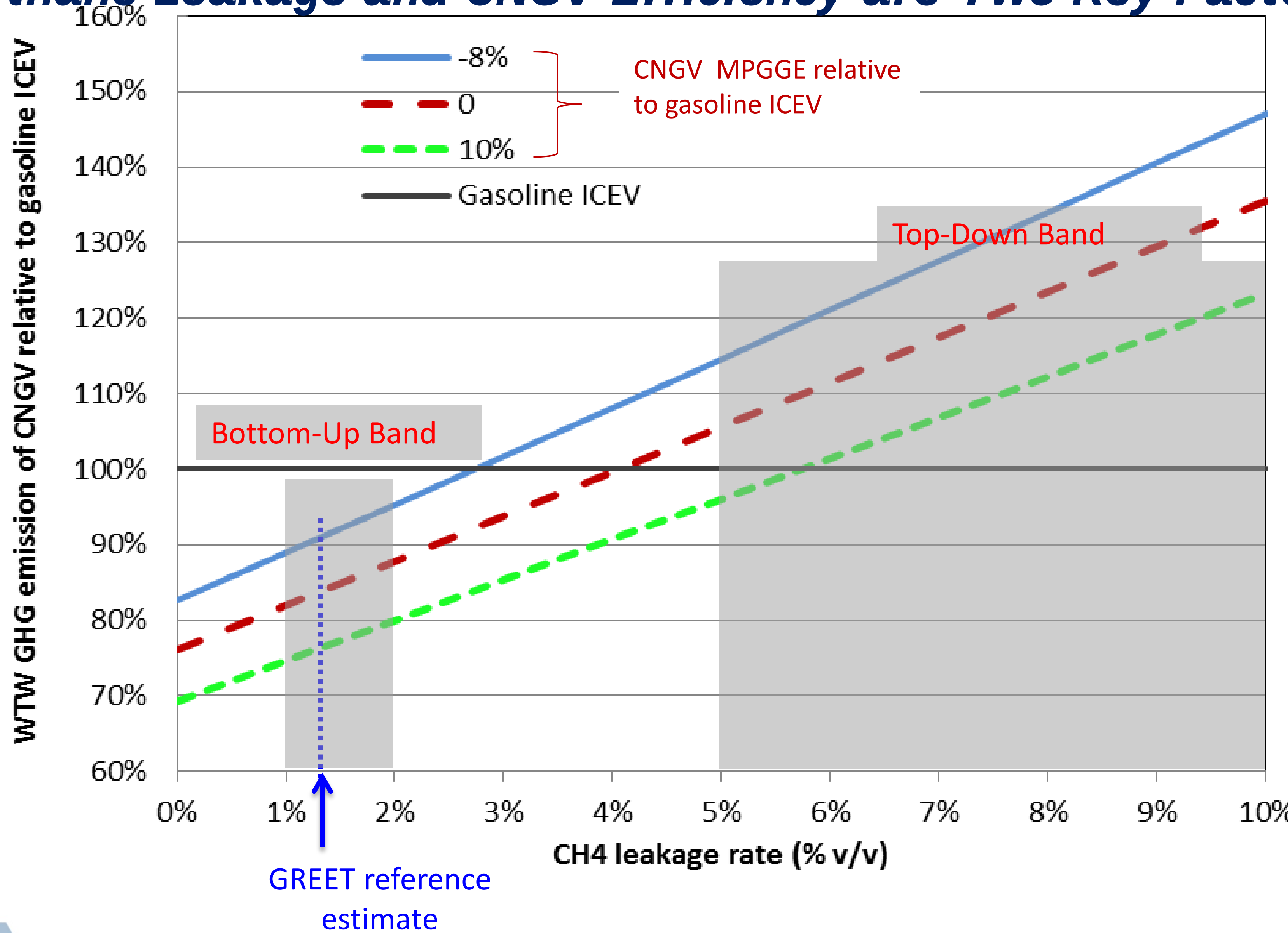
- 85% of NG electricity for BEV recharging is from NGCC
- NG electricity is used for NG compression to refuel CNGV (250 bar)
- NG electrciity is used for H2 compression to refuel FCEV (700 bar)
- CH4 leakage contributes 6-8% of WTW GHG emissions

Vehicle Technology	Gasoline ICEV	Diesel ICEV	CNGV	BEV [including charging losses]	H2 FCEV
Current Fuel Economy [MPGGE]ǂ	25	30	23	84	52
Future Fuel Economy [MPGGE]ǂ	40	44	38	105	70

*GREET1_2014 model, http://greet.es.anl.gov/

ǂ Adjusted for on-road performance

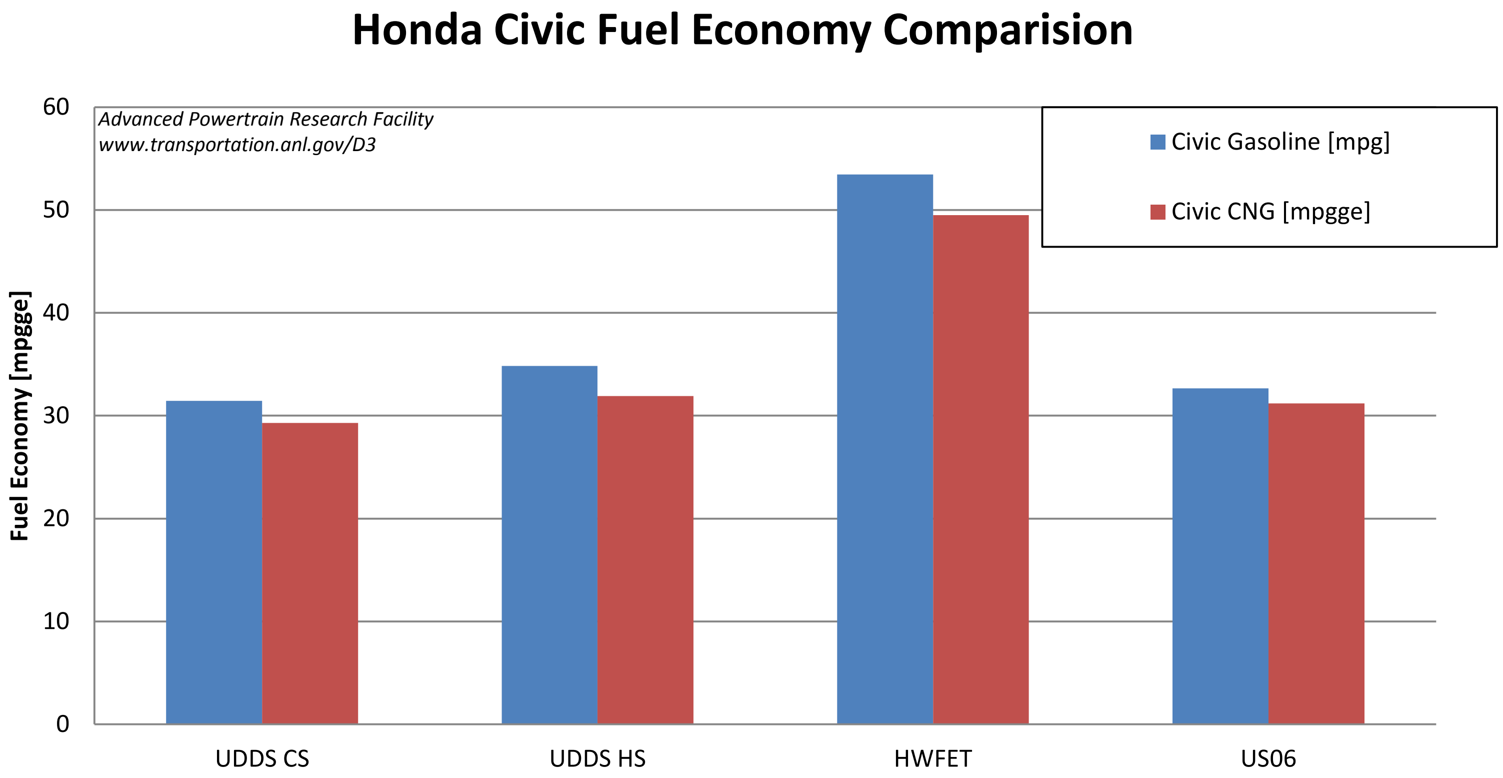
WTW GHG Emissions of CNG Vehicles vs. Gasoline Vehicles — Methane Leakage and CNGV Efficiency are Two Key Factors



Engine Design and CNG Tank Weight Impact CNGV Fuel Economy

Argonne tested 2012 gasoline and CNG Honda Civics

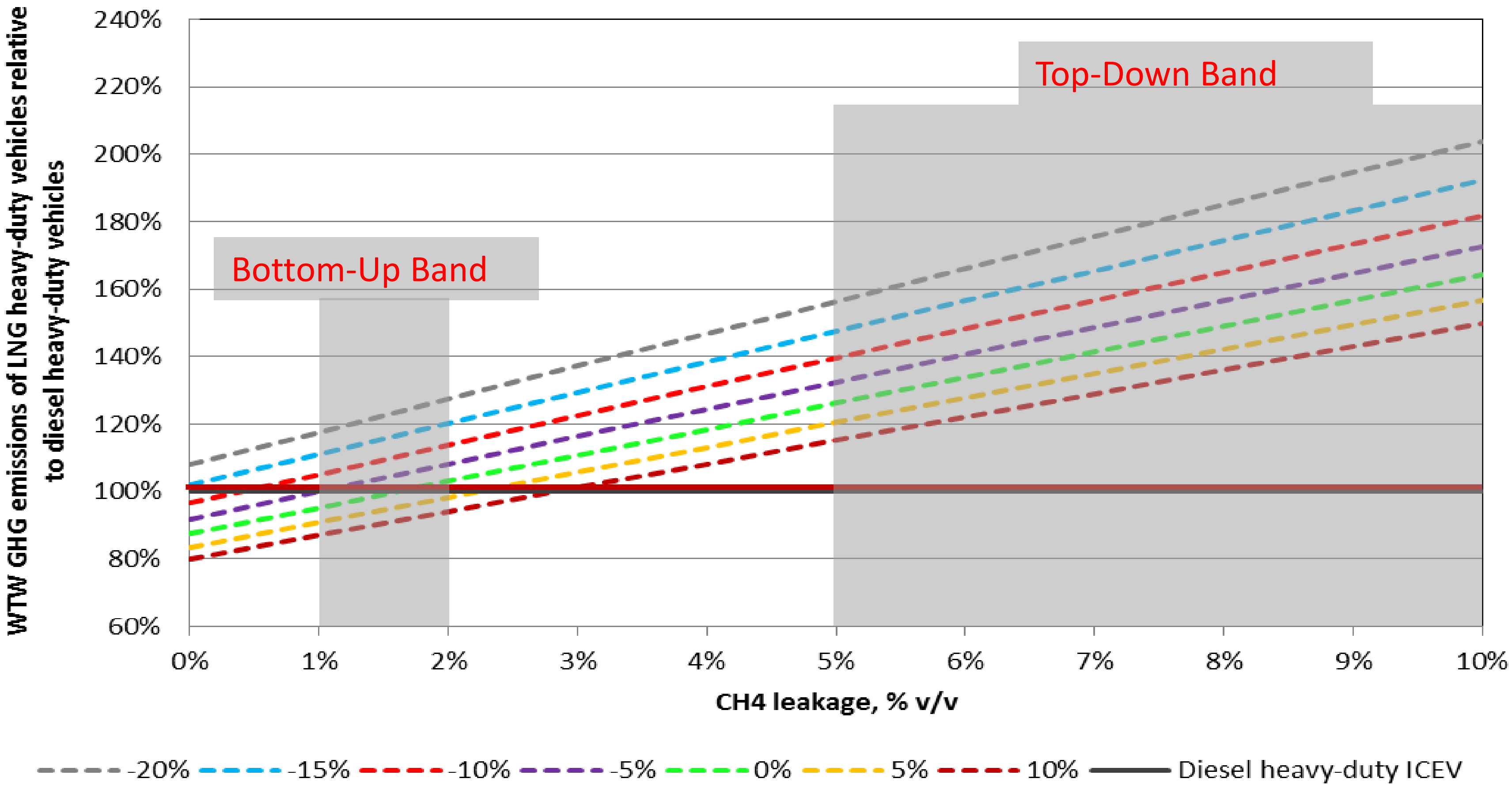
- CNG Civic uses carbon fiber tank with weight of ~ 70 lb
- CNG fuel economy penalty of 3% to 10%
- Fueleconomy.gov show a fuel economy penalty of 3% to 4% for CNG Civic



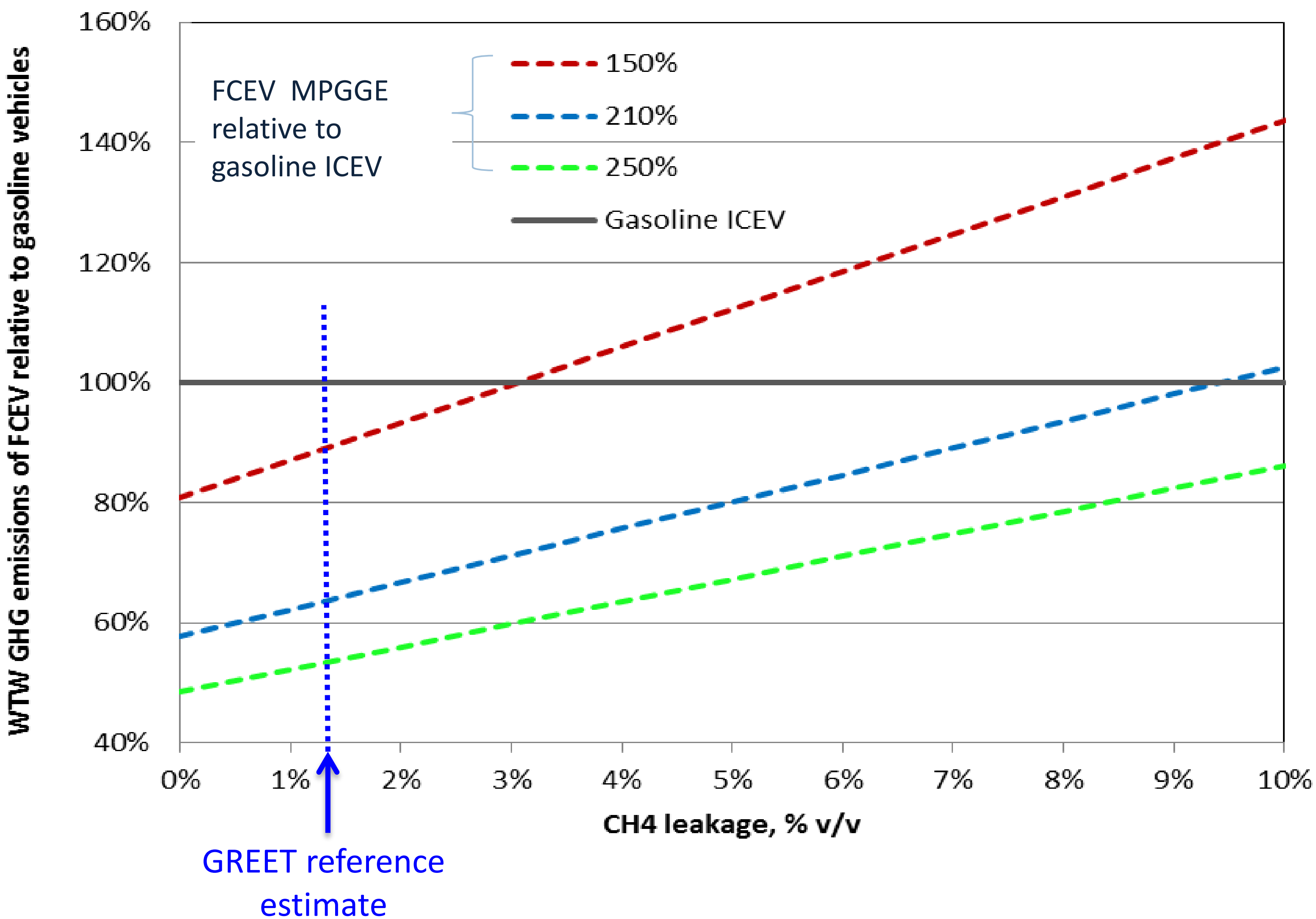
Fuel Economy Penalties for NG HDVs vs. Diesel HDVs Can Be Significant

- Most CNG HDV testing has been on transit buses
  - Fuel economy penalties ranged from 16% to 25%
    - Spark-ignited (SI) engines have lower efficiency at low speeds and loads
- NG SI engines have closed the fuel economy gap on compression-ignition (CI) engines
  - Efficiency penalty due to emission controls for diesels to meet stringent standards
  - Cummins reported < 10% penalty during full-load testing of its ISL engine
    - CNG trucks with less low speed “stop and go” driving will have lower penalties
- Westport’s NG/diesel pilot ignition CI engine matches diesel engine fuel economy and performance
  - Uses small amount of diesel (5% by energy) for pilot ignition

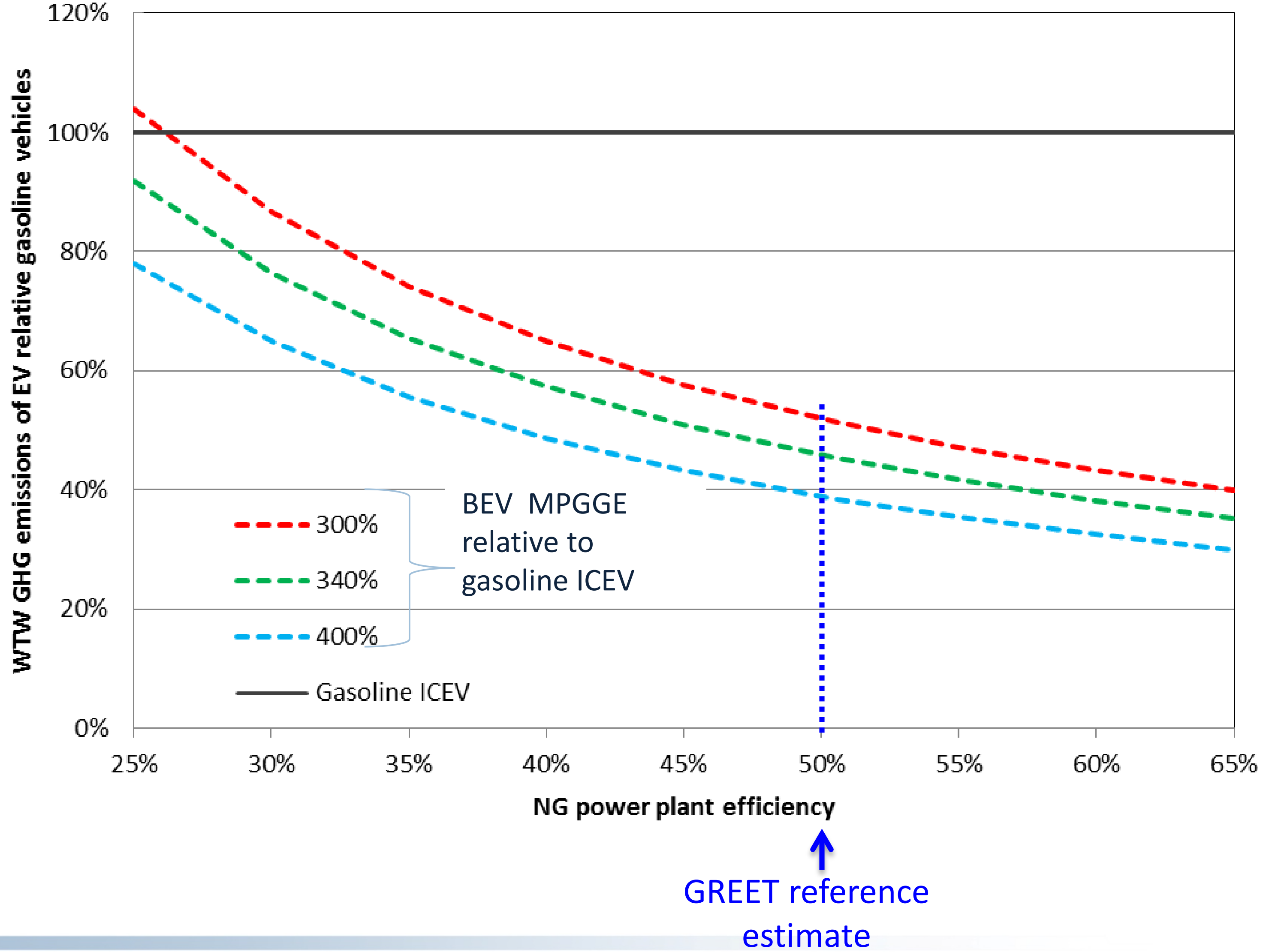
NGV efficiency and CH_4 leakage are two key factors of WTW GHG emissions of LNG HDVs vs. diesel HDVs



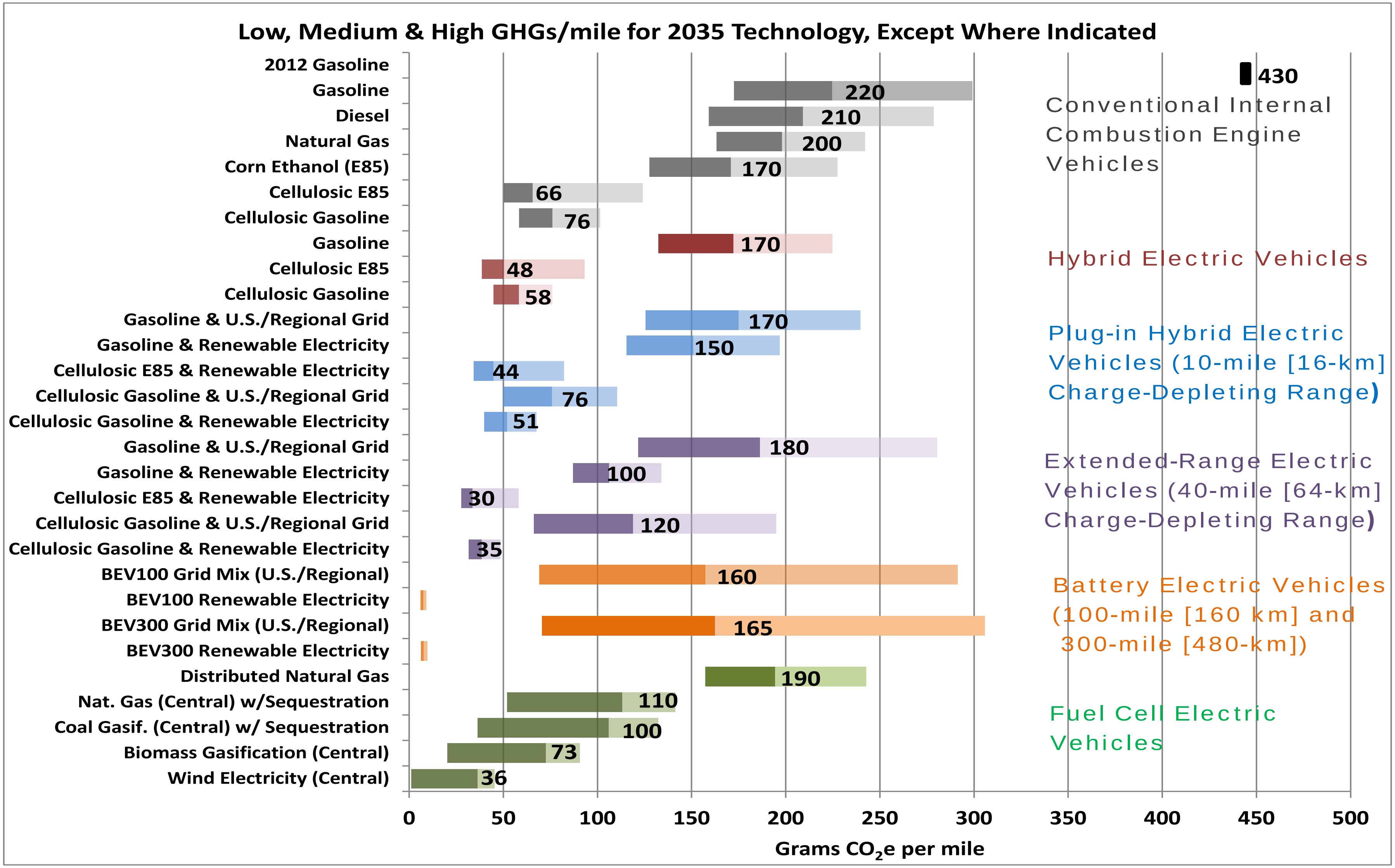
WTW GHG Emissions of SMR H2 FCEVs vs. Gasoline Vehicles – Methane Leakage and FCEV Efficiency are Two Key Factors



WTW GHG Emissions of BEVs with NG Electricity vs. Gasoline Vehicles – NG Plant Efficiency and BEV Efficiency are Two Key Factors



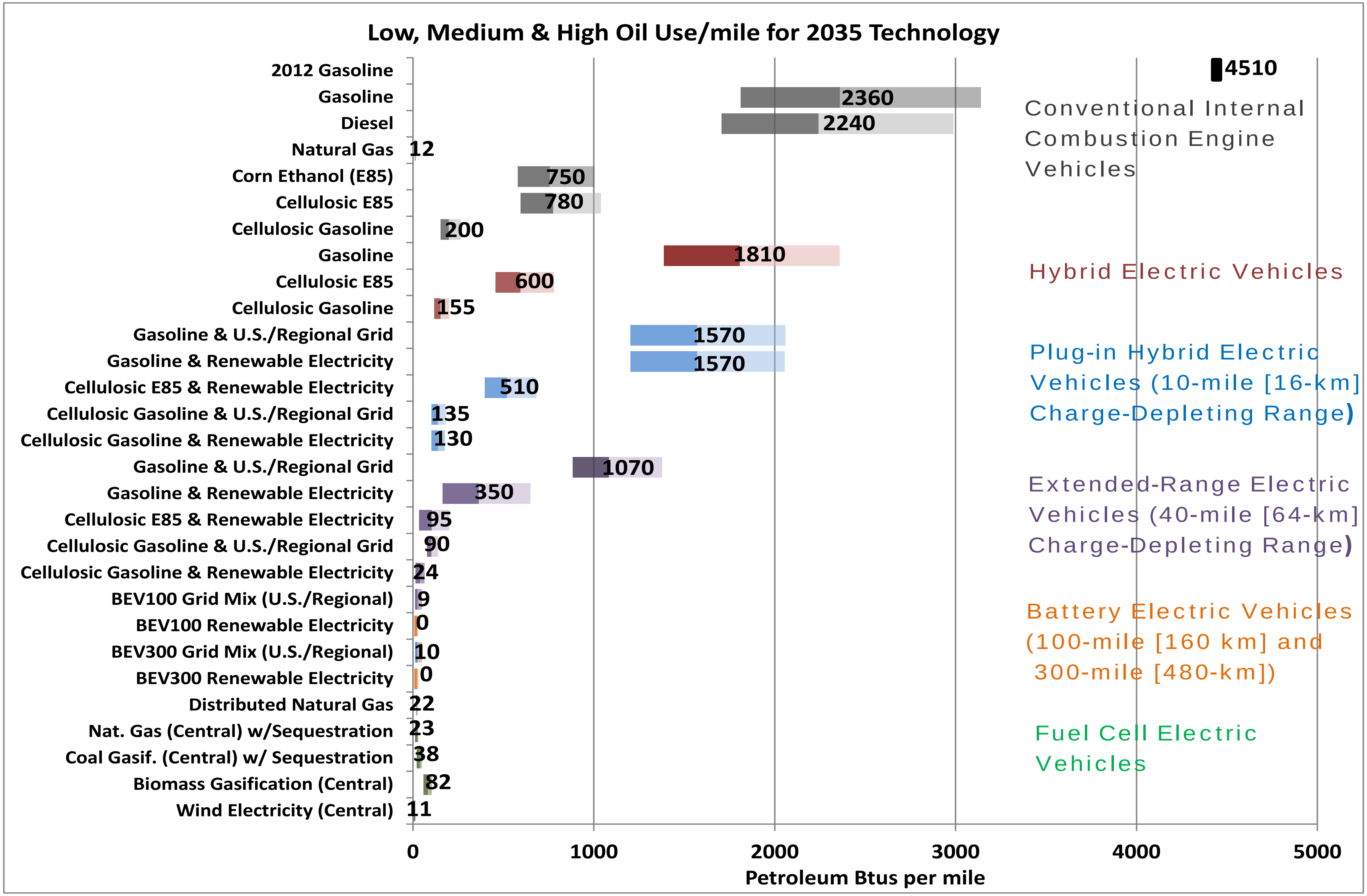
WTW GHG Emissions in g CO2e/mile: 2035 Mid-Size Car



Low/high band: sensitivity to uncertainties associated with projected fuel economy values and selected fuel pathway parameters

(DOE EERE April 25 2013, Record 13005)

WTW Petroleum Use in BTU/mile: 2035 Mid-Size Car



Low/high band: sensitivity to uncertainties associated with projected fuel economy values and selected fuel pathway parameters

(DOE EERE April 25, 2013, Record 13005)

Summary of LCA GHG Results of NG Use in Transportation

- Argonne updated GREET's NG CH_4 leakage estimates
  - Our bottom-up leakage rate has dropped by 30%
  - Top-down estimates are significantly higher
  - GREET LCA, and other LCAs, needs reliable leakage estimates
- GHG benefits of NG vehicles are influenced heavily by fuel economy
  - Relative fuel economy of NGVs are affected by NG tank weight, vehicle performance, engine technology and design
- With reductions in methane leakage and improvements in NGV efficiencies, NGVs could provide GHG reductions
- Electrification via batteries and fuel cells, with NG as the primary energy source, can significantly reduce GHG emissions

For GREET model and technical reports, please visit

greet.es.anl.gov