Life-Cycle Analysis of Natural Gas for Transportation Use

Michael Wang and Andy Burnham

Systems Assessment Group

Energy Systems Division

Argonne National Laboratory

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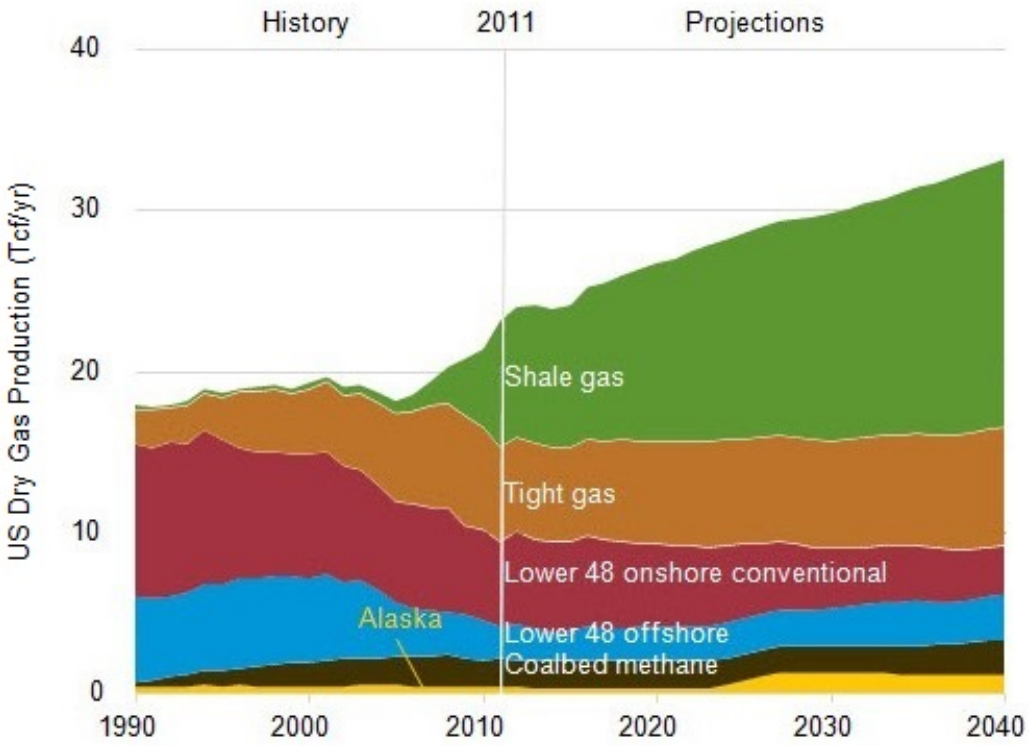
Shale Gas Is A "Game Changer"

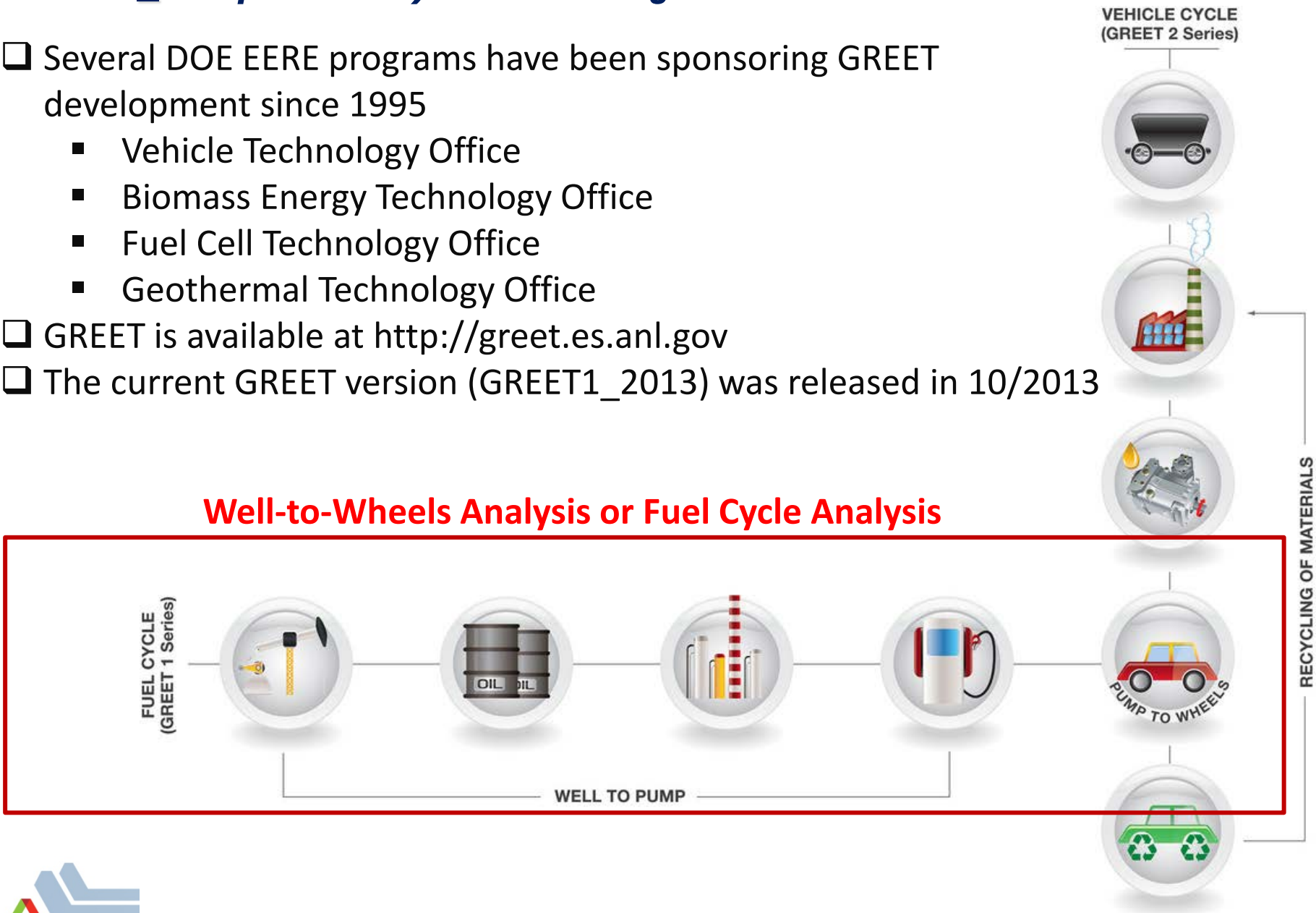
- Large-scale production made possible by advancements
  - Horizontal drilling
  - Hydraulic fracturing
- Has generated interest in expanding NG use in several sectors
  - Displacement of coal by NG already occurred in electric sector
  - Expansion into transportation sector will reduce vehicle operation costs, among other benefits



Source: EIA - Annual Energy Outlook 2013

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

- Several DOE EERE programs have been sponsoring GREET development since 1995
  - Vehicle Technology Office
  - Biomass Energy Technology Office
  - Fuel Cell Technology Office
  - Geothermal Technology Office
- GREET is available at http://greet.es.anl.gov
- The current GREET version (GREET1_2013) was released in 10/2013



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

- Energy use
  - Total energy; fossil energy; petroleum;
- Greenhouse gases (GHGs)
  - CO_2, CH_4, and N_2O
  - CO_2e of the three (with their global warming potentials)
  - Black carbon will be added in new GREET version
- Criteria pollutants
  - VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, and SO_x
- Water consumption will be added in new GREET version
- GREET LCA functional units
  - Per mile driven
  - Per unit of energy (million Btu, MJ, gasoline gallon equivalent)
  - Other units (such as per passenger-km for aviation, per ton-km for mariane)

GREET Includes More Than 100 Fuel Production Pathways from Various Energy Feedstocks

Petroleum
- Conventional
- Oil Sands

→ Gasoline, Diesel, Liquefied Petroleum Gas, Residual Oil (to electricity), Jet Fuel

Natural Gas
- North American
- Shale Gas
- Non-North American

→ Compressed Natural Gas, Liquefied Natural Gas, Liquefied Petroleum Gas, Hydrogen, Methanol, Dimethyl Ether, Fischer-Tropsch Diesel, Fischer-Tropsch Jet Fuel

Corn → Ethanol, Butanol

Sugarcane → Ethanol

Soybeans → Biodiesel, Renewable Diesel, Renewable Gasoline, Renewable Jet Fuel

Coke Oven Gas, Petroleum Coke, Nuclear Energy → Hydrogen

Coal → Hydrogen, Methanol, Dimethyl Ether, Fischer-Tropsch Diesel, Fischer-Tropsch Jet Fuel

Renewable Natural Gas
- Landfill Gas
- Biogas from anaerobic digestion

→ Compressed Natural Gas, Liquefied Natural Gas, Hydrogen, Methanol, Dimethyl Ether, Fischer-Tropsch Diesel, Fischer-Tropsch Jet Fuel

Cellulosic Biomass
- Switchgrass
- Fast Growing Trees
- Crop Residues
- Forest Residues

→ Ethanol, Hydrogen, Methanol, Dimethyl Ether, Fischer-Tropsch Diesel, Fischer-Tropsch Jet Fuel

Residual Oil, Coal, Natural Gas, Biomass, Other Renewables (hydro, wind, solar, geothermal) → Electricity

Algae → Biodiesel, Renewable Diesel, Renewable Gasoline, Renewable Jet Fuel

The yellow boxes contain the names of the feedstocks and the red boxes contain the names of the fuels that can be produced from each of those feedstocks.

GREET Examines More Than 80 Vehicle/Fuel Systems

Conventional Spark-Ignition Engine Vehicles
- Gasoline
- Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
- Gaseous and liquid hydrogen
- Methanol and ethanol

Spark-Ignition, Direct-Injection Engine Vehicles
- Gasoline
- Methanol and ethanol

Compression-Ignition, Direct-Injection Engine Vehicles
- Diesel
- Fischer-Tropsch diesel
- Dimethyl ether
- Biodiesel

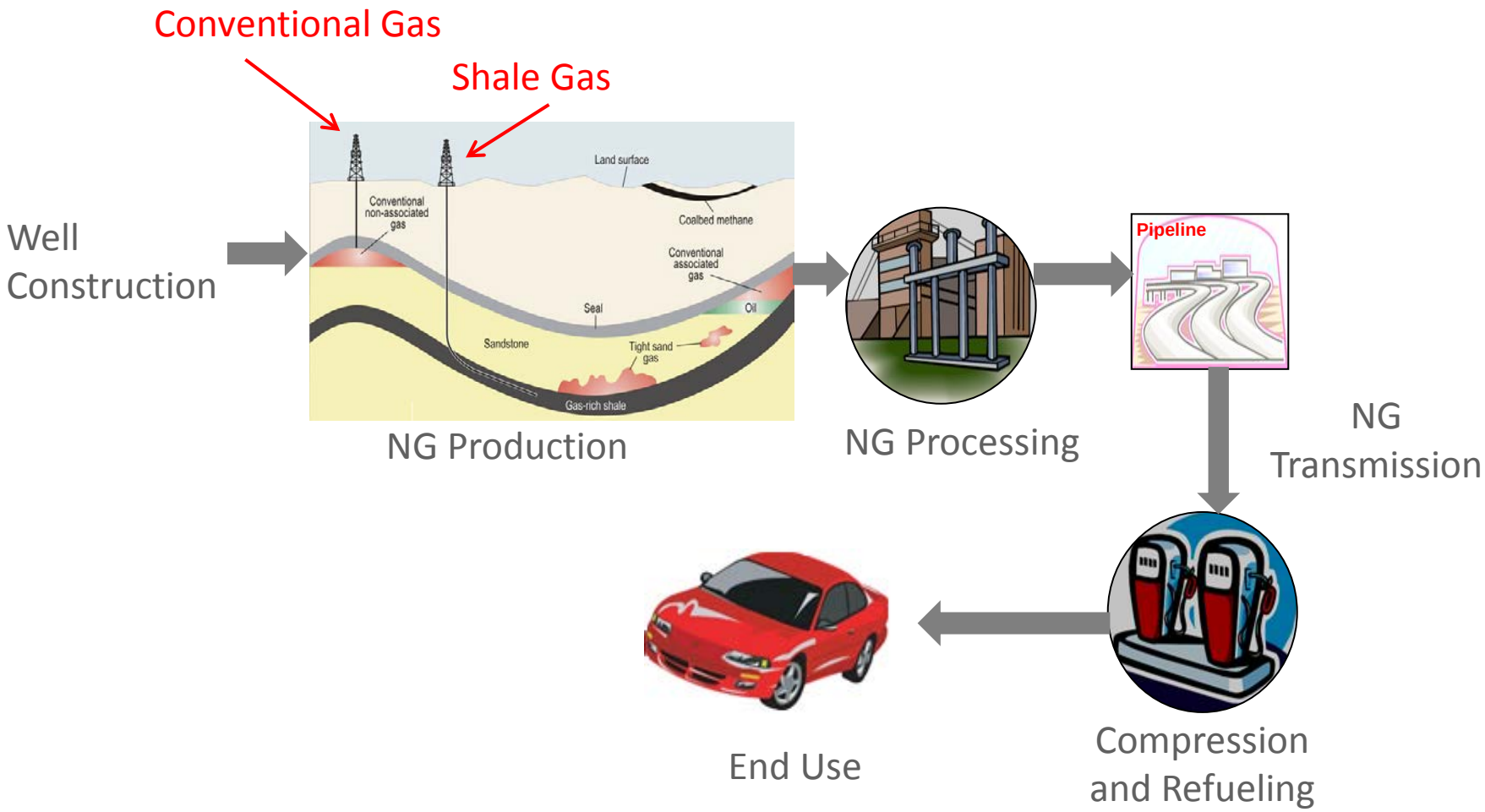
Fuel Cell Vehicles
- On-board hydrogen storage
  - Gaseous and liquid hydrogen from various sources
- On-board hydrocarbon reforming to hydrogen

Battery-Powered Electric Vehicles
- Various electricity generation sources

Hybrid Electric Vehicles (HEVs)
- Spark-ignition engines:
  - Gasoline
  - Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
  - Gaseous and liquid hydrogen
  - Methanol and ethanol
- Compression-ignition engines
  - Diesel
  - Fischer-Tropsch diesel
  - Dimethyl ether
  - Biodiesel

Plug-in Hybrid Electric Vehicles (PHEVs)
- Spark-ignition engines:
  - Gasoline
  - Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
  - Gaseous and liquid hydrogen
  - Methanol and ethanol
- Compression-ignition engines
  - Diesel
  - Fischer-Tropsch diesel
  - Dimethyl ether
  - Biodiesel

LCA System Boundary: Compressed Natural Gas



- CH4 leakage during the entire supply chain
- Emissions from process fuels for recovery, transportation, and compression; and NG combustion
- Infrastructure-related emissions are usually small

Updated CH_4 Leakage Estimates in GREET

- 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_2013 uses EPA's 2013 inventory data
  - ✓ Liquid unloading emissions
  - ✓ Shale gas completion/workover frequency and emissions
  - ✓ Well equipment emissions
  - ✓ Estimated Ultimate Recovery (EUR) per gas well

Liquid Unloading Emissions

- In prior EPA inventory, liquid unloadings accounted for nearly 50% of NG production emissions
  - Assumed only conventional NG wells required unloading
- EPA 2013 Inventory used API/ANGA survey data to update assumptions
  - Reduced emissions per well requiring unloading by 80%
  - Reduced wells requiring unloading from 41% to 13%
  - Included shale gas well liquid unloadings as survey found many shale gas wells needing this operation

Shale Gas Completion/Workover Frequency and Emissions

- Workover frequency
  - Prior EPA Inventory assumed 10% workover rate (2 per 30 yr well lifetime)
  - Based on NSPS analysis, EPA 2013 Inventory revised to 1% workover rate (0.2 per 30 yr lifetime)
- Completion emissions; potentially overestimated in prior EPA Inventory
  - Applicability of NG STAR program activities to calculate baseline emissions
  - Use of initial production rates to estimate flowback emissions
- EPA 2013 Inventory uses NESHAP regulations and NG STAR reporting to estimate amount of NG flared and captured by industry practices
  - Latest estimate was 46% reduction of CH_4 emissions
  - 2011 NSPS rules require flaring through 2015, after that requires RECs

Well Equipment Emissions

- Argonne prior analysis examined both EPA Inventory and a GAO analysis
  - The emission factor from GAO, which were based on a WRAP analysis, was ~100% higher than the EPA's
- Argonne used EPA Inventory data as it provided a consistent data source and the WRAP analysis was not updated

Estimated Ultimate Recovery per Gas Well

- Shale gas EUR is highly uncertain as industry is still in its early stage
  - Previous Argonne analysis used the average of EIA data (low estimate) and industry data (high estimate)
- Latest EUR estimates have been closer to EIA averages for plays, so Argonne adjusted GREET to take this into account
  - Industry results were for the more productive areas
  - As production expands average EUR has decreased

	Low EUR Estimate (Bcf, EIA, GREET1.2013)	High EUR Estimate (Bcf, Industry)
Barnett	1.4	3.0
Marcellus	1.4	5.2
Fayetteville	1.7	2.6
Haynesville	3.5	6.5
Shale Per-Well Weighted Avg.	**1.6**	**5.3**

Methane Leakage Rates of Various Studies With Basis of Gross Withdrawals

Sector	CH_4 Emissions: Percent of Volumetric NG Produced (Gross)								
	EPA - Inventory 5 yr avg (2011)	NREL - Barnett Shale (2012)	API / ANGA Survey (2012)	NOAA - DJ Basin (2012)	NOAA - Uintah Basin (2013)	Exxon Mobil - Marcellus (2013)	EPA - Inventory 5 yr avg (2013)	EPA - Inventory 2011 data (2013)	Univ. Texas (2013)
Gas Field	1.16	1.0	0.75	2.3-7.7	6.2-11.7	0.61	0.59	0.44	0.40
Completion/ Workover		0.8				0.008	0.19	0.14	0.03
Unloading		0	0.06			0.05	0.08	0.04	0.04
Other Sources		0.2				0.56	0.33	0.26	0.35
Processing	0.15	0				0.17	0.15	0.16	
Transmission	0.39	0.5				0.42	0.36	0.34	
Distribution	0.28						0.26	0.23	
Total	1.97						1.36	1.17	

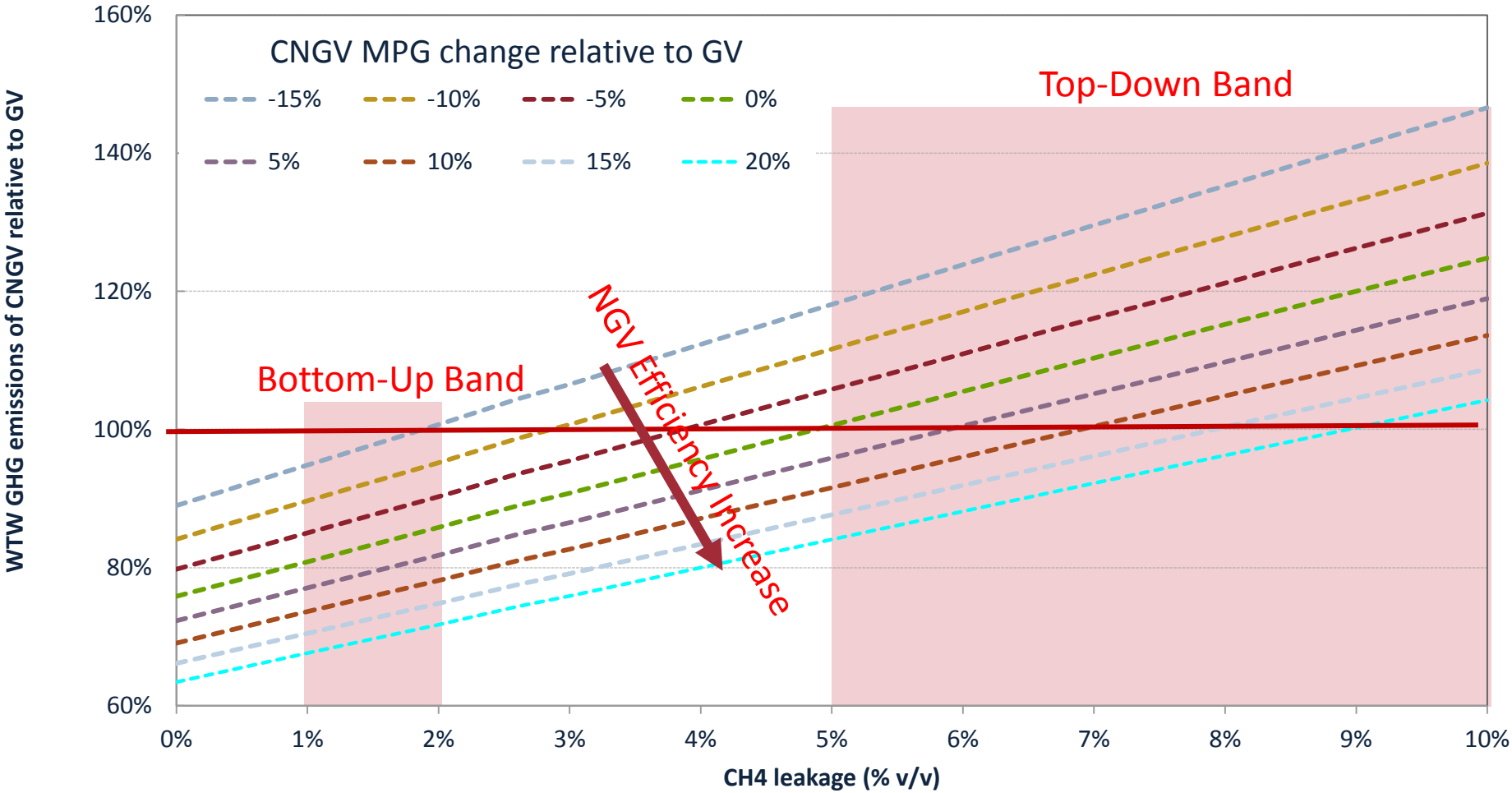
- A major discrepancy between the “Top down” approach (NOAA studies) and the “Bottom up” approach (other studies)

Using Stage Throughput Estimates Leakage Rates More Accurately 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

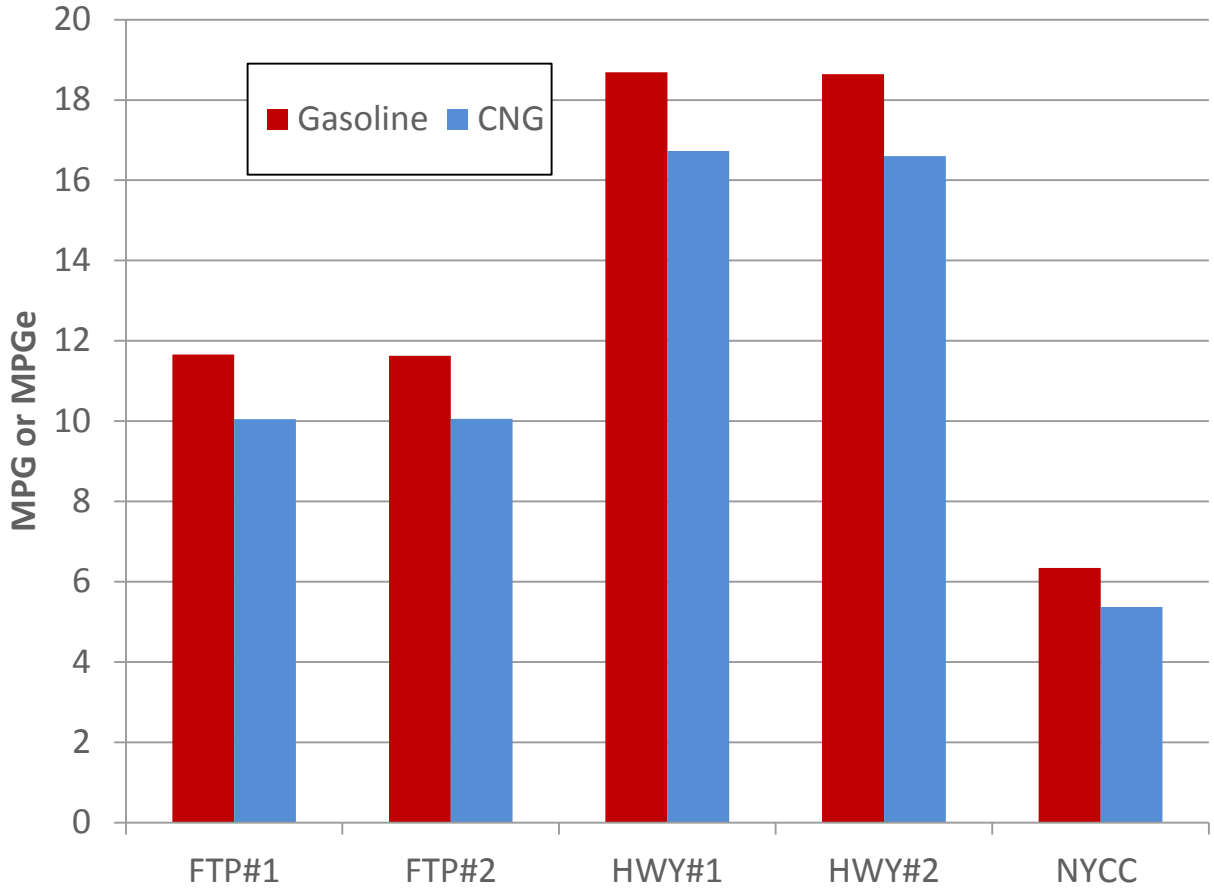
CNGV efficiency and CH_4 leakage are Two key factors of WTW GHG emissions of CNG vehicles vs. gasoline vehicles



Weight of CNG Tanks Reduces NGV Fuel Economy

Argonne tested performance of 2011 gasoline and CNG Ford E-250 vans

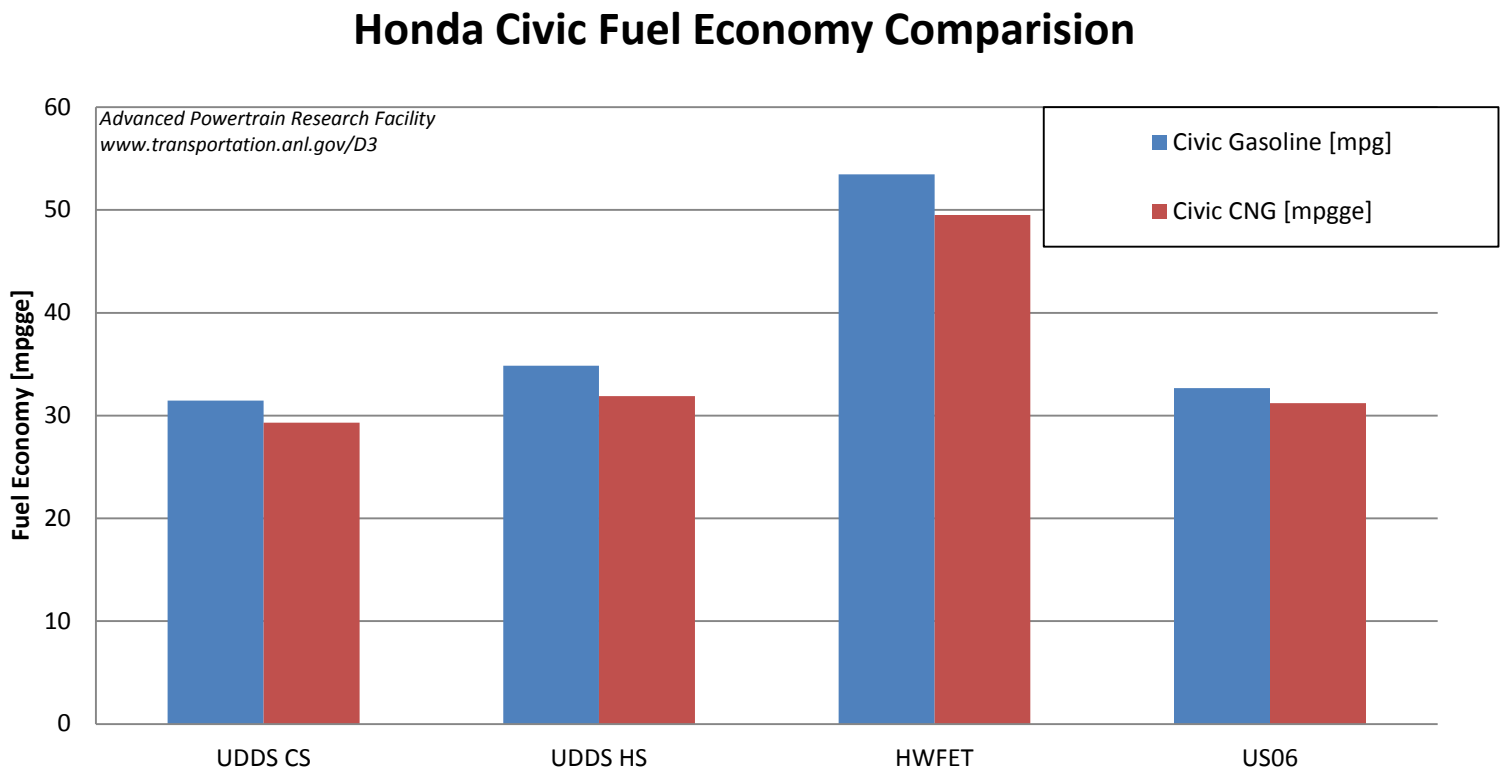
- CNG van uses steel tank with weight ~ 750 lb
- CNG fuel economy penalty of 11% to 15%



CNG Engine Design Also Impacts Fuel Economy

Argonne tested 2012 gasoline and CNG Honda Civics

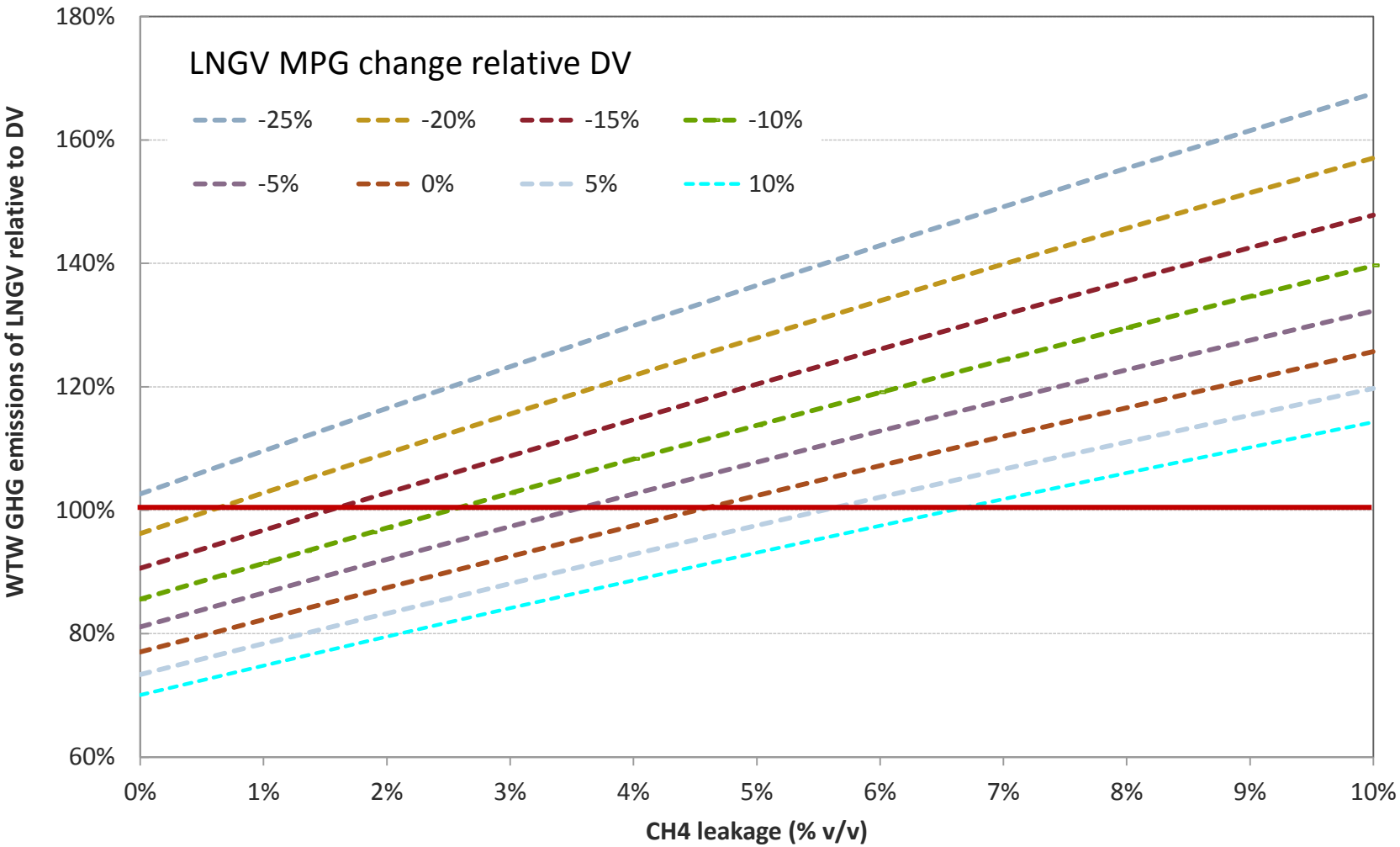
- CNG Civic uses carbon fiber tank with weight of ~ 70 lb
- CNG fuel economy penalty of 3% to 10%
- Fueleconomy.gov show a fuel economy penalty of 3% to 4% for CNG Civic



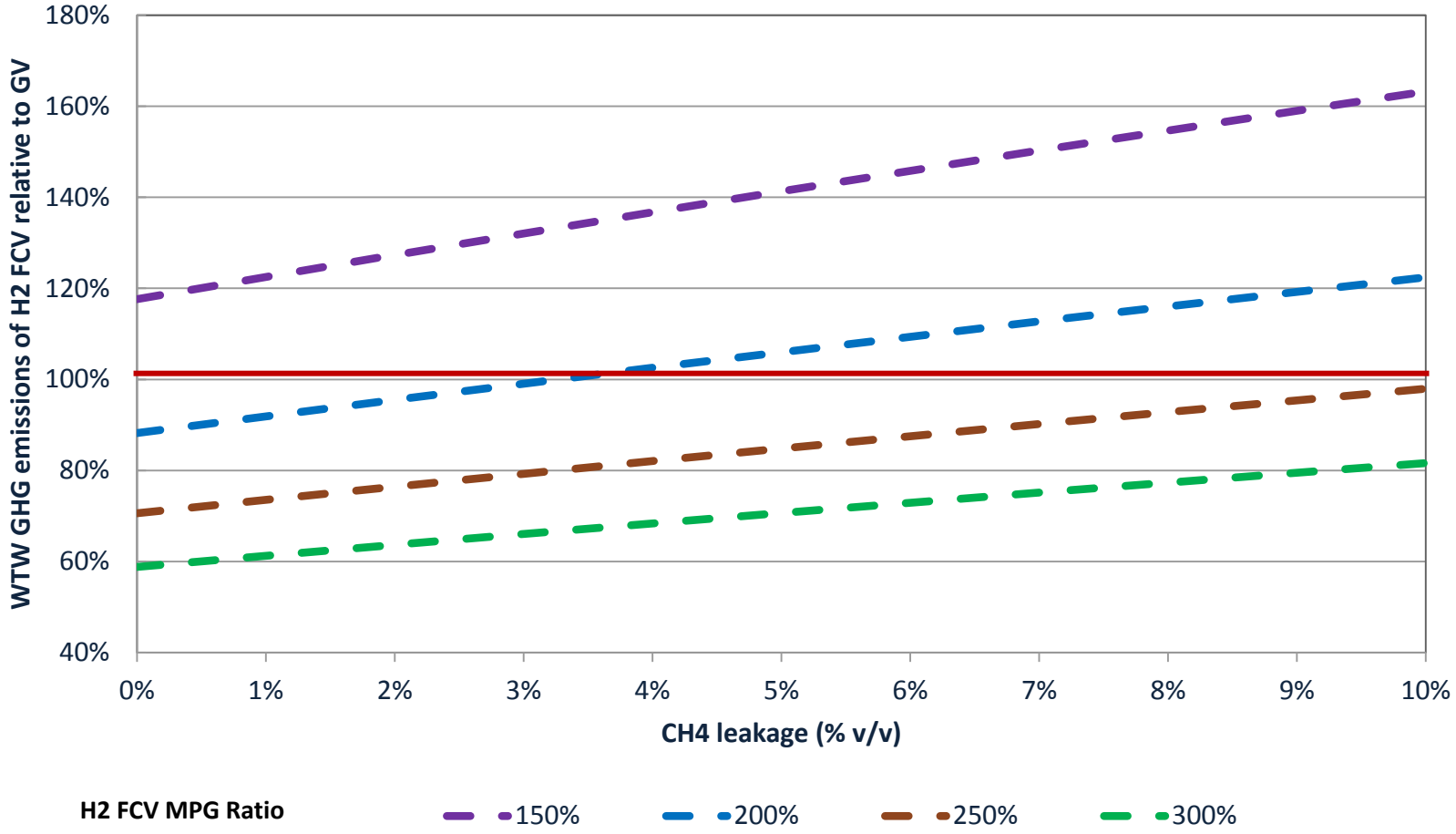
Fuel Economy Penalties for NG HDVs vs. Diesel HDVs Can Be Significant

- 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

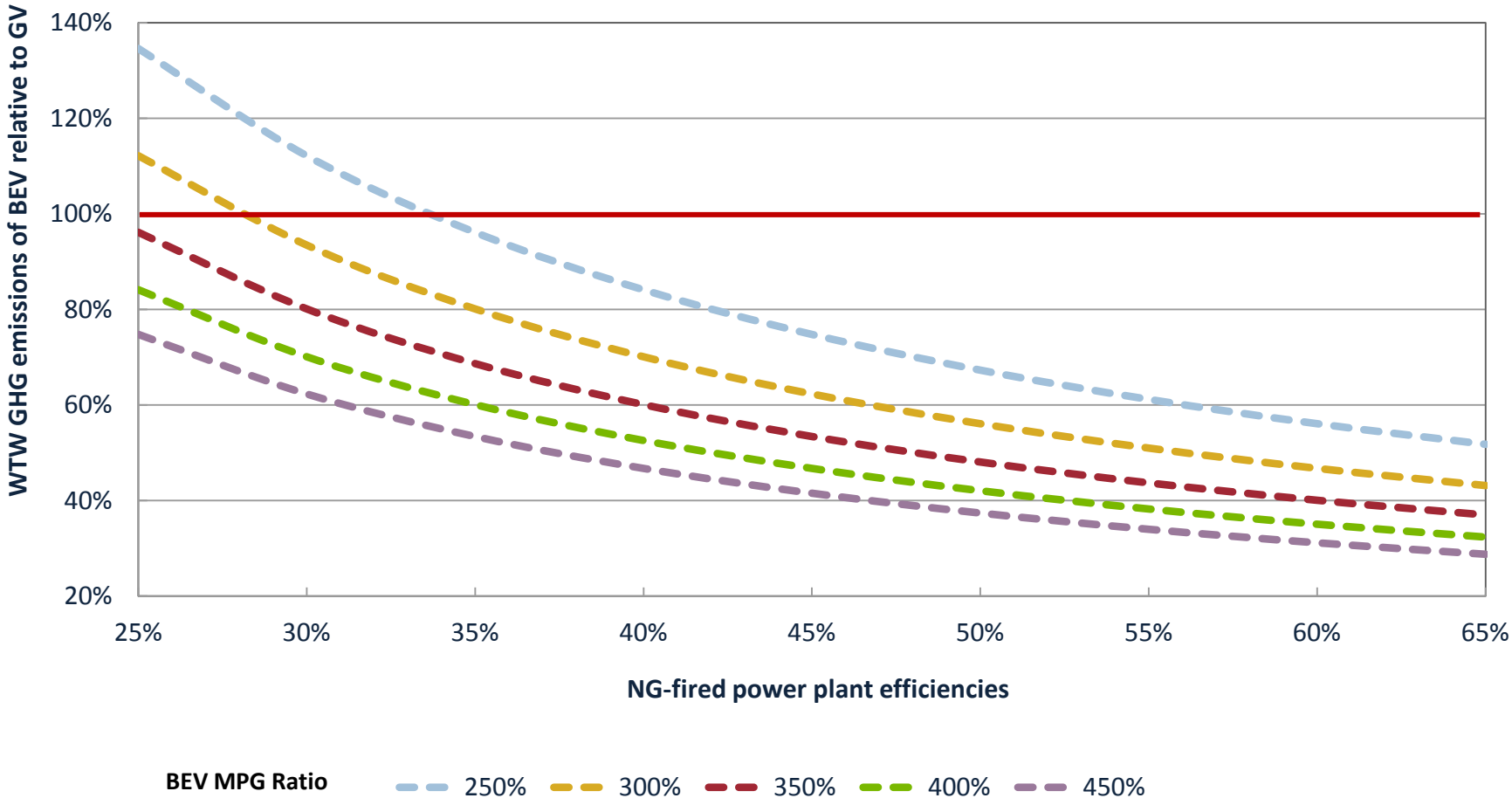
NGV efficiency and CH_4 leakage are two key factors of WTW GHG emissions of LNG HDVs vs. diesel HDVs



WTW GHG Emissions of SMR H2 FCVs vs. Gasoline Vehicles – Methane Leakage and FCV Efficiency Are Two Key Factors



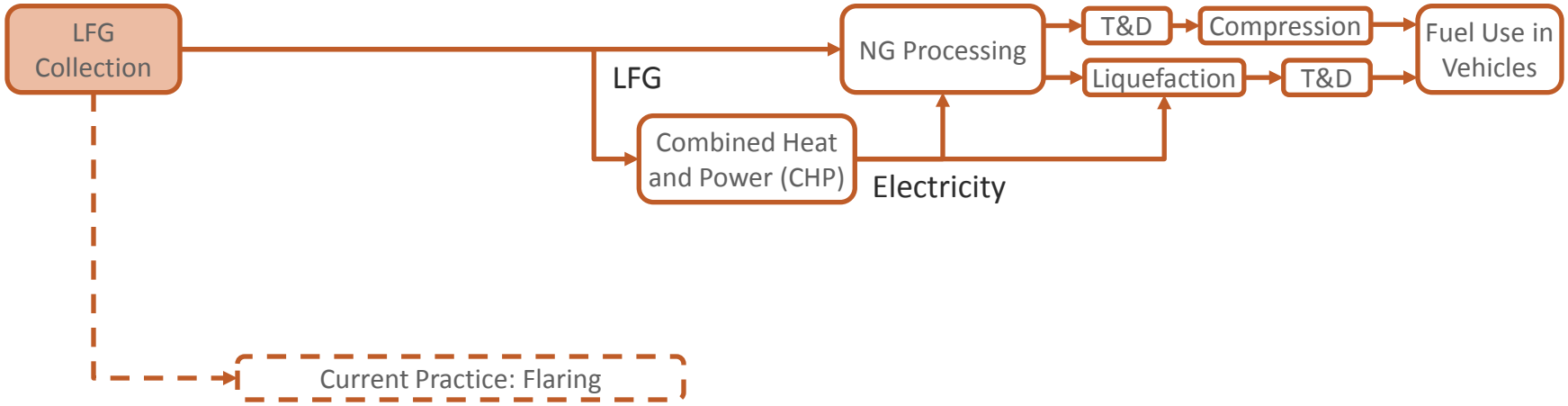
WTW GHG Emissions of Battery EVs with NG Electricity vs. Gasoline Vehicles – NG Plant Efficiency and EV Efficiency Are Two Key Factors



Renewable natural gas (RNG) can help reduce NGV GHG footprint

- RNG can be produced from a variety of sources
  - Landfill gas
  - Biogas from anaerobic digestion of manure and waste water treatment plant (WWTP) sludge
- Potential RG production from these three sources could be 0.5 quads a year

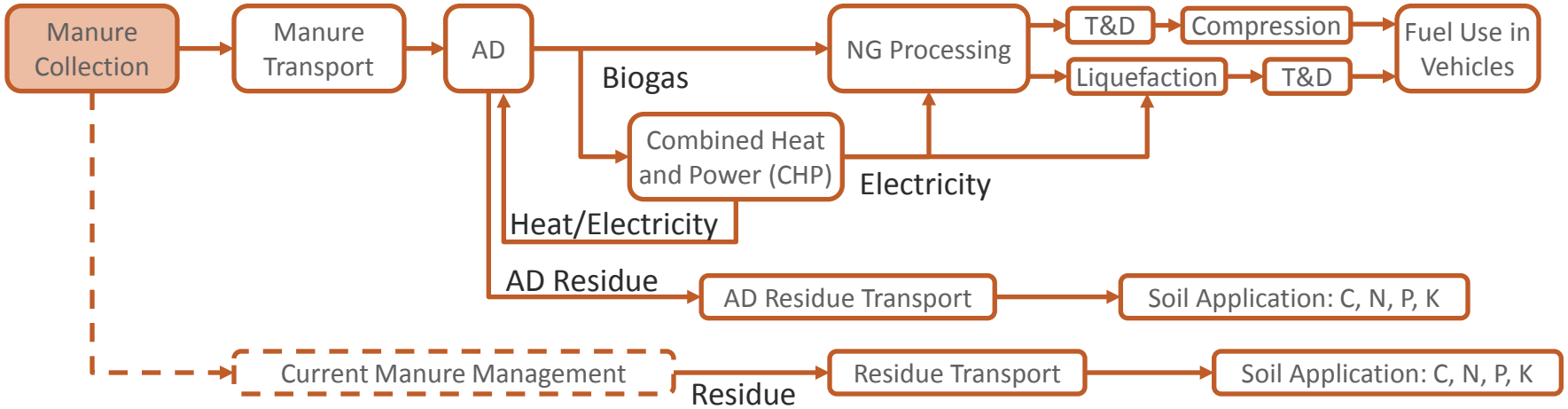
Landfill Gas (LFG) Pathway



Shared stages (dark blocks) are excluded

- Key Parameters
  - NG processing efficiency: 94.4%
  - CHP electrical and thermal efficiency: 30% and 50%, respectively
  - CH_4 leakage rate in NG processing: 2%
  - Compression efficiency: 97.1%
  - Liquefaction efficiency: 96.4%

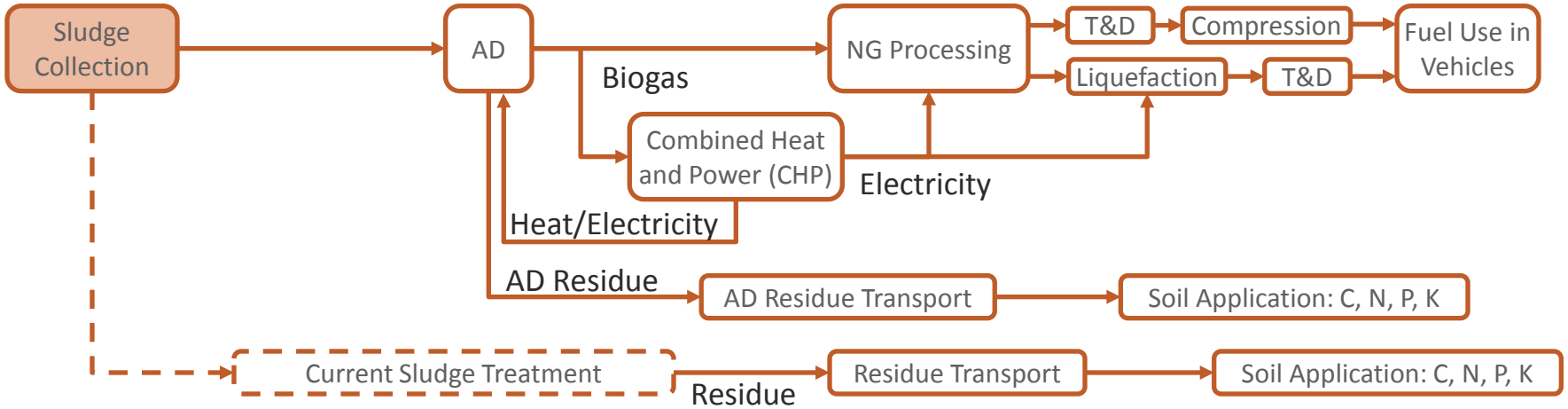
Manure-Based Anaerobic Digestion (AD) Pathway



Shared stages (dark blocks) are excluded

- Key Parameters
  - NG processing efficiency: 94.4%
  - CHP electrical and thermal efficiency: 30% and 50%, respectively
  - CH_4 leakage rate in NG processing: 4.3%
  - Compression efficiency: 97.1%
  - Liquefaction efficiency: 96.4%
  - Biogas yield from manure by AD: 0.13 lb CH_4/lb TS
  - Heat and electricity requirements by AD: 260 and 510 Btu/lb TS, respectively

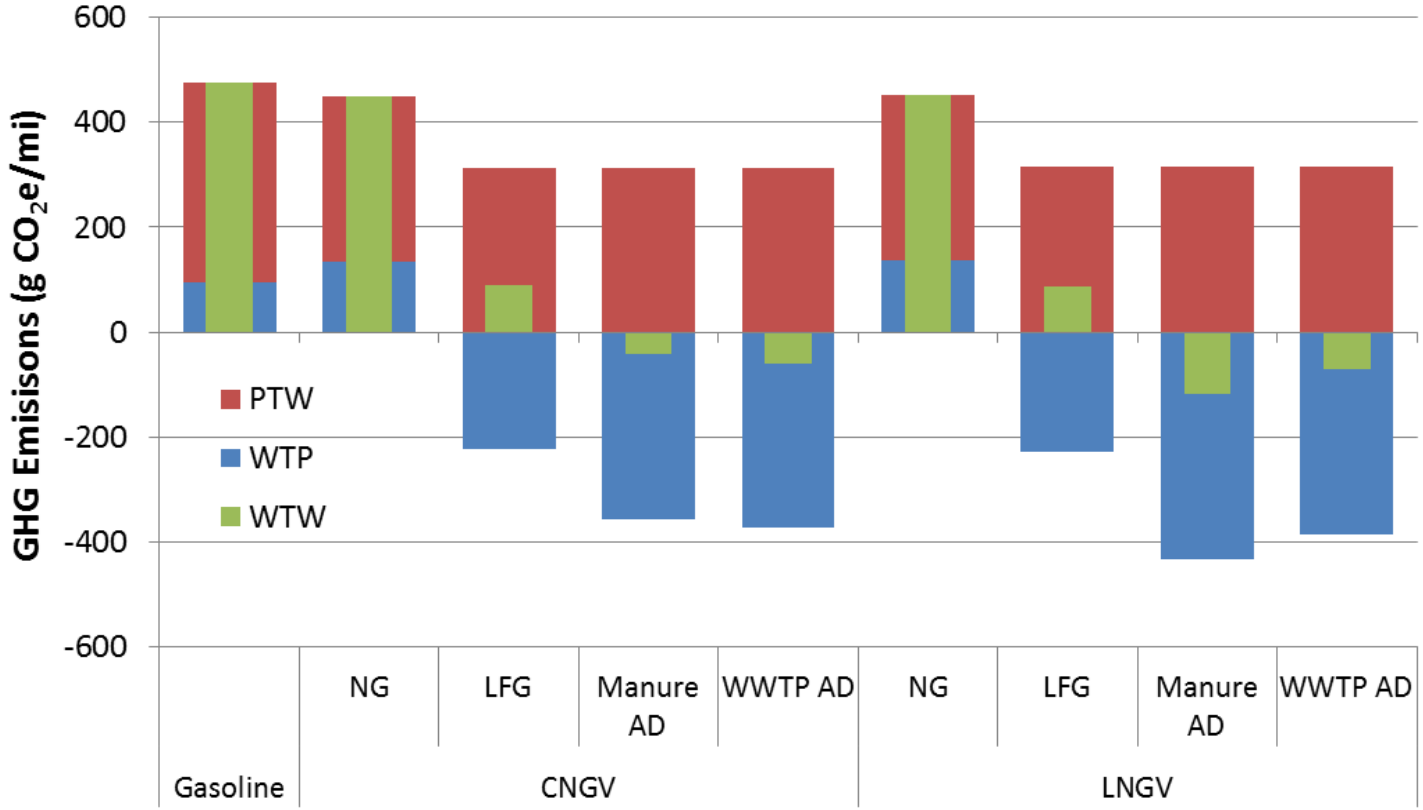
Wastewater Treatment Sludge-Based AD Pathway



Shared stages (dark blocks) are excluded

- Key Parameters
  - NG processing efficiency: 94.4%
  - CHP electrical and thermal efficiency: 30% and 50%, respectively
  - CH_4 leakage rate in NG processing: 7.5%
  - Compression efficiency: 97.1%
  - Liquefaction efficiency: 96.4%
  - Biogas yield from **sludge** by AD: 0.28 lb CH_4/lb TS
  - Heat and electricity requirements by AD: 280 and 1,250 Btu/lb TS, respectively

All RNG pathways reduce WTW GHG emissions >80% relative to petroleum gasoline



- GHG emissions of AD pathways are negative relative to reference case (109–125% less for manure, 113–115% less for WWTP sludge) because of credits from avoided CH4 emissions

Summary of NGV LCA GHG Results

- 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 improvement in these two key areas, NGVs can provide GHG reductions
- RNG, allowed by EPA for RFS compliance, can significantly help reduce NGV GHG emissions