Life Cycle Greenhouse Gas (GHG) Emissions from Natural Gas Pathways for On-Road Vehicles

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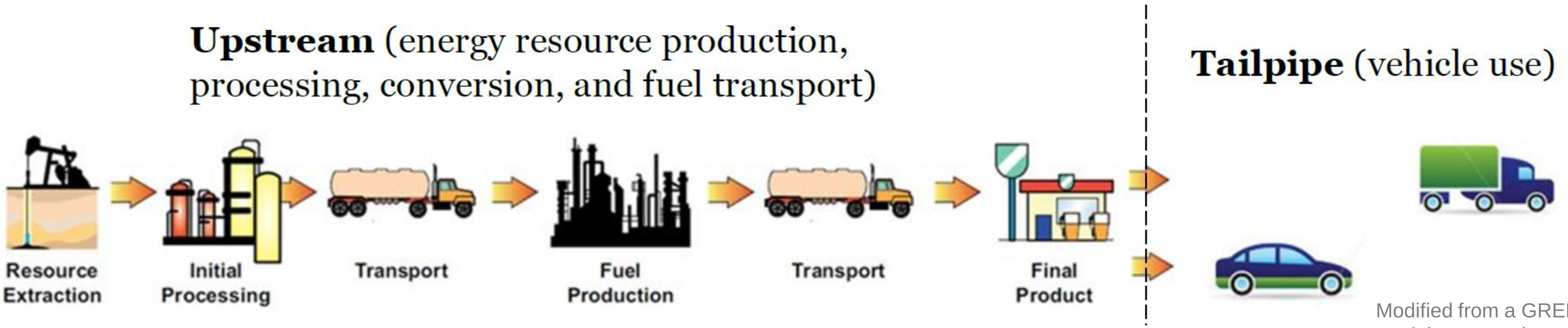
A Transition to Natural Gas Pathways?

- Research Gaps
  - Previous studies do not account for recent developments in natural gas **(e.g. methane leakage)** extractions and current vehicle technologies.
  - Findings from previous studies on life cycle GHG emissions of natural gas developments and heavy-duty vehicles are **mixed and contradictory**.
- Research Questions
  - Which **natural gas pathways** or which **vehicle segments** provide GHG emissions reductions compared to petroleum fuels?
  - How sensitive are the results to **methane leakage rates** and other factors?

Bottom-up Attributional Life Cycle Assessment (LCA)



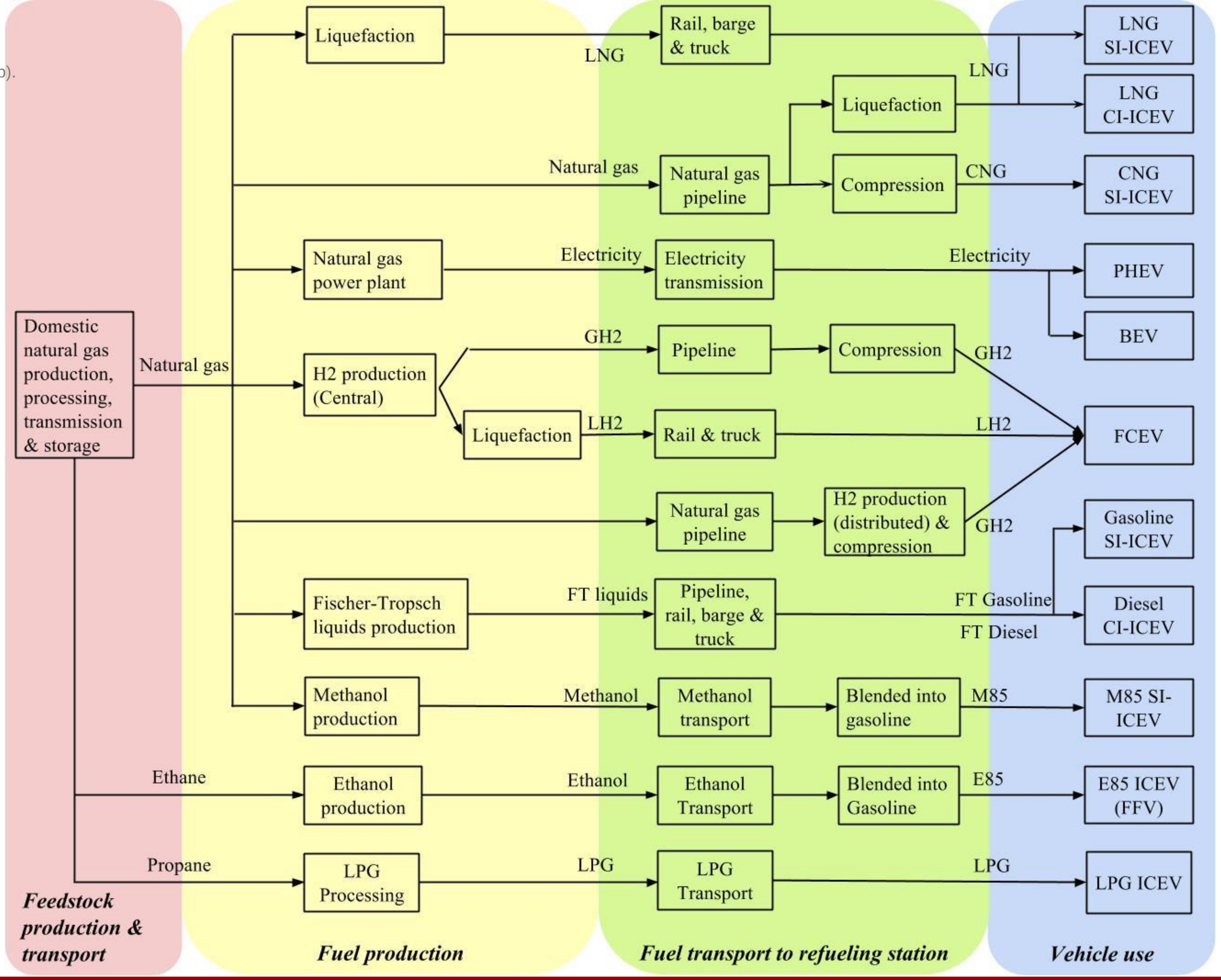
Modified from a GREET model presentation (Argonne National Lab)

- **Emission Sources**
  - Resource extraction: natural gas and oil (baseline).
  - Fuel production, transport, distribution.
  - Vehicle operation (tailpipe).
  - Vehicle manufacturing emissions (esp., battery and fuel cells).
  - ~~Emissions from infrastructure construction.~~
  - ~~Emissions from end-of-life disposal or treatment.~~

- **GHGs**
  - CO_2, CH_4, N_2O
  - Global warming potential (GWP)
  - IPCC AR5 values.
  - Uncertainty in GWPs.

- **Functional Unit**
  - Vehicle distance (kilometer)
  - Freight distance (metric ton-km)

Modified from Tong et al. (2015a, 2015b).



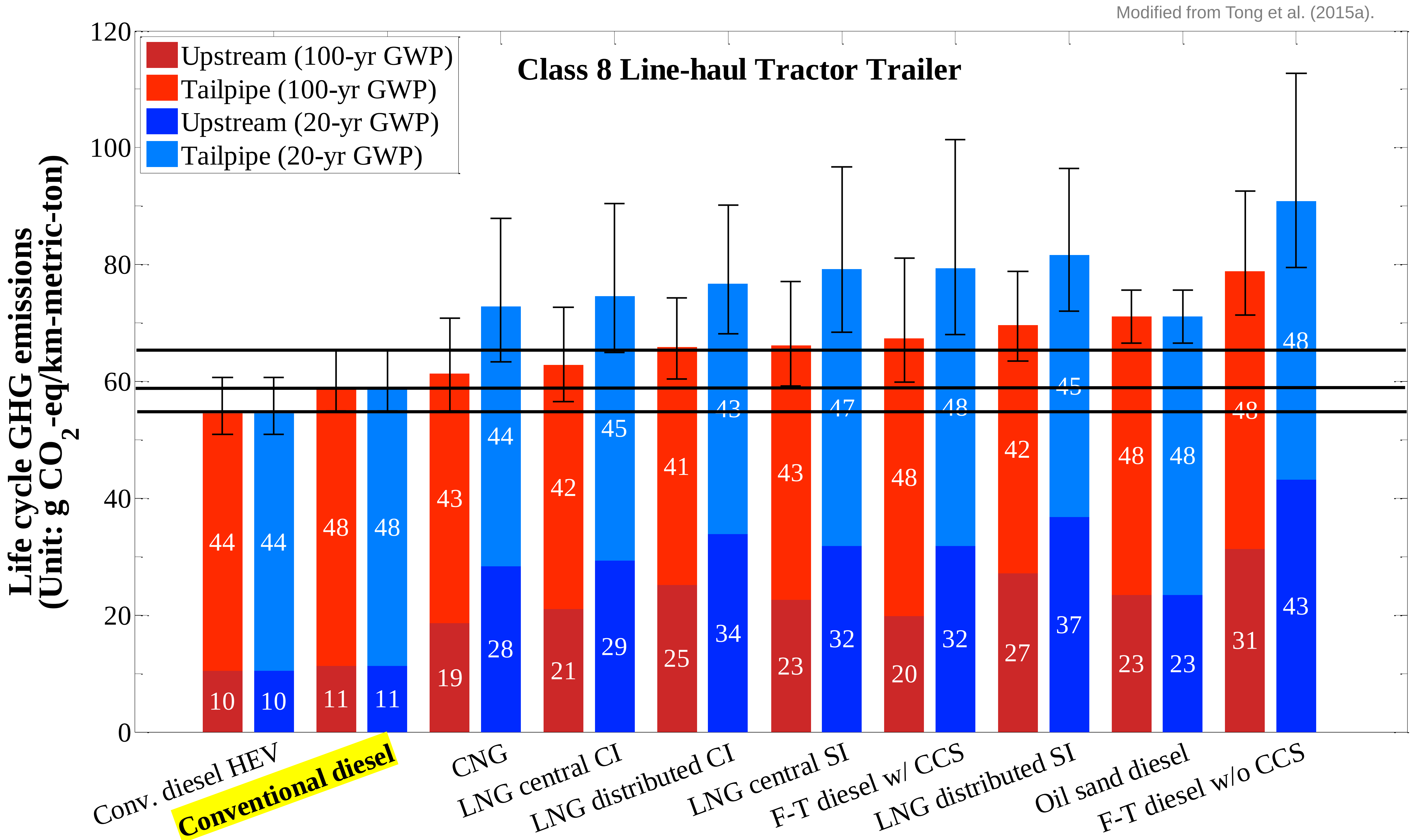
Not All Transportation Fuels Can be Used to Fuel Every Vehicle Type

	Class 1 Passenger vehicle	Class 1 Sports utility vehicle (SUV)	Class 2b Pick-up truck/van	Class 4 Parcel delivery van	Class 6 Box truck	Class 8 Transit bus	Class 8 Refuse truck	Class 8 Tractor trailer local-haul	Class 8 Tractor trailer line-haul
Unit of fuel economy+	MPG (gasoline gallon)			MPG (diesel gallon)					
Gasoline (SI-ICEV)	33.0	25.0	14.0	-	-	-	-	-	-
Diesel (CI-ICEV)	32.3	26.2	16.1	11.5	7.0	4.0	3.3	4.3	6.5
Gasoline-HEV(SI-ICEV)	45.0	33.0	16.8	10.9	-	-	-	-	-
Diesel-HEV (CI-ICEV)	-	-	19.3	14.4	9.3	4.8	3.6	5.2	7.2
CNG (SI-ICEV)	31.0	-	14.0	10.8	6.6	3.6	2.9	3.9	5.9
LNG (SI-ICEV)	-	-	-	-	-	3.6	2.9	3.9	5.9
LNG (CI-ICEV)	-	-	-	-	-	-	-	4.2	6.4
M85 (SI-ICEV)	35.3	-	-	-	-	-	-	-	-
E85 (SI-ICEV)	31.6	24.7	-	-	-	-	-	-	-
Propane (SI-ICEV)	-	-	14.0	-	-	-	-	-	-
BEV	110.0	76.0	42.0	34.5	21.0	16.8/14.0	-	-	-
H_2-FCEV	61.0	49.0	-	-	-	7.6/30.9	-	-	-

Modified from Tong et al. (2015a, 2015b).

- More fuel options for light-duty vehicles; less fuel options for heavy-duty trucks.
- CNG is the only fuel that spans over all vehicle classes.

Sample Results - Natural Gas Pathways Are Worse.



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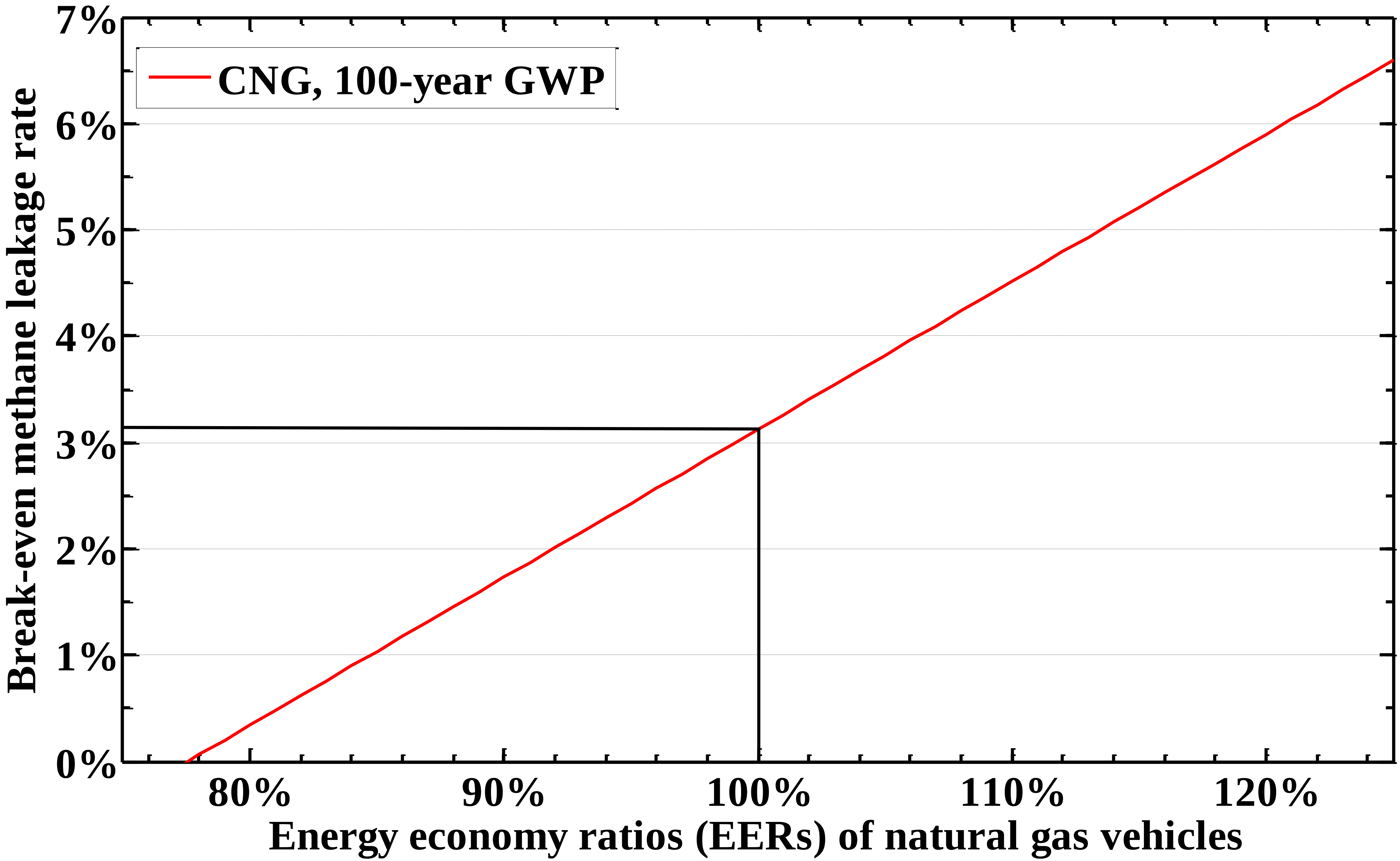
Many pathways **do not achieve** emissions **reduction** yet

Definitely a lot of potentials			
	Electricity + Battery electric vehicles Gaseous Hydrogen + Fuel cell electric vehicles	Passenger vehicle, SUVs, and transit buses.	Efficient fuel production, zero tailpipe emissions, & highly efficient vehicle technologies.
Marginally good or bad			
	CNG LNG Propane	Almost all vehicle applications. Heavy-duty trucks. Light-duty & medium-duty trucks.	Simple fuel production & comparable vehicle technologies.
Very likely to increase emissions			
	Methanol, Ethanol, and liquid hydrogen Fischer-Tropsch liquids	Passenger vehicles All vehicles	Complex fuel production (penalty) & comparable vehicle technologies.

- **4 scenarios * 9 vehicle types**
  - Baseline/Pessimistic methane emissions estimates.
  - 100-year/20-year GWP metrics.

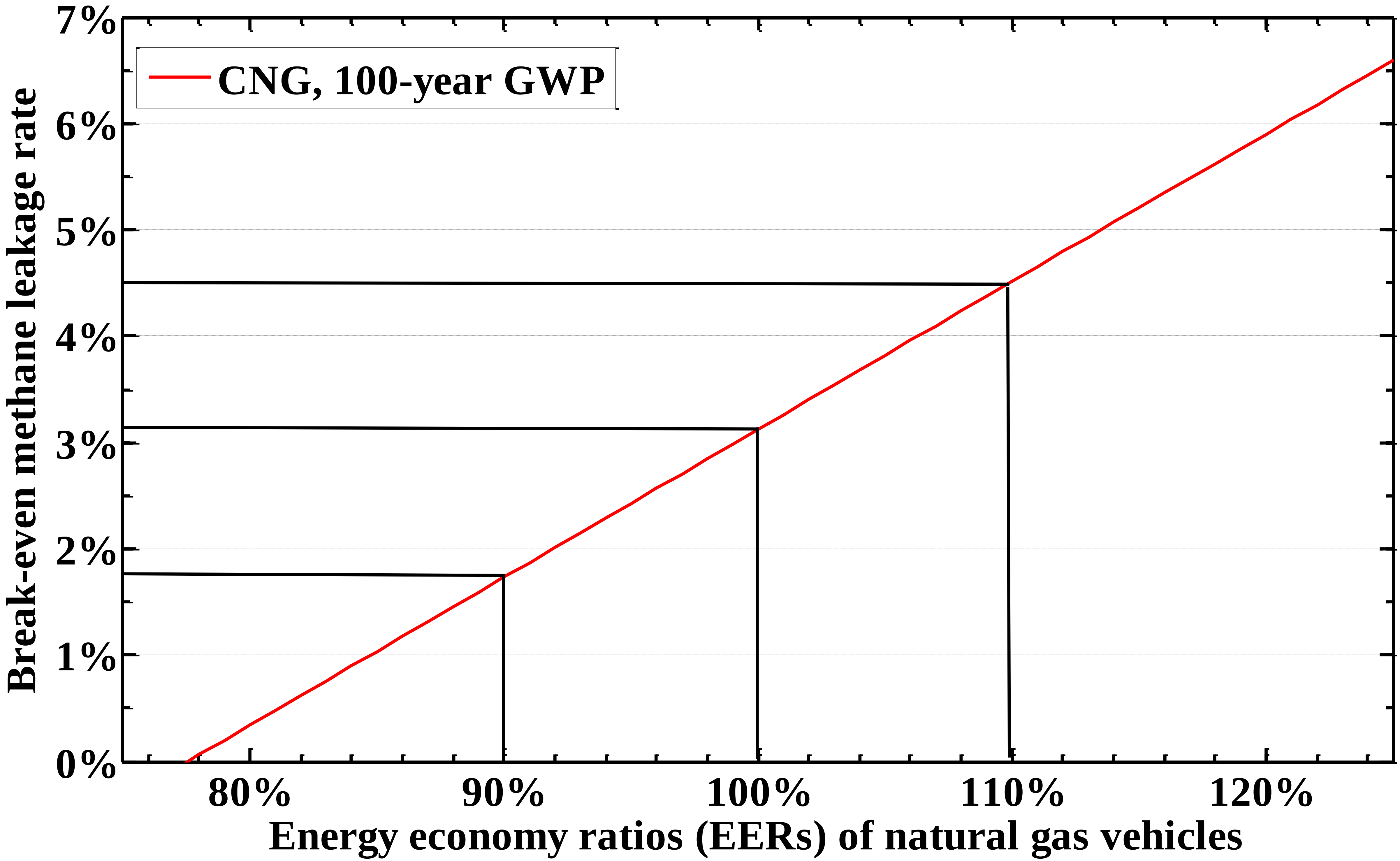
$$Life\ Cycle = \frac{fuel\ carbon\ intensity}{vehicle\ \ fuel\ efficiency} + tailpipe\ nonCO_2$$

If natural gas vehicles have the same fuel efficiency as diesel vehicles, then it allows up to 3.1% of methane leakage rate to achieve emissions reduction.



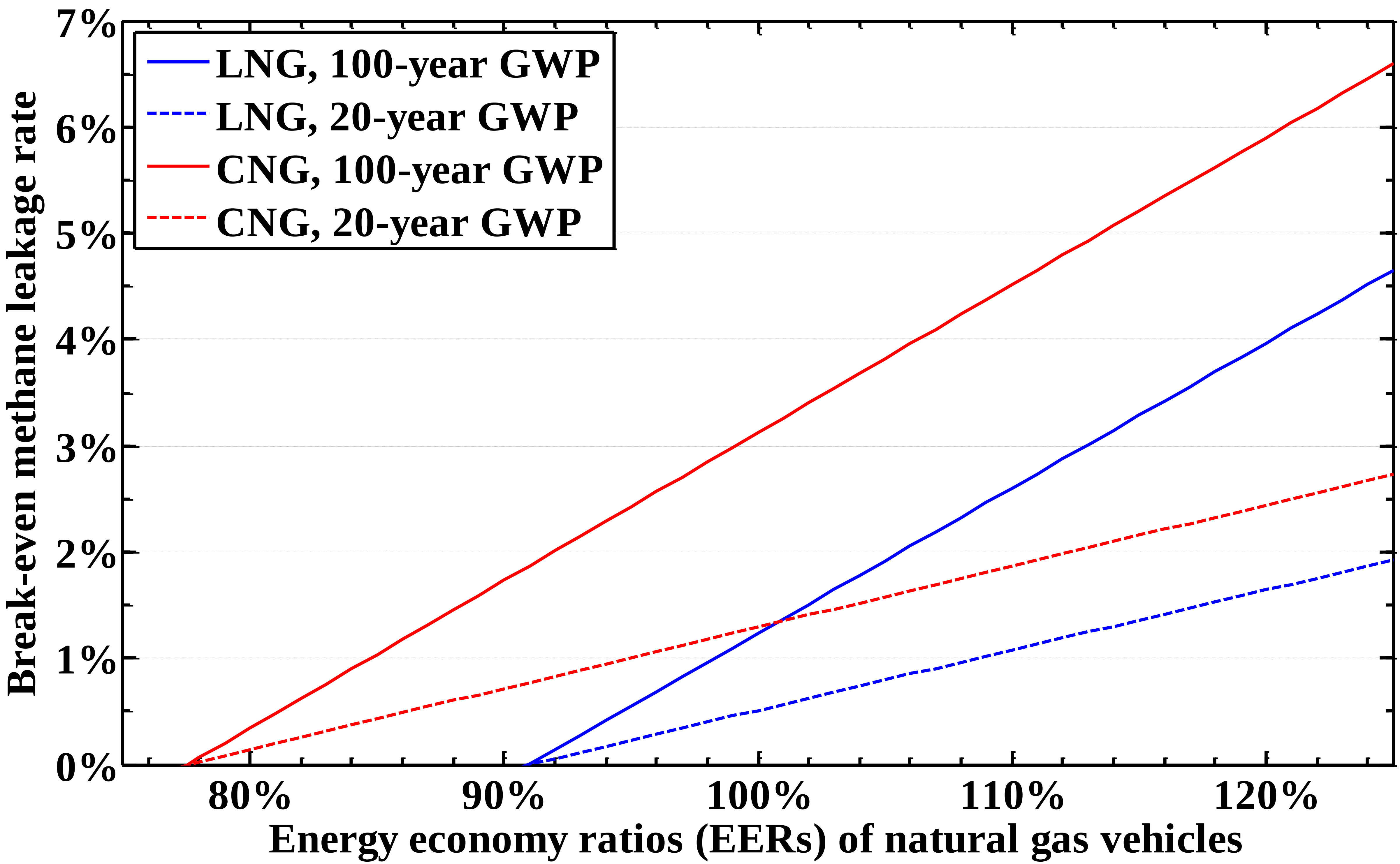
Modified from Tong et al. (2015a).

Higher or lower relative vehicle fuel efficiency allows higher or lower methane leakage.



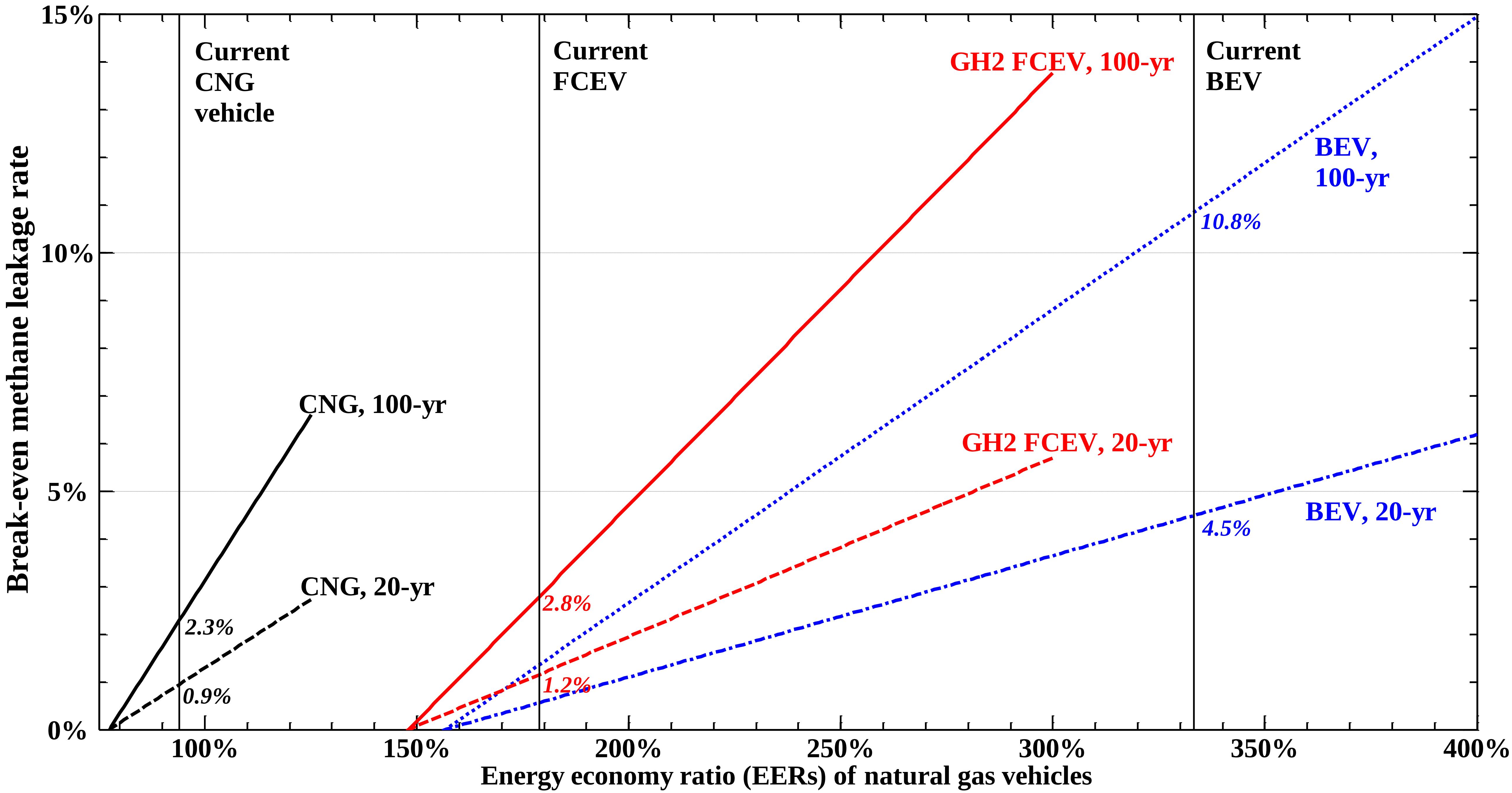
Modified from Tong et al. (2015a).

LNG/CNG vs. Diesel (MHDVs)



Modified from Tong et al. (2015a).

Natural Gas Pathways vs. Gasoline (LDVs)



Modified from Tong et al. (2015b).

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Comparison of Life Cycle Greenhouse Gases from Natural Gas Pathways for Medium and Heavy-Duty Vehicles

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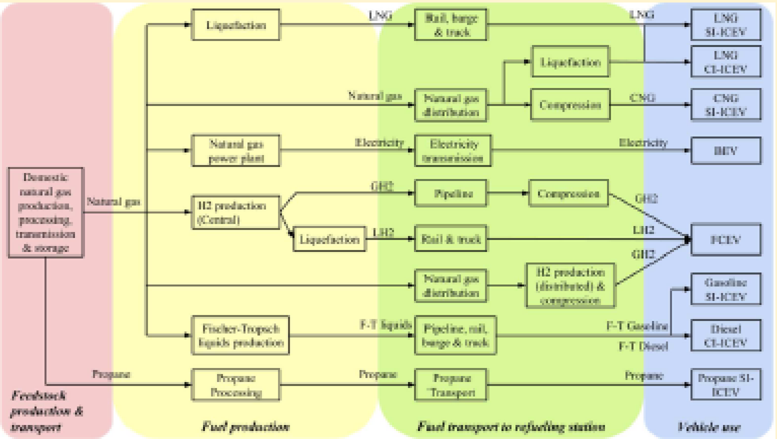
Supporting Information



ABSTRACT: The low-cost and abundant supply of shale gas in the United States has increased the interest in using natural gas for transportation. We compare the life cycle greenhouse gas (GHG) emissions from different natural gas pathways for medium and heavy-duty vehicles (MHDVs). For Class 8 tractor-trailers and refuse trucks, none of the natural gas pathways provide emissions reductions per unit of freight-distance moved compared to diesel trucks. When compared to the petroleum-based fuels currently used in these vehicles, CNG and centrally produced LNG increase emissions by 0−3% and 2−13%, respectively, for Class 8 trucks. Battery electric vehicles (BEVs) powered with natural gas-produced electricity are the only fuel-technology combination that achieves emission reductions for Class 8 transit buses (31% reduction compared to the petroleum-fueled vehicles). For non-Class 8 trucks (pick-up trucks, parcel delivery trucks, and box trucks), BEVs reduce emissions significantly (31−40%) compared to their diesel or gasoline counterparts. CNG and propane achieve relatively smaller emissions reductions (0−6% and 19%, respectively, compared to the petroleum-based fuels), while other natural gas pathways increase emissions for non-Class 8 MHDVs. While using natural gas to fuel electric vehicles could achieve large emission reductions for medium-duty trucks, the results suggest there are no great opportunities to achieve large emission reductions for Class 8 trucks through natural gas pathways with current technologies. There are strategies to reduce the carbon footprint of using natural gas for MHDVs, ranging from increasing vehicle fuel efficiency, reducing life cycle methane leakage rate, to achieving the same payloads and cargo volumes as conventional diesel trucks.

INTRODUCTION

In recent years, the successful combination of technologies, such as hydraulic fracturing, horizontal drilling, and seismic mapping have led to significant production of unconventional natural gas resources, which in turn has attracted industrial interests in using natural gas as a transportation fuel.[1−18] While economic considerations have dominated this discussion, environmental impacts of natural gas-based fuels are likely to be of interest to multiple stakeholders.[17,19,20] A recent NRC report[17] analyzed the impacts of natural gas to fuel medium- and heavy-duty vehicles (MHDVs) and concluded that "more studies and data are needed to determine the well-to-tank GHG emissions of NG vehicles."

There are several approaches to evaluate the GHG emissions of MHDVs. Both vehicle simulation[21−29] and vehicle tests[30−42] provide estimates of emissions from the use phase. These tests are limited in that they fail to account for emission sources beyond tailpipe. Thus, vehicle simulations and tests may not be appropriate for making generalized recommendations regarding GHG emissions. Life cycle assessment (LCA) studies[5,40,43−55,62−65] overcome this shortcoming as they account

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Comparison of Life Cycle Greenhouse Gases from Natural Gas Pathways for Light-Duty Vehicles

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Supporting Information

ABSTRACT: Low prices and abundant resources open new opportunities for using natural gas, one of which is the production of transportation fuels. In this study, we use a Monte Carlo analysis combined with a life cycle analysis framework to assess the greenhouse gas (GHG) implications of a transition to natural gas-powered vehicles. We consider six different natural gas fuel pathways in two representative light-duty vehicles: a passenger vehicle and a sport utility vehicle. We find that a battery electric vehicle (BEV) powered with natural gas-based electricity achieves around 40% life cycle emissions reductions when compared to conventional gasoline. Gaseous hydrogen fuel cell electric vehicles (FCEVs) and compressed natural gas (CNG) vehicles have comparable life cycle emissions with conventional gasoline, offering limited reductions with 100-year global warming potential (GWP) yet leading to increases with 20-year GWP. Other liquid fuel pathways (methanol, ethanol, and Fischer−Tropsch liquids) have larger GHG emissions than conventional gasoline even when carbon capture and storage technologies are available. Life cycle GHG emissions of natural gas pathways are sensitive to the vehicle fuel efficiency, to the methane leakage rates of natural gas systems, and to the GWP assumed. With the current vehicle technologies, the break-even methane leakage rates of CNG, gaseous hydrogen FCEV, and BEV are 0.9%/2.3%, 1.2%/2.8%, and 4.5%/10.8% (20-year GWP/100-year GWP). If the actual methane leakage rate is lower than the break-even rate of a specific natural gas pathway, that natural gas pathway reduces GHG emissions compared to conventional gasoline; otherwise, it leads to an increase in emissions.

INTRODUCTION

The past decade has seen a significant increase in U.S. natural gas production due to the technological success in extracting natural gas from unconventional resources. While in 2005 the United States (U.S.) shale gas production was negligible, by 2012 it reached 25.7 billion cubic feet per day (BCF/d),[1] and today it accounts for 40% of total dry natural gas production in the U.S.[2] The U.S. Energy Information Agency (EIA) forecasts that shale gas production will reach 45.8 BCF/d by 2040.[3] The rapid increase of natural gas supply has led to a large decrease in wellhead prices, which dropped from $7.97 per thousand cubic feet (Mcf) in 2008 to $2.66/Mcf in 2012.[4] As a result of the emergence of this domestic natural gas resource, there is a growing interest in using natural gas for electricity generation, for producing transportation fuels, for petrochemical manufacturing, and also for exports.[3]

Light duty vehicles (LDV) are the largest providers of mobility services to the U.S. population. More than 90% of U.S. families have at least one vehicle, and, on average, each household owns more than two vehicles.[5] Currently, there are more than 244 million LDVs in use in the U.S., and each year around 15 million new LDVs are sold.[5] In 2013, more than half (54%) of the new LDVs were gasoline-powered passenger vehicles, while the other half were gasoline-powered sport utility vehicles (SUVs) (32%), and pick-up trucks (11%).[5] By comparison, there are less than 1.2 million alternative fuel vehicles (AFVs) in use,[5] representing only 0.5% of the LDV fleet.

In the transportation sector, gasoline and distillate fuel from petroleum meet more than 90% of energy consumption.[5] The emergence of natural gas supply may open the opportunity for use of natural gas for transportation.[6−15] If so, several different pathways can be used. For example, natural gas could be used directly as a transportation fuel through compression or liquefaction, or it can be converted into other transportation fuels, such as hydrogen, electricity, and even gasoline and diesel via the Fischer−Tropsch process.

Life cycle analysis (LCA) is a widely used method to assess the environmental effects of a product or service from production to end of life.[16] There is an extensive body of research about the life cycle greenhouse (GHG) emissions of alternative transportation fuels, including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and hydrogen fuel cell electric vehicles (FCEVs).[17−40] Similarly, another large body of work has analyzed the life cycle GHG emissions of using natural gas to meet end uses (including transportation).[19,34,37−53] In 1999, Wang et al.[19] evaluated the life cycle GHG emissions of nine natural gas-based fuels, compressed natural gas (CNG), liquefied natural gas (LNG), liquid petroleum gas (LPG), electricity, methanol, gaseous hydrogen, liquid hydrogen, Fischer−Tropsch diesel, and dimethyl ether (DME), and they found that the "use of NG-based fuels can help reduce per-mile fossil energy use considerably and eliminate petroleum use in most cases; all [but near-term M85 FFVs] help reduce GHG emissions." More recently, Venkatesh et al.[34] used a Monte Carlo analysis to characterize the uncertainty of the life cycle GHG emissions of CNG and gasoline HEVs for passenger

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Tong (2015a). Tong, F.; Jaramillo, P.; Azevedo, I. Comparison of Life Cycle Greenhouse Gases from Natural Gas Pathways for Medium and Heavy-Duty Vehicles. *Environ. Sci. Technol.* **2015**, *49*, 7123–7133.

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Please refer to Tong et al. (2015a, 2015b) for a full list of relevant literature on this topic.

Questions?

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