Climate, Energy Transition and the Use of Natural Gas in Freight Transportation: Pros and Cons

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Webinar Series | Chair in Energy Sector Management,
HEC Montréal
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About STEPS

• **STEPS** is a multidisciplinary research consortium, part of the Institute of Transportation Studies at the University of California Davis (ITS-Davis) – a world leading university center on sustainable transportation.

• **Research**: generate new insights and tools, grounded in technical and economic realities, to study the sustainable transportation energy future for California, the U.S. and the world.

• **Consortium**: bring together the world's leading auto OEMs, energy companies, and government agencies to collaborate on sustainable vehicle and energy solutions; inform industry planning and government policy with timely and sophisticated science-based analysis.

• **Website**: steps.ucdavis.edu
Context for use of natural gas in transportation: CO$_2$ and NO$_x$ emission reductions
Québec and California Link

Both Quebec and California participate in the Western Climate Initiative (WCCI)
Québec GHG Targets and Transportation

-20 % by 2020
-37.5% by 2030
-80% by 2050

- Electricity is local and 99% renewable
  = 47% primary energy

- Hydrocarbons are imported
  = 53% primary energy

- Freight transportation account for 37% of all energy consumed in the transportation sector and is the fastest growing (GHG and energy consumption levels)

“Natural gas for vehicles: A proven solution.”

“Generally less expensive and always more environmentally friendly than diesel, natural gas has a major potential in the transportation sector.”

“For the 2015 fiscal year, the 22 fueling sites in Québec and 630 vehicles that run on natural gas helped replace 14.8 million liters of diesel.”

“In total, 19,404 tons of CO₂ equivalent were avoided by using natural gas as fuel during the 2015 fiscal year, including 12,900 tons by using renewable natural gas produced by EBI.”

“[NGVs] reduces CO\textsubscript{2} emissions by 25% compared to gasoline, and reduces NO\textsubscript{x} emissions by 80% compared to light diesel vehicles.”

To be clear: **Near-ZEV** refers to criteria pollutants only

- Natural gas is low NOX and low PM
  Sometimes called Zero Emission Vehicles (ZEV) or near-ZEV
- Refers to criteria pollutants, not GHG
- For GHG, Natural gas is **allowed 20% reduction** (not 100%) from gasoline/diesel in California LCFS
Pounds of CO$_2$ emitted per million British thermal units (Btu) of energy for various fuel (combustion only)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>CO$_2$ Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel fuel and heating oil</td>
<td>161.3</td>
</tr>
<tr>
<td>Gasoline</td>
<td>157.2</td>
</tr>
<tr>
<td>Propane</td>
<td>139.0</td>
</tr>
<tr>
<td>Natural gas</td>
<td>117.0</td>
</tr>
</tbody>
</table>

Source: https://www.eia.gov/tools/faqs/faq.php?id=73&t=11
But it is a little more complicated than that

Life Cycle Analysis
or Well to Wheels (WTW):
- Well to Pump (WTP)
- Pump to Wheels (PTW)

Well-to-Pump Methane Leakage
(a.k.a. Upstream or Fuel Cycle)
Methane Leaks

Source: EPA, [www.epa.gov/gasstar/tools/videos.html](http://www.epa.gov/gasstar/tools/videos.html)
Upstream Methane Leakage

Methane Leakage Rates from the Natural Gas System

- Drilling and fracturing
- Production
- Processing
- Transportation and distribution
- End use

EPA Inventory: 0.2% leakage
0.4%
0.2%
0.7%
Not included

Total NG leakage - EPA: 1.5%

Source: EDF based on 2013 EPA GHGI
EPA estimates of leakage goes up and down a little

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas Systems</td>
<td>773.9</td>
<td>717.4</td>
<td>722.4</td>
<td>717.4</td>
<td>714.4</td>
<td>721.5</td>
<td>730.8</td>
</tr>
<tr>
<td>Enteric Fermentation</td>
<td>206.8</td>
<td>177.3</td>
<td>166.2</td>
<td>170.1</td>
<td>172.6</td>
<td>175.6</td>
<td>176.1</td>
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<tr>
<td>Landfills</td>
<td>179.6</td>
<td>154.0</td>
<td>142.1</td>
<td>144.4</td>
<td>142.3</td>
<td>144.3</td>
<td>148.0</td>
</tr>
<tr>
<td>Petroleum Systems</td>
<td>38.7</td>
<td>48.8</td>
<td>54.1</td>
<td>56.3</td>
<td>58.4</td>
<td>64.7</td>
<td>68.1</td>
</tr>
<tr>
<td>Coal Mining</td>
<td>96.5</td>
<td>64.1</td>
<td>82.3</td>
<td>71.2</td>
<td>66.5</td>
<td>64.6</td>
<td>67.6</td>
</tr>
<tr>
<td>Manure Management</td>
<td>37.2</td>
<td>56.3</td>
<td>60.9</td>
<td>61.5</td>
<td>63.7</td>
<td>61.4</td>
<td>61.2</td>
</tr>
<tr>
<td>Wastewater Treatment</td>
<td>15.7</td>
<td>15.9</td>
<td>15.5</td>
<td>15.3</td>
<td>15.0</td>
<td>14.8</td>
<td>14.7</td>
</tr>
<tr>
<td>Rice Cultivation</td>
<td>13.1</td>
<td>13.0</td>
<td>11.9</td>
<td>11.8</td>
<td>11.9</td>
<td>11.9</td>
<td>11.9</td>
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<tr>
<td>Stationary Combustion</td>
<td>8.5</td>
<td>7.4</td>
<td>7.1</td>
<td>7.1</td>
<td>6.6</td>
<td>8.0</td>
<td>8.1</td>
</tr>
<tr>
<td>Abandoned Underground Coal Mines</td>
<td>7.2</td>
<td>6.6</td>
<td>6.6</td>
<td>6.4</td>
<td>6.2</td>
<td>6.2</td>
<td>6.3</td>
</tr>
<tr>
<td>Composting</td>
<td>0.4</td>
<td>1.9</td>
<td>1.8</td>
<td>1.9</td>
<td>1.9</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Mobile Combustion</td>
<td>5.6</td>
<td>2.7</td>
<td>2.3</td>
<td>2.2</td>
<td>2.2</td>
<td>2.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Field Burning of Agricultural Residues</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
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<tr>
<td>Petrochemical Production</td>
<td>0.2</td>
<td>0.1</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Ferroalloy Production</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Silicon Carbide Production and Consumption</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Iron and Steel Production &amp; Metallurgical Coke Production</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Incineration of Waste</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Table ES-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (MMT CO₂ Eq.)

Production also changes a little

Natural Gas Gross Withdrawals and Production
(Volumes in Million Cubic Feet)

<table>
<thead>
<tr>
<th>Show Data By:</th>
<th>Data Series</th>
<th>Area</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>View History</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross Withdrawals</td>
<td>□</td>
<td></td>
<td>26,056,893</td>
<td>26,816,085</td>
<td>28,479,026</td>
<td>29,542,313</td>
<td>30,005,254</td>
<td>31,895,427</td>
<td>1936-2014</td>
</tr>
<tr>
<td>From Gas Wells</td>
<td>□</td>
<td></td>
<td>14,414,287</td>
<td>13,247,498</td>
<td>12,291,070</td>
<td>12,504,227</td>
<td>11,255,616</td>
<td></td>
<td>1967-2013</td>
</tr>
<tr>
<td>From Oil Wells</td>
<td>□</td>
<td></td>
<td>5,674,120</td>
<td>5,834,703</td>
<td>5,907,919</td>
<td>4,965,833</td>
<td>5,427,676</td>
<td></td>
<td>1967-2013</td>
</tr>
<tr>
<td>From Shale Gas Wells</td>
<td>□</td>
<td></td>
<td>3,958,315</td>
<td>5,817,122</td>
<td>8,500,983</td>
<td>10,532,858</td>
<td>11,896,204</td>
<td></td>
<td>2007-2013</td>
</tr>
<tr>
<td>From Coalbed Wells</td>
<td>□</td>
<td></td>
<td>2,010,171</td>
<td>1,916,762</td>
<td>1,779,055</td>
<td>1,539,395</td>
<td>1,425,757</td>
<td></td>
<td>2002-2013</td>
</tr>
<tr>
<td>Repressuring</td>
<td>□</td>
<td></td>
<td>3,522,090</td>
<td>3,431,587</td>
<td>3,365,313</td>
<td>3,277,588</td>
<td>3,331,456</td>
<td></td>
<td>1936-2013</td>
</tr>
<tr>
<td>Vented and Flared</td>
<td>□</td>
<td></td>
<td>165,360</td>
<td>165,928</td>
<td>209,439</td>
<td>212,848</td>
<td>260,394</td>
<td></td>
<td>1936-2013</td>
</tr>
<tr>
<td>Nonhydrocarbon Gases Removed</td>
<td>□</td>
<td></td>
<td>721,507</td>
<td>836,698</td>
<td>867,922</td>
<td>768,598</td>
<td>722,527</td>
<td></td>
<td>1973-2013</td>
</tr>
<tr>
<td>Marketed Production</td>
<td>□</td>
<td></td>
<td>21,647,936</td>
<td>22,381,373</td>
<td>24,036,352</td>
<td>25,283,278</td>
<td>25,690,878</td>
<td>27,271,326</td>
<td>1900-2014</td>
</tr>
<tr>
<td>Dry Production</td>
<td>□</td>
<td></td>
<td>20,623,854</td>
<td>21,315,507</td>
<td>22,901,879</td>
<td>24,033,266</td>
<td>24,333,709</td>
<td>25,718,448</td>
<td>1930-2014</td>
</tr>
</tbody>
</table>

* = No Data Reported; -- = Not Applicable; NA = Not Available; W = Withheld to avoid disclosure of individual company data.


EPA: ~1.5% Leakage
But Many Disagree with EPA....

Methane Research:
The 16 Study Series

An unprecedented look at methane from the natural gas system

Methane (CH4) is a growing environmental concern. Methane is a potent greenhouse gas that is contributing to climate change. Science confirms methane is a problem that requires urgent attention. Reducing emissions of both methane and carbon dioxide is critical to slowing the rate of earth’s warming and limiting peak warming.
Found a range of estimates
Bottom-up vs. Top-down

- **Bottom-up** studies coincide with EPA
- **Top-down** studies find EPA estimates are low.

Why!?!?
EPA might be missing a small number of super emitters

Table S6. Evidence of heterogeneity of emissions magnitudes across studies.

<table>
<thead>
<tr>
<th>Study name</th>
<th>Industry stage</th>
<th>Measurement technique</th>
<th>Degree of heterogeneity noted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allen et al. 2013</td>
<td>Production</td>
<td>Direct measurement of unloading events</td>
<td>&quot;Four of nine events contribute more than 95% of total emissions&quot;</td>
</tr>
<tr>
<td>Alvarez 2012</td>
<td>Production</td>
<td>Analysis of reported emissions</td>
<td>&quot;10% of well sites accounted for 70% of emissions&quot;</td>
</tr>
<tr>
<td>Chambers 2006</td>
<td>Processing</td>
<td>Down-wind differential absorption LIDAR</td>
<td>&quot;At plant A a single intermittent leak from a pressure relief valve was located that increased site emissions from 104 kg/hr to 450 kg/hr.&quot;</td>
</tr>
<tr>
<td>Clearstone 2002</td>
<td>Processing</td>
<td>Direct measurement using Hi-Flow sampler</td>
<td>&gt;100,000 devices sampled across 4 facilities. between 35.7% and 64.6% of leakage from each facility was found leaking from top 10 leaks in each facility.</td>
</tr>
<tr>
<td>Cormack, 2007</td>
<td>Transmission compressors</td>
<td>Direct measurement with Hi-Flow sampler</td>
<td>Top single leak accounted 40% of leakage. Top 20% of leaking components accounted for 80% of leakage.</td>
</tr>
<tr>
<td>Harrison et al. 2011</td>
<td>Compressor stations</td>
<td>IR camera, Hi-Flow sampler</td>
<td>Reported data in Appendix B show outliers. For example, ~2,800 valves and flanges were screened with IR camera and 29 leaks were found. The single largest of these leaks (&gt;1000 mscf/year) is &gt;100,000 times larger than valve and flange EF (0.05 or 0.09 mscf/year). Similar results seen elsewhere. See, e.g., blowdown line leaks from centrifugal compressors (table B2) where largest leak represents 70% of the total leakage.</td>
</tr>
<tr>
<td>NGML, Clearstone, IES 2006</td>
<td>Processing, well sites, gathering compressor stations</td>
<td>Direct measurement using Hi-Flow sampler and optical methods</td>
<td>&gt; 74,000 components sampled. Approx. 1600 were found to be leaking (~25%). From executive summary: &quot;Repairs to 10 largest emitting cost-effective-to-repair components at each site…would reduce natural gas losses by approximately…58%&quot;</td>
</tr>
<tr>
<td>Picard, 2005</td>
<td>All stages</td>
<td>Sampling via various methods</td>
<td>&quot;Top 10 leaks typically contribute more than 80% of emissions from leaks.&quot;</td>
</tr>
<tr>
<td>Shorter, 1997</td>
<td>All stages</td>
<td>Remote sampling via tracer methods</td>
<td>Repeated evidence of skewed emissions distributions: See tables 1–7. Evidence includes: top emitters of size 100x to 10,000x larger than small emitters (table 9); standard deviations in excess of mean emissions rate in many cases, indicating heavy-tailed distribution (table 7).</td>
</tr>
<tr>
<td>Trefiak 2006</td>
<td>Compressor stations and gas plants</td>
<td>Optical measurement and Hi-Flow sampler</td>
<td>23% of the 144 fugitive emissions sources were responsible for 77% of leakage.</td>
</tr>
</tbody>
</table>

EPA not measuring abandoned wells

- Mary Kang (Princeton) Summer 2014 Thesis: Leakage from Abandoned Oil and Gas Wells
- Methane emissions from AOG wells are not accounted for in any GHG emissions inventories, either at the state or national levels in the U.S. or abroad.
- Leakage rates are equivalent to 0.3 to 0.5% of gross gas withdrawal (in PA for 2010)

More or less established: Actual leakage 25-75% higher than EPA’s estimate

EPA: 1.5%
Corrected: 1.85% - 2.95% due to underestimation of super emitters

• Unaccounted for: abandoned wells, other sources, add 0.5% points

Solutions to Reduce Upstream Methane Leakage
EPA Natural Gas STAR Program (voluntary reductions)

• There is also for Coalmining, agriculture, landfills

• Objective: Voluntary reductions in methane

• As of May 2016 Methane Rule in NSPS... but those only apply to new and modified wells, not old, not abandoned, etc...
Where are the leaks?

2009 U.S. methane emissions from oil and natural gas industry:
624 Bcf (3.8% of total U.S. greenhouse gas emissions)

- Oil Downstream: 2 Bcf (<1%)
- Distribution: 72 Bcf (11%)
- Transmission and Storage: 110 Bcf (18%)

**Production**
- Storage Tanks: 14 Bcf
- Pneumatic Devices: 67 Bcf
- Recompressing Compressors: 18 Bcf

**Gathering & Processing**
- Plant Fugitive: 2 Bcf
- Gas Engine Exhaust: 8 Bcf
- Compressor Fugitive, Venting, and Engine Exhaust: 16 Bcf

**Transmission**
- Pipeline Leaks: 8 Bcf
- Station Fugitive: 6 Bcf
- Station Ventsing: 6 Bcf

**Distribution**
- Customer Meter Leaks: 6 Bcf
- Gas Main/Service: 6 Bcf
- Plastic Main/Service: 6 Bcf
- Unprotected Steel Main/Service: 16 Bcf

# Technology Payback

## Table 4: Methane Capture Technology Costs and Benefits

<table>
<thead>
<tr>
<th>Technology</th>
<th>Investment Cost</th>
<th>Methane Capture</th>
<th>Profit</th>
<th>Payout</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green Completions</td>
<td>$8,700 to $33,000 per well</td>
<td>7,000 to 23,000 Mcf/well</td>
<td>$28,000 to $90,000 per well</td>
<td>&lt; 0.5 – 1 year</td>
</tr>
<tr>
<td>Plunger Lift Systems</td>
<td>$2,600 to $13,000 per well</td>
<td>600 to 18,250 Mcf/year</td>
<td>$2,000 to $103,000 per year</td>
<td>&lt; 1 year</td>
</tr>
<tr>
<td>TEG Dehydrator Emission Controls</td>
<td>Up to $13,000 for 4 controls</td>
<td>3,600 to 35,000 Mcf/year</td>
<td>$14,000 to $138,000 per year</td>
<td>&lt; 0.5 years</td>
</tr>
<tr>
<td>Desiccant Dehydrators</td>
<td>$16,000 per device</td>
<td>1,000 Mcf/year</td>
<td>$6,000 per year</td>
<td>&lt; 3 years</td>
</tr>
<tr>
<td>Dry Seal Systems</td>
<td>$90,000 to $324,000 per device</td>
<td>18,000 to 100,000 Mcf/year</td>
<td>$280,000 to $520,000 per year</td>
<td>0.5 – 1.5 years</td>
</tr>
<tr>
<td>Improved Compressor Maintenance</td>
<td>$1,200 to $1,600 per rod packing</td>
<td>850 Mcf/year per rod packing</td>
<td>$3,500 per year</td>
<td>0.5 years</td>
</tr>
<tr>
<td>Pneumatic Controllers Low-Bleed</td>
<td>$175 to $350 per device</td>
<td>125 to 300 Mcf/year</td>
<td>$500 to $1,900 per year</td>
<td>&lt; 0.5 – 1 year</td>
</tr>
<tr>
<td>Pneumatic Controllers No-Bleed</td>
<td>$10,000 to $60,000 per device</td>
<td>5,400 to 20,000 Mcf/year</td>
<td>$14,000 to $62,000 per year</td>
<td>&lt; 2 years</td>
</tr>
<tr>
<td>Pipeline Maintenance and Repair</td>
<td>Varies widely</td>
<td>Varies widely but significant</td>
<td>Varies widely by significant</td>
<td>&lt; 1 year</td>
</tr>
<tr>
<td>Vapor Recovery Units</td>
<td>$36,000 to $104,000 per device</td>
<td>5,000 to 91,000 Mcf/year</td>
<td>$4,000 to $348,000 per year</td>
<td>0.5 – 3 years</td>
</tr>
<tr>
<td>Leak Monitoring and Repair</td>
<td>$26,000 to $59,000 per facility</td>
<td>30,000 to 87,000 Mcf/year</td>
<td>$117,000 to $314,000 per facility per year</td>
<td>&lt; 0.5 years</td>
</tr>
</tbody>
</table>

Note: Profit includes revenue from deployment of technology plus any O&M savings or costs, but excludes depreciation. Additional details provided in Appendix A. Source: NRDC analysis of available industry information. Individual technology information sources cited in Chapter 4.
EPA Natural Gas STAR Program

In 2016, leakage reduced by 16% while production increased by 35%.

Upstream Leakage Summary

- Variable: Company culture and geography often reflect regulations
- Measured with Bottom-up vs. Top-down
- EPA bottom-up average is under 1.5%
- Realistically, could be as high as ~3% or 3.5%
- In some specific cases, top-down suggests as high as 8%, but difficult to attribute to sources.
My way to deal with uncertainty?

Test scenarios for upstream leakage:

• **Baseline**: 1.14%
• **Zero Leakage Scenario**
• **High Leakage Scenario** (up to 10%)

And I will get to that in a minute...
Vehicle

Upstream

Source: Dominguez-Faus, R. The CARBON INTENSITY of NGV C8 TRUCKS. STEPS Working Paper
Natural Gas Supply Chain
Vehicle Emissions (vehicle Leakage)
Methane leakage in Long-Haul Trucks
(based on data provided by Westport)

Diesel:
- 0.005 gCH₄/mi (methane slip)

Natural Gas:
- 3.6 g CH₄/mi HPDI
- 6.3 g CH₄/mi Si

(For natural gas fueled engines that will be used in long-haul trucks)

It will be different in other applications
Source of difference with other studies

ARB: Uses values for average application using natural gas (was traditionally a mix of taxis and buses)

Me: Long-haul Trucks

1. Different drive cycles means Different Emission Profile and Fuel Economies

2. Natural gas is substituting gasoline in taxis and buses (whereas natural gas substitutes diesel in long haul trucks)
What does it matter which fuel it substitutes?

- **Related to the efficiency of the combustion process**
- Diesel: Uses Compression Ignition – Efficiency of 55%
- Gasoline: Spark Ignition (SI) engines about 10% less efficient than compression ignition (CI) diesel engines
- Natural gas engines: Spark Ignition (SI) engines about 10% less efficient than compression ignition (CI) diesel engines

So.....

- In taxis and buses ➔ No difference in efficiency when switching from gasoline to natural gas
- In long-haul trucks ➔ 10% efficiency loss when switching from diesel to natural gas.
Newer models seem to control crank-case leakage, but exhaust Ch4 is still a bit tricky

- Crank case
  - Easy to control

- Exhaust
  - Not so easy to control: Incomplete combustion promoted when combustion temperature lowered for NOx control
Westport designs the HPDI dual fuel engine which has efficiency similar to diesel’s

- 10% diesel for compression ignition (great efficiency)
- 90% on natural gas

I will test both for the SI and HPDI natural gas engines in long haul applications
Well-to-Wheel Carbon Intensity of CNG and LNG
### My Baseline Assumptions about

<table>
<thead>
<tr>
<th>Upstream</th>
<th>Conventiona l NG</th>
<th>Shale gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovery - Completion CH4 Venting</td>
<td>0.00%</td>
<td>0.03%</td>
</tr>
<tr>
<td>Recovery - Workover CH4 Venting</td>
<td>0.00%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Recovery - Liquid Unloading CH4 Venting</td>
<td>0.05%</td>
<td>0.05%</td>
</tr>
<tr>
<td>Well Equipment - CH4 Venting and Leakage</td>
<td>0.25%</td>
<td>0.25%</td>
</tr>
<tr>
<td>Processing - CH4 Venting and Leakage</td>
<td>0.13%</td>
<td>0.13%</td>
</tr>
<tr>
<td>Transmission and Storage - CH4 Venting and Leakage</td>
<td>0.41%</td>
<td>0.41%</td>
</tr>
<tr>
<td>Distribution - CH4 Venting and Leakage</td>
<td>0.33%</td>
<td>0.33%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.18%</strong></td>
<td><strong>1.22%</strong></td>
</tr>
</tbody>
</table>

Average ~1.2%

### Vehicle

<table>
<thead>
<tr>
<th></th>
<th>Vehicle leakage</th>
<th>Vehicle fuel economy</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SI</td>
<td>6.3 g/mi</td>
<td>4.68 mpg</td>
</tr>
<tr>
<td>HPDI (CI)</td>
<td>3.6 g/mi</td>
<td>5.36 mpg</td>
</tr>
<tr>
<td>Diesel</td>
<td>CI</td>
<td></td>
</tr>
<tr>
<td>0.005 g/mi</td>
<td>5.36 mpg</td>
<td></td>
</tr>
</tbody>
</table>

Vehicle leakage and vehicle fuel economy.
Carbon intensity of Diesel and 3 combinations of natural gas trucks

Another study by Carnegie Mellon University (CMU) offers probabilistic ranges rather than point estimates in order to account for the variety in fuels and transportation systems.

For the WTW emissions, in addition to the variability in feedstock systems, they include variability in vehicles and fuel options.

“for Class 8 tractor-trailers and refuel trucks, none of the natural gas pathways provide emissions reduction per unit of freight-distance moved compared to diesel trucks”.

When compared with petroleum fuels, CNG and centrally produced LNG emissions increased by 0-3% and 2-13%, respectively.

EDF and Columbia University (long-haul trucks)

• They consider the difference in the engine efficiencies of natural gas 8.9L and 11.9 L spark ignition (SI) engines and include a 15L HPDI engine technology.

• Relative efficiencies of the SI and high performance direct injection (HPDI) are 13% and 5.5% lower than diesel respectively.

• For methane slip (i.e., methane from the vehicle) is 4.2 gCH4/mi for HPDI and 2.6 g/CH4 for the SI.

• Converting heavy-duty truck fleets (to natural gas) leads to damages to the climate for several decades.

• After some period of time, 72 years (CNG) and 90 years (LNG) in the case of the SI NGV trucks and 51 years in the case of the HPDI truck (LNG), a climate benefit occurs as the initial warming created by methane dissipates and the benefits of lower CO2 emissions are reaped.

LCFS
(buses and taxis)

• The LCFS value is revised periodically.
  – In the original LCFS lookup tables calculate gasoline, diesel, CNG and LNG at a carbon intensity of 95.86, 94.71, 68, and 72.38 gCO₂e/MJ (not EER adjusted) respectively.
  – In more recent public hearings, ARB is considering a modification to 98.38, 98.03, 75.56, 80.42 g/MJ (not EER adjusted) or 100.53, 102.76, 88.29, 96.19 g/MJ respectively if EER adjusted.

• Reductions of 12-28% (CNG), and 6-24% (LNG)

Source: https://www.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm
Why different? And Which variables are more important?

Testing the Sensitivities
But is upstream leakage really that important in the LCA?

Source: Dominguez-Faus, R. The CARBON INTENSITY of NGV C8 TRUCKS. STEPS Working Paper
Carbon Intensity under different methane leakage

Source: Dominguez-Faus, R. The CARBON INTENSITY of NGV C8 TRUCKS. STEPS Working Paper
One value does not fit all. One single estimate is not valid, there is variability, there is uncertainty, not only in upstream leakage but also vehicle leakage and fuel economy (largest sensitivities)
I am not saying....

Natural Gas cannot provide GHG reductions

I am saying....

1. It is not always the case
2. Upstream leakage is important, but so is what happens in the vehicle
3. Vehicle depends on:
   - The application: Bus, truck, marine?
   - The fuel it substitutes
4. There are ways to lower carbon intensity of NG:
   - Reduce upstream methane (effect: high)
   - Reduce vehicle methane (effect: high)
   - Increase fuel economy (effect: higher)
5. Reductions will be modest (unless you blend with H$_2$ or RNG). Definitely not a Near-ZEV in terms of GHG
Studies in STEPS website

• Exploring the Role of Natural Gas in U.S. Trucking (Revised Version)

• The CARBON INTENSITY of NGV C8 TRUCKS
Thank you.

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Email: rdominguezfaus@ucdavis.edu
Website: https://steps.ucdavis.edu/
EPA Inventory: Actual Methane Leakage, 2012

Official
EPA = 1.12%

Source: EPA
U.S. Methane Rule
(May 2016)

- 20-30% reductions from Energy industry
- Not clear how to achieve the rest up to 40% reduction over next decade (over 2012 levels) Obama’s Climate Action Plan
- That is 40% of 35% of 900BCF = 126 BCF
- 14% of total leakage
- Applies to new or modified wells and storage tanks (NSPS) and expands restrictions to wells producing less than 15b/d.
- Does not apply to existing, abandoned wells.
- Will cost $530M in 2025
- Will produce benefits of $690
- Will eliminate:
  - About 510,000 tonnes of methane (11 million metric tons of CO2)
  - 210,000 tonnes of ozone-forming VOCs
  - 3,900 tonnes of air toxics such as toluene, benzene, ethylbenzene and xylene.
- Now ICR for data for existing sources.

Make sure is tonnes not short tons!!!
Renewable Natural Gas in Transportation: Key Findings

Blending of Dairy and MSW RNG with fossil natural gas produces the most carbon benefits but blending landfill or WWTP (waste water treatment plant) with fossil natural gas produces more limited improvements in its climate performance.

<table>
<thead>
<tr>
<th>% RNG ble</th>
<th>Landfill</th>
<th>WWTP</th>
<th>MSW</th>
<th>Dairy</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%</td>
<td>-2%</td>
<td>-4%</td>
<td>-6%</td>
<td>-23%</td>
</tr>
<tr>
<td>15%</td>
<td>-6%</td>
<td>-11%</td>
<td>-19%</td>
<td>-68%</td>
</tr>
<tr>
<td>20%</td>
<td>-8%</td>
<td>-15%</td>
<td>-26%</td>
<td>-90%</td>
</tr>
<tr>
<td>25%</td>
<td>-10%</td>
<td>-19%</td>
<td>-32%</td>
<td>-113%</td>
</tr>
<tr>
<td>35%</td>
<td>-14%</td>
<td>-26%</td>
<td>-45%</td>
<td>-158%</td>
</tr>
<tr>
<td>45%</td>
<td>-18%</td>
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<td>-204%</td>
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<tr>
<td>50%</td>
<td>-20%</td>
<td>-38%</td>
<td>-65%</td>
<td>-226%</td>
</tr>
<tr>
<td>55%</td>
<td>-22%</td>
<td>-41%</td>
<td>-71%</td>
<td>-249%</td>
</tr>
<tr>
<td>65%</td>
<td>-26%</td>
<td>-49%</td>
<td>-84%</td>
<td>-294%</td>
</tr>
<tr>
<td>75%</td>
<td>-31%</td>
<td>-56%</td>
<td>-97%</td>
<td>-339%</td>
</tr>
<tr>
<td>80%</td>
<td>-33%</td>
<td>-60%</td>
<td>-103%</td>
<td>-362%</td>
</tr>
<tr>
<td>85%</td>
<td>-35%</td>
<td>-64%</td>
<td>-110%</td>
<td>-385%</td>
</tr>
<tr>
<td>100%</td>
<td>-41%</td>
<td>-75%</td>
<td>-129%</td>
<td>-452%</td>
</tr>
</tbody>
</table>
Quebec’s 2030 Energy Policy

The Efficiency of Freight Transportation (p.36)

- Support the conversion of transportation vehicles already on the road to fuels with lower carbon content, in particular liquefied natural gas (LNG), compressed natural gas (CNG) and propane.
- Support the decarbonization of transportation in the industrial sector by promoting therein forms of energy with lower GHG emissions.
- Enhance the eco-trucking program to promote conversion to natural gas for heavy-duty vehicles.

The distribution of alternative fuels (p.38)

- Establish within the coming year a network of multi-fuel service stations offering gasoline, biofuels, natural gas, propane, electricity and hydrogen and extend it by 2030 throughout Québec.
- Support Gaz Métro’s objective of increasing by 15% by 2030 the heavy-duty vehicle fleet powered by LNG or CNG. To ensure supplies, the government will collaborate with Gaz Métro to evaluate the possibility of extending along the north-south axis the Blue Corridor, a network of LNG fueling stations for heavy-duty vehicles, which would ensure complete coverage of Québec.

Natural gas supply (p.54)

- Natural gas is a transition energy that is profitable for Québec and will play a key role in the coming decades in supporting economic development and the competitiveness abroad of Québec companies. The government therefore intends to ensure that Québec households and businesses have reliable, secure, stable access to natural gas throughout the territory where demand and economic profitability warrant it. To this end, the government intends to: pursue the extension of the gas network; develop a liquefied natural gas supply network; expand renewable natural gas production.