# Lifecycle Emissions Analysis for Converted In-Use Light-Duty Alcohol Fuel Vehicles

## Phase 2 Study, Part 1: Vehicle-Level Benefits

**For the Fuel Freedom Foundation and the Natural Resources Defense Council**

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**Study Objective:** assess and compare life-cycle emissions profiles for in-use late-model LDVs if legally converted to operate on alcohol-gasoline blends

**Key Assumptions / Notables:**

- Most popular (high VMT) in-use LDV models (2006 and newer) are converted
- Baseline pathway is reformulated gasoline used in conventional LDVs
- CNG and battery-electric vehicles also assessed to provide dedicated AFV benchmarks

**Existing and Emerging Pathways of Primary Interest:**

1. Reformulated Gasoline (RFG):
   a) Conventional petroleum-refining pathway, with and without 10% ethanol added
   b) Natural gas to ethylene to gasoline pathway (emerging technology, not yet commercial)
2. E-85 (85% ethanol blended into 15% RFG)
   a) Corn pathway
   b) Cellulosic pathway
   c) Natural gas pathway (emerging technology, not yet commercial)
3. M-60: (60% methanol blended into 40% RFG)
   a) Natural gas (steam methane or autothermal reforming) pathway
   b) Various "renewables" pathways
4. CNG: pipeline natural gas, compressed to 3,600 psi
5. Electricity: average U.S. grid mix (natural gas combined cycle)

## Original Statement of Work for "Phase 2" Study

### Task 1: Vehicle-Level Benefits

1A – Assess Fuel Cycle Emissions for In-Use Light-Duty Automobiles

- ☑ ▪ Criteria Pollutants
- ☑ ▪ GHGs
- ☑ ▪ Air Toxics

1B – Other Subtasks

- ☑ ▪ Create New Fuel Pathway for Ethanol from Natural Gas **(Attempted)**
- ☑ ▪ Expand Analysis to In-Use Light-Duty Trucks
- ☑ ▪ Assess Marginal Crude Oil
- ☑ ▪ Modify Natural Gas Hydraulic Fracturing Pathway
- ☑ ▪ Research Conventional vs. Alternative Fuel Direct-Vehicle Emissions

### Task 2: Fleet- and Society-Level Benefits

- Criteria Pollutants
- GHGs / Air Toxics
- Petroleum Displacement

NOTE: as described below, Task 2 could not be performed due to lack of sufficient data to fully characterize vehicle-level benefits

1 **Introduction / Background**

- Study Objective and Scope
- **LCA Definition and Methodology**

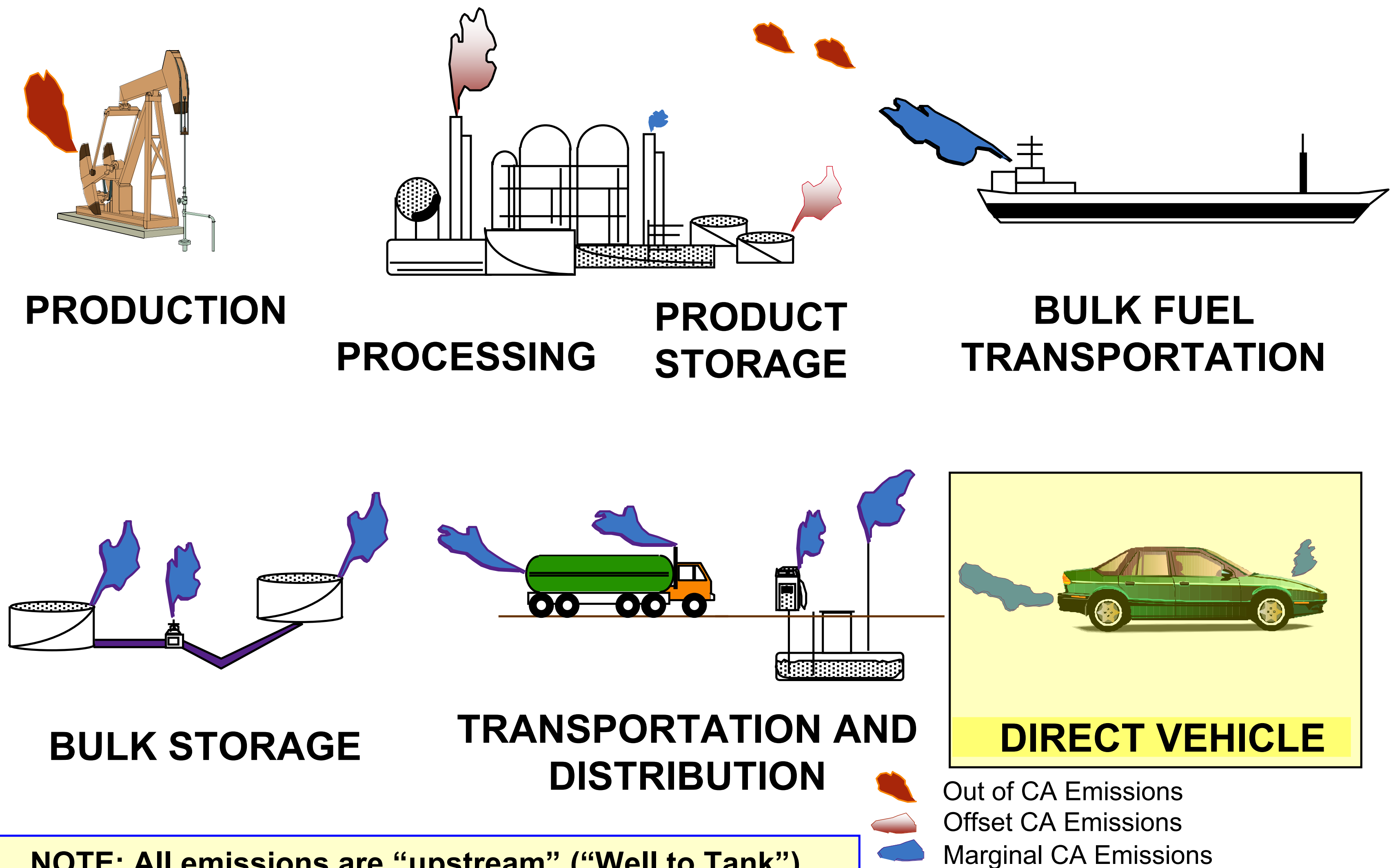
2 LCA Results / Findings

3 Focus on Greenhouse Gases

- Methane Emissions
- LCA Issues and Uncertainties

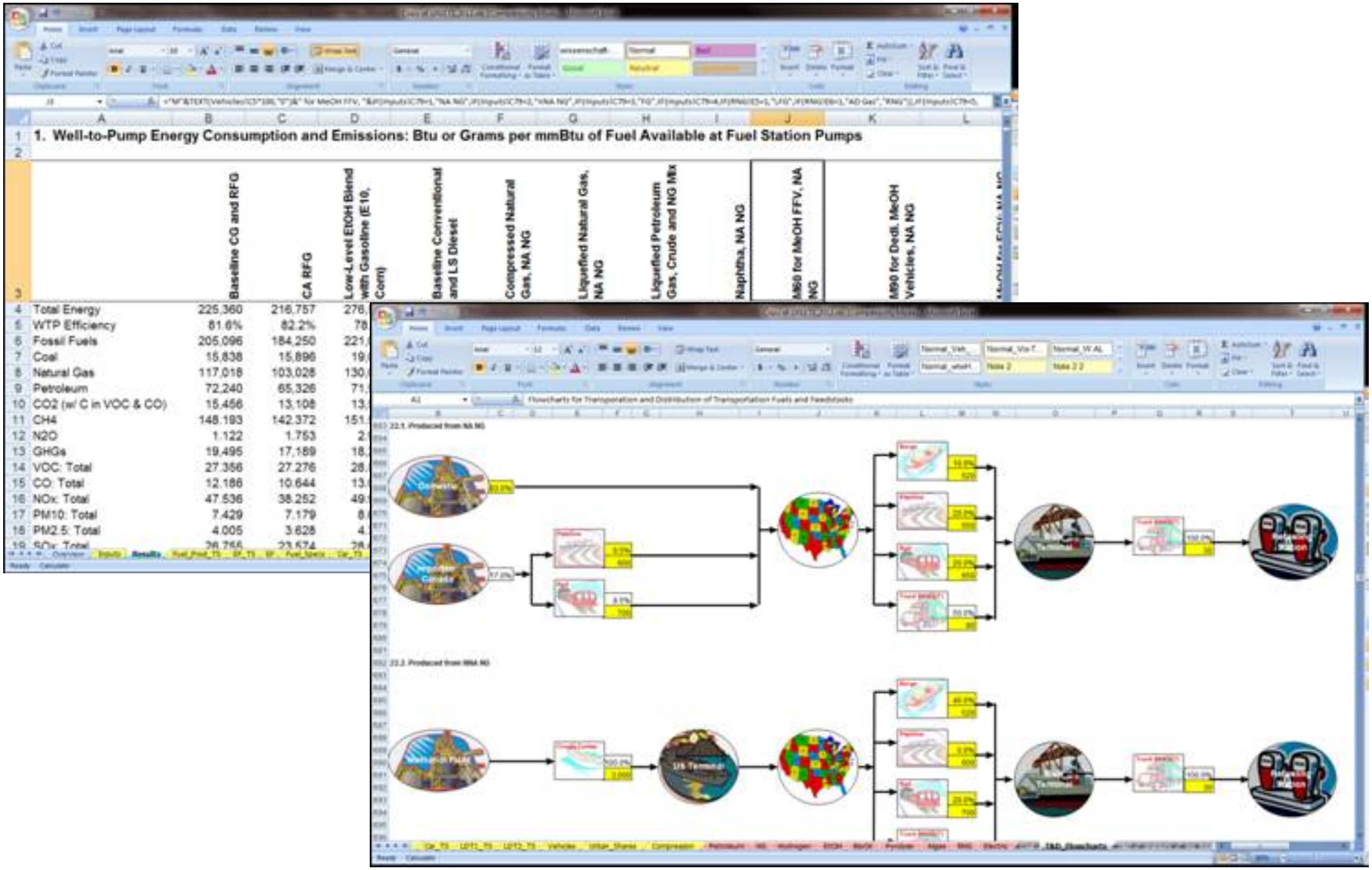
4 Findings and Conclusions

## LCA takes into account all fuel / vehicle emissions events, from "Well to Wheels"




**NOTE: All emissions are "upstream" ("Well to Tank") except DIRECT VEHICLE emissions ("Tank to Wheels").**

# Argonne Nat'l Lab's GREET* was used to estimate "upstream" emissions (WTT)




*Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation

## GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation)

- Original GREET created by Argonne Nat'l Lab (ANL), released in 1996
- ANL has frequently updated and expanded the model (e.g., GREET1_2011 shale gas pathway)
- Current GREET versions:
  - GREET 1 2012 rev2 (fuel-cycle analysis)
  - GREET 2.7 (vehicle-cycle analysis)
- For a given vehicle and fuel system, GREET separately calculates the following:
  - Consumption of total energy (non-renewable and renewable)
  - Fossil fuels (petroleum, natural gas, and coal)
  - Emissions of $CO_2$-equivalent GHGs (primarily $CO_2$, $CH_4$, and $N_2O$)
  - Emissions of six criteria pollutants: VOCs, CO, $NO_x$, $PM_{10}$ / $PM_{2.5}$, and $SO_x$
- ANL often releases peer-reviewed documents about specific pathways or modifications
- GREET 1 2012 rev2 includes many pathway and input updates, including the following:
  - Added renewable natural gas pathway
  - Updated sugarcane ethanol pathways
  - Updated electricity generation mixes, shale gas shares and oil sand shares
- Main source: EIA "Annual Energy Outlook 2013 Early Release" (#DOE/EIA-0383ER, 2013)
- However, GREET 1 2012 still includes EPA's controversial factors for $CH_4$ leakage
- California GREET ("CA-GREET"): provides CA-specific pathways but also defers to GREET
  - CA-GREET has not yet adopted EPA's $CH_4$ leakage factors

**Source: Argonne National Laboratory, "Summary of Updates in GREET1_2012 (Revision 2)," December 2012**

Starting assumption for a vehicle-conversion strategy to deploy alcohol AFVs:

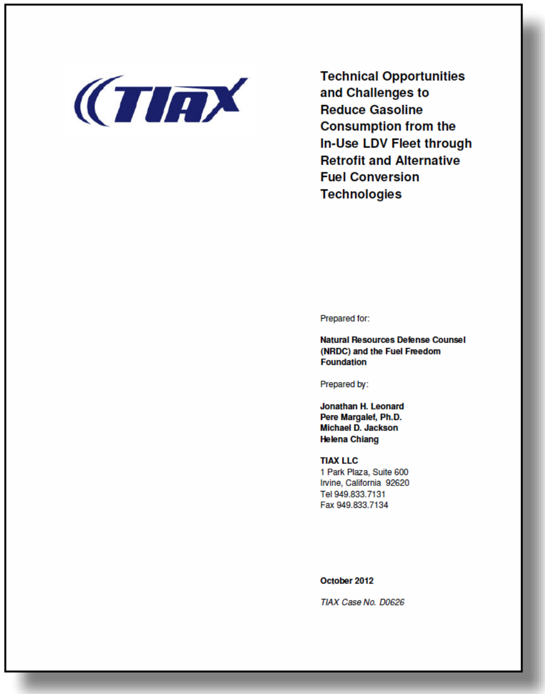
Direct-vehicle emissions for alcohol fuel options will not change when the baseline (RFG) vehicle is converted into an alternative fuel vehicle

**NOTE:** by definition, the electricity pathway (for BEVs) has **zero** direct-vehicle emissions

Rationale for making this assumption:

- ✓ **EPA / CARB Requirements:** a converted vehicle's regulated emissions are not allowed to exceed the pre-conversion certification values
- ✓ **Manufacturer's Preference:** conversion system makers will certify to the highest allowable emissions levels, to manage risk and minimize costs
- ✓ **Lack of Consumer Demand:** potential users have little incentive to convert LDVs solely to reduce emissions
- ✓ **Technical Uncertainty:** little hard information exists about the ability to cost-effectively optimize converted FFVs for reduced emissions

This also provides a useful lower boundary for the estimated emissions benefits of converting LDVs to use alcohol blends


Technical Opportunities and Challenges to Reduce Gasoline Consumption from the In-Use LDV Fleet through Retrofit and Alternative Fuel Conversion Technologies

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TIAX Case No. D0626

TIAX's Phase 1 and NRDC / TIAX Phase 3 studies document the challenges of certifying alternative fuel conversion systems

Note: Later, we account for potential to reduce direct-vehicle emissions

- Scenario 1 we compared full fuel cycle emissions from "typical" late-model (~2007) light-duty automobiles (LDAs) and light-duty trucks (LDTs)
  - ☑ Population: millions on American roads today (of which many are "flex fuel" capable)
  - ☑ Logistics: can be converted to use high alcohol-gasoline blends at relatively low cost
- Conventional gasoline LDV compared to 6 different fuel / vehicle types
- Alternative fuel vehicles are assumed to be aftermarket conversions

**VEHICLES / FUELS**

**Conventional Light-Duty Vehicle**

- 100 Reformulated Gasoline **(RFG)**
- 90% RFG / 10% Corn Ethanol **(E10)**

**Flexible Fuel Vehicle**

- 60% Methanol / 40% RFG **(M60)**
- 85% Cellulosic Ethanol / 15% RFG **(E85)**
- 85% Corn Ethanol / 15% **(E85)**

**Dedicated Alternative Fuel Vehicle**

- Compressed Natural Gas **(CNG)**
- Battery Electric / Grid Electricity **(BEV)**

**Typical 2007 Light-Duty Automobile**

**Typical 2007 Light-Duty Truck**

# Initial Findings (GREET_1_2012): "WTW" Emissions for Converted LDVs:

## Criteria Pollutant Emissions: (excluding diesel PM)

- E85 pathways are generally higher than baseline (RFG) pathway (for all criteria pollutants)
- M60 pathway is roughly comparable to RFG and E10 (upstream PM emissions are higher)

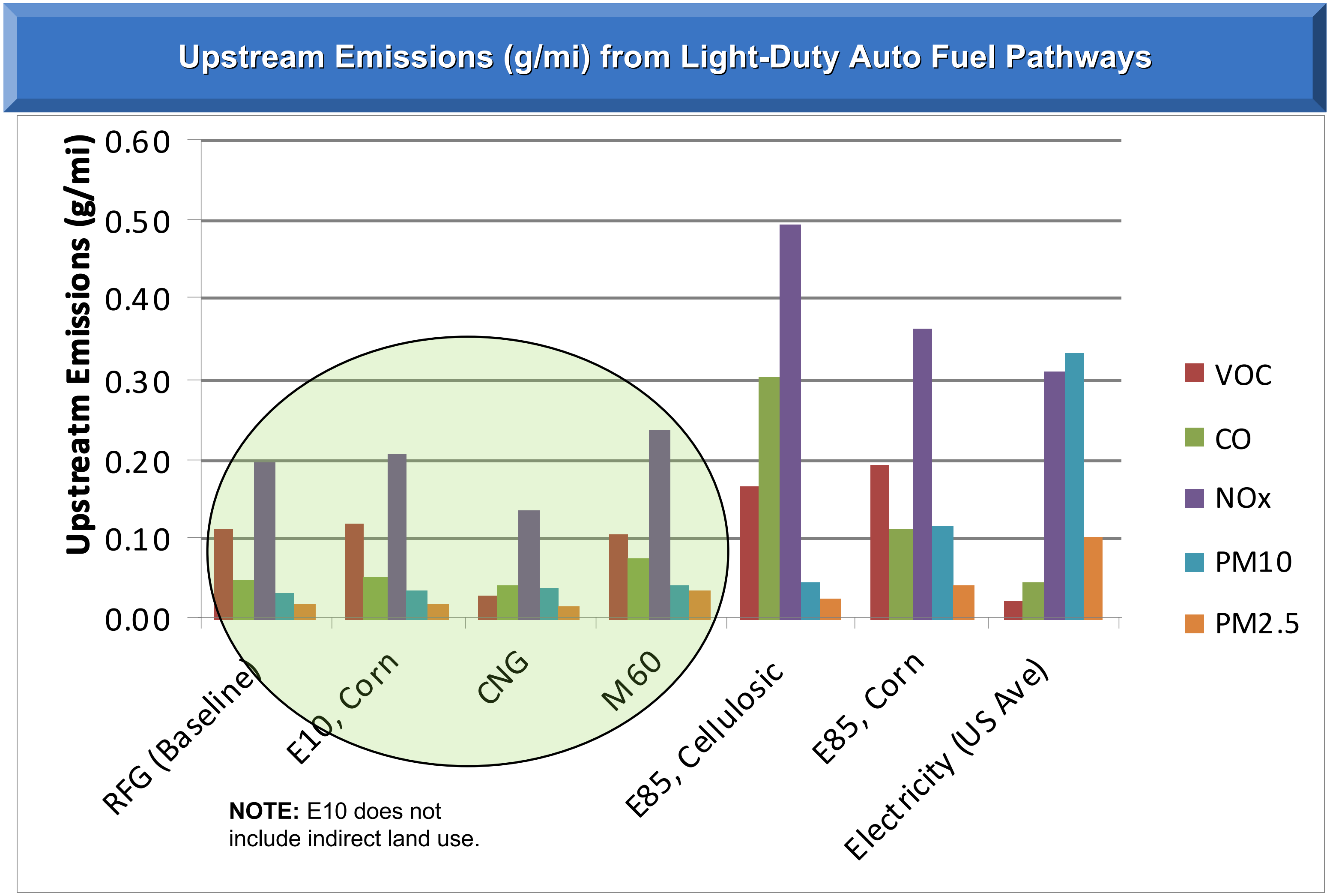
## Air Toxic Emissions: (including diesel PM)

- E-85 pathways: show high diesel PM from heavy-duty engines (farming, harvesting and transport)
- M-60: basically a "wash" by mass; tradeoffs on toxicity (e.g. HCHO vs benzene) appear net positive

## GHG Emissions ($CO_2$ equivalents):

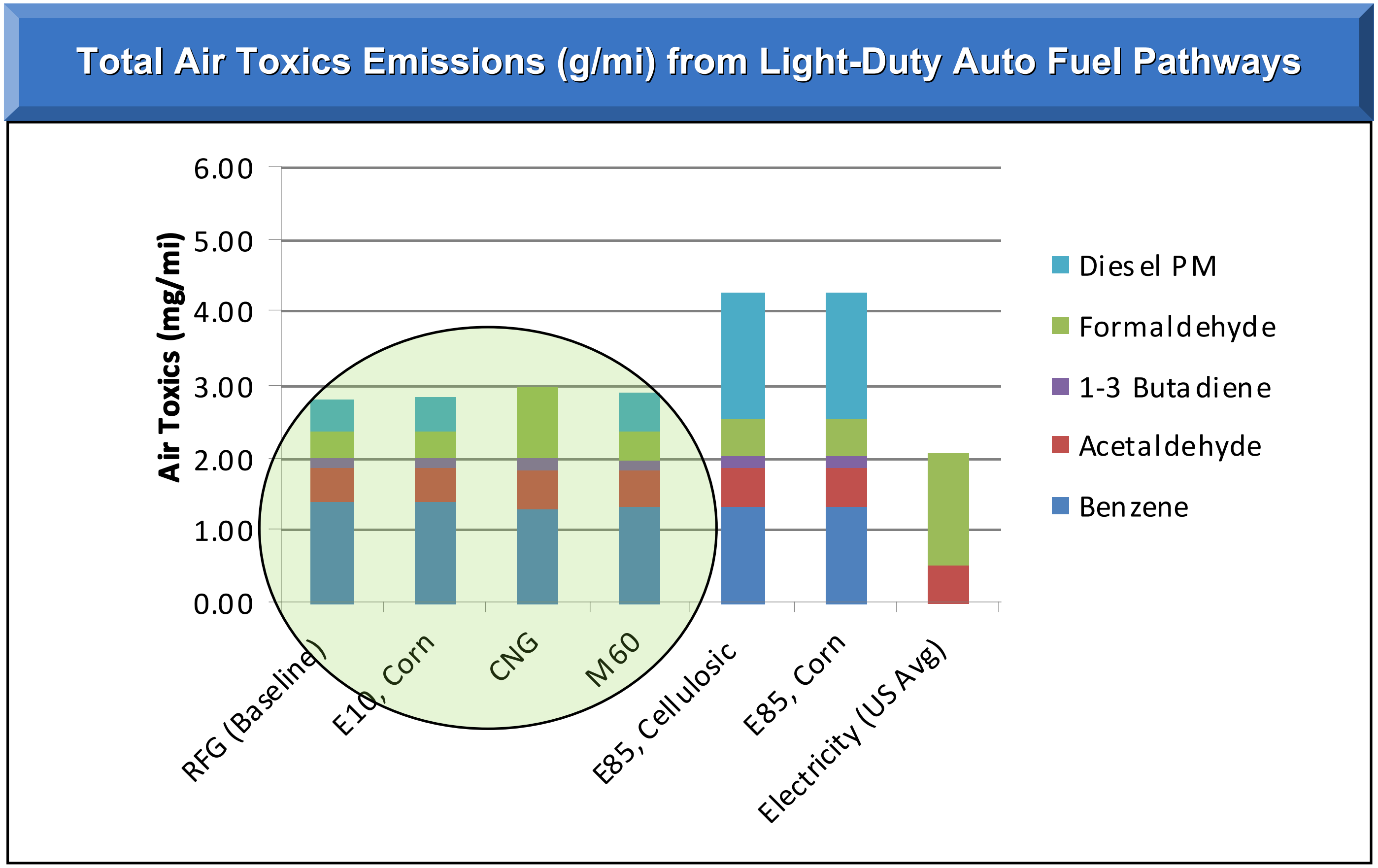
- E85 pathways: good reductions compared to RFG (-25% to -68%)
- CNG pathway: at least a 9% reduction; this would be significantly higher with better control of upstream methane emissions
- M60 conventional pathway: ranges from slightly worse to significantly better; depends on uncertain and evolving assumptions for:
  - Vehicle fuel efficiency (relative to pre-conversion vehicle on gasoline)
  - Methanol production efficiency (steam methane vs. autothermal reforming)
  - Methane leakage factors assumed for natural gas pathway
- M60 renewable pathway (e.g., landfill gas): dramatically better
- Most important factors in realizing M60's strong potential as a low-GHG transportation fuel:
  - **Upstream:** manage and minimize methane leakage when producing natural gas
  - **Downstream:** maximize vehicle fuel efficiency (optimize for methanol's combustion advantages)

## Criteria Pollutant Emissions: Total (Well to Wheels) L-D Autos



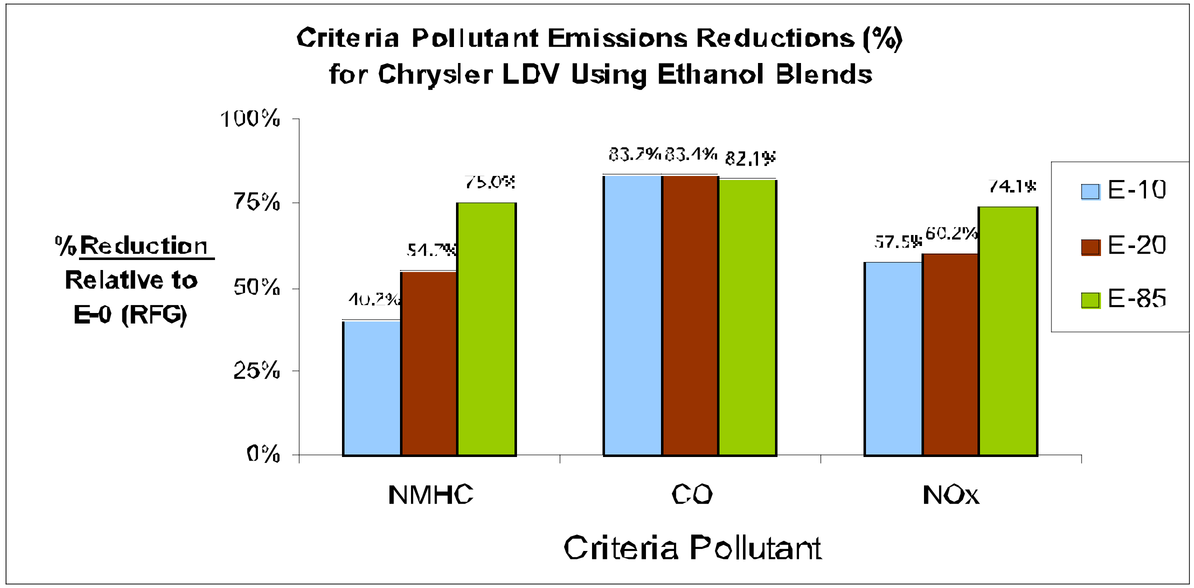

**Source: GREET 12, Argonne National Laboratory**

## Air Toxics Emissions: Total (Well to Wheels) L-D Autos




**Note: these data are preliminary. Insufficient data from CARB or EPA. Upstream air toxics emissions data are from TIAX's AB 1007 FFCA report. Downstream (tailpipe) emissions are from prior UC-Riverside CE-CERT testing.**

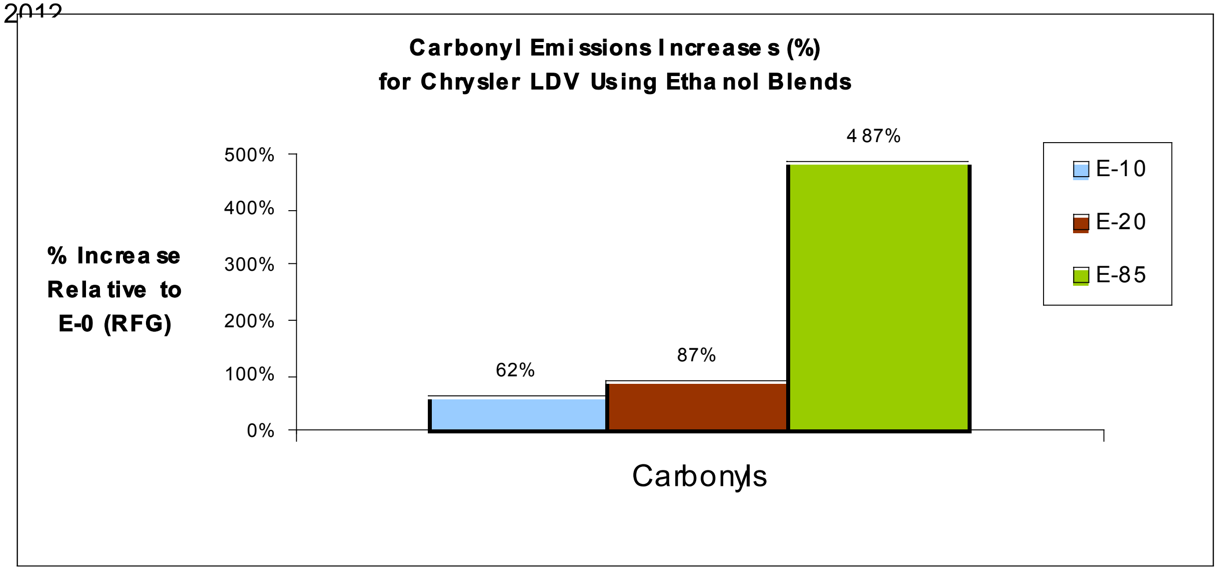
% **Reduction** in criteria pollutants generally **improves** with increasing ethanol content (less gasoline)




**Source:** *Impact of Ethanol Fuels on Regulated Tailpipe Emissions*, SAE Paper #2012-01-0872, April 16, 2012

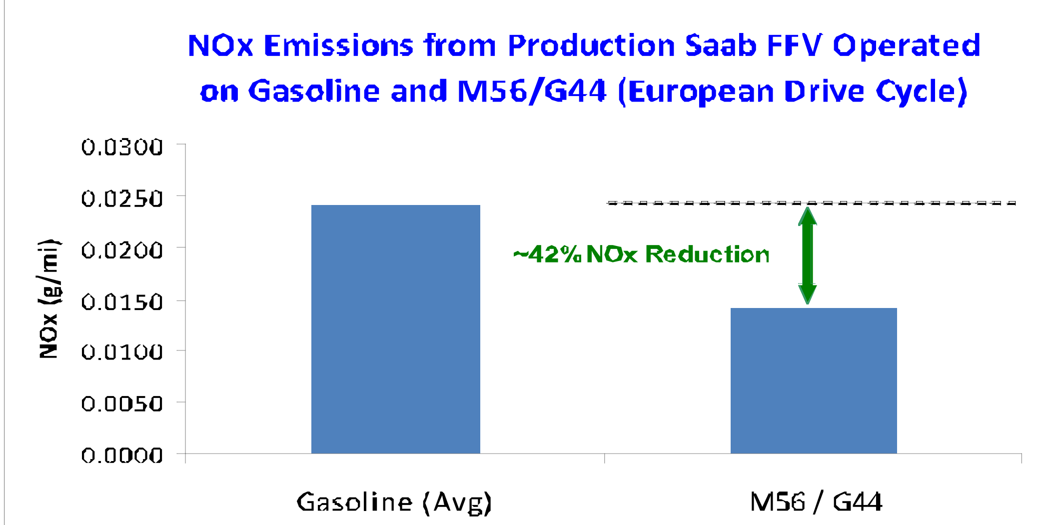
Emissions Dichotomy for E-85 FFVs

% **Increase** in carbonyl emissions (e.g., aldehydes) **worsens** with increasing ethanol content



## Vehicle emissions and fuel economy from LDVs using GEM fuels (up to M60)

- Most tailpipe emissions data involving methanol vehicles are derived from older M85 FFVs
- Little data exists for late-model LDVs fueled by GEM blends with up to 60% methanol
- Lotus Engineering has emissions-tested a 1.8 liter Saab station wagon (New European Drive Cycle)
  - ✓ ~ **42% reduction in $NO_x$ emissions** when using M56 / G44 blend compared to G100
  - ✓ ~ **7% reduction in $CO_2$ emissions** (i.e., an equivalent increase in fuel efficiency)
  - ✓ Significant reductions in HC and CO emissions

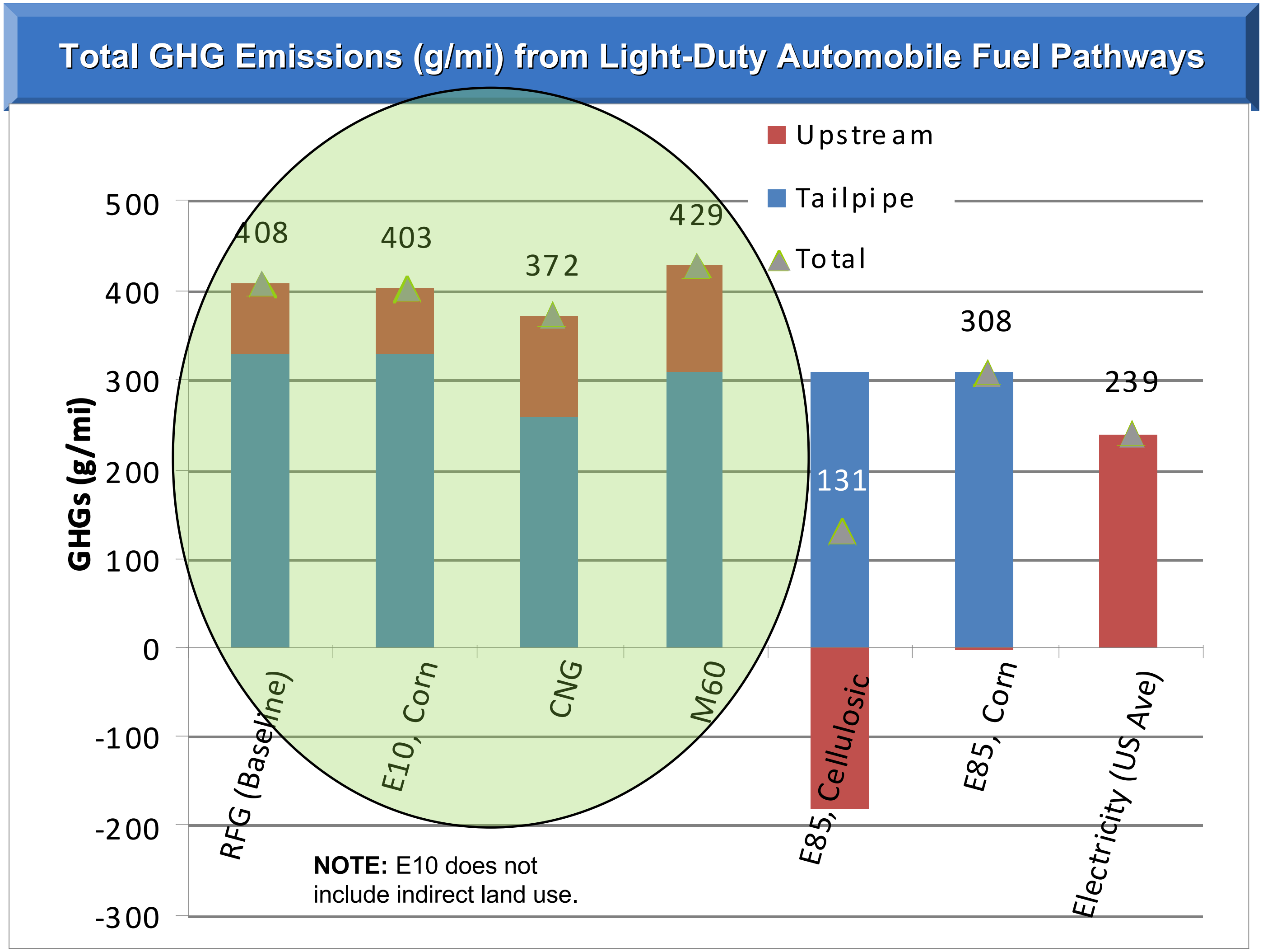



Source: Turner, James, "Evolution of Alcohol Fuel Blends Towards a Sustainable Transport Energy Economy," presented at 2012 MITEI Symposium on Prospects for Flexible- and Bi-Fuel Light Duty April 19, 2012

A Saab production FFV achieved a reduction in NOx emissions of approximately 42% when operated on M56 / G44 (compared to G100).

**This highlights good potential to achieve low ozone-precursor emissions and high fuel efficiency.**

# Current GREET for GHG Emissions: Total (Well to Wheels) L-D Autos




**GREET 12. RFG (G100) assumed as baseline (27.4 mpg). E-10 is typical retail fuel. Alcohol blends use RFG.**

## Complex variables in LCA models like GREET make it challenging to accurately compare relative GHG impacts for converted GEM fuel LDVs

"Upstream" variables in the modeling tools include (but are not limited to) the following:

- Assumptions and inputs involving petroleum fuels (baseline)
  - Industry average vs refinery-specific processes
  - Relative percentages of conventionally and unconventionally produced crude
  - Accounting for co-products (e.g., LPG)
  - Allocation of flared or vented associated natural gas
- Assumptions and inputs involving natural gas (feedstock for methanol pathway)
  - Relative percentages of conventional and unconventional natural gas
  - Methane leakage factors
  - Role of renewables
- Assumptions and inputs involving alcohol fuels (ethanol and methanol)
  - Production process
    - Methanol: SMR or ATR to process natural gas? Role of renewables?
    - Ethanol: corn or cellulosic? Whose process? Role of renewables?

Vehicle-side variables include: what fuel efficiency to assume for converted LDVs?

**The Challenge**: to accurately portray moving targets with imperfect tools (LCA models)

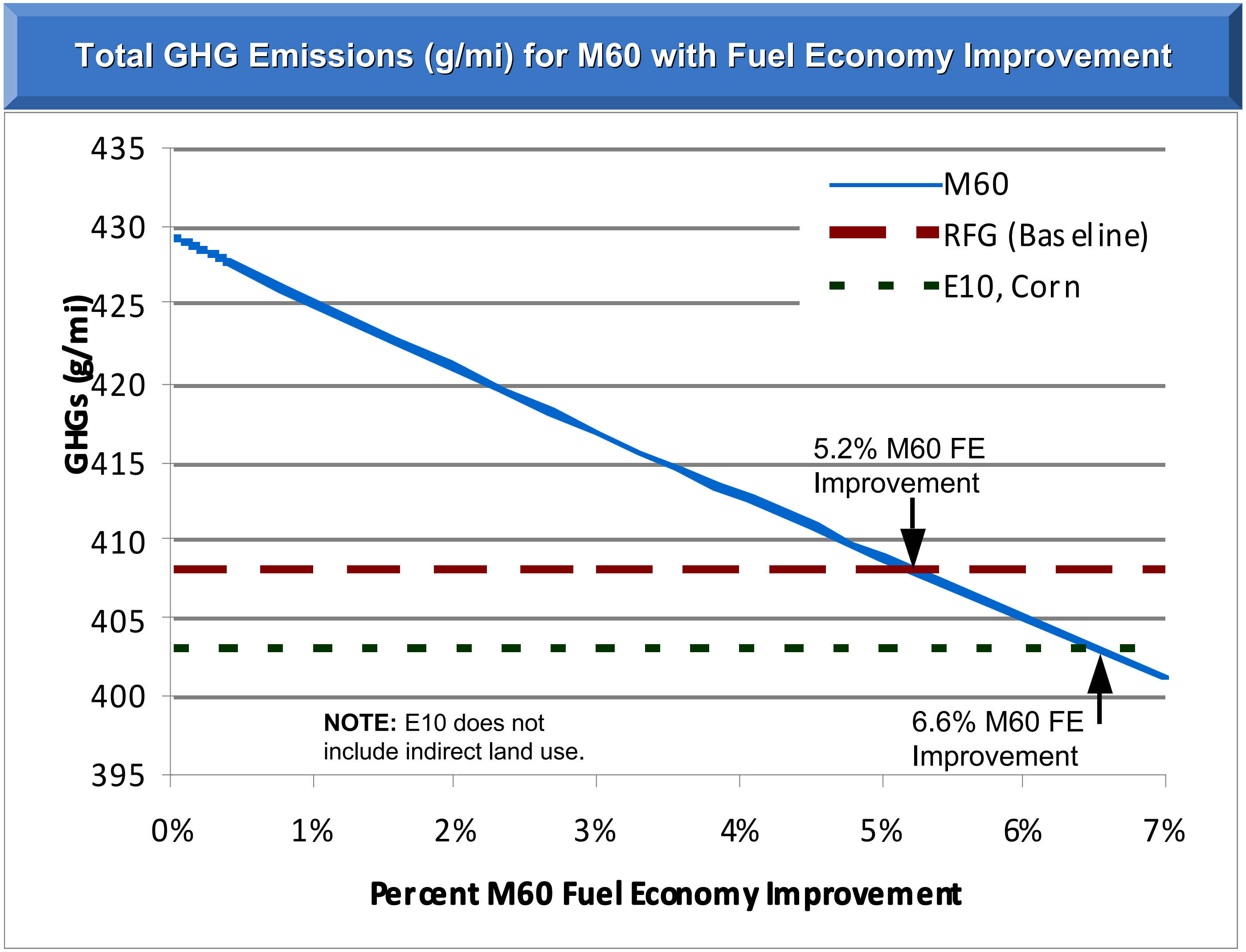
# Efforts made to better define potential GHG impacts of a GEM fuel strategy

| Activity / Event | Objective / Accomplishment / Finding |
|---|---|
| Telecon with **Siluria Corp**. | • Obtain inputs to **characterize low GHG natural gas to gasoline pathway**<br>• Insufficient data to create GREET pathway |
| Telecon with **Celanese Corp**. | • Obtain inputs to **characterize low GHG natural gas to ethanol pathway**<br>• Insufficient data to create GREET pathway |
| Telecon with Dr. **Robert Zubrin** and review of technical papers | • Understand inputs for **GEM vehicle fuel efficiency** and **improved methanol production processes**<br>• Numbers used for new analysis |
| Telecon with **Haldor Topsoe** and modeling of technical inputs | • Investigate Autothermal Reforming **(ATR) process to produce methanol** as alternative to SMR<br>• Numbers used for new analysis |
| **Re-run GREET** calculations under various new scenarios | • Re-calculate estimates for GHG impacts (Zubrin and Haldor-Topsoe inputs) to better reflect potential changes in **methanol production and end use** |
| Telecon with **Dr. Adam Brandt**, Stanford University<br><br>Review **EPA 2012 N**SPS / **Natural Gas STAR Program** | • Investigate and characterize opportunities to make methanol from **natural gas co-produced at "tight oil" operations** (e.g., Eagle Ford or Bakken)<br>• Investigate GHG implications of **associated gas operations** and **whether flaring is correctly allocated** to oil production pathway<br>• Better understand expected **methane reductions under EPA** regulation and **existing best practices** at many **hydraulically fractured wells** |
| Extensive **literature search on CH4 leakage** | • Better understand **methane leakage factors** by various sources and their associated uncertainties |
| Extensive **literature search on GEM vehicle efficiency** | • Better understand how a **GEM fuel** strategy might constrain or enable fuel **efficiency improvements** for converted FFVs compared to baseline gasoline vehicles |
| Email exchanges with senior **CARB officials** | • Better understand **differences between GREET and CA-GREET**, and assess when / if CARB will **update methane emissions factors** |

**Downstream (direct-vehicle) $CO_2$ emissions** are significantly more important than upstream GHG emissions as a determinant of total (WTW) GHG emissions in GREET

- This makes it very important to assign the correct fuel economy values in GREET to FFVs when operated on gasoline versus GEM fuels
- There is a general lack of reliable fuel economy data on GEM-fueled vehicles
- However, data on modern FFVs suggest that GEM fuel LDV conversions can achieve fuel efficiency gains of 3% to 7%, compared to when operated solely on gasoline (typically, E10)
  – EPA fuel economy data from 2013 E85 FFVs
  – Lotus Engineering's test data on an FFV using M56
- This phenomenon has been attributed to various superior combustion characteristics of the alcohol fuels, including:
  – Higher octane rating: newer engines with knock sensors can take advantage of higher octane by advancing timing to the onset of knock, resulting in more efficient engine operation
  – Charge air cooling: due to higher latent heat of vaporization, there is an increase in the density of the air charge, resulting in less work by the piston
- TIAX assessed how the total WTW GHG emissions score of an M60 FFV improves when a 3% to 7% fuel efficiency gain is assumed in GREET
- **Finding:** assuming a fuel economy increase of ~5% makes M60 equivalent to RFG for total WTW GHG emissions (next slide)

## Greenhouse Gas Emissions: Total (Well to Wheels) L-D Autos




**Note: RFG is G100 with no added oxygenates. M60 uses RFG.**

# However, upstream GHG emissions also play an important role in GREET

- TIAX used GREET 12 to compare GHG "scores" with EPA vs API factors for methane leakage
- TIAX also compared the GREET 12 model to CA-GREET, which has not adopted EPA's 2011 factors

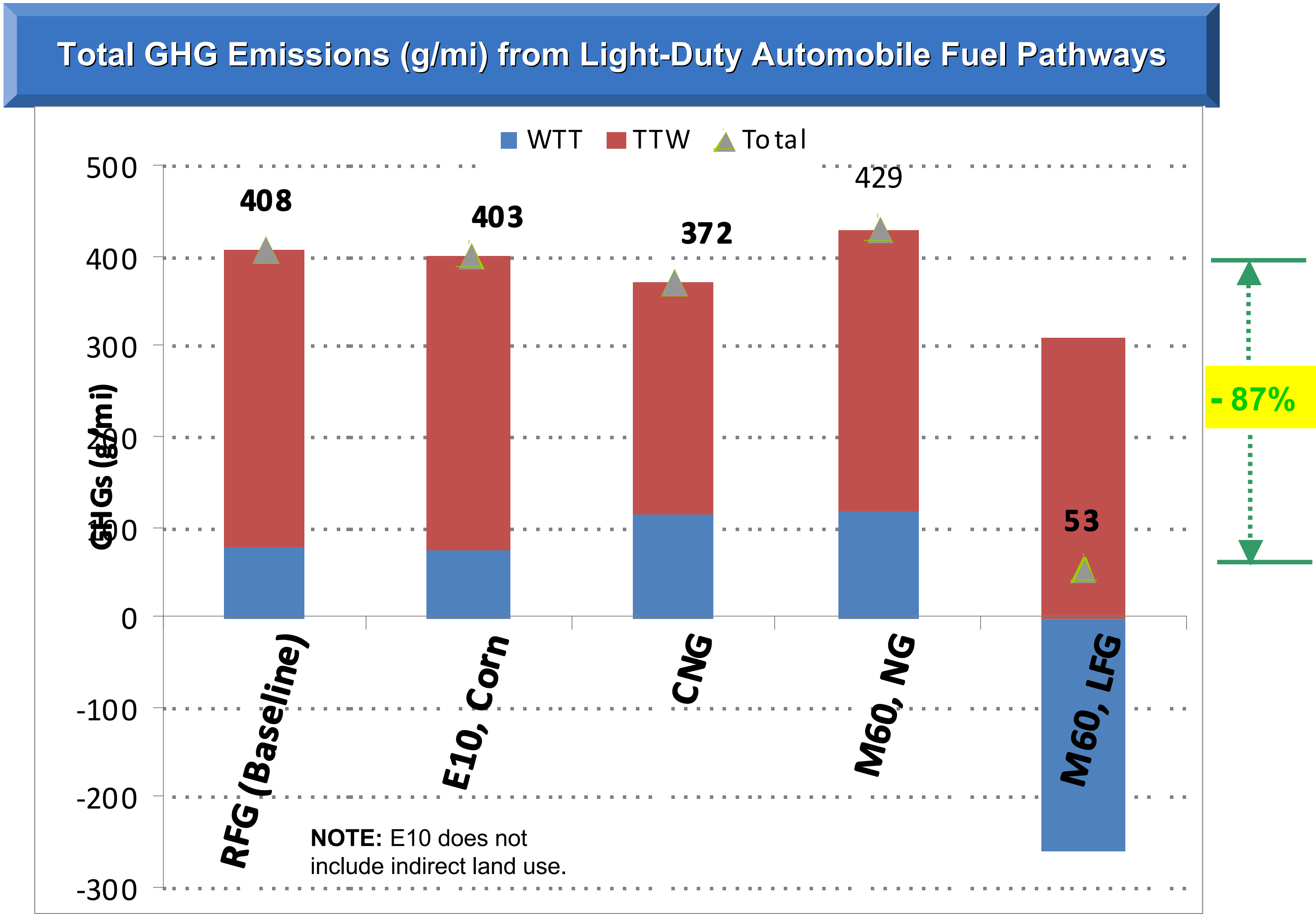
| Model / Data Source | Fuel | Pathway | Methodology / Assumption | GHG Emissions (C02e, g/mi) | | | % Diff from RFG |
|---|---|---|---|---|---|---|---|
| | | | | Upstream | Vehicle | Total | |
| GREET 12 | RFG | Crude Oil (Conventional) | w/ associated gas venting / flaring | 80 | 328 | **408** | |
| | CNG | N.A. Natural Gas | EPA 2011 CH4 leak factors | 113 | 259 | **372** | **-8.8%** |
| | M60 | N.A. Natural Gas / SMR | EPA 2011 CH4 leak factors | 119 | 310 | **429** | **5.1%** |
| GREET 12 / API | RFG | Crude Oil (Conventional) | w/ associated gas venting / flaring | 80 | 328 | **408** | |
| | CNG | N.A. Natural Gas | Amer. Petro Inst. CH4 leak factors | 99 | 259 | **358** | **-12.3%** |
| | M60 | N.A. Natural Gas / SMR | Amer. Petro Inst. CH4 leak factors | 110 | 310 | **420** | **2.9%** |
| GREET 12 | RFG | Crude Oil (Conventional) | w/ associated gas venting / flaring | 80 | 328 | **408** | |
| CA-GREET (Vers 1.8b) | CNG | N.A. Natural Gas | CARB CH4 leak factors | 47 | 259 | **306** | **-25.0%** |
| | M60 | N.A. Natural Gas / SMR | CARB CH4 leak factors | 49 | 310 | **359** | **-12.0%** |

- Baseline GREET 12 is shown first (same relative scores as previously provided); venting and flaring of "associated gas" is allocated to the crude oil pathway, but LCA model is imperfect (as discussed later)
- Applying **API's** newest upstream leakage factors improves the GHG "scores" of pathways based on North American natural gas:
  - CNG improves to -12.3%, M-60 improves to +2.9% (relative to RFG baseline)
- Applying **CARB's** current methane leakage factors (per CA-GREET 1.8b) essentially goes back to GREET's pre-EPA 2011 benefits for CNG (-25%) and M60 (-12%)

## An emerging upstream pathway to low GHG scores: Renewable Methanol

- Methanol from renewable feedstock has potential to significantly reduce GHG emissions from the transportation sector
- At least four renewable methanol pathways are under development:
  - Municipal waste
  - Industrial waste
  - Biomass
  - Carbon dioxide
- Several worldwide producers exist:
  - BioMCN (Netherlands)
  - Blue Fuel Energy and Enerkem (Canada)
  - Carbon Recycling International (Iceland)
  - Chemrec and VärmlandsMetanol (Sweden)
- Producers estimate that renewable methanol offers GHG-reduction benefits ranging from 65 percent to 90 percent, on a full fuel-cycle basis
- TIAX's custom pathway in GREET corroborates this
- Such GHG benefits are among the highest for alternative fuels that can displace gasoline and diesel.
- **The challenge:** currently, worldwide production of renewable methanol is low

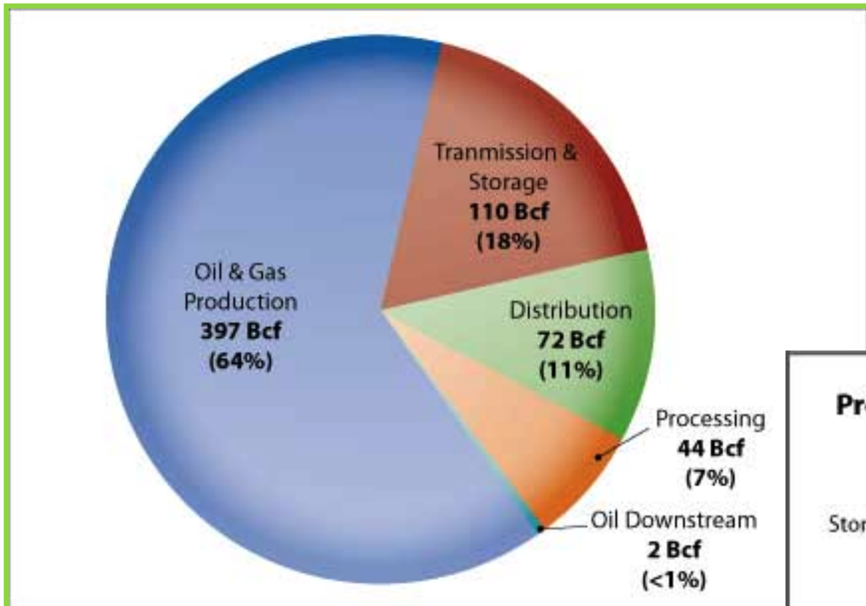
## GREET GHG Emissions w/ Renewable Methanol: Total (WTW) L-D Autos




**GREET 12. "M60, LFG" refers to 60% methanol from landfill gas and 40% RFG. "M60,NG" refers to methanol made from conventional steam methane reforming of natural gas.**

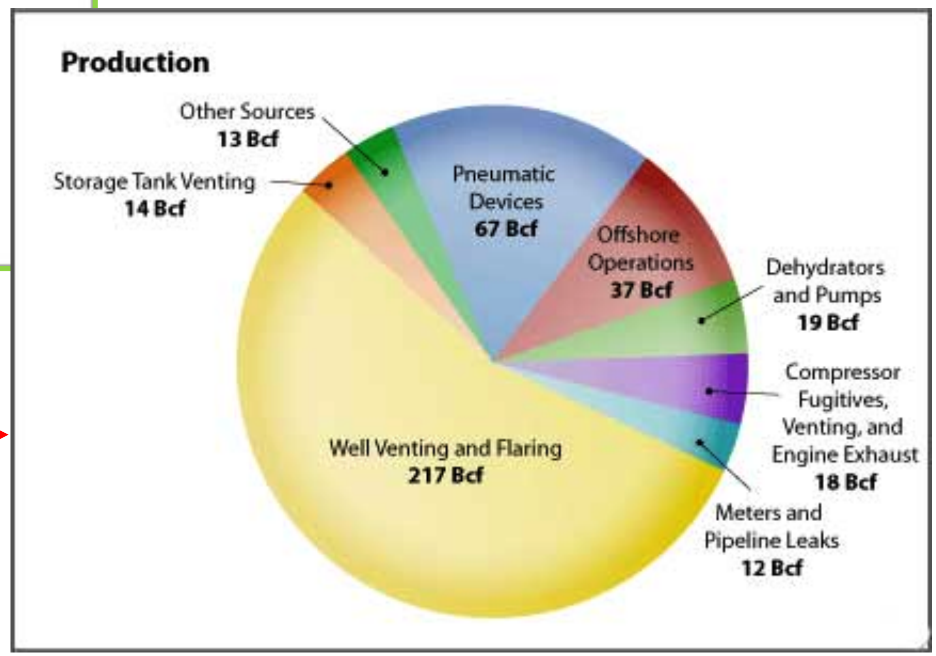
## U.S. Methane Emissions by Major Oil and Gas Sectors

- Oil & gas systems: 37% of $CH_4$ emissions / 3.8% of total GHG emissions




**64% of the U.S. aggregate methane emissions comes from oil and gas production**

**Well venting and flaring contributes 55% of these oil and gas production emissions**




**Source: U.S. EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990 – 2009, April 2011**

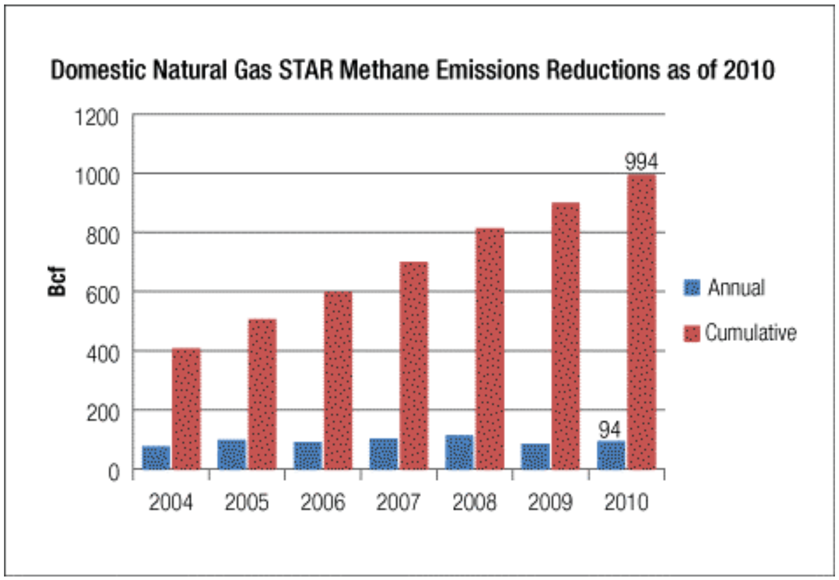
## EPA's New Source Performance Standard (NSPS) *indirectly* goes after $CH_4$

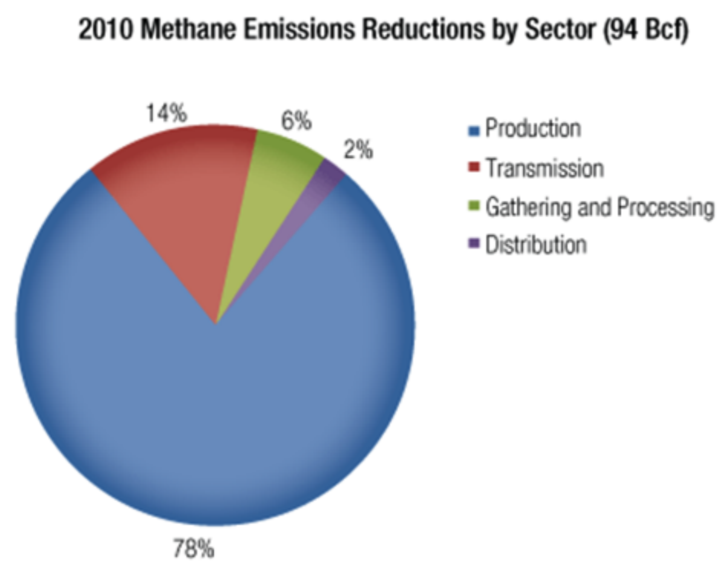
- EPA estimate: each year, 11,400 new wells are hydraulically fractured in the U.S., and 1,400 existing wells are re-fractured
- The 2012 NSPS regulates various pollutants from upstream sources and processes **not covered by previous rules**, most notably well completions
- Relies on "proven, cost-effective technology and practices" already in use today at ~50% of U.S. fractured NG wells
- Focuses on flow-back stage, which can emit high-volume mixture of VOCs, methane, benzene, and other air toxics
- Although the new NSPS does not directly address methane emissions, EPA estimates it will result in the following reductions (upon full implementation)
  - 1.0 to 1.7 million short tons of methane emissions
  - Equivalent to ~19 to 33 million tonnes of $CO_2e$ emissions
- NG producers must phase in reduced emissions ("green") completions at fracked wells
- Recent Questions / Issues:
  - Disputes about Inventory:
    - 2012 Oil &Gas industry estimates are 53% below EPA's estimates (did EPA fail to account for best practices already being implemented?)
    - 2013 OIG report strongly questions EPA's methods and records, suggests inventory is low
  - Efficacy / Legality: some states suing EPA for not going far enough on methane emissions

**Source: EPA Summary document of NSPS, April 2012**

# Natural Gas STAR Program: Industry Best Practices to Reduce $CH_4$ levels

- "Partners" from all major NG sectors (Production, Gathering and Processing, Transmission, and Distribution)
- 59% of U.S. NG industry is represented
- Over its 20 year history:
  - 150 "cost-effective technologies and practices applied
  - 994 Bcf of methane emissions eliminated (about 75% comes from Production sector)

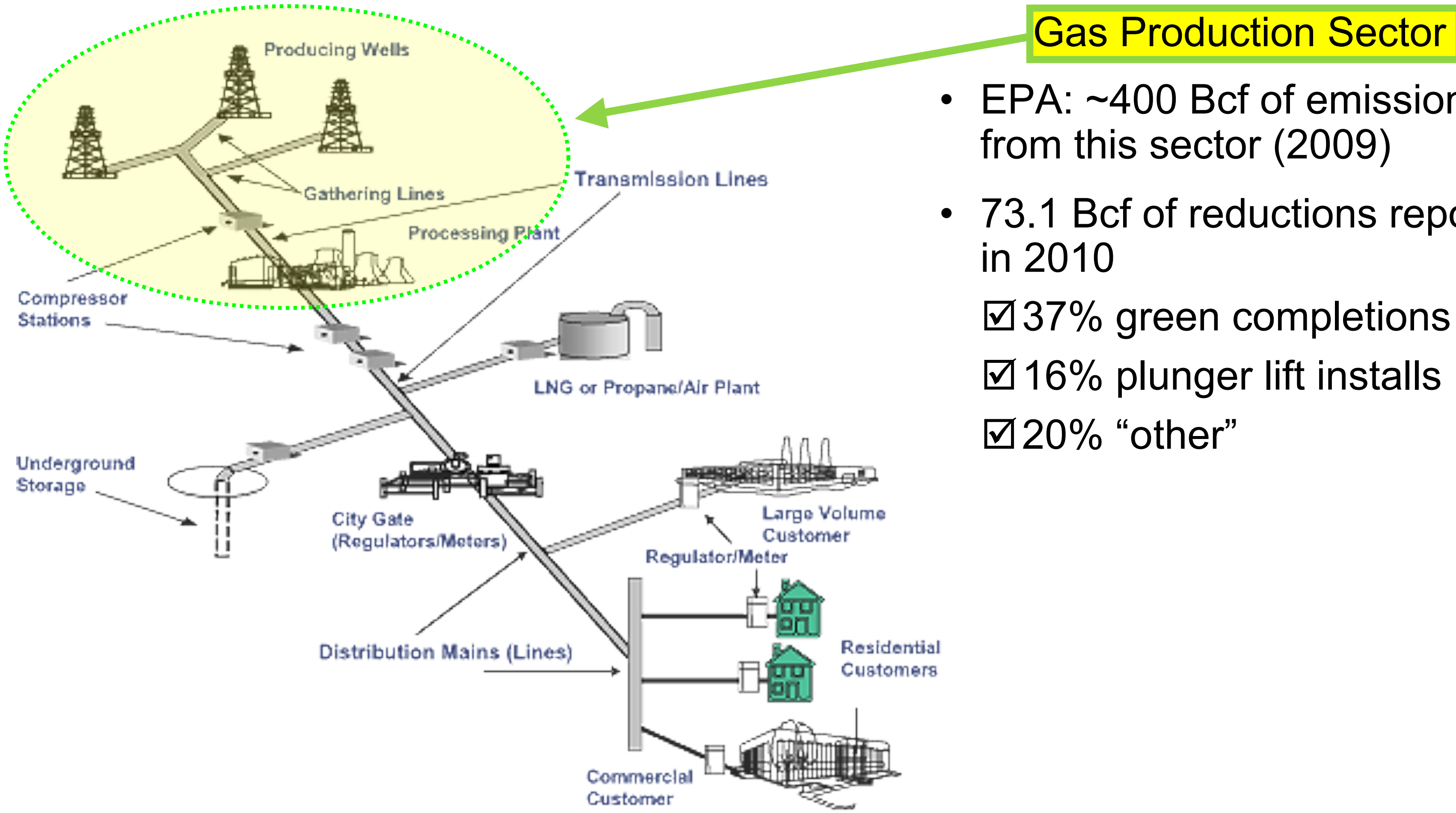



- **NOTE:** An international version of NG STAR was established in 2006

**Source: U.S. EPA, http://www.epa.gov/gasstar/basic-information/index.html#overview1**

## Natural Gas STAR Program's "Top Methane Reduction Opportunities"




- EPA: ~400 Bcf of emissions from this sector (2009)
- 73.1 Bcf of reductions reported in 2010
  - ☑ 37% green completions
  - ☑ 16% plunger lift installs
  - ☑ 20% "other"

**Source: U.S. EPA, http://www.epa.gov/gasstar/basic-information/index.html#overview1**

# "Green" or Reduced Emission Completions (RECs) for oil and gas wells

- Conventional completions: venting or flaring that "can last weeks"
- RECs: up to 99% of gases recovered
- **Benefits of RECs**
  - Compliance path for regulations
  - Enables capture and sale of gas
  - Eliminates visible flares
- **Costs**
- ">$50k" per well
  - Operational pipeline
  - Capture mechanism
  - Other specialized equipment (e.g., surface dryers and meters)
  - Low pressure gas reservoirs are especially costly for "REC-ing"
- **Cost Effectiveness**
  - Payback can be within 1 year (EPA)

**"Green" Completion Unit**

**Well Completions:** Process that allows flow of petroleum or natural gas from newly-drilled wells to expel drilling and reservoir fluids and test reservoir flow characteristics. These steps **may vent produced gas** to the atmosphere via an open pit or tank. This process may also include high-rate flowback of injected gas, water, oil, and proppant (which) **may vent large quantities** of produced gas to the atmosphere.

Source: U.S. EPA, PDF 13-P-0161

**Source: "Using Reduced Emission Completions (RECs) to Minimize Emissions During Flow-Back of Hydraulically Fractured Gas Wells, British Petroleum, presentation of 10/14/11,onlne at http://www.globalmethane.org/documents/events_oilgas_101411_tech_smith.pdf.**

## Anadarko's "Scorecard" for DJ Basin: Conventional vs. "Green" Completions

| Completion Method | Wells Frac'd | Average Vent Time | Estimated Gas Vented | Revenue Lost |
|---|---|---|---|---|
| | | Days/well | MMSCF | |
| Conventional | 421 | 12 | 2072.6 | $6.2 MM |
| Green | 613 | 0.08 | 20.5 | $143.1 M |
| **Comparison G vs. C** | **+192** | | **-2052.1** | **+$6.1 MM** |

- Data are specific to Anadarko's operations in the DJ Basin (CO)
- Average wellhead venting time went from ~**2 weeks** to **2 hours**
- Gas venting reduced by 99%
- $6.1 million saved (2006 to 2008)
- Why isn't EVERYONE doing this?

**Source: "Reduced Emission Completions in DJ Basin and Natural Buttes, presentation at Producers Technology Transfer Workshop, Anadarko Petroleum Corp., May 1, 2008**

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**3 Focus on Greenhouse Gases**

- Methane Emissions
- **LCA Issues and Uncertainties**

4 Findings and Conclusions

# Life Cycle Analysis currently has "major areas of uncertainty," including:

- Emissions related to changes in cultivation and land use
- Treatment of market-mediated effects (e.g., **co-products**, changes in process emissions in response to changing production quantities)
- **Treatment of scenario inputs (e.g. average vs. marginal)**
- **Carbon Equivalency Factors (CEFs) for GHGs**
- Impacts from Land use change (LUC) and indirect land use change (iLUC)
- N2O emissions from agricultural processes and inputs
- **Natural gas leakage from pipelines**
- **Natural gas flaring from oil production**
- Feedstock resource mix
- Indirect effects on resource mix
- **Vehicle efficiency**

That said, LCA models like GREET and CA-GREET are widely used and/or cited by EPA, CARB and other regulatory agencies. Fortunately, much is being done to improve them. The science has been **RAPIDLY evolving** over the last year.

**Source:** Review of Transportation Fuel Life Cycle Analysis, Coordinating Research Council Report No. E-88, February 2011.

## Specific Issues and Remedies for GREET and other LCA Methodologies

- Lack of harmonization exists in areas of LCA definition and application
- No strong consensus about allocating GHG emissions to "co-products"
  - Creates uncertainties and inconsistencies in different pathways
  - Need more-uniform understanding of model structures and underlying data sources
- Improvements needed for baseline pathways (gasoline and diesel)
  - Oil production fields vary individually (type, production efficiencies, recovery methods, etc.)
  - Variability typically dealt with by reporting industry-wide average conditions (e.g. GREET)
  - Some models use "more complex, non-transparent" methodologies
  - Major need to:
    - Reduce uncertainties
    - Assess other contributing factors (oil exploration, facility construction, co-products refining effects, materials recycling, etc.)
- Indirect Land Use Change (iLUC) is a "universally recognized" concept, but little standardization exists
- To address these and other LCA needs, CRC issued an RFP in August 2102
- CARB and EU funding "engineering-based, bottom-up LCA model" to better assess GHG emissions from specific oil and gas operations
  - Incorporate exploration activities, drilling, production, separation and surface processing, waste treatment and disposal, and shipping/transport to refinery
  - Complexity of this model requires additional crude-specific data
  - First version for peer review expected by mid 2012.

Source: "Transportation Fuel Life Cycle Assessment: Validation and Uncertainty of Well-to-Wheel GHG Estimates." (CRC Project No. E-102).

## Uncertainty especially seems to dominate the debate about $CH_4$ emissions

- Argonne Nat'l Lab (Burnham, Wang et al):
  - Base case: shale gas LCA emissions 6% lower than conventional NG and 23% lower than RFG gasoline, *but*
  - Statistical uncertainty makes these findings questionable
- EPA: US shale gas emissions from fracking operations in 2010 were ~3.6% of all natural gas production related fugitive emissions
- EPA Office of Inspector General (OIG) February 2013:
  - Due to paucity of data, oil and gas emissions are "likely understated"
  - EPA has limited directly-measured data on air toxics and criteria pollutants for important O&G production processes and sources (e.g. well completions)
  - EPA needs to better understand emissions and risks from O&G production
  - U.S. lacks comprehensive strategy for improving air emissions data
- MIT 2012 study:
  - Hydraulically fractured wells must be cleaned up, but they "have not materially altered total GHG emissions from the NG sector"
  - Vast majority of newer wells use reduced emissions completions (RECs) that recover costs
- Coordinating Research Council's list of areas to improve include:
  - Gaps on CH4 leaks (especially from "fracked" shale wells)
  - Emissions from non-U.S. gas production assumed to be comparable to U.S.
  - Variability in gas composition and effects on GHG emissions

## Some uncertainty seems to exist throughout the O&G industry

- 2011 Workshop Summary:
  - Significant uncertainties with conventional gasoline and diesel paths (baselines)
  - More focus needed on marginal fossil fuel sources
  - Lack of consensus:
    - boundary conditions for modeling conventional fuels
    - determining which indirect effects should be considered

*Co-product allocation of GHG emissions remains an area of significant disagreement among LCA modeling approaches. Differences in allocation methods can have large effects on the estimated CI values of fuels/fuel pathways. The choice of a particular allocation method can "change the sign" by making a favorable fuel/pathway look unfavorable, and vice versa."*

- Heather MacLean (Univ. of Toronto)
  - Higher-quality data needed from oil sand operations **(current and future)** to better understand GHG impacts
- Uwe Fritsche (Oeko Institute)
  - Growing EU interest to evaluate LCA of unconventional fossil fuels, including high carbon intensity crude oils and shale gas
- **Interesting NOTE:** EU expanding LCA beyond emissions to assess biodiversity, land use, water use, and other social factors

**Source, Coordinating Research Council Workshop on Life Cycle Analysis of Biofuels, ANL October 18-19, 2011**

# Typical LCA assumptions and uncertainties for crude oil

- Carbon intensity factors for crude oil production vary among studies and LCA models

**GREET**

- Crude oil production inputs based on Dept. of Commerce survey data for U.S.
- Associated gas venting & flaring appears to be properly allocated to crude oil path
  - Assumed 2:1 ratio of international to U.S. emissions
- Refining efficiency differs with refinery products on a process-allocation basis (EIA data)
- Product-specific refining intensity estimates result in overall refinery efficiency of 88.3%
- ANL is considering ways to better account for **"crude heaviness"** in refinery efficiency

**CA-GREET**

- CA crude mix comes from many regions and countries (e.g. CA, AK, Saudi Arabia, Ecuador, Iraq, Brazil)
- CA RFG blend stock (CARBOB) has estimated refinery efficiency value about 4% lower than GREET value of 88%
- GHG results differ from GREET largely regarding NG flaring and transport distances
- Venting and flaring adjusted based on petroleum resource mix

**Source:** Review of Transportation Fuel Life Cycle Analysis, Coordinating Research Council Report No. E-88, February 2011.

# California is taking a hard look at the oil production side

- CA's "Oil Production Greenhouse Gas Emissions Estimator (OPGEE) being improved/updated
- "Open-source public LCA tool" to estimate GHGs from oil production
- "Engineering-based bottom-up model" for production, processing, storage and transport
- Draft version A has been released for comment
- One goal: "clarify and model in detail . . . associated gas flaring
- To date: "removed allocation of off-site GHG emissions", "corrected flaring emissions calculations
- CARB looking at refinery-specific basis to account for varying carbon intensity of crude oils and fuels

## Conventional oil model corrections and improvements

- Changed heater/treater calculations
  - Default oil emulsion (14% emulsified water) gives fraction of emulsified water irrespective of WOR
- Improved compressor model
  - Compressor now varies between 1 and 5 stages
  - Conversations and data from Statoil suggested need for compressors with more stages
- Corrections and clarifications
  - Corrected the AGR unit venting emissions calculation (eliminated double counting of non-$CO_2$ emissions)
  - Corrected two typos in bulk assessment worksheet
  - Corrected flaring emissions calculations (use preprocessing gas composition)

**Source: "Oil Production Greenhouse Gas Emissions Estimator (OPGEE) Version 1.1 draft A Model updates & changes", Brandt et al, 3/5/13**

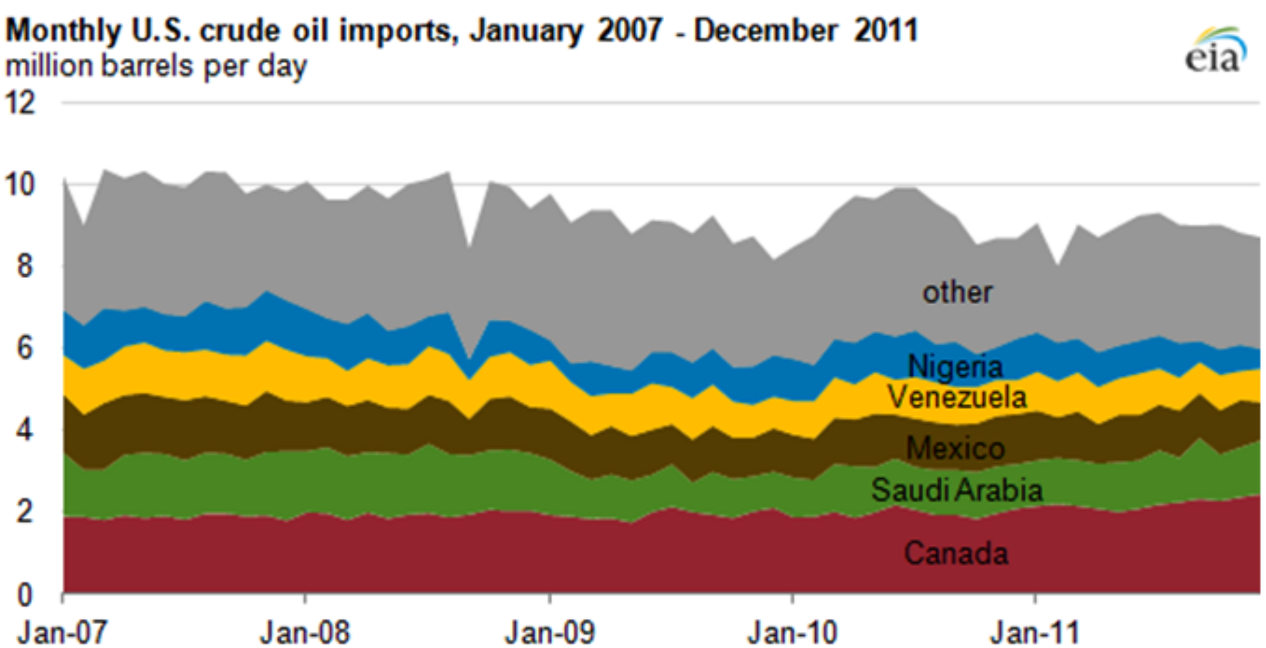
## Increasingly, the need is to compare "unconventional" oil and gas resources

- **Extra heavy oil** (high viscosity, lower API gravity)
- **Oil (tar) sand** (contains bitumen)
- **Oil shale** (sedimentary rock containing kerogen)
- **Tight gas** (natural gas with low permeability)
- **Shale gas** (natural gas associated with shale oil)
- Development and production requires differing processes and technologies vs conventional
- Producing unconventional oil is a **particularly energy intensive process** (large heat requirements)
- Energy used as a percentage of energy produced:
  - ~20% to 25% for extra heavy oil
  - 30% for oil sand
  - 30% for oil shale
  - 6% for conventional oil and gas
  - This ratio is also "relatively small" for tight gas and shale gas
- $CO_2$ emissions (natural gas assumed for heating)
  - 9.3 to 15.8 g/MJ for oil sand and extra heavy oil
  - 13 to 50 g/MJ for oil shale
  - Unconventional gas (tight gas, shale gas) generally has a "lower energy requirement"
- Total upstream GHG emissions ($gCO_2eq/MJ$) during production are **highest for unconventional oil**

**Source: "Unconventional Oil & Gas Production," Energy Technology Systems Analysis Programme, Technology Brief P02, May 2010**

# Example: Canadian Tar Sand Oil :

- EIA: nearly 69% of U.S. crude oil imports in 2011 originated from five countries
- Of these, Canada is already the largest source of U.S. oil imports, and is expected to be one of the largest sources of global growth (near- and long-term)
- Canadian production could grow to 6.6 million barrels per day by 2035 "due to an expansion of unconventional output from the oil sands" (2011 International Energy Outlook)
- Canada's most important oil-producing resource is the Alberta "tar sands" region




**As demand grows, where will U.S. oil come from? How will it compare on GHG emissions?**

## Summary and Conclusions

This study found the following about the life cycle emissions for a potential LDV GEM fuel strategy:

- Criteria pollutants: Strong potential exists to reduce ozone-precursor and other criteria emissions; additional direct-vehicle data are needed from independent labs under controlled test conditions
- Air toxic pollutants: GEM-fueled FFVs would likely emit lower levels of certain air toxics (benzene, 1,3-butadiene) but higher levels of carbonyls (e.g., formaldehyde); technical solutions exist to manage such tradeoffs
- Greenhouse Gases:
  - Depending on assumptions made for vehicle fuel efficiency and methanol production, the current GREET model indicates that LDVs converted from gasoline to GEM fuels could emit modestly higher to significantly lower GHGs per mile
  - Significant uncertainty exists about critical inputs and assumptions used by GREET (and other similar LCA models); much effort is now underway to improve these models
  - Important **"upstream"** modifications & updates underway or needed include incorporation of:
    - ✓ Improved methane leakage factors that fully account for GHG emissions reductions being realized under near-term regulatory efforts and industry best practices
    - ✓ Improved methanol production processes and/or renewable feedstock
    - ✓ Better capability to account for marginal and unconventional gasoline pathways that will increasingly utilize high-carbon-intensity crude sources (e.g., tar sands)
  - Important **"downstream"** modifications & updates underway or needed include:
    - ✓ More data to better define the potential of GEM fuels to improve LDV fuel efficiency, which is the most important determinant for full fuel cycle GHG emissions per mile
  - Near-term updates of GREET (or other LCA models) may indicate that GEM-fueled vehicles can provide significant, if not strong, GHG-reduction benefits

# Summary and Conclusions (cont'd)

- **Sensitivity evaluation:** accounting for the minimum 3% fuel economy improvement when FFVs are operated on M60 -- combined with relatively modest improvements in upstream processes associated with methanol production -- appears to take M60 to the "crossover point at which it becomes a net-positive GHG control strategy (see next slide)
- **Open question:** to fairly compare upstream emissions, what mix of crude should be used to estimate the full fuel cycle emissions of LDVs converted in the future to operate on GEM fuels?
  - Large percentages of the gasoline displaced by GEM-ready vehicles may be high-carbon-intensity "unconventional" crude oil (domestic oil shale plays, Canadian tar sands, countries like Nigeria that flare large amounts of associated gas)
  - Assigning high percentages of these crude types to the U.S. gasoline pool will significantly worsen the baseline gasoline GHG "score" in GREET
  - The natural gas-to-methanol pathway is likely to get "cleaner", due to EPA's regulations and industry best practices that are already reducing methane emissions at natural gas wellheads
  - Making methanol from landfill gas or other renewable sources would greatly improve the upstream GHG score of GEM-fueled vehicles
  - At least four companies are working on renewable methanol, but costs are not yet known and no commercial products currently exist
- All these uncertainties make it very hard to accurately portray the relative "upstream" greenhouse gas implications of GEM fuels versus gasoline in a conversion strategy for LDVs
- The most important immediate focus is to corroborate "downstream" fuel efficiency improvements of converted GEM-fueled vehicles; this will likely result in net-benefit GHG scores for GEM fuels in GREET and/or other evolving LCA models

## Summary of Sensitivity Analysis:

### Baseline: RFG (G100) is 408 grams of $C0_2$ equivalent per mile (E10 is 403)

| Scenario Assumed for Calculating Upstream and Direct GHG Emissions in GREET | Grams of C02 eq per mile | | |
|---|---|---|---|
| | **M100** | **M85** | **M60** |
| Methanol Base in GREET (assumes fuel economy based on straight BTU content = lower than RFG) | 470 | 454 | 435 |
| 1. Reduced Feedstock Leakage (API factors) | 438 | 430 | 421 |
| 2. Higher Meoh Production Efficiency (89% vs 82%) | 434 | 427 | 419 |
| 3. Higher Fuel Economy Over RFG (+3%) | 421 | 415 | 407 |
| 4. Higher Fuel Economy Over RFG (+5%) | 409 | 401 | 391 |
| 5. Higher Fuel Economy Over RFG (+10%) | 385 | 374 | 361 |
| 6. Combination of 1. + 2. | 402 | 404 | **406** |
| 7. Combination of 1. + 3. | 390 | 395 | **400** |

- As shown by the green shading, two combined scenarios (shown by 6 and 7 above) bring the M60 GHG "score" below the RFG baseline of 408 grams CO2 eq per mile
  - Upstream only: API's reduced methane leakage factors + higher production efficiency for methanol = **406 grams CO2 eq per mile**
  - Upstream and direct vehicle: API's reduced methane leakage factors + assumption that M60 FFV will have a 3% fuel economy increase (over RFG) = **400 grams CO2 eq per mile**
- **Implication:** a modest fuel economy benefit for GEM fuels (3% or better) is very plausible (but must be laboratory corroborated). Combined with very near-term improvements in controlling methane leakage for natural gas pathways, the M60 pathway becomes a net positive GHG-reduction strategy for converted light-duty vehicles.

## Recommended Next Steps

Improvement of **"downstream"** GREET inputs:

•It's essential to obtain hard data (baseline vs conversions) by emissions testing late-model LDVs legally converted to operate on GEM fuels up to M60

- ✓ Fuel economy
- ✓ Tailpipe and evaporative emissions

Improvement of **"upstream"** GREET inputs:

•Stakeholders should collaborate to obtain and incorporate the following:

- ✓ Methane leakage factors in natural gas pathways that reflect new EPA regulations and industry best practices for control of upstream emissions
- ✓ Assumptions for state-of-the-art methanol production (e.g., autothermal reformation)
- ✓ Improved and/or updated *renewable* methanol pathways based on one or more emerging processes
- ✓ Better data and methodologies to account for increasing percentages of high-carbon-intensity marginal crude oil from sources such as tar sands

# Thanks for your attention!  Discussion & Questions.

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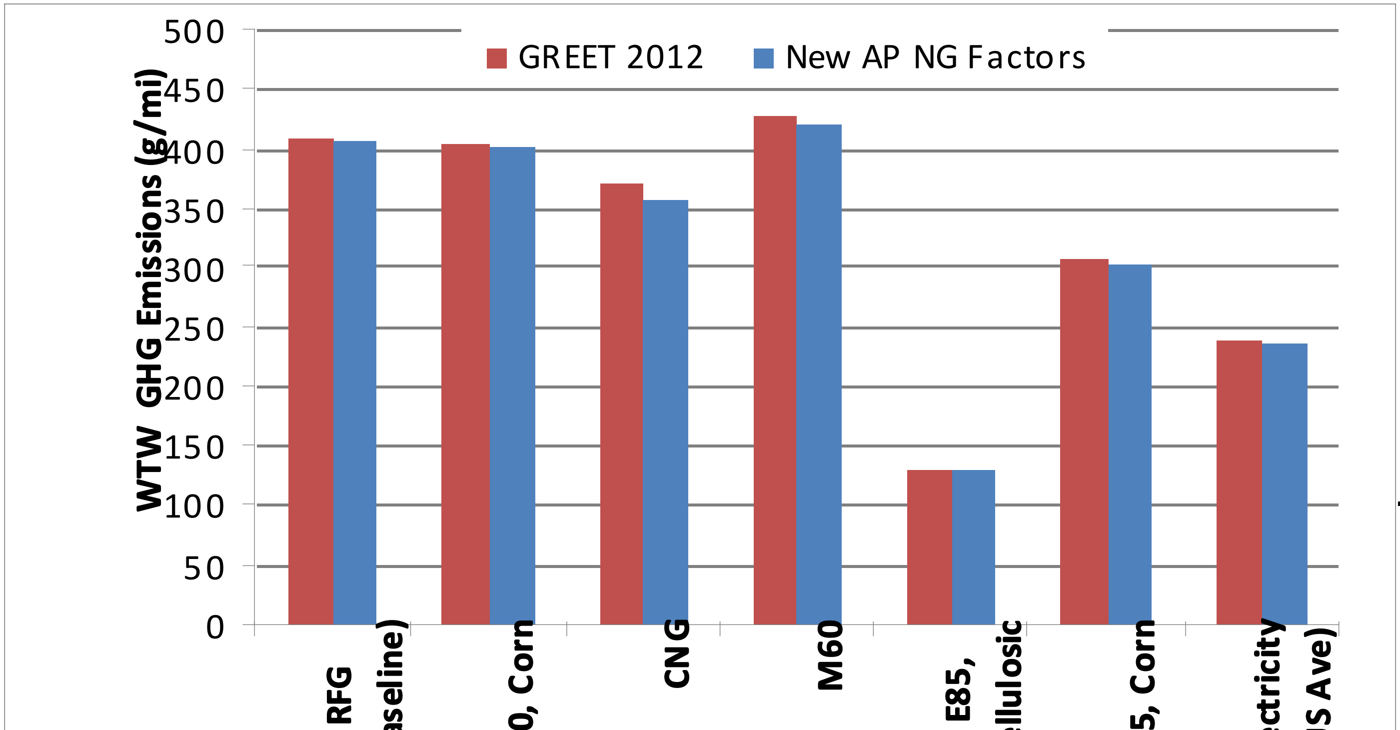
# Additional / Backup Slides

## GHG Emissions API $CH_4$ Leakage Factors: Total (WTW) L-D Autos

### Total GHG Emissions (g/mi) from Light-Duty Automobile Fuel Pathways

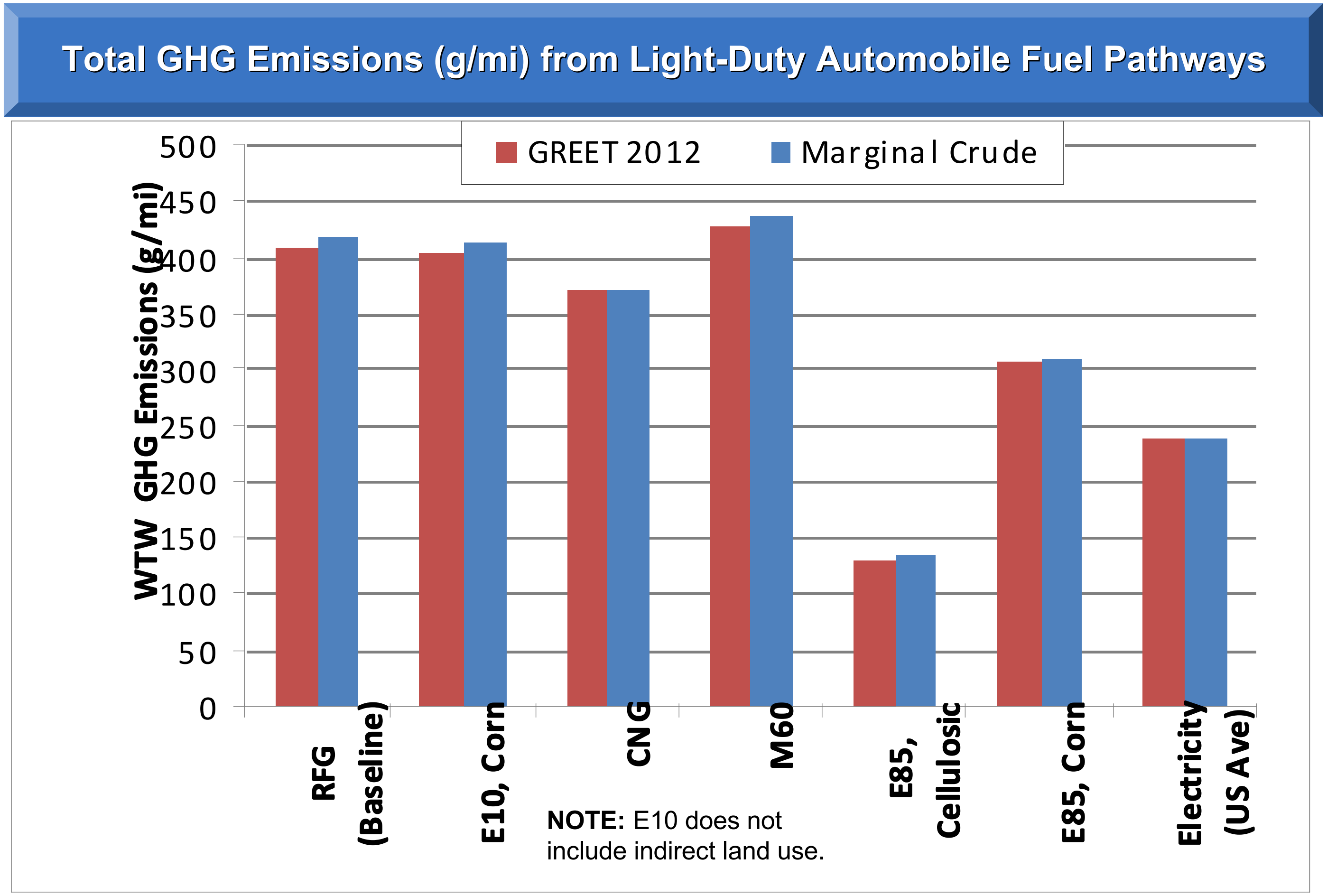



**NOTE:** E10 does not include indirect land use.

**GREET 12 with latest American Petroleum Institute ("AP") CH4 leakage factors. RFG is G100.**

**NOTE: As discussed, significant uncertainty has emerged on CH4 leakage factors.**

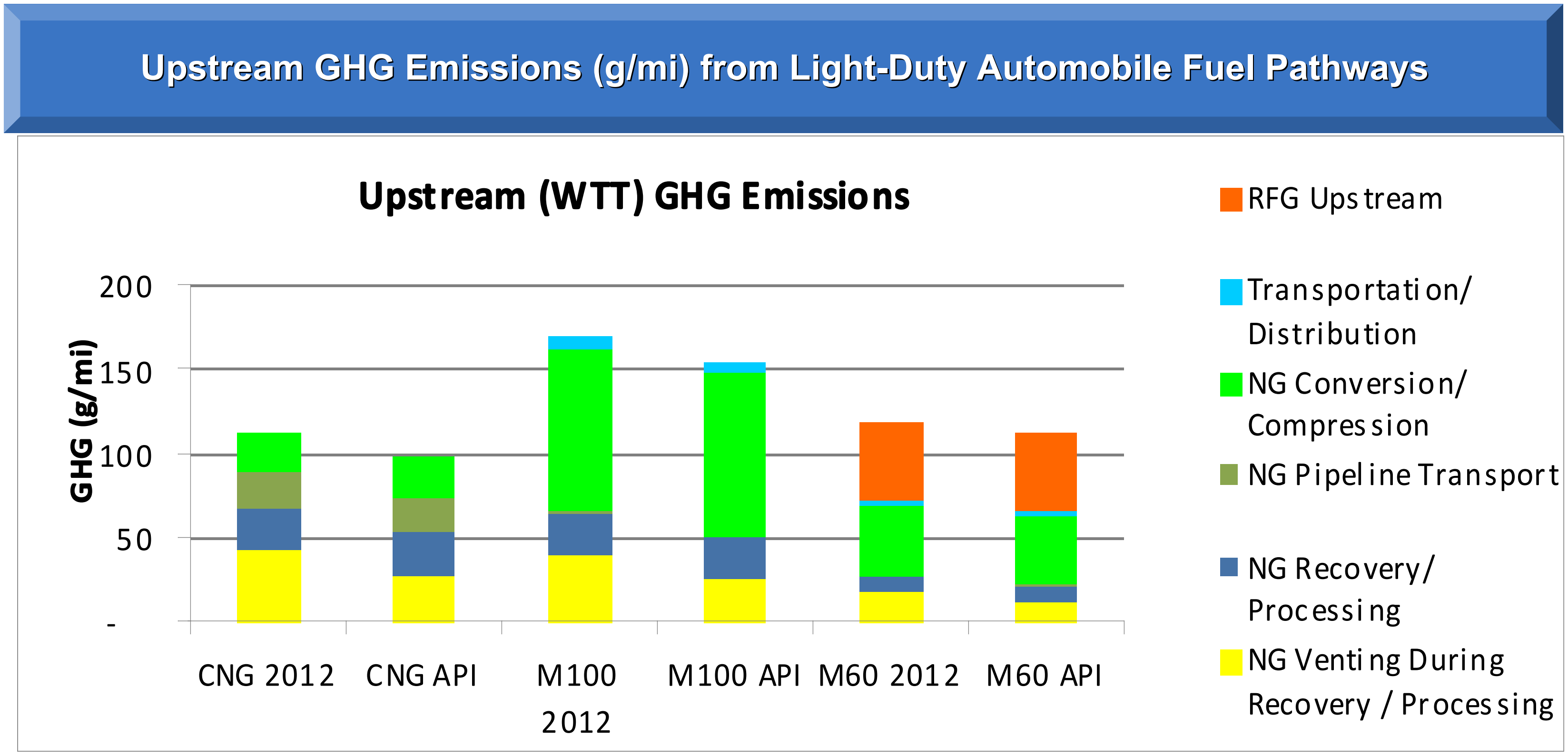
## GHG Emissions: GREET w/ Marginal Crude factors Total (WTW) L-D Autos




**GREET 12 with TIAX adjustments for . RFG is 100% gasoline. All alcohol blends use RFG.**

**NOTE: As discussed, significant uncertainty exists with unconventional crude pathways.**

## GHG Emissions Breakout by Upstream Sources: (WTT) L-D Autos




**GREET 2012 using EPA vs API factors for methane emissions**

Note that all sectors in the upstream CNG and M100 pathways show modest **GHG decreases** under the API methane emissions scenario. M60 pathway proportionally affected except for "RFG Upstream" portion.

- TIAX reviewed info and data provided by GEM fuel advocate Dr. Robert Zubrin from his testing of an LDV converted to operate on M60 and M100
- The summaries below compare Zubrin's data for M100 compared to RFG (conventional & tar sand)

| Model / Data Source | Fuel | Pathway | Methodology / Assumption | GHG Emissions (C02, g/mi) | | | % Diff from RFG |
|---|---|---|---|---|---|---|---|
| | | | | Upstream | Vehicle | Total | |
| Robert Zubrin | RFG (E-10) | Crude Oil (Conventional) | Unspecified Tests on Personal Vehicle | 47 | 260 | 307 | |
| Robert Zubrin | M100 | N.A. Natural Gas / **ATR** | Unspecified / Personal Tests | 12 | 168 | **180** | **-41.4%** |

| Model / Data Source | Fuel | Pathway | Methodology / Assumption | GHG Emissions (C02, g/mi) | | | % Diff from RFG |
|---|---|---|---|---|---|---|---|
| | | | | Upstream | Vehicle | Total | |
| Robert Zubrin | RFG (E-10) | Crude Oil **(Tar Sands)** | Calculated from 2.5 X Upstream CO2 of Conventional Crude | 118 | 260 | 378 | |
| Robert Zubrin | M100 | N.A. Natural Gas / **ATR** | Unspecified Tests on Personal Vehicle | 12 | 168 | **180** | **-52.3%** |

## Summary:

- Dr. Zubrin: LDV operated on M100 emitted 41% less $C0_2$ compared to same vehicle on RFG (E10). Assumes: 1) ATR process to make methanol, and 2) LDV on M100 achieves 89% F.E. of RFG
- 2$^{nd}$ table assumes RFG made from **tar sand crude;** Dr. Zubrin notes this would result in 2.5 times more upstream $CO_2$. With that assumption, the M100-fueled LDV would provide an even greater reduction in total $CO_2$ emissions (about 52%)
- Note that a major change in upstream $CO_2$ emissions does not result in a large total (WTW) change

**Issue w/ this comparison:** lacks details (e.g., test protocols / equipment, vehicle modifications, fuel specifications) to assess significance of such testing on viability of a GEM fuel strategy for in-use LDVs

## **Lifecycle Emissions Analysis of Retrofitted AFVs** *LCA Results / Findings  GHG Impacts (cont'd)*

TIAX used GREET 12 to model Dr. Zubrin's inputs for an alternative comparison of M60 to RFG

- **Upstream:** used methanol production efficiencies of 1) 82% (SMR baseline) and 2) 89% (confirmed to be highest end for ATR, through extensive discussions with Haldor Topsoe)
- **Downstream:** used two different vehicle fuel efficiencies (relative to RFG) for the M60 case: 1) 70% (high baseline) and 2) 89% (highest per Zubrin, not independently verified)

| Model / Data Source | Fuel | Pathway | Methodology / Assumption | GHG Emissions (C02e, g/mi) | | | % Diff from RFG |
|---|---|---|---|---|---|---|---|
| | | | | Upstream | Vehicle | Total | |
| GREET 12 | RFG | Crude Oil (Conventional) | GREET 12 Base | 80 | 328 | **408** | |
| | M60 | N.A. Natural Gas / SMR | GREET 12 Base @ 82% Eff. / 70% FE | 119 | 310 | **429** | **5.1%** |
| GREET 12 / Zubrin Assumptions | M60 | N.A. Natural Gas / **ATR** | GREET 12 @ **89% Eff** / 70% FE | 105 | 310 | **415** | **1.7%** |
| | M60 | N.A. Natural Gas / **ATR** | GREET 12 @ 82% Eff / **89% FE** | 95 | 244 | **339** | **-16.9%** |
| | M60 | N.A. Natural Gas / **ATR** | GREET 12 @ **89% Eff** / 89% FE | 83 | 244 | **327** | **-19.9%** |

## Summary:

- The baseline comparison shows the previously displayed modest GHG increase (~5%) for M60
- Changing the methanol production efficiency (upstream) from 82% to 89%  improves the M60 GHG "score" to nearly equivalent (1.7% higher) with RFG
- Returning the production efficiency back to 82% but increasing the vehicle's fuel efficiency from 70% to 89% has a dramatic effect:
  - The total (WTW) GHG score is now **nearly 17% lower** than the same vehicle on RFG
- Increasing the production efficiency up to 89% has a modest effect to further improve M60's score

**Key Implication:** in GREET, vehicle fuel efficiency is significantly more important than upstream fuel production efficiency as a determinant of a fuel / vehicle pathway's total (WTW) GHG "score"