FULL FUEL CYCLE ANALYSES FOR AB1007

Presented at

CEC-ARB Workshop on Developing a State Plan to Increase the Use of Alternative Transportation Fuels

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1. Introduction
2. Methodology
3. Example Results—2012 Only
4. Summary

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2. Methodology
3. Example Results—2012 Only
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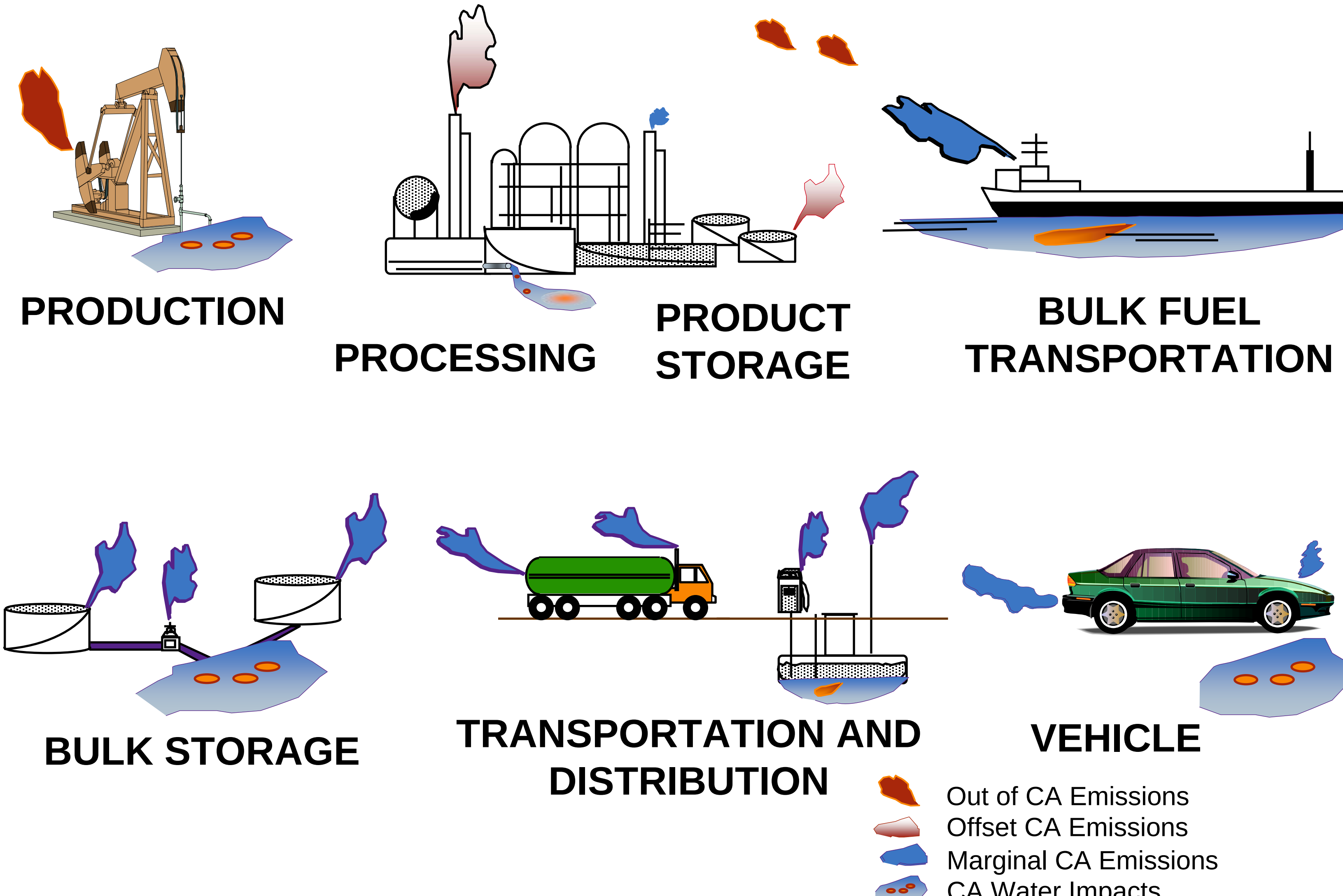
In Assembly Bill 1007, Pavley, Air Quality: Alternative Fuels the California Legislature stated:

- The production, marketing and distribution, and use of petroleum fuels causes significant degradation of public health and environmental quality
- Clean alternative fuels have the potential to considerably reduce these impacts and are important strategies to attain air and water quality goals
- Research, development, and commercialization of alternative fuels have the potential to strengthen California's economy by providing job growth and helping to reduce the state's vulnerability to petroleum price volatility
- CEC and ARB recommended in their report to legislature—"Reducing California's Petroleum Dependency"—that the state adopt a goal of 20 percent nonpetroleum fuel use in 2020 and 30 percent by 2030

In AB 1007, Legislature required CEC in cooperation with ARB and other state agencies to develop and adopt a state plan to increase the use of alternative transportation fuels

- The plan shall include an evaluation of alternative fuels on a ***full fuel cycle assessment*** of emissions of criteria air pollutants, air toxics, greenhouse gases, water pollutants, and other substances that are known to damage human health, and impacts on petroleum consumption
- "Alternative fuel" means a nonpetroleum fuel, including electricity, ethanol, biodiesel, hydrogen, methanol, or natural gas
- The plan shall set goals for 2012, 2017, and 2022

Number of emission events throughout fuel cycle



Marginal Analysis Assumptions for Conventional Fuels

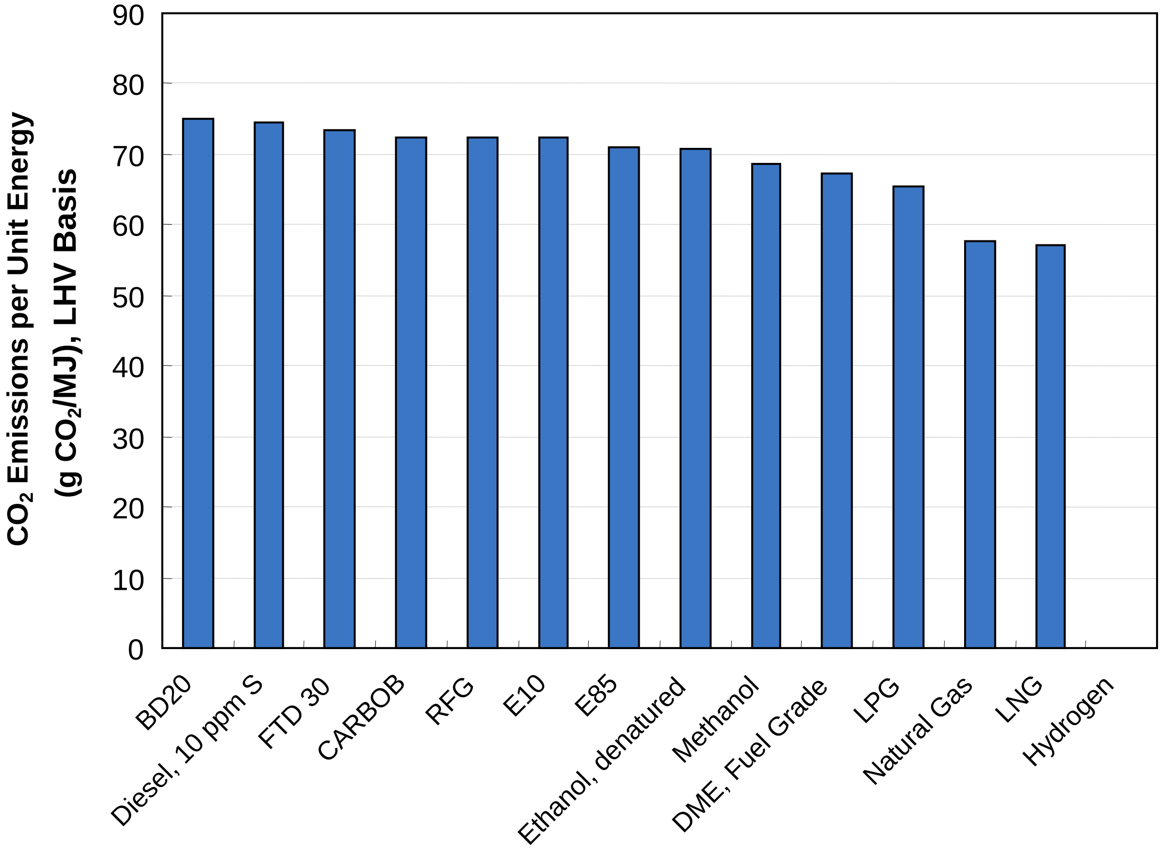
- Gasoline and diesel are imported to California to meet growth in consumption beyond existing refinery capacity
  - Refined products (gasoline and gasoline blend components) imported by ships into California
- Natural gas continued to be shipped to California by pipelines from U.S. and Canada
  - LNG imported by ships
- Electric power generated by natural gas combined cycle plants meeting California's RPS (renewable portfolio standard)
  - No hydro or nuclear considered

Factors that FFCA need to consider

- Vehicle exhaust and evaporative emissions depend on fuel production and delivery scenarios
- Delivery logistics and energy density affect ship, rail, truck emissions
- Fuel losses and impact on toxics such as benzene and PAHs
- Accounting of local emissions vs. U.S. vs. rest of world
- Impact of fuels on water pollution in California
- Potential for less greenhouse gas emissions (CO_2, N_2O, and CH_4)
  - Less carbon in fuel
  - Biofuels recycling CO_2 through plant photosynthesis
  - Improved efficiency for production and vehicle technologies

Alternative fuels have lower carbon content in fuel relative to heating value and result in lower CO_2 emissions

- Need to account for fuel cycle and vehicle energy use in comparing CO_2 emiss



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2. **Methodology**
3. Example Results—2012 Only
4. Summary

Full fuel cycle analyses provide a basis for determining the energy inputs and emissions from various fuel and vehicle options

Objectives

- Compare fuel options based on impacts of fuel production and vehicle operation

Fuel Pathways

- Petroleum, natural gas, coal, biofuels, renewable power

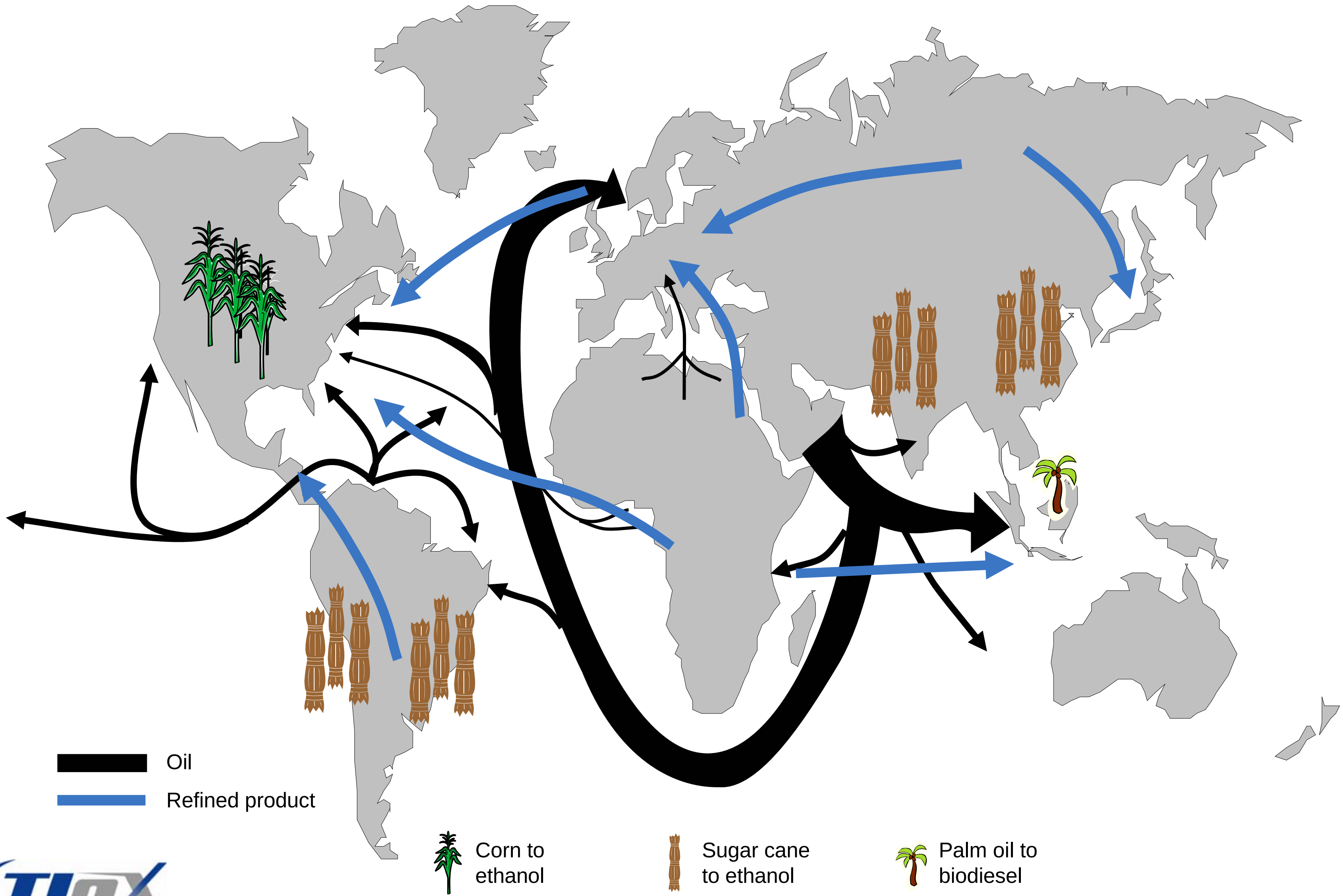
Vehicles

- Light-, medium-, and heavy-duty vehicles, off road vehicles
- Emissions occurring in 2012, 2017, 2022, and 2030
- New vehicle and blended fuel strategies for existing vehicles (E10, biodiesel—BD20, FT fuels—FTD30)

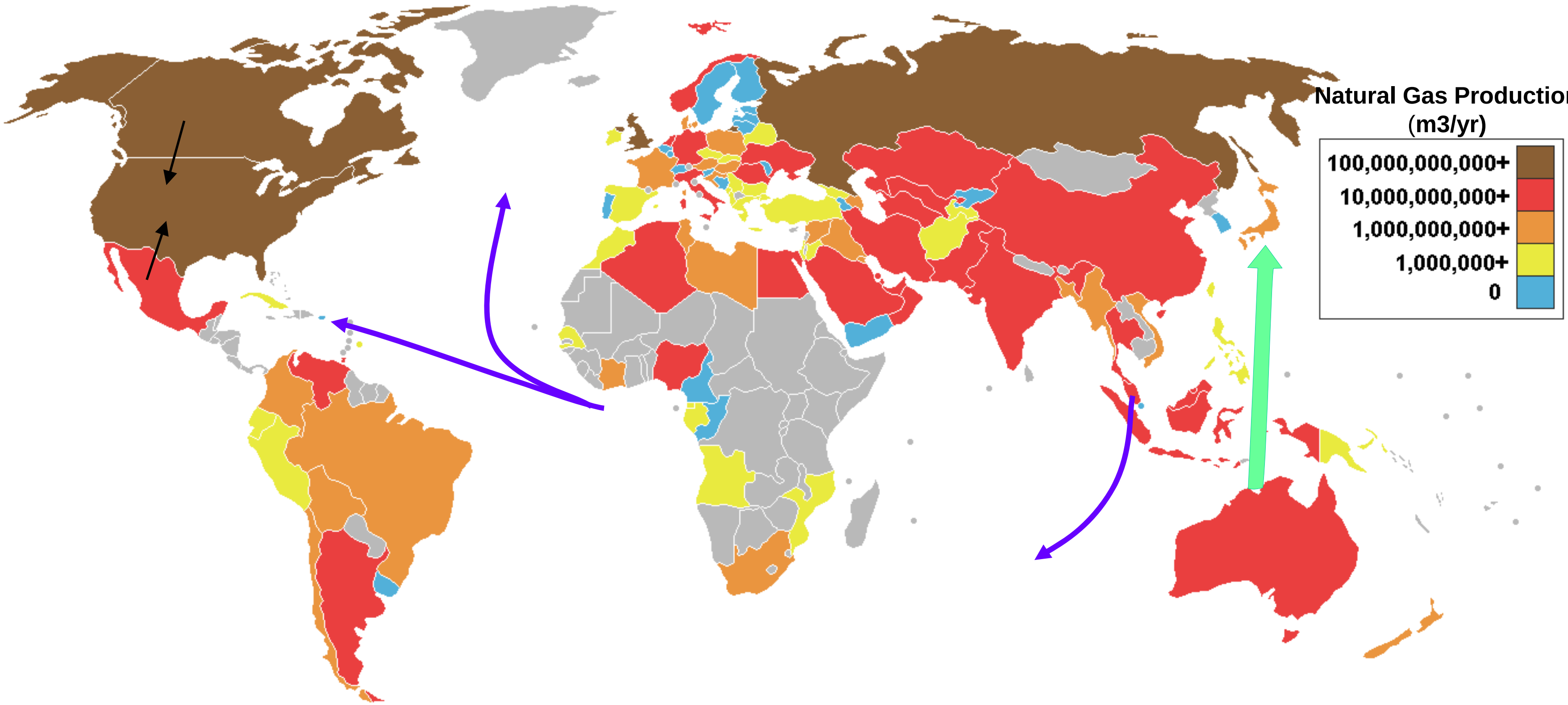
Emission Sources and Boundaries

- Criteria pollutants, toxics, and water impacts estimated based on local, state, and Federal standards and rules
- Location of sources: California, North America, and rest of the world
- Global GHG emissions

World Energy Flows



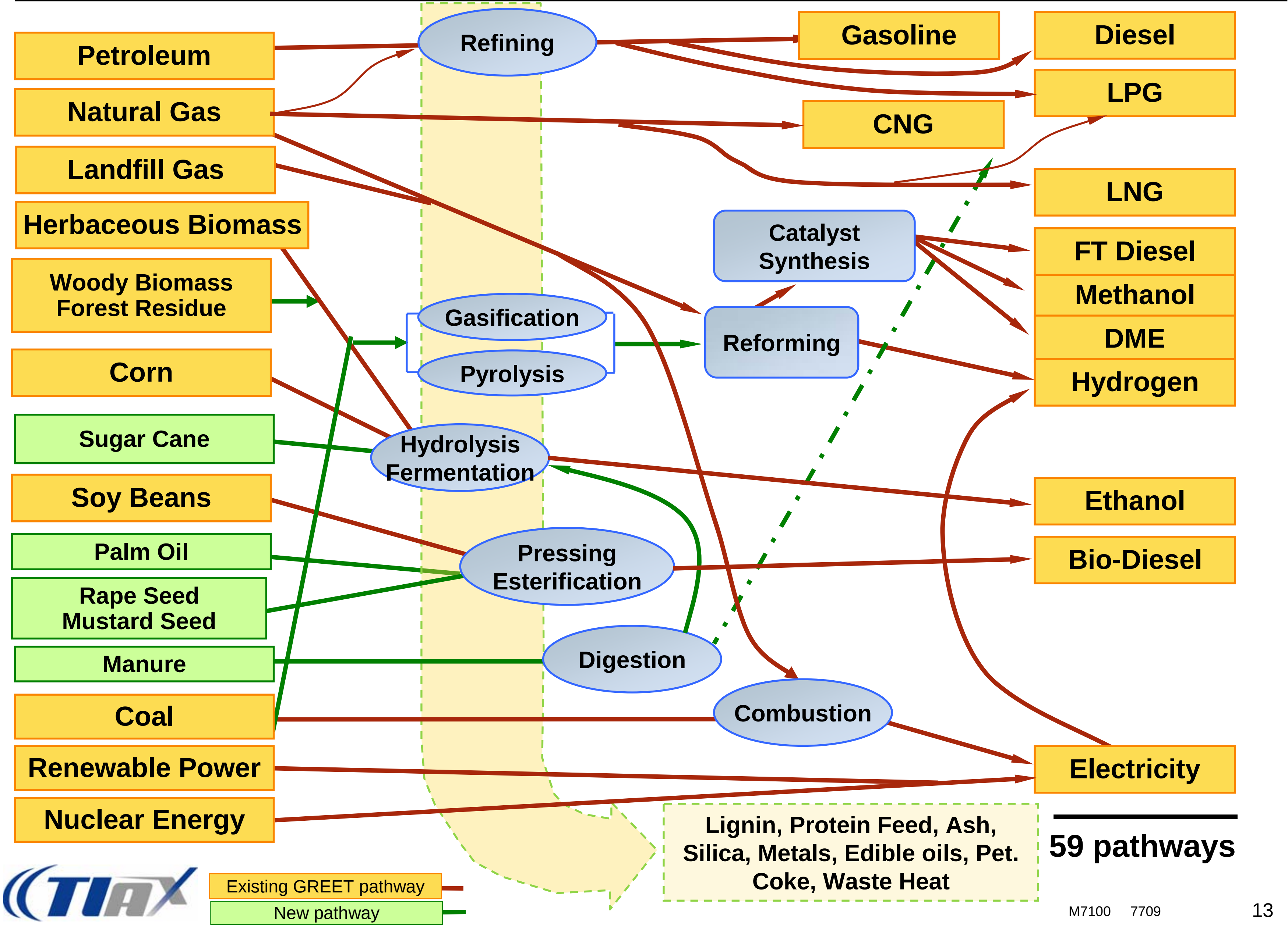
World Energy Flows



LNG

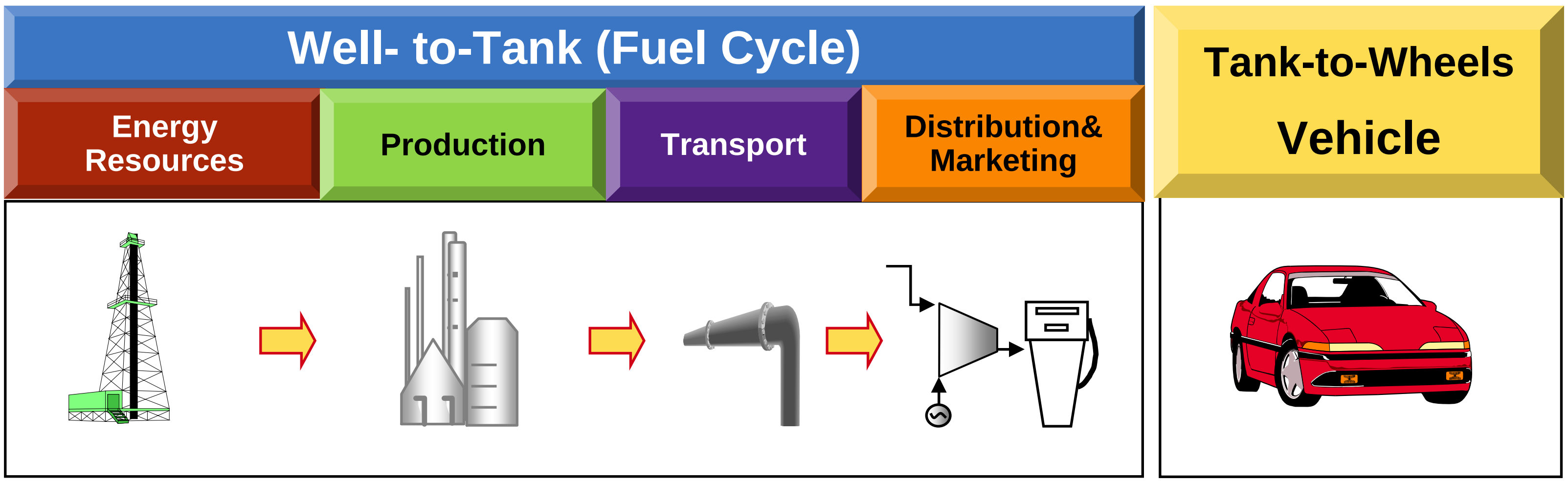
FT Diesel

Natural Gas Pipeline


Petroleum
Natural Gas
Landfill Gas
Herbaceous Biomass
Woody Biomass
Forest Residue
Corn
Sugar Cane
Soy Beans
Palm Oil
Rape Seed
Mustard Seed
Manure
Coal
Renewable Power
Nuclear Energy
Refining
Gasification
Pyrolysis
Hydrolysis
Fermentation
Pressing
Esterification
Digestion
Combustion
Catalyst
Synthesis
Reforming
Gasoline
CNG
Diesel
LPG
LNG
FT Diesel
Methanol
DME
Hydrogen
Ethanol
Bio-Diesel
Electricity
Lignin, Protein Feed, Ash,
Silica, Metals, Edible oils, Pet.
Coke, Waste Heat
Existing GREET pathway
New pathway

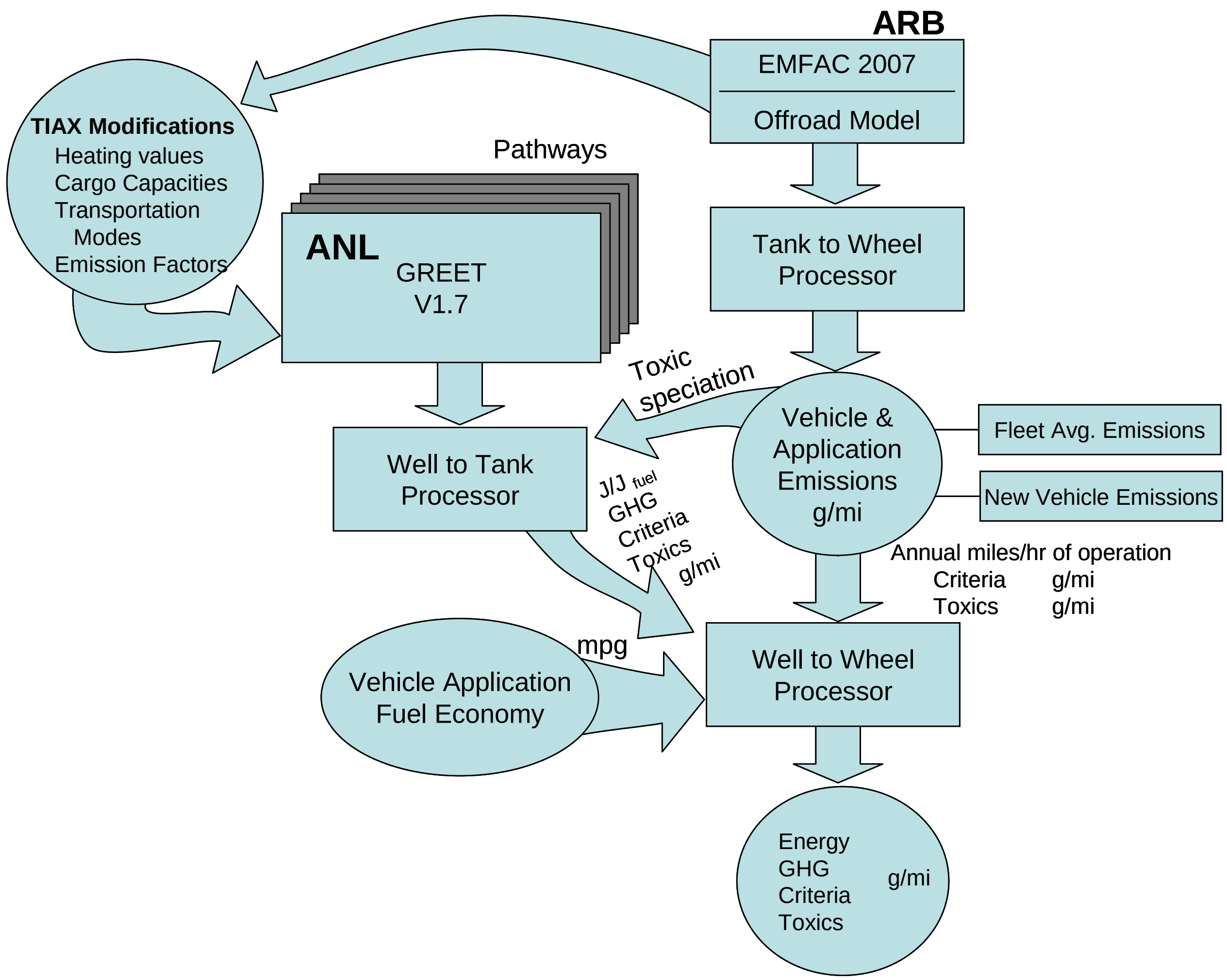
59 pathways

"Well-to-Wheels" Full Fuel Cycle Emission Steps



- Full fuel cycle emissions correspond to resource extraction, fuel production, delivery, and vehicle exhaust, running/evaporative
- Includes combustion, fugitive, and spillage emissions, water discharges
- Emissions from facility and vehicle manufacturing are not included (LCA)
- Energy inputs for fuel cycle are also included

GREET Used as Backbone of Analysis Methodology for WTT Data



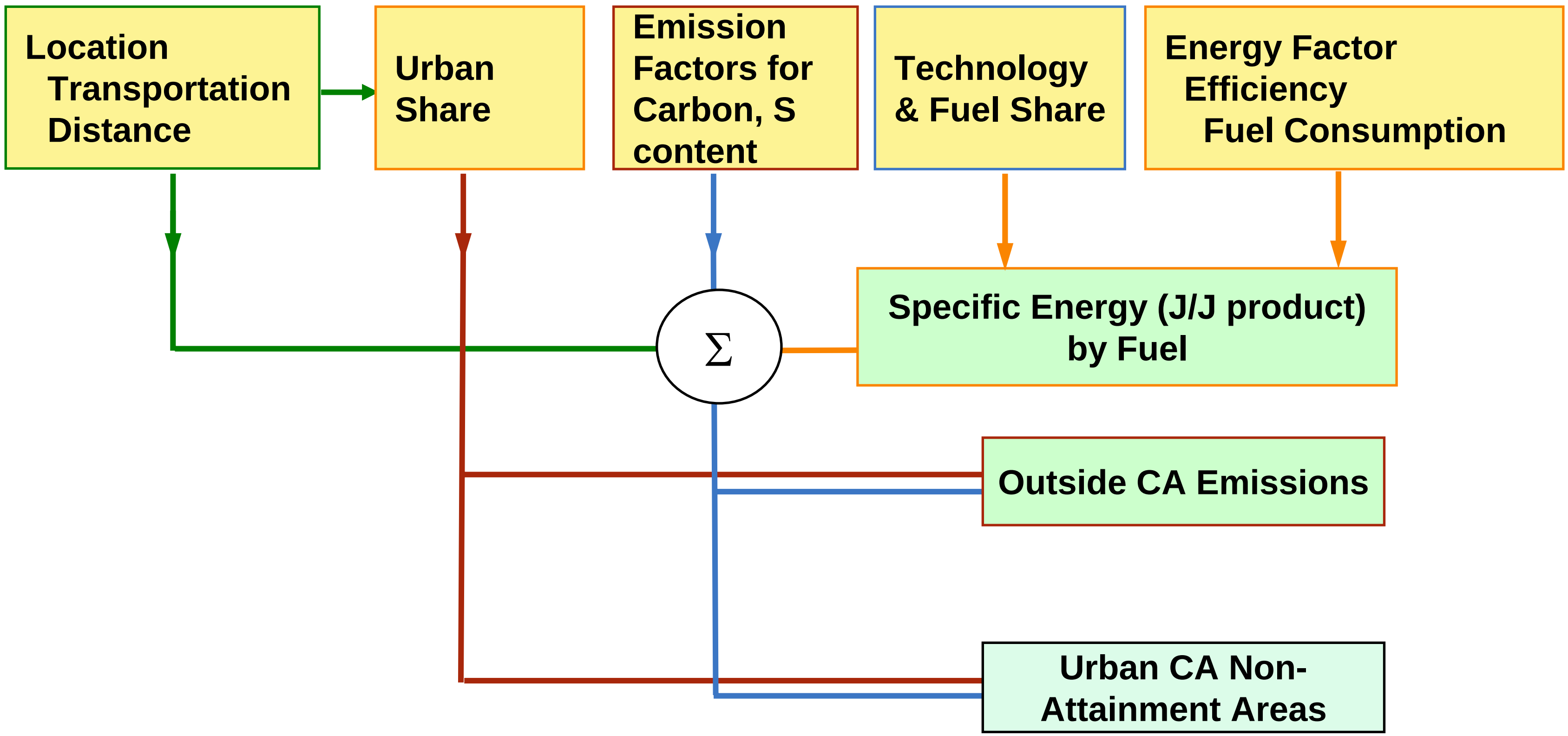
The WTT analysis was based on a modified version of the GREET 1.7 model from ANL

- TIAX modified both baseline inputs and calculations in the model to reflect emission and fuel production scenarios for California.
- Transportation distances reflect the marginal delivery of fuels to California
- Three scenarios reflect fuel production in the U.S., California, and rest of world
- Emission factors for delivery trucks and off road equipment meet California standards
- Emission factors for natural gas transmission equipment in California meet BACT requirements
- Marine and Rail emissions reflect in-port and rail switcher activity with an adjustment factor for urban emissions
- Natural gas transmission and distribution losses reflect data from gas utilities

The WTT analysis was based on a modified version of the GREET 1.7 model from ANL

- Urban emission shares reflect facility and transportation equipment in California
- Model modify to calculate urban emission shares based on the urban distance and total transport distance
- Emissions from facilities requiring offset emissions are set to zero. These include SOx, NOx, and VOC emissions from power plants and large stationary facilities in California.
- The heating values and carbon contents were adjusted for FTD, reformulated gasoline, and hydrogen.

Fuel cycle model inputs need to capture California boundaries



GREET 1.7 is used to calculate well to tank (WTT) or fuel cycle emissions. Several GREET models are configured with different regional emission assumptions. A WTT factor for each fuel is based on the composite of regional WTT results.

Emissions of toxics occur from fuel, engine exhaust, and fuel production/processing facilities

Toxic Contaminants

- State of California Listed Toxics
- ROG and exhaust sources in the fuel cycle
- Fuel spills, vapor losses, vehicle and engine exhaust, production facilities

Toxic Contaminant	Sources		
	Fuel	Vehicle	Facilities
Benzene			
1,3 butadiene			
Formaldehyde			
Acetaldehyde			
Diesel PM			
Metals			

Calculation Method

- Toxics = Source x Speciation
- $T_a = S_1 \times \chi_{a1} + S_2 \times \chi_{a2}$ ..
- Example speciation for gasoline exhaust:

Toxic	Benzene	1-3 Butadiene	Formaldehyde	Acetaldehyde
HC Running Exhaust	2.64%	0.55%	1.70%	0.24%

Weighting of Toxic Air Contaminants

Toxic Compound	Inhalation Unit Cancer Risk $(\mu g/m^3)^{-1}$	Unit Risk Normalized to Formaldehyde
Acetaldehyde	2.70E-06	0.45
Benzene	2.90E-05	4.8
1,3-Butadiene	1.70E-04	28
Chromium Compounds*	1.50E-01	25,000
Ethylene Dibromide	7.10E-05	12
Formaldehyde	6.00E-06	1.0
Lead & Lead Compounds	1.20E-05	2.0
Methyl Tertiary-Butyl Ether	2.60E-07	0.043
Nickel and Nickel Compounds	2.60E-04	43
Tetrachloroethylene	5.90E-06	1.0
Dioxins (PCDD)	3.80E+01	6,333,333
PAH	1.10E-03	183
Naphthalene	3.40E-05	5.7
Diesel Particulate Matter	3.00E-04	50

Water impacts will be determined from spills and fuel transport as well as fuel production

Fuel sources

- Tanker ships
- Pipelines
- Tank truck delivery
- Underground tanks
- Fuel processing facilities
- Vehicle fueling

Vehicles

- Motor oil
- PM, Nitrates, sulfates

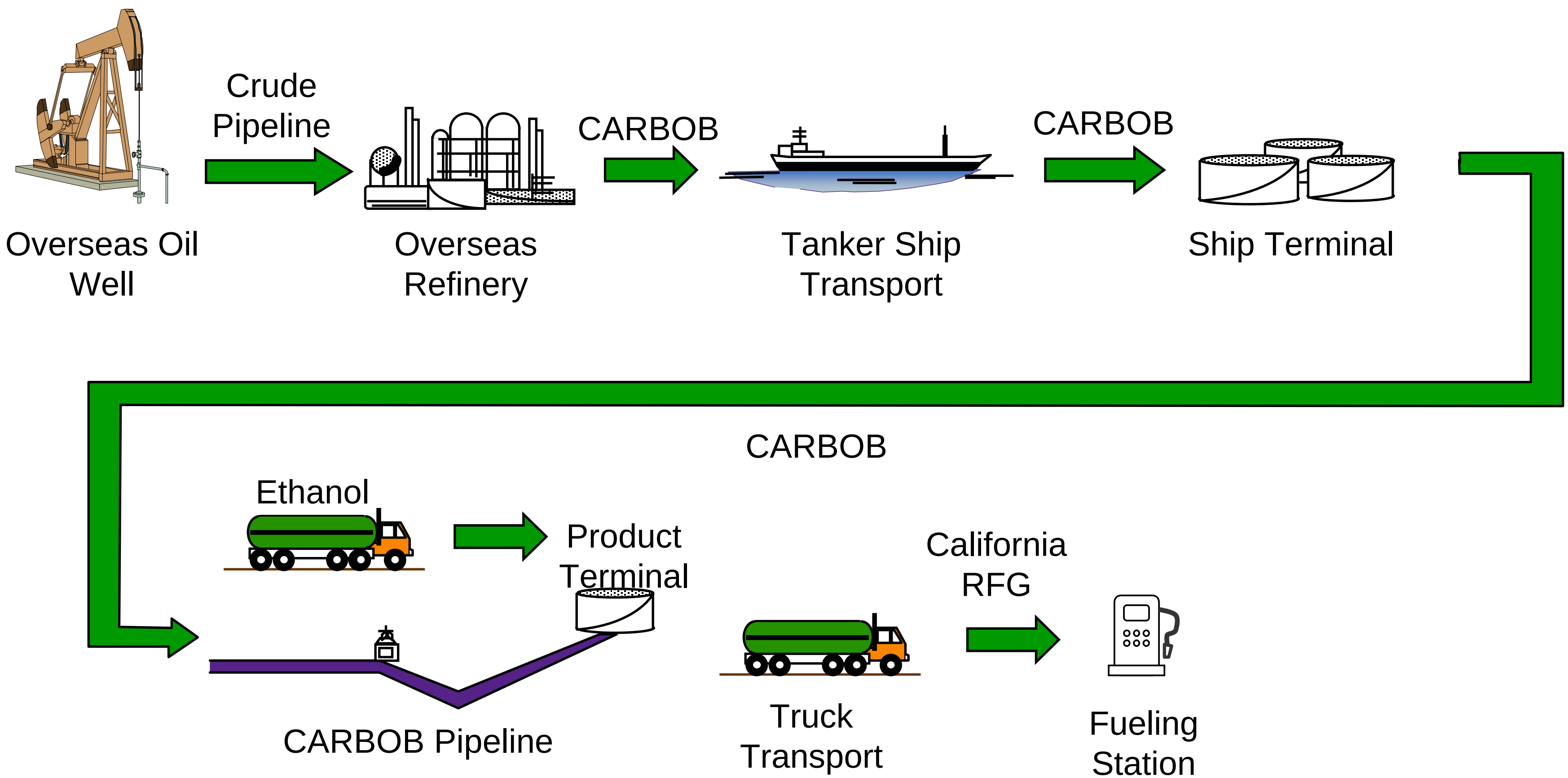
Facilities

- Water use and discharges from processing plants
- Oil and gas field
- Agricultural run off

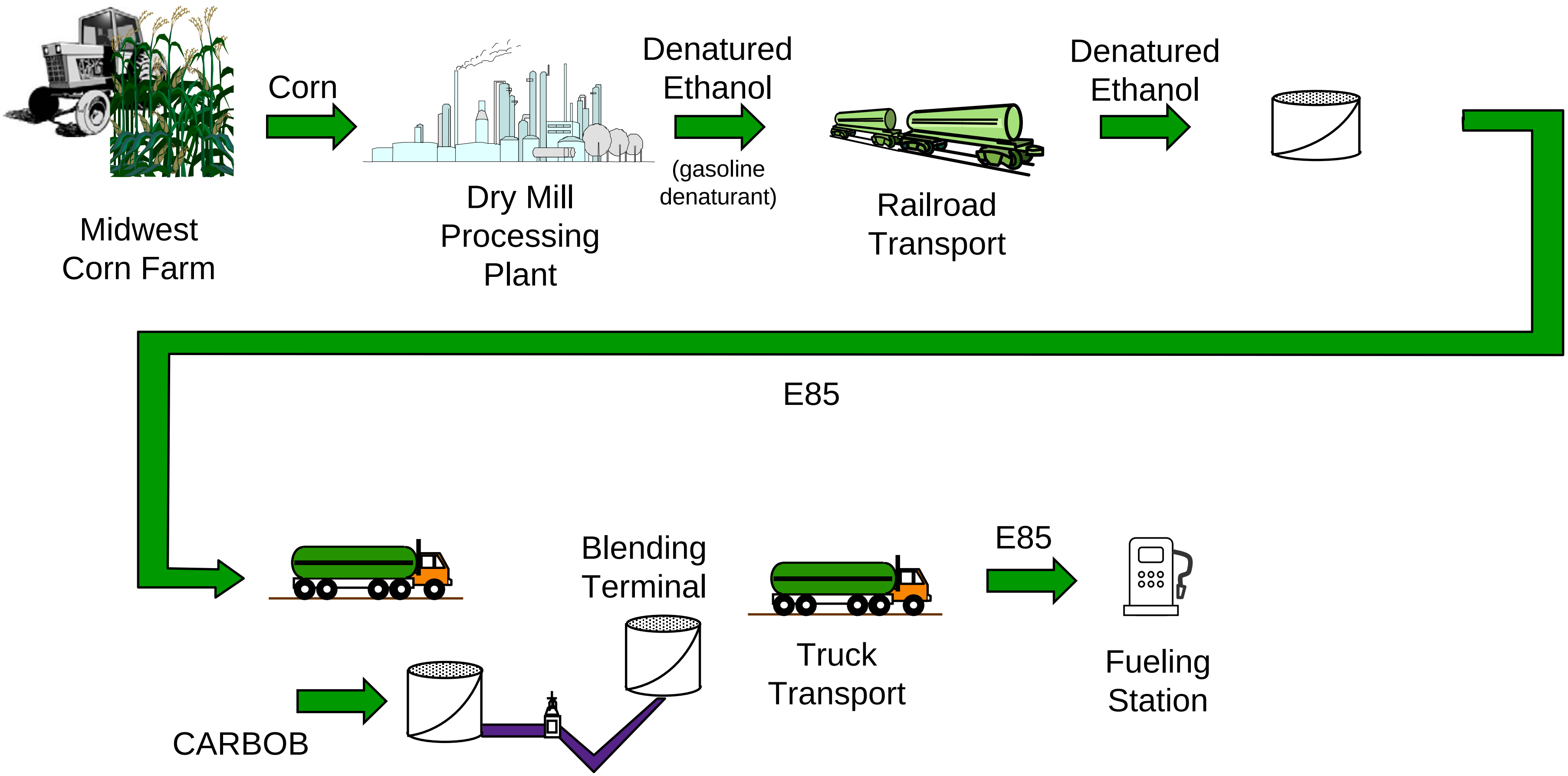
Water Pollutant	Sources		
	Fuel	Vehicle	Facilities
Hydrocarbons			
Alcohols			
Metals			
Chemical Oxidation			
Water use			

Fuel transport losses based on summary in AB2076 report. Data from water discharges from permit applications, and data from CA Department of Water Resources and CA Water Resources Control Board

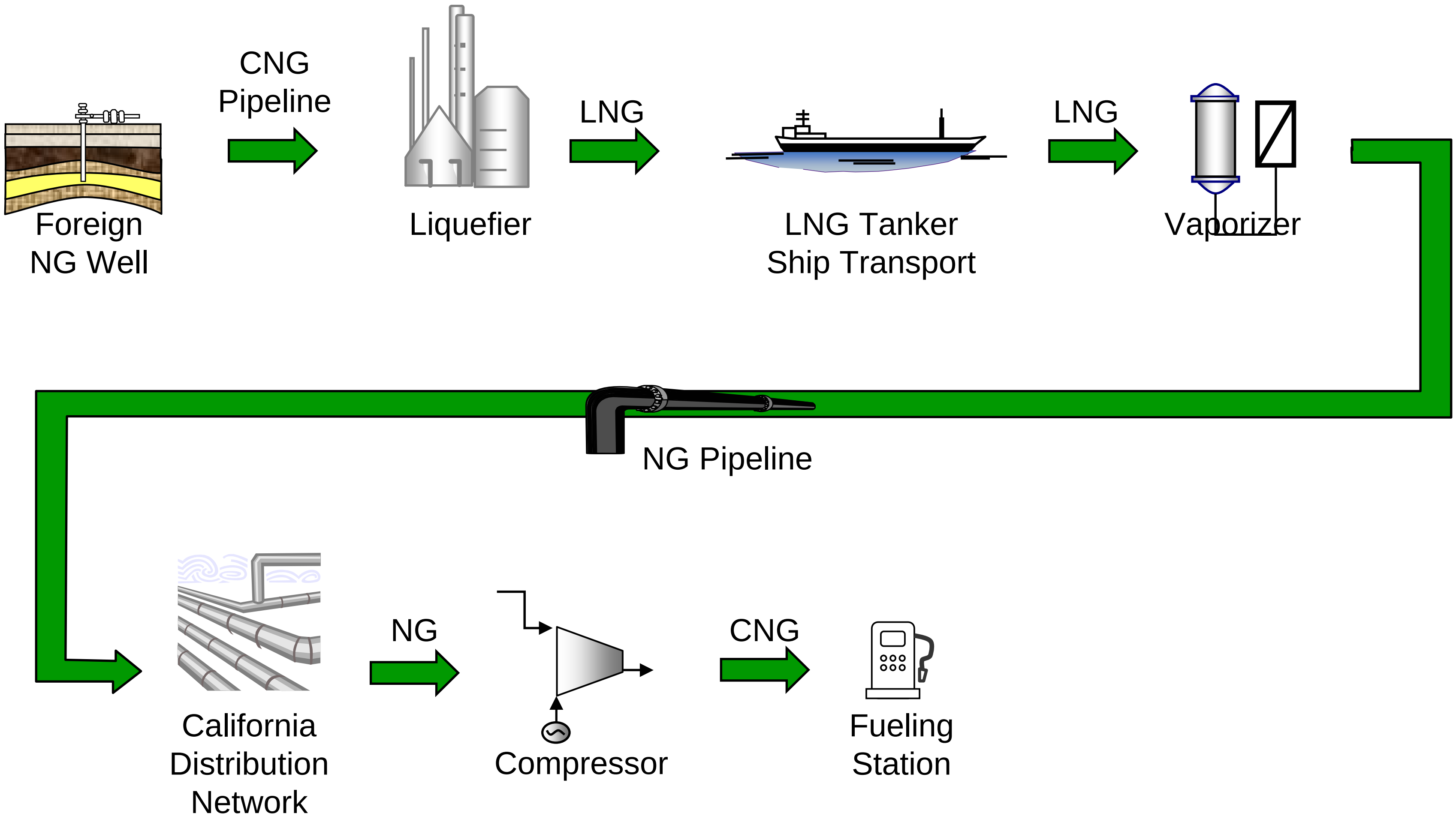
Imported CARBOB from Middle East to California RFG



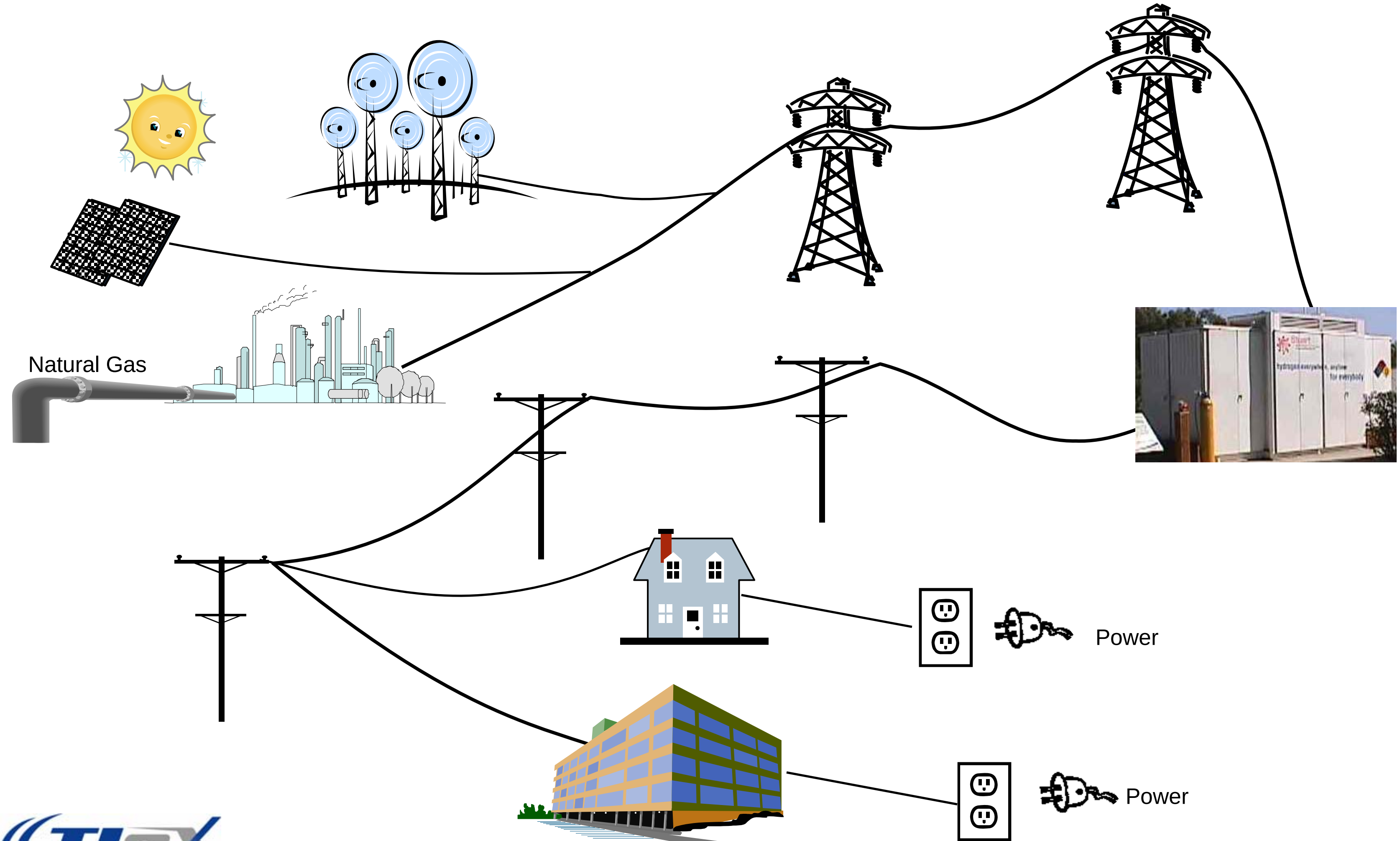
Midwest Corn Based Ethanol Pathway to E85



Imported LNG from Remote Natural Gas to CNG



Marginal Electricity Generation in California



Upward of 59 pathways X 2 vehicle applications X 4 analysis years for criteria pollutants, WTT energy, WTW GHG, toxics, and water pollution

- Six (6) Conventional Fuel Pathways
  - California RFG
  - California ULSD
- Ten (10) Blend Fuel Pathways
  - E10
  - Biodiesel (BD20)
  - FTD (30 percent with Ca ULSD)
  - E-Diesel
- Forty three (43) Neat Fuel Pathways
  - CNG – LNG – LPG
  - Ethanol – Methanol
  - DME
  - Electricity
  - Hydrogen

Analysis Years: 2012, 2017, 2022, 2030

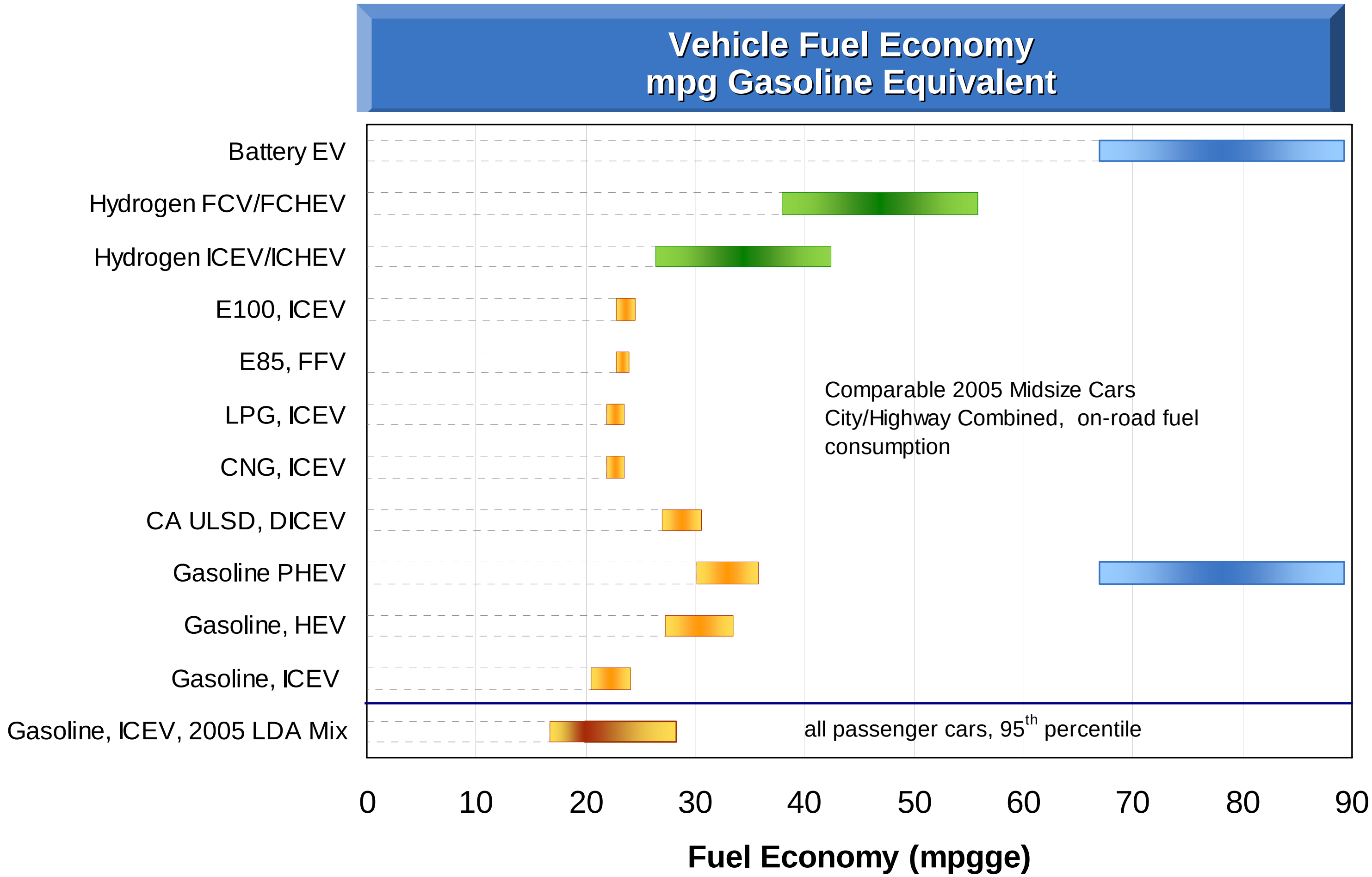
1 Introduction

2 Methodology

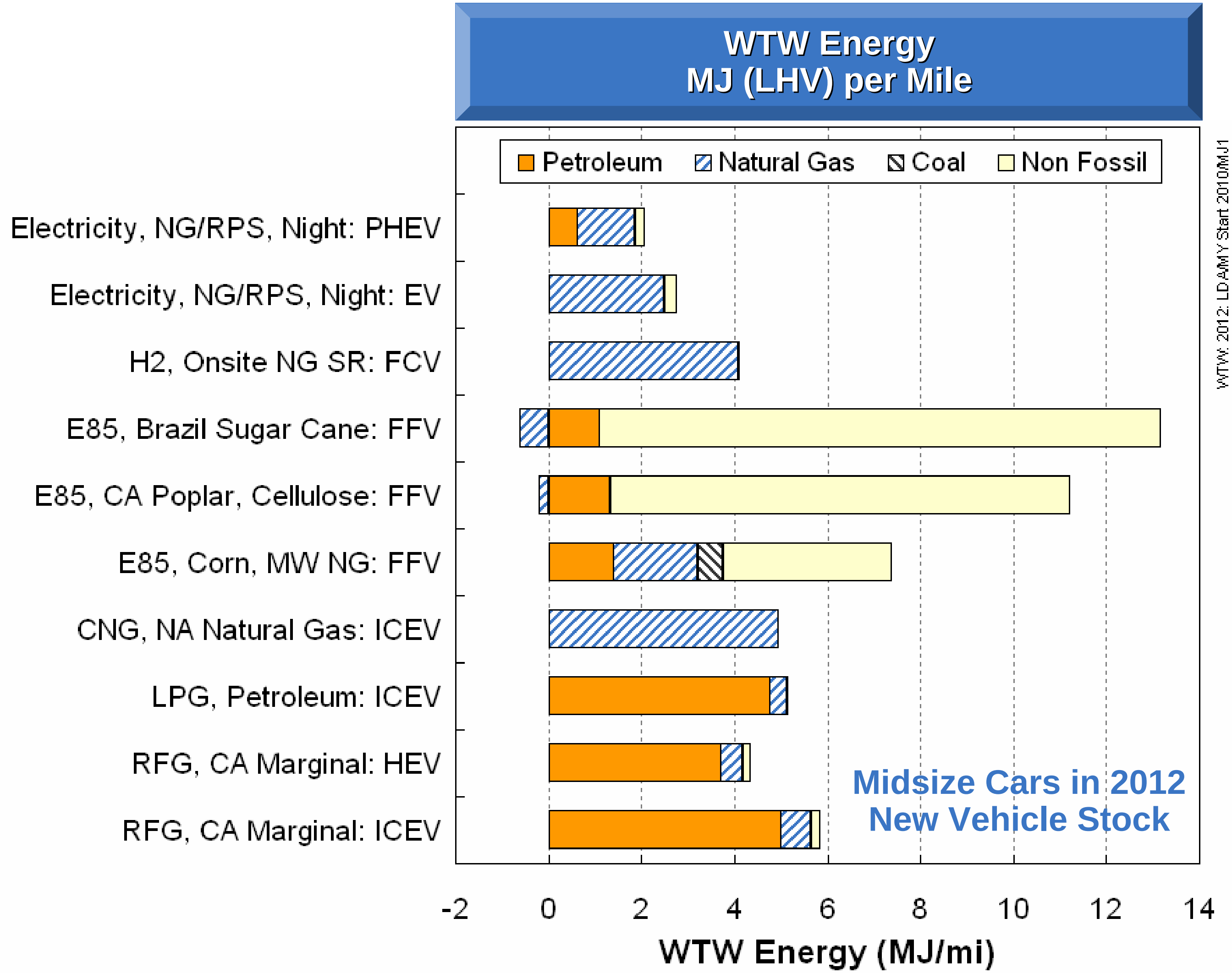
3 **Example Results—2012 Only**

4 Summary

Assumed Midsized Auto Fuel Economy

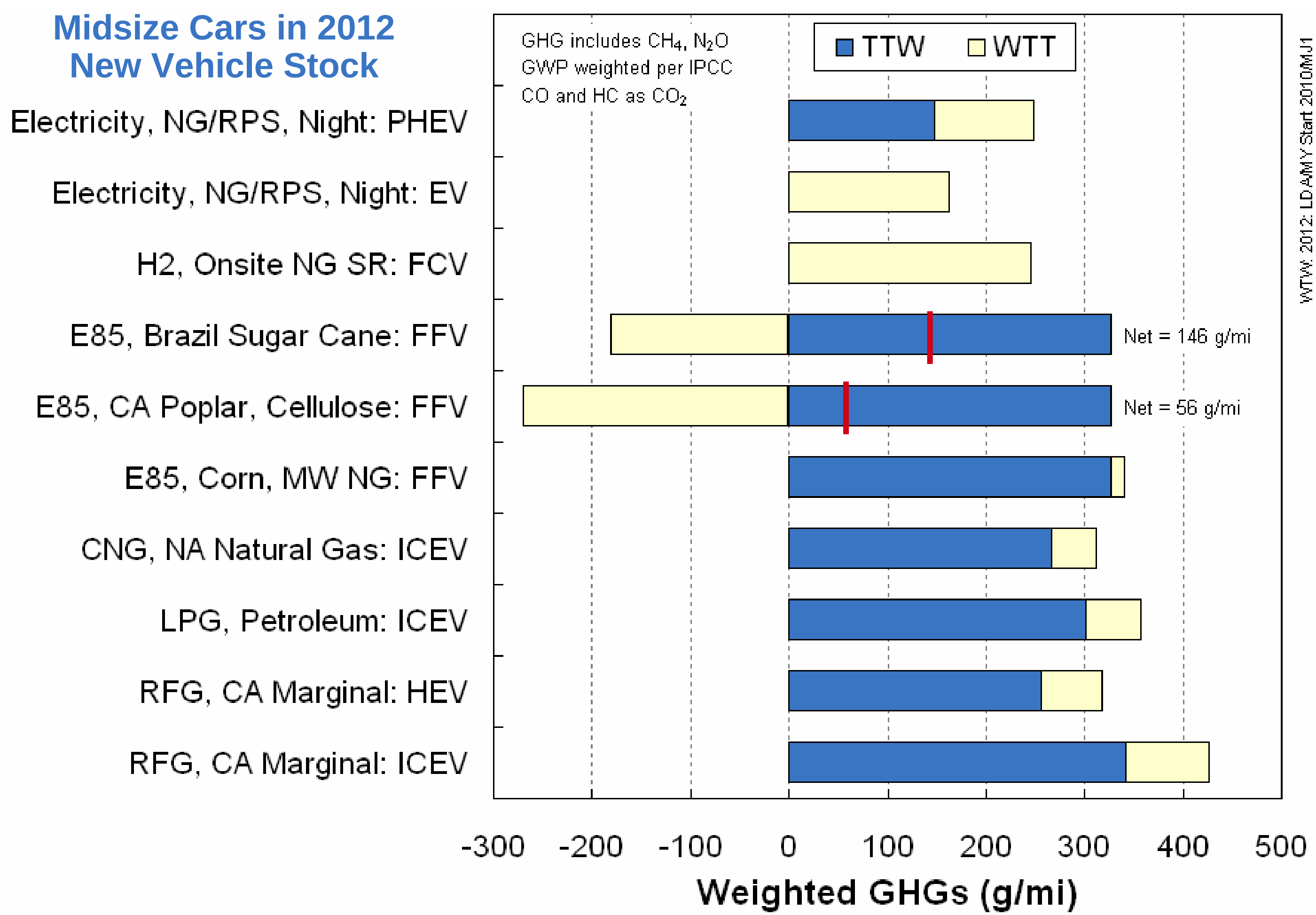


"Well-to-Wheels" Energy Comparison Midsize Auto

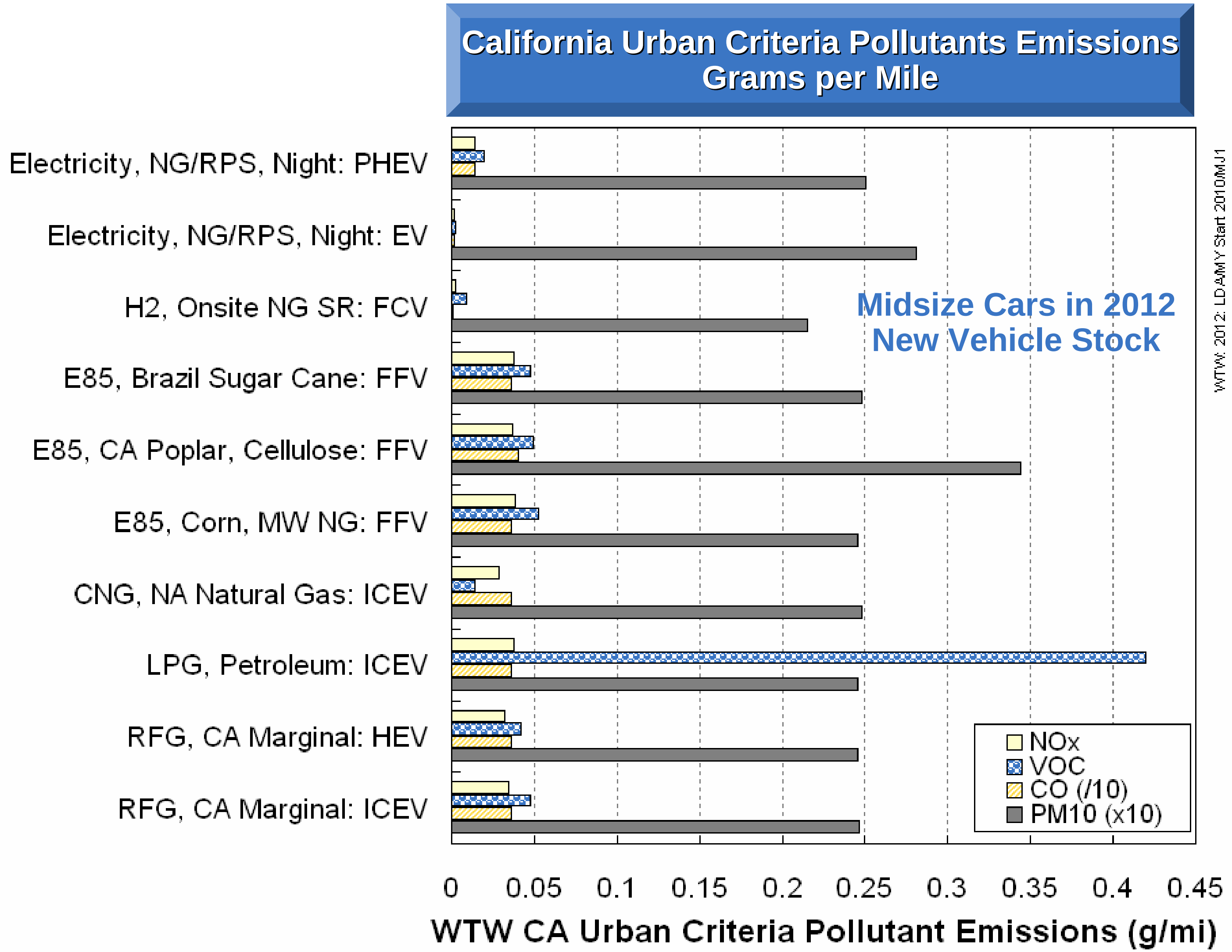


"Well-to-Wheels" GHG Emissions Midsize Auto

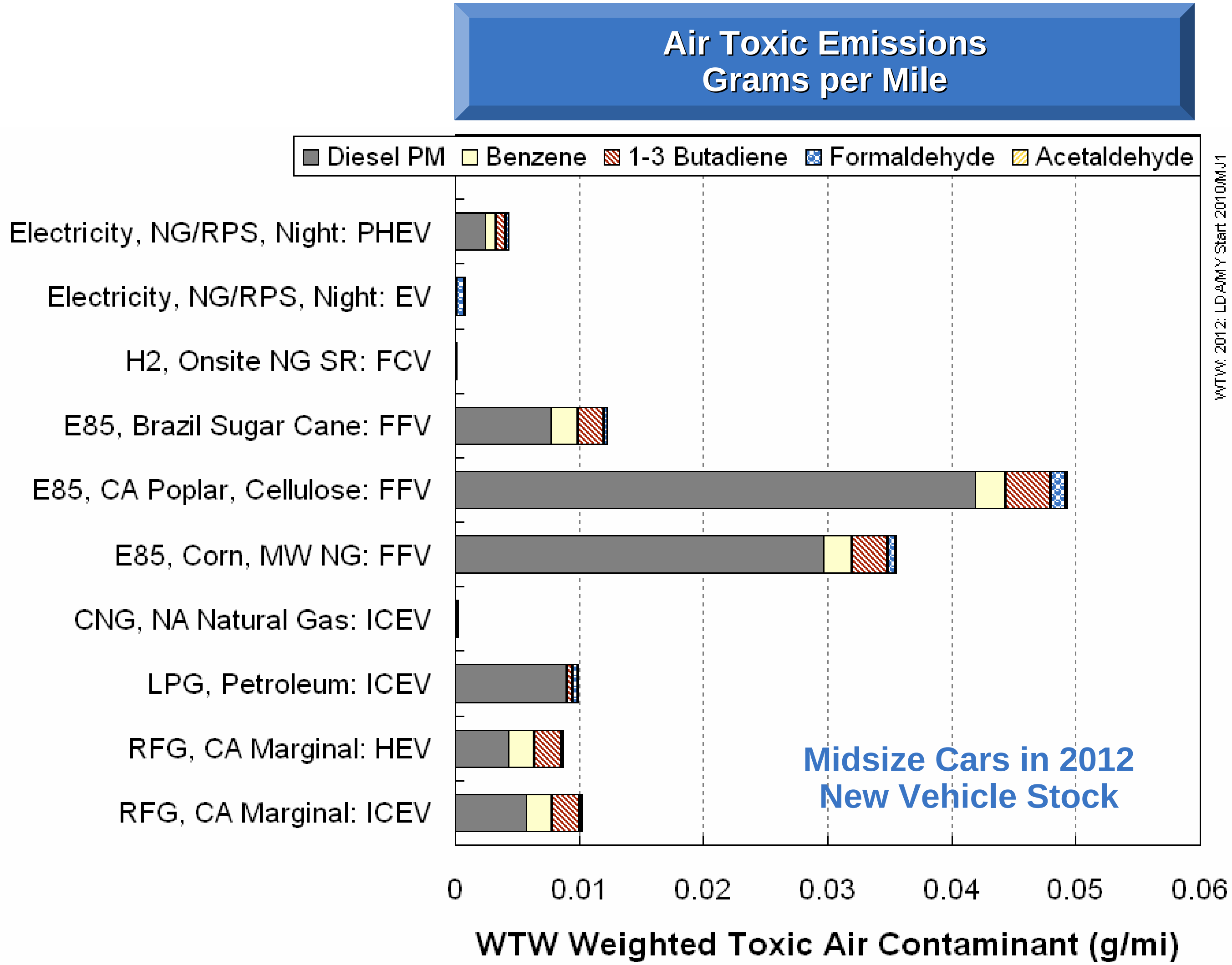
Greenhouse Gas Emissions
Grams of CO_2 Equivalent per Mile



"Well-to-Wheels" Criteria Pollutant Emissions Midsize Auto



"Well-to-Wheels" Toxic Emissions Midsize Auto



"Well to Wheels" Preliminary Observations Midsize Autos

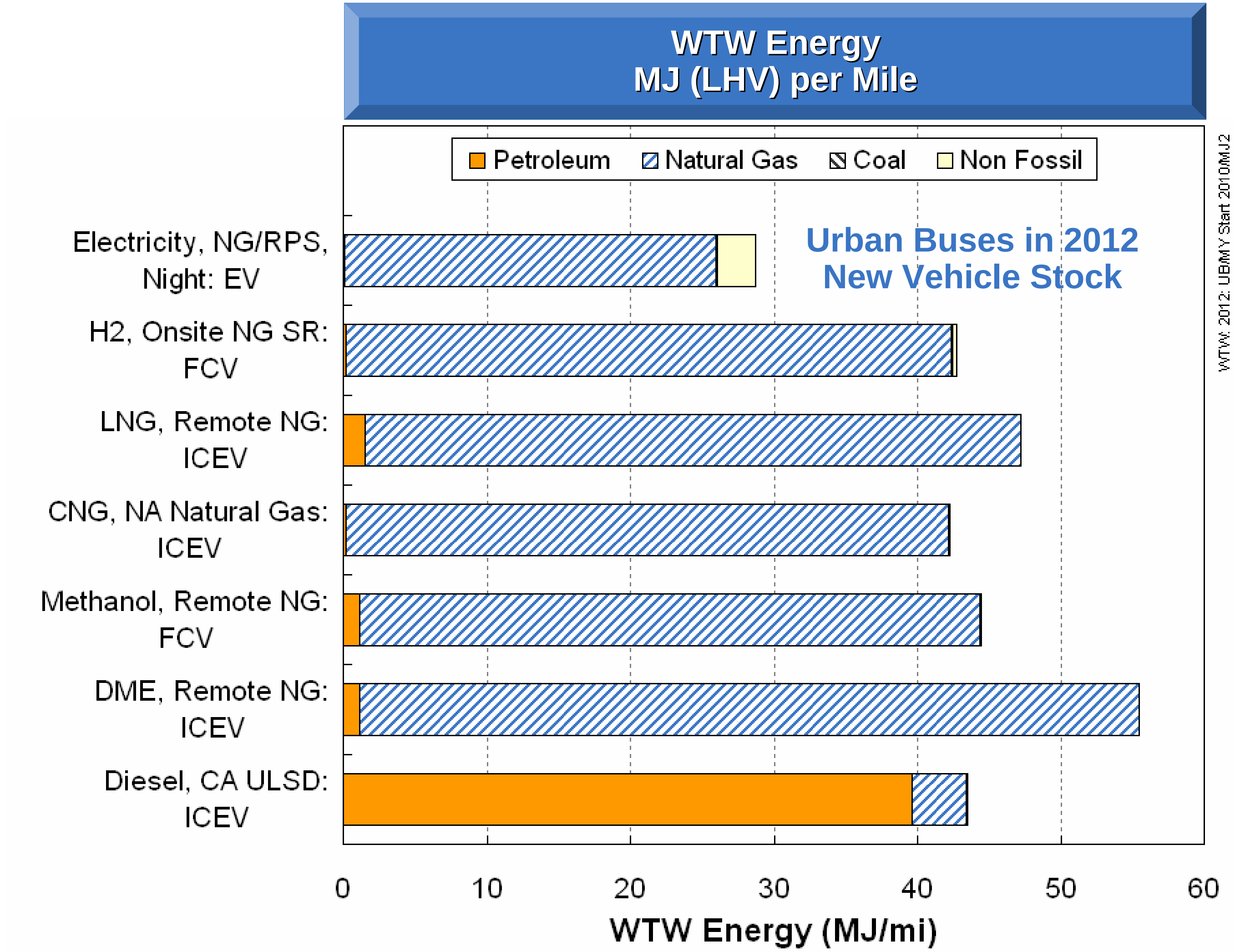
- Primary energy impacts depend on fuel pathway
  - Electricity from renewables to electricity from coal
  - Ethanol from corn, sugar cane, cellulosic biomass
  - Differences largest in GHG emissions but pathway also affects criteria and toxic emissions
- Using alternative fuels reduces GHG impacts compared to gasoline[1]

Fuel	GHG Benefit	Fuel	GHG Benefit
Corn Ethanol	0 to 30%	LPG	18 to 23%
Cellulosic Ethanol	70 to 87%	PHEV/ Battery EV	40 to 50%
CNG	27%	Local NG reformed Hydrogen	40 to 50%

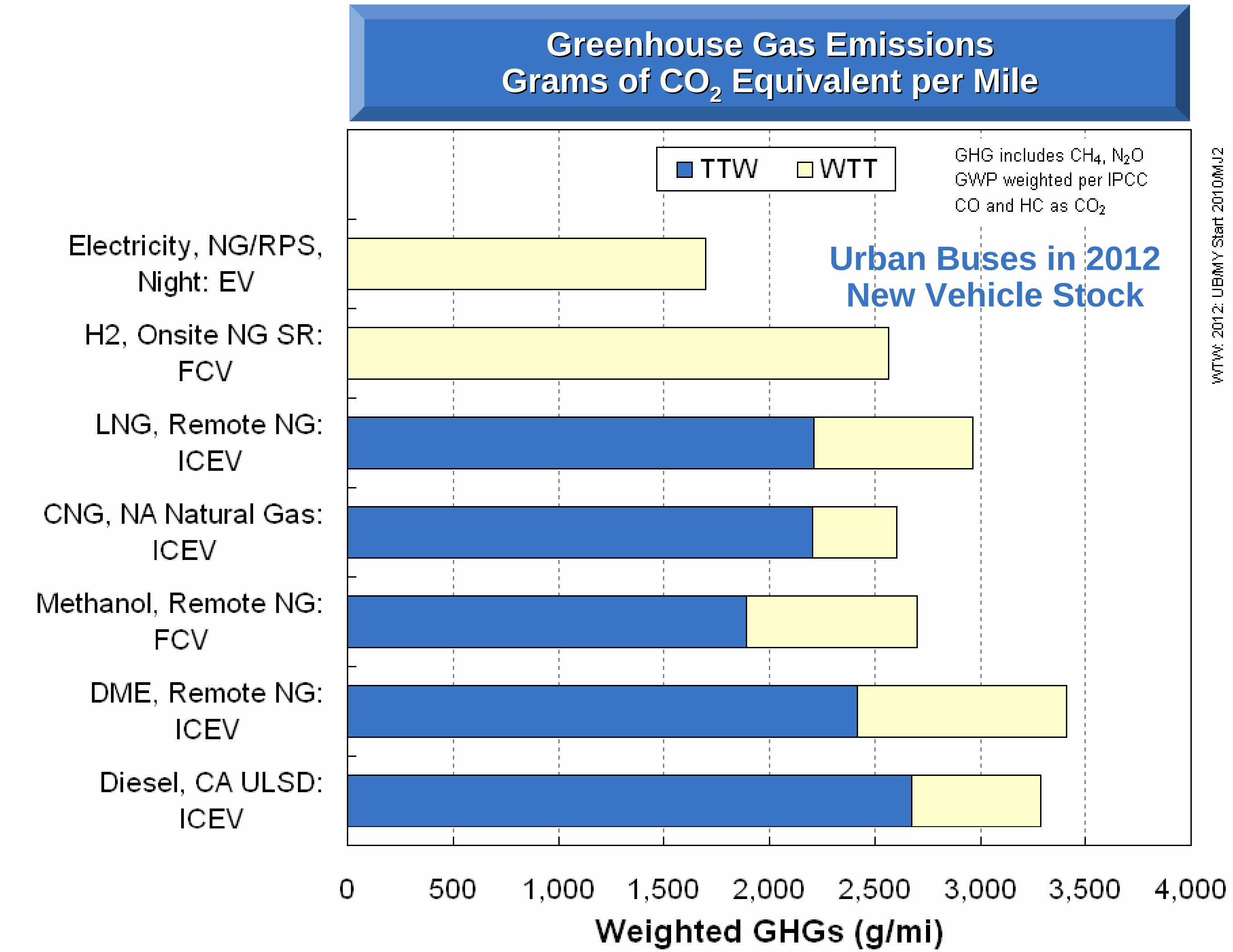
- Alternative fuel pathways result in criteria emissions comparable to gasoline
  - LPG VOCs higher if not controlled
  - California cellulosic ethanol increases PM emissions slightly
  - Natural gas based hydrogen and electric pathways reduce criteria pollutants
- Air toxics dominated by diesel exhaust PM

"1. Results for fossil fuel based pathways (except for cellulosic ethanol). Renewable pathways result in lower GHG emissions.

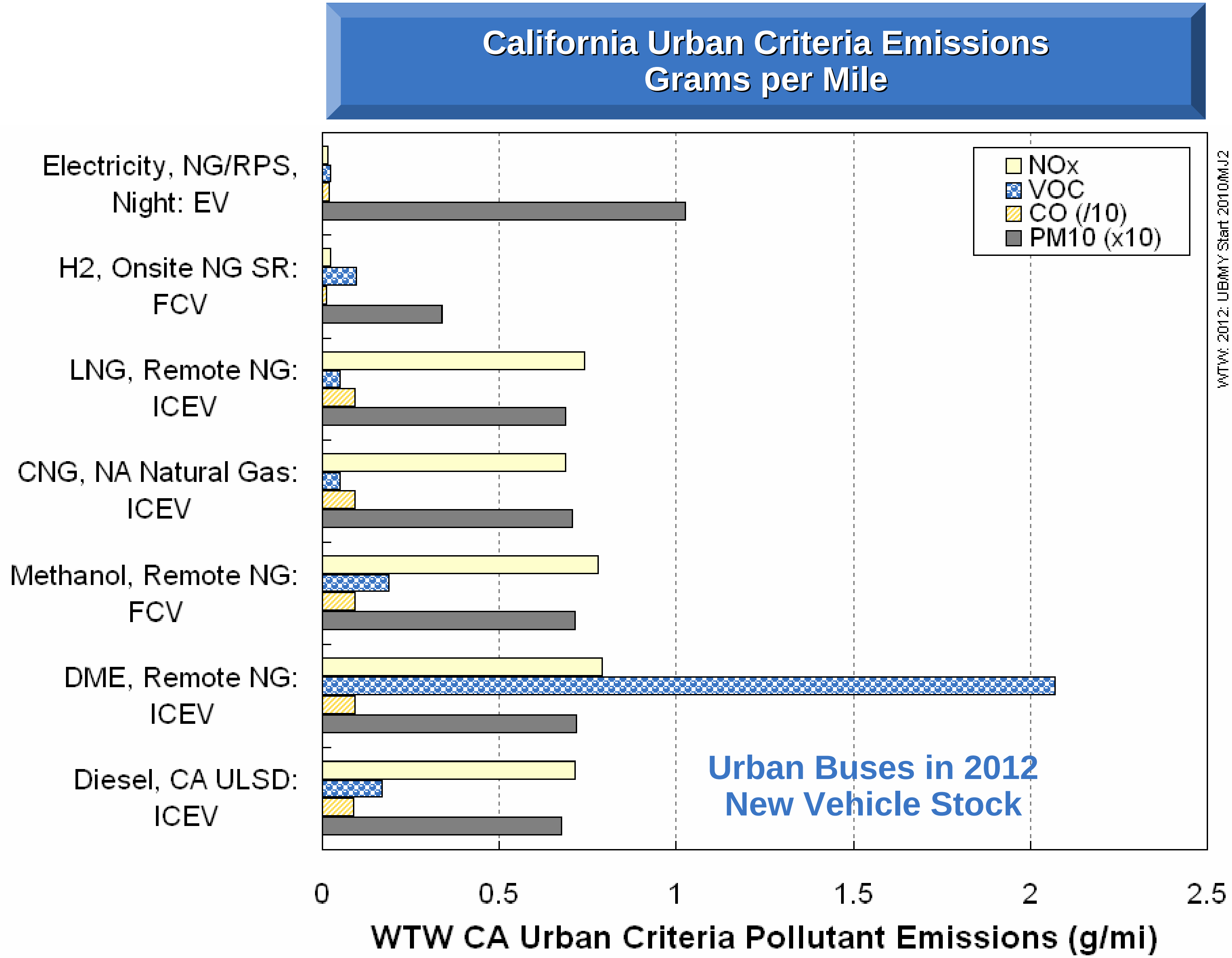
"Well to Wheels" Energy Comparison Urban Buses



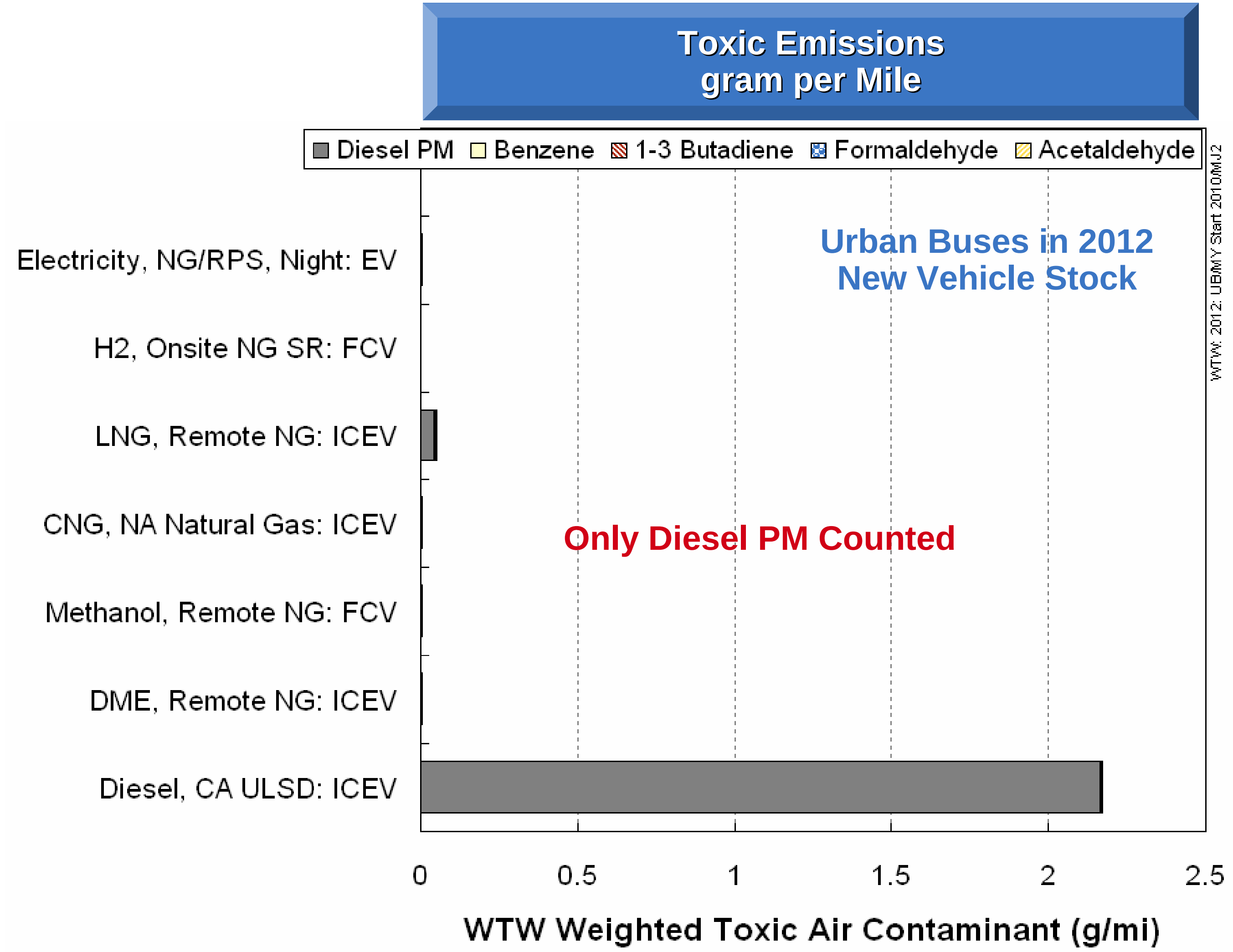
"Well-to-Wheels" GHG Emissions Urban Buses



"Well-to-Wheels" Criteria Emissions Urban Buses



"Well-to-Wheels" Toxic Emissions Urban Buses



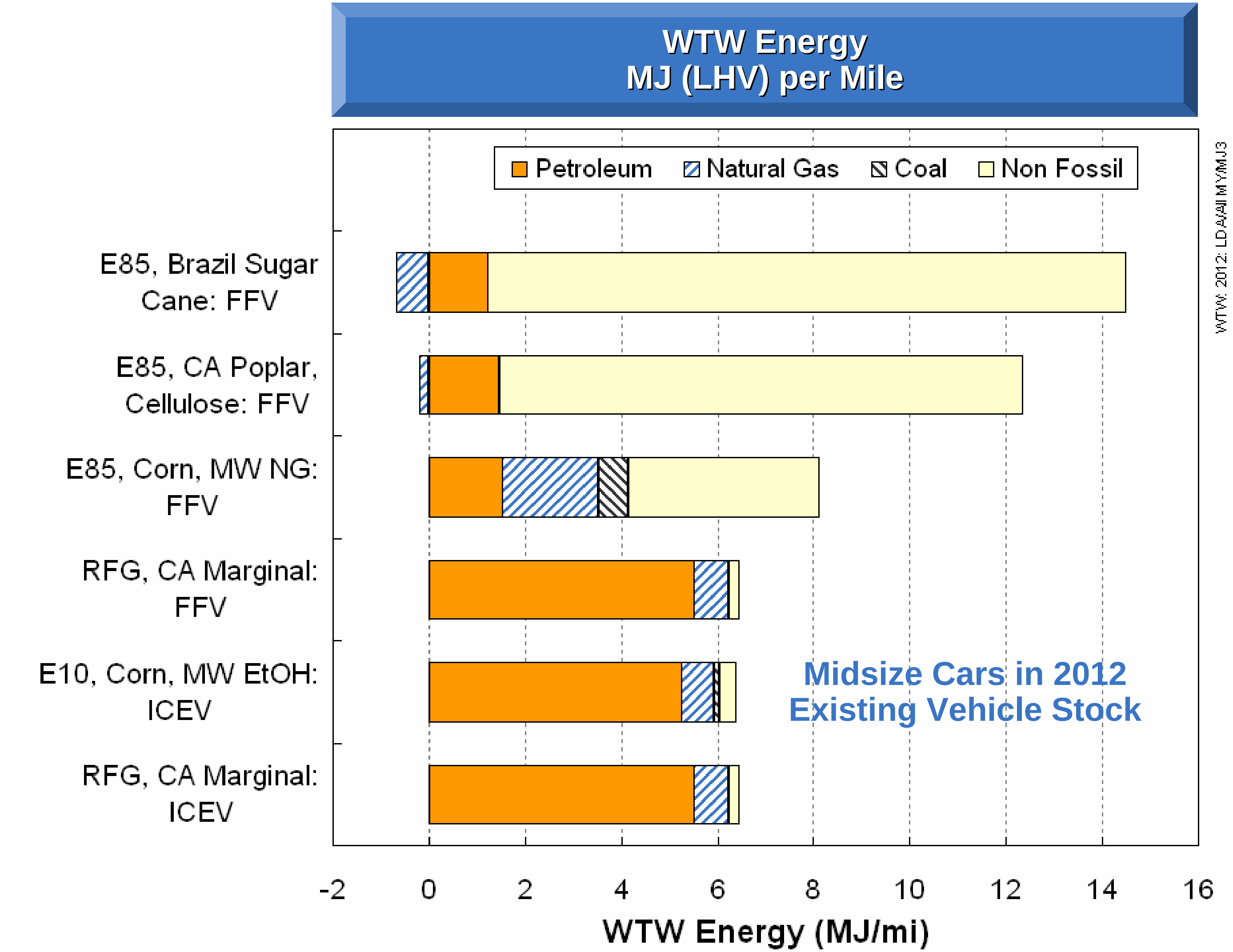
"Well to Wheels" Preliminary Observations Urban Buses

- Zero emission technologies provide largest GHG benefit depending on fuel and fuel pathway
- CNG provides GHG benefits comparable to hydrogen (local stream reforming) and methanol (remote natural gas)

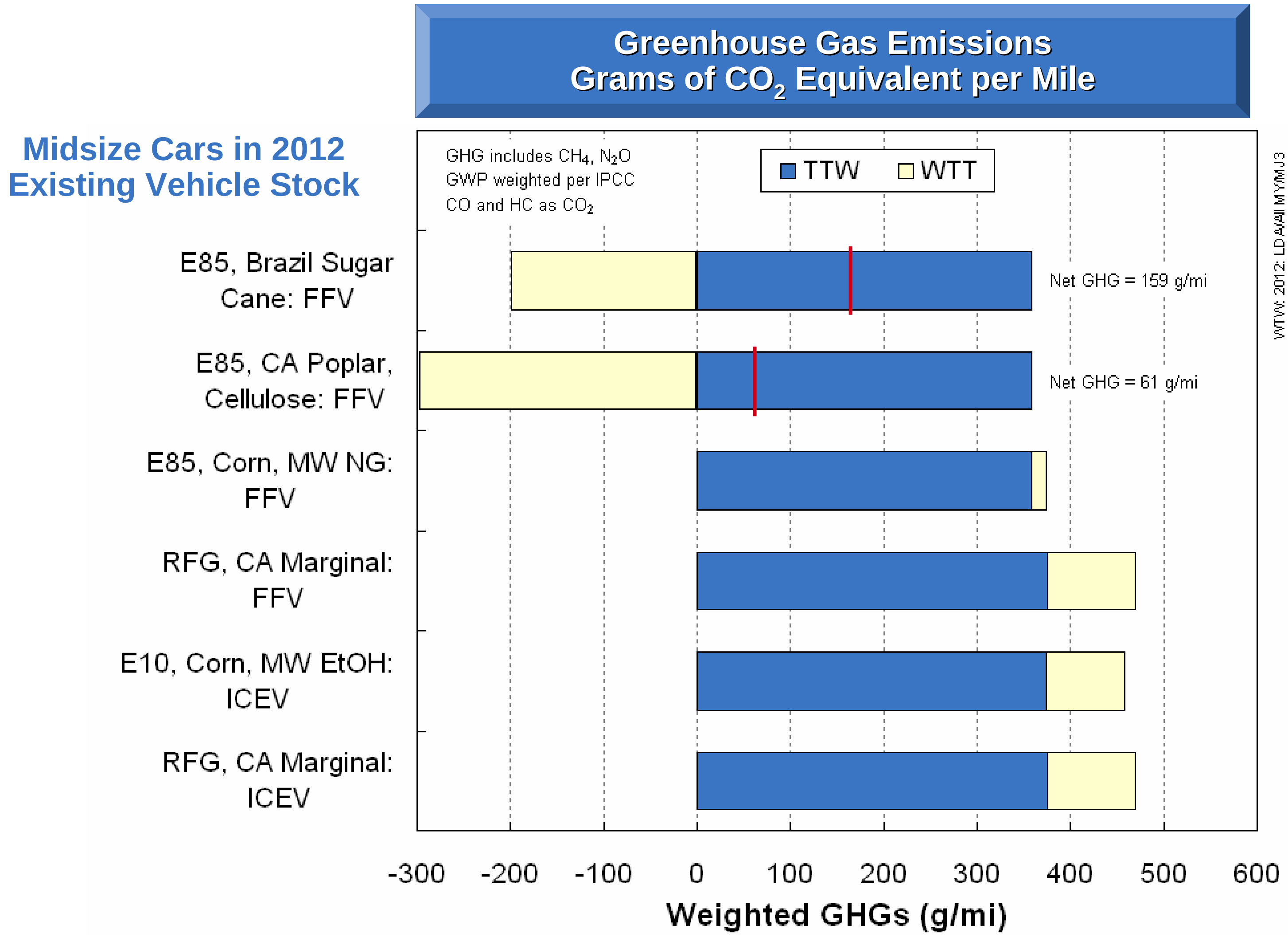
Fuel	GHG Benefit	Fuel	GHG Benefit
CNG	21%	Battery EV	48%
LNG	10%	Hydrogen Fuel Cell	22%
DME	(4%)	Methanol Fuel Cell	18%

- Criteria pollutants comparable to diesel for all alternatives
  - Hydrogen and electricity the lowest
  - High VOC for DME but like LPG could be controlled
  - High PM for electric drive technology questionable
- Toxic emissions dominated by diesel PM

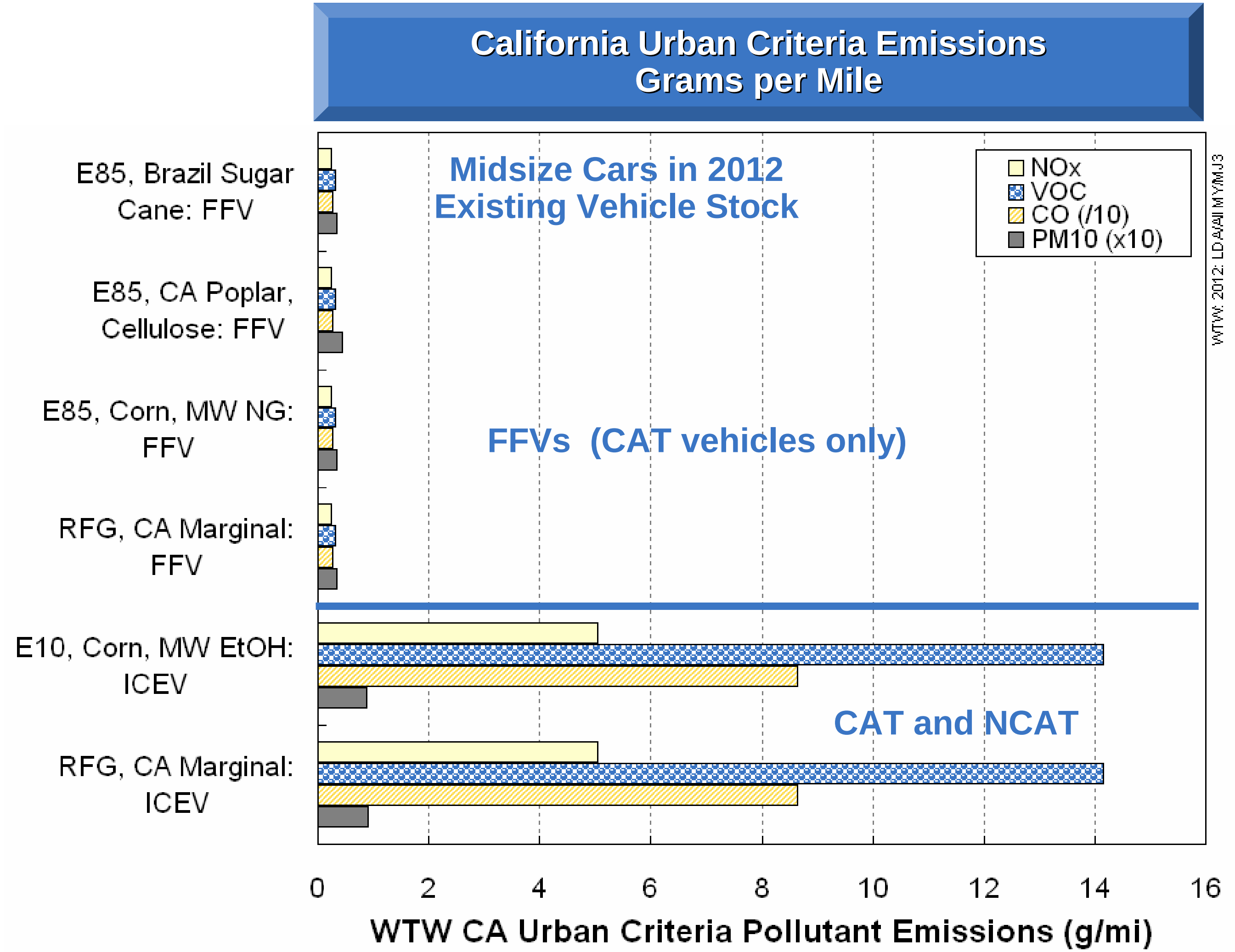
"Well-to-Wheels" Energy Comparison RFG Blending Options



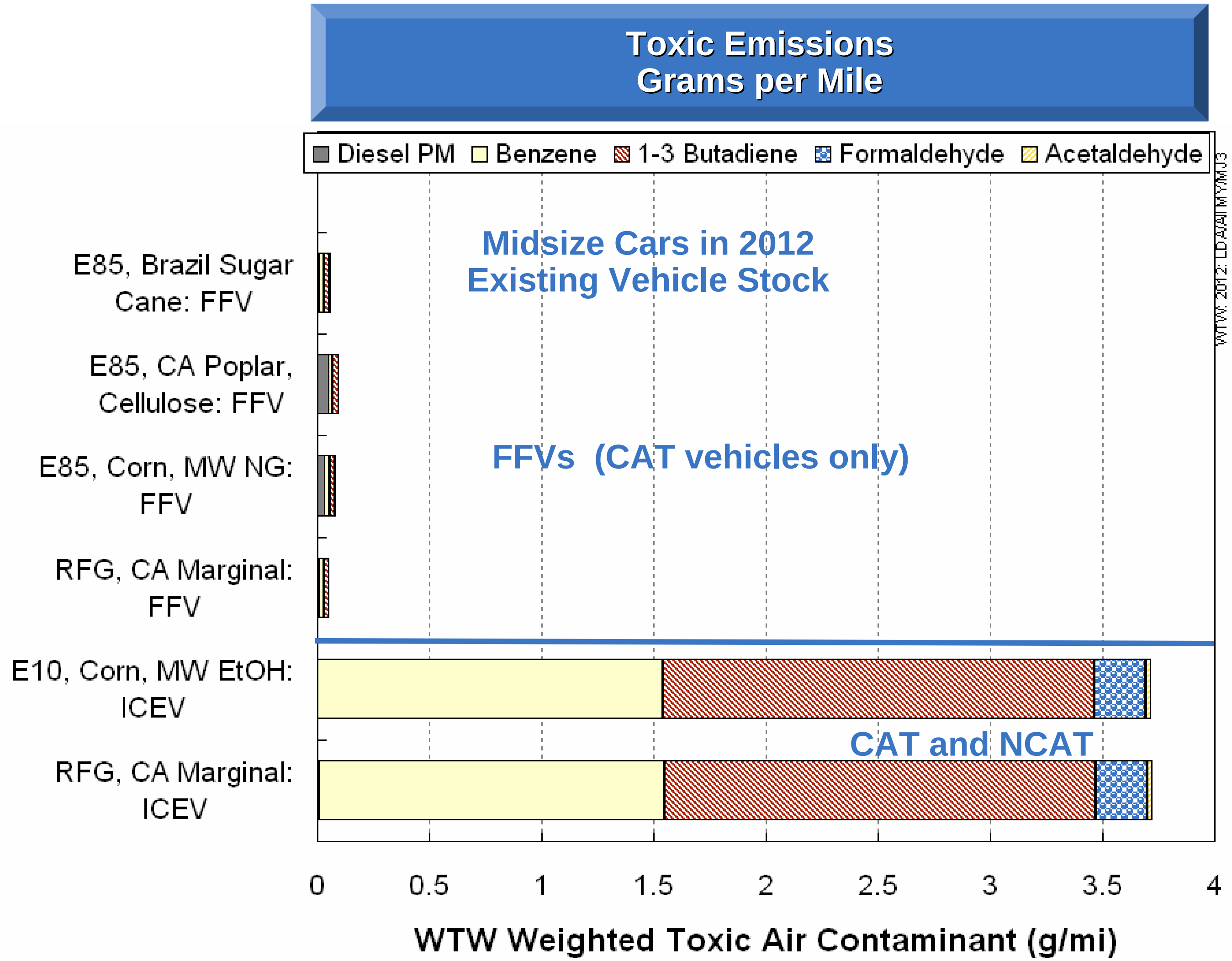
"Well-to-Wheels" GHG Emissions RFG Ethanol Blend Strategies



"Well-to-Wheels" Criteria Emissions RFG Ethanol Blend Strategies



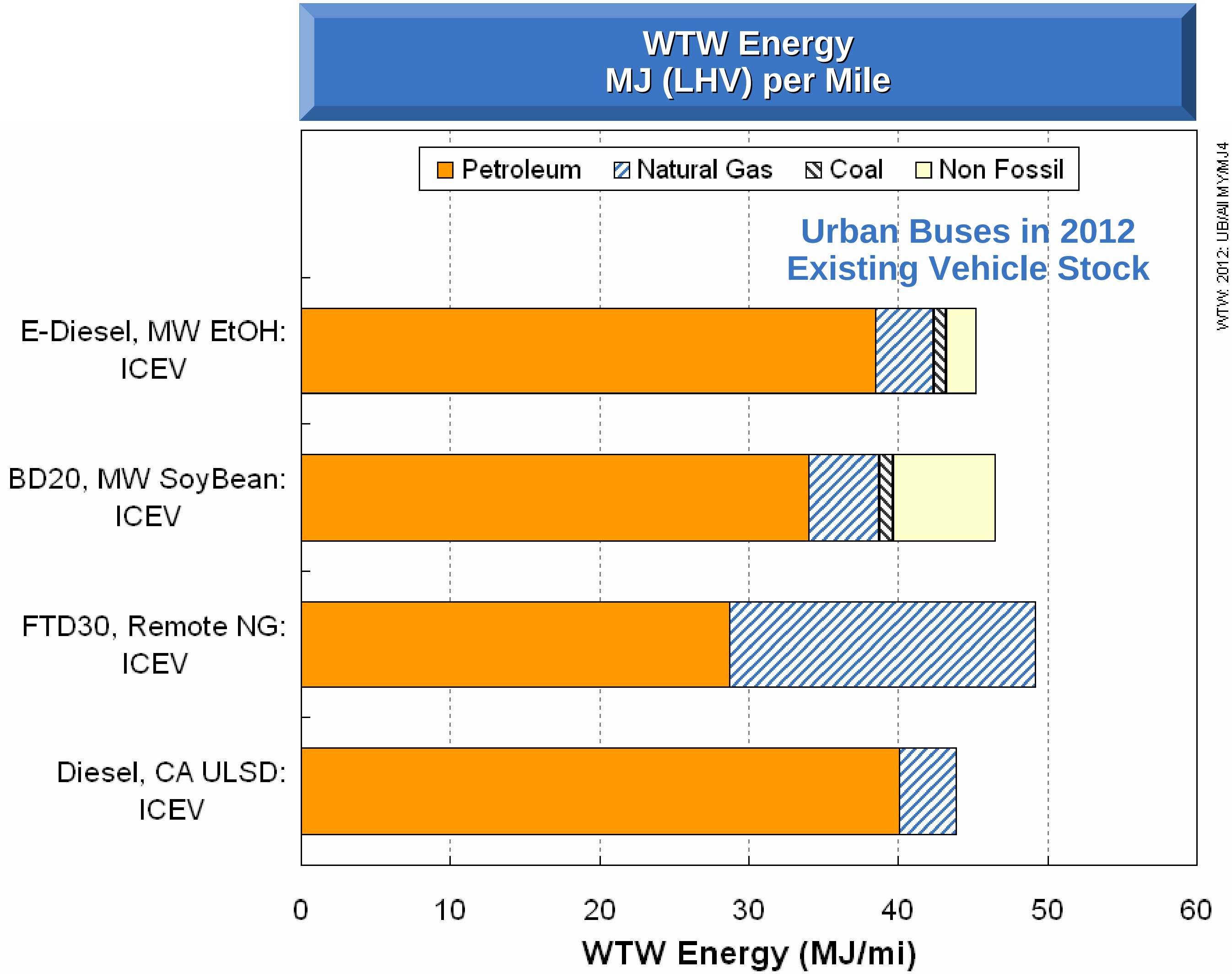
"Well-to-Wheels" Toxic Emissions RFG Ethanol Blend Strategies



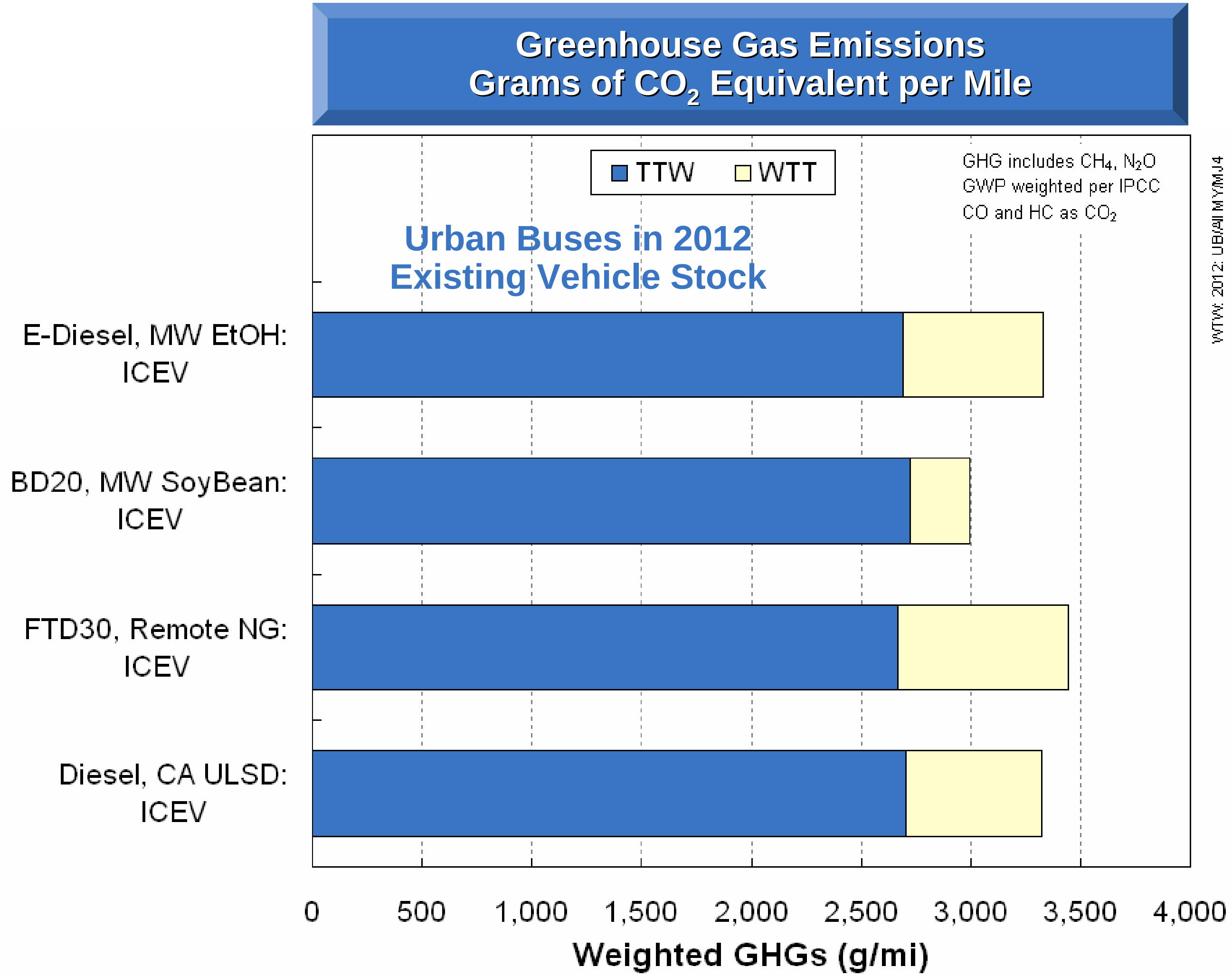
"Well to Wheels" Preliminary Observations RFG Ethanol Blends

- GHG benefits of gasoline blends depends on the carbon intensity of petroleum resources and ethanol blending component
  - E10 using corn based ethanol provides 2 percent GHG benefit compared to RFG at 5.7 percent by volume
  - E85 Blends with cellulosic or sugar cane ethanol reduce GHG emissions by 80+%
  - Criteria pollutant emissions comparable to gasoline
  - Toxic emissions also comparable to gasoline

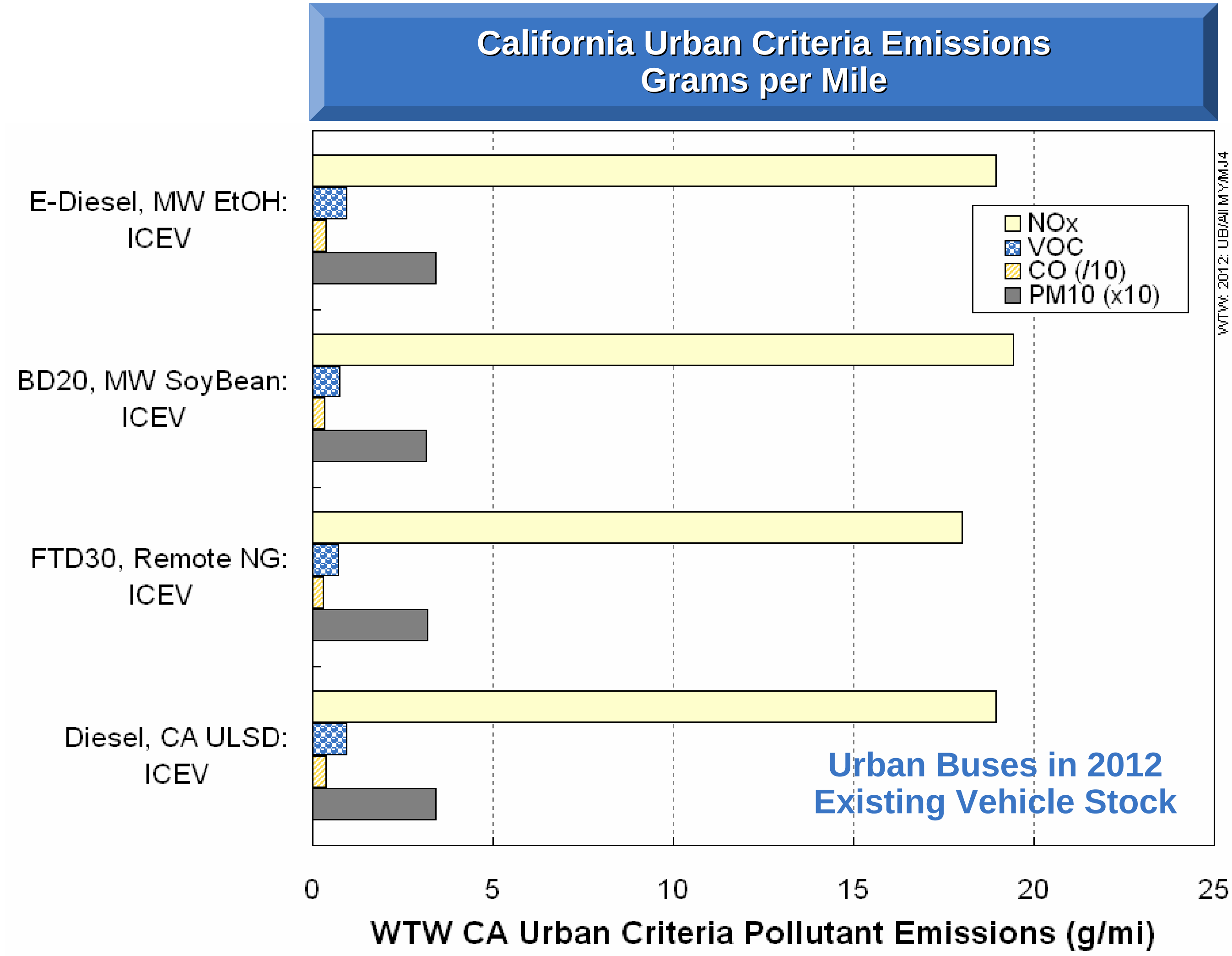
"Well-to-Wheels" Energy Comparison Heavy Duty Fuel Blends



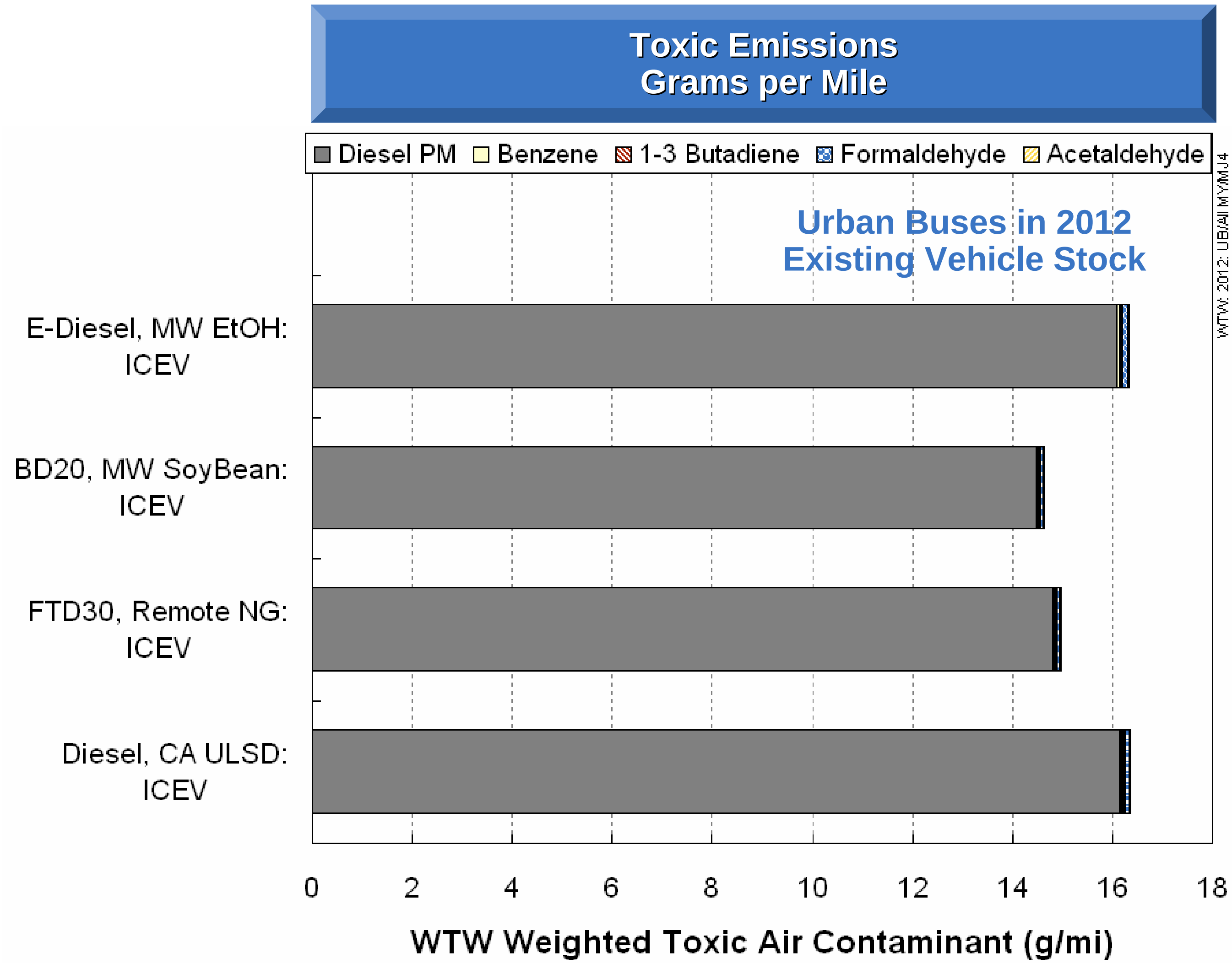
"Well-to-Wheels" GHG Emissions Heavy Duty Fuel Blends



"Well-to-Wheels" Criteria Emissions Heavy Duty Fuel Blends



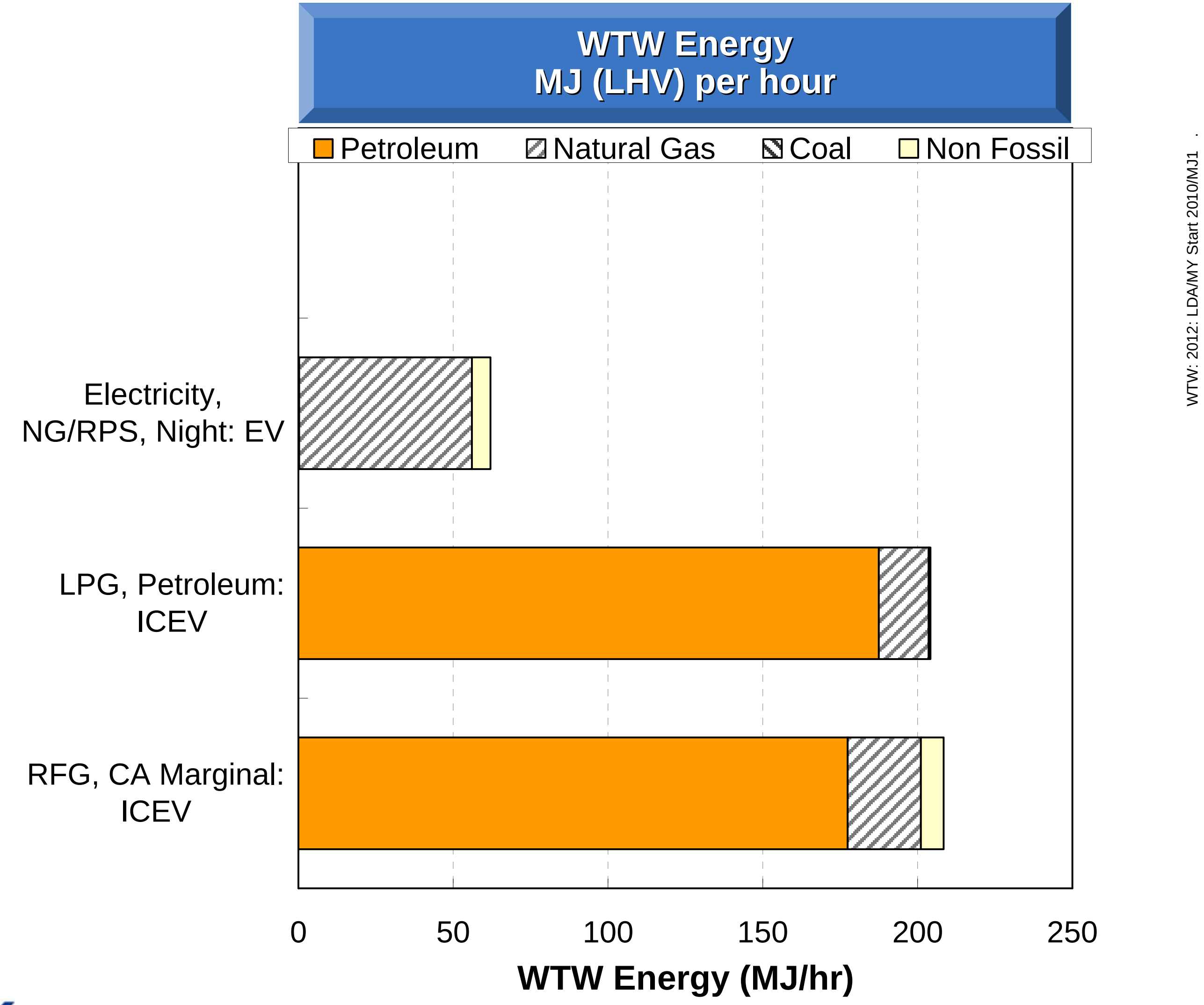
"Well-to-Wheels" Toxic Emissions Heavy Duty Fuel Blends



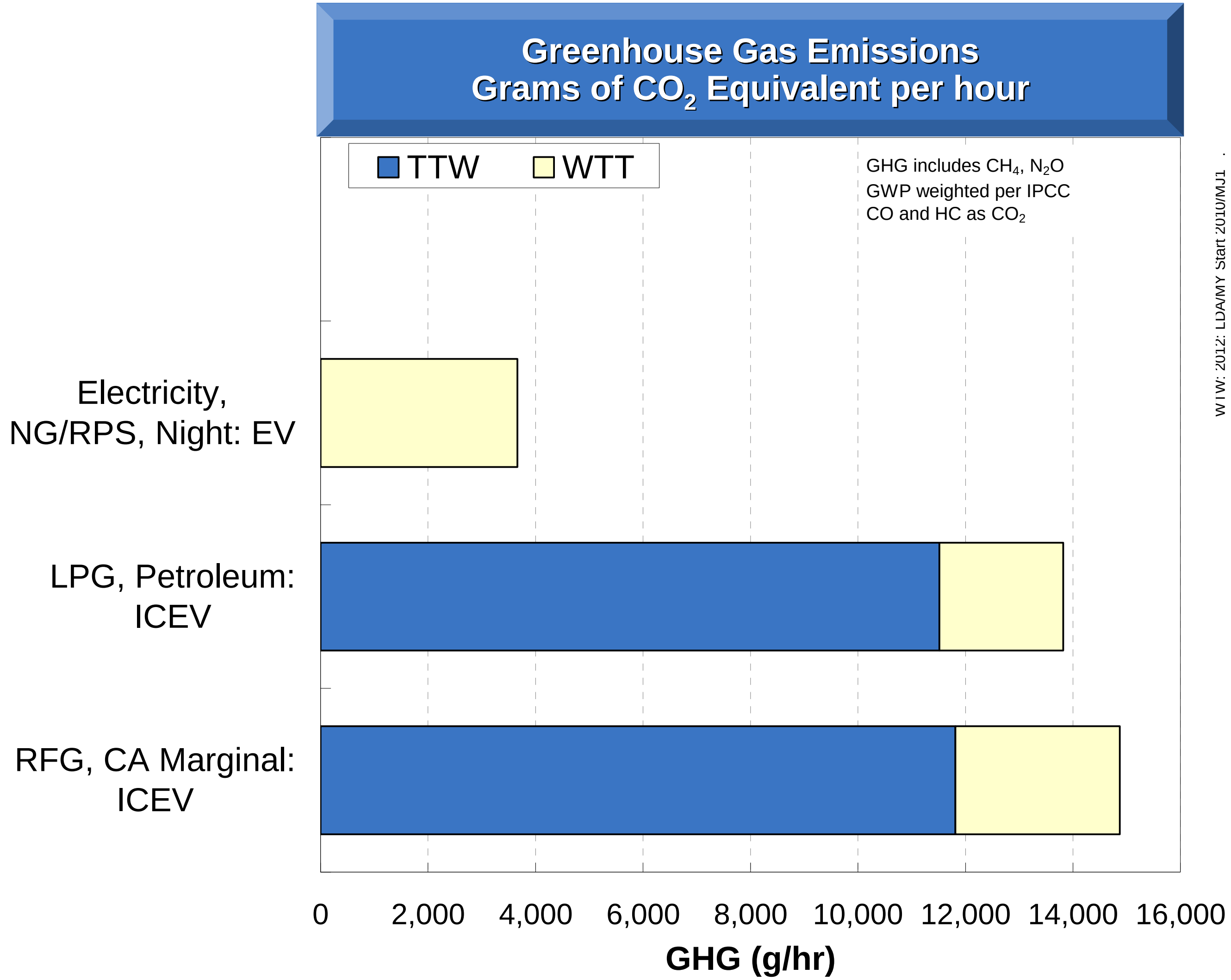
"Well to Wheels" Preliminary Observations - Diesel Fuel Blends

- Only BD20 provides a GHG emission benefit at about 10%
  - FTD30 and E-diesel comparable to California ULSD
  - Dedicated FTD100 engines could result in improved efficiency and GHG emission benefit
  - Need to account for any changes in land use for biodiesel
- All blends have comparable criteria emissions as California ULSD
- Toxic emissions slightly lower for BD20 and FTD30 and same for E-Diesel

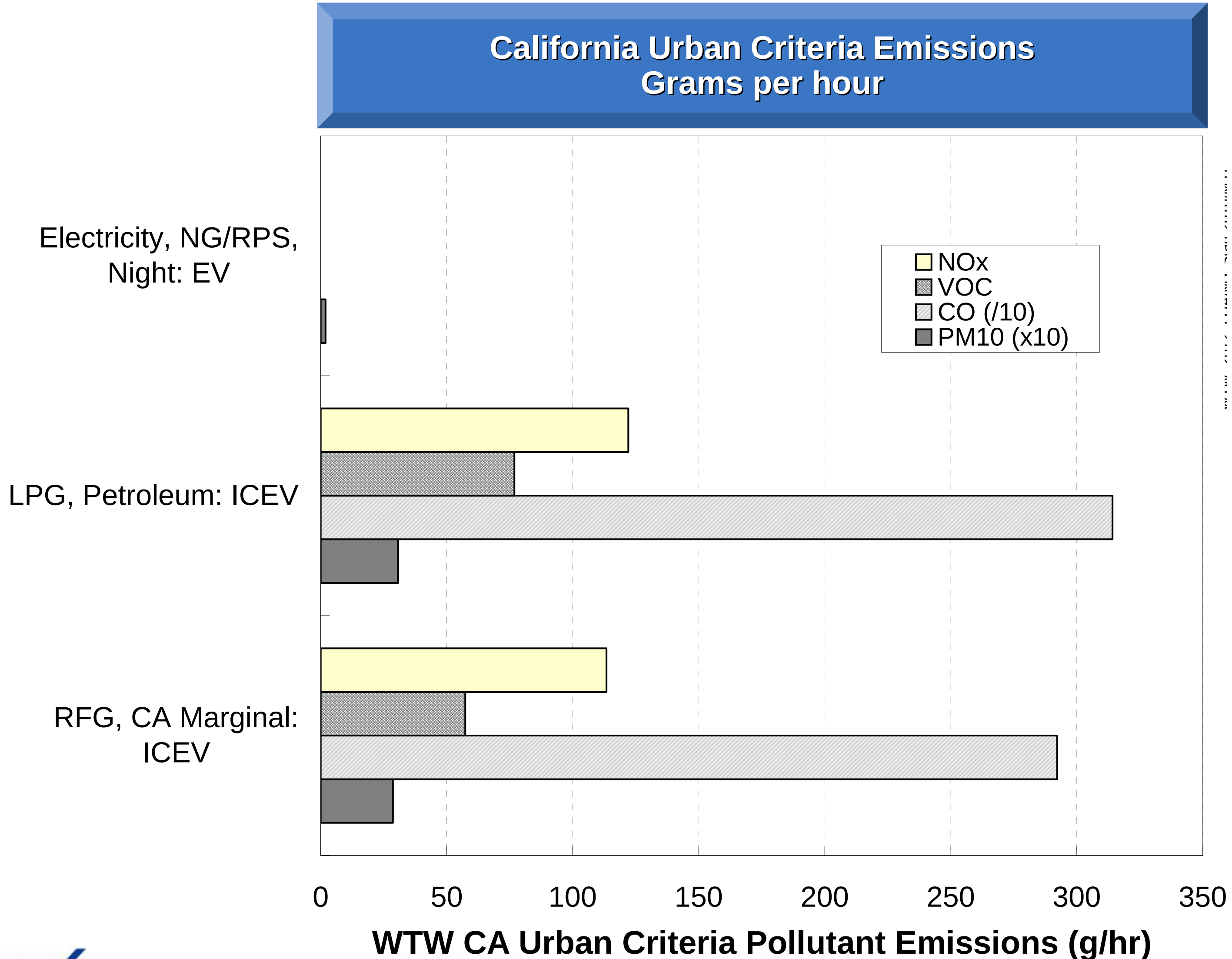
"Well-to-Wheels" Energy Comparison Forklift Application



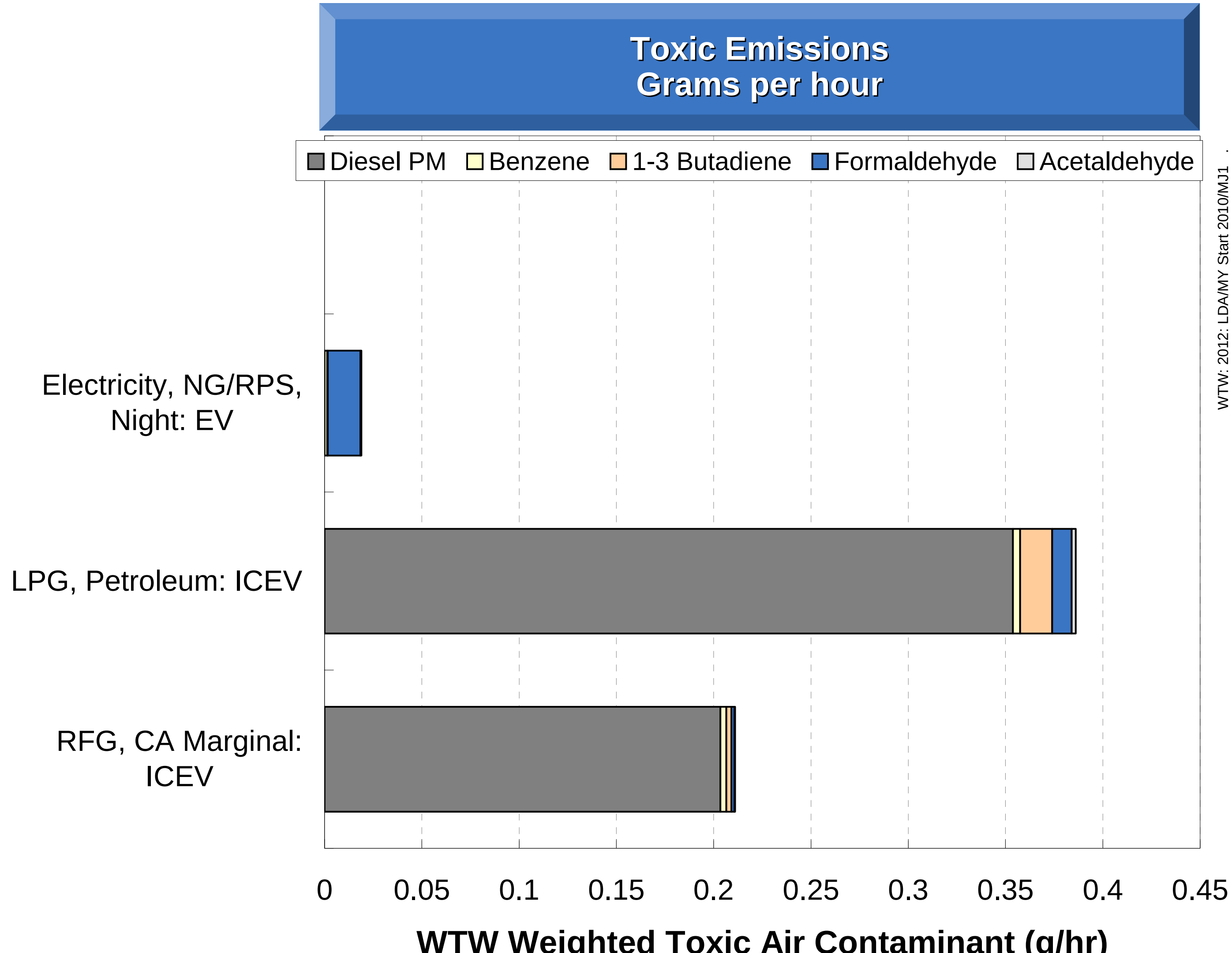
"Well-to-Wheels" GHG Emissions Forklift Application



"Well-to-Wheels" Criteria Emissions Forklift Application



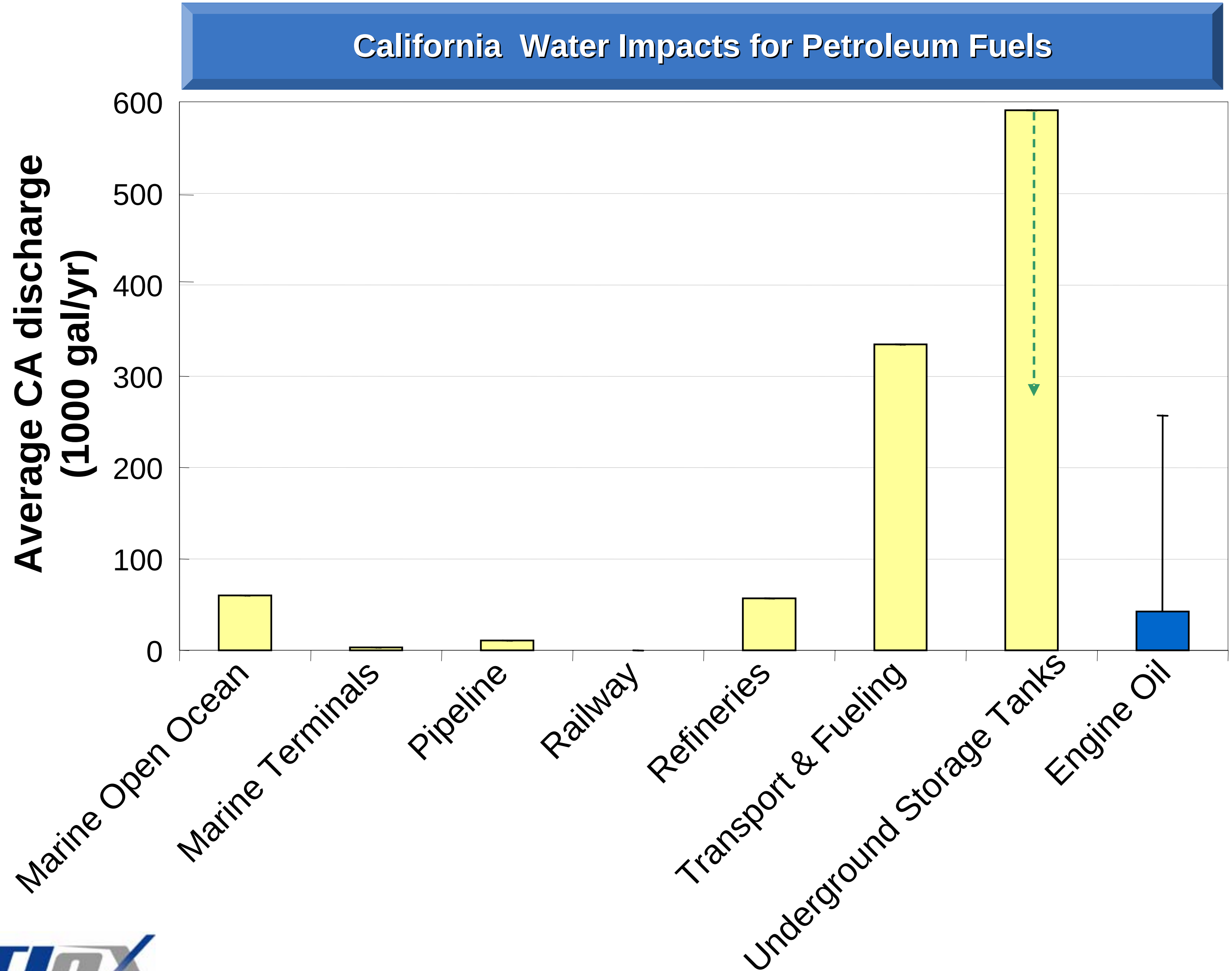
"Well-to-Wheels" Toxic Emissions Forklift Application



"Well to Wheels" Preliminary Observations - Forklift Application

- Electric drive forklift technology substantially reduces GHG emissions as well as criteria and toxic emissions
- Propane (LPG) and gasoline technologies about the same for criteria emissions
- Propane toxic emissions dominated by diesel PM

"Well-to-Wheels" Multi Media Impacts



"Well to Wheels" Preliminary Observations—Multi-Media Impacts

- Alternative pathways eliminate many sources of multi media impacts in the fuel delivery chain, for example gaseous fuels eliminate ocean, marine terminals, and underground tank discharges
- Engine oil pollution comparable spills from liquid fuel transport and fueling

1 Introduction

2 Methodology

3 Example Results—2010 Only

4 Summary

Alternative Fuels Provide Significant GHG Benefits in Midsize Autos but moderate or no Benefit in Urban Buses

- Depending on fuel pathway alternative fuels like ethanol, natural gas, LPG, electricity and hydrogen can provide significant reductions in well to wheels GHG emissions when used in midsize autos
  – Biofuels provide the largest reductions (80%+ compared to gasoline) depending on processing intensity since CO_2 emissions are recycled through plant photosynthesis
  – Low carbon containing fuels like natural gas and LPG also reduce GHG emissions (up to 27% compared to gasoline)
  – Zero carbon fuels/power also substantially reduced GHG emissions depending on fuel or power production technologies and pathways
    - Hydrogen produced from natural gas using steam reforming provides 42% reduction
    - Electricity in PHEV reduces GHG by 41%
- Similar reductions for urban buses with 21% reduction for CNG and 48% reduction for battery electric buses. DME slightly increases GHG emissions

Most pathways result in comparable emissions of criteria and toxic emissions for both midsize autos and urban buses

- For midsize autos alternative fuel pathways result in criteria emissions comparable to gasoline
  - LPG VOCs higher if refueling not controlled
  - Local biomass conversion (California cellulosic ethanol) increases PM emissions
  - Natural gas based hydrogen and electric pathways reduce criteria pollutants
  - Toxics dominated by diesel exhaust PM
- For urban buses alternative fuel pathways also comparable to diesel
  - Hydrogen and electric drive have lower emissions than diesel
  - Toxics dominated by diesel PM emissions and options roughly comparable

Gasoline and Diesel Fuel Blends Could be an Effective Strategy to Reduce GHG Emissions

- Higher ethanol blends in gasoline can be very effective for reducing GHG, criteria, and toxic emissions compared to gasoline if ethanol is produced from low GHG ethanol production pathways
  - Cellulosic feedstocks and sugar cane
- Only biodiesel provides an estimate GHG benefit compared to California ULSD. Biodiesel as BD20 is estimated to reduce PM, CO, and HC but will have a small impact on NOx

What are the Major Conclusions of the Full Fuel Cycle Analyses?

- Improved efficiency lowers GHG, criteria, and toxic emissions
  - Production
  - Distribution
  - End-use
- Electricity provides lowest overall impact on GHG, criteria, toxic emissions and water pollution
- Biofuels very effective at recycling carbon and providing low GHG emissions, but harvesting, collection, production, and fuel distribution can affect GHG and local emissions
- Neat fuel use provides greatest per vehicle GHG benefits
- Alternative fuel blends with existing gasoline and diesel fuels can also be an effective strategy to reduce GHG emissions

Thank you for your Attention

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