Air Quality Impacts of Changes in Emissions due to GHG Mitigation Strategies

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UNIVERSITY of CALIFORNIA · IRVINE

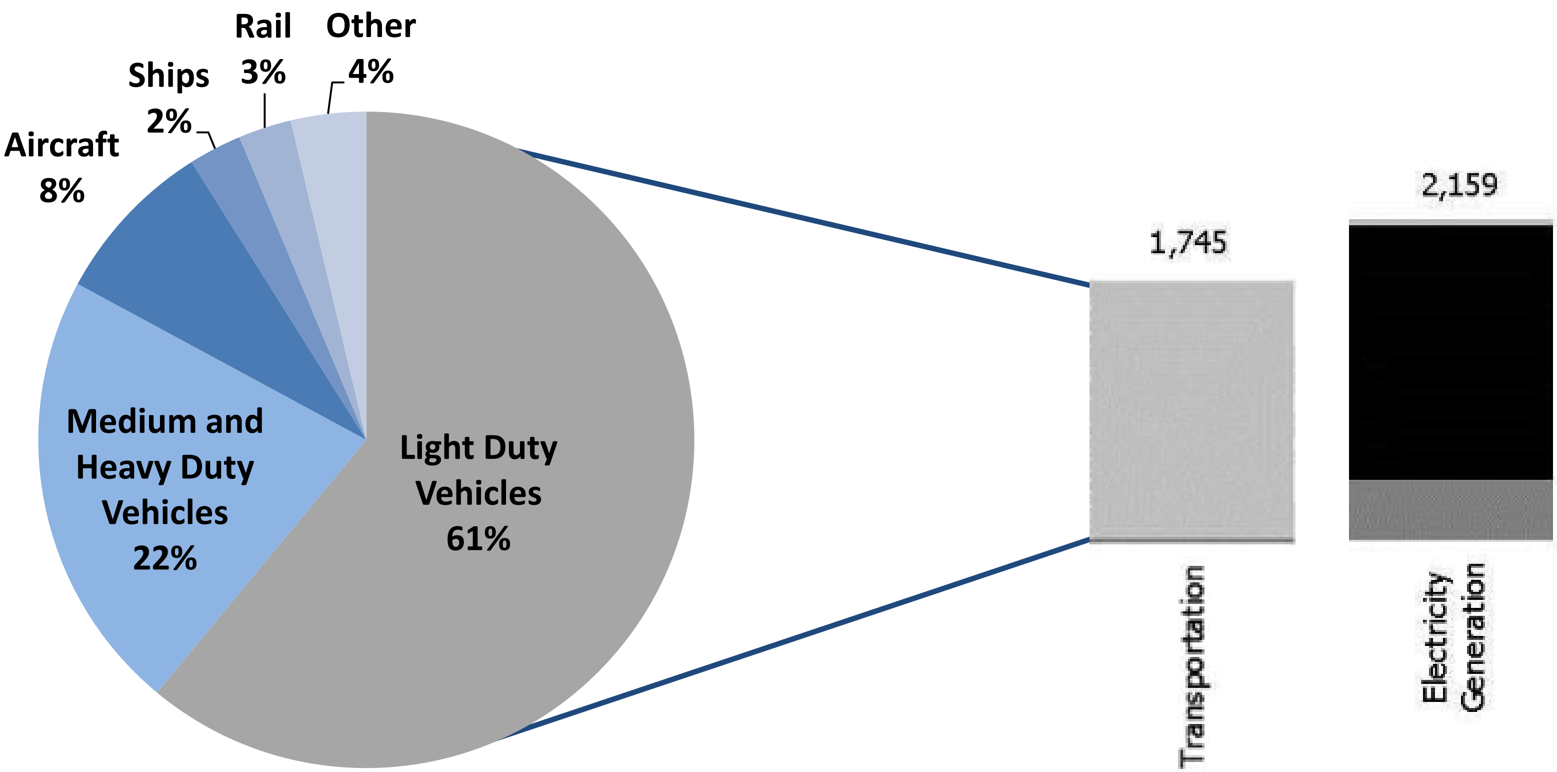
Outline

- Introduction & Motivation
- Methodology
- Results
- Conclusion

U.S. Energy Emissions

Energy technologies central to U.S. GHG and pollutant emissions

- 86% of domestic GHG emissions[1], > 90% of anthropogenic NO_x , SO_2 [2]
- Emissions dominated by fossil fuel use in power generation and transportation
    - LDV sector responsible for 61% of transportation GHG emissions



Source(s):

[1] U.S. EPA 2013

[2] U.S. EPA 2005

Literature Review: Power Sector

Life cycle GHG emissions dependent on fuel/conversion pathway

– Traditional Coal: 687-1689 $gCO_2eq/kWhr$ (Average: 944) [1-8]

Strategy		GHG Reduction [Average Coal]	Potential AQ Impact	Reference(s)
Gas-Fired Power		28-76%	**+/- : introduce emissions, improvement from coal**	[1-4, 9-13]
Nuclear Power		77-99%	**+++: high benefits**	[3, 4, 9, 11, 14-20]
Renewable Power	Wind	96-99%	**++/-: emissions free but can have impacts system-wide with emission consequences**	[3, 4, 10, 11, 21-31]
	Solar PV	89-98%		[4, 30, 32-40]
	Solar CST	74-99%		[41-46]
	Biopower	62-163%	**++/--: pathway dependent**	[3, 30, 47-64]
	Geothermal	94-99%	**++: emissions free**	[4, 27, 65, 66]
	Ocean	94-99%	**+/-: likely positive, uncertain**	[27, 67, 68]
CCS	Coal (PC)	50-94%	**+/--: Pathway specific, Potential increases from efficiency penalty**	[6-8, 73-76]
	NG	59-88%		[7,8, 73-75]
Efficiency Gains	Generation	2.5-3.7%**	**+: will reduce emissions**	[77-85]
	Transmission	1-4.3%**		
	End-use	7.6-30%**		

** denotes a reduction in total demand for power

Literature Review: Transportation (LDV)

Life cycle GHG emissions dependent on:

– Vehicle propulsion efficiency, utilized fuel, and production pathway

Strategy	Technology	GHG Reduction [Avg. gasoline]	Potential AQ Impact	Reference(s)
Efficiency	Conventional	5 to 50%	**+ : reduce emissions**	[1-9]
Efficiency	HEVs	37 to 87%	**+ : reduce emissions**	[1-3, 7, 8, 10, 11]
Hydrogen	FCEVs	14 to 99%	**+++/- : Dependent on the chosen supply chain**	[1, 3, 7-24]
Electricity	PHEVs	15 to 68%	**+++/- : Dependent on the chosen supply chain**	[1, 3, 7, 8, 10, 11, 25-31]
Electricity	BEVs	28 to 99%	**+++/- : Dependent on the chosen supply chain**	[1, 7, 8, 10, 11, 32, 33]
Biofuels	Corn Ethanol	+93 to 67%	**+/- - : Dependent on life cycle and direct vehicle emissions**	[4, 7, 11, 34-41]
Biofuels	Cel. Ethanol	+50 to >100%	**+/- - : Dependent on life cycle and direct vehicle emissions**	[3, 4, 7, 11, 35, 37, 39, 42-46]
Modal Shift	Various	0.4-2%	**+: will reduce vehicle emissions**	[47-50]

Alternative Energy Strategies

Power Generation

Efficiency

Transportation (LDV)

Renewables

Biopower

Nuclear

Carbon Capture (CCS)

Climate Change

Air Quality

Alter emission patterns

- Spatially & temporally

Impacts?

Natural Gas

Hydrogen Fuel Cells (FCEVs)

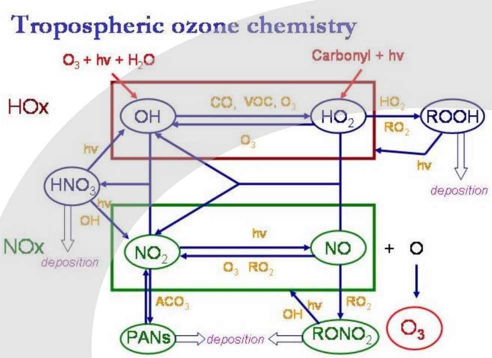
Electric Vehicles

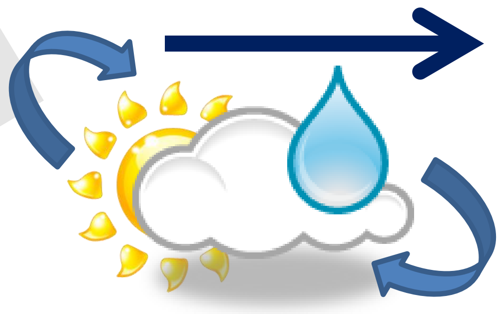
Biofuels (Ethanol)

Modal Shift

Assessing AQ Impacts

Atmospheric Chemistry + **Dilution/Mixing/Transport** = **Ambient Concentrations**





Deposition

+

[Ozone]

[Particulate Matter]

Emissions

NO_x VOC PM SO_2 CO

Solely quantifying emissions neglects atmospheric impacts

Robust assessment includes simulations of atmospheric chemistry/transport

- Requires spatial and temporal emissions data

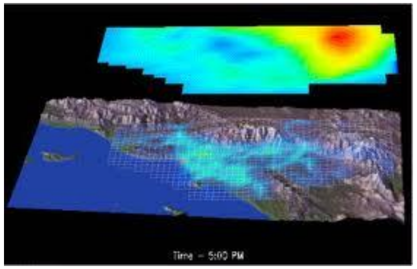
Effects on Receptors

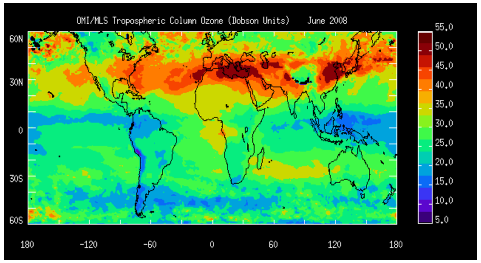
Morbidity & Mortality

Motivation

Problem Statement

- Climate change concerns influencing shifts to alternative technologies and fuels in major energy sectors
  - Transition will alter direct pollutant and GHG emissions
    - Quantity, composition, spatial and temporal patterns
- Emission perturbations directly influence future AQ
  - Formation and fate of atmospheric chemical species of concern for human health
    - Ozone (O_3) and fine particulate matter ($PM_{2.5}$)





Goal

- Investigate future (2055) GHG and AQ impacts of transitions to alternative energy pathways
  - Identify and characterize opportunities to maximize co-benefits while avoiding any unforeseen costs

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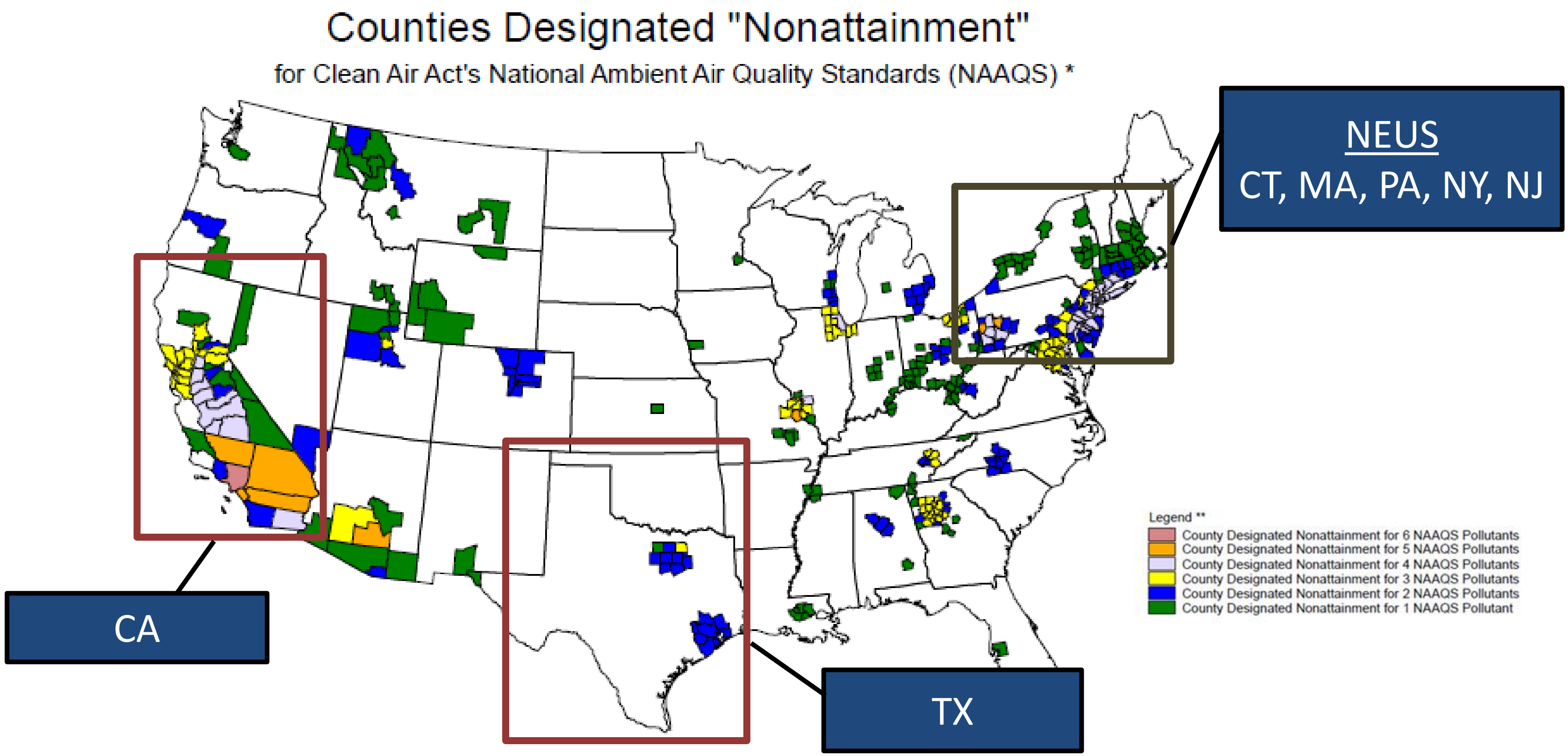
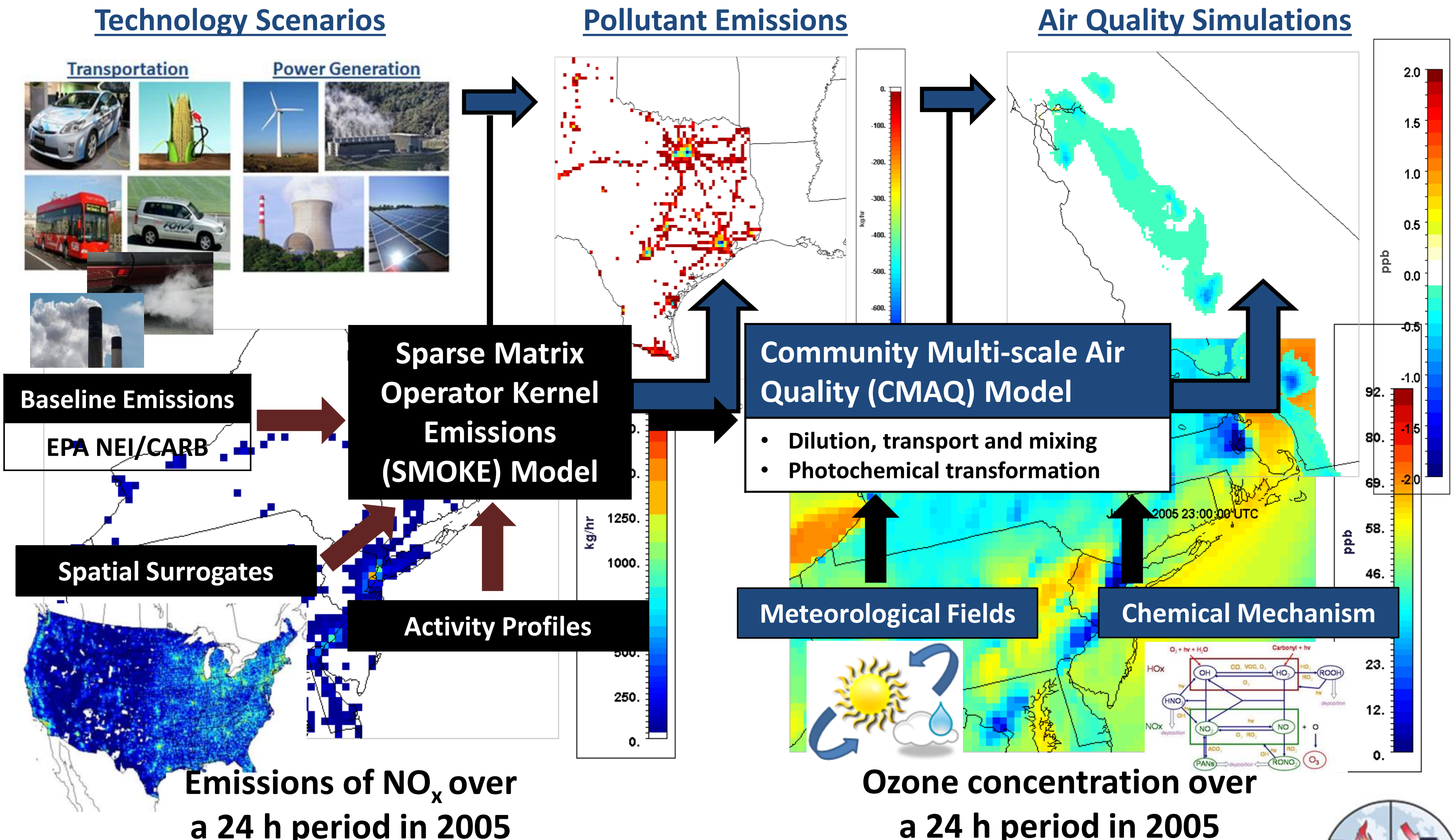
Regions of Interest



<u>Region selection focused on:</u>

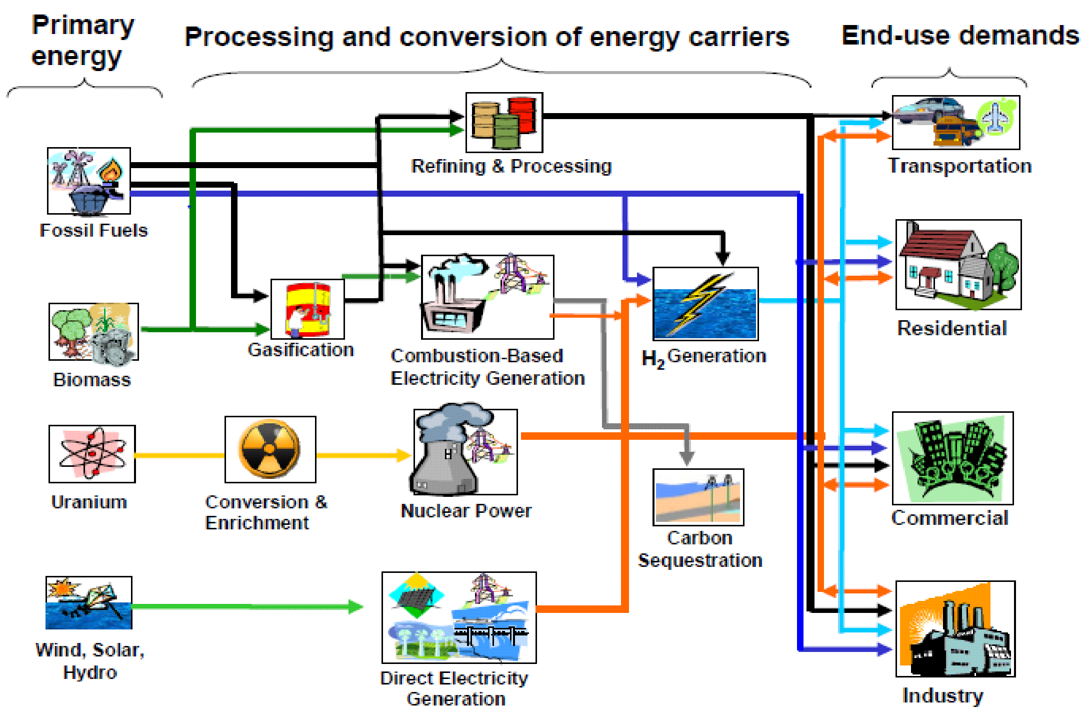
- Existing and expected future AQ challenges
- Variation in regional sources to facilitate comparison and identify trends
- Current/expected focus on GHG mitigation and alternative technology deployment

Methodology



Methodology: Base Case

- Characterize and assess baseline (Base Case) AQ in 2055
  - Prediction of future emissions difficult due to uncertainties underlying drivers
    - Technology advancement, regulatory changes, energy prices, economic growth, weather
  - **MARKet ALocation (MARKAL) model →EPA**
    - Represents energy system evolution to targeted horizon (2055)
    - Calibrated to U.S. Energy Information Administration Reference Case

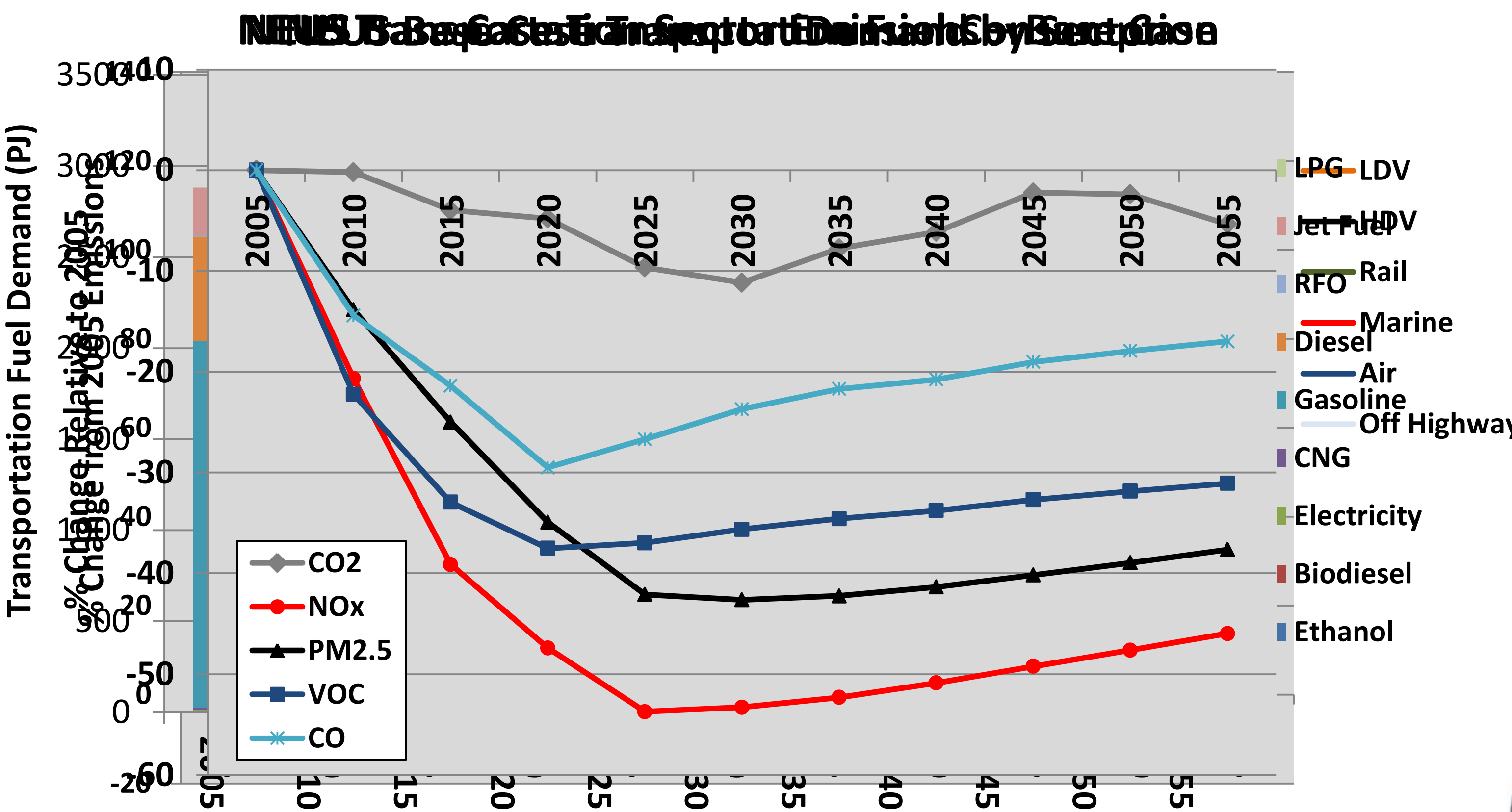


Source: Loughlin et al. 2011

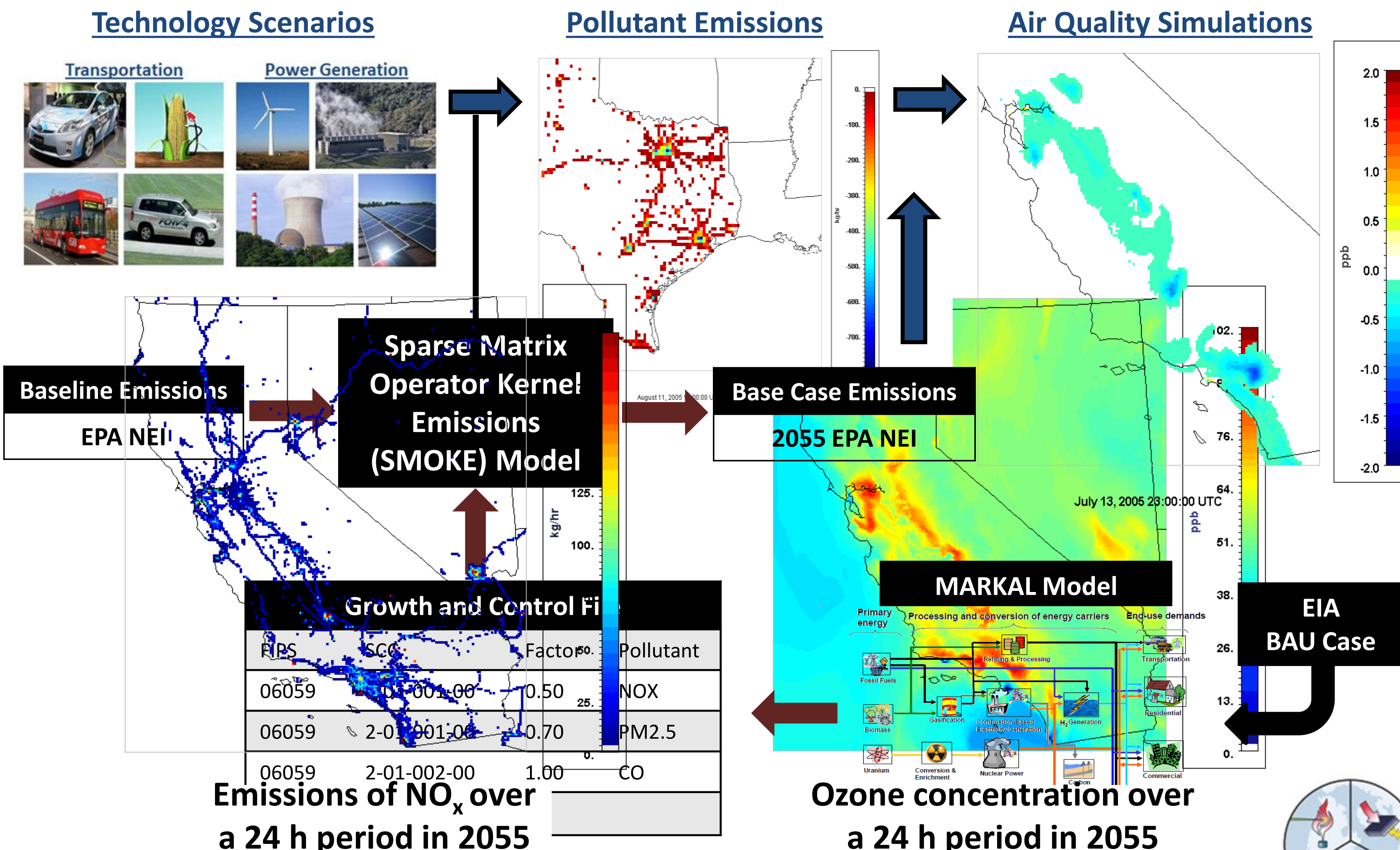
Methodology: Base Case

Justifiably project emission evolution in response to major drivers

- Sector and sub-sector energy demand growth
- Advancement and selection of technologies and fuels to meet demands
- **Emissions from utilized technologies and fuels**



Methodology: Base Case



FIPS	SCC	Factor	Pollutant
06059	2-01-001-00	0.50	NOX
06059	2-01-001-00	0.70	PM2.5
06059	2-01-002-00	1.00	CO

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Air Quality Impacts of FCEVs

Hydrogen Fuel Cell Vehicle Deployment Modeling

- Hydrogen can be generated from a wide range of pathways
  - Reformation (SMR, ATR), Gasification, Electrolysis
  - Delivery methods
    - On-site production, Truck delivery, Pipeline delivery
- Electric load increase depends on production/delivery method:
  - Low(SMR) to high(electrolysis)

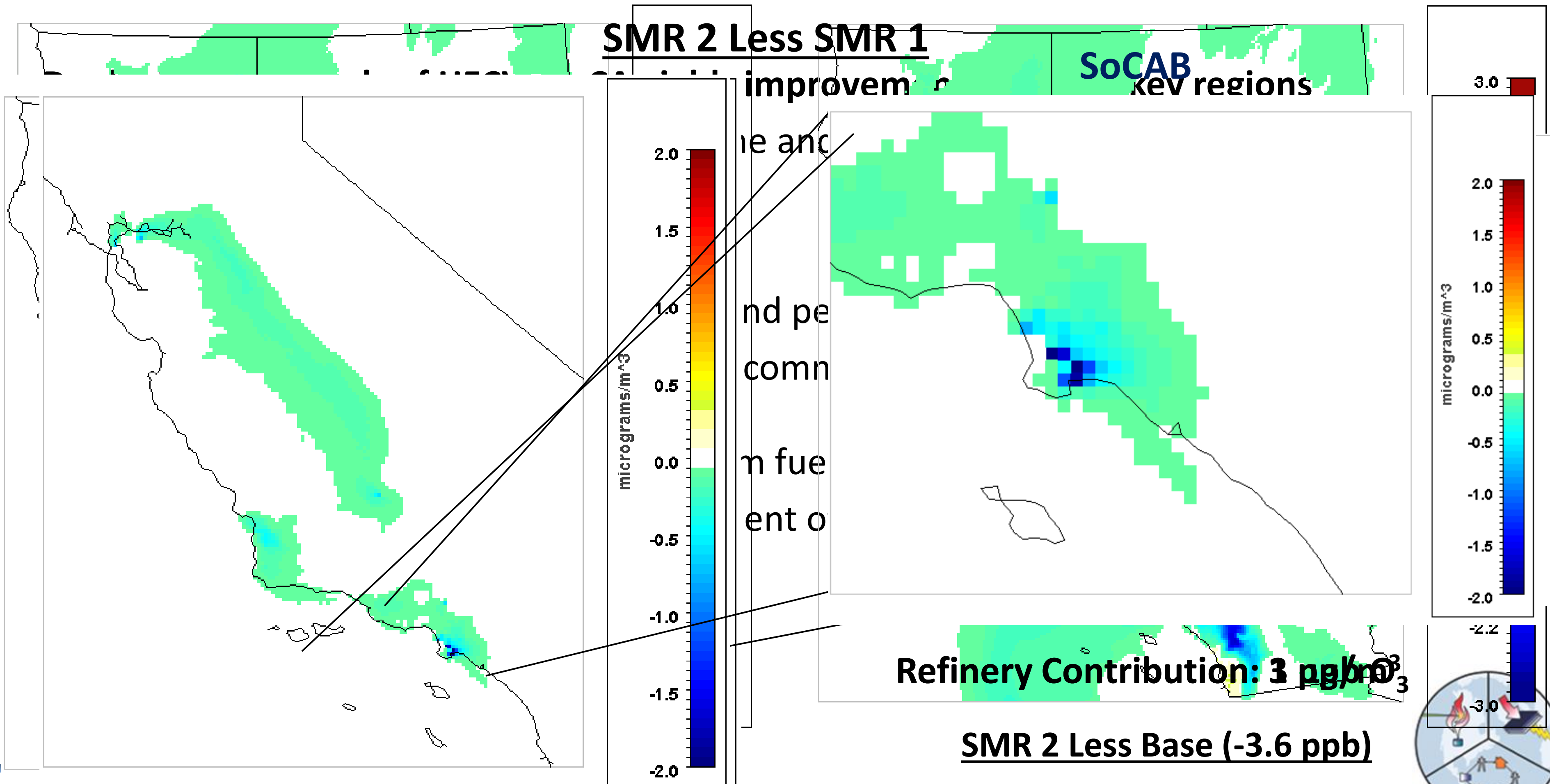
Emissions and AQ Modeling of Deployment Scenario

- **Direct vehicle emissions reduced from conventional fleet**
- **Novel emissions from production/delivery pathways added**
  - **Vary in spatial and quantitative impact e.g., SMR plant vs. grid for electrolysis**
  - **Delivery method important → HDV vs. pipeline**
- **Potential for reduction in petroleum fuel infrastructure emissions**
  - **Uncertain due to socio-economic factors → both cases evaluated**

Air Quality Impacts of FCEVs

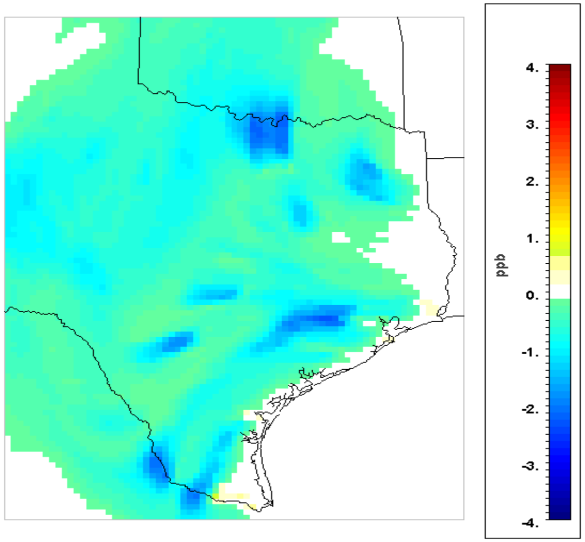
Two Cases of Hydrogen Fuel Cell Vehicle Deployment in 2050 (SMR 1 and SMR 2)

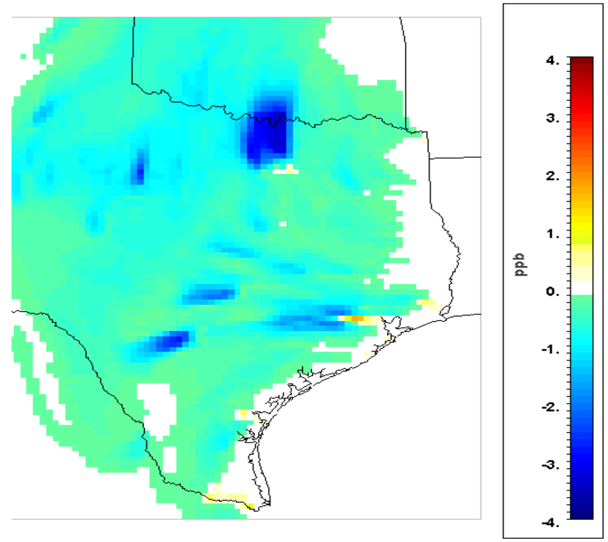
- Both Cases have been adjusted to account for vehicle emissions (-74%), power sector emissions (+ 0.005%), and the addition of SMR plant emissions
  - For the SMR 2 Case petroleum refinery emissions (-25%)



Transportation Sector O_3 Impacts

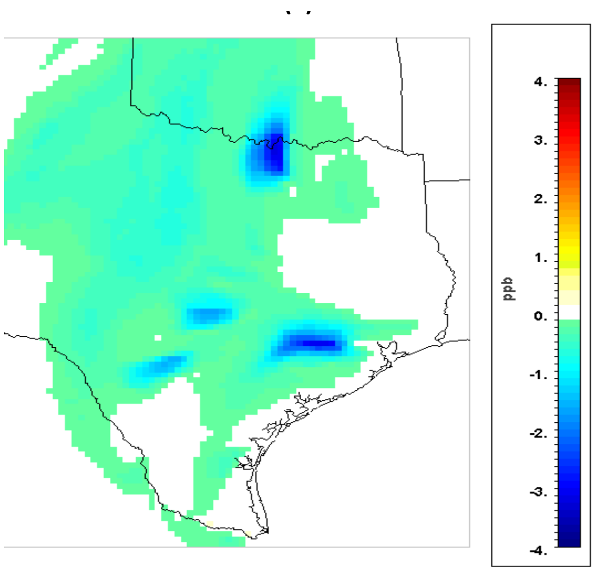
Light Duty
Vehicles
-2.4 ppb

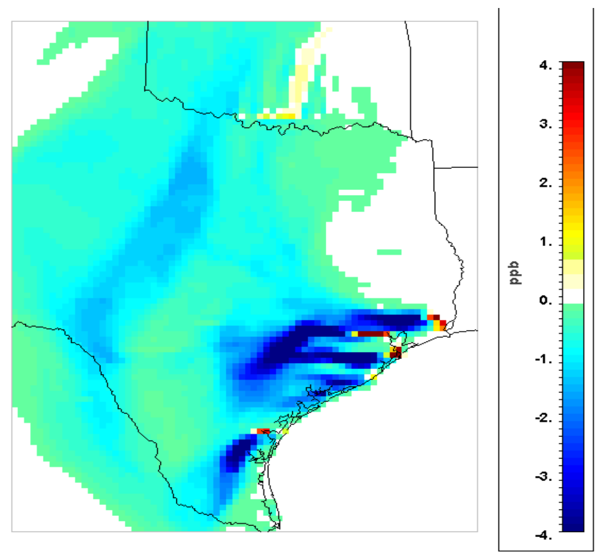




Heavy Duty
Vehicles
-2.6 ppb

Offroad
-3.3 ppb





Marine & Rail
-4.3 ppb

Air Quality Impacts of Cold Ironing OGVs

Provision of shore-to-ship power important mitigation strategy

- Auxiliary engines at berth comprise significant fraction of total OGV & Port emissions
  - Power needs can be provided by vessel linkage to shore → grid, distributed tech.

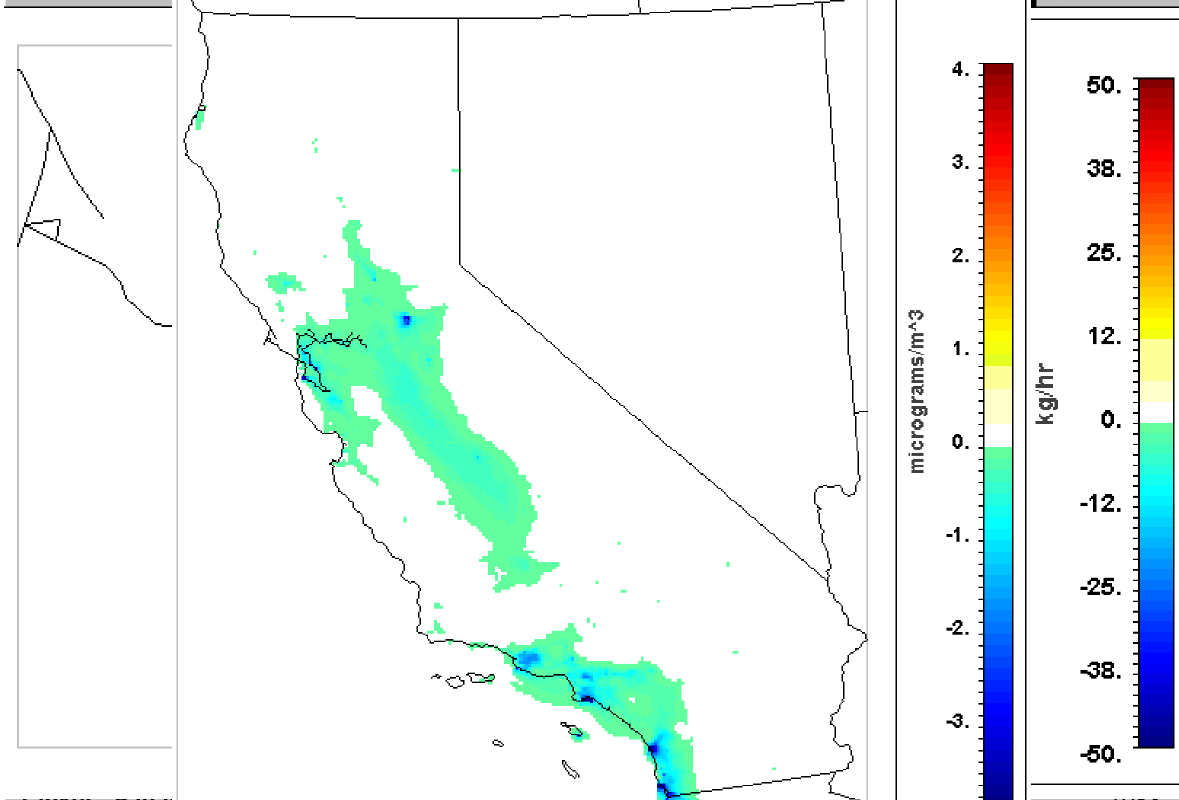
Requires projection of:

1. Port activity: vessel calls/types
2. Electricity requirements
3. Emission impacts
   - **OGVs ≈ - 18 to 45%**
   - **Power ≈ + 0.25%**

For major ports in CA:

- Long Beach/L.A.
- Oakland and Bay Area (4)
- San Diego
- Hueneme

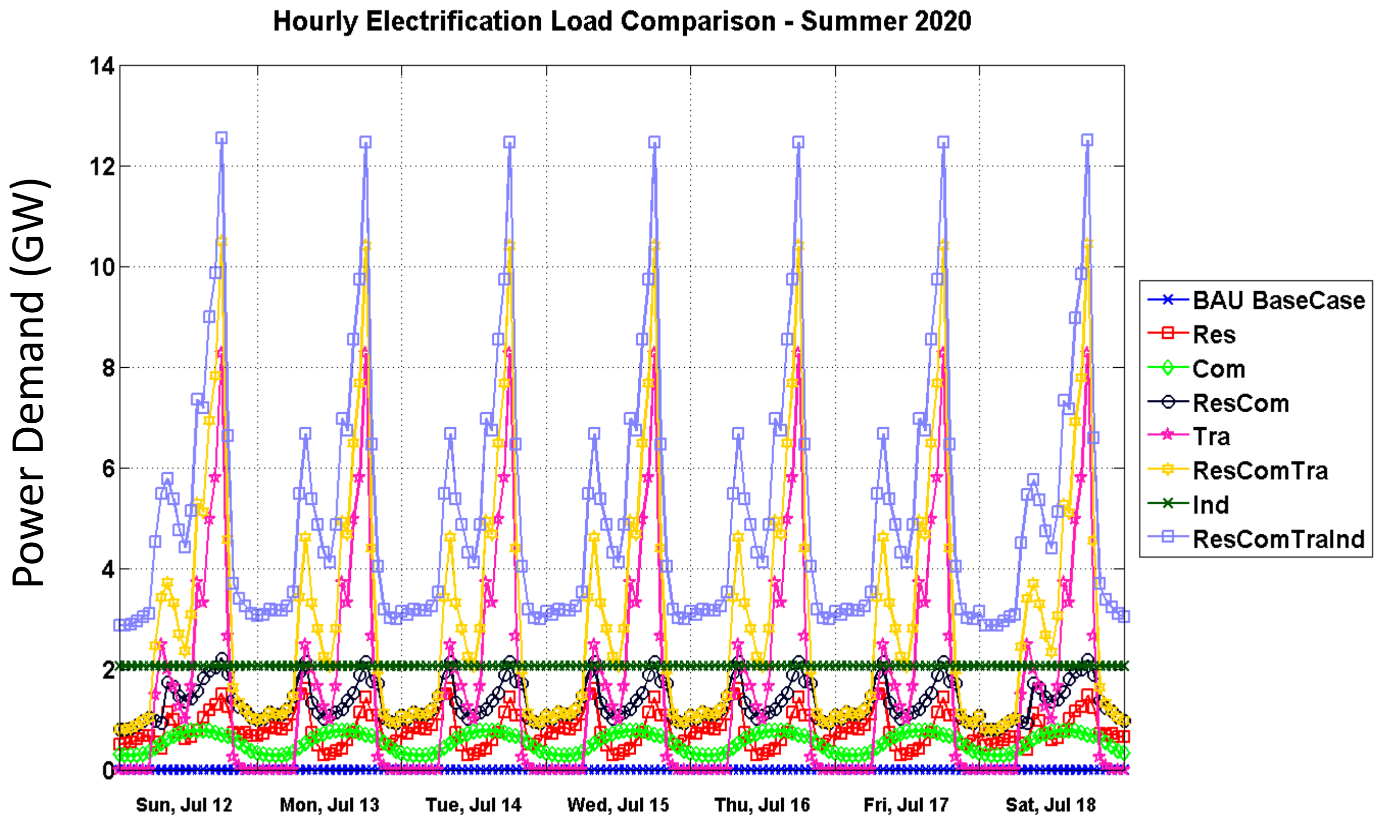
Vessel Type	Vessel Calls	Average Auxiliary Engine Size (kW)	Average Time at Berth (hours)	Auxiliary Engine Load Factor	Total Power (kW-hr)
Auto Carrier					1961
Tanker - Panai…					1038?
Total					*119418*



AQ Impacts of Renewable Resources and Electrification

AQ and GHG impacts of increasing renewable generation in tandem with electrification of additional sectors in CA

- Grid modeling platform: HiGRID in combination with Plexos
  - **Consideration of T & D requirements, dynamics, complementary strategies, etc.**
- Potential implementation scenarios for electrification in various sectors
  - **Residential, Commercial, Industrial, Transportation**

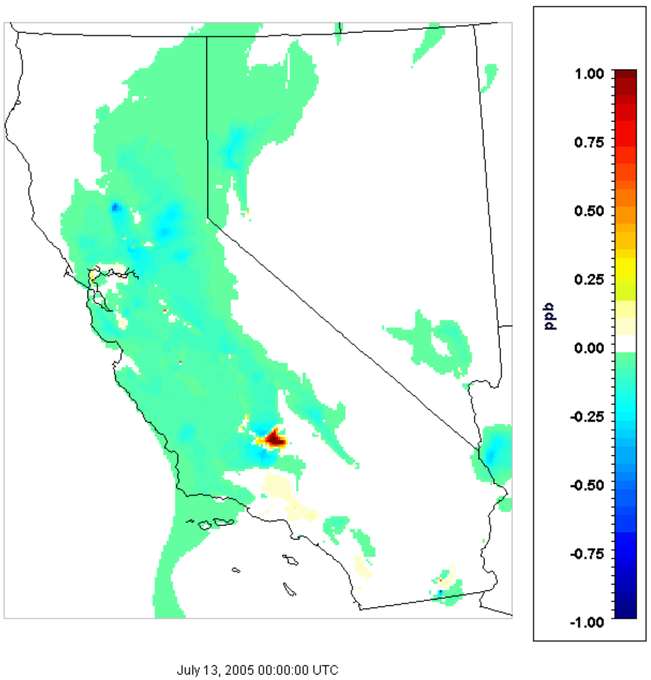


AQ Impacts of Renewable Resources and Electrification

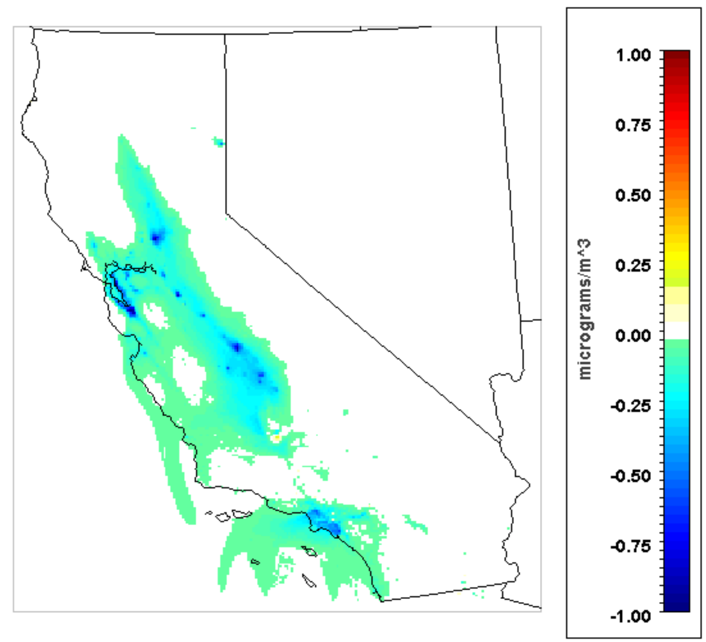
AQ impacts vary (+ and -) spatially and in magnitude

- Emission reductions from energy sectors yield moderate improvements
  - Generally occur with larger spatial distribution
  - Seasonally dependent, e.g., ozone in summer and $PM_{2.5}$ in winter
- Emission increases from fossil generators yield areas of localized AQ worsening
  - Generally occur with higher peak magnitude
  - Potentially mitigated by co-deployment of advanced comp. strategies (**next step**)

Δ O_3 Commercial Case (Summer 2020)



Δ $PM_{2.5}$ Commercial Case (Winter 2020)



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Conclusions

- **Strategies to mitigate GHG emissions will in tandem impact regional AQ**
  - Emission perturbations alter atmospheric concentrations of pollutants
    - Potential for co-benefits (avoid problem shifting)
- **AQ impact assessment requires detailed atmospheric modeling**
  - Account for chemical and physical processes post emissions release
  - Spatial and temporal distributions of primary and secondary pollutants
- **Emission inventories key input for methodology**
  - Provide foundation for projection and spatial and temporal distribution
  - Advances will directly improve overall AQ modeling results
- **Methodology has been applied to assess AQ impacts of various advanced energy technologies that can reduce GHG emissions**
  - Transportation: Fuel Cell Electric Vehicles, Electric Vehicles, Ocean Going Vessels, Heavy Duty Vehicles
  - Power: Renewable resources, Biopower, Distributed Generation
  - Industrial

Acknowledgments

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  - Dr. Dan Loughlin

Tropospheric Ozone Chemistry

Formation of tropospheric ozone governed by complex set of chemical reactions

– NO_x + VOCs + Sunlight = O_3

$OH^{\cdot} + VOC \rightarrow {}^{\cdot}HOCO$

${}^{\cdot}HOCO + O_2 \rightarrow HO_2^{\cdot} + CO_2$

$NO + HO_2^{\cdot} \rightarrow {}^{\cdot}OH + NO_2$

Generates radical which rapidly converts emitted NO to NO_2

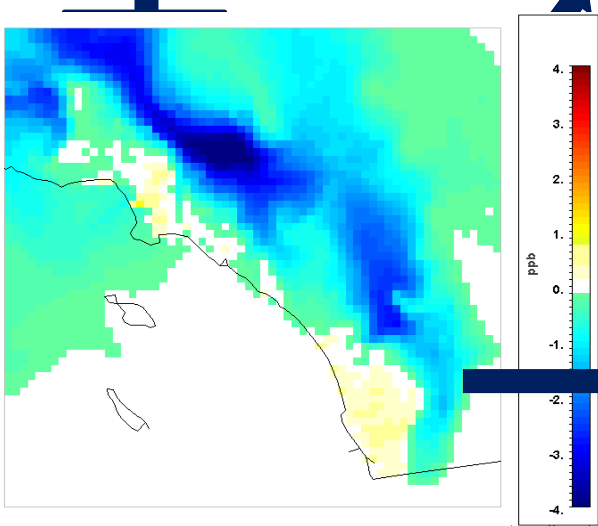
$NO_2 + HV \rightarrow NO + O^{\cdot}$

$O^{\cdot} + O_2 + M \rightarrow O_3 + M$

Results in formation of an O_3 molecule

$NO + O_3 \rightarrow NO_2 + O_2$

Results in destruction of an O_3 molecule



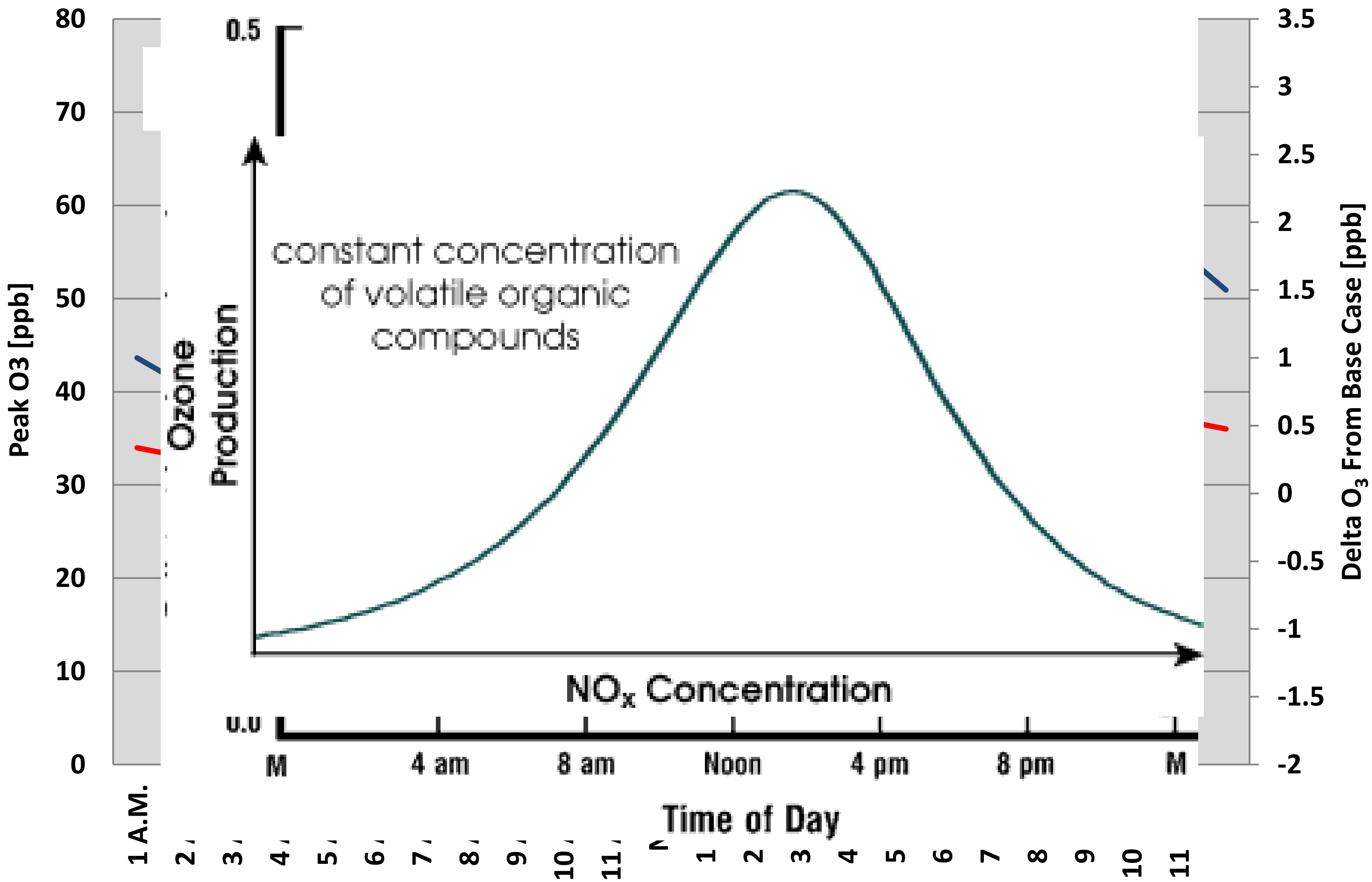
In urban areas (e.g., SoCAB) we have more NO

... where the emissions are occurring

Temporal Impacts on O_3

<u>O_3 reductions occur during important times in important locations</u>

- Increases occur during off-peak times in areas of lower concentrations

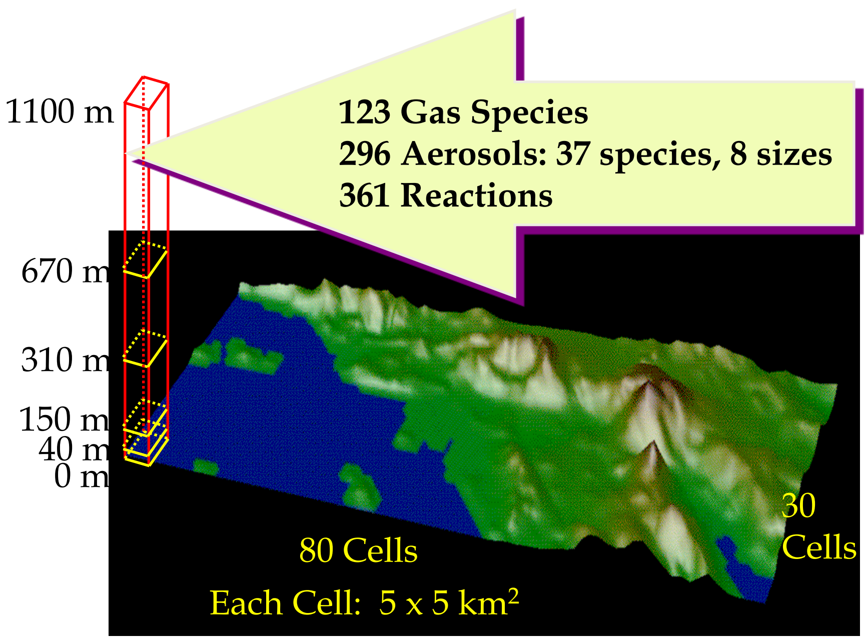


CMAQ

Governing Dynamic Equation:

- Numerical solution of the atmospheric diffusion equation
  - Advective transport, sources/sinks, chemical production/loss, size /chemically resolved aerosol formation

$$\frac{\partial Q_m^k}{\partial t} + \nabla \cdot \left(u Q_m^k \right) = \nabla \cdot \left(K \nabla Q_m^k \right) + \left(\frac{\partial Q_m^k}{\partial t} \right)_{sources/sinks} + \left(\frac{\partial Q_m^k}{\partial t} \right)_{aerosol} + \left(\frac{\partial Q_m^k}{\partial t} \right)_{chemistry}$$

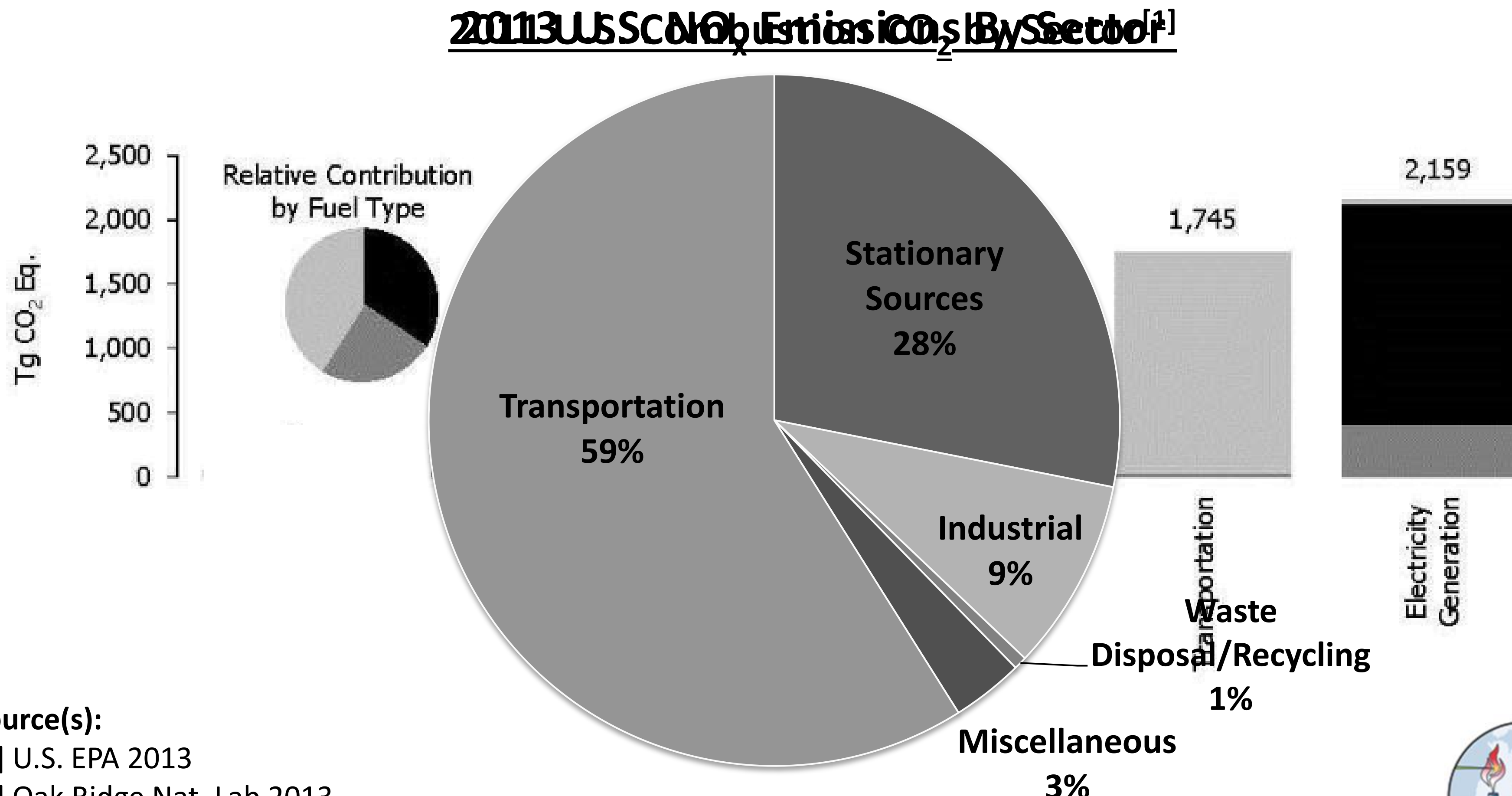


- Widespread use in AQ modeling community
- Modular chemical mechanisms
  - CBIV, SAPRC99, CB05
- Met fields include encompass temperature field, wind field, UV radiation field, and information of the terrain such as surface roughness to calculate deposition velocities, etc…

U.S. Energy Emissions

Energy technologies key contributor of U.S. emissions

- 86% of domestic GHG emissions[1], > 90% of anthropogenic NO_x , SO_2 [2]
- Emissions result from combustion of fossil fuels



Source(s):
[1] U.S. EPA 2013
[2] Oak Ridge Nat. Lab 2013

Combustion: Emission Impacts



During combustion components of fossil fuels combine with O_2 from air to yield water vapor, CO_2, and trace pollutants

- **E.g., for octane (C_8H_{18}) combustion**

$$2C_8H_{18} + 25O_2 \rightarrow 18H_2O + 16CO_2 + \text{pollutants}$$

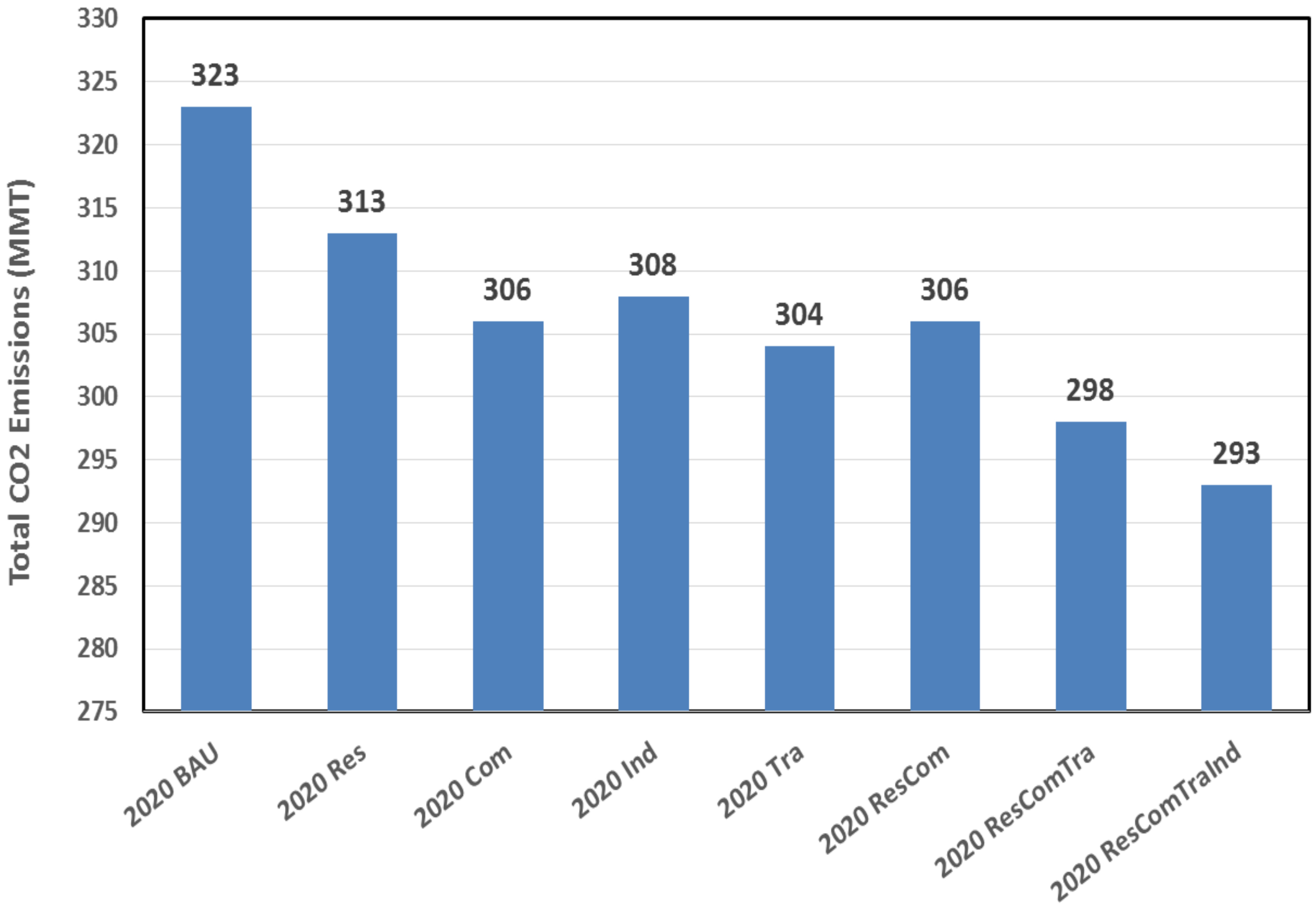
Global Climate Change
- Human Health Impacts
- Economic Impacts
- Ecosystems Impacts
- …

Air Pollution (Quality)
- Human Health Impacts
- Environmental Impacts
- Materials Degradation
- …

1. **Fossil fuel combustion contributes to climate change and air quality concerns → Transitions to cleaner alternatives**
   - **Additional drivers: energy security/independence, sustainability, environmental concerns, …**
2. **Shifts to alternative technologies/fuels will impact both emissions of GHG and pollutants due to common sources**
   - **Opportunity to simultaneously address climate change and air quality**

Source: Brown 2011

2020 Electrification GHG Results

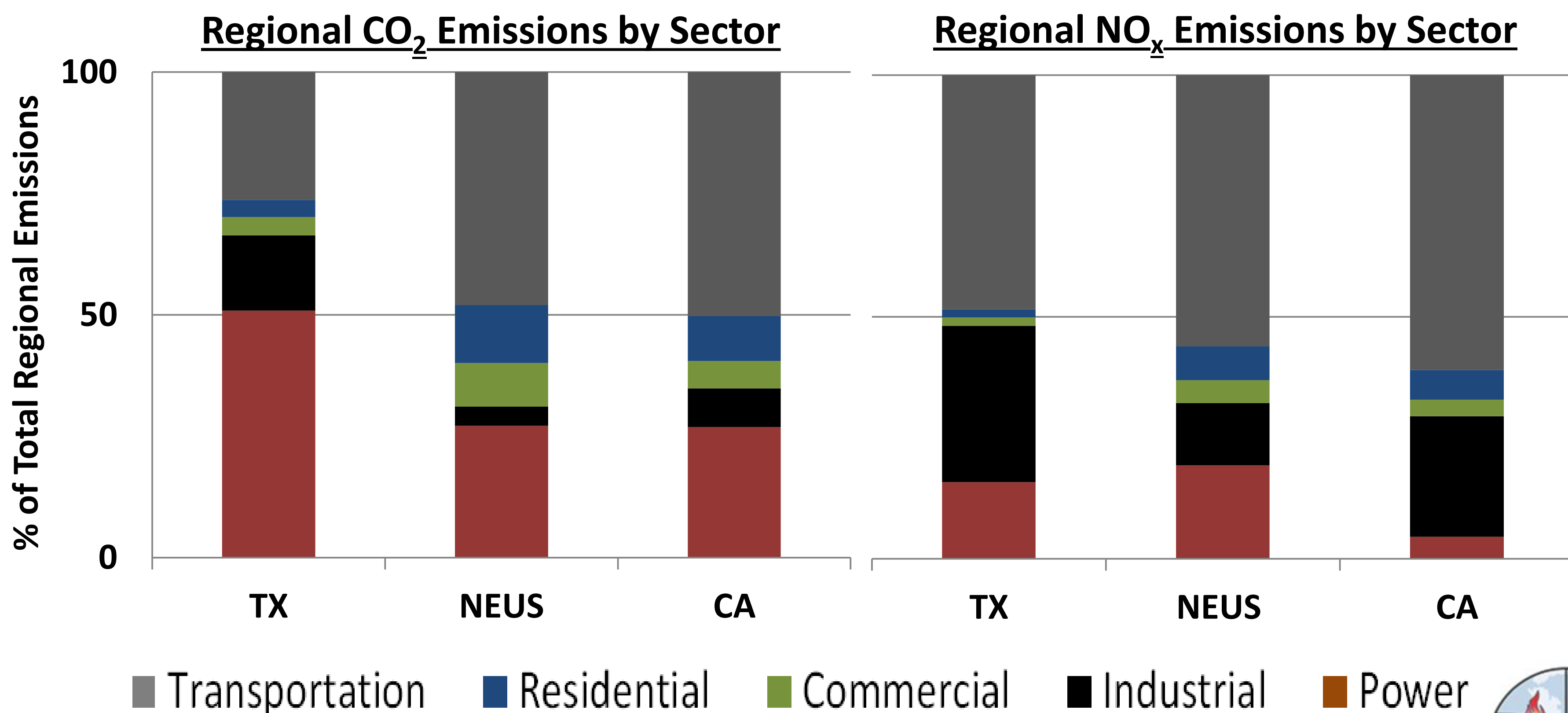


Energy Sector Regional Emissions

Transportation major contributor of GHG and NO_x Emissions

– Power sector important for GHG emissions

– Industrial sector pollutant emissions significant in all regions



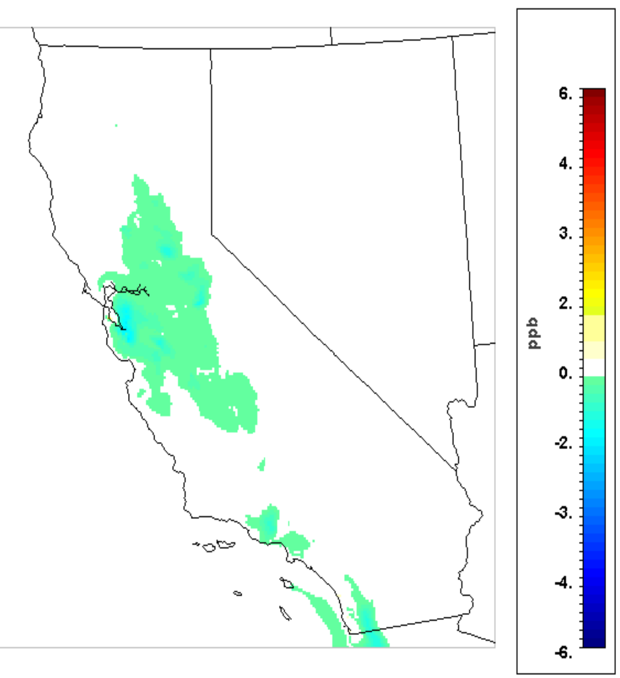
Energy Sector O_3 Impacts

Transportation sector yields largest improvements in all regions

- Power more localized than industrial but with higher magnitude (TX, NEUS)
- Industrial impacts significant, particularly for CA

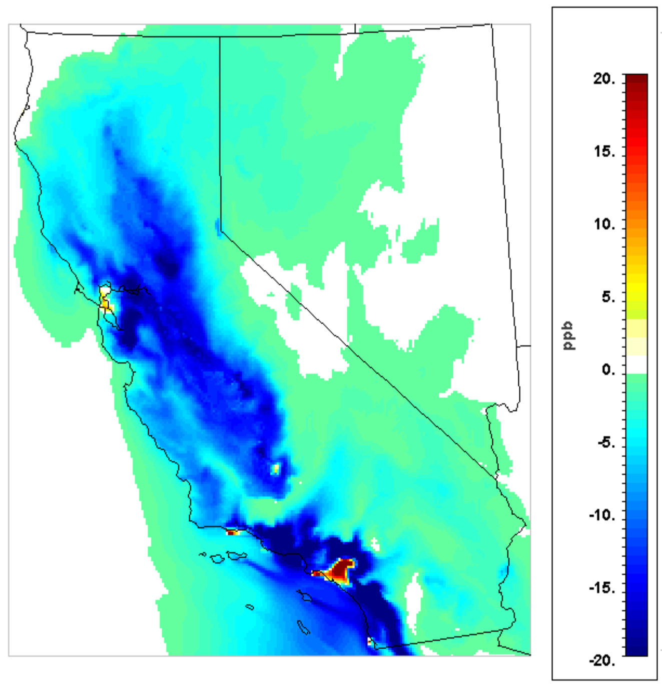
Δ O_3 From Base

Power Generation



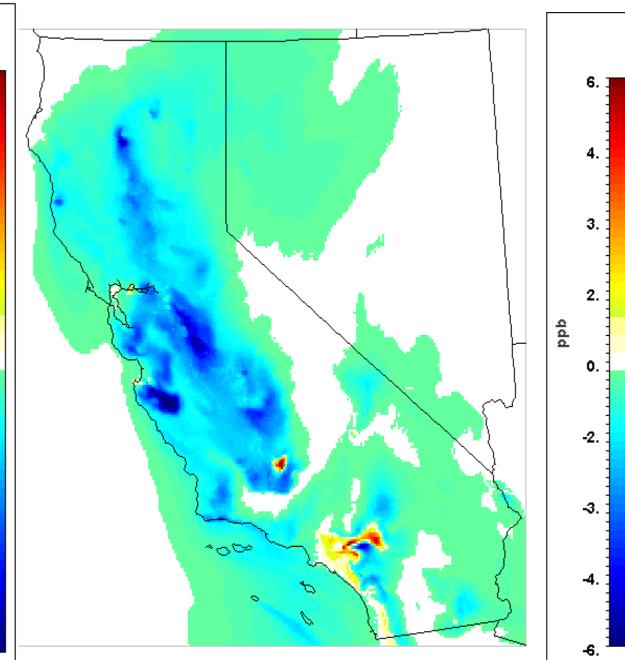
-1.4 ppb O_3

Transportation



-25.8 ppb

Industrial



-6.2 ppb

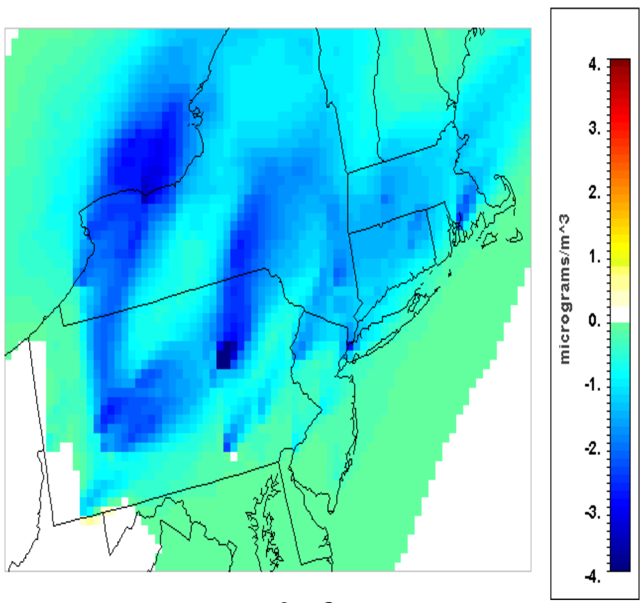
Energy Sector $PM_{2.5}$ Impacts – NEUS

NEUS power generation contributes significantly to ambient levels

- Transportation sector impacts upwind of NYC
- Industrial sector impacts have localized importance

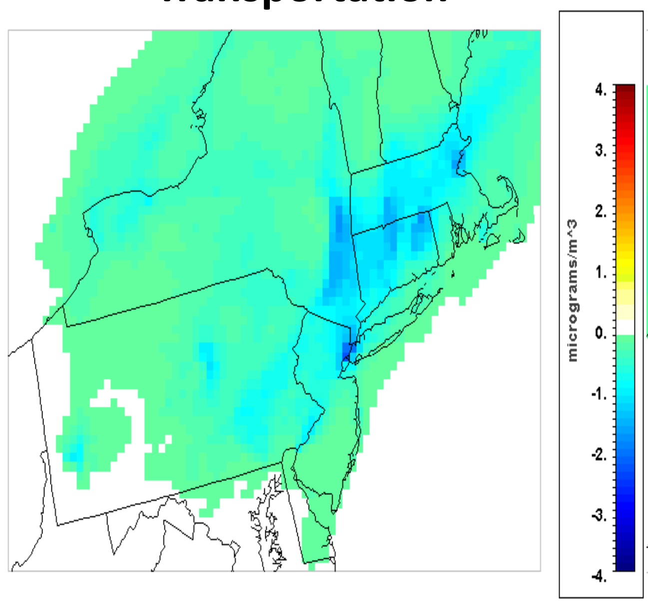
Δ 24-h Average $PM_{2.5}$ From Base

Power Generation



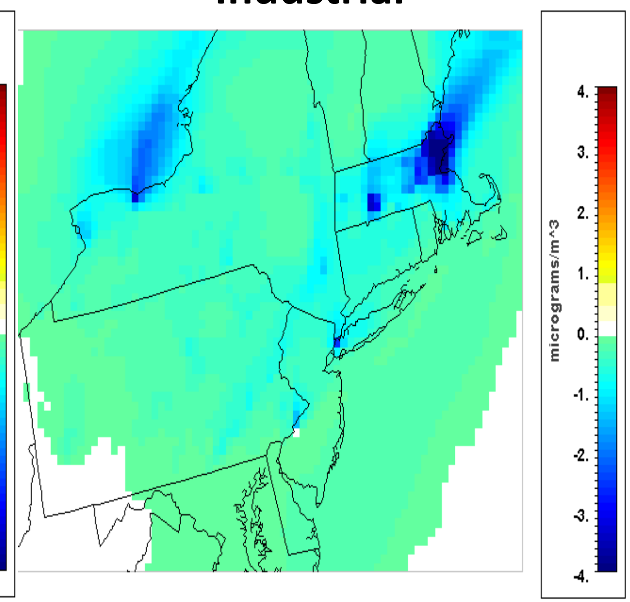
-5.1 μg/m³ $PM_{2.5}$

Transportation



-2.3 μg/m³ $PM_{2.5}$

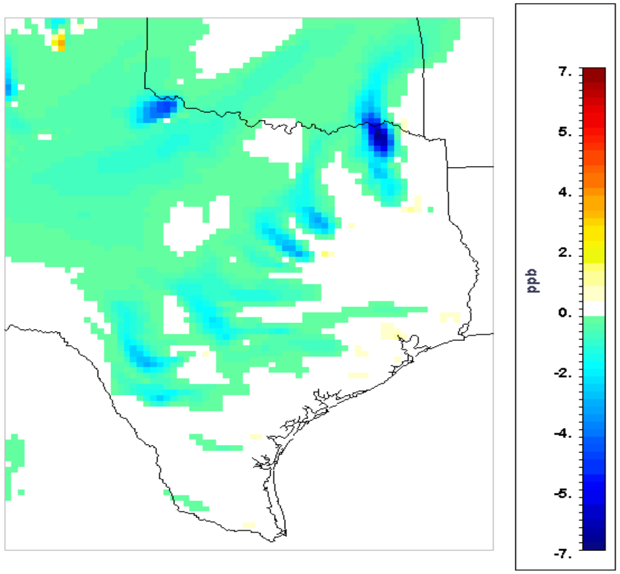
Industrial



-7.2 μg/m³ $PM_{2.5}$

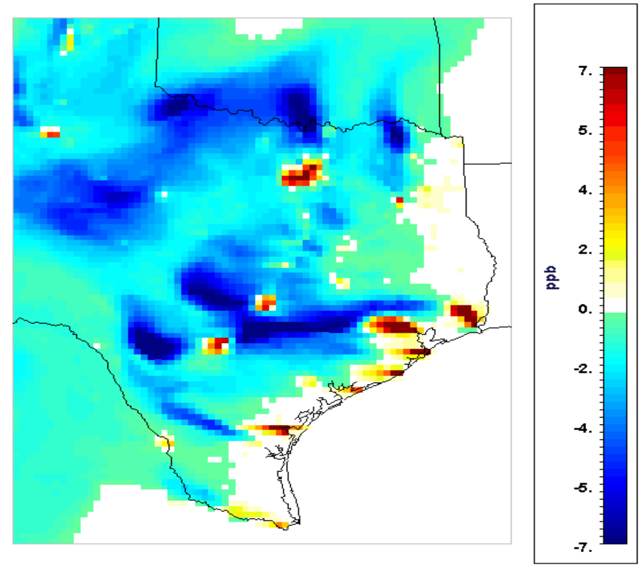
Energy Sector O_3 Impacts

-7.5 ppb



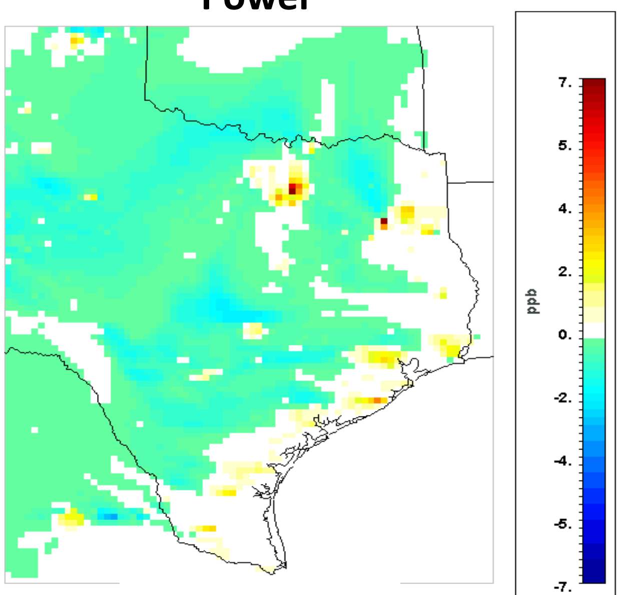
Power

-15.3 ppb



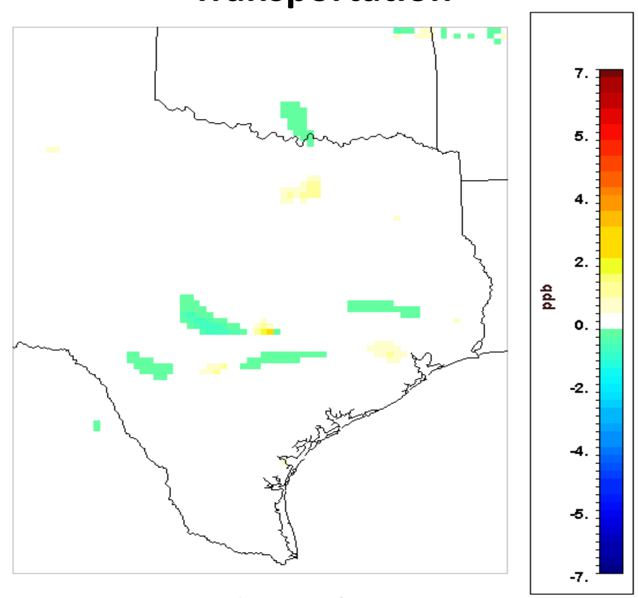
Transportation

-3.6 ppb



Industrial

-1.8 ppb



Residential

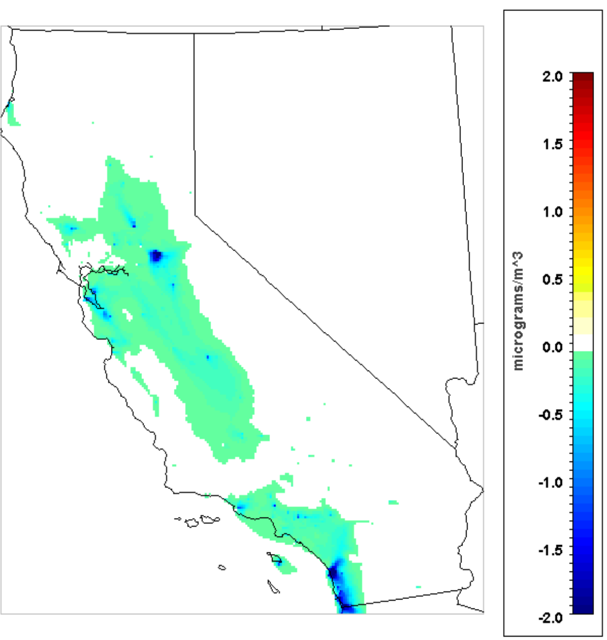
Energy Sector $PM_{2.5}$ Impacts – CA

Regional variation in magnitude & spatial distribution of improvements

- Transportation dominant contributor to ambient concentrations in CA
- Industrial of high importance in select CA regions, i.e., Central Valley

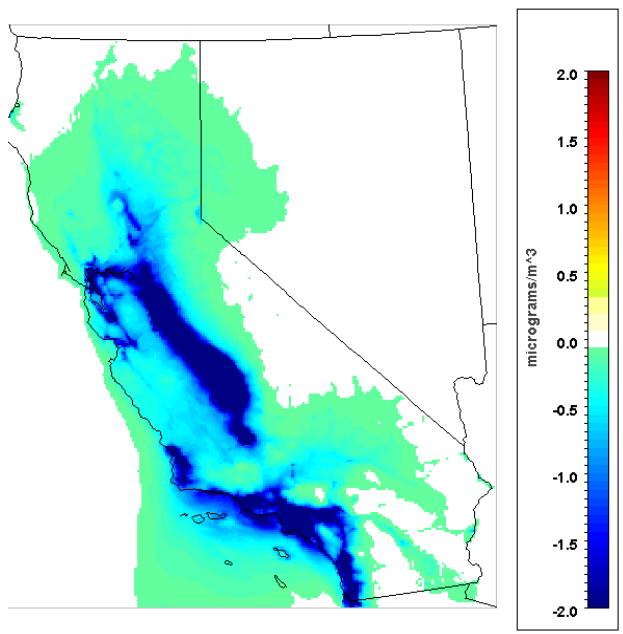
Δ 24-hour Average $PM_{2.5}$ From Base

Power Generation



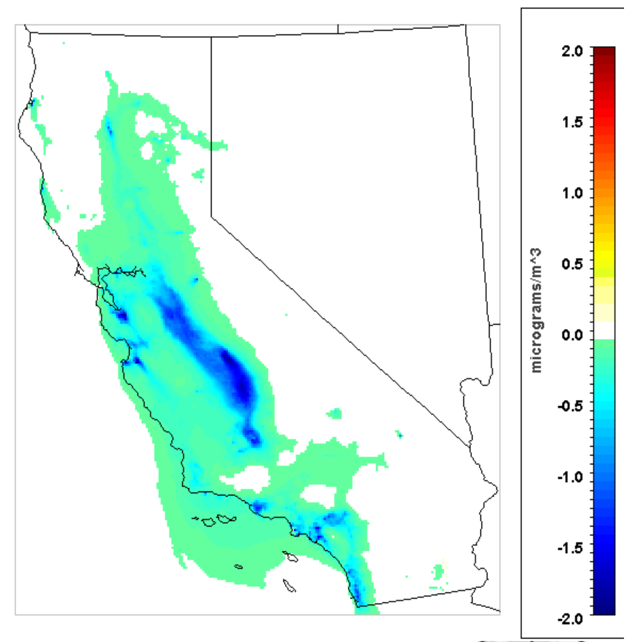
-2.5 µg/m³

Transportation



-44.6 µg/m³

Industrial



-2.6 µg/m³

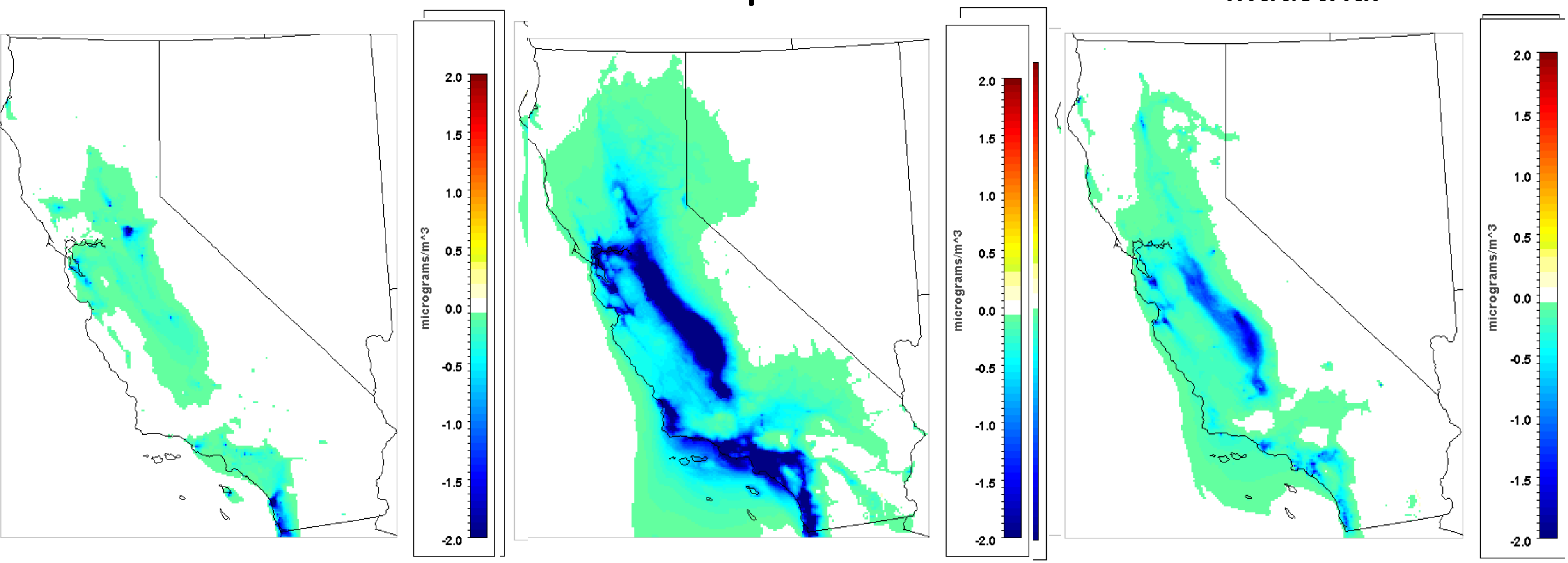
Transportation Sector AQ Impacts

Transportation sector emissions significantly impact regional AQ

- Primary and secondary pollutants → Ozone and Particulate Matter (PM)
- Significantly more than other major energy sectors in CA

Δ 24-Hour Average PM$_{2.5}$ From Base

Power Generation | **Transportation** | **Industrial**

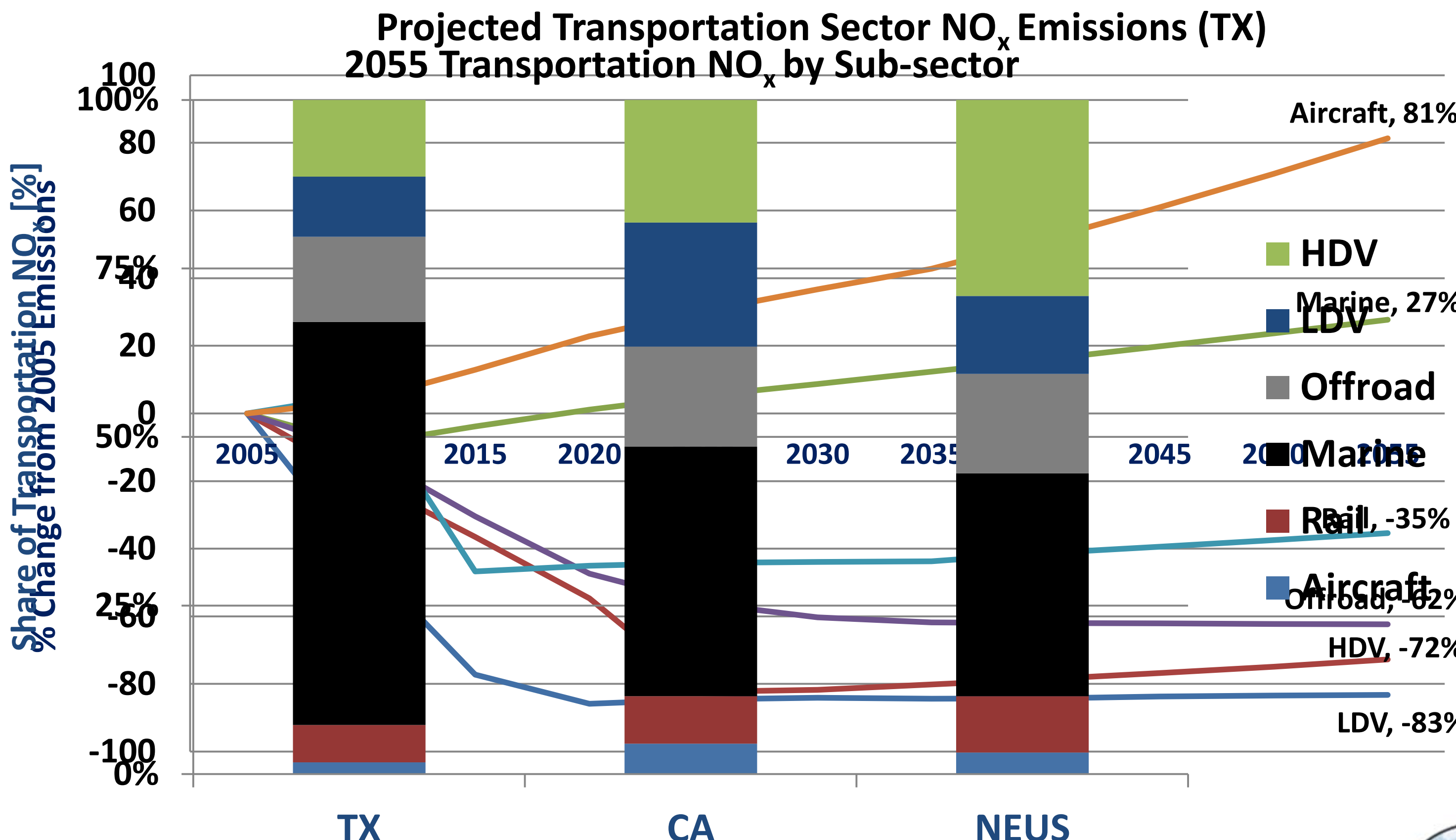


-2.5 μg/m³ | **-44.6 μg/m³** | **-2.6 μg/m³**

Projected Transportation Emissions to 2055

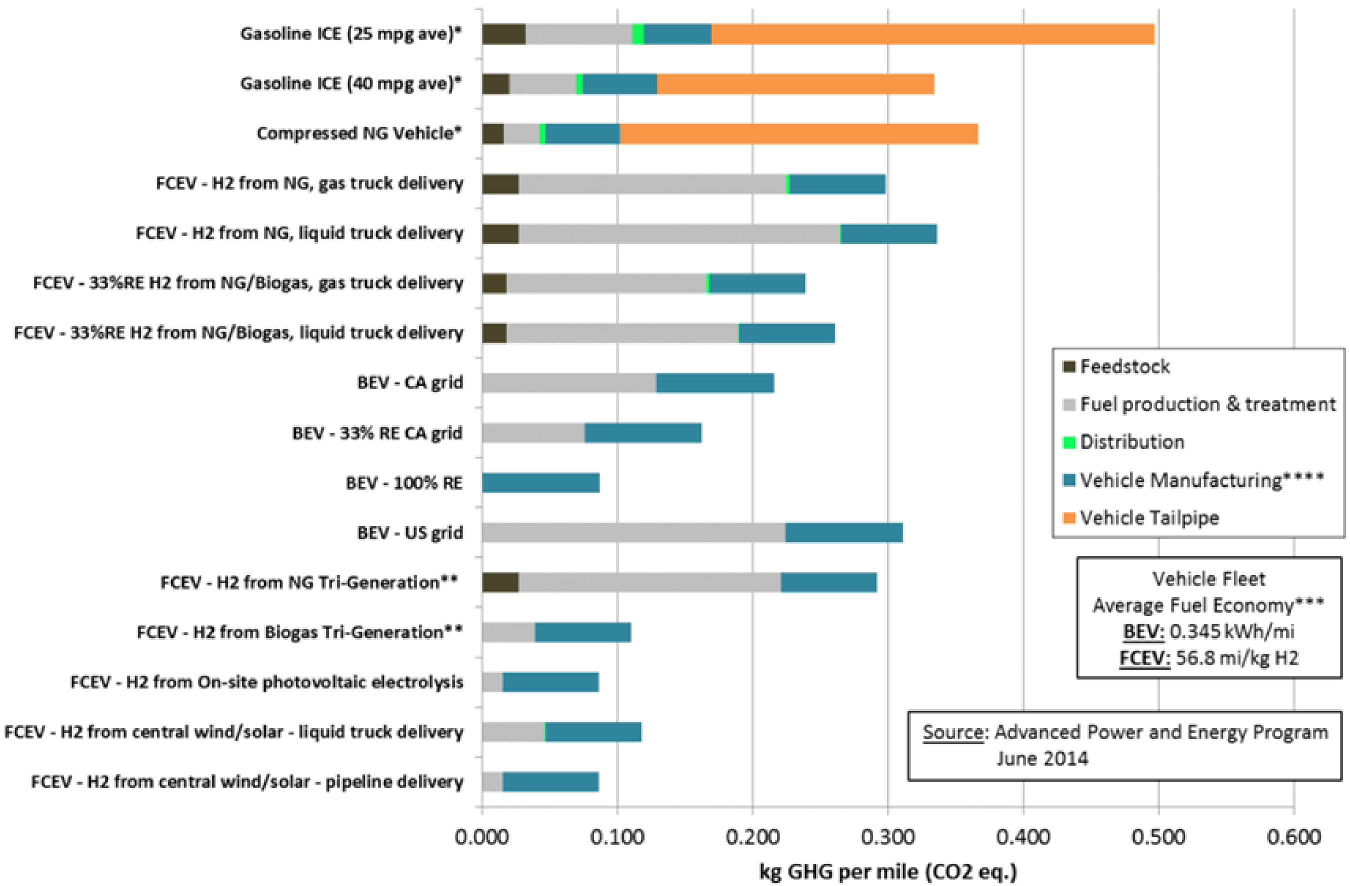
Significant variance in projected emissions amongst sub-sectors

- Result of current regulatory focus, technology advancement, etc.
- In 2055 GM sectors contribute majority of emissions → Ships, Off-road



Source: MARKAL 2010

Life Cycle GHG Emissions for LDVs



* Gasoline ICE and Compressed NG vehicle WTW information obtained from the Low Carbon Fuel Standard, except vehicle manufacturing.

**Tri-Generation is a novel technology that was conceived by the National Fuel Cell Research Center in 2001 to simultaneously generate electricity, hydrogen, and heat. It was developed into the first prototype in collaboration with FuelCell Energy, Inc., and Air Products and Chemicals, Inc. The first demonstration of this technology in the world is currently being demonstrated at the Orange County Sanitation District while operated on renewable biogas derived from the wastewater treatment process. For more information on Tri-Generation please visit: http://www.apep.uci.edu/3/research/partnership_TRI-GEN.aspx

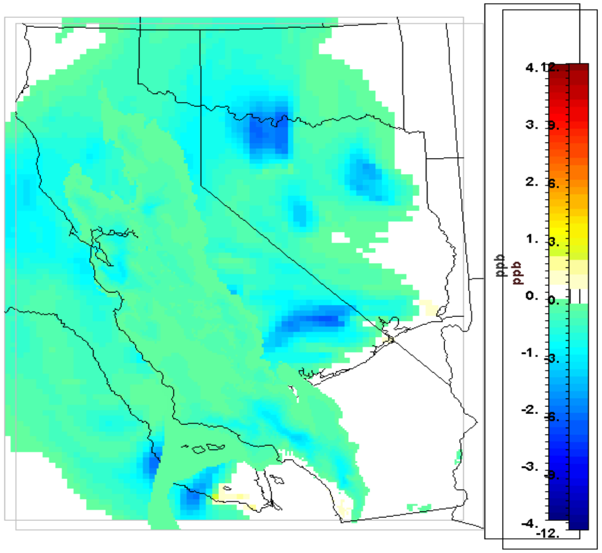
***Fleet-wide average fuel economy is the representative fuel economy of the average vehicle in the light-duty vehicle fleet. This is a weighted average of the fuel economy of different size vehicles. Each vehicle class is weighted by their contribution to the total light-duty vehicle fleet according to the CARB EMFAC model.

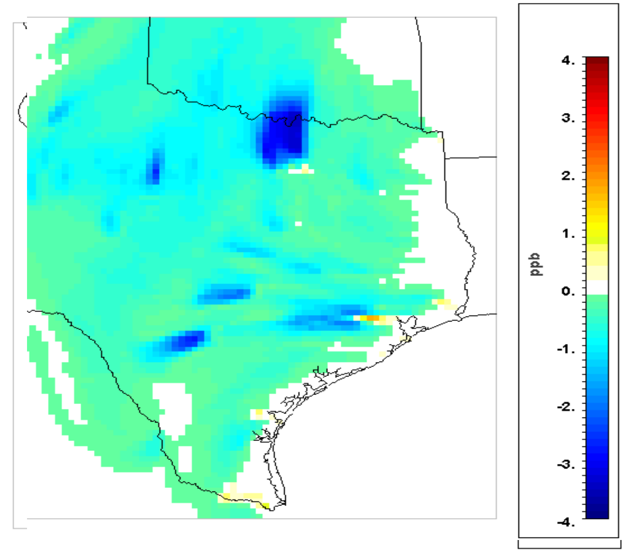
****Vehicle manufacturing emissions obtained from automaker data input.

Transportation Sector O_3 Impacts

Light Duty Vehicles

-4.0 ppb



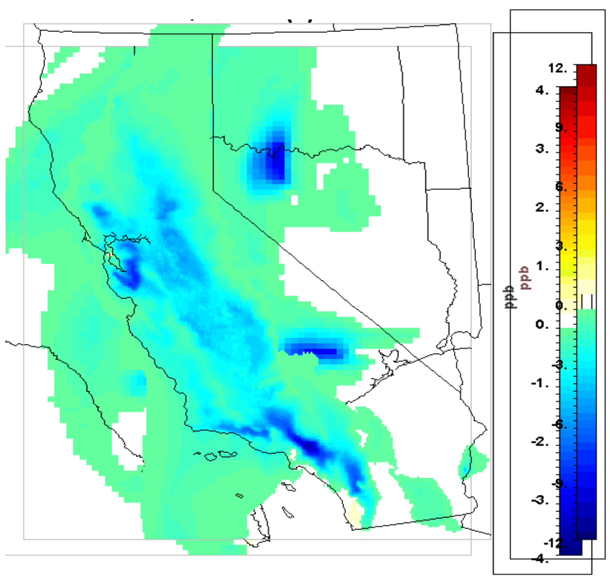


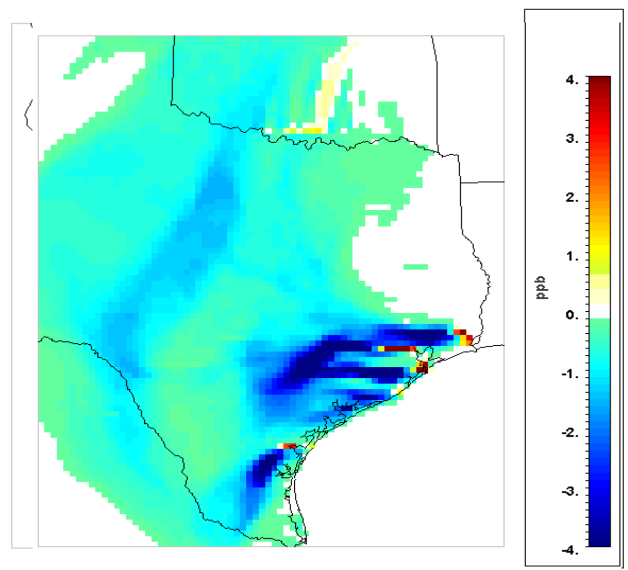
Heavy Duty Vehicles

-12.0 ppb

Offroad

-13.7 ppb





Marine & Rail

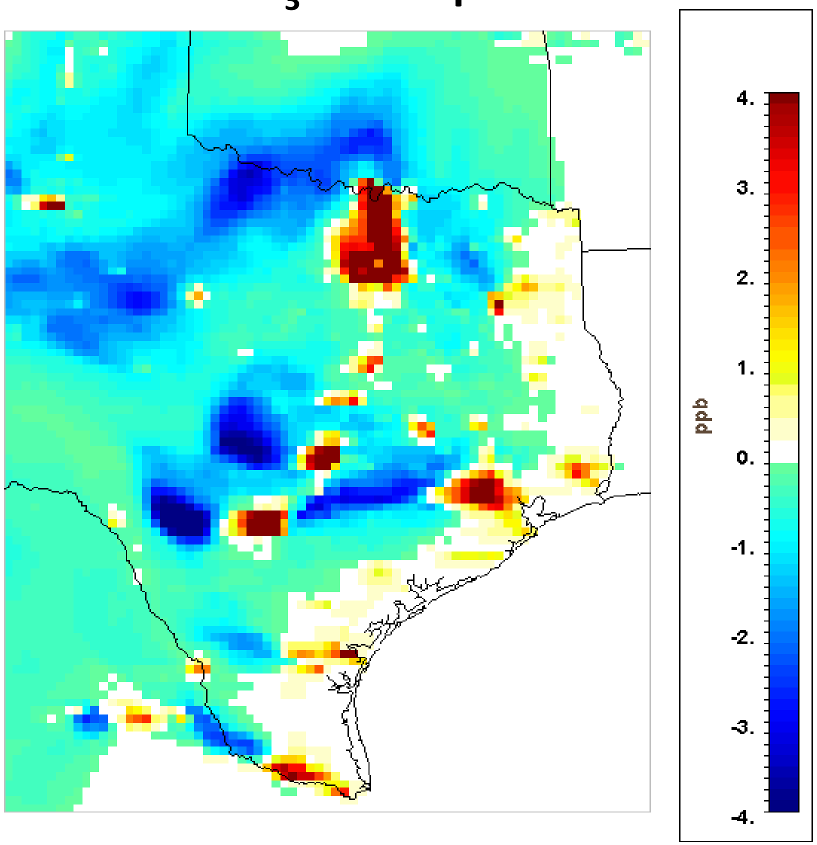
-20.6 ppb

Evolution of LDV Impacts

The relative AQ impacts of LDVs are modest in 2055…BUT

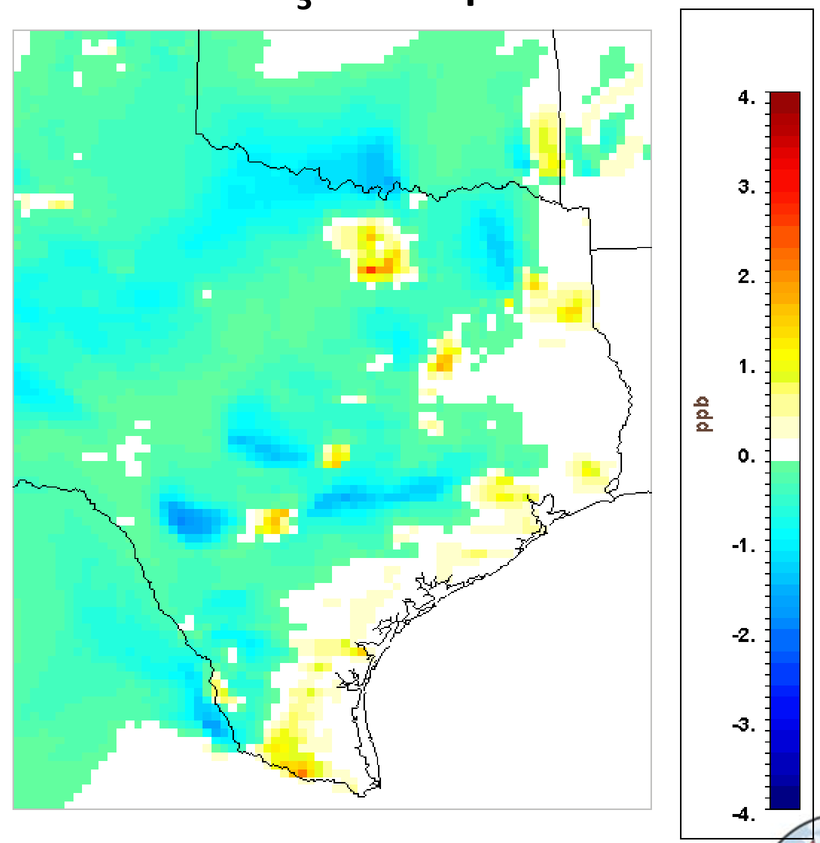
- Improvements occur in highly populated areas →Important health benefits
- Emissions of GHGs still have high importance → Need for mitigation

2005 O_3 LDV Impacts



-6.8 ppb O_3

2055 O_3 LDV Impacts

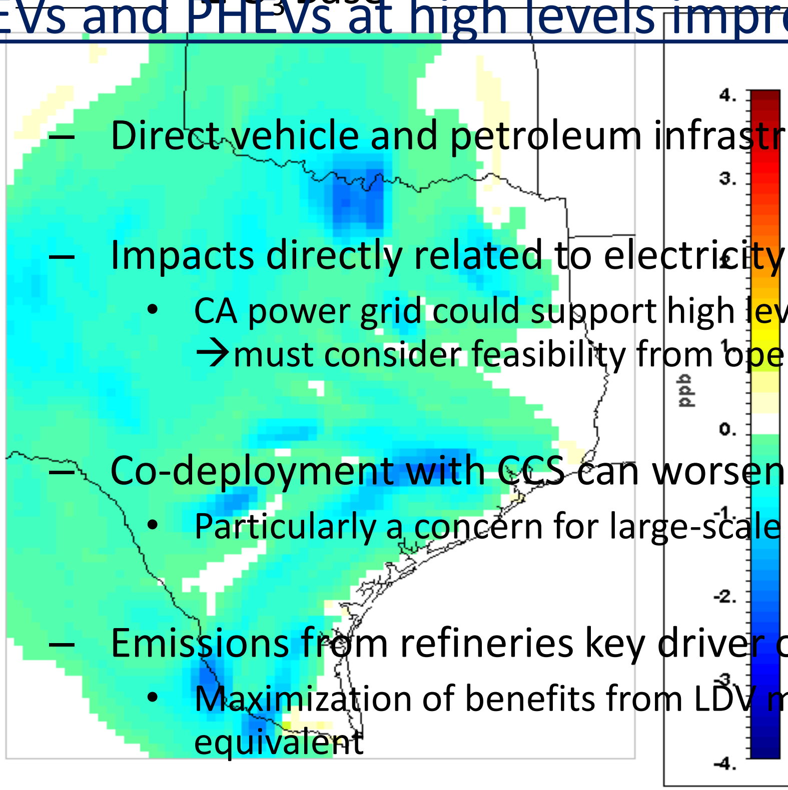


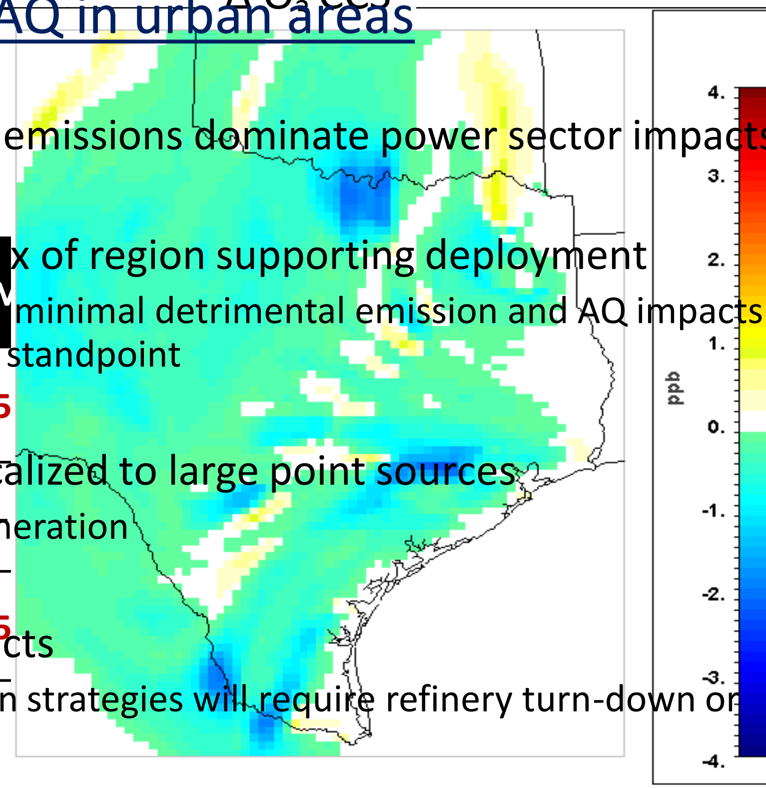
-2.4 ppb O_3

Air Quality Impacts of Electric Vehicles

Impact of Battery Electric (BEV) and Plug-in Hybrid Electric (PHEV) Deployment

- Direct reductions in vehicle and petroleum fuel infrastructure pathways
- Increase in emissions from electricity generation





Power
ons
PM
% +15
% +15

BEVs and PHEVs at high levels improves AQ in urban areas

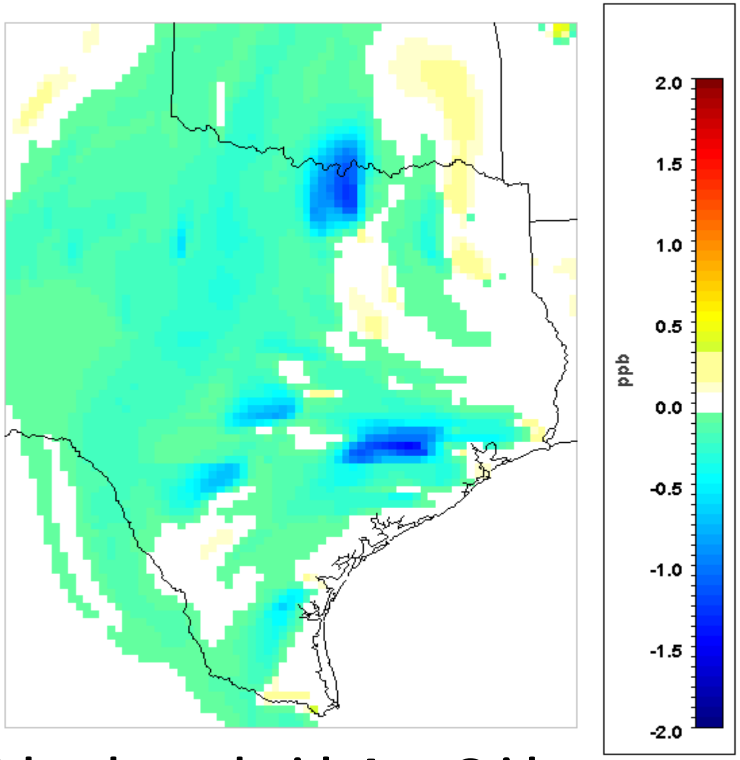
- Direct vehicle and petroleum infrastructure emissions dominate power sector impacts
- Impacts directly related to electricity x of region supporting deployment
  - CA power grid could support high lev minimal detrimental emission and AQ impacts →must consider feasibility from operational standpoint
- Co-deployment with CCS can worsen AQ localized to large point sources
  - Particularly a concern for large-scale coal generation
- Emissions from refineries key driver of impacts
  - Maximization of benefits from LDV mitigation strategies will require refinery turn-down or equivalent

Electric Vehicle Impacts

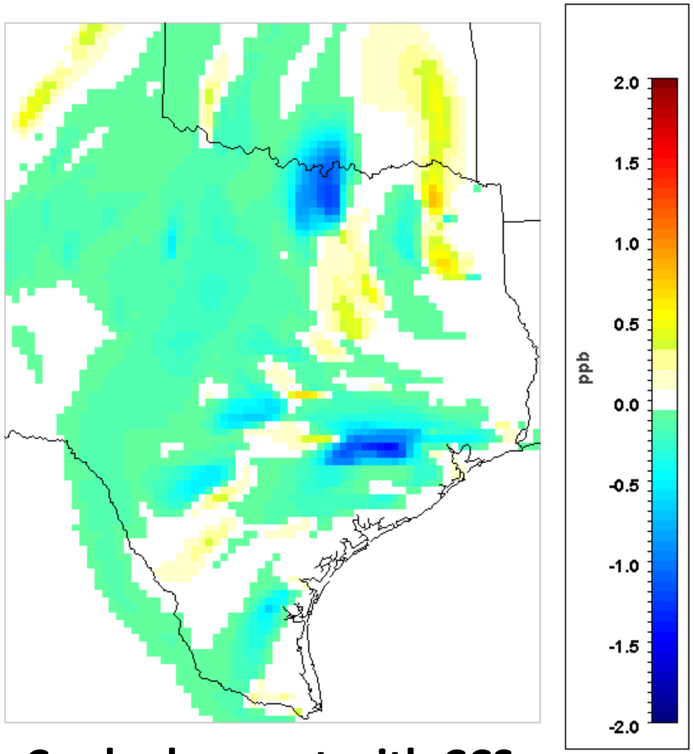
AQ impacts driven by vehicle emission reductions

– Complete deployment of BEVs in the LDV sector
– Additional power (11% increase) met by existing generation mix

Difference in $[O_3]$ Relative to Base



Vehicles charged with Avg. Grid

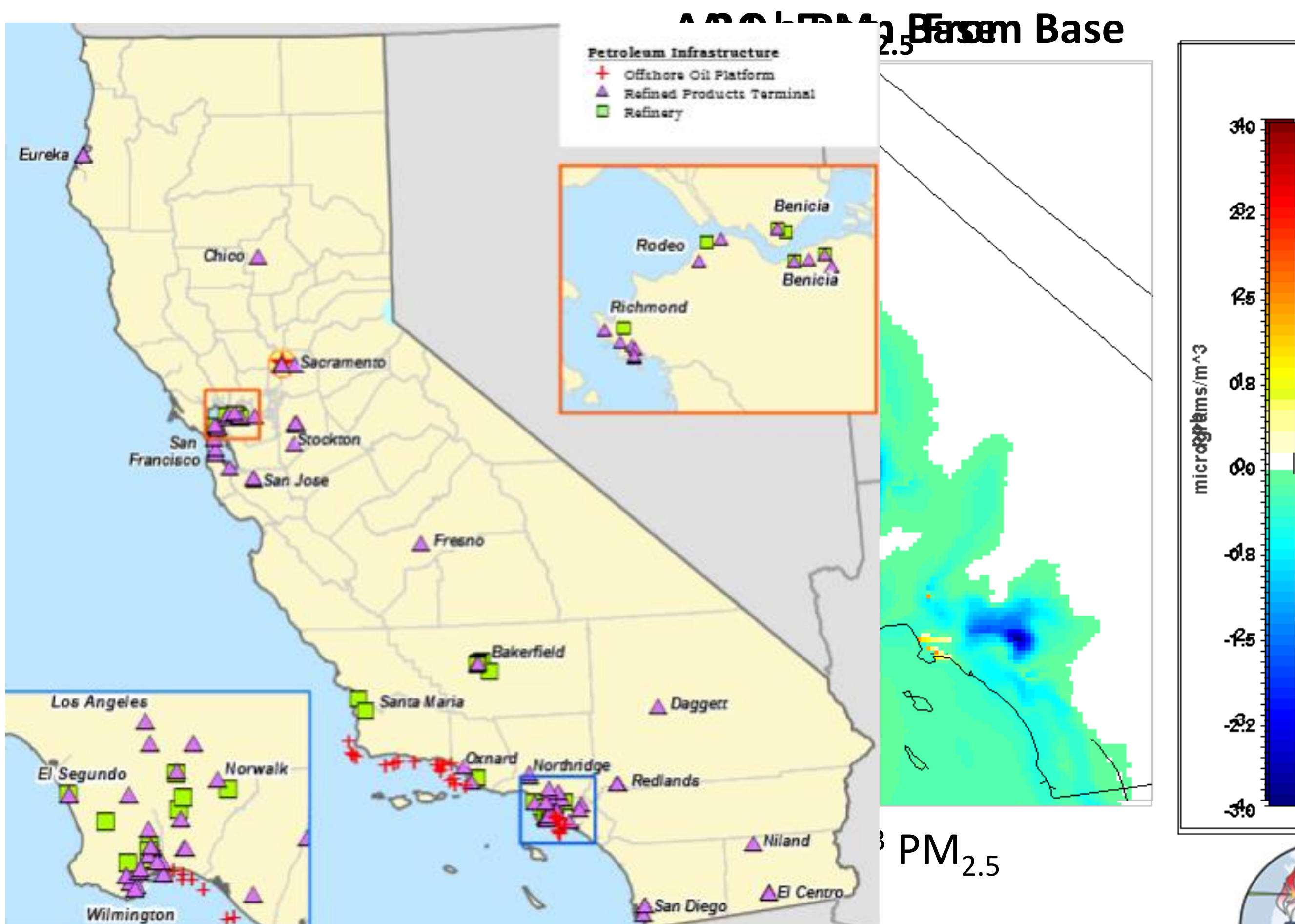


Co-deployment with CCS

Air Quality Impacts of Petroleum Refining

Petroleum fuel production/distribution important to AQ & GHG

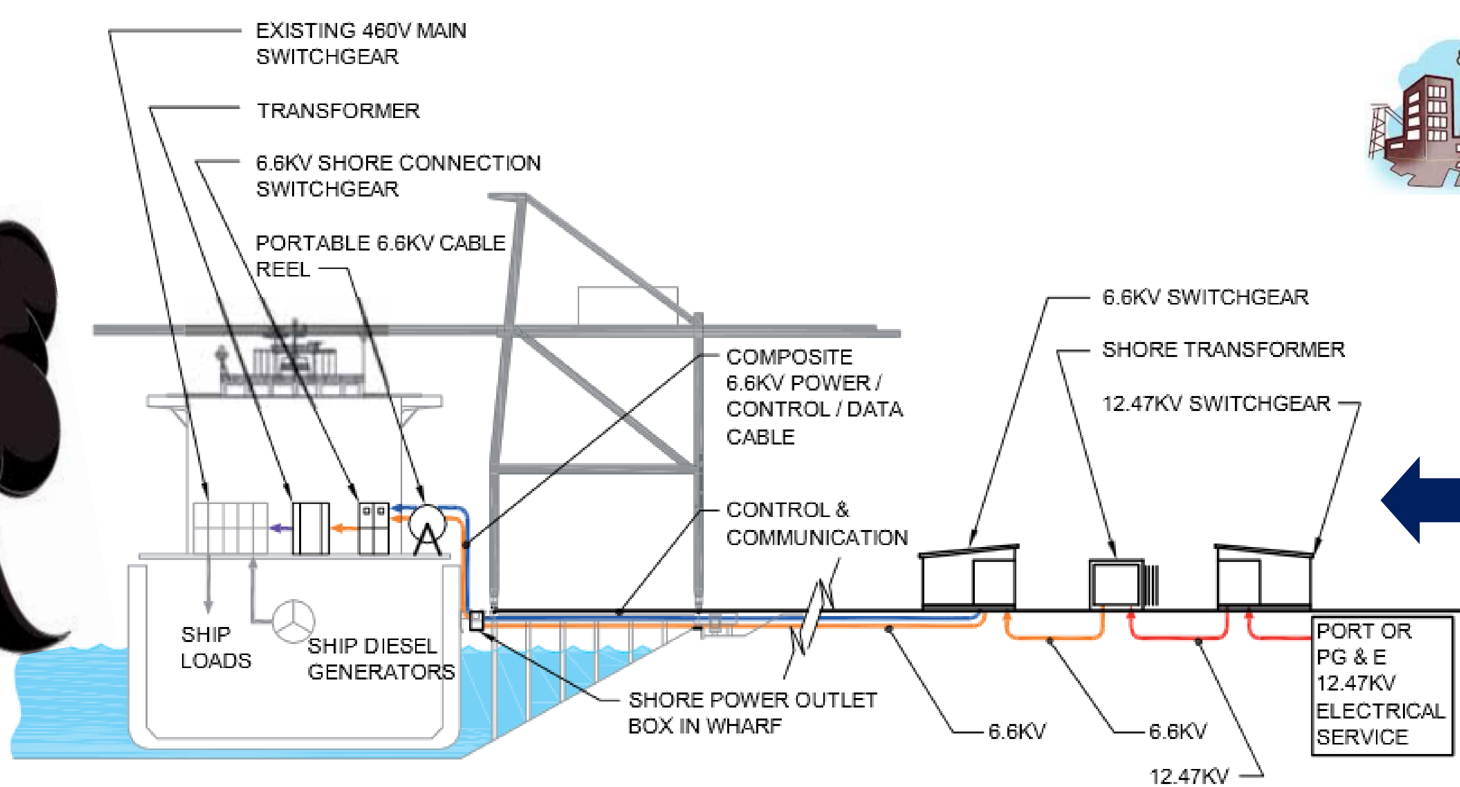
- Substantial reductions in O_3 and $PM_{2.5}$ for key CA regions
- Further motivation supporting transitions to alternative LDV strategies



OGV Emissions Mitigation: Cold Ironing (CI)

Provision of ship-to-shore power (CI) important mitigation strategy

- Auxiliary engines at berth comprise significant fraction of total OGV & Port emissions
  - Power needs can be provided by vessel linkage to shore → grid, distributed tech.
    - CA: At-berth regulation requires 80% reduction by 2020



Source: Borner-Brown et al., Port Technology International

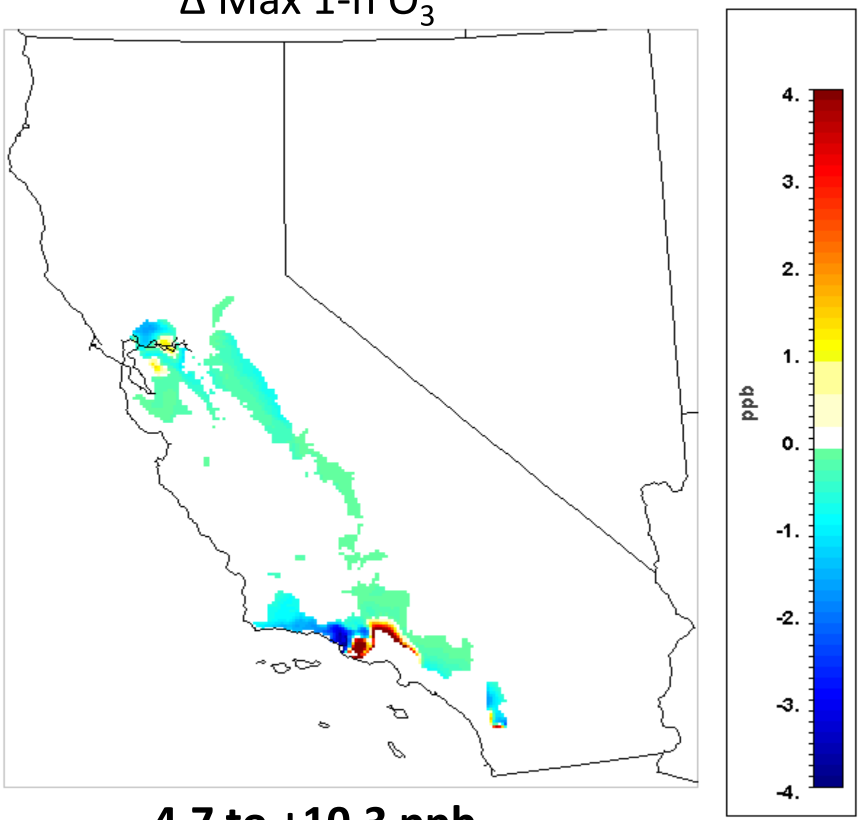
OGV Emissions Mitigation: Cold Ironing (CI)

CI Cases demonstrate benefits to AQ in urban regions of the State

- Substantial reductions in $PM_{2.5}$ in important areas, e.g., SoCAB
- Ozone impacts include increases from reduced scavenging from large NO_x reductions

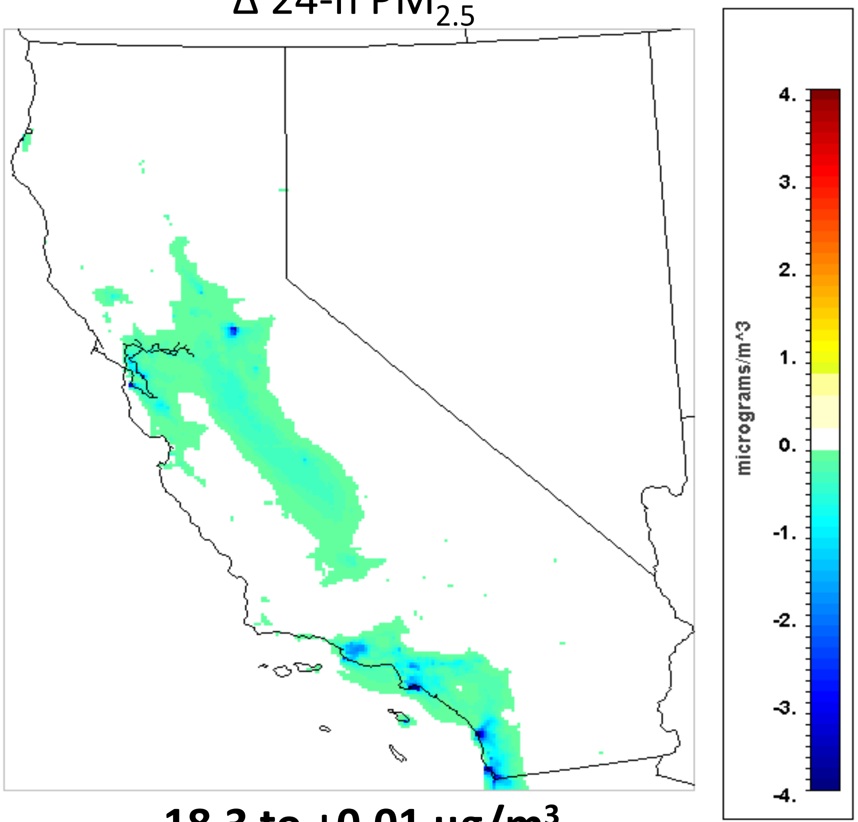
Difference from Baseline for CI Projected Case

Δ Max 1-h O_3



-4.7 to +10.3 ppb

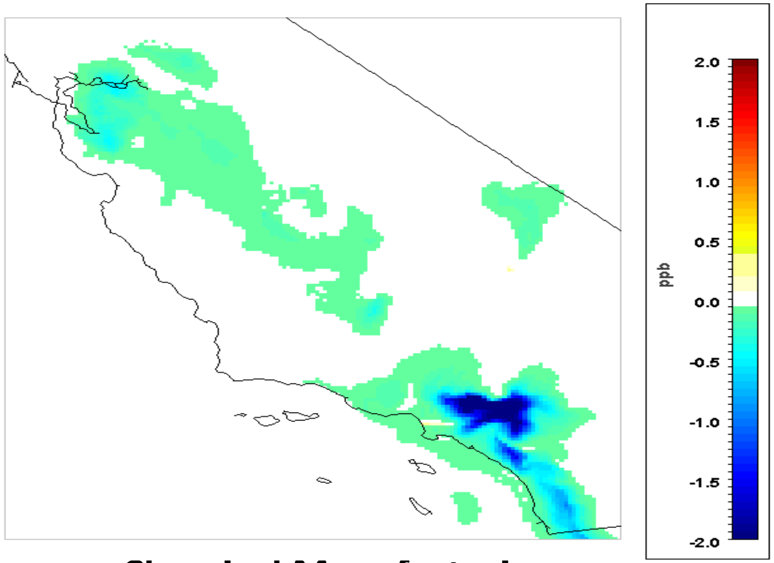
Δ 24-h $PM_{2.5}$



-18.3 to +0.01 μg/m³

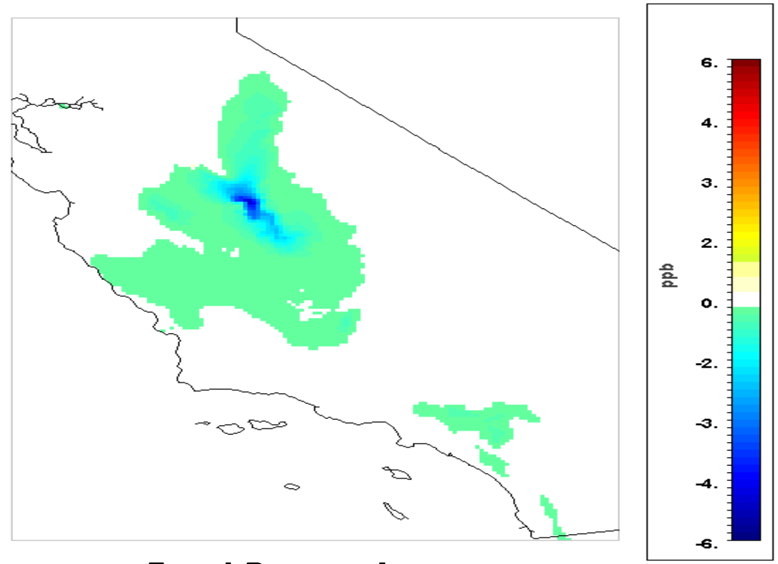
Industry Sub-sector O_3 Impacts

-3.9 ppb



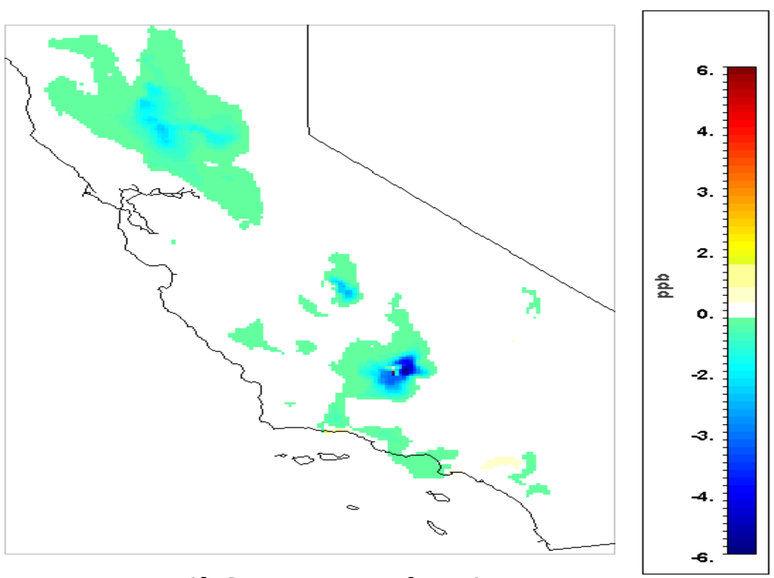
Chemical Manufacturing

-6.46 ppb



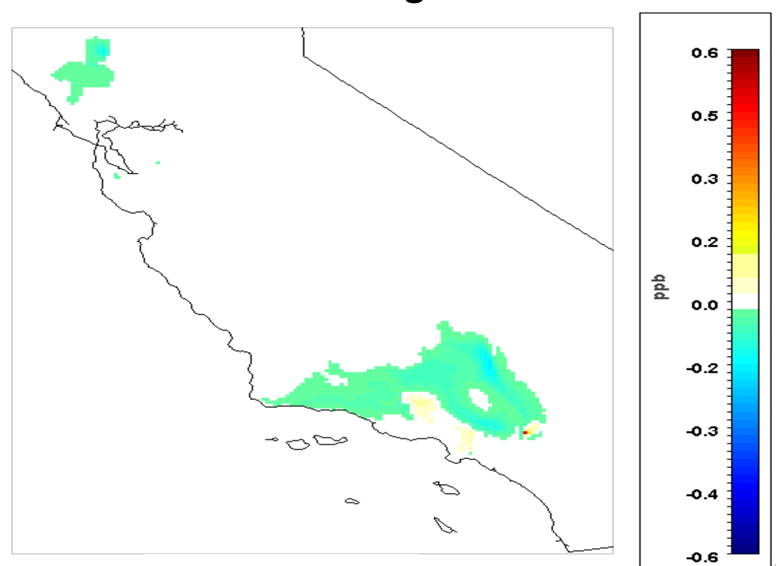
Food Processing

-6.8 ppb



Oil & Gas Production

-0.63 ppb

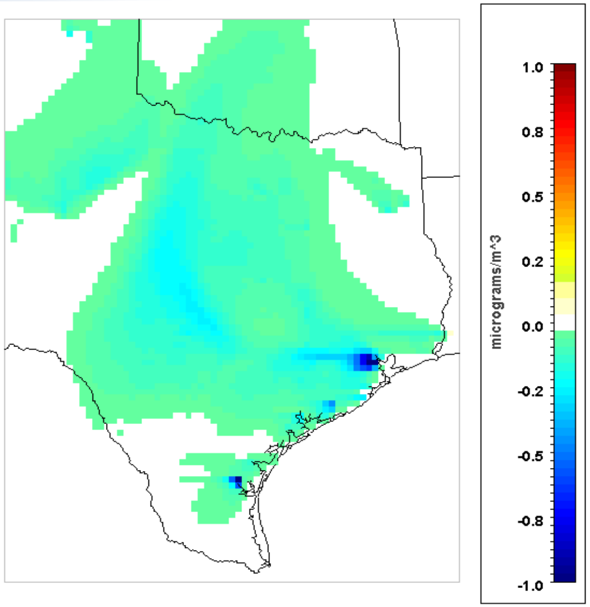


Metals

Industry Sub-sector $PM_{2.5}$ Impacts – TX

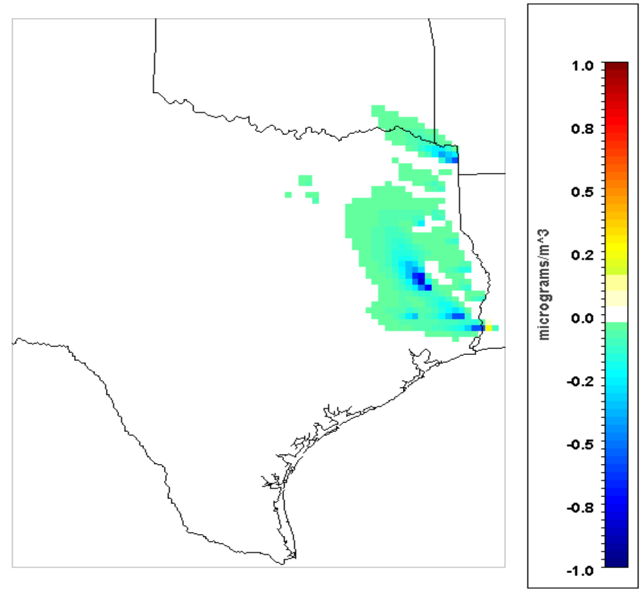
Chemical Manufact.

-1.68 μg/m³



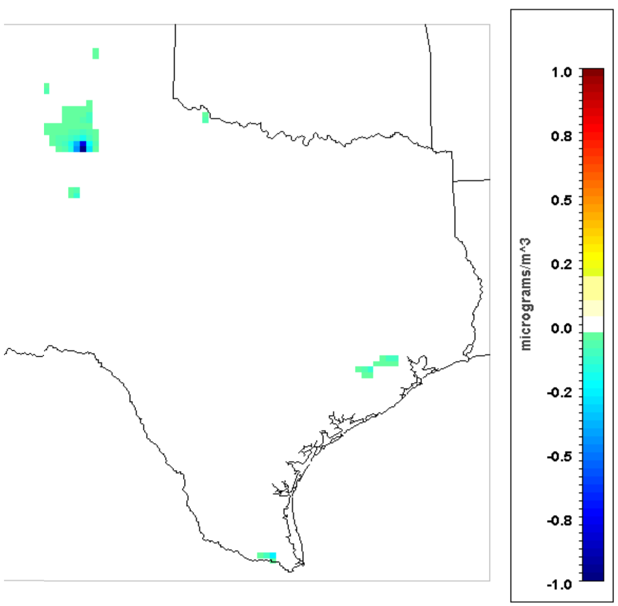
Paper/Pulp

-9.00 μg/m³



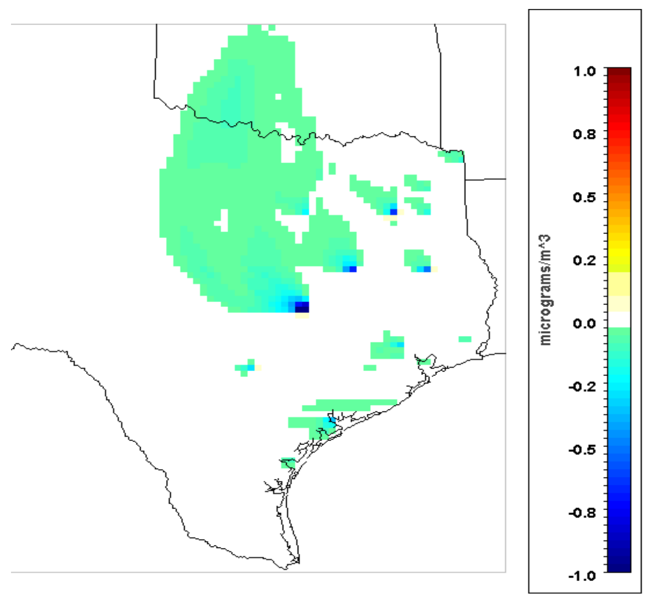
Food Processing

-2.18 μg/m³



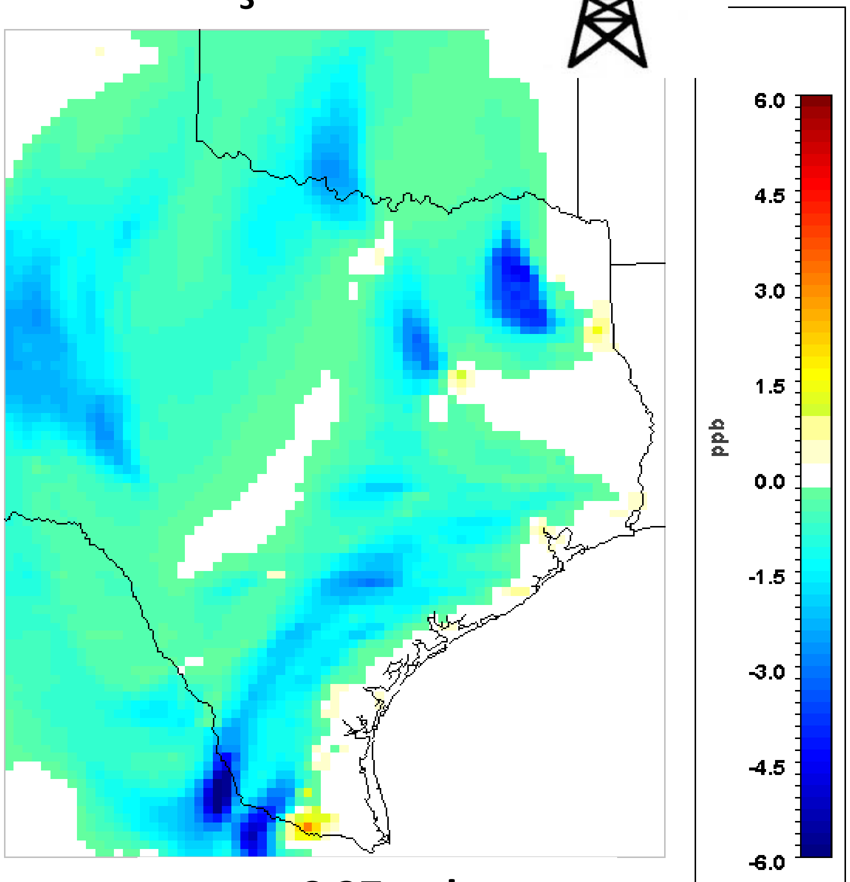
Metals

-2.18 μg/m³



Industry – Oil and Gas Production

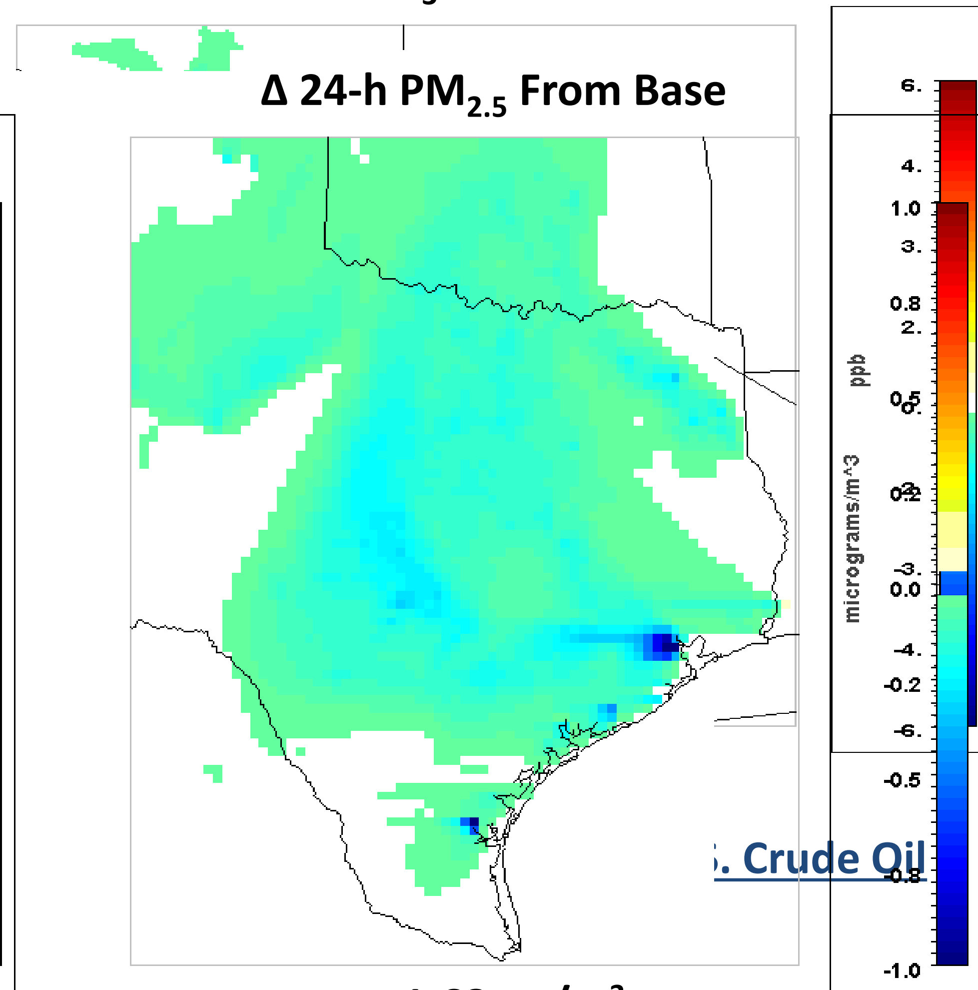
Δ O_3 From Base



-6.37 ppb

Δ O_3 From Base

Δ 24-h $PM_{2.5}$ From Base



-1.68 μg/m^3

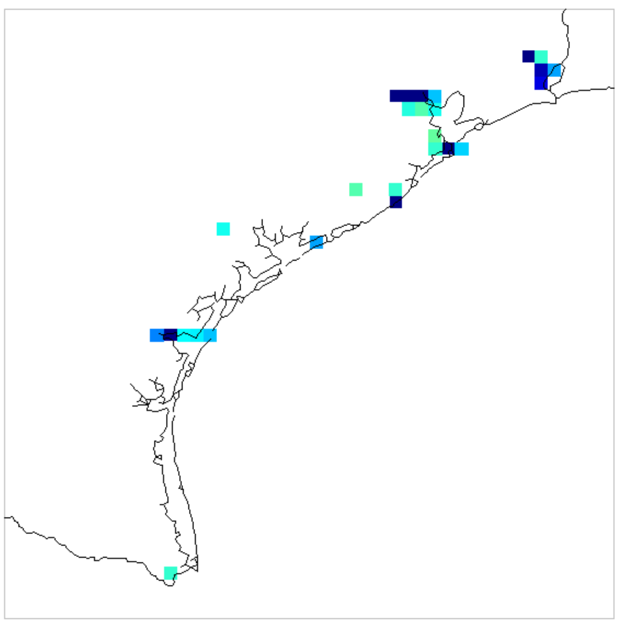
Marine Vessel Impacts

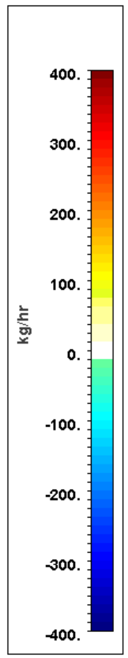
Deployment of advanced vessel strategies achieves high co-benefits

- International Marine Organization potential emission reduction estimates
  - Ship design, propulsion, machinery, vessel operation, alternative fuels

Δ O_3 From Base

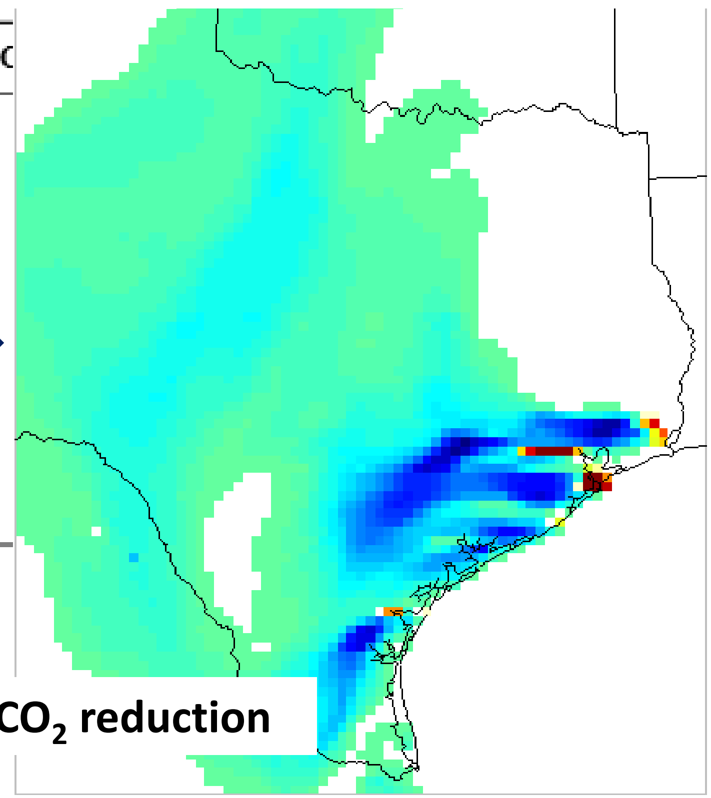
Assessment of Potential Reductions of CO_2 from Ocean Going Vessels

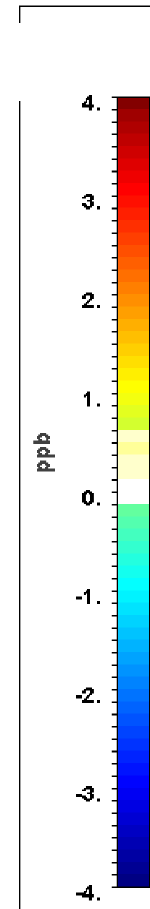




Saving (%) of C
2–50†
2–20
5–15
5–15*
1–10
5–50†
1–10
1–10

speed.





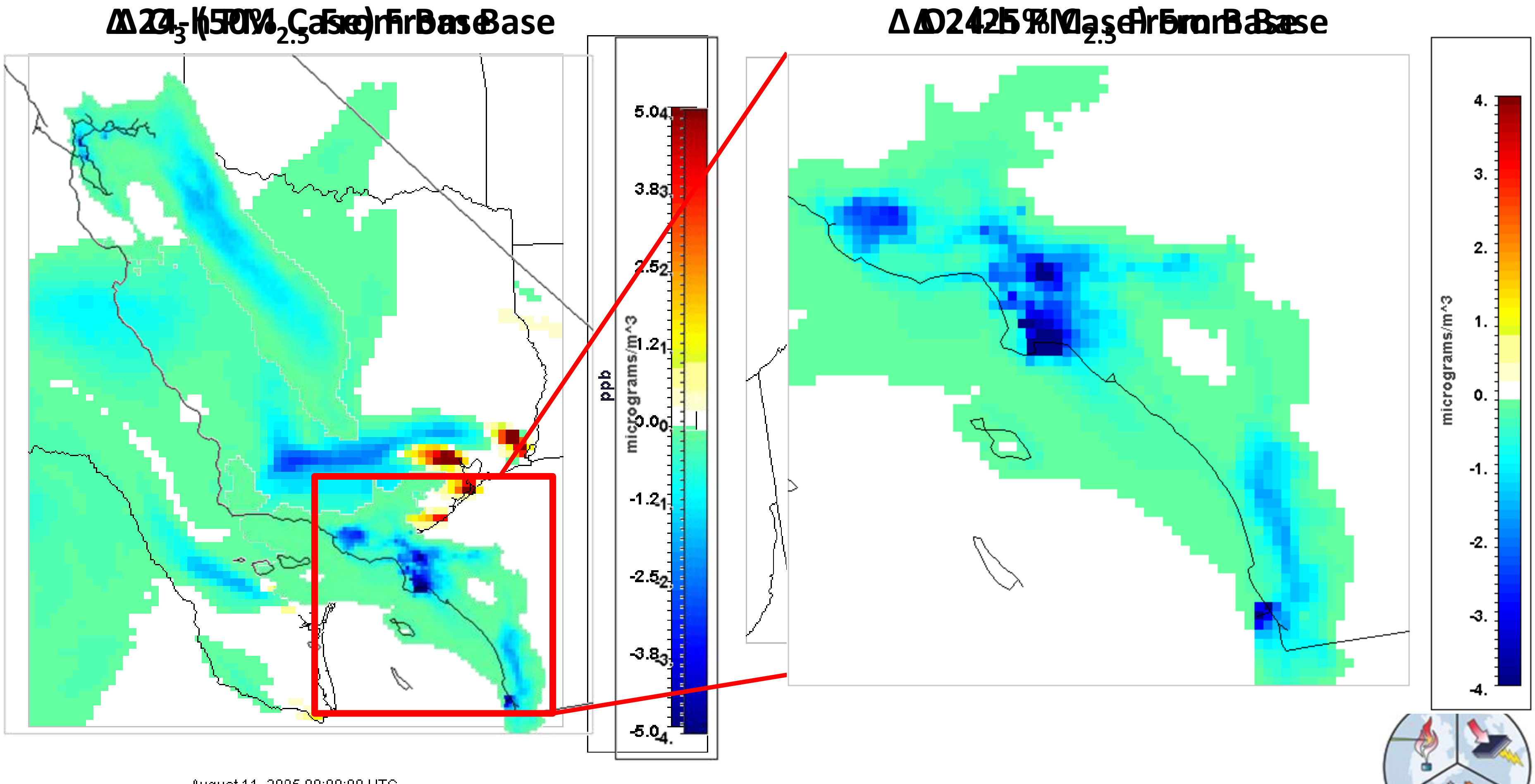
All measures in total ≈ 70% CO_2 reduction

Source: IMO 2009

Goods Movement Sector

GM sector emission reductions yield important AQ benefits

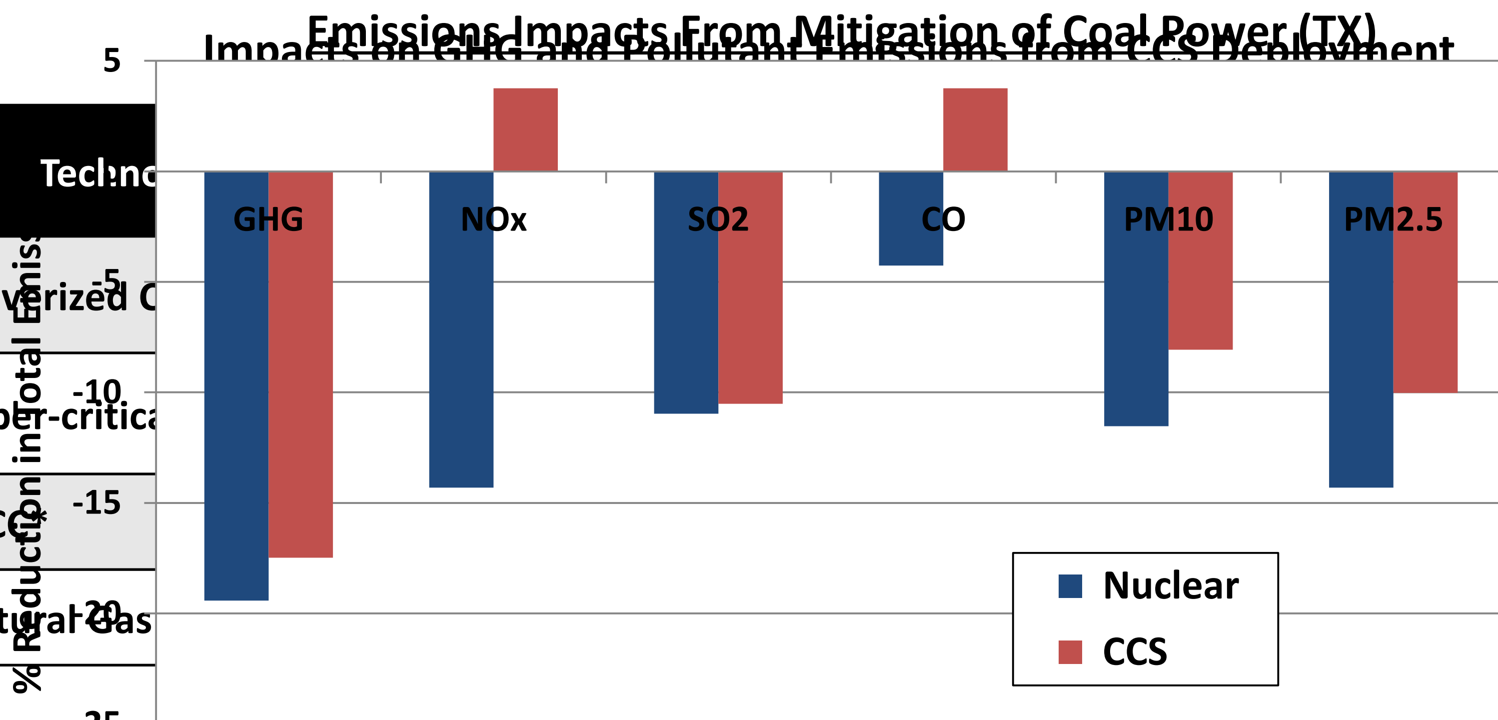
- Heavily impacted communities adjacent/upwind of major U.S. shipping ports
  - **Long Beach/L.A, Oakland, Houston, New York City, Philadelphia**



Coal Mitigation

Strategies to mitigate GHG emissions from coal power plants in TX

- **Nuclear Power**
  - Free of direct pollutant emissions, life cycle emissions comparable
- **Carbon Capture and Storage (CCS)**
  - Efficiency penalty → Net increase of some pollutants (NO_x)
  - Impacts of capture → Decrease per kWhr of some pollutants (SO_2)



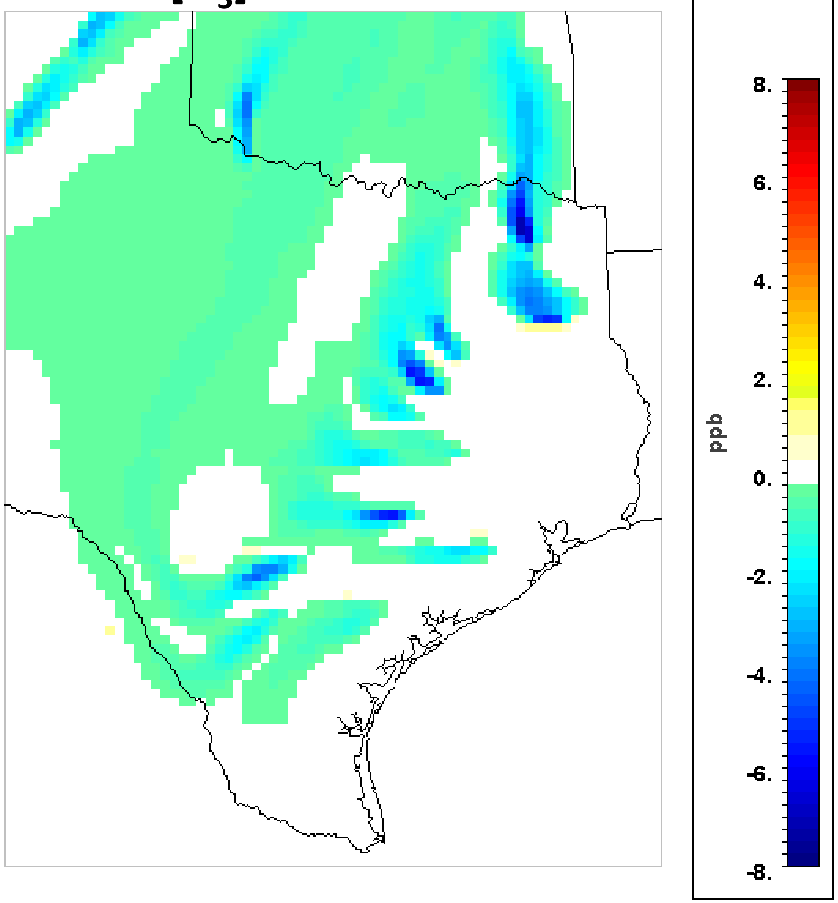
Techno	PM
Pulverized C	29-35)%
Super-critica	35-49)%
IGCC*	0-41)%
Natural Gas	to +25%

*** Integrated Gasification Combined Cycle**

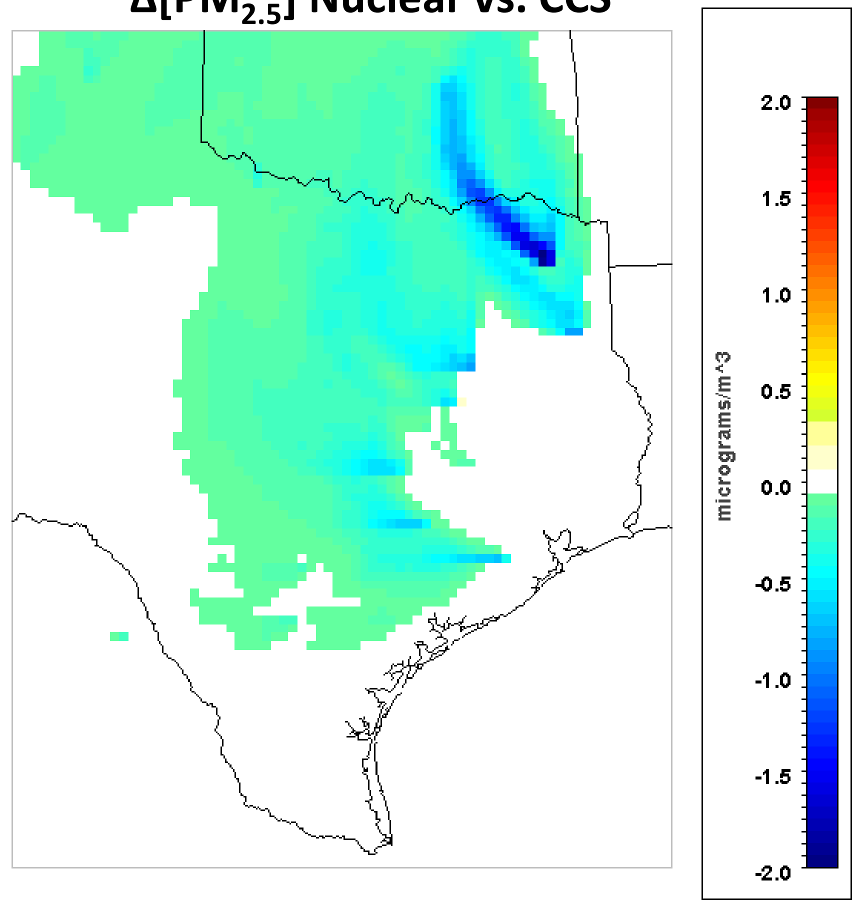
AQ co-benefits maximized by nuclear power relative to CCS

- Peak O_3 difference of 8 ppb localized to large capacity generators
- Reductions in 24-h $PM_{2.5}$ reach 2 μg/m^3 for nuclear scenario

$\Delta[O_3]$ Nuclear vs. CCS



$\Delta[PM_{2.5}]$ Nuclear vs. CCS

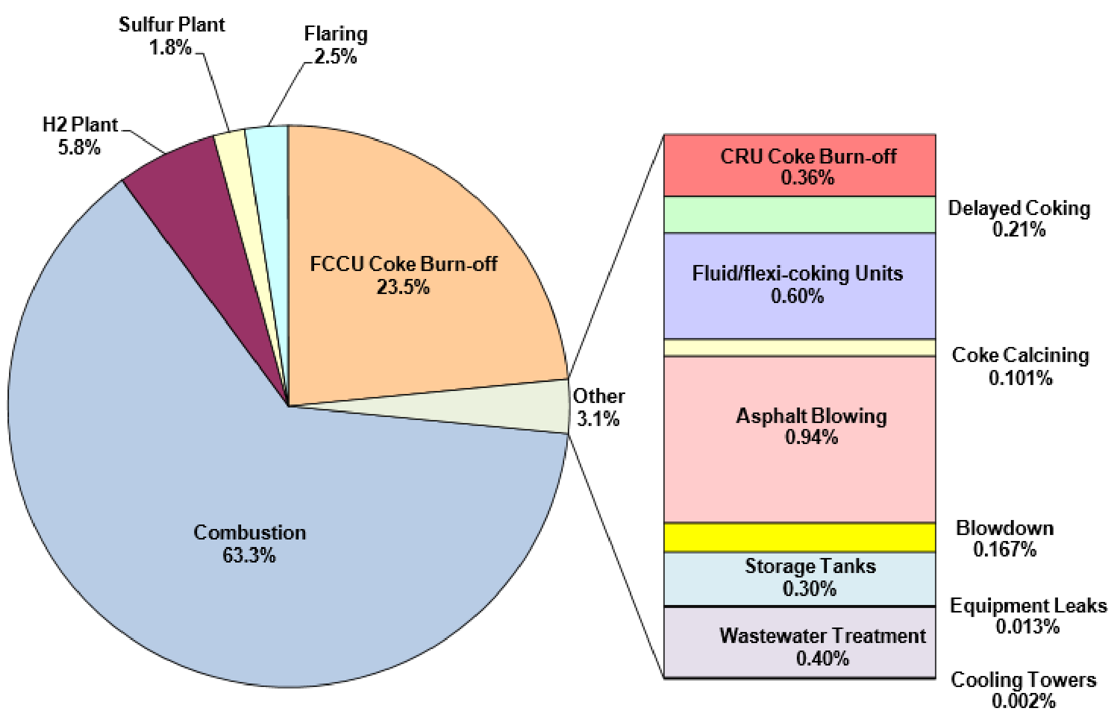


Industry – Petroleum Fuel Refining

Crude oil refining emissions reflect complexity of process

- Stationary combustion for heat/power/steam → limited large sources
  - CO_2, NO_x
- Various (vents, leaks, stacks, cooling towers) → diffuse, continuous or episodic
  - CO_2, CH_4, VOCs (potentially highly reactive)

Source Contribution of GHG emissions From Petroleum Refineries



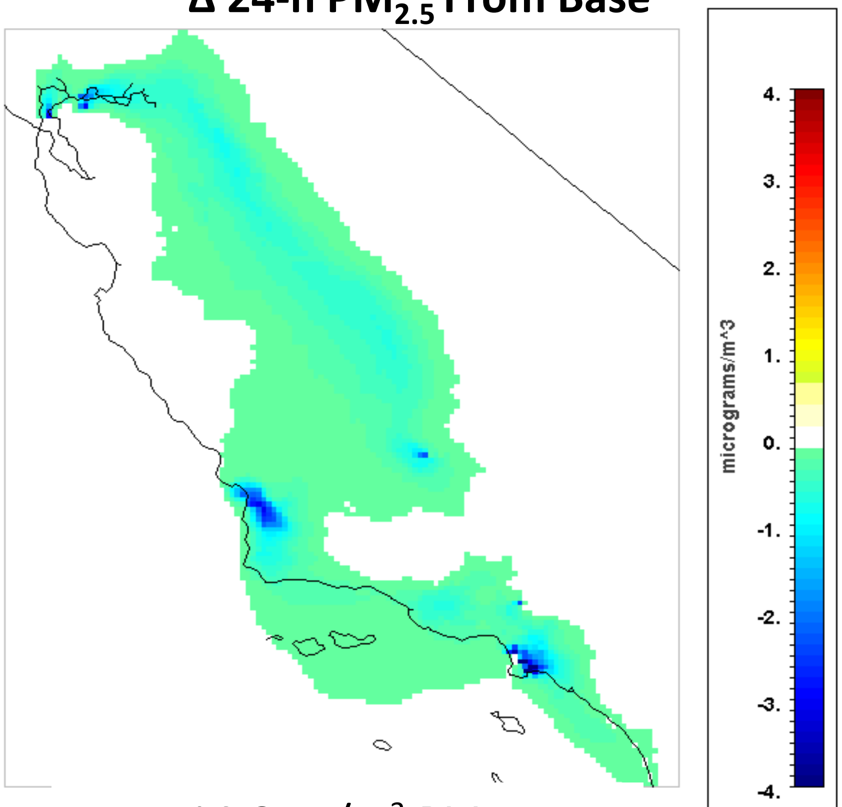
Source: U.S. EPA 2010

Petroleum Refinery Impacts

Petroleum fuel production/distribution has important AQ & GHG impacts

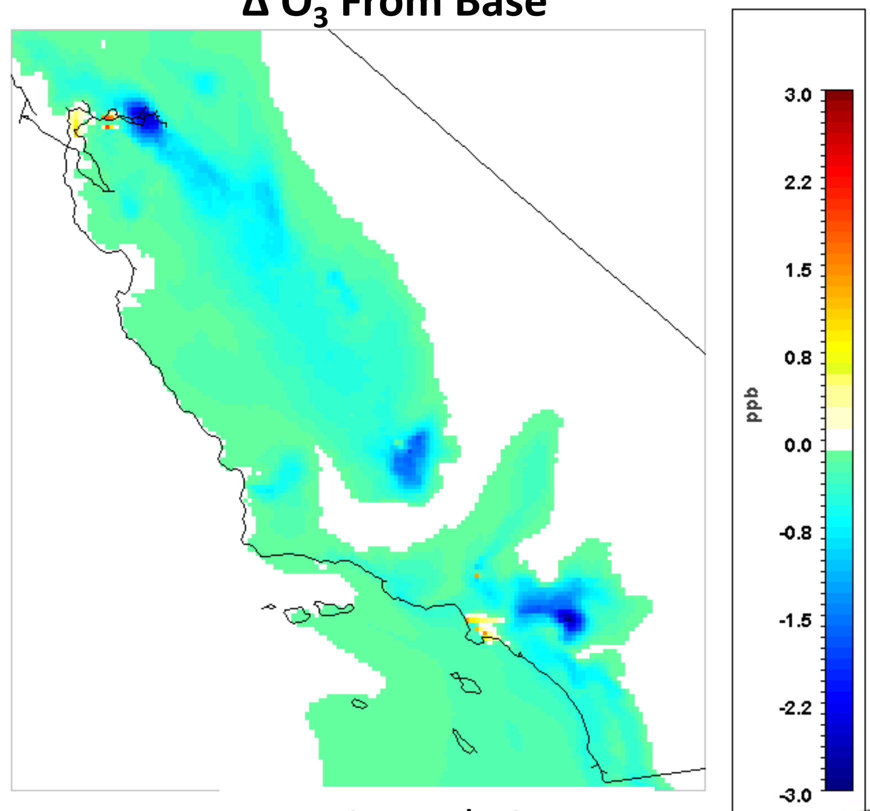
- Substantial reductions in O_3 and $PM_{2.5}$ for important CA regions
- Further motivation supporting transitions to alternative LDV strategies

Δ 24-h $PM_{2.5}$ From Base



-14.6 μg/m^3 $PM_{2.5}$

Δ O_3 From Base



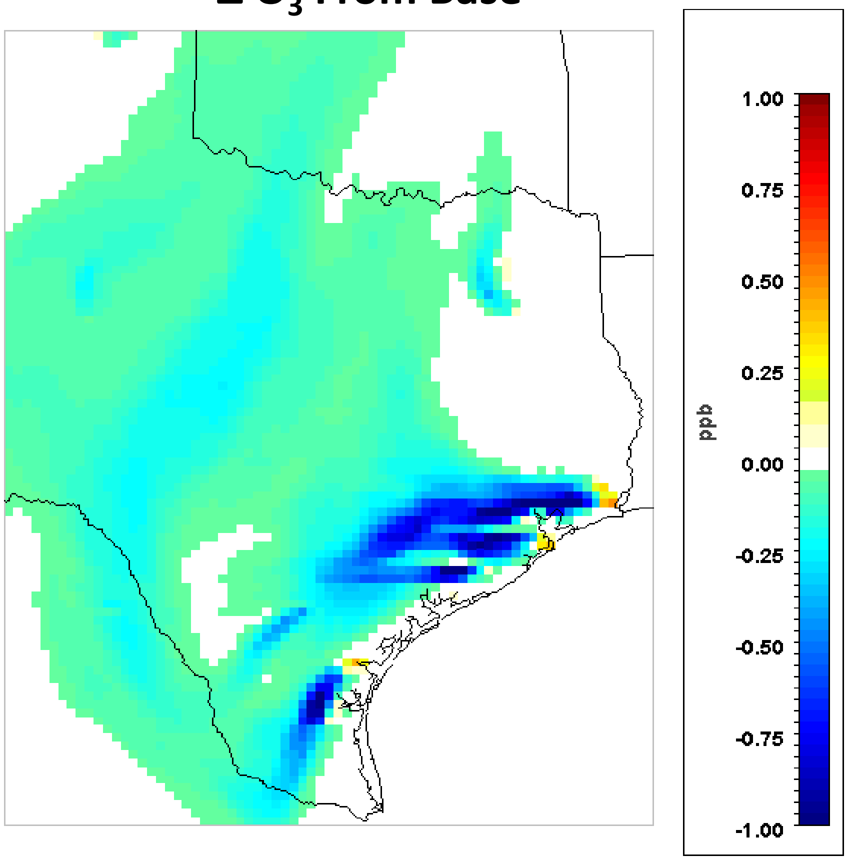
-3.5 ppb O_3

Industry – Petroleum Fuel Refining

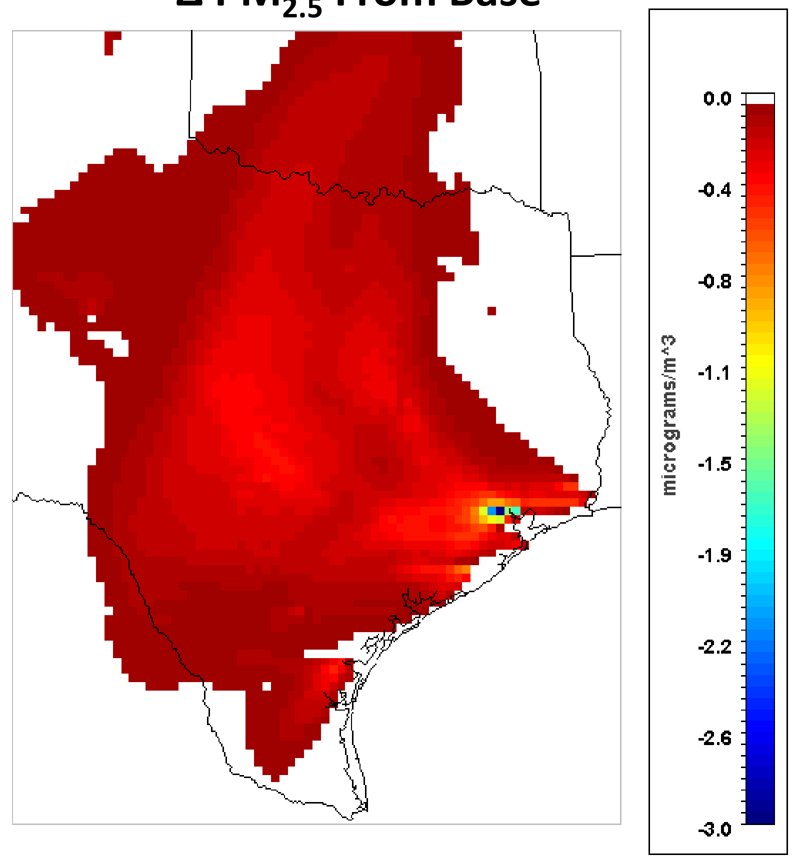
Petroleum fuel production/distribution important to AQ & GHG

- Annual GHG emissions for a large refinery ≈ 500 MW coal plant[1]
- Reductions in O_3 and $PM_{2.5}$ impact population centers in TX

Δ O_3 From Base



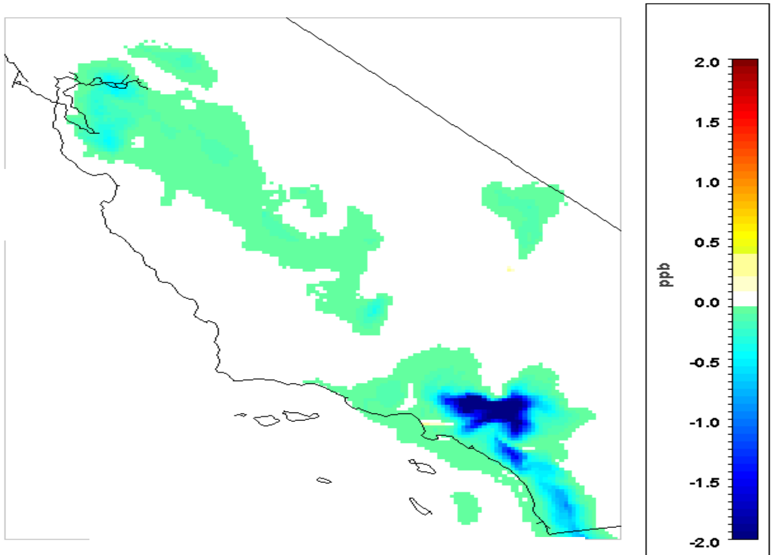
Δ $PM_{2.5}$ From Base



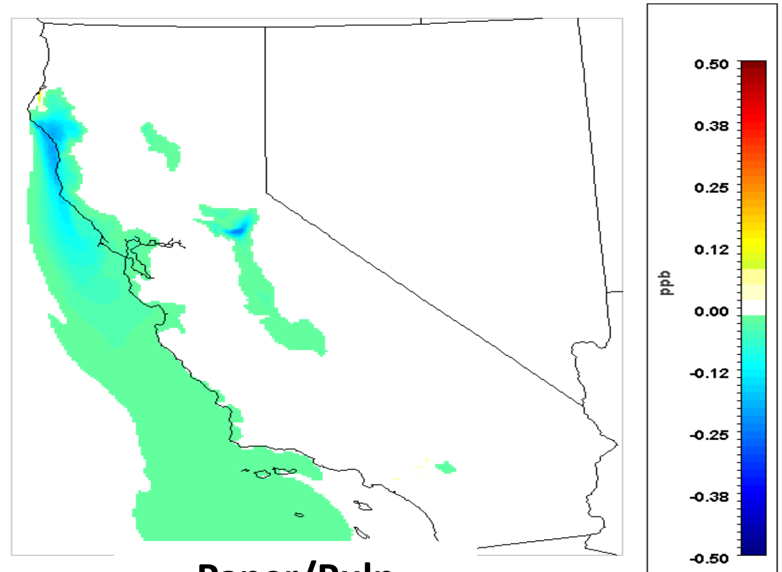
Source: Abella & Bergerson 2012

Industry Sub-sector O_3 Impacts – CA

-3.9 ppb



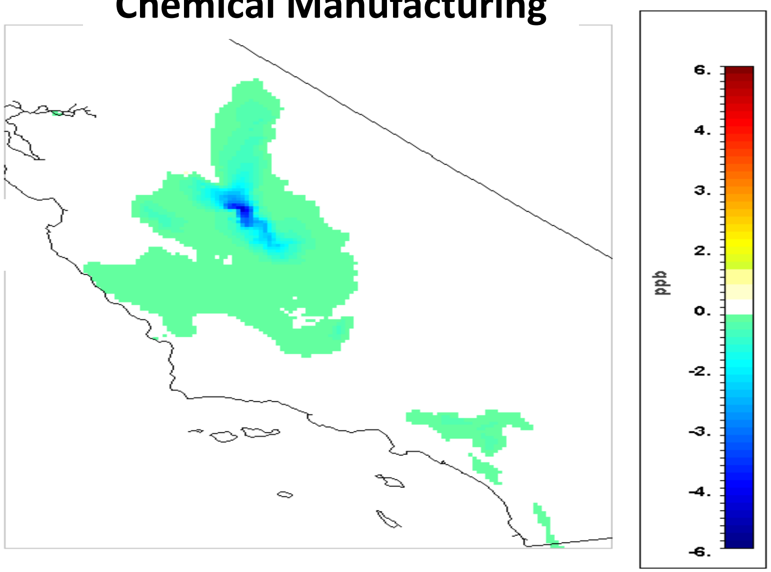
Chemical Manufacturing



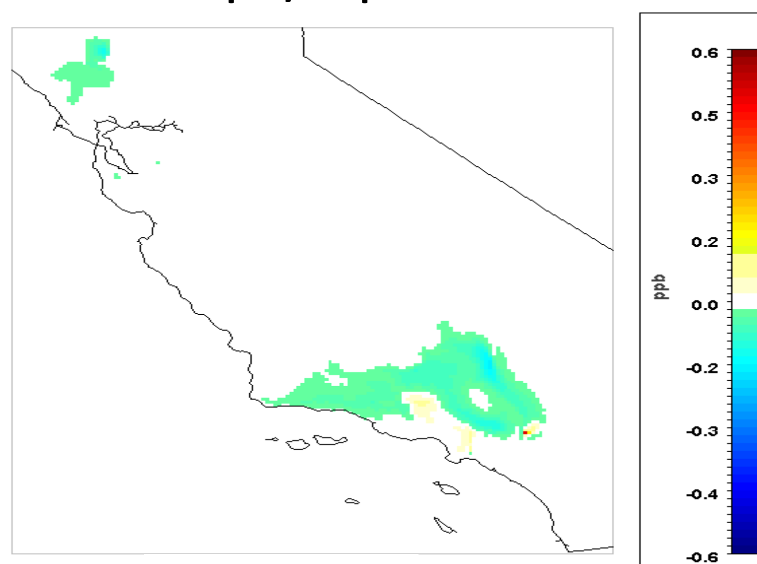
-1.07 ppb

Paper/Pulp

-6.5 ppb



Food Processing



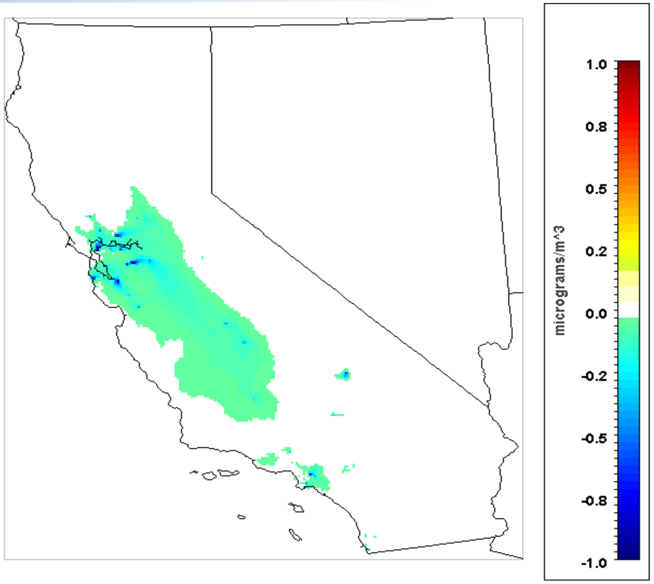
-0.63 ppb

Metals

Industry Sub-sector $PM_{2.5}$ Impacts – CA

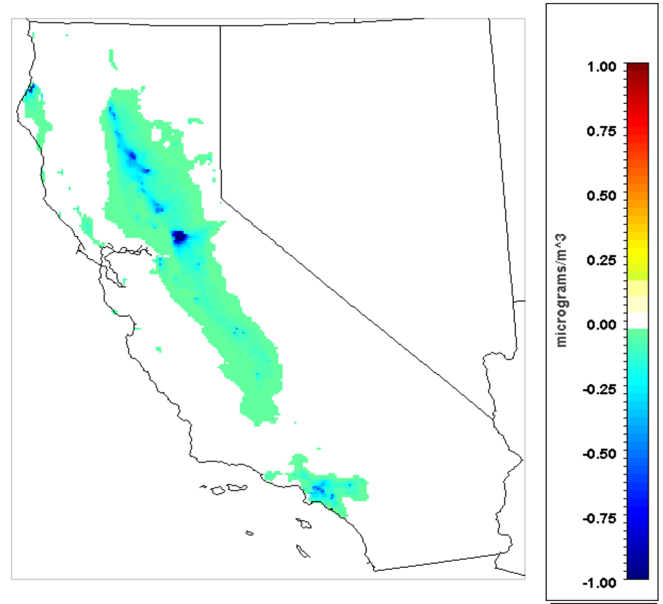
Chemical Manufact.

-2.66 μg/m³



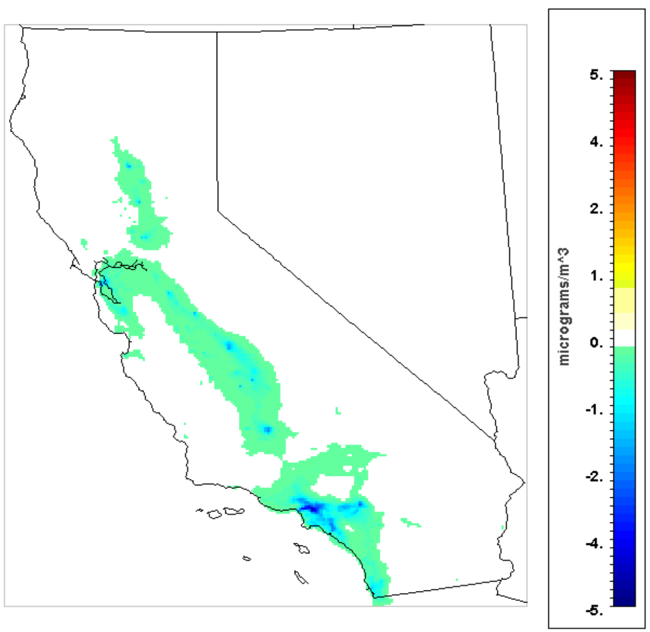
Paper/Pulp

-9.00 μg/m³



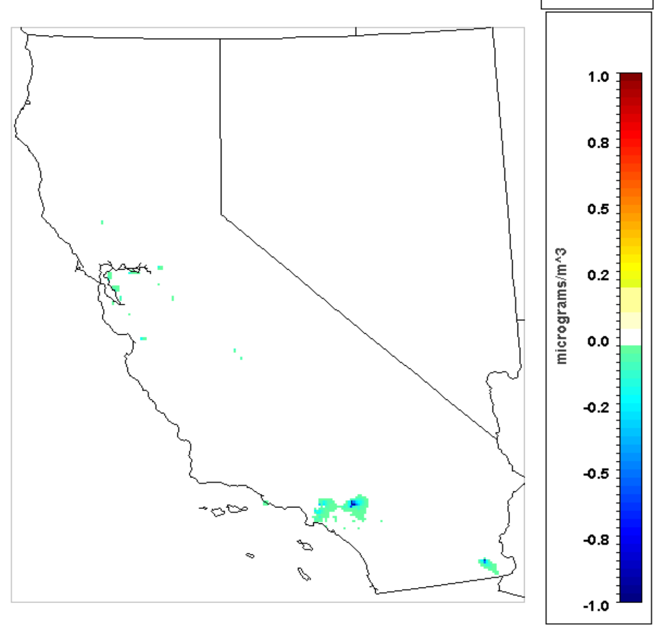
Food Processing

-5.82 μg/m³



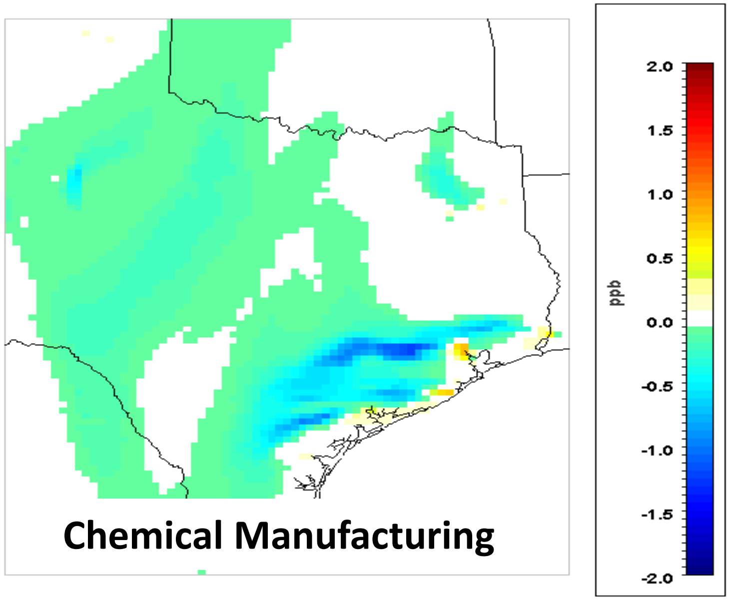
Metals

-3.32 μg/m³

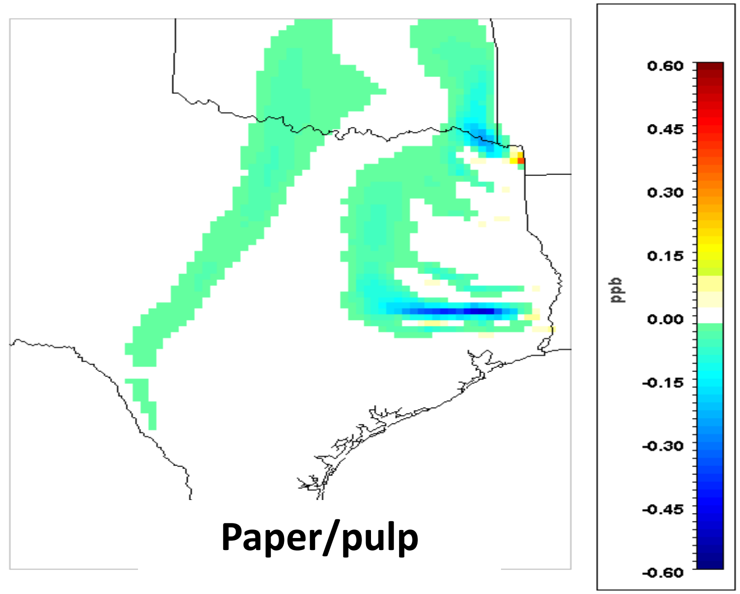


Industry Sub-sector O_3 Impacts – TX

-1.44 ppb



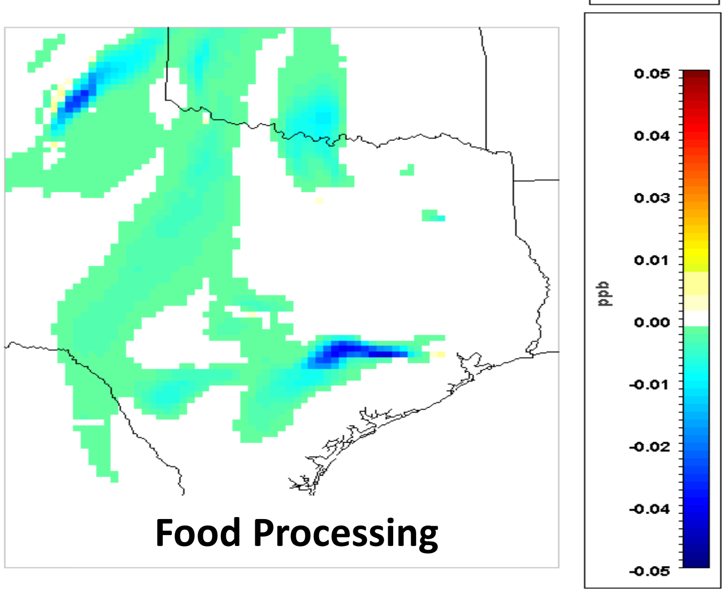
Chemical Manufacturing



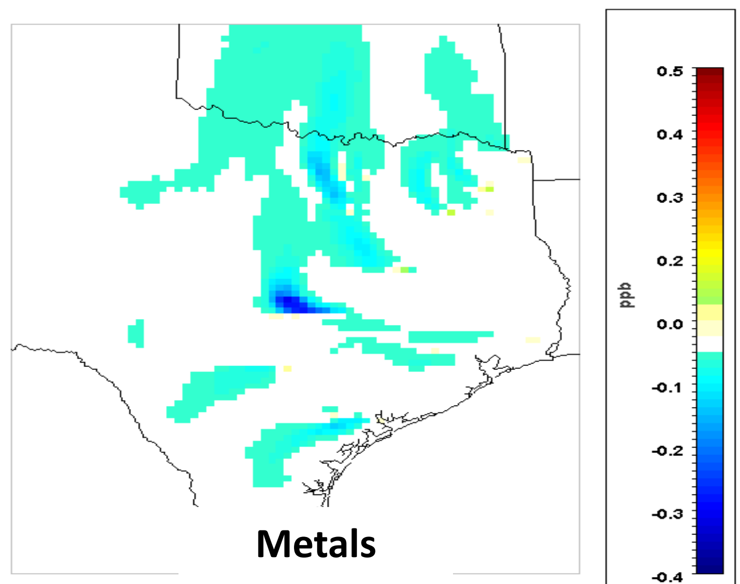
Paper/pulp

-0.78 ppb

-0.05 ppb



Food Processing

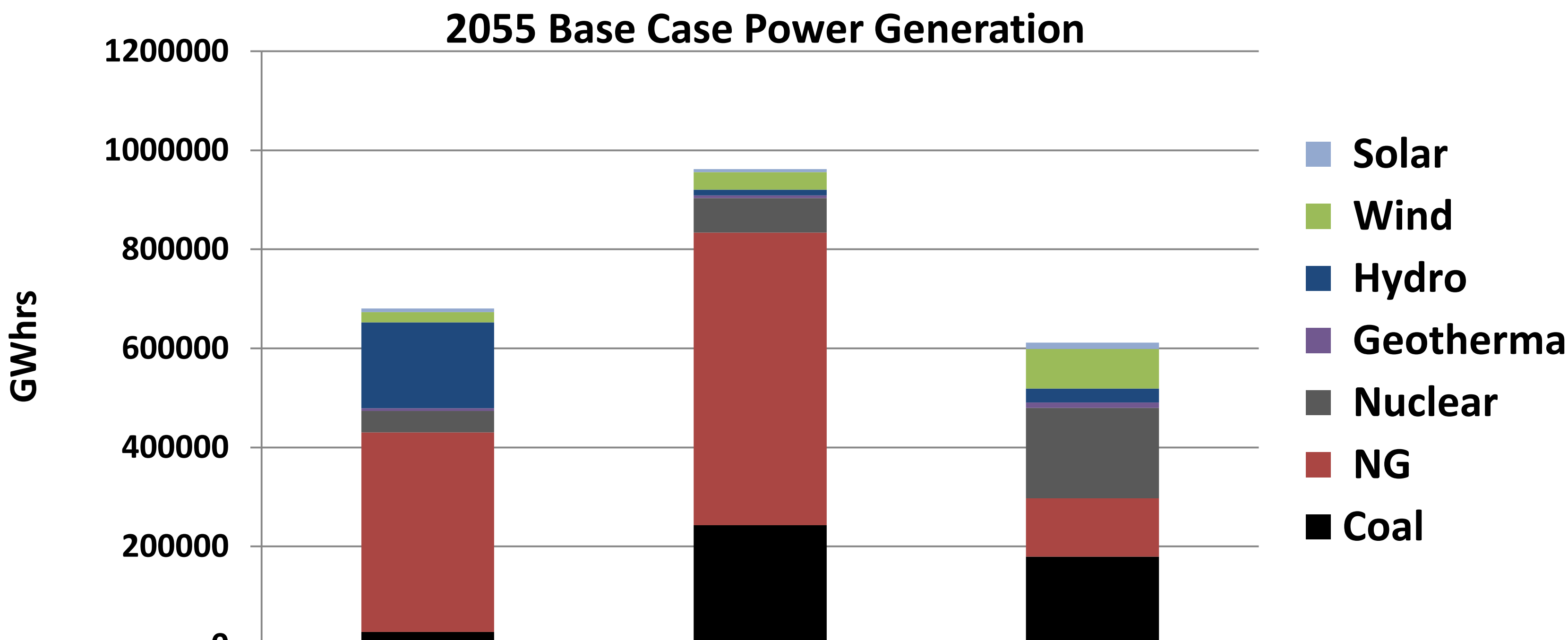


Metals

-0.43 ppb

Significant regional variation in utilized technologies and fuels

- Gas-fired generation growth substantial → Impacts of shale gas
- Coal utilized in TX and NEUS (offset in NEUS by significant nuclear power)
- CA relatively clean grid mix



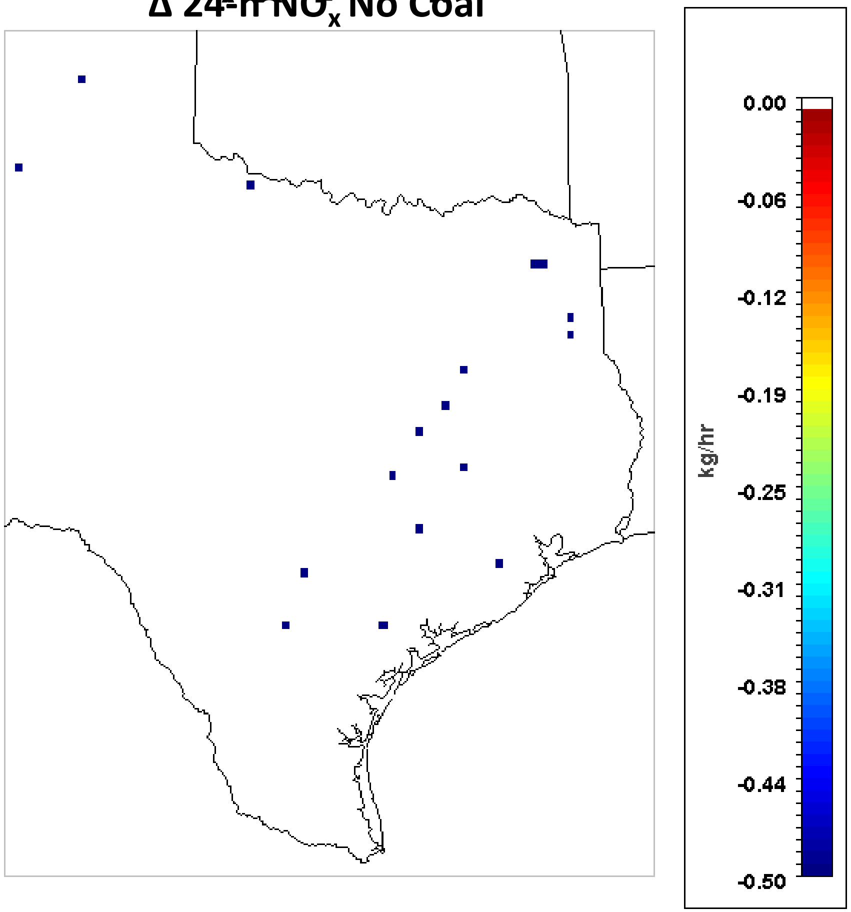
	CA	TX	NEUS	
Carbon Intensity:	243	466	262	g CO_2/kWh

Impacts of Coal Generation

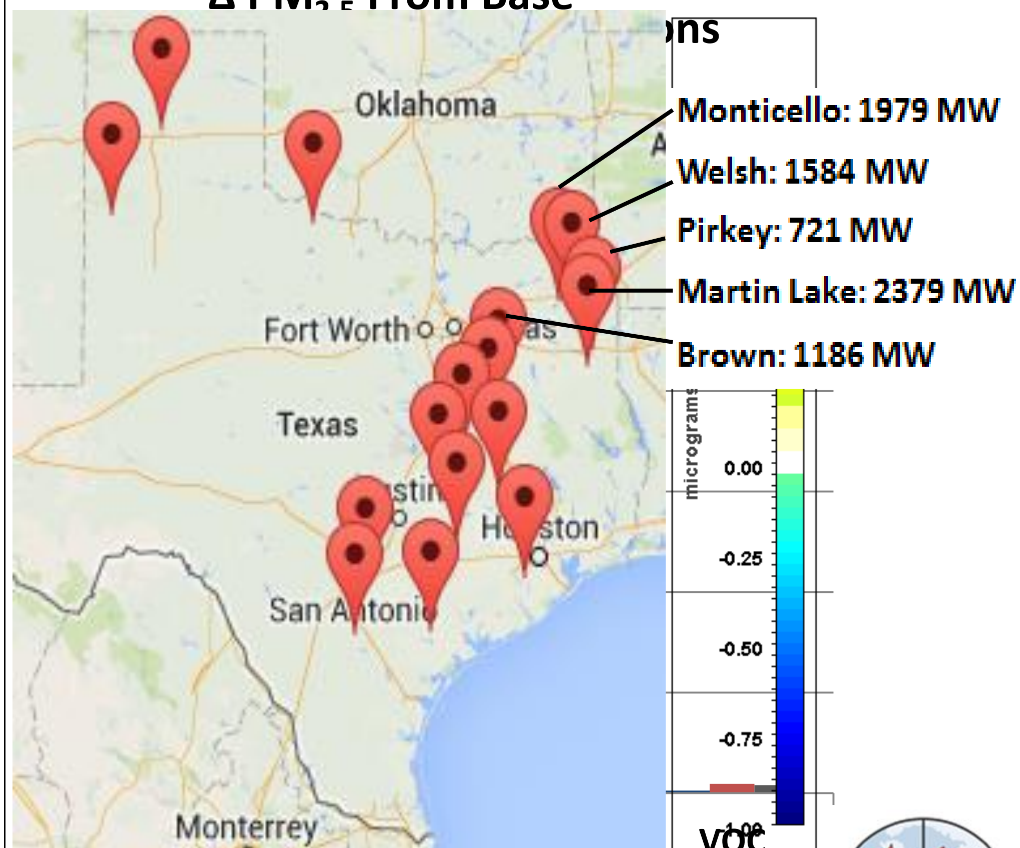
GHG and AQ impacts of coal generation important in 2055

– Despite optimistic outlook of natural gas displacement
  - 2055 share of total generation TX: 25%, NEUS R1: 11%, NEUS R2: 36%

Δ 24-h NO_x No Coal



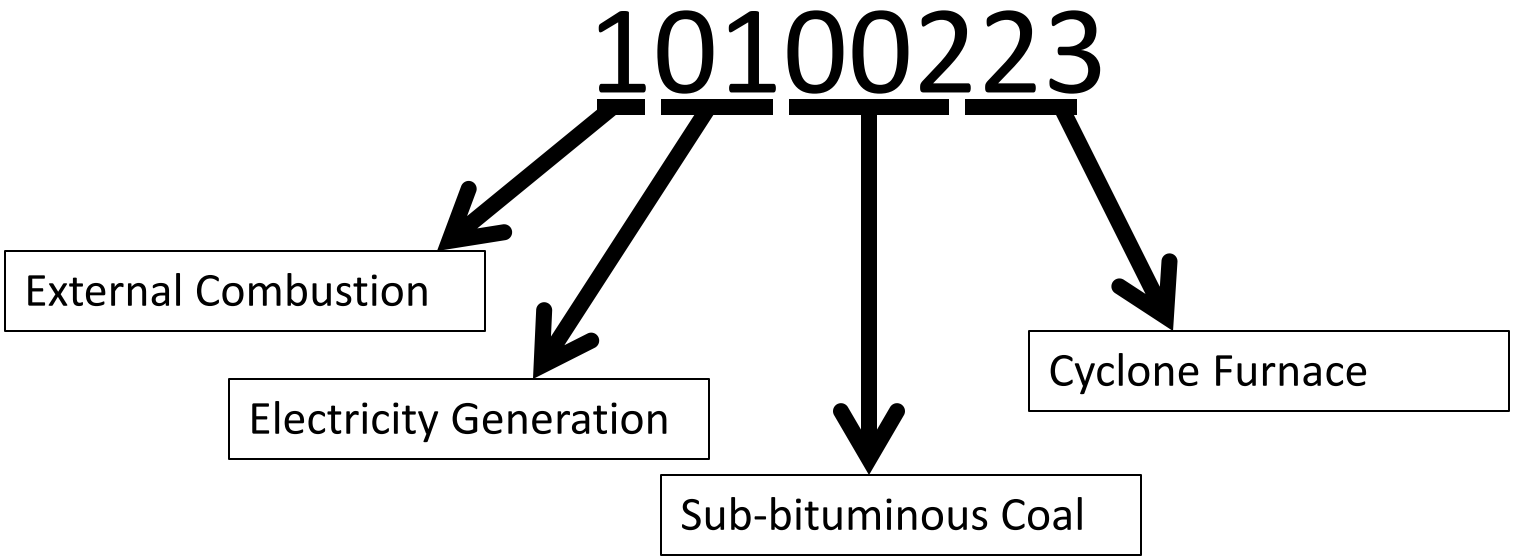
Δ $PM_{2.5}$ From Base



Methodology: Base Case

Detailed emissions apportionment based on Source Classification Codes (SCC)

- Assigned to specific emissions sources accounted for in NEI
- Allows emissions perturbations at desired level of specificity
  - Sectoral →Technology →Fuel



References: Power Sector

1. Dones, R., X. Zhou, and C. Tian, *Life Cycle Assessment (LCA) of Chinese energy chains for Shandong electricity scenarios.* International Journal of Global Energy Issues, 2004. 22(2): p. 199-224.
2. Odeh, N.A. and T.T. Cockerill, *Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage.* Energy Policy, 2008. 36(1): p. 367-380.
3. Dones, R., et al., *Life cycle inventories of energy systems: results for current systems in Switzerland and other UCTE countries.* Data v1, 2007a. 1.
4. Hondo, H., *Life cycle GHG emission analysis of power generation systems: Japanese case.* Energy, 2005. 30(11-12): p. 2042-2056.
5. Zhang, J., L. Basson, and M. Leach. *Review of life cycle assessment studies of coal-fired power plants with carbon capture and storage*. 2009: IEEE.
6. Ansolabehere, S., et al., *The future of coal: An interdisciplinary MIT study.* Massachusetts Institute of Technology, 2007.
7. Rubin, E.S., A.B. Rao, and C. Chen. *Comparative assessments of fossil fuel power plants with CO_2 capture and storage*. 2005.
8. Hammond, G.P., S. Akwe, and S. Williams, *Techno-economic appraisal of fossil-fuelled power generation systems with carbon dioxide capture and storage.* Energy, 2011. 36(2): p. 975-984.
9. Badea, A.A., I. Voda, and C.F. Dinca, *Comparative Analysis of Coal, Natural Gas, and Nuclear Fuel Life Cycle by Chains of Electrical Energy Production. .* UPB Scientific Bulletin, Series C: Electrical Engineering 72(2): 221-238, 2010.
10. Dolan, S.L., *Life cycle assessment and energy synthesis of a theoretical offshore wind farm for Jacksonville, Florida*. 2007, University of Florida.
11. Dones, R., et al., *Externalities of Energy: Extension of Accounting Framework and Policy Applications.* Paul Scherer Institute, 2005.
12. Kannan, R., et al., *Life cycle energy, emissions and cost inventory of power generation technologies in Singapore.* Renewable and Sustainable Energy Reviews, 2007. 11(4): p. 702-715.
13. Spath, P.L. and M.K. Mann, *Life cycle assessment of a natural gas combined-cycle power generation system*. 2000: National Renewable Energy Laboratory Golden, CO.
14. Kuemmel, B., B. Sorensen, and S.K. Nielsen, *Life-cycle Analysis of the Total Danish Energy System: An Assessment of the Present Danish Energy System and Selected Future Scenarios*. 1997: Roskilde Universitetscenter.
15. Chataignere, A. and D. Boulch, *Wind turbine (WT) systems.* ECLIPSE-Environmental and Ecological Life Cycle Inventories for present and future Power Systems in Europe. Final Report. www. eclipse-eu. org/pubres_guide. html (29.09. 2006), 2003.
16. Jungbluth, N., et al., *Life Cycle Assessment for Emerging Technologies: Case Studies for Photovoltaic and Wind Power (11 pp).* The International Journal of Life Cycle Assessment, 2005. 10(1): p. 24-34.
17. Schleisner, L., *Life cycle assessment of a wind farm and related externalities.* Renewable Energy, 2000. 20(3): p. 279-288.
18. Pehnt, M., *Dynamic life cycle assessment (LCA) of renewable energy technologies.* Renewable Energy, 2006. 31(1): p. 55-71.
19. Weinzettel, J., et al., *Life cycle assessment of a floating offshore wind turbine.* Renewable Energy, 2009. 34(3): p. 742-747.
20. Crawford, R., *Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield.* Renewable and Sustainable Energy Reviews, 2009. 13(9): p. 2653-2660.
21. Jacobson, M.Z., *Review of solutions to global warming, air pollution, and energy security.* Energy & Environmental Science, 2009. 2(2): p. 148-173.
22. Khan, F.I., K. Hawboldt, and M. Iqbal, *Life cycle analysis of wind-fuel cell integrated system.* Renewable Energy, 2005. 30(2): p. 157-177.
23. Martinez, E., et al., *Life-cycle assessment of a 2-MW rated power wind turbine: CML method.* The International Journal of Life Cycle Assessment, 2009. 14(1): p. 52-63.

References: Power Sector

24. Rule, B.M., Z.J. Worth, and C.A. Boyle, *Comparison of life cycle carbon dioxide emissions and embodied energy in four renewable electricity generation technologies in New Zealand.* Environmental science & technology, 2009. 43(16): p. 6406-6413.
25. Fthenakis, V.M., H.C. Kim, and E. Alsema, *Emissions from photovoltaic life cycles.* Environmental science & technology, 2008. 42(6): p. 2168-2174.
26. Fthenakis, V., et al. *Update of PV Energy Payback Times and Life-cycle Greenhouse Gas Emissions.* . in *24nd European Photovoltaic Solar Energy Conference and Exhibition.* . 2009. Hamburg, Germany.
27. Raugei, M. and P. Frankl, *Life cycle impacts and costs of photovoltaic systems: Current state of the art and future outlooks.* Energy, 2009. 34(3): p. 392-399.
28. Pacca, S., D. Sivaraman, and G. Keoleian, *Life cycle assessment of the 33 kW photovoltaic system on the Dana Building at the University of Michigan: Thin film laminates, multi-crystalline modules, and balance of system components.* University of Michigan: Michigan, USA, 2006.
29. Raugei, M., S. Bargigli, and S. Ulgiati, *Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si.* Energy, 2007. 32(8): p. 1310-1318.
30. Alsema, E., *Energy pay-back time and CO2 emissions of PV systems.* Progress in Photovoltaics: Research and Applications, 2000. 8(1): p. 17-25.
31. Alsema, E., M. de Wild-Scholten, and V. Fthenakis. *Environmental impacts of PV electricity generation-a critical comparison of energy supply options*. 2006.
32. Stoppato, A., *Life cycle assessment of photovoltaic electricity generation.* Energy, 2008. 33(2): p. 224-232.
33. Jungbluth, N., M. Stucki, and R. Frischknecht, *Photovoltaics.* . Dubendorf, Switzerland: Ecoinvent: Swiss Centre for Life Cycle Inventories 2009(6-XII).
34. Weinrebe, G., M. Bohnke, and F. Trieb, *Life cycle assessment of an 80 MW SEGS plant and a 30 MW Phoebus power tower.* Solar Engineering, 1998: p. 417-424.
35. Becerra-Lopez, H.R. and P. Golding, *Dynamic exergy analysis for capacity expansion of regional power-generation systems: Case study of far West Texas.* Energy, 2007. 32(11): p. 2167-2186.
36. Viebahn, P., et al., *Final report on technical data, costs, and life cycle inventories of solar thermal power plants.* NEEDS Project Final Report, www. needs-project. org. Accessed November, 2008. 1: p. 2009.
37. Burkhardt III, J.J., G.A. Heath, and C.S. Turchi, *Life Cycle Assessment of a Parabolic Trough Concentrating Solar Power Plant and the Impacts of Key Design Alternatives.* Environmental science & technology, 2011.
38. Burkhardt III, J.J., G. Heath, and E. Cohen, *Life Cycle Greenhouse Gas Emissions of Trough and Tower Concentrating Solar Power Electricity Generation. Systematic Review and Harmonization.* . Journal of Industrial Ecology, 2012. 16(S1): p. S93-S109.
39. Martin, J.A., *A total fuel cycle approach to reducing greenhouse gas emissions: Solar generation technologies as greenhouse gas offsets in US utility systems.* Solar energy, 1997. 59(4): p. 195-203.
40. Frick, S., M. Kaltschmitt, and G. Schroder, *Life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs.* Energy, 2010. 35(5): p. 2281-2294.
41. Rogge, S. and M. Kaltschmitt, *Electricity and heat production from geothermal energy-an ecologic comparison.* Erdoel Erdgas Kohle, 2003. 119(1): p. 35-40.
42. Woollcombe-Adams, C., M. Watson, and T. Shaw, *Severn Barrage tidal power project: implications for carbon emissions.* Water and Environment Journal, 2009. 23(1): p. 63-68.
43. Kelly, K., M. McManus, and G. Hammond, *An energy and carbon life cycle assessment of tidal power case study: The proposed Cardiff-Weston severn barrage scheme.* Energy, 2012.
44. Denholm, P. and G.L. Kulcinski, *Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems.* Energy Conversion and Management, 2004. 45(13): p. 2153-2172.
45. Horvath, A., *Decision-making in electricity generation based on global warming potential and life-cycle assessment for climate change.* University of California Energy Institute, 20[illegible]

References: Power Sector

46. Pacca, S., *Impacts from decommissioning of hydroelectric dams: a life cycle perspective.* Climatic Change, 2007. 84(3): p. 281-294.
47. Ribeiro, F.M. and G.A. da Silva, *Life-cycle inventory for hydroelectric generation: a Brazilian case study.* Journal of Cleaner Production, 2009. 18(1): p. 44-54.
48. Dubuisson, X. and I. Sintzoff, *Energy and CO2 balances in different power generation routes using wood fuel from short rotation coppice.* Biomass and Bioenergy, 1998. 15(4-5): p. 379-390.
49. Hacatoglu, K., P.J. McLellan, and D.B. Layzell, *Feasibility study of a Great Lakes bioenergy system.* Bioresource technology, 2011. 102(2): p. 1087-1094.
50. Gartner, S., *Final report on technical data, costs and life cycle inventories of biomass CHP plants.* NEEDS Deliverable, 2008(13.2-RS).
51. Fan, J., et al., *Life cycle assessment of electricity generation using fast pyrolysis bio-oil.* Renewable Energy, 2011. 36(2): p. 632-641.
52. Elsayed, M., R. Matthews, and N. Mortimer, *Carbon and energy balances for a range of biofuels options*. 2003: Resources Research Unit, Sheffield Hallam Univ.
53. Kirkinen, J., et al., *Greenhouse impact due to the use of combustible fuels: life cycle viewpoint and relative radiative forcing commitment.* Environmental Management, 2008. 42(3): p. 458-469.
54. Cherubini, F., et al., *Energy-and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations.* Resources, Conservation and Recycling, 2009. 53(8): p. 434-447.
55. Lu, W. and T. Zhang, *Life-cycle implications of using crop residues for various energy demands in china.* Environmental science & technology, 2010. 44(10): p. 4026-4032.
56. Hong, S.W., *The usability of switchgrass, rice straw, and logging residue as feedstocks for power generation in East Texas*. 2007, Texas A&M University.
57. Searcy, E. and P.C. Flynn, *Processing of straw/corn stover: comparison of life cycle emissions.* International Journal of Green Energy, 2008. 5(6): p. 423-437.
58. Forsberg, G., *Biomass energy transport: Analysis of bioenergy transport chains using life cycle inventory method.* Biomass and Bioenergy, 2000. 19(1): p. 17-30.
59. Froese, R.E., et al., *An evaluation of greenhouse gas mitigation options for coal-fired power plants in the US Great Lakes States.* Biomass and Bioenergy, 2010. 34(3): p. 251-262.
60. McKechnie, J., et al., *Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels.* Environ. Sci. Technol. 45: p. 789-795.
61. Daugherty, E. and H. Stripple, *Biomass Energy Systems Efficiency: Analyzed through a Life Cycle Assessment.* Lund Univesity, 2001.
62. Yoshida, Y., et al., *Comprehensive comparison of efficiency and CO2 emissions between biomass energy conversion technologies-position of supercritical water gasification in biomass technologies.* Biomass and Bioenergy, 2003. 25(3): p. 257-272.
63. Heller, M.C., et al., *Life cycle energy and environmental benefits of generating electricity from willow biomass.* Renewable Energy, 2004. 29(7): p. 1023-1042.
64. Roedl, A., *Production and energetic utilization of wood from short rotation coppiceâ€"a life cycle assessment.* The International Journal of Life Cycle Assessment, 2010. 15(6): p. 567-578.
65. Edenhofer, O., et al., *Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change*. 2011: Cambridge University Press.
66. Spath, P.L. and M.K. Mann, *Biomass Power and Conventional Fossil Systems with and without CO2 Sequestration--Comparing the Energy Balance, Greenhouse Gas Emissions and Economics*. 2004, National Renewable Energy Lab., Golden, CO.(US).
67. Lecointe, C., et al., *Final report on technical data, costs and life cycle inventories of nuclear power plants.* 2007.
68. Warner, E.S. and G.A. Heath, *Life Cycle Greenhouse Gas Emissions of Nuclear Electricity Generation.* Journal of Industrial Ecology, 2012.
69. Lenzen, M., *Life cycle energy and greenhouse gas emissions of nuclear energy: A review.* Energy Conversion and Management, 2008. 49(8): p. 2178-2199.

References: Power Sector

70. Fthenakis, V.M. and H.C. Kim, *Greenhouse-gas emissions from solar electric-and nuclear power: A life-cycle study.* Energy Policy, 2007. 35(4): p. 2549-2557.
71. Beerten, J., et al., *Greenhouse gas emissions in the nuclear life cycle: A balanced appraisal.* Energy Policy, 2009. 37(12): p. 5056-5068.
72. Rashad, S. and F. Hammad, *Nuclear power and the environment: comparative assessment of environmental and health impacts of electricity-generating systems.* Applied Energy, 2000. 65(1): p. 211-229.
73. Sovacool, B.K., *Valuing the greenhouse gas emissions from nuclear power: A critical survey.* Energy Policy, 2008. 36(8): p. 2950-2963.
74. IPCC, *IPCC Special Report on Carbon Dioxide Capture and Storage*, B. Metz et al., Editor. 2005, Intergovernmental Panel on Climate Change: New York
75. Viebahn, P., et al., *Comparison of carbon capture and storage with renewable energy technologies regarding structural, economic, and ecological aspects in Germany.* International Journal of Greenhouse Gas Control, 2007. 1(1): p. 121-133.
76. Pehnt, M. and J. Henkel, *Life cycle assessment of carbon dioxide capture and storage from lignite power plants.* International Journal of Greenhouse Gas Control, 2009. 3(1): p. 49-66.
77. Greene, D.L., et al., *Energy Assurance: Essential Energy Technologies for Climate Protection and Energy Security*. 2009, Oak Ridge National Laboratory (ORNL).
78. EPRI, *The Power to Reduce CO2 Emissions: The Full Portfolio – 2009 Technical Report* 2009, Electronic Power Research Institute: 2009 http://my.epri.com/portal/server.pt?open=512&objID=216&&PageID=229721&mode=2 (Accessed September 20, 2011).
79. Williams, J.H., et al., *The technology path to deep greenhouse gas emissions cuts by 2050: the pivotal role of electricity.* Science, 2012. 335(6064): p. 53-59.
80. ASES, *Tackling climate change in the U.S.: Potential carbon emissions reductions from energy efficiency and renewable energy by 2030*, Kutscher, C., Ed; American Solar Energy Society (ASES): 2007. http://ases.org/images/stories/file/ASES/climate_change.pdf (accessed September 8, 2011).
81. McKinsey & Co., *Reducing US Greenhouse Gas Emissions: How Much at What Cost?*, McKinsey & Co.: 2007. http://mckinsey.com/clientservice/ccsi/greenhousegas.asp (accessed September 13, 2011).
82. McKinsey & Co., *Unlocking Energy Efficiency in the U.S. Economy*, McKinsey & Co.: 2009. http://www.mckinsey.com/Client_Service/Electric_Power_and_Natural_Gas/Latest_thinking/Unlocking_energy_efficiency_in_the_US_economy.aspx (accessed July 20, 2011).
83. NETL, *Improving the Efficiency of Coal-Fired Power Plants for Near Term Greenhouse Gas Emissions Reductions*. 2010, U.S. Department of Energy
84. EPRI, *The Green Grid: Energy Savings and Carbon Emissions Reductions Enabled by a Smart Grid*. 2008, Electric Power Research Institute.
85. U.S. DOE, *The Smart Grid: An Introduction* U.S. Department of Energy: 2008 http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/DOE_SG_Book_Single_Pages%281%29.pdf

References: Transportation

1. Bandivadekar, A., et al., *On the road in 2035: Reducing transportation's petroleum consumption and GHG emissions.* Report No. LFEE, 2008. 5.
2. NESCCAF, *Reducing Greenhouse Gas Emissions from Light-Duty Motor Vehicles* 2004, Northeast States Center for a Clean Air Future (NESCCAF)
3. Pickrel, D., *Fuel Options for Reducing Greenhouse Gas Emissions from Motor Vehicles* 2003, U.S. Department of Transportation (DOT), Cambridge MA.
4. Lutsey, N.P. and D. Sperling, *Transportation and greenhouse gas mitigation.* 2008.
5. Brinckerhoff, P., *Greenhouse Gas (GHG) and Energy Mitigation for the Transportation Sector.* 2009.
6. Greene, D.L. and P.C.o.G.C. Change, *Reducing greenhouse gas emissions from US transportation*. 2003: Pew Center on Global Climate Change.
7. Greene, D.L. and S.E. Plotkin, *Reducing Greenhouse Gas Emissions from U.S. Transportation* 2011, Pew Center of Global Climate Change.
8. U.S. DOT, *Transportation's Role in Reducing US Greenhouse Gas Emissions: Volume 1: Synthesis Report and Volume 2: Technical Report*, U.S. Department of Transportation: 2010 http://ntl.bts.gov/lib/32000/32700/32779/DOT_Climate_Change_Report_-_April_2010_-_Volume_1_and_2.pdf (accessed July 2, 2011).
9. Thomas, S., *Transportation options in a carbon-constrained world: Hybrids, plug-in hybrids, biofuels, fuel cell electric vehicles, and battery electric vehicles.* International Journal of Hydrogen Energy, 2009. 34(23): p. 9279-9296.
10. Kromer, M. and J. Heywood, *Electric Powertrains: Opportunities And Challenges in the US Light-Duty Vehicle Fleet, LFEE 2007-03 RP.* Sloan Automotive Laboratory, Massachusetts Institute of Technology, Cambridge, MA, 2007.
11. Andress, D., T.D. Nguyen, and S. Das, *Reducing GHG emissions in the United States' transportation sector.* Energy for Sustainable Development, 2011.
12. Stephens-Romero, S. and G.S. Samuelsen, *Demonstration of a novel assessment methodology for hydrogen infrastructure deployment.* International Journal of Hydrogen Energy, 2009. 34(2): p. 628-641.
13. Thomas, C., *Fuel cell and battery electric vehicles compared.* International Journal of Hydrogen Energy, 2009. 34(15): p. 6005-6020.
14. Stephens-Romero, S., et al., *Determining air quality and greenhouse gas impacts of hydrogen infrastructure and fuel cell vehicles.* Environmental Science & Technology, 2009. 43(23): p. 9022-9029.
15. NREL. *Fuel Cell Vehicle Fuel Economy, Greenhouse Gas, and Stack Efficiency*. Hydrogen Fuel Cells and Research:Composite Data Products by Topic 2009b [cited 2011 October 28]; Available from: http://www.nrel.gov/hydrogen/cdp_topic.html#economy.
16. Brouwer, J., *On the role of fuel cells and hydrogen in a more sustainable and renewable energy future.* Current Applied Physics, 2010. 10(2): p. S9-S17.
17. Greene, D.L., et al., *Analysis of the Transition to Hydrogen Fuel Cell Vehicles and the Potential Hydrogen Energy Infrastructure Requirements.* Oak Ridge National Laboratory, US Department of Energy, 2008.
18. Granovskii, M., I. Dincer, and M.A. Rosen, *Life cycle assessment of hydrogen fuel cell and gasoline vehicles.* International Journal of Hydrogen Energy, 2006. 31(3): p. 337-352.
19. National Research Council, *Transitions to Alternative Transportation Technologies - A Focus on Hydrogen*. Committee on Assesment of Resource Needs for Fuel Cell and Hydrogen Technologies, 2008: Washington D.C.

References: Transportation

20. Kobayashi, S., S. Plotkin, and S.K. Ribeiro, *Energy efficiency technologies for road vehicles.* Energy Efficiency, 2009. 2(2): p. 125-137.
21. Granovskii, M., I. Dincer, and M.A. Rosen, *Exergetic life cycle assessment of hydrogen production from renewables.* Journal of Power Sources, 2007. 167(2): p. 461-471.
22. Colella, W., M. Jacobson, and D. Golden, *Switching to a US hydrogen fuel cell vehicle fleet: The resultant change in emissions, energy use, and greenhouse gases.* Journal of Power Sources, 2005. 150: p. 150-181.
23. Jacobson, M.Z., *Effects of wind-powered hydrogen fuel cell vehicles on stratospheric ozone and global climate.* Geophys. Res. Lett, 2008. 35: p. 19.
24. Dougherty, W., et al., *Greenhouse gas reduction benefits and costs of a large-scale transition to hydrogen in the USA.* Energy Policy, 2009. 37(1): p. 56-67.
25. Stephan, C.H. and J. Sullivan, *Environmental and energy implications of plug-in hybrid-electric vehicles.* Environmental science & technology, 2008. 42(4): p. 1185-1190.
26. Kempton, W., et al., *Large CO2 reductions via offshore wind power matched to inherent storage in energy end-uses.* Geophysical Research Letters, 2007. 34(2): p. L02817.
27. Samaras, C. and K. Meisterling, *Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: Implications for policy.* Environmental Science & Technology, 2008. 42(9): p. 3170-3176.
28. Elgowainy, A., et al., *Well-to-wheels energy use and greenhouse gas emissions analysis of plug-in hybrid electric vehicles*. 2009, Argonne National Laboratory (ANL).
29. Kliesch, J., T. Langer, and E. American Council for an Energy-Efficient. *Plug-in hybrids: an environmental and economic performance outlook*. 2006: American Council for an Energy-Efficient Economy Washington, DC, US.
30. Kintner-Meyer, M., K. Schneider, and R. Pratt, *Impacts assessment of plug-in hybrid vehicles on electric utilities and regional US power grids part 1: Technical analysis.* Pacific Northwest National Laboratory, 2007.
31. Knipping, E., *Environmental Assessment of Plug-In Electric Hybrid Vehicles Volume 2: United States Air Quality Analysis Based on AEO-2006 Assumptions for 2030*. 2007b, Electric Power Research Institute (EPRI): Palo Alto, CA.
32. Yang, C., et al., *Meeting an 80% reduction in greenhouse gas emissions from transportation by 2050: A case study in California.* Transportation Research Part D: Transport and Environment, 2009. 14(3): p. 147-156.
33. Burke, A., et al., *Battery Electric Vehicles: An Assessment of the Technology and Factors Influencing Market Readiness.* California Energy Commission, Davis, Public Interest Energy Research Program final report, 2007.
34. Kaliyan, N., R.V. Morey, and D.G. Tiffany, *Reducing life cycle greenhouse gas emissions of corn ethanol by integrating biomass to produce heat and power at ethanol plants.* Biomass and Bioenergy, 2011.
35. Wang, M.Q., et al., *Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes.* Biomass and Bioenergy, 2011.
36. Liska, A.J., et al., *Improvements in Life Cycle Energy Efficiency and Greenhouse Gas Emissions of Corn Ethanol.* Journal of Industrial Ecology, 2009. 13(1): p. 58-74.
37. Cherubini, F., et al., *Energy-and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations.* Resources, Conservation and Recycling, 2009. 53(8): p. 434-447.
38. Tyner, W.E., et al., *Land use changes and consequent CO2 emissions due to US corn ethanol production: A comprehensive analysis.* Department of Agricultural Economics, Purdue University, 2010.

References: Transportation

39. Hill, J., *Environmental costs and benefits of transportation biofuel production from food-and lignocellulose-based energy crops: a review.* Sustainable Agriculture, 2009: p. 125-139.
40. Wang, M., M. Wu, and H. Huo, *Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types.* Environmental Research Letters, 2007. 2: p. 024001.
41. Heath, G.A., et al., *Life Cycle Assessment of the Energy Independence and Security Act of 2007: Ethanol–Global Warming Potential and Environmental Emissions*. 2009, National Renewable Energy Laboratory (NREL), Golden, CO.
42. Unnasch, S., et al., *Full fuel cycle assessment well to wheels energy inputs, emissions, and water impacts.* Sacramento: California Energy Commission, 2007.
43. Greene, N., et al., *NRDC Report "Growing energy: how biofuels can help end America's oil dependence"(December).* 2004.
44. Searchinger, T., et al., *Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change.* Science, 2008. 319(5867): p. 1238.
45. Farrell, A.E., et al., *Ethanol can contribute to energy and environmental goals.* Science, 2006. 311(5760): p. 506.
46. Brinkman, N., et al., *Well-to-wheels analysis of advanced fuel/vehicle systems—a North American study of energy use, greenhouse gas emissions, and criteria pollutant emissions.* Argonne Natl. Lab, Argonne, IL, 2005.
47. National Research Council . Committee for the Study on the Relationships Among Development Patterns, V.M.T., et al., *Driving and the Built Environment: The Effects of Compact Development on Motorized Travel, Energy Use, and CO2 Emissions*. 2009: Transportation Research Board.
48. Ewing, R.H. and S.G. America, *Growing cooler: evidence on urban development and climate change*. 2008: ULI.
49. Ewing, R. and A. Nelson, *CO2 Reductions Attributable to Smart Growth in California.* report prepared for the California Air Resources Board, Sacramento, CA, 2008.
50. Cambridge Systematics, *Moving Cooler: An Analysis of Transportation Strategies for Reducing Greenhouse Gas Emissions*. 2009: Washington, DC.