Air Quality Impacts of Electrification in tandem with Intermittent Renewable Resources

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Combustion
Fuel Cells
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Introduction and Motivation

California Policy Drivers

- Increase renewable electricity generation
  - 50% by 2030
- Dramatically reduce economy-wide GHG emissions
  - 80% below 1990 levels by 2050
- Improve regional AQ

Required Pathway for CA GHG Goals[1,2,3,4]

- **Extensive electrification of end-use sectors**

and

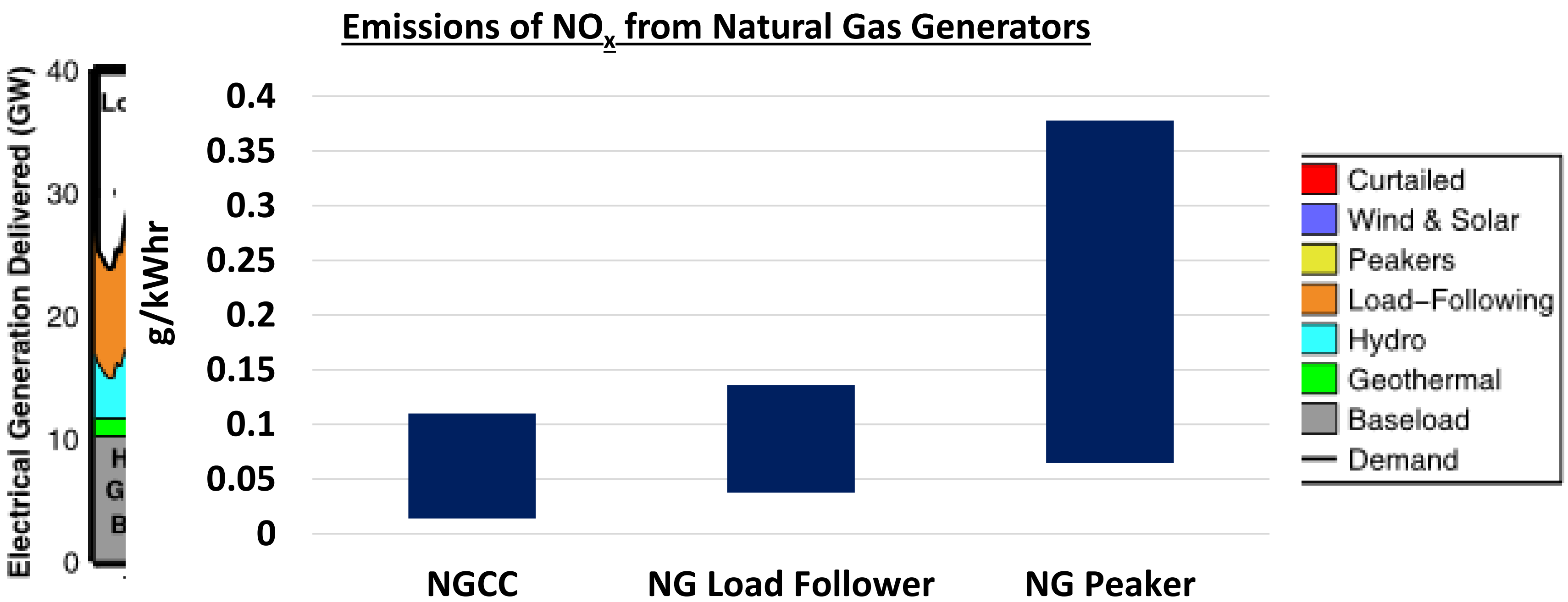
- **Decarbonization of electricity supply**
  - Increase in wind and solar power

1: Williams et al., 2012**, 2:** McCollum et al., 2012**, 3:** Morrison et al., 2015**, 4:** Yang et al., 2015

Introduction and Motivation

Integrating intermittent renewables can impact generator dispatch/dynamics – potentially increasing emissions locally

- Increased start/stops, part-load, ramping, cycling
- Could yield localized emission consequences impacting regional AQ



Source(s): NGCC – IEAGHG, DOE/NETL, & Rubin et al., 2005. LF & Peaker – Shaffer et al., 2015

Source: Eichmann et al., 2013

Project Goal

Analyze emissions and AQ impacts of wide-spread electrification of end-use sectors in tandem with renewable resource integration

- Assess emissions accounting for (1) **dynamics and physical constraints of future electrical grid** and (2) **reductions in electrified end-use sectors**
- Quantify and spatially resolve impacts on ground-level ozone and $PM_{2.5}$

Provide insight on how electrification and renewables can achieve maximum GHG and AQ co-benefits

- Avoid unforeseen AQ consequences

Approach – Scenario Development

Develop scenarios of electrification in principal energy end-use sectors in excess of business-as-usual in 2020, <u>2030</u>, and 2050

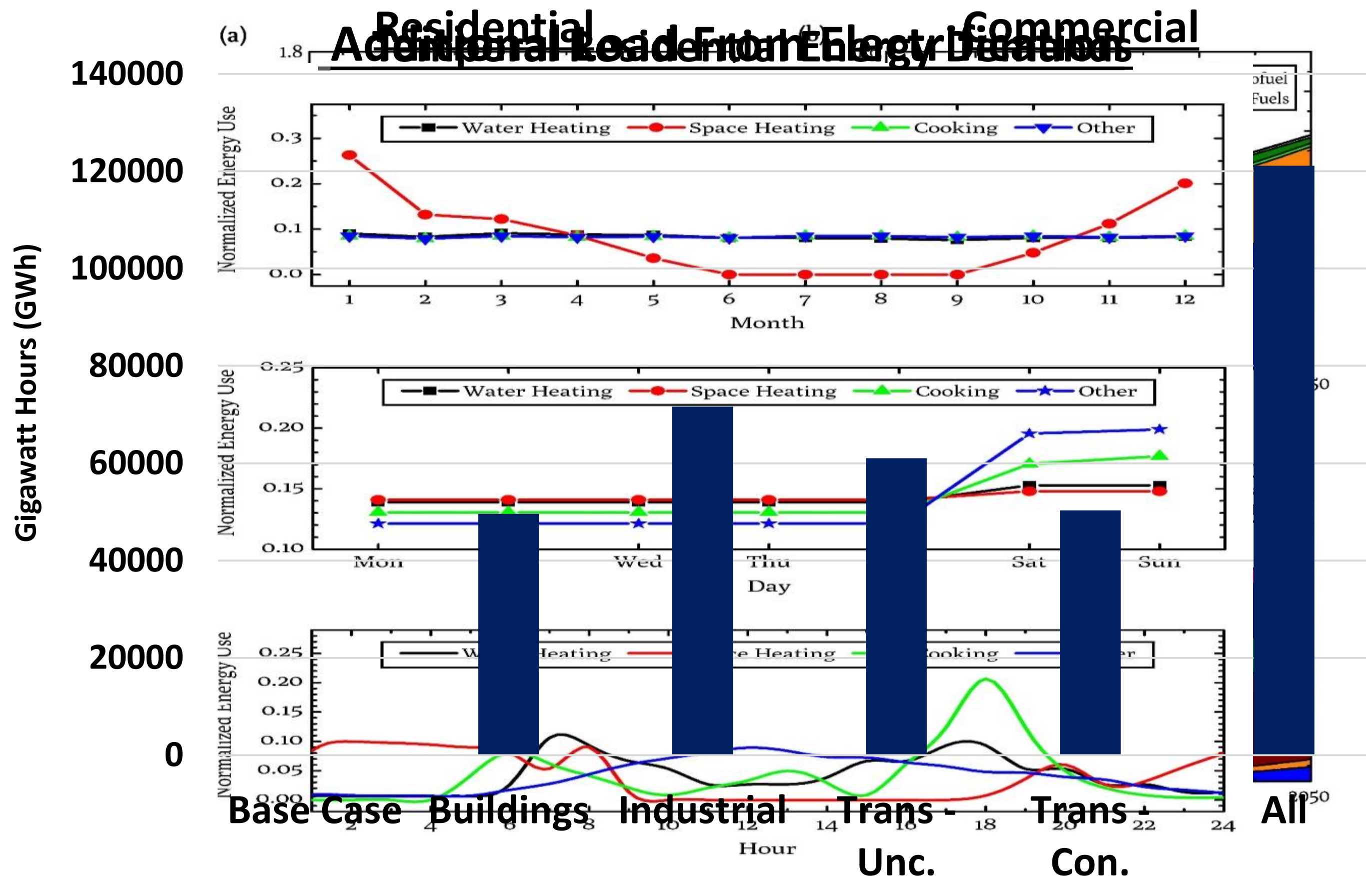
- With 50% penetration of renewable electricity

Case	End-use Sector	Technologies	2030 BAU [%]	2030 Elect. [%]
Buildings	Commercial & Residential	Cooking, space heating, water heating	56.9% 36.9%	79.6% 71.2%
Industrial	Industrial	Boilers/HVAC only	7.4%	24.%
Transportation – Uncontrolled	Light Duty Vehicles: <u>Uncontrolled charging</u>	Battery Electric Vehicles	1.1%	9.3%
Transportation – Controlled	Light Duty Vehicles: <u>Controlled charging</u>	Battery Electric Vehicles	1.1%	7.7%
All Sectors	All the above	All the above	Above	Above

Approach – Scenario Development

Quantify and temporally resolve additional load from electrification

- Project energy demand and fuel distribution to 2030 for end-use sectors
- Establish feasible electrification potential and quantify additional load
- Determine temporal electrification load profile



Approach – Grid Modeling

Utilize a state-of-the art grid modeling software platform to simulate electrical grid in horizon years

– Capture a physical representation of future grid infrastructure

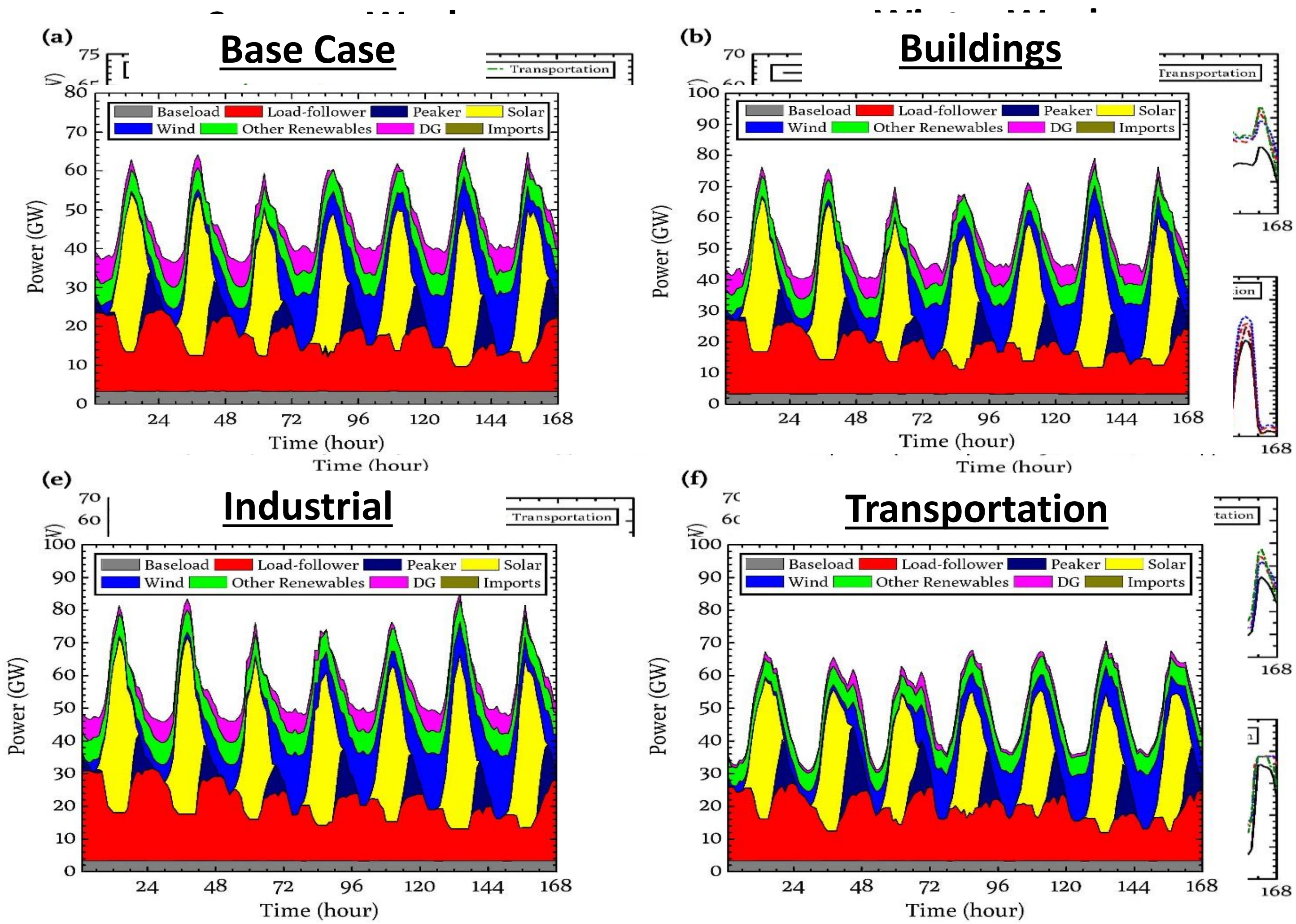
Models for balancing dynamics and dispatch

– Holistic Grid Resource Integration and Deployment (HiGRID) Tool
  - **Provides temporal load for renewable and complementary technologies**

– PLEXOS Solutions Software
  - **Provides utility generator dispatch (spatial and temporal)**

Approach – Grid Modeling

Modeling to resolve a temporal load & temporal/spatial dispatch profile

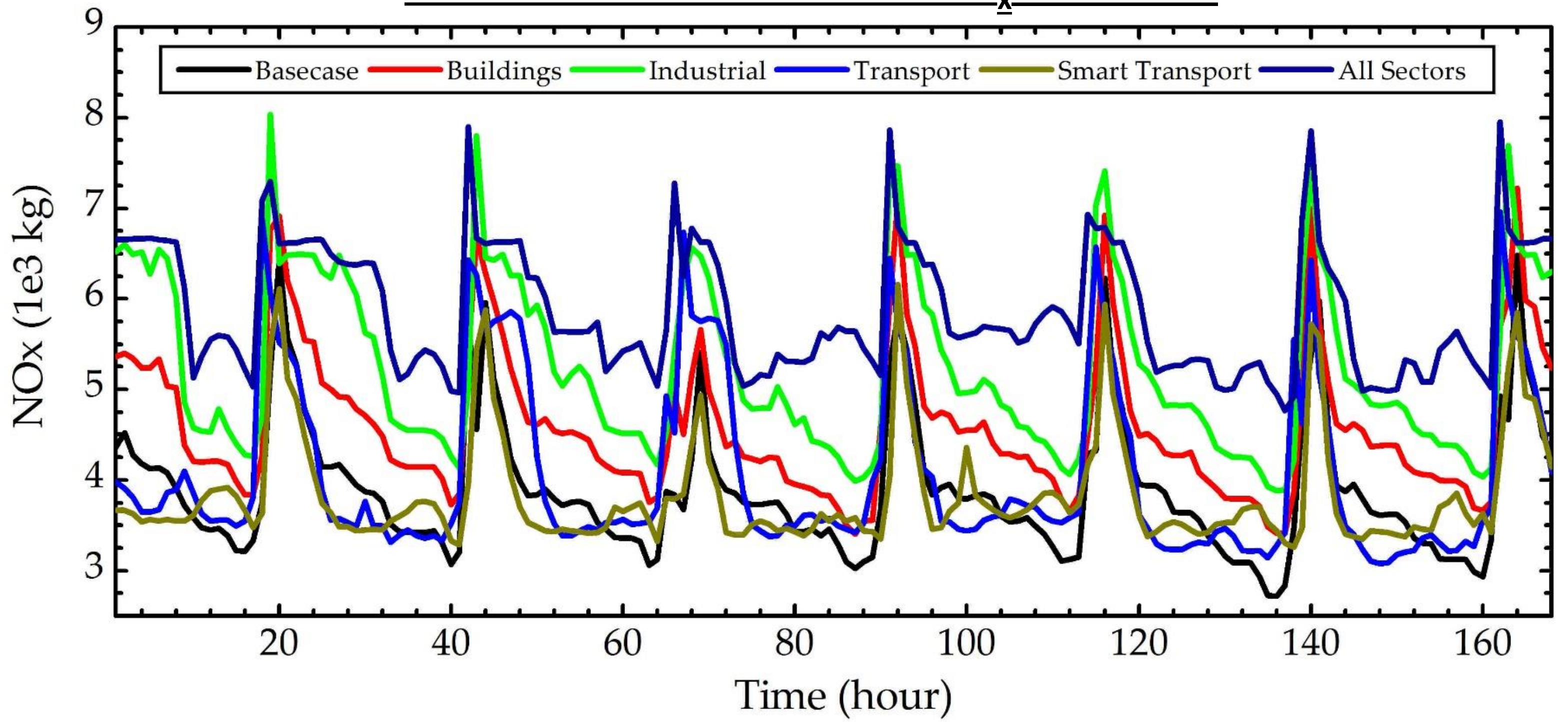


Approach – Emission Impacts

Account for generator emissions and end-use emission changes

- **Dispatched Generators**
  - Steady state and dynamic penalties
    - **Part-load, start-up, ramping emission factors**

Summer Week: Generator NO_x Emissions



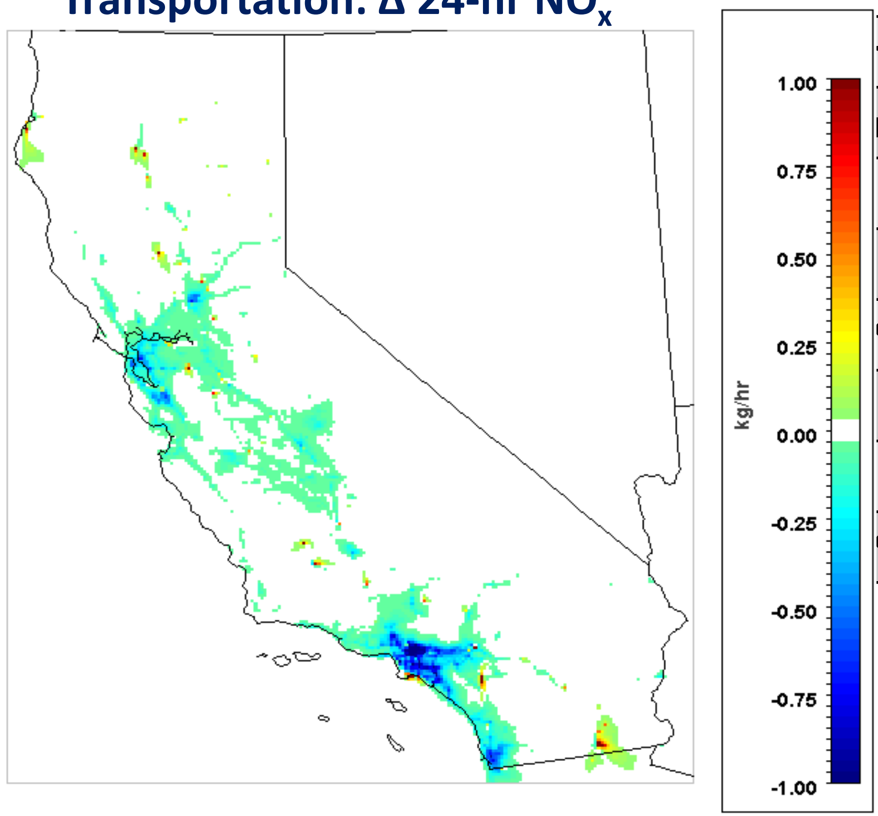
Approach – Emission Impacts

Quantify and resolve emissions in end-use sectors

- 2005 EPA NEI projected to 2020, 2030 (ARB) & 2050 (MARKAL)
- Impacted sources adjusted to account for electrification penetration
- Spatial and temporal allocation, speciation via the SMOKE model

	ns Reduction		
Case	rial	Transportation	
		LDV	Refinery
2030 Buildings		----	----
2030 Industrial	%	----	----
2030 Transportation (Imm		-38.0%	-18.7%
2030 Transportation (Sma		-31.4%	-15.4%
2030 All Sectors	%	-31.4%	-15.4%

Transportation: Δ 24-hr NO_x

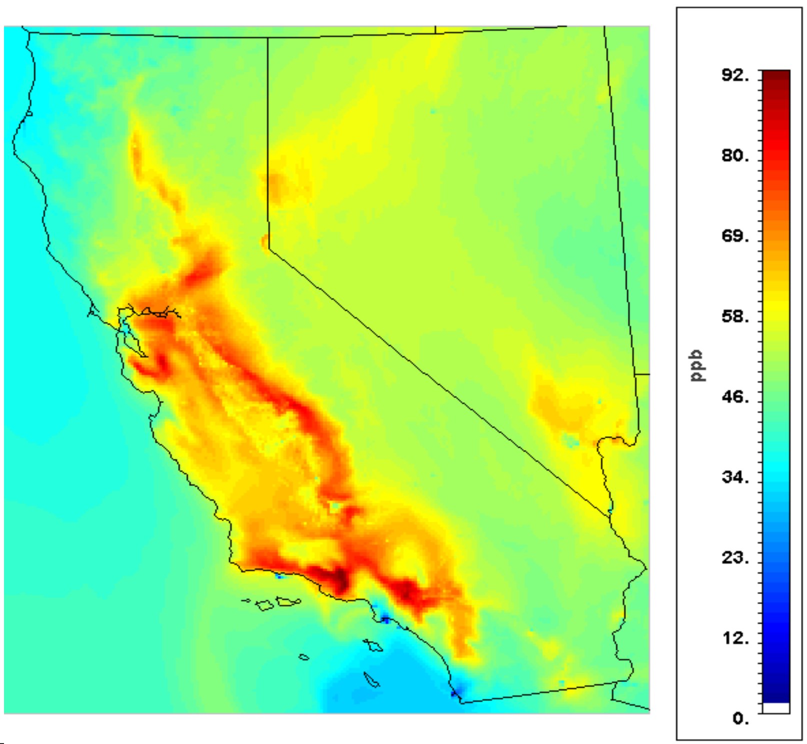


Approach – Air Quality Modeling

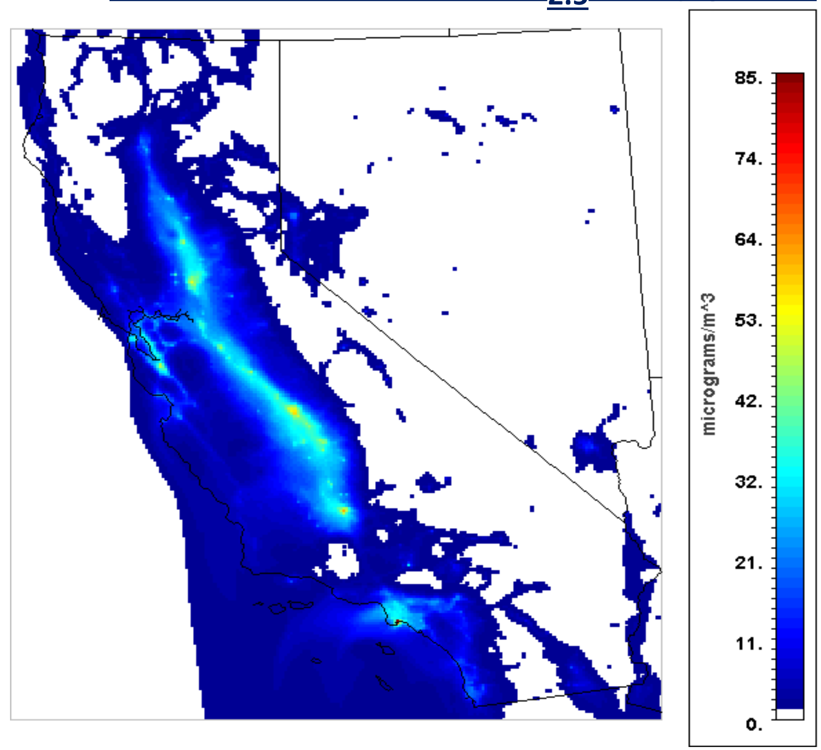
Simulations of atmospheric chemistry and transport via CMAQ

- **CMAQ version 4.7.1 –** CBO5CL, 4 km x 4 km grid
- **WRF-ARW, NCEP Final Operational Global Analysis 1 x 1 grid**
  - Summer (July 7-13, 2005) with high observed ozone & PM concentrations
  - Winter (December 1-7, 2005) with high observed PM concentrations

Summer Base Max 8-hr Ozone (93 ppb)



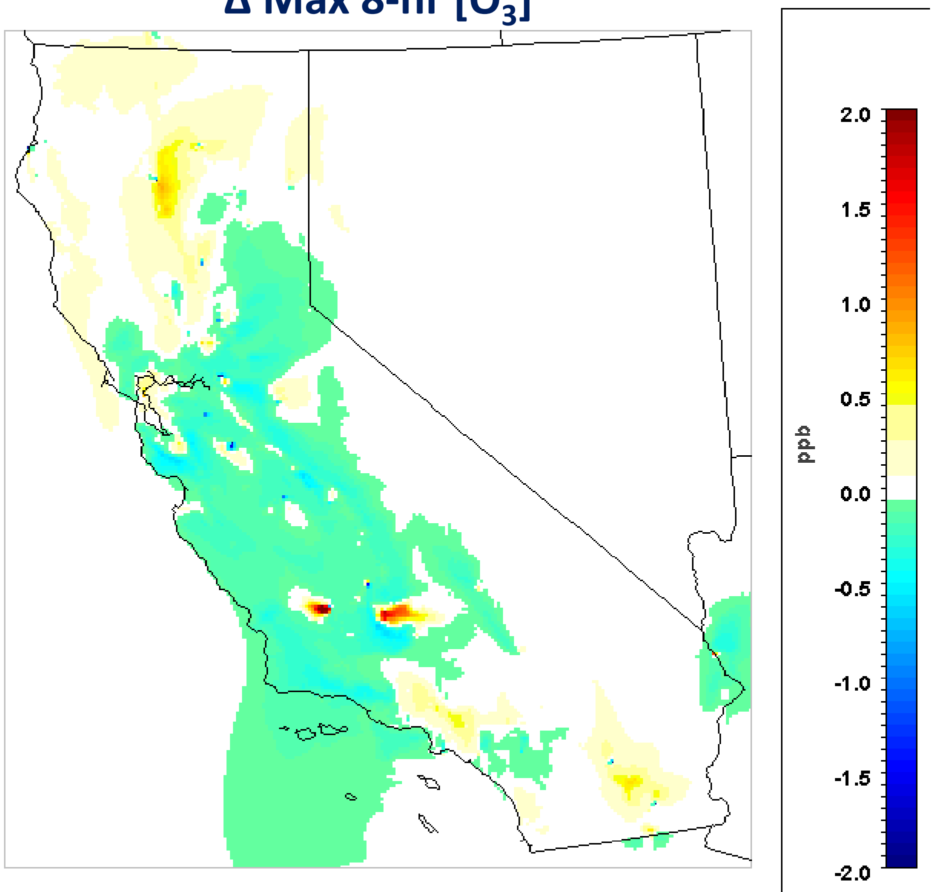
Winter Base 24-hr $PM_{2.5}$ (85 µg/m³)



Results – Buildings Case (Summer)

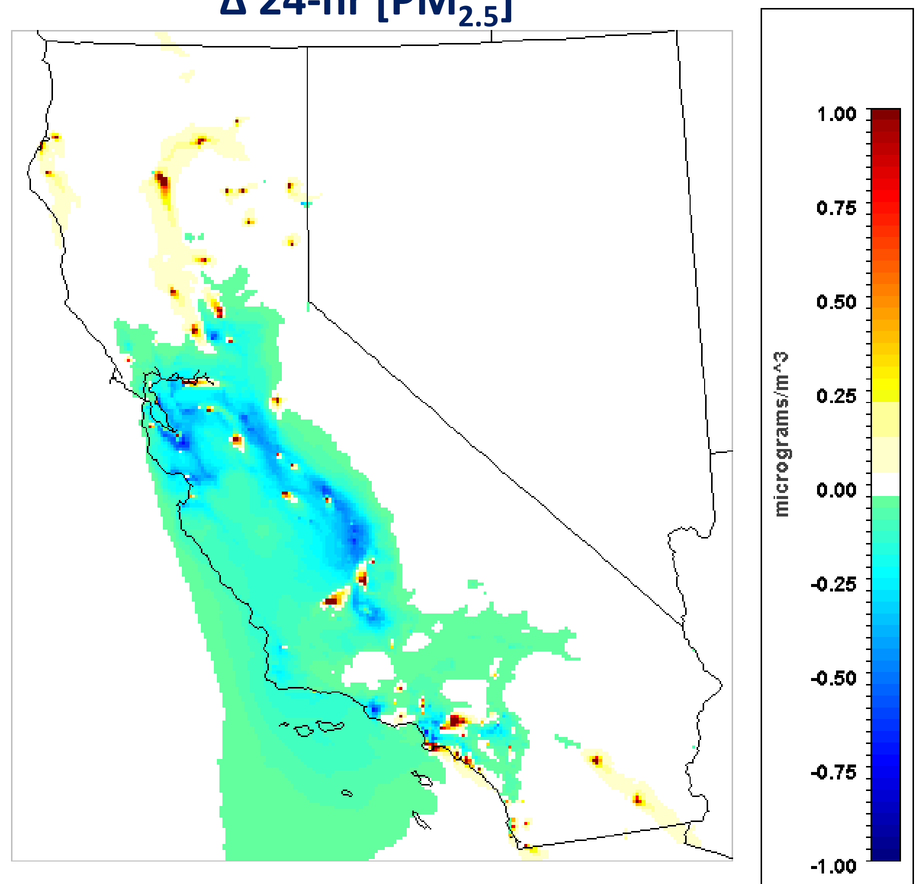
- **Large areas of moderate improvements with localized worsening**
  - Magnitude of $PM_{2.5}$ increase notable

Δ Max 8-hr $[O_3]$



-3.55 to +2.66 ppb

Δ 24-hr $[PM_{2.5}]$

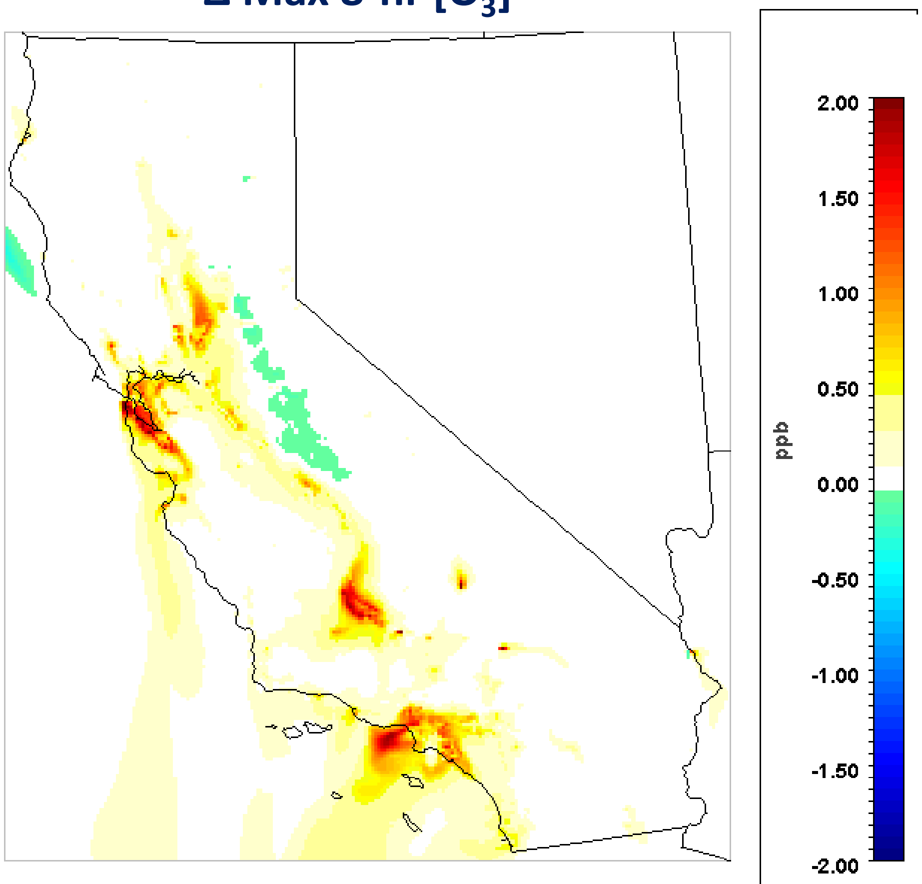


-0.74 to +12.58 μg/m³

Results – Buildings Case (Winter)

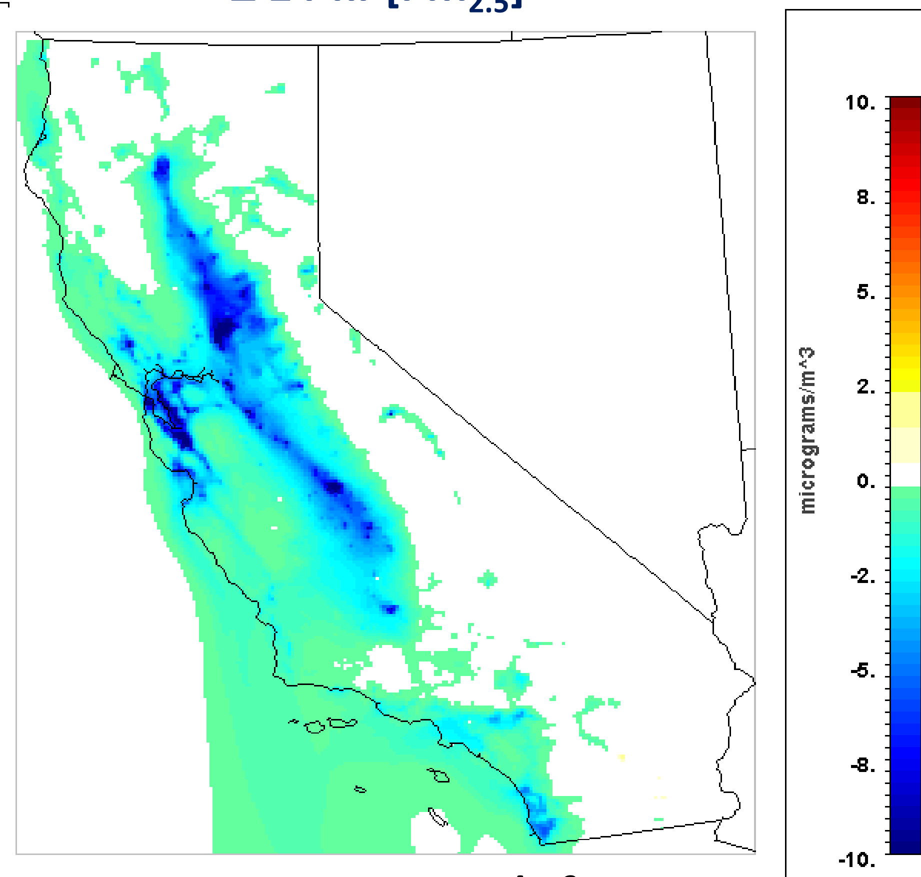
- **$PM_{2.5}$ levels notably improve for winter episode**
  - Larger energy demand for heating, off-set of wood burning, PM chemistry

Δ Max 8-hr [O_3]



-0.35 to +2.65 ppb

Δ 24-hr [$PM_{2.5}$]

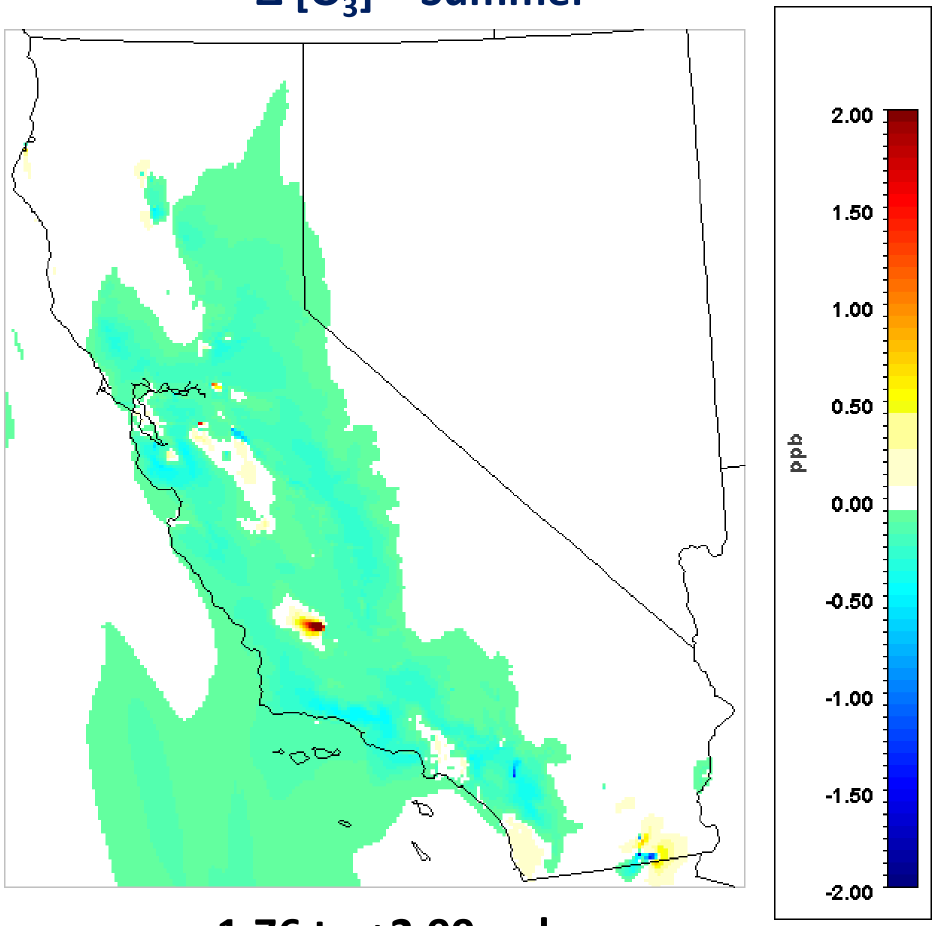


-15.22 to +1.42 μg/m^3

Results – Transportation Case (Uncontrolled)

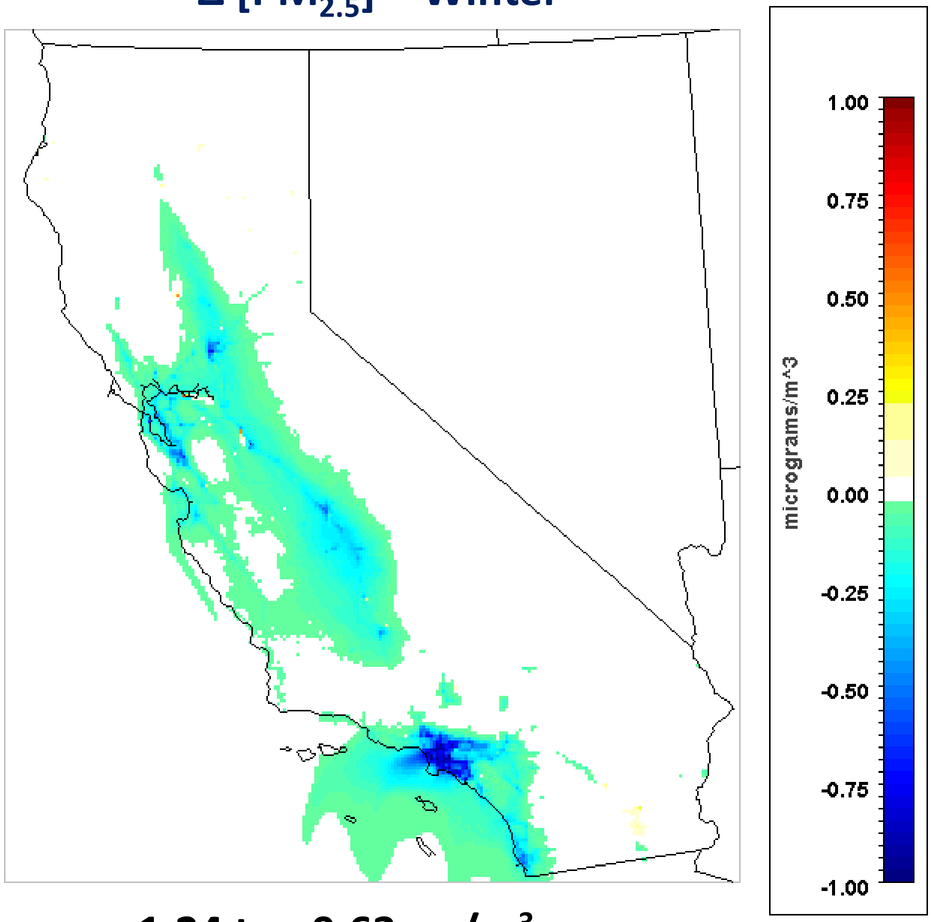
- **Important improvements in urban regions (large vehicle fleet, refineries)**
  - <u>Refineries have a major impact</u>

Δ [O_3] – Summer



-1.76 to +2.99 ppb

Δ [$PM_{2.5}$] – Winter

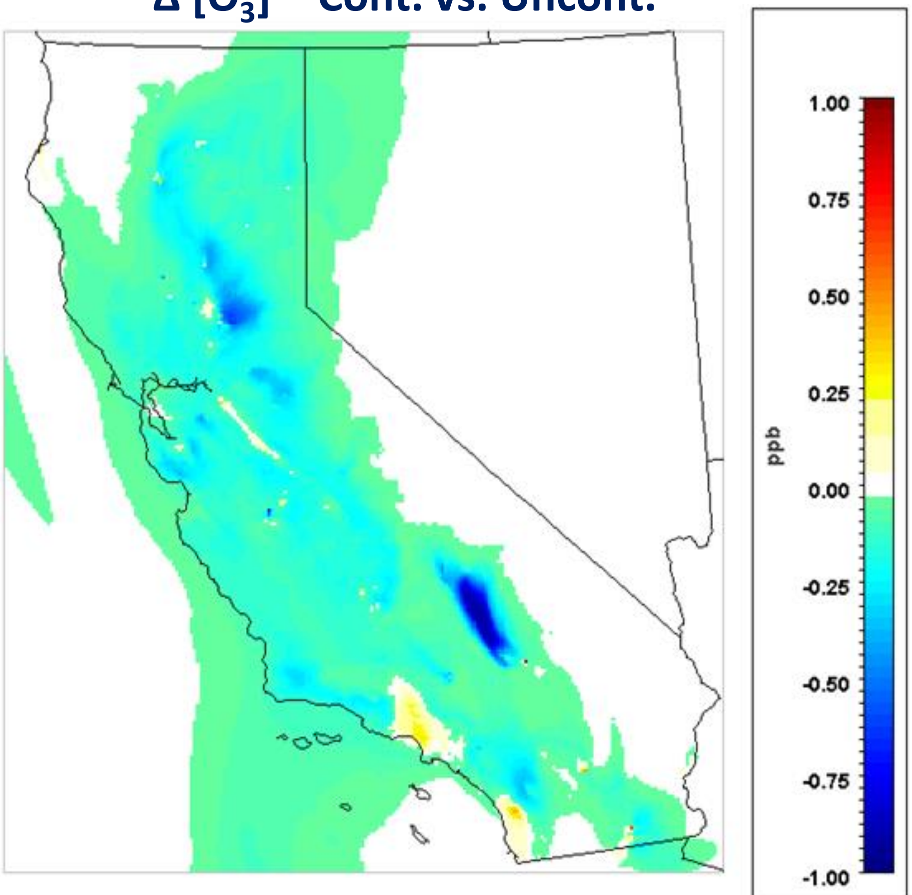


-1.24 to +0.63 μg/m^3

Results – Transportation (Controlled vs. Uncontrolled)

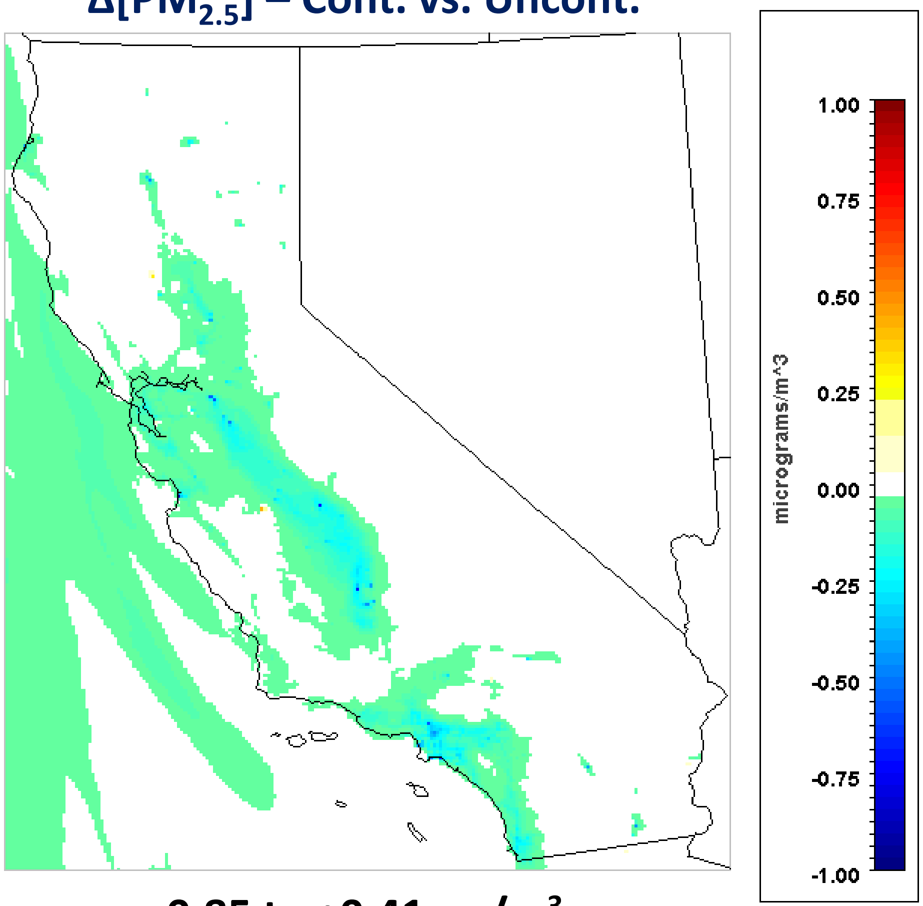
- **Complementary strategies can maximize energy, GHG and AQ benefits**
  - Reduce grid dynamic consequences and enhance renewable utilization

Δ [O_3] – Cont. vs. Uncont.



-0.96 to +1.03 ppb

Δ[$PM_{2.5}$] – Cont. vs. Uncont.

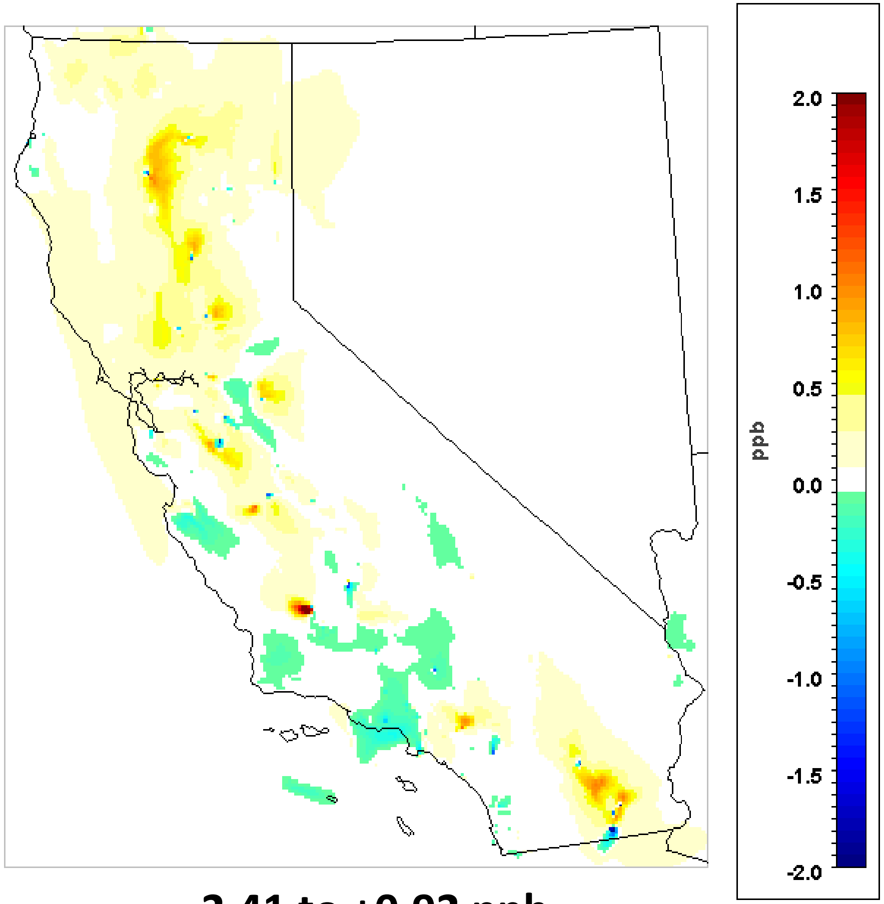


-0.85 to +0.41 μg/m^3

Results – Industrial Sector

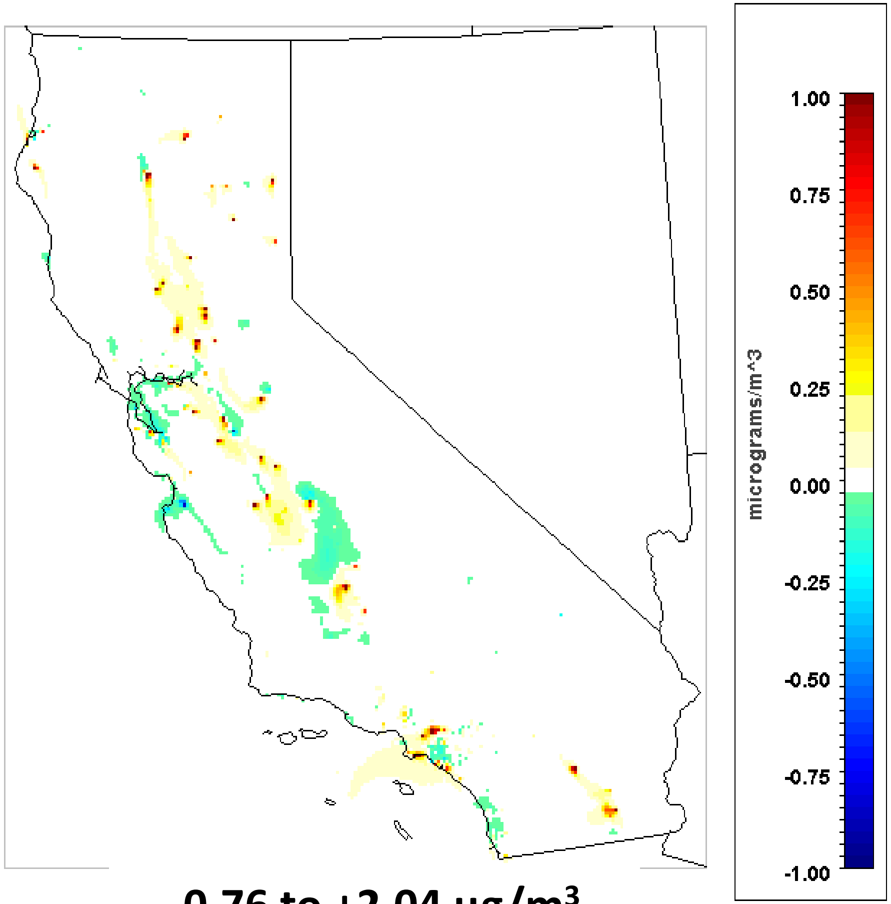
- **Challenging to electrify, characterized by worsening relative to other sectors**
  - Requires comprehensive planning and understanding of process electrification potential

Δ [O_3] – From Base (Summer)



-2.41 to +0.92 ppb

Δ[$PM_{2.5}$] – From Base (Winter)



-0.76 to +2.04 μg/m^3

Conclusion and Future Work

Conclusions

– Electrification generally translates to improvements in ozone and $PM_{2.5}$
    - **Impacts vary markedly by pollutant, sector, horizon year, season, and location**

– Increased electricity demand and altered grid dynamics can result in localized worsening at sites of emitting utility-scale power generators
    - **Should be interpreted via population exposure**

– Holistic strategies needed to achieve maximum AQ and GHG co-benefits

Future Work

– Expand and enhance modeling strategies
    - **Consider additional models for grid representation**
    - **Increase the modeling episode in CMAQ**
    - **<u>Health impact assessment to better resolve results</u>**

– Expand assessment to more thoroughly evaluate realistic advanced complementary technologies/strategies

Thank You

Acknowledgements

- **California Energy Commission**
- **Marla Mueller – California Energy Commission**
- **Dan Loughlin – US EPA**
- **Katie Leong**
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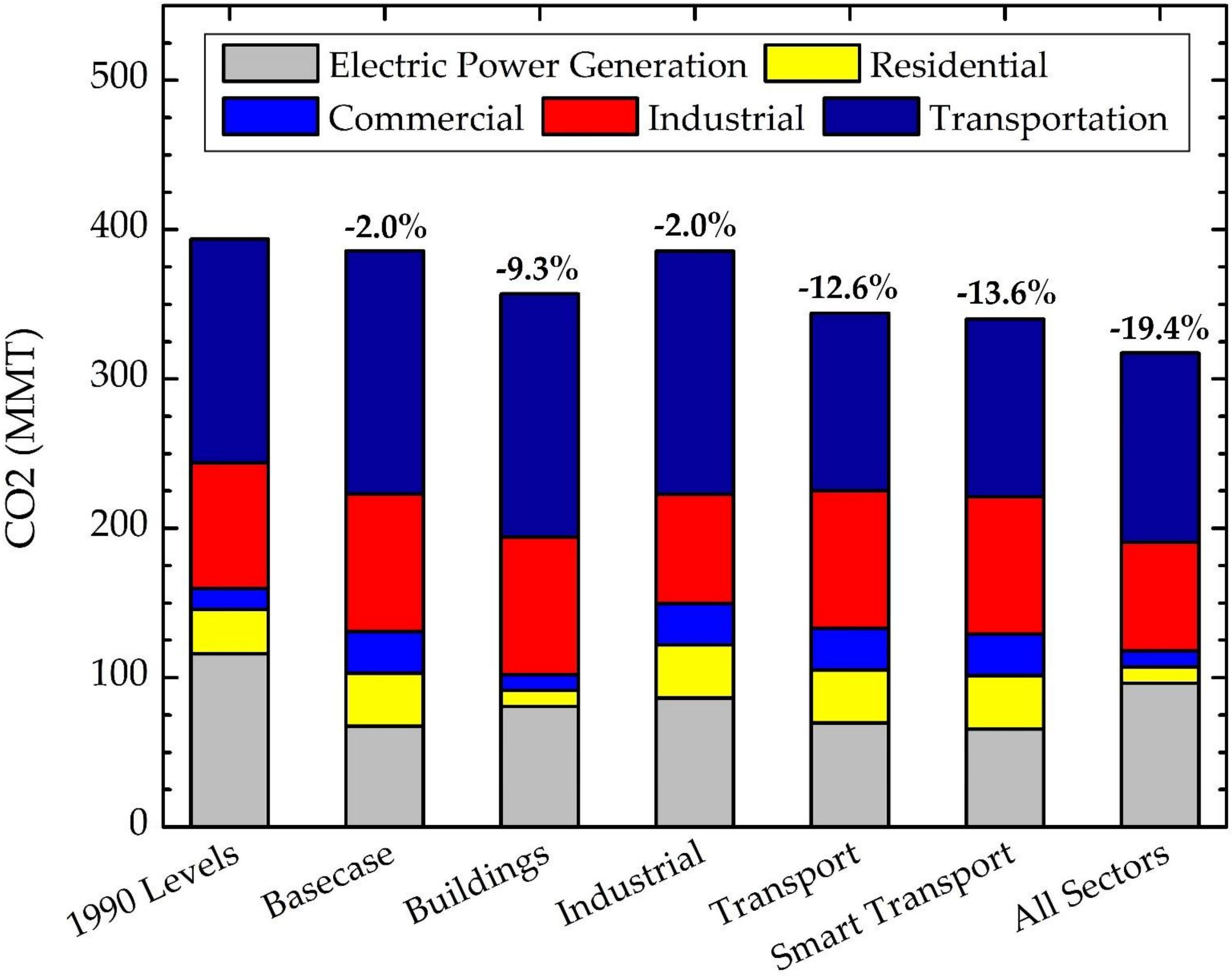
Results – GHG Emissions



Results – Peak Ozone and $PM_{2.5}$

Summary of peak impacts on 8-hour max ozone and 24-hour $PM_{2.5}$ for 2030 Cases

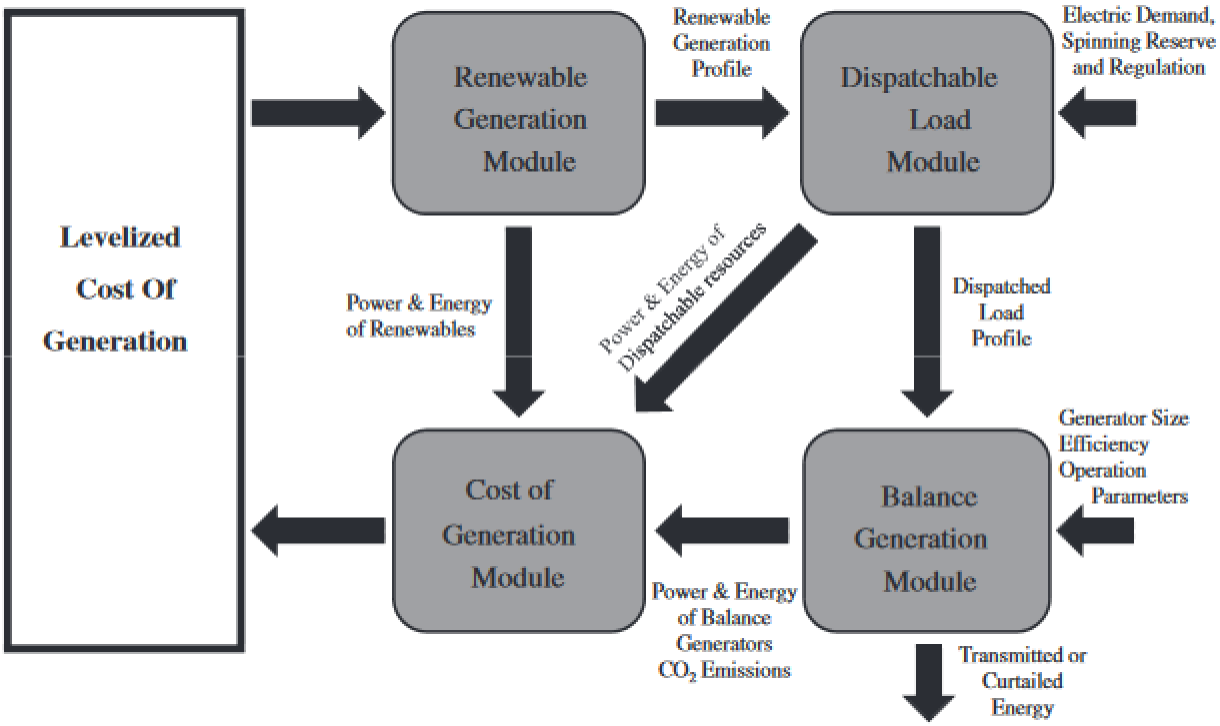
Case		Δ 8-hour Ozone [ppb]	Δ 24-hour $PM_{2.5}$ [$\mu g/m^3$]
2030 Buildings	Summer	-3.55 to +2.66	-0.74 to +12.58
	Winter	-0.35 to +2.65	-15.22 to +1.42
2030 Industrial	Summer	-4.13 to +2.87	-0.24 to +18.31
	Winter	-0.45 to +1.28	-1.14 to +4.55
2030 I. Transportation	Summer	-1.76 to +2.99	-3.83 to +4.95
	Winter	-0.07 to +0.47	-1.24 to +0.63
2030 S. Transportation	Summer	-1.89 to +0.63	-0.96 to +1.02
	Winter	-0.81 to +0.69	-1.65 to +0.39
2030 All Sectors	Summer	-6.5 to +3.05	-1.19 to +27.99
	Winter	-0.63 to +2.83	-15.95 to +4.10

HiGRID Model

Holistic Grid Resource Integration and Deployment (HiGRID)

- Resolve interaction between baseload, dispatchable, and intermittent renewable generation to study cost/benefit of installing renewable generation capacity
- Evaluate

HiGrid Model Flowchart



HiGRID Model

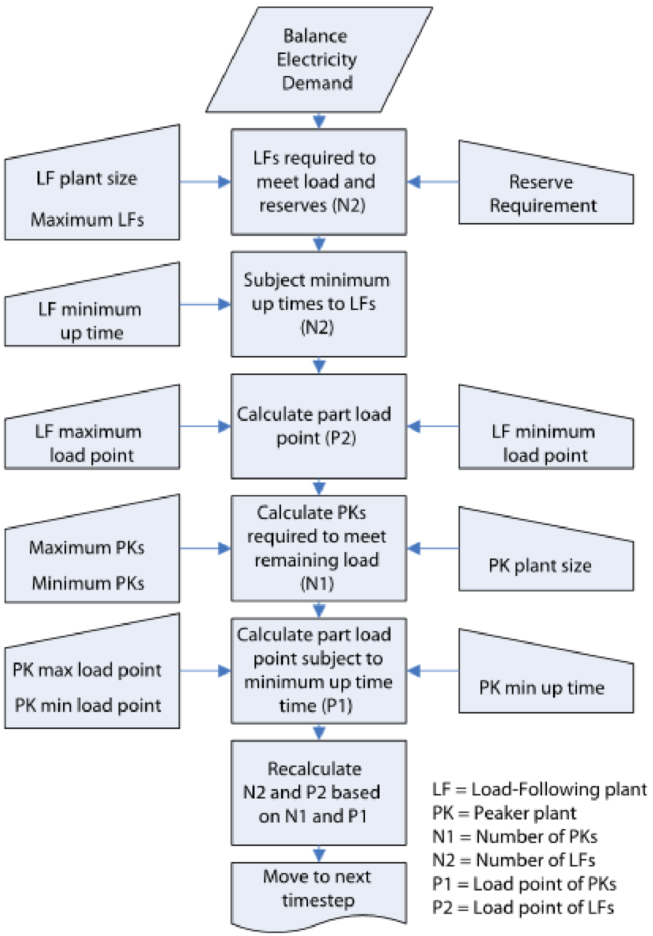


Fig. 4. Balance generation model flowchart.

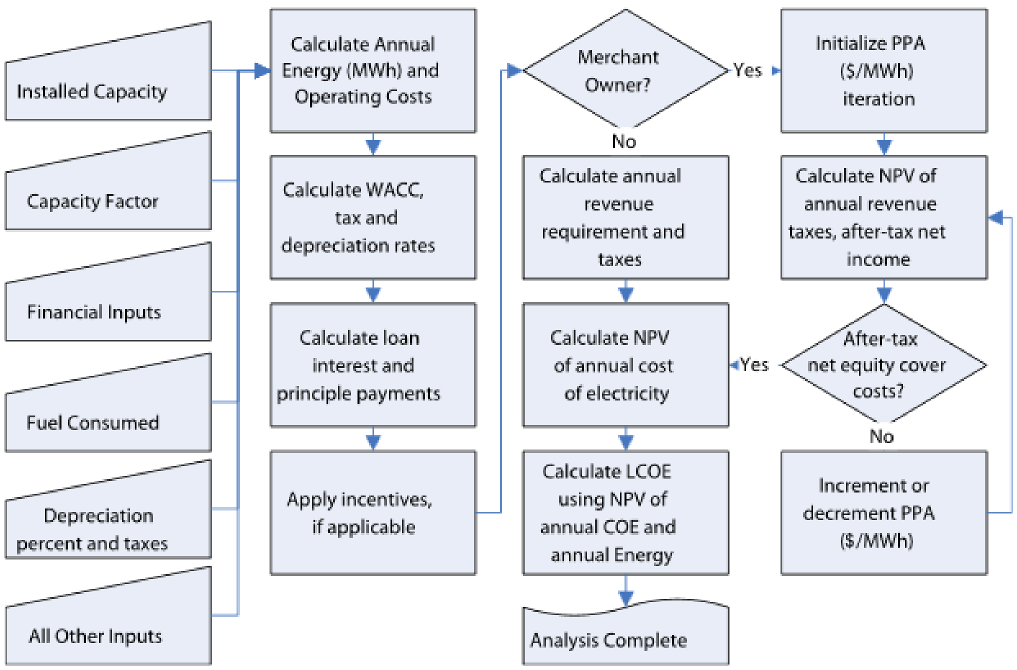
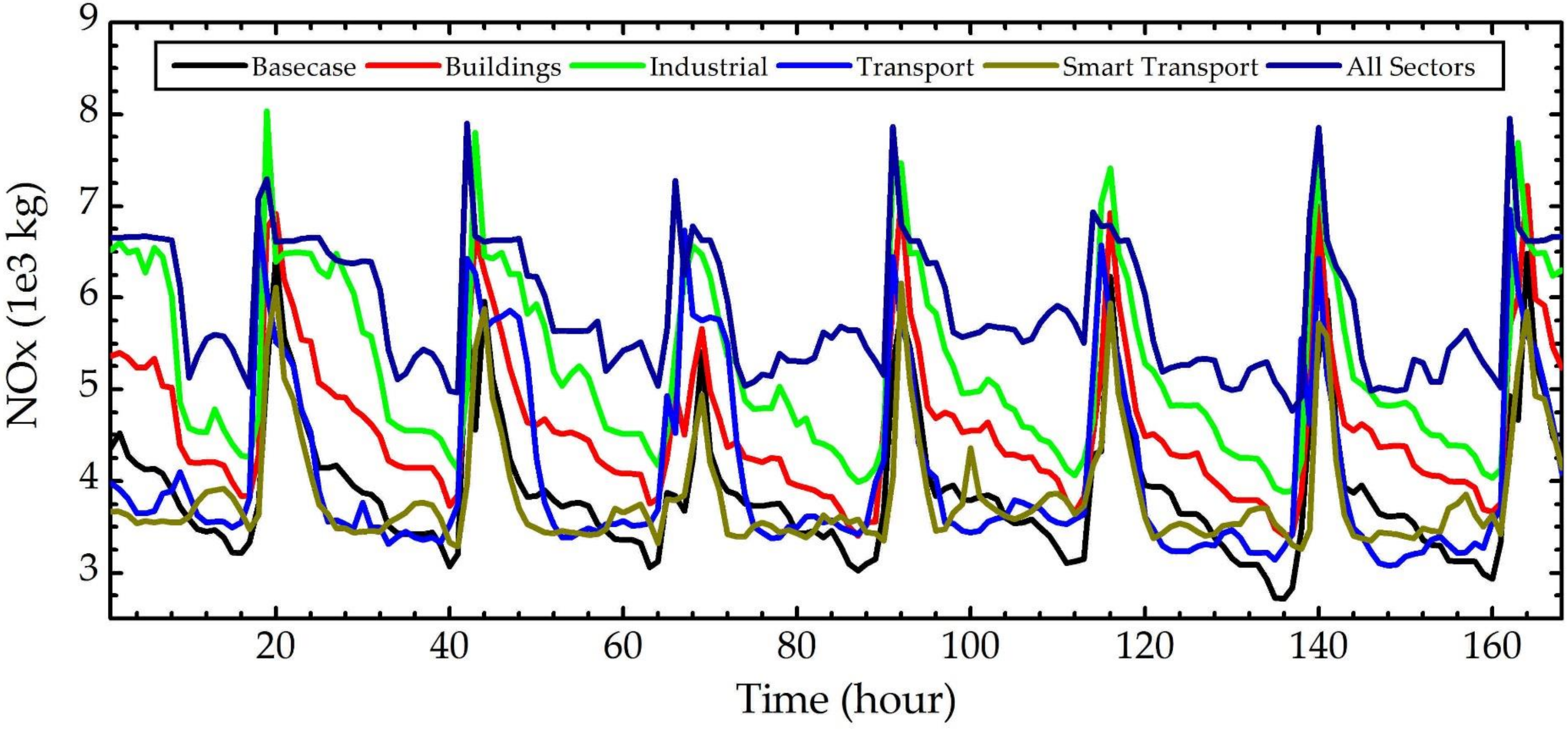


Fig. 5. Cost of generation model flowchart.

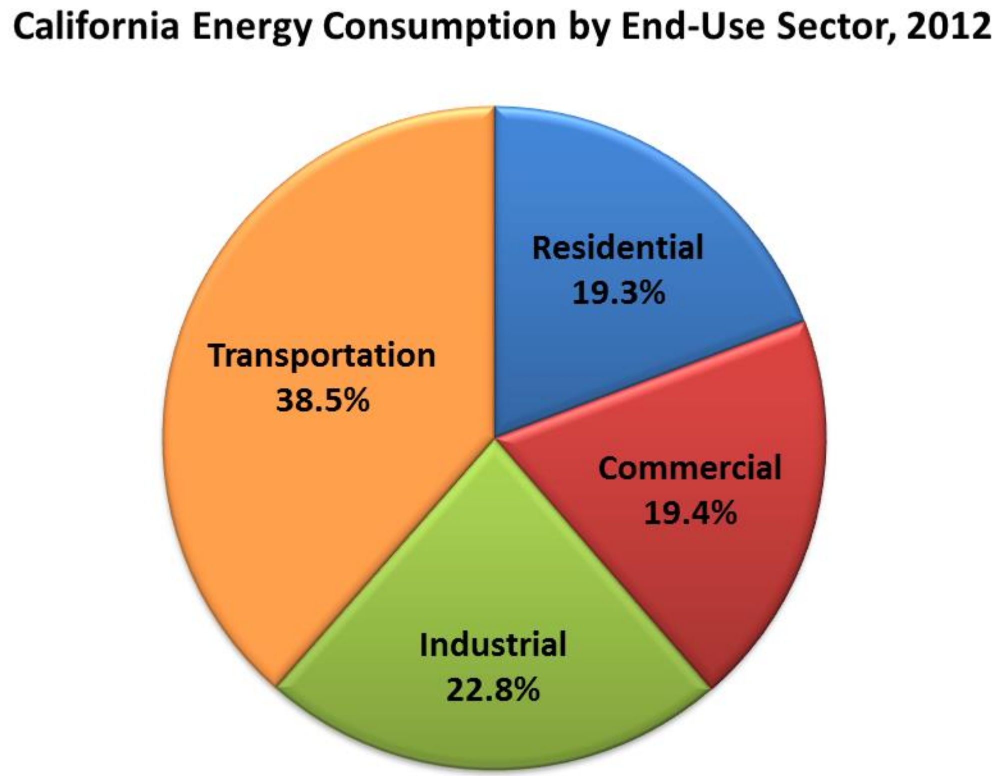
Electric penetration of energy end-uses (%) in 2012 and 2030

Energy Sector	End-Use	2012	2030					
			Base Case	Buildings	Industrial	Uncontrolled Transportation	Smart Transportation	All
Residential	Total	36.0	36.9	71.3	36.9	36.9	36.9	71.3
	Space Heating	2.9	3.0	40.0	3.0	3.0	3.0	40.0
	Water Heating	2.5	2.6	40.0	2.6	2.6	2.6	40.0
	Cooking	20.2	20.7	50.0	20.7	20.7	20.7	50.0
	Pool & Spa	4.3	4.4	40.0	4.4	4.4	4.4	40.0
	Clothes Dryer	42.9	43.7	70.0	43.7	43.7	43.7	70.0
Commercial	Total	58.0	57.0	79.7	57.0	57.0	57.0	79.7
	Space Heating	5.3	5.2	40.0	5.4	5.4	5.4	40.0
	Water Heating	4.0	3.9	40.0	4.1	4.1	4.1	40.0
	Cooling	86.7	86.5	90.0	86.9	86.9	86.9	90.0
	Cooking	22.5	22.1	50.0	22.1	22.1	22.1	50.0
	Process	5.5	5.4	40.0	5.4	5.4	5.4	40.0
	Other	84.0	83.7	90.0	90.0	90.0	90.0	83.7
Industrial	Total	11.0	7.5	7.5	24.3	7.5	7.5	24.3
	Boiler	0.0	0.0	0.0	40.0	0.0	0.0	40.0
	HVAC	16.3	11.3	11.3	50.0	11.3	11.3	50.0
	Process Heat	2.9	1.9	1.9	1.9	1.9	1.9	1.9
	Other Process	65.8	55.6	55.6	55.6	55.6	55.6	55.6
	Other	11.0	7.5	7.5	7.5	7.5	7.5	7.5
Transportation	Total	0.1	1.1	1.1	1.1	9.3	7.8	7.8


Basecase
Buildings
Industrial
Transport
Smart Transport
All Sectors
9
8
7
6
5
4
3
NOx (1e3 kg)
20
40
60
80
100
120
140
160
Time (hour)

Background and Motivation

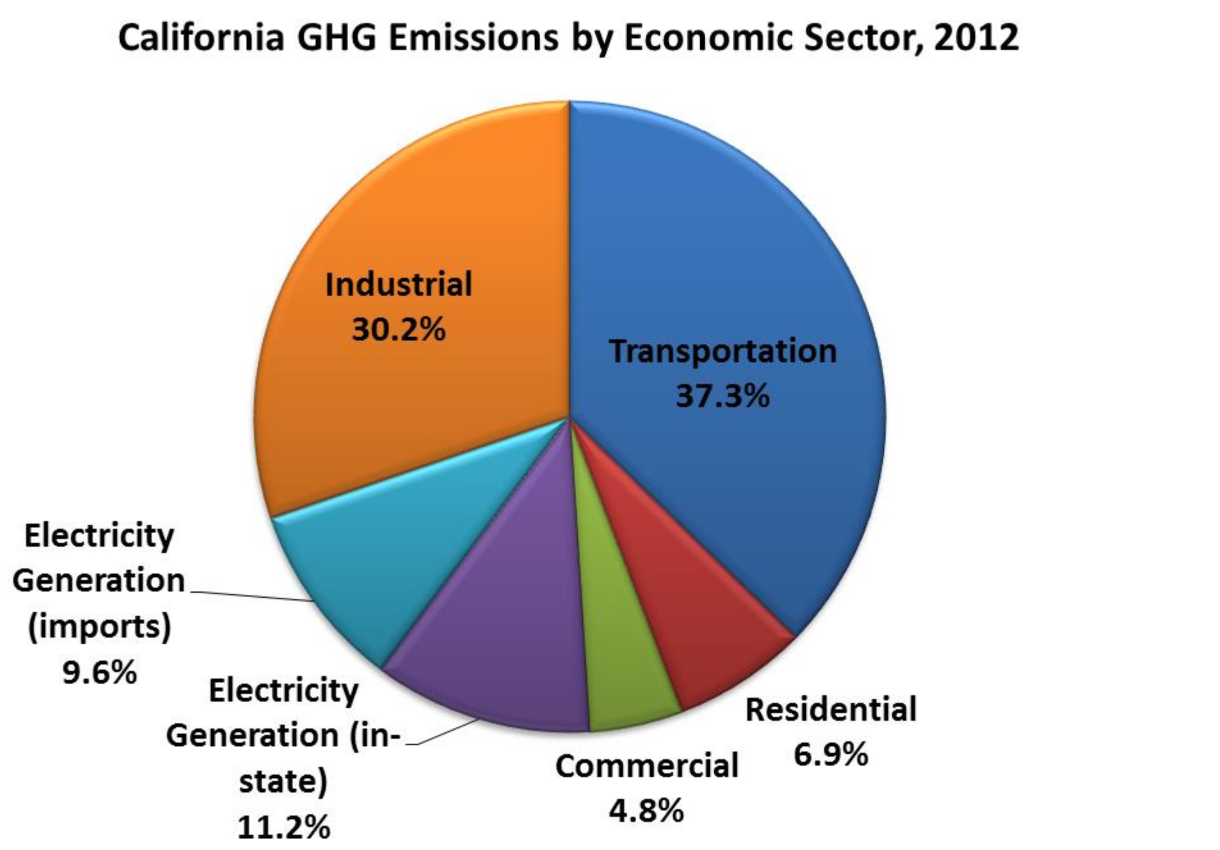
- California Energy Use



Reference: U.S. Energy Information Administration. "State Profile and Energy Estimates of California"

Background and Motivation

- California GHG Emissions

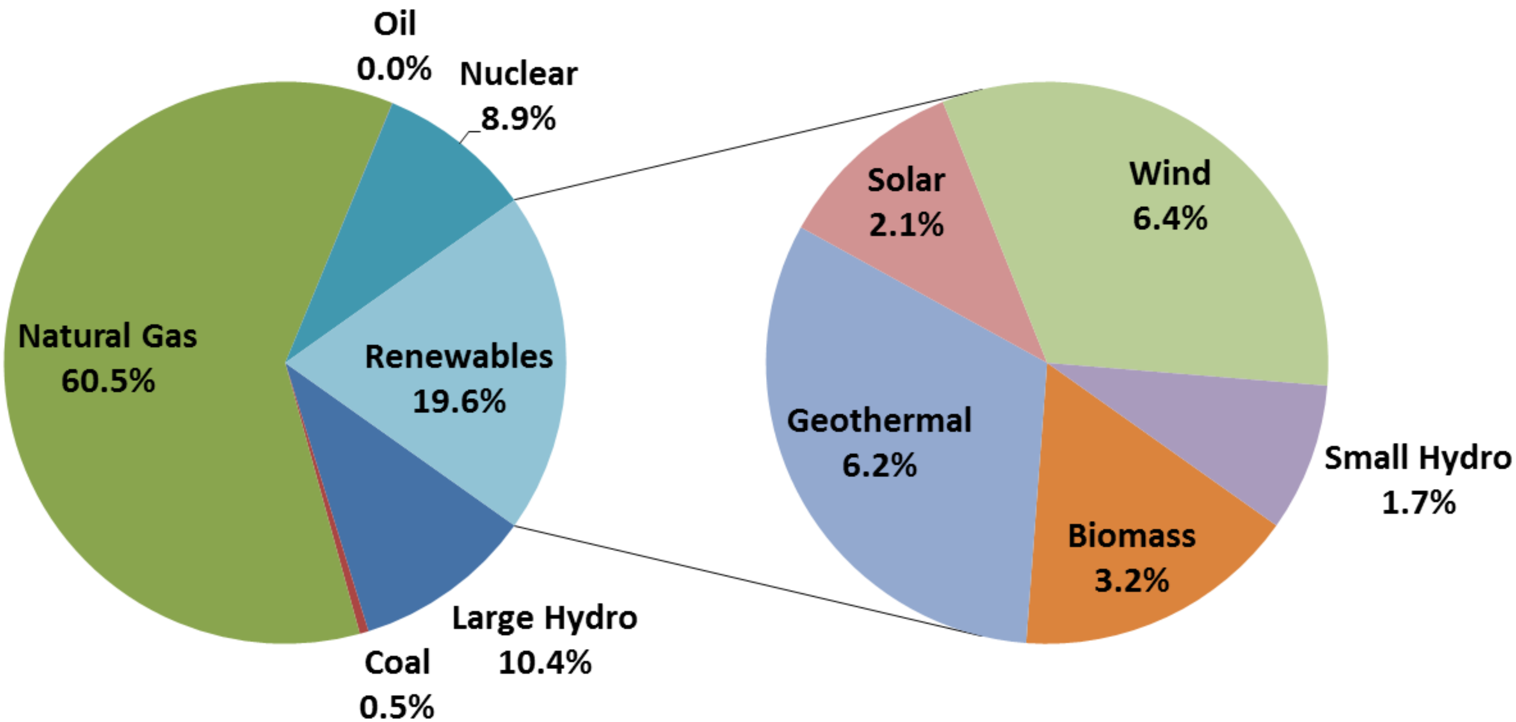


Reference: California Air Resources Board. 2014. "California Greenhouse Gas Emission Inventory: 2000-2012".

Background and Motivation

- California Electricity Generation

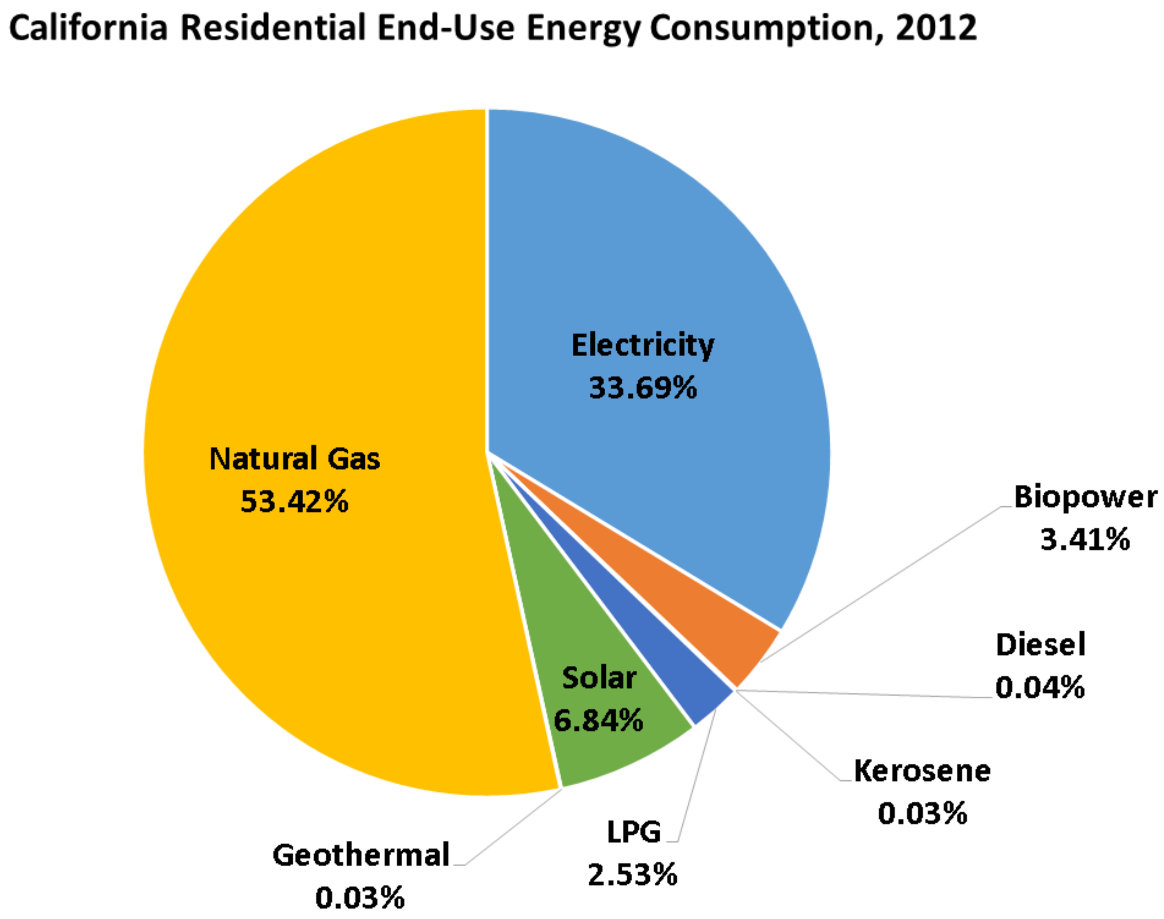
California in-state Electricity Generation Mix, 2013



Reference: U.S. Energy Information Administration. "State Profile and Energy Estimates of California"

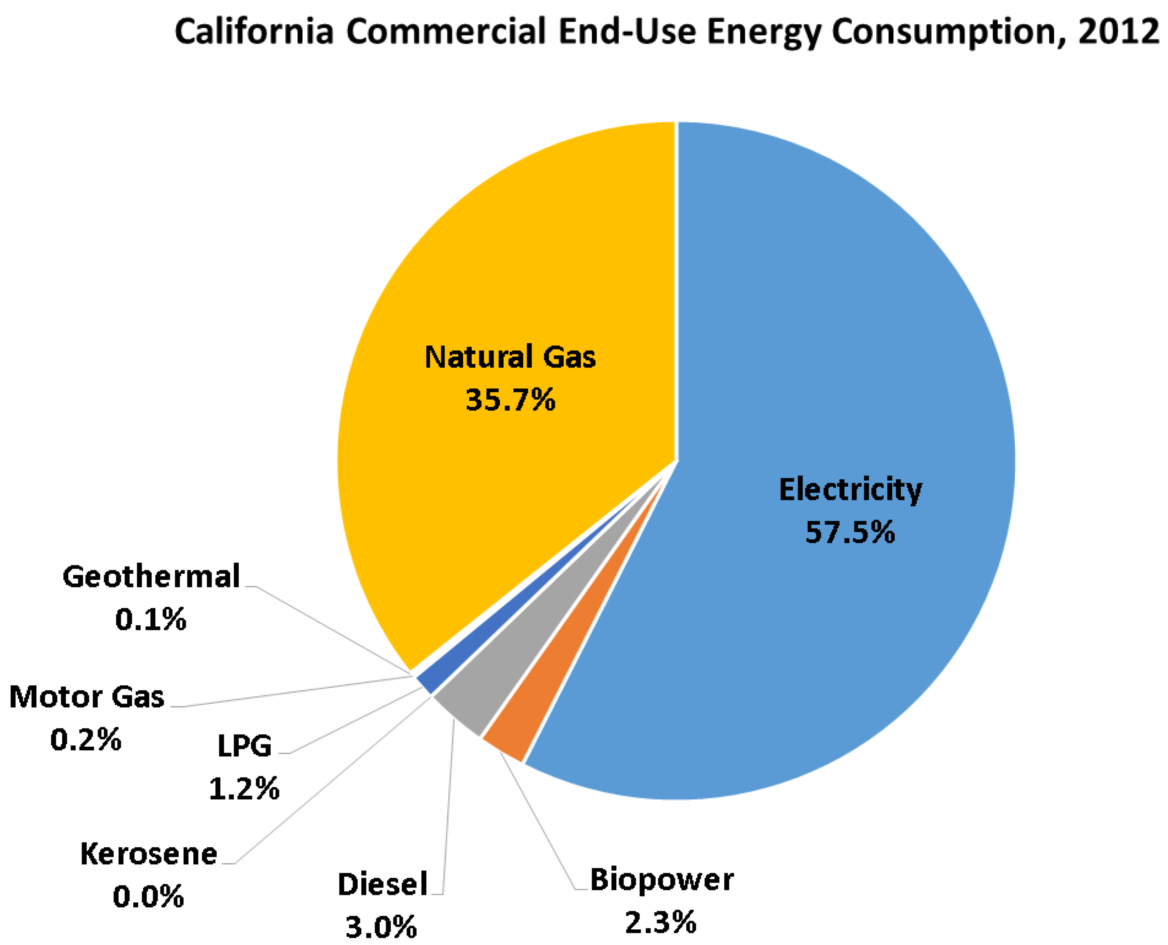
Background and Motivation

- Residential Electrification Potential



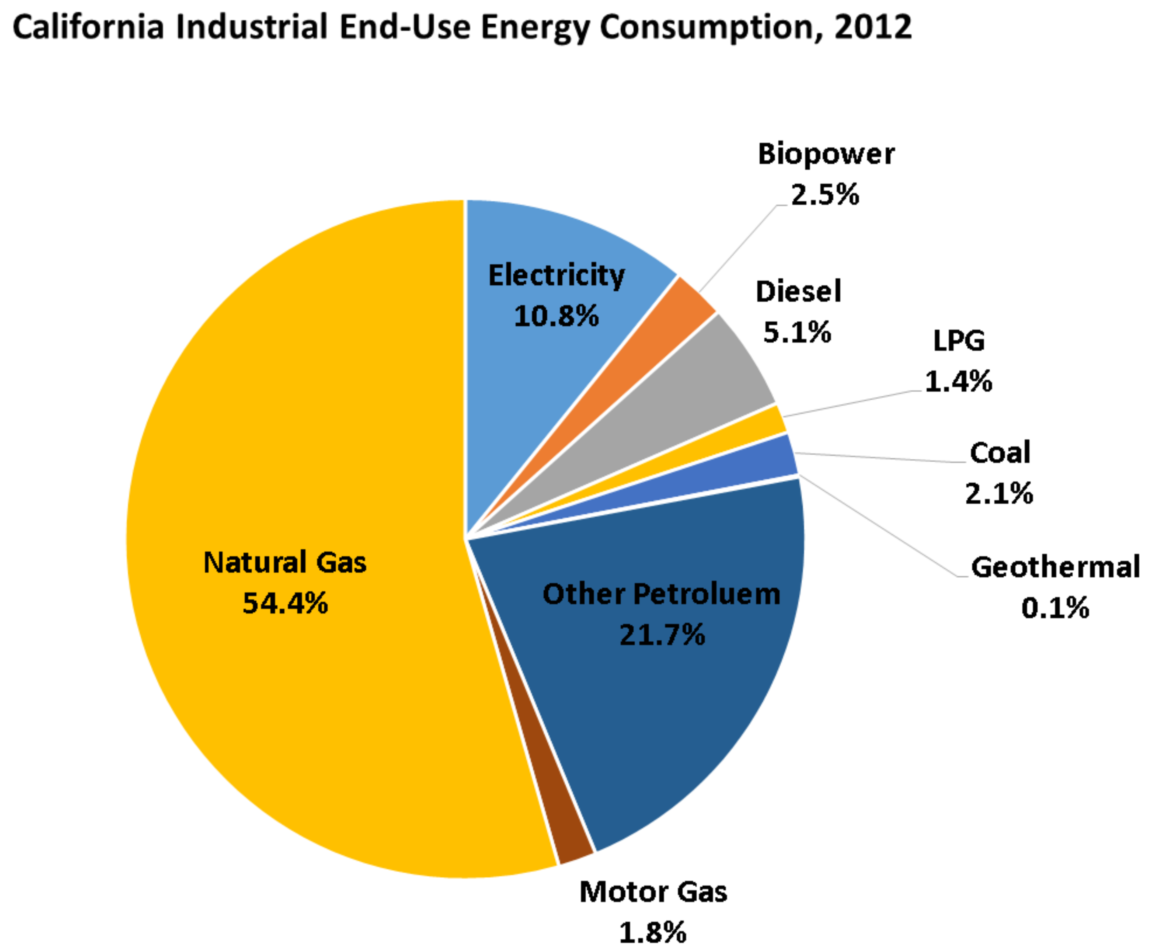
Background and Motivation

- Commercial Electrification Potential



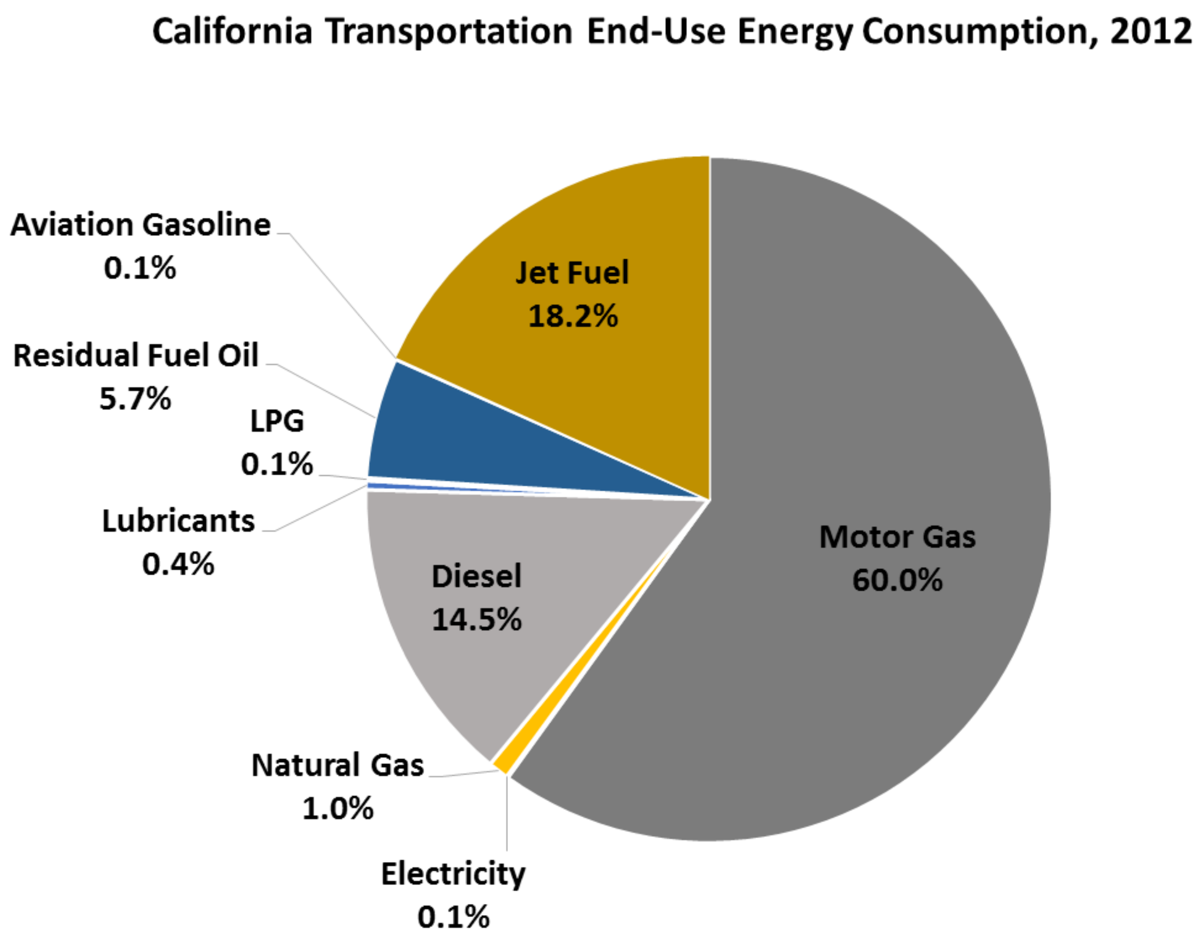
Background and Motivation

- Industrial Electrification Potential



Background and Motivation

- Transportation Electrification Potential



Approach and Methodology

- Method used for adjusting projected statewide electricity demand profile after implementing electrification

Total Electrification Load

- **Find BAU electric penetration from fuel consumption projections**
- **Determine total amount of non-electric fuel removed**
- **Compute total electricity load added by accounting for efficiency ratios**

Electrification Temporal Load Profile

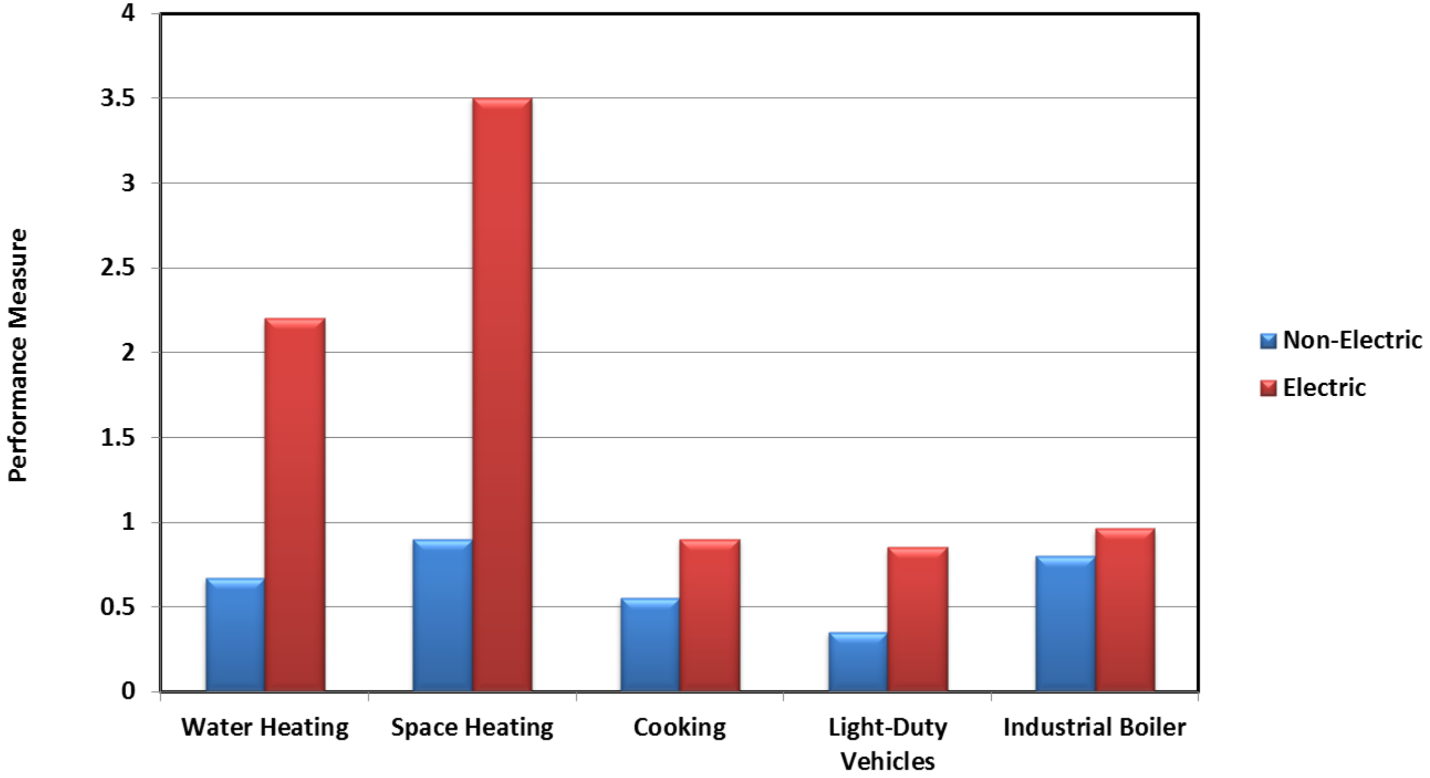
- **Find temporal electrification load profile using hourly Load Shapes for each EPA SCC code (residential, commercial, industrial)**
- **Adjust electrification load Profile for scenarios including transportation using ZEV-NET EV charging data**

Adjusted statewide demand profile

- **Add temporal electrification load profile to state original demand profile**

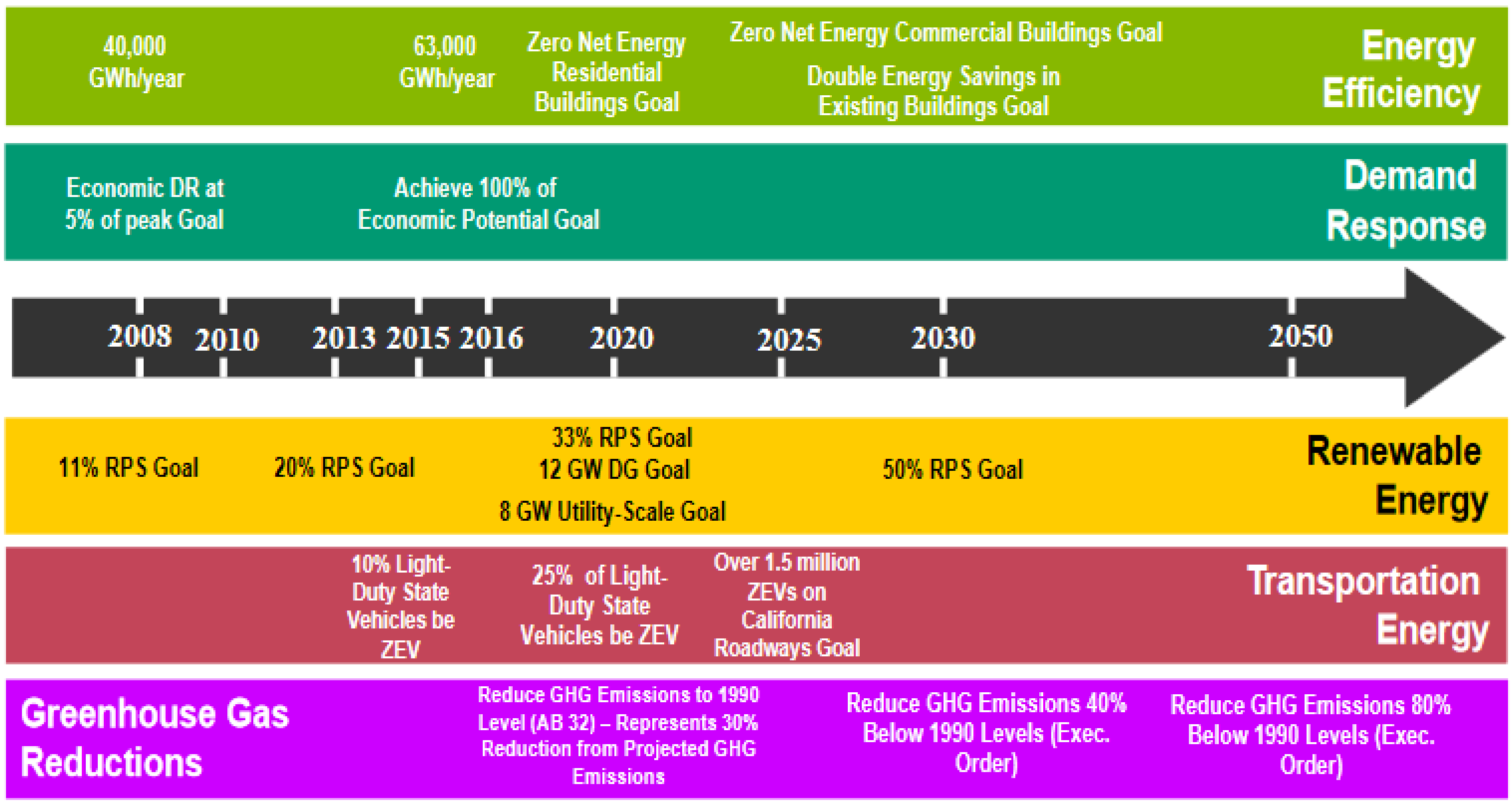
Approach and Methodology

- Non-Electric vs. Electric Efficiency Comparison



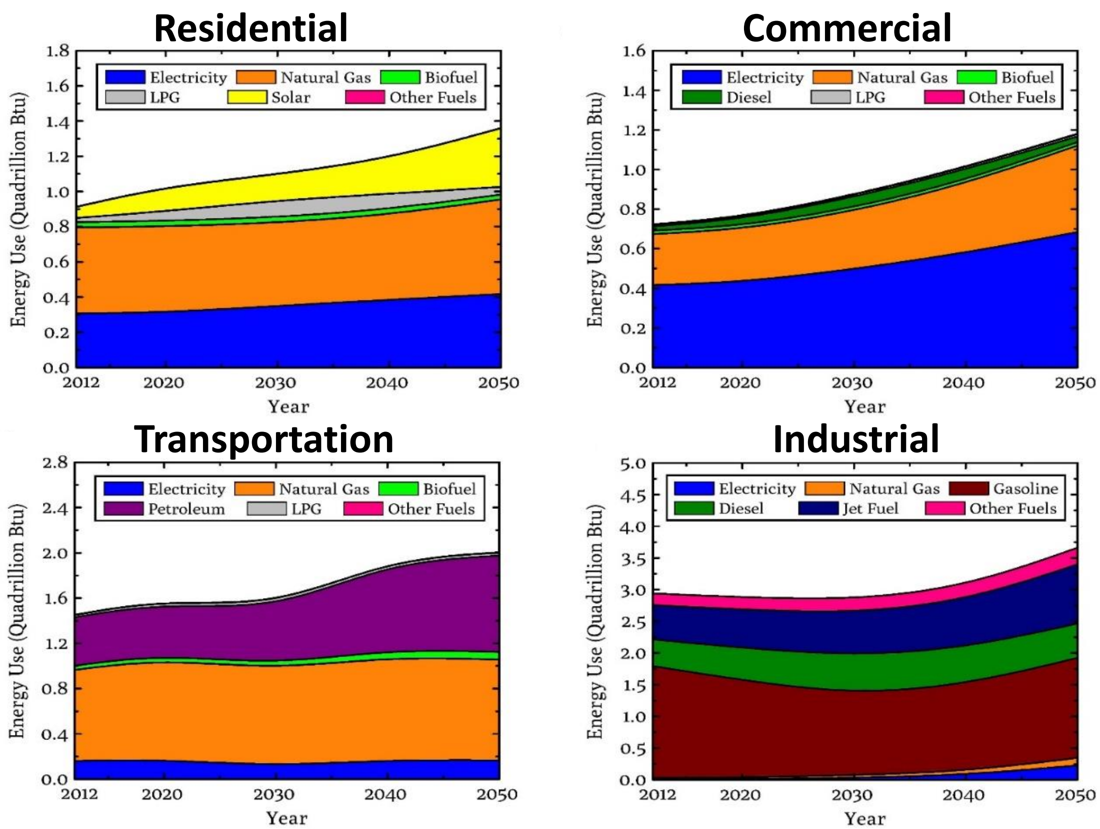
CA CO2 Emissions Reductions After Electrification (MMTCO2) 2030 Cases									
Cases	**BAU 2030**	**Res 2030**	**Com 2030**	**Ind 2030**	**Immediate Tra 2030**	**Smart Tra 2030**	**ResCom 2030**	**ResComTra 2030**	**ResComTraInd 2030**
Residential	36	**13**	36	36	36	36	**13**	**13**	**13**
Commercial	28	28	**10**	28	28	28	**10**	**10**	**10**
Industrial	92	92	92	**67**	92	92	92	92	**67**
Transportation	163	163	163	163	**141**	**129**	163	**141**	**141**
Power	59	65	63	81	60	61	69	80	104
Total (MMTCO2)	378	360	363	374	357	346	346	336	334
% Change	0.0%	-4.6%	-3.8%	-1.0%	-5.5%	-8.3%	-8.3%	-11.0%	-11.5%

Introduction and Motivation



Projected Business-as-usual fuel demand & distribution by sector

- California energy consumption data & Market Allocation (MARKAL) Model
- Trends based on the projected fuel price & demand and supply regulations



Approach – Scenario Development

Develop scenarios of electrification in principal energy end-use sectors in excess of business-as-usual in 2020, <u>2030</u>, and 2050

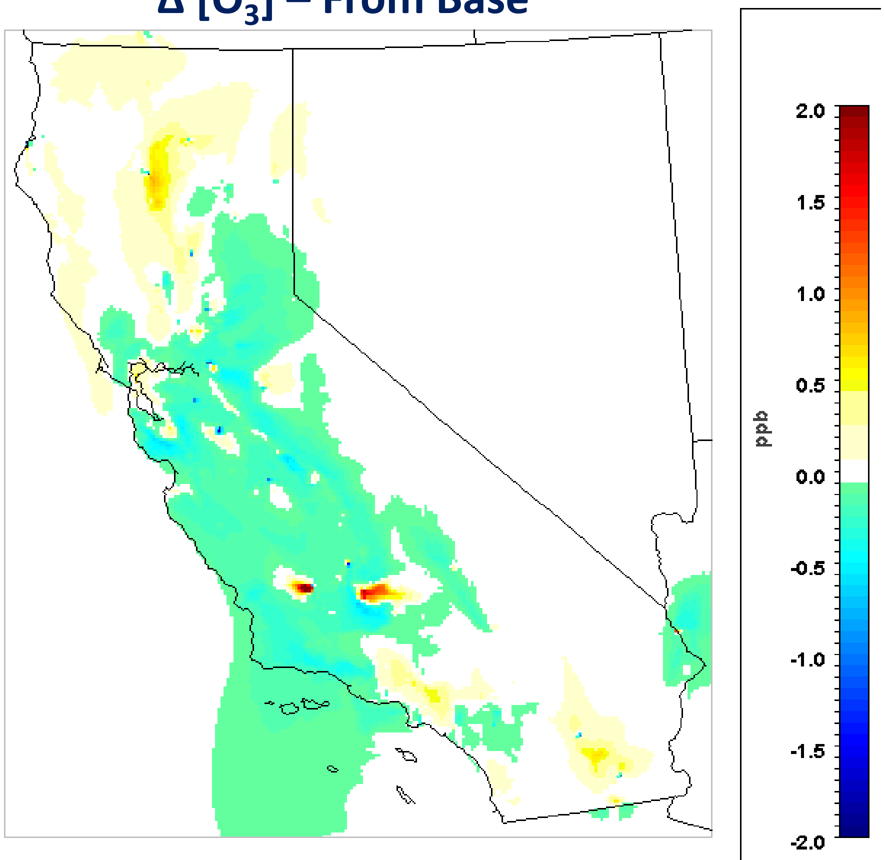
- Project energy demand and fuel distribution for end-use sectors to establish potential feasible additional electrification
- Quantify and characterize additional load from electrification
  - Projected electrification load for feasible technology deployment
    - **Sector-specific end-use considerations**
    - **Energy efficiency ratios (non-electric vs. electric)**
  - Determine temporal electrification load profile
    - **Sector- and fuel-specific temporal profiles, e.g., Industrial is 24/7 with no seasonal variation, residential peaks on weekends**

Results - Buildings Case (Summer)

AQ impacts for building electrification

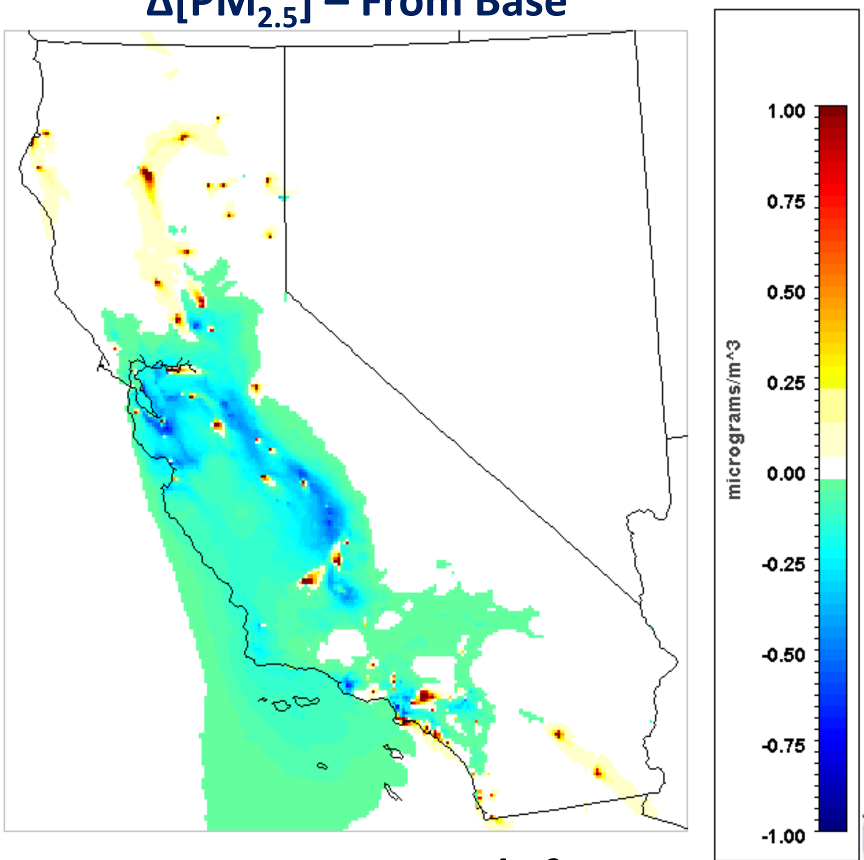
- Improvements in ozone (summer) and PM (summer/winter) significant
- Localized ozone (summer) worsening adjacent to some generator sites

Δ [O_3] – From Base



-3.55 to +2.66 ppb

Δ[$PM_{2.5}$] – From Base



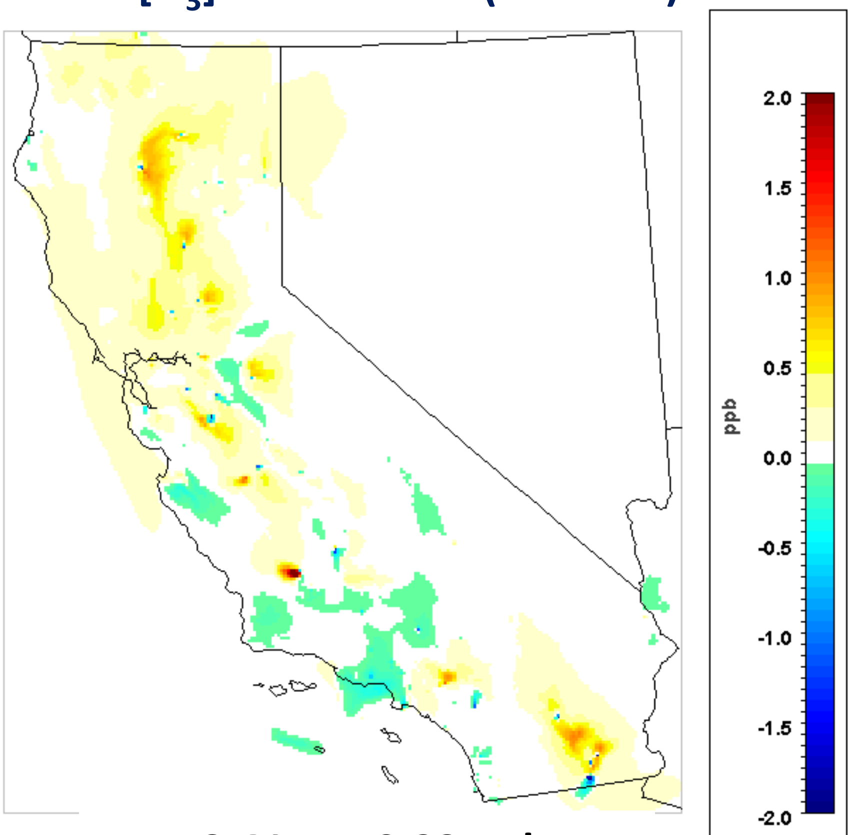
-0.74 to +12.58 μg/m³

Results – Industrial Sector

Industrial sector electrification requires further assessment

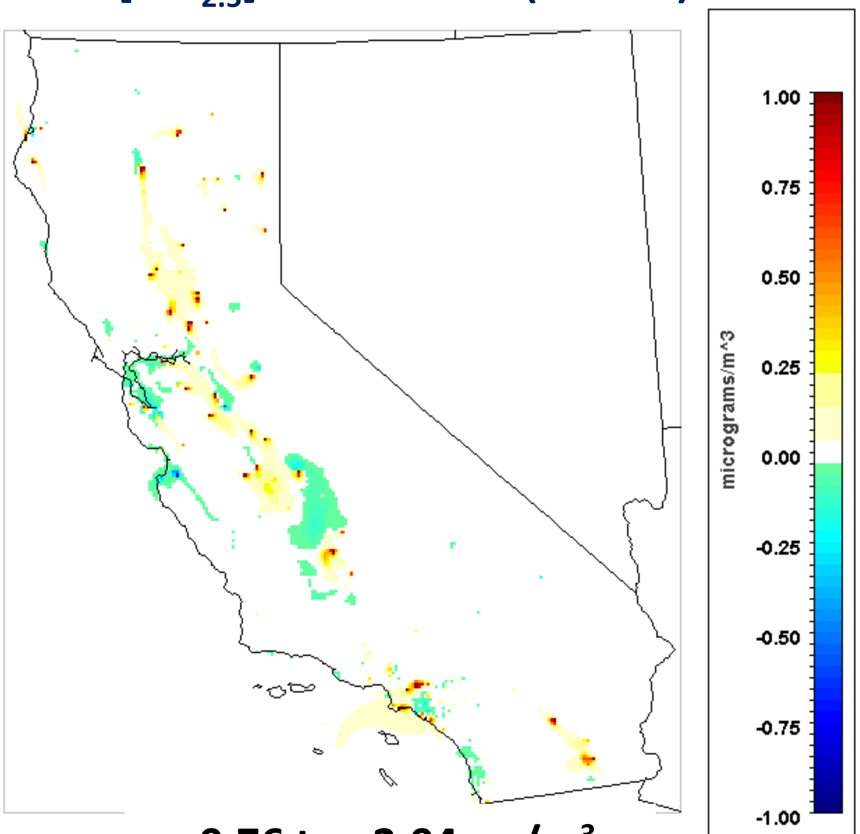
- **Challenging to electrify – assume only boiler and HVAC electrification**
- **Significant degree of worsening relative to other sectors**
  - Requires comprehensive planning and understanding of process electrification potential

Δ [O_3] – From Base (Summer)



-2.41 to +0.92 ppb

Δ[$PM_{2.5}$] – From Base (Winter)



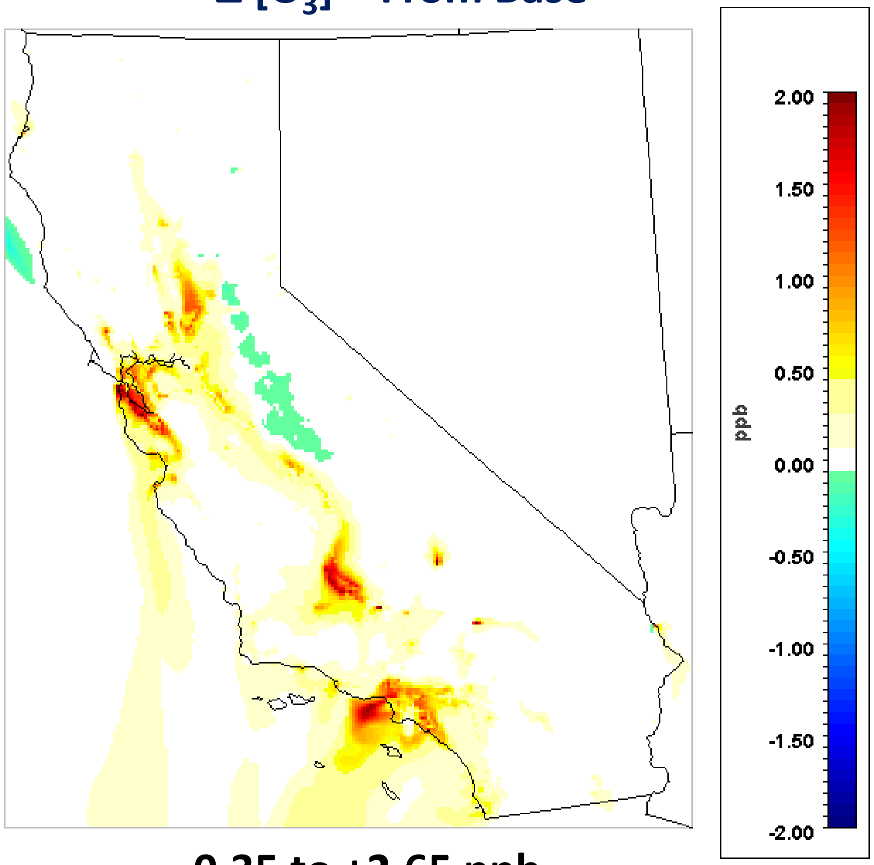
-0.76 to +2.04 μg/m^3

Results - Buildings Case (Winter)

AQ impacts for building electrification

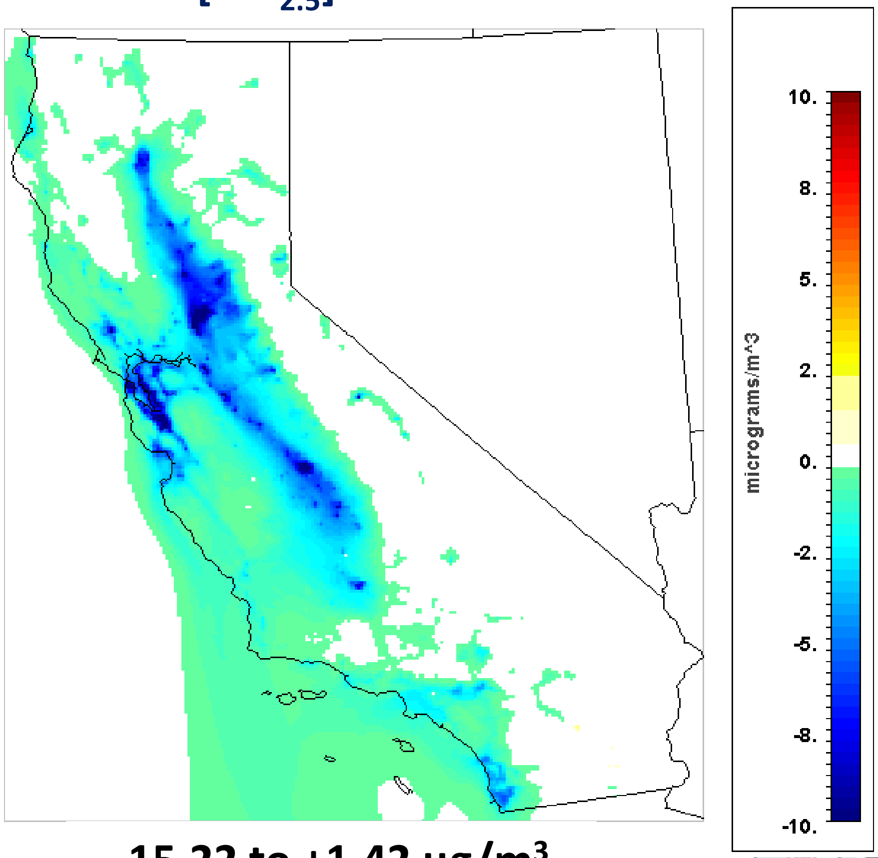
- Improvements in ozone (summer) and PM (summer/winter) significant
- Localized ozone (summer) worsening adjacent to some generator sites

Δ [O_3] – From Base



-0.35 to +2.65 ppb

Δ[$PM_{2.5}$] – From Base



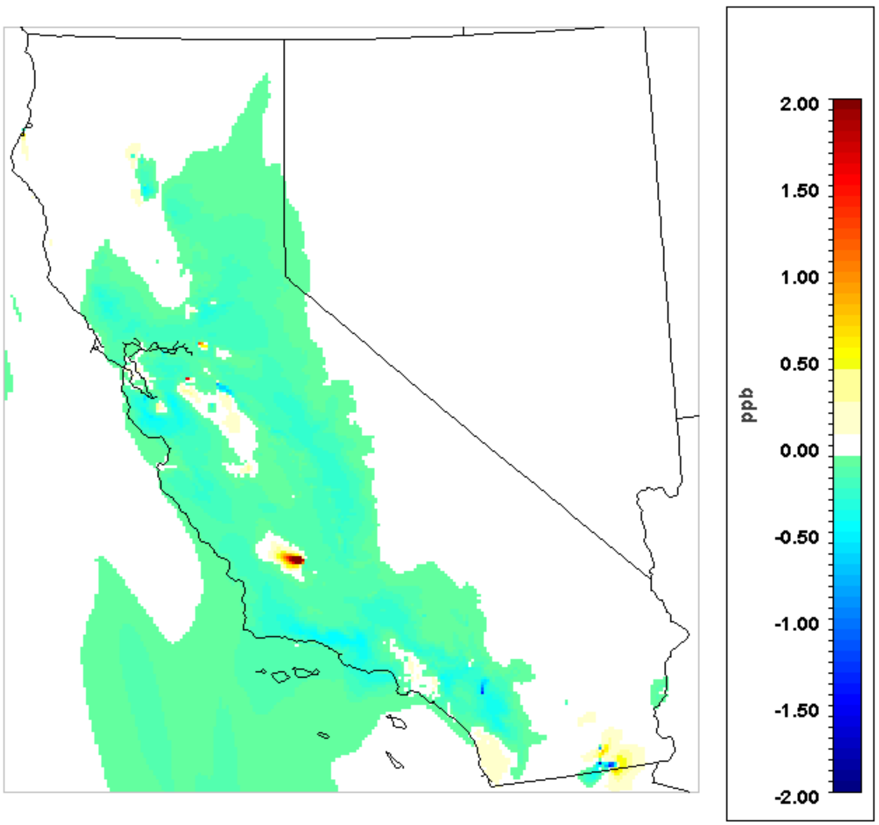
-15.22 to +1.42 μg/m³

Results – Transportation (LDV) Case

AQ impacts for LDV electrification multifaceted

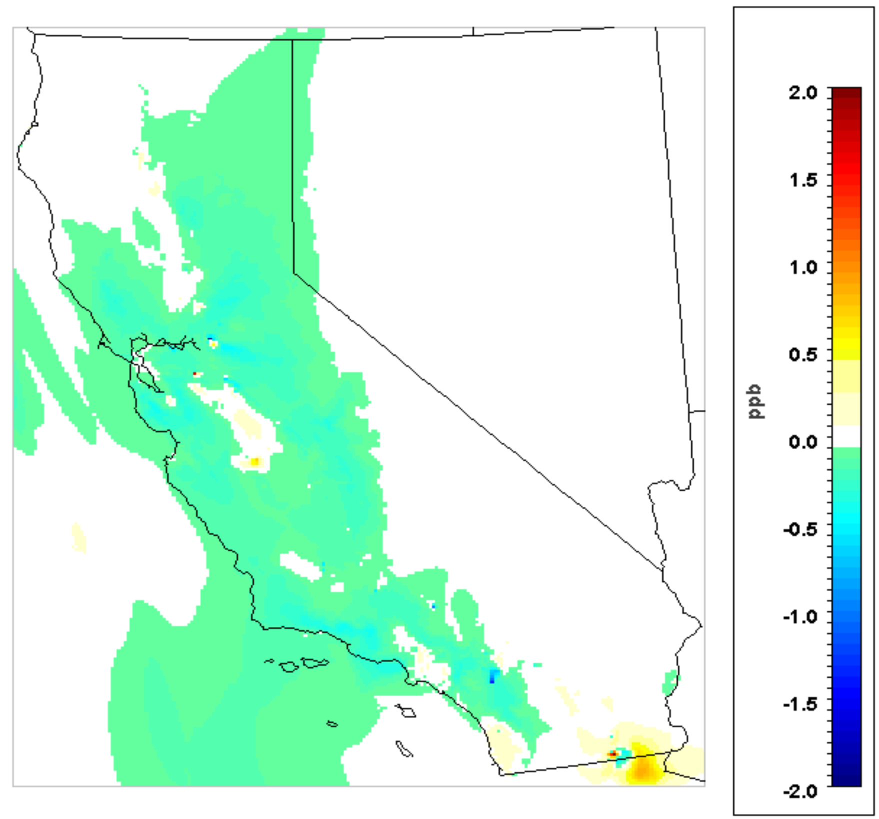
- **Important improvements in urban regions (high vehicle fleet, refinery presence)**
- **Complementary strategies can maximize AQ benefits & avoid harmful outcomes**

Δ [O_3] – Immediate Charging



-1.76 to +2.99 ppb

Δ [O_3] – Smart Charging



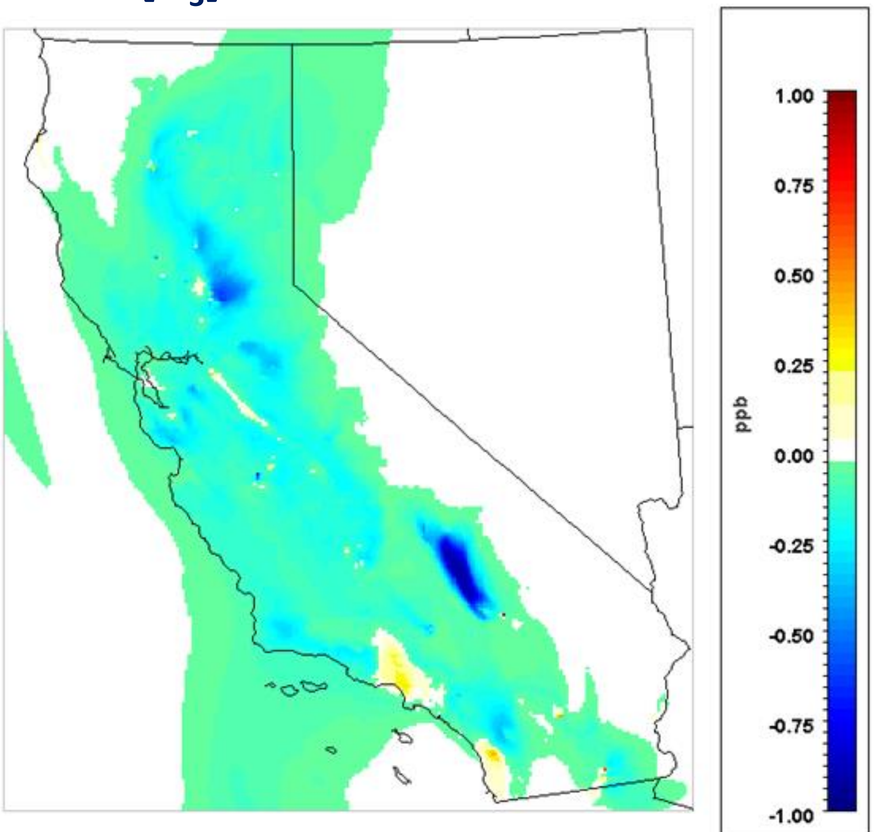
-4.38 to +2.04 ppb

Results – Transportation (Smart vs. Immediate)

AQ impacts for Light Duty Vehicle electrification multifaceted

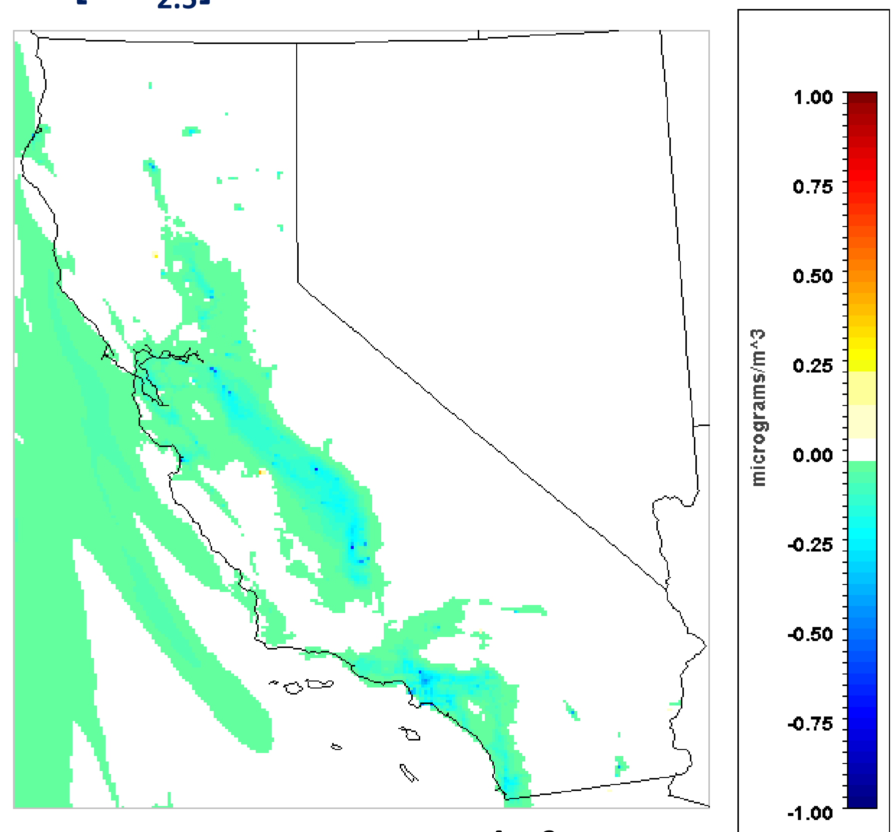
– **Complementary strategies can maximize energy, GHG and AQ benefits**
  - Reduce grid dynamic consequences and enhance renewable utilization

Δ [O_3] – Smart vs. Immediate



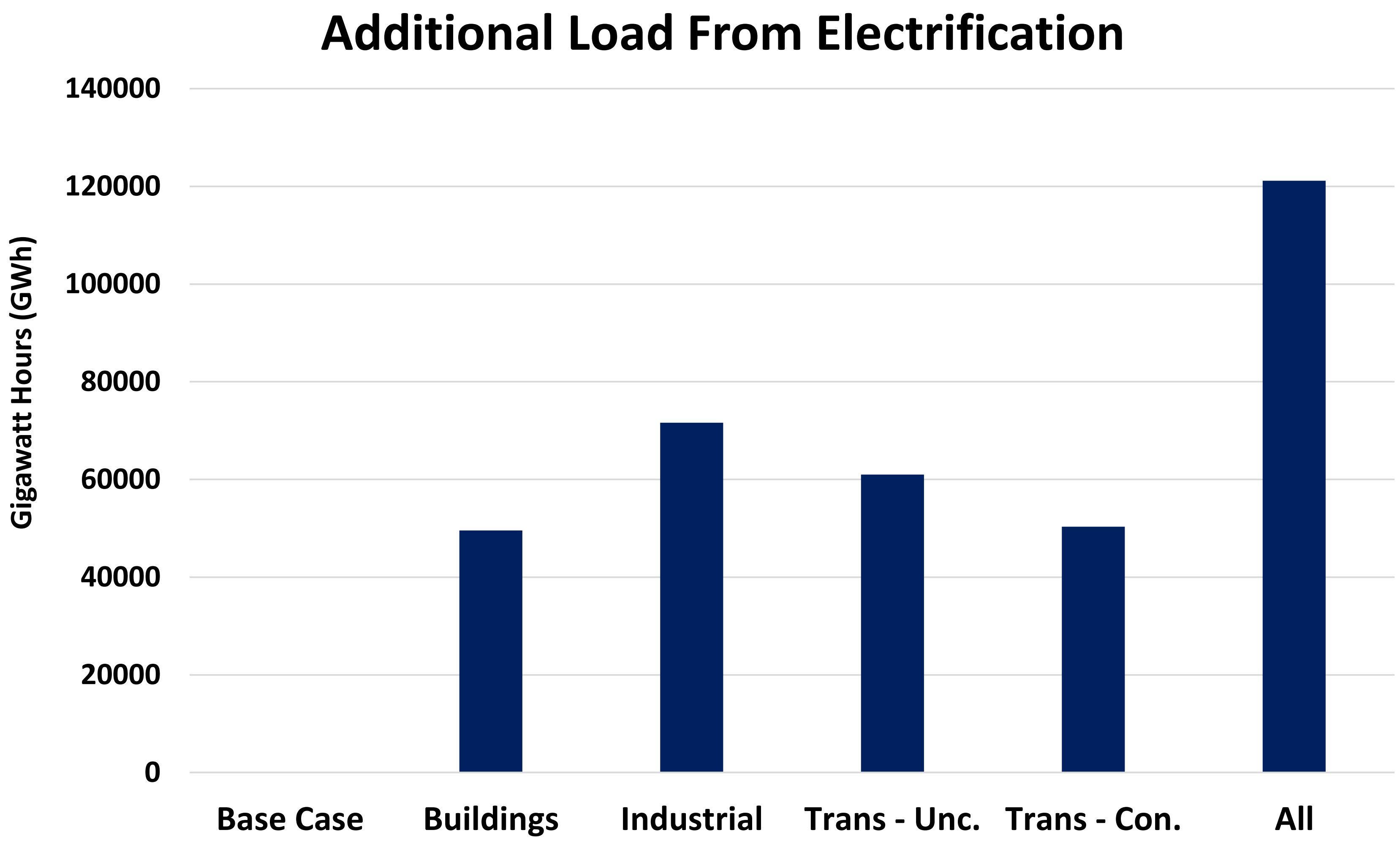
-0.96 to +1.03 ppb

Δ[$PM_{2.5}$] – Smart vs. Immediate



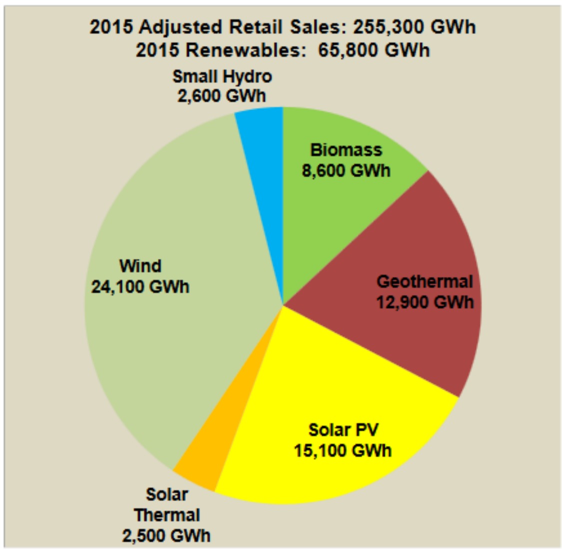
-0.85 to +0.41 μg/m^3

Case	Additional Load [MWh]	Renewable Capacity [MW]	BAU [%]	2030 [%]
Buildings	49,556,400	92674		
Industrial	71,601,800	99159		
Transportation – Immediate	61,000,000	81789		
Transportation – Smart	50,310,000	75857		
All Sectors	121,158,000	105079		


Additional Load From Electrification
Gigawatt Hours (GWh)
140000
120000
100000
80000
60000
40000
20000
0
Base Case
Buildings
Industrial
Trans - Unc.
Trans - Con.
All

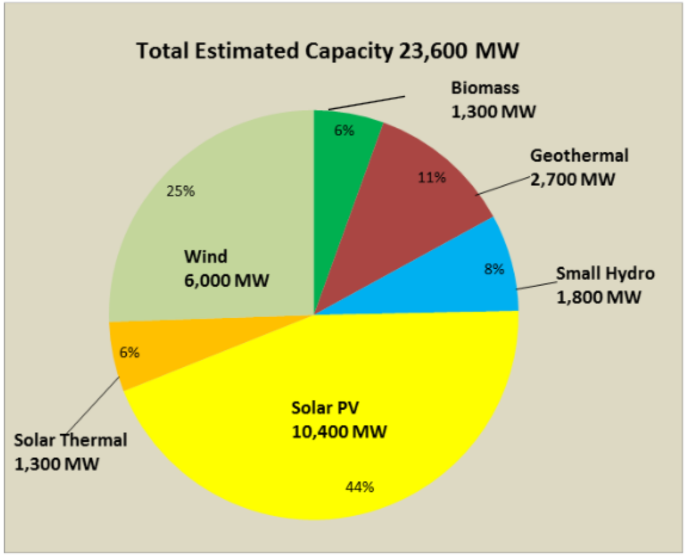
- California Renewable Energy
  - In 2015 26% of electricity retail sales from renewable generation

Figure 3: 2015 Generation From Renewable Facilities Serving California



Source: Energy Commission staff based on Quarterly Fuels and Energy Report (QFER) [8], 2015 Power Source Disclosure Filings [11], S-2 Filings [D2], CPUC compliance filings [12], and Energy Commission RPS Compliance Filings [13]. Updated July 2016.

Figure 4: In-State Renewable Capacity by Resource Type, Includes Self-Generation (as of June 30, 2016)



Source: Energy Commission staff based on Quarterly Fuel and Energy Report, source [8], Renewable Distributed Generation sources [D1]-[D14], Data include only facilities physically located in California. However, there are some instances where in-state facilities have contracted to sell power outside California. See notes for Table 2 for additional information about the data. Not included in Figure 4 are 1,650 MW of renewable energy facilities that are physically located out-of-state but have the first point on interconnection in California. Totals may not sum due to rounding. Also, not included in the pie chart is 144 MW of self-generation for which the fuel type is undefined. The 144 MW is included, however, in the 23,600 MW of total estimated capacity.

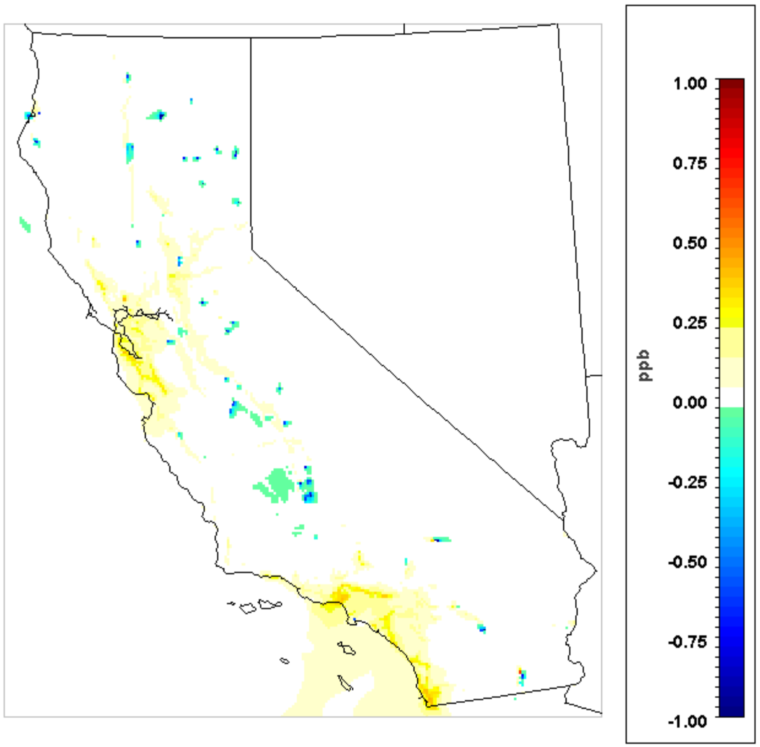
Case	Sector/Sub-sector	Technologies	BAU [%]	2030 [%]
Buildings	Commercial & Residential	Cooking, space heating, water heating	56.9% 36.9%	79.6% 71.2%
Industrial	Industrial	Boilers only - no process	7.4%	24.%
Transportation – Immediate	Light Duty Vehicles: Uncontrolled charging	Battery Electric Vehicles	1.1%	9.3%
Transportation – Smart	Light Duty Vehicles: Controlled charging	Battery Electric Vehicles	1.1%	7.7%
All Sectors	All the above	All the above	Above	Above

Results – Winter Cases

AQ impacts differ for same scenario in Winter

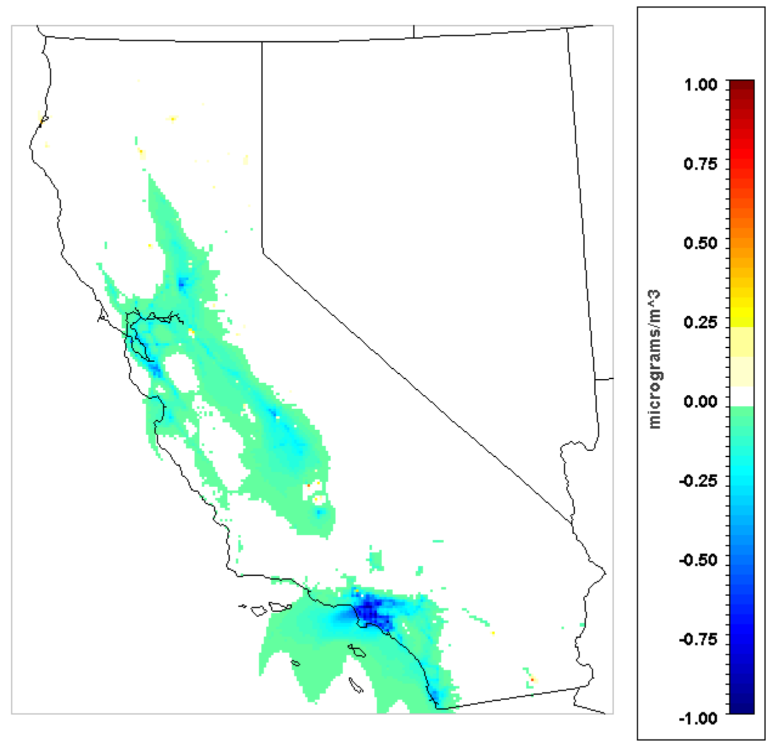
- Complexity of tropospheric ozone formation and lower baseline values
- PM impacts generally enhanced including improvements in ground-level conc.
  - Important for some regions of the State → Central Valley

Δ $[O_3]$ Relative to Base



-1.63 to +0.67 ppb

Δ$[PM_{2.5}]$ Relative to Base



-01.08 to +0.60 $\mu g/m^3$

Approach – Scenario Development

Develop scenarios of wide-spread electrification in principal economic sectors in excess of business-as-usual

- Transportation
  - LDV only, 1 case uncontrolled charging and 1 case smart charging strategies
  - Temporal distribution - National Household Travel Survey & VMT demand data
- Service/Commercial/Residential = Buildings
  - Only space heating, water heating, cooking
  - NG load shapes for Res from eQuest, for Com from historical profiles from survey data
  - Space heating varies throughout the year , weekends vs. midday
- Industrial
  - Only boiler (40%) and HVAC (50%) end-uses are electrified
  - 24/7, annual demand is steady

Approach – Scenario Development

- **Projected statewide load**
  - **From CPUC renewable integration study[1] , adjusted with MARKAL projections**
  - **50% renewables in 2030, renewable mix determined by CAISO/CPUC scenarios[2]**
- **Balancing dynamics**
  - **Temporal renewable load profile determined by HiGRID[3]**
    - **Intermittent balanced by DR, DG, ES, and EV dispatched in order of flexibility**
    - **Any remaining demand estimated by HiGRID is then balanced by dispatching power plants in PLEXOS**
- **Plexos**
  - Grid simulation tool based economic optimization methods while consider balancing requirements and transmission constraints
  - Generator dispatch

- **Plexos**
  - Grid simulation tool based economic optimization methods while consider balancing requirements and transmission constraints
  - Generator dispatch
- **Determine additional load from electrification**
  - Projected statewide demand + electrification load while considering temporal distribution and energy efficiency ratios (non-electric vs. electric)
- **Determine temporal electrification load profile**
  - Sector- and fuel-specific temporal profiles, e.g., industrial is 24/7 and consistent throughout the year