Energy+Environmental Economics

Deep Decarbonization in a High Renewables Future

Updated results from the California PATHWAYS model

CEC EPIC-14-069 Draft Final Study Results

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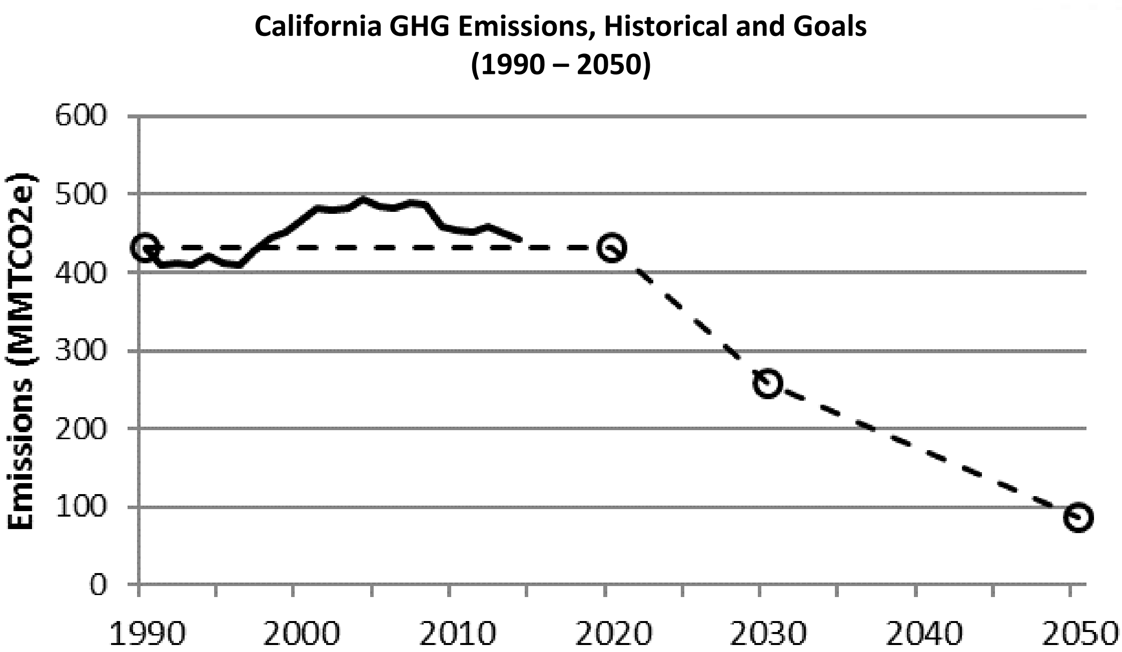
Agenda

- Project Background
- High Electrification Mitigation Scenarios
- Alternative Mitigation Scenarios
- Conclusions

- *Appendix*

California's Greenhouse Gas (GHG) Reduction Goals

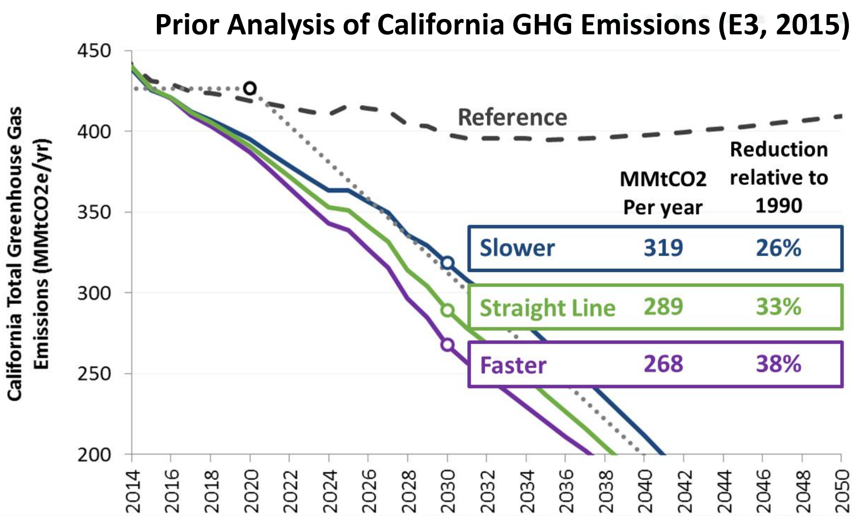
+ **By 2020: return GHGs to 1990 levels** (AB 32, 2006)
+ **By 2030: 40% below 1990 levels** (SB 32, 2015)
+ **By 2050: 80% below 1990 levels** (B-30-15 and S-3-05)



Project Background

+ This research extends the work of past projects :

- **2012:** Williams et al, *Science* "The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal role of Electricity"
- **2014/15:** Inter-agency "Energy Principals" E3 PATHWAYS analysis: "What 2030 GHG emissions target should California set?"

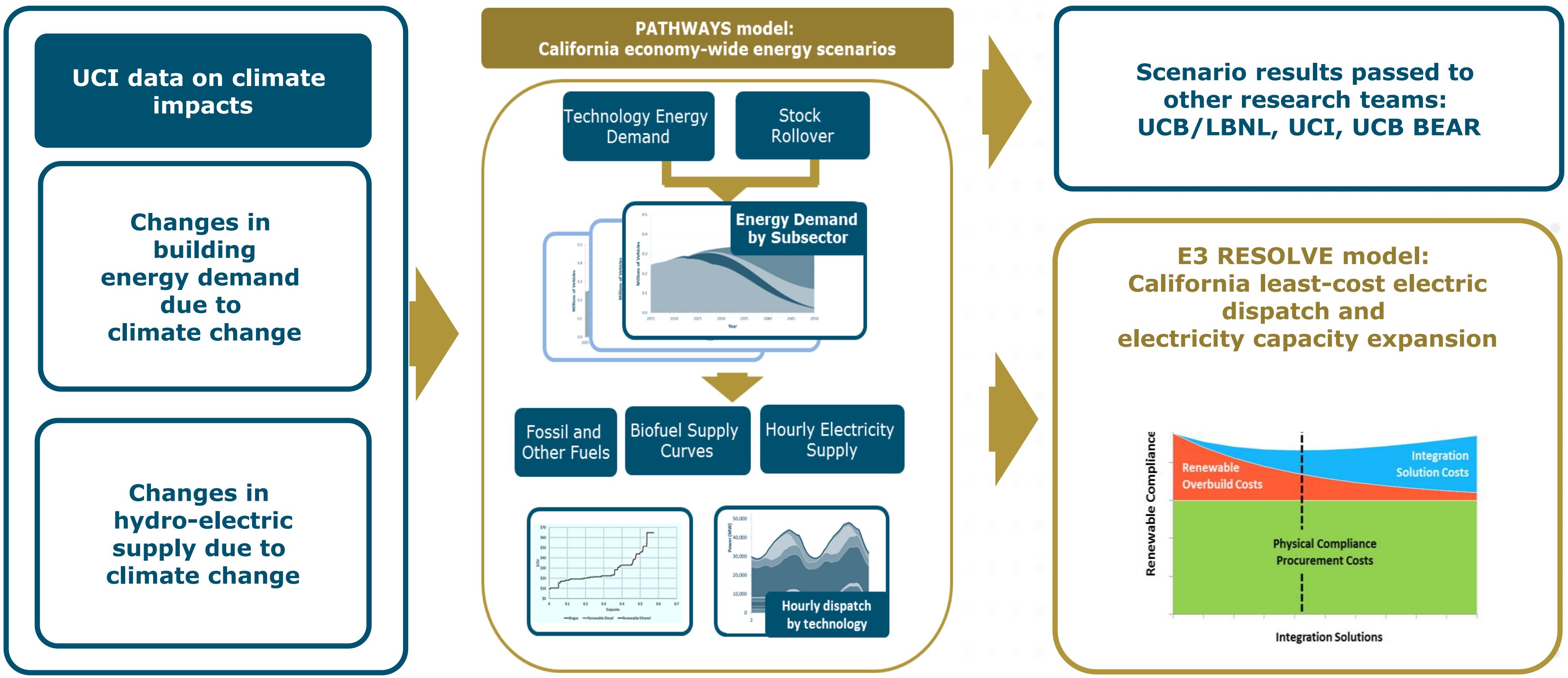


- **2016/17:** ARB 2017 Climate Change Scoping Plan Update
  - Evaluates impact of current policies plus cap & trade to meet state's 2030 GHG goals using PATHWAYS model and macroeconomic analysis

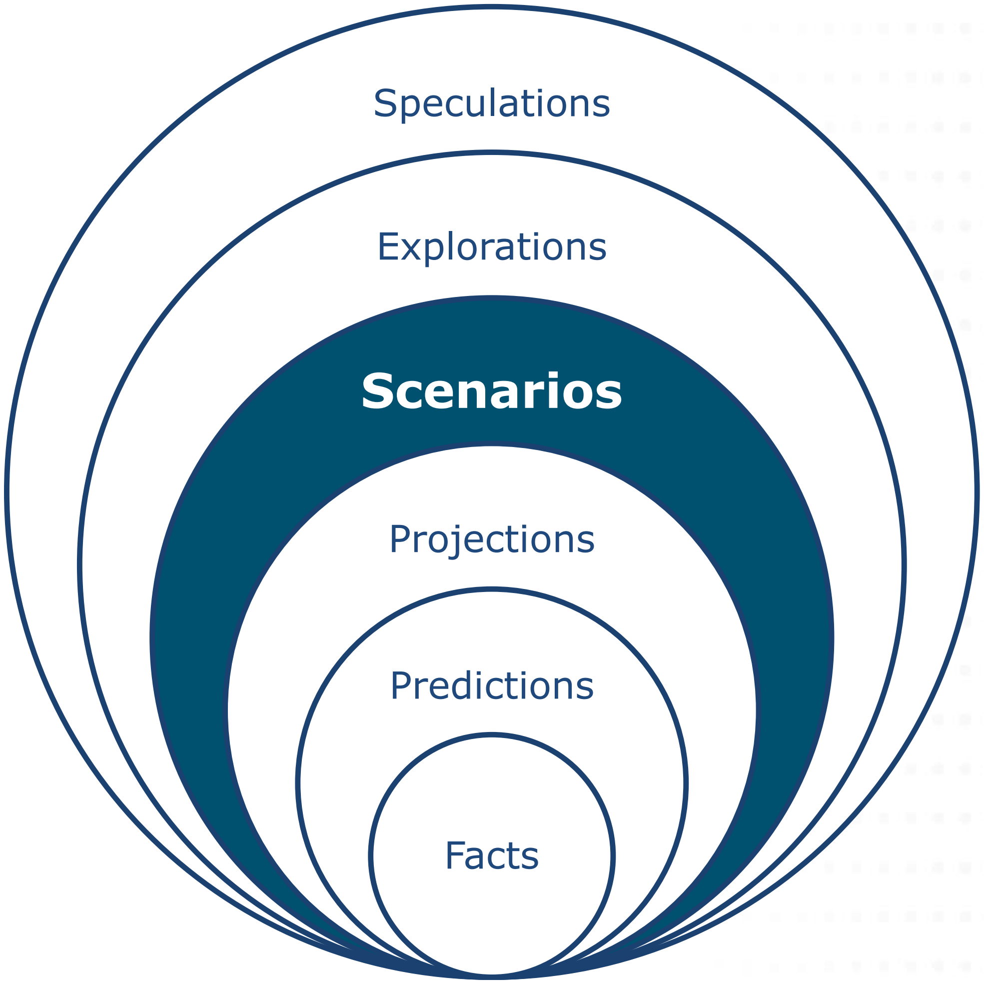
Key Research Questions

+ **What are the priority, near-term strategies needed to enable achievement of California's 2030 and 2050 GHG reduction goals? We identify priority strategies in terms of:**
  - Deployment
  - Market Transformation
  - Reach Technologies
+ **What are the risks to, and potential cost implications of, meeting the state's GHG goals if key mitigation strategies aren't as successful as hoped?**
+ **For example:**
  - Less biofuels (in-state resources only), more renewables & electrification
  - No building electrification, more electrification, renewables and power-to-gas
  - Less energy efficiency, more renewables and electrification

Economy-wide Energy Scenarios Model (PATHWAYS) is combined with Electricity Cost Optimization (RESOLVE)



PATHWAYS scenarios evaluate uncertain and complex futures



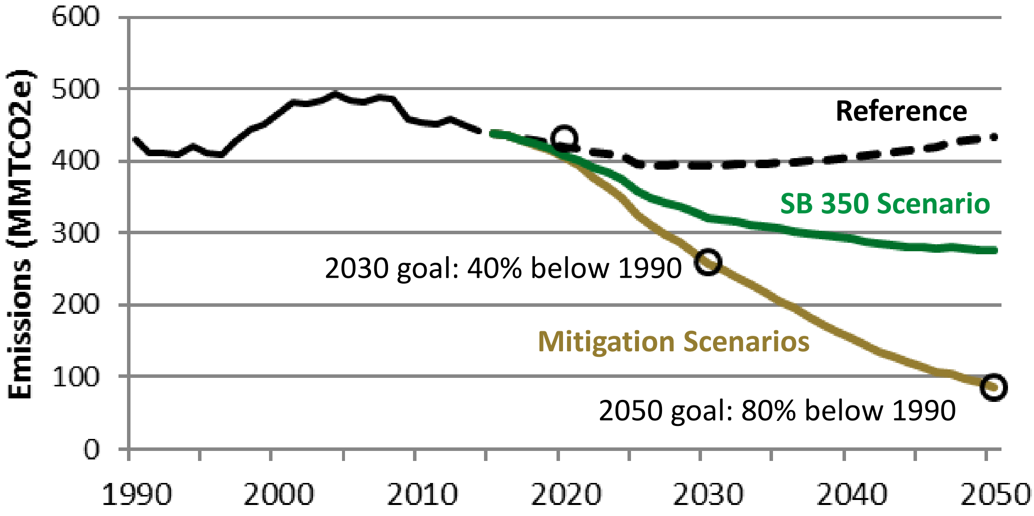
3 Types of Scenarios are Evaluated

1. Reference Scenario

- ✓ Reflects pre-SB 350 policies (e.g. 33% RPS, historical energy efficiency goals)

2. SB 350 Scenario

- ✓ Includes SB 350 (50% RPS by 2030), mobile source strategy Cleaner Technology and additional reductions in non-combustion GHGs



3. Ten Mitigation Scenarios

- ✓ Include additional GHG reduction strategies beyond SB 350 Scenario to meet GHG goals

- ✓ Cap and trade (AB 398) and criteria pollutant regulations (AB 617 & AB 1647) are likely to help achieve the higher adoption rates of GHG mitigation technologies that are assumed in the Mitigation Scenarios, but the impacts of these policies are not explicitly quantified or modeled due to uncertain future carbon prices & policy design

Ten Mitigation Scenarios Test Different GHG Reduction Strategies & Risks

Mitigation Scenarios	Scenario description
High Electrification	Electrification of buildings and transportation, high energy efficiency, renewables, limited biomethane
No Hydrogen	No fuel cell vehicles or hydrogen fuel, includes industrial electrification
Reference Smart Growth	Less reductions in vehicle miles traveled, additional GHG mitigation measures in other sectors
Reduced Methane Mitigation	Higher fugitive methane leakage, additional GHG mitigation measures in other sectors
Reference Industry EE	Less industrial efficiency, additional GHG mitigation measures in other sectors
In-State Biomass	Less biofuels with no out-of-state biomass used, additional GHG mitigation measures in other sectors
Reference Building EE	Less building efficiency, additional GHG mitigation measures in other sectors
No Building Electrification with Power-to-Gas	No heat pumps or building electrification, additional GHG mitigation measures in other sectors
High Biofuels	Higher biofuels, including purpose grown crops, fewer GHG mitigation measures in other sectors
High Hydrogen	More fuel cell trucks, fewer all-electric vehicles

Four "Pillars" of Decarbonization

Energy efficiency & conservation
- Industrial efficiency
- Building efficiency & conservation
- Vehicle efficiency & smart growth

Electrification
- Industrial electrification
- Building electrification
- Vehicle and freight electrification

Low-Carbon Fuels
- Nuclear, Carbon Capture & Storage*
- Biofuels
- Renewables and hydroelectric

Sequester carbon & reduce non-combustion GHGs
- Soil & forest carbon, CO2 removal, black carbon*
- F-gases, N_2O, CO_2 from cement
- Methane (manure, dairy, gas leaks, etc.)

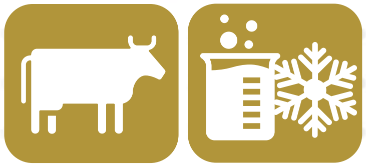
* Nuclear, Carbon Capture and Storage, CO2 removal technologies, and emissions from Land Use, Land-Use Change and Forestry (LULCF) and black carbon are not included in analysis.

Four Pillars of GHG Reduction are Needed Across All Scenarios Evaluated

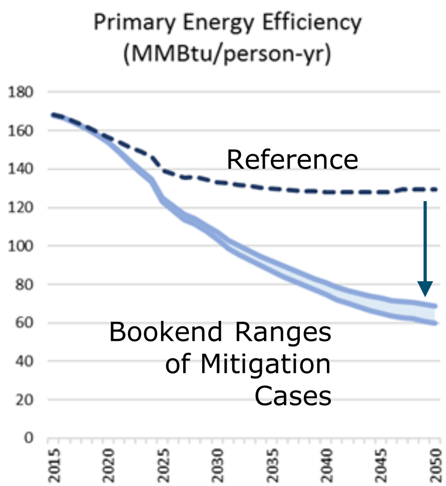
Energy efficiency & conservation

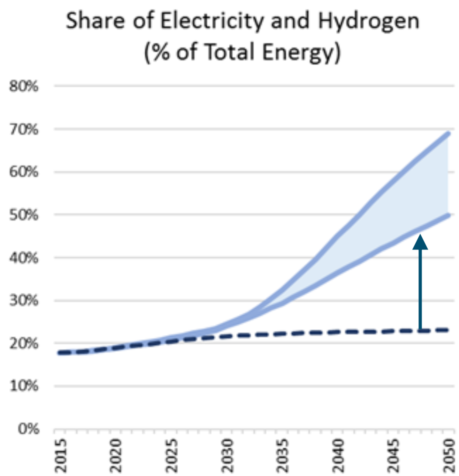
Electrification

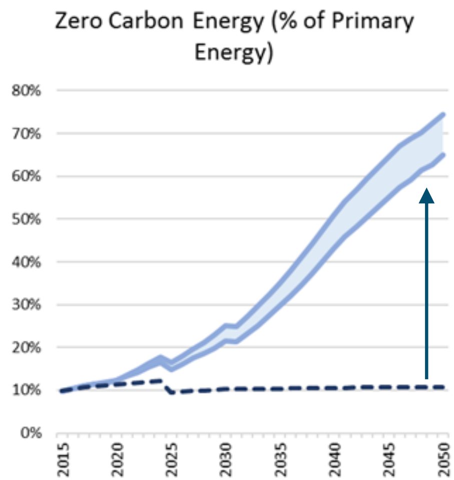
Low-Carbon Fuels

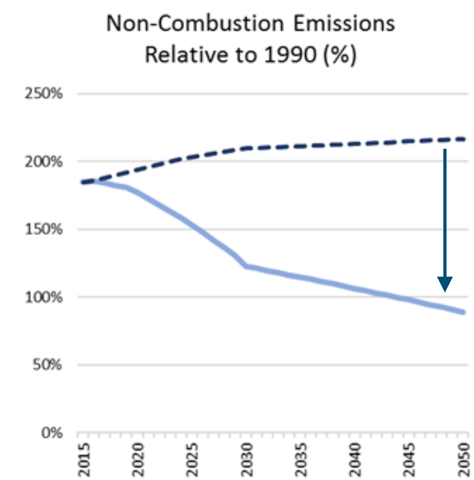


Reduce non-combustion emissions





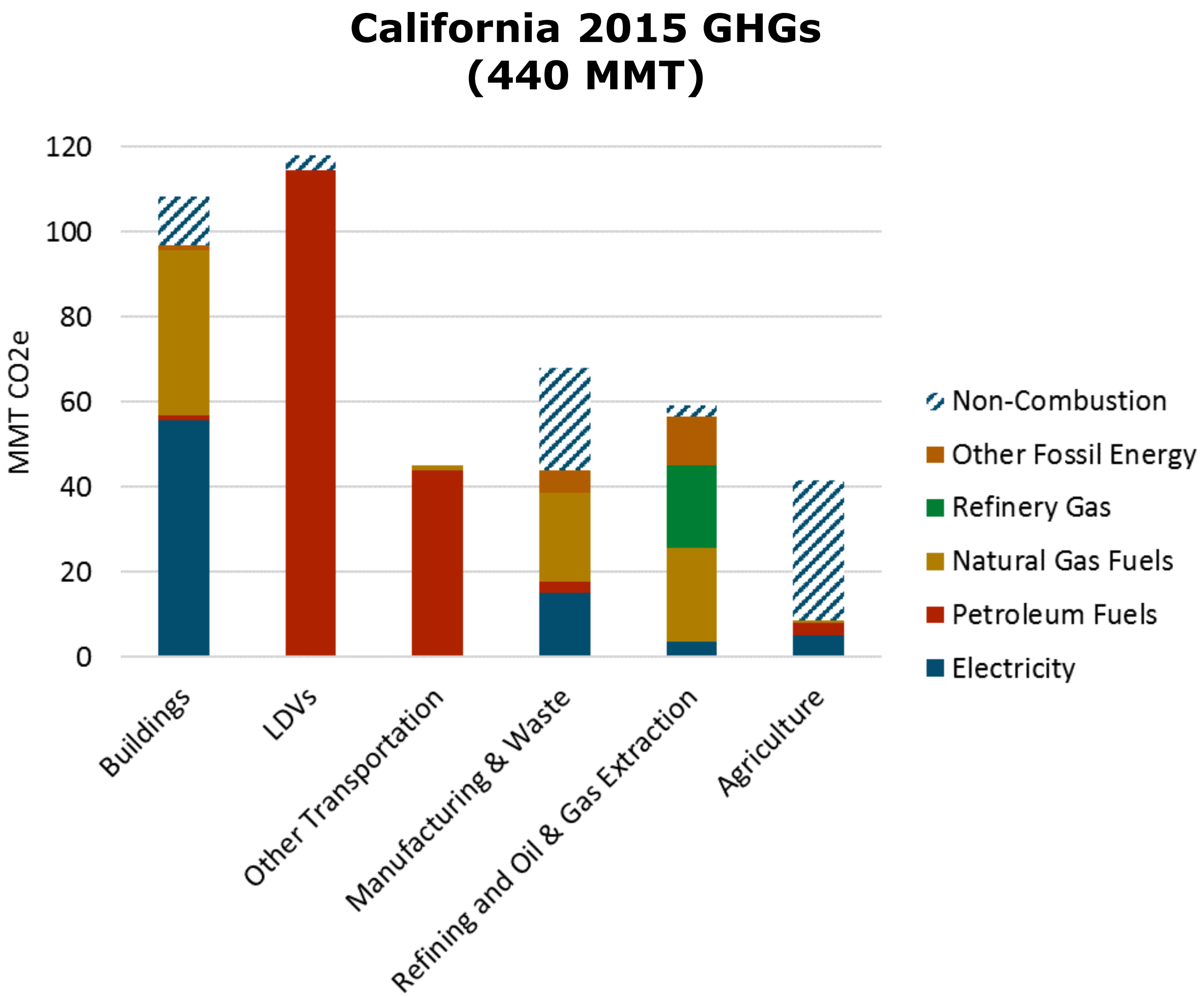




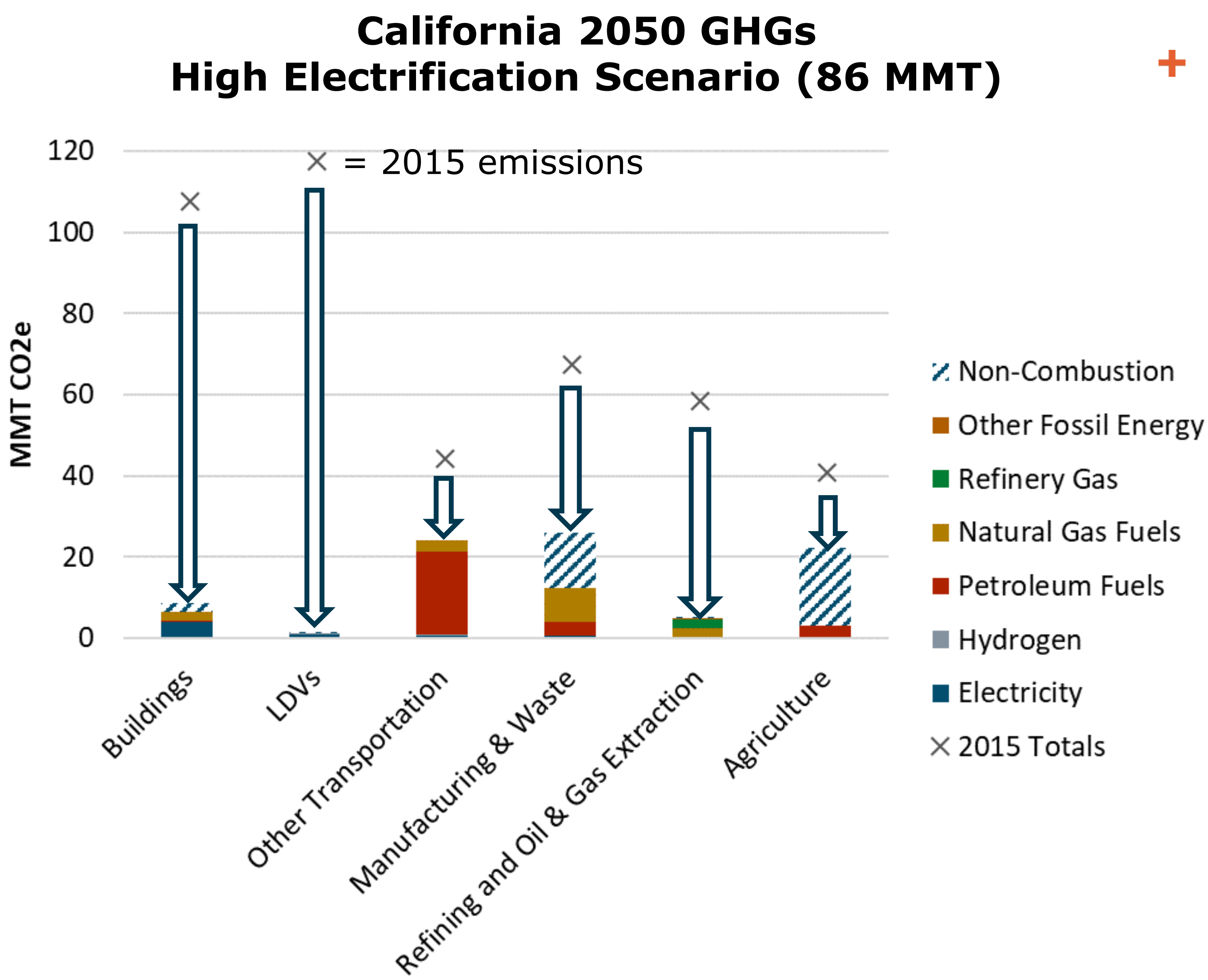
- Significant progress is needed across all four pillars, with fastest ramp-up between today and 2030

HIGH ELECTRIFICATION SCENARIO RESULTS

Light duty vehicles (LDVs) represent ~30% of California's GHG emissions today

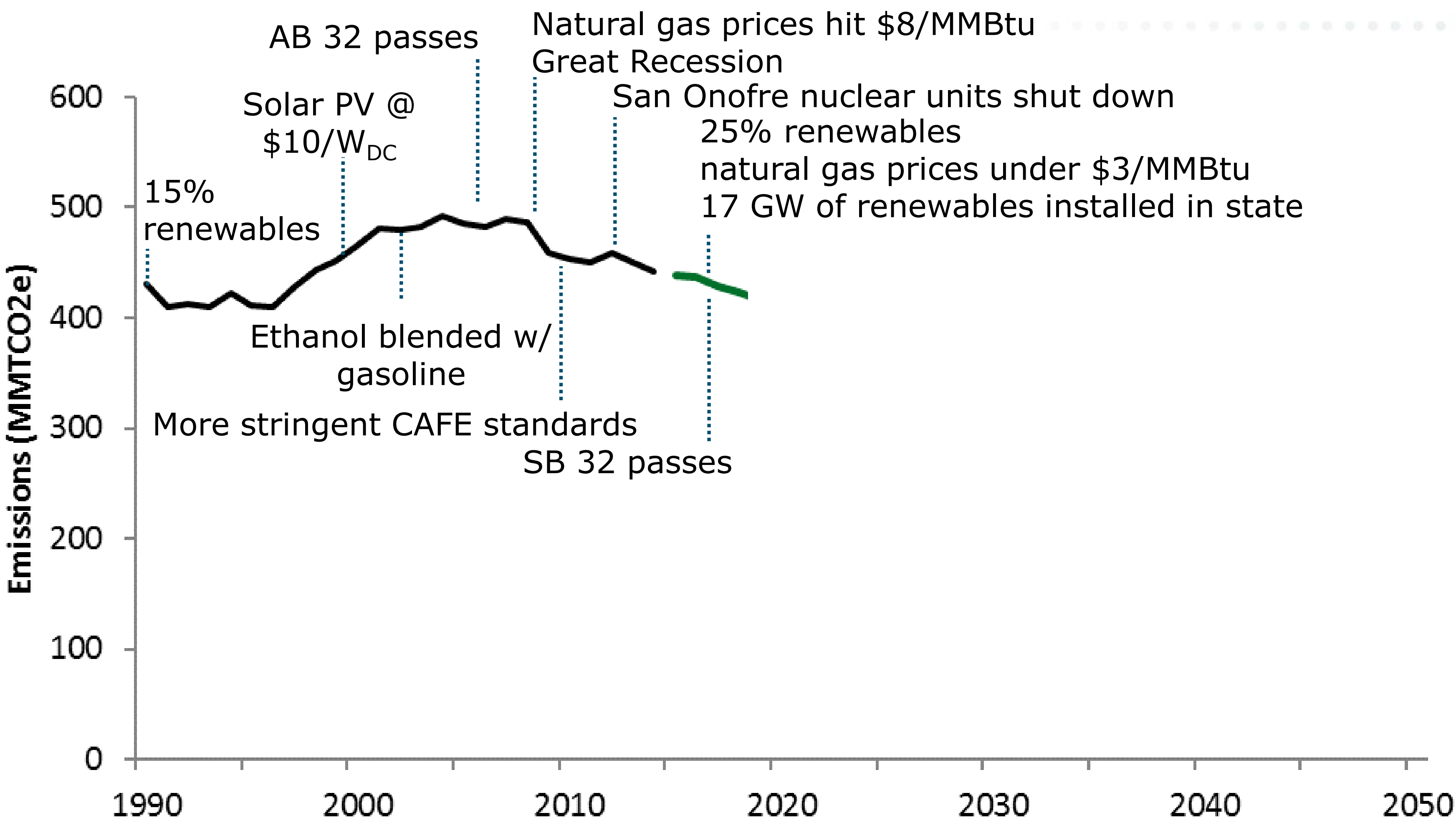


By 2050, GHGs are in difficult to reduce sectors, largely non-combustion GHGs

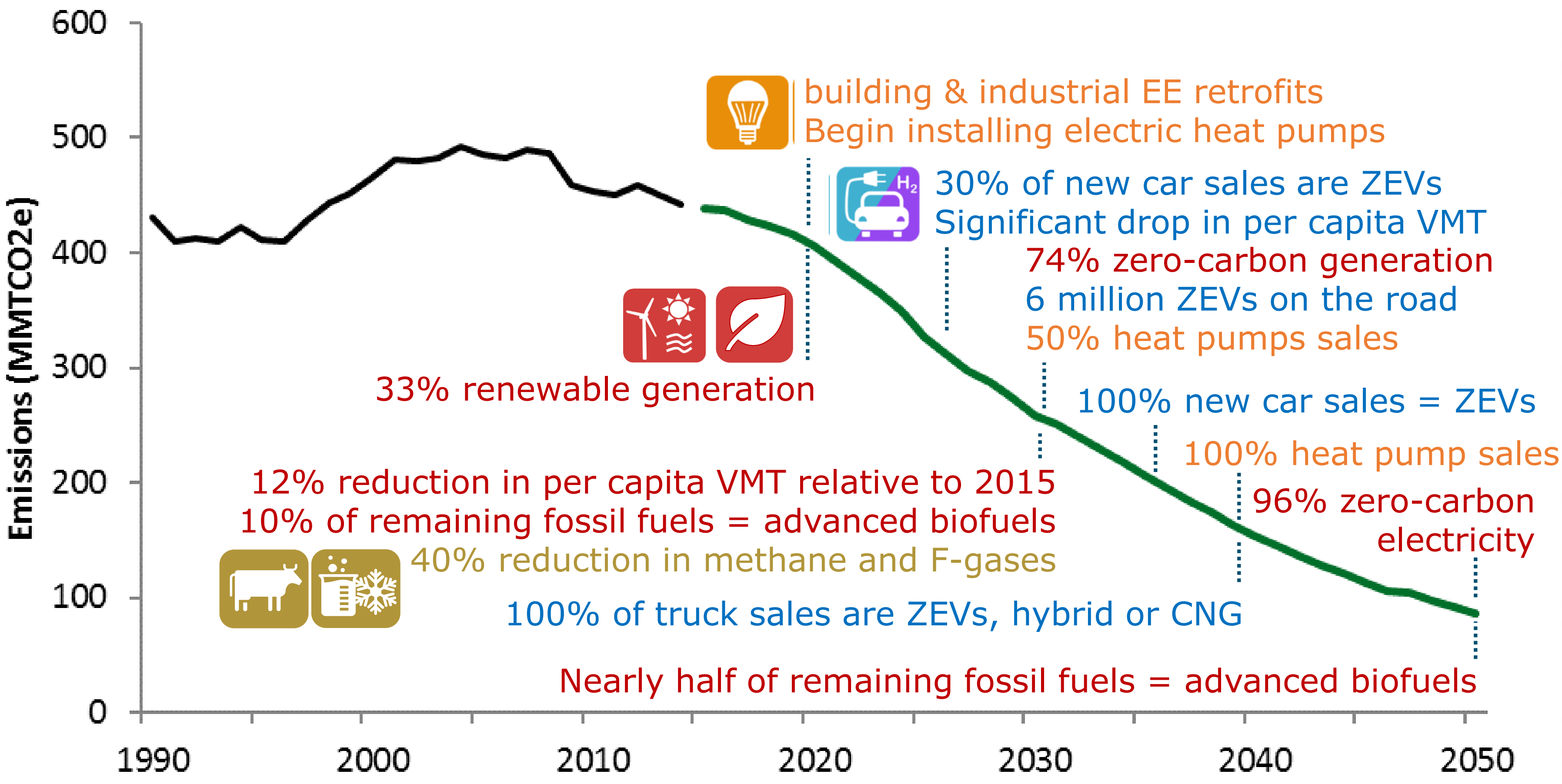


- *Remaining 2050 emissions are mostly from trucking, aviation, cement, and waste, dairy & agricultural methane*

Timeline of Statewide GHG Emissions

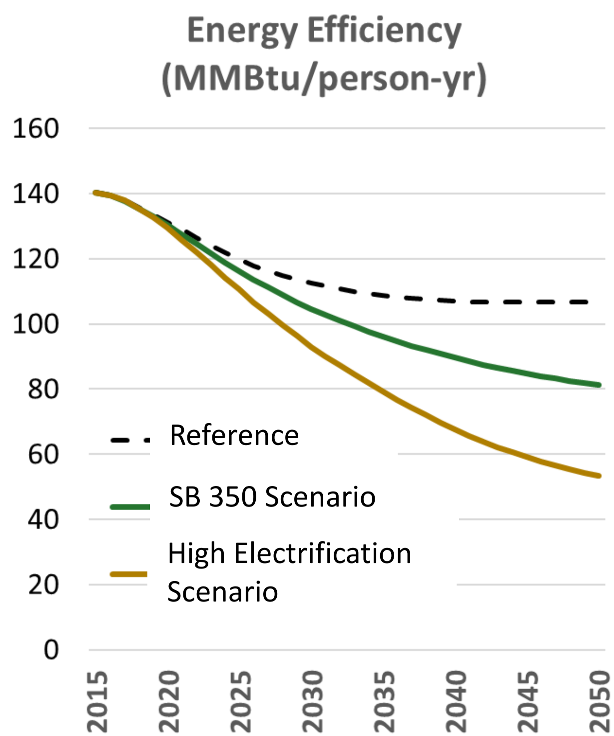


Timeline of GHG Reduction Measures in High Electrification Scenario

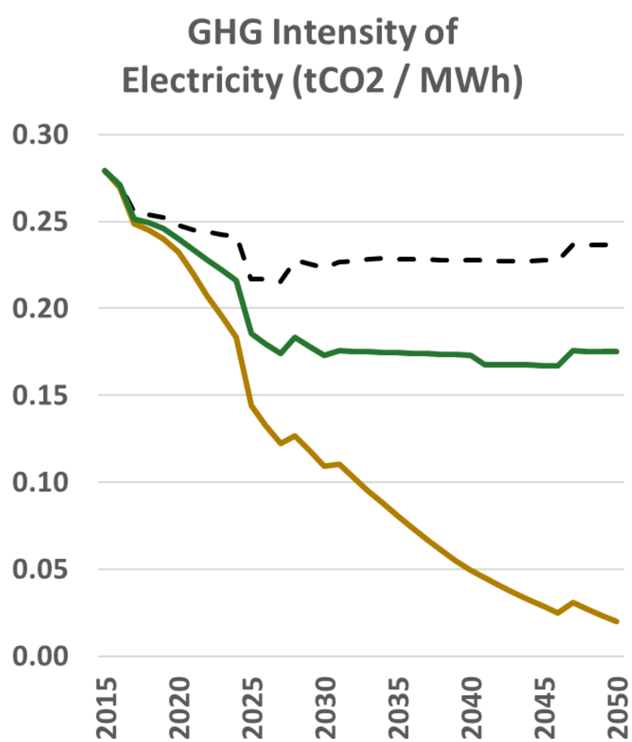


High reliance on energy efficiency and renewables, less reliance on biofuels than prior analyses

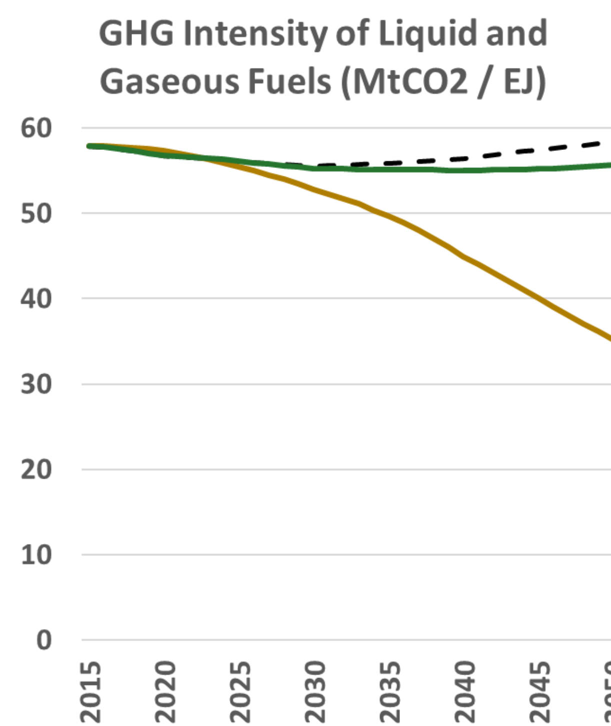
Energy efficiency & conservation



Renewables and hydropower



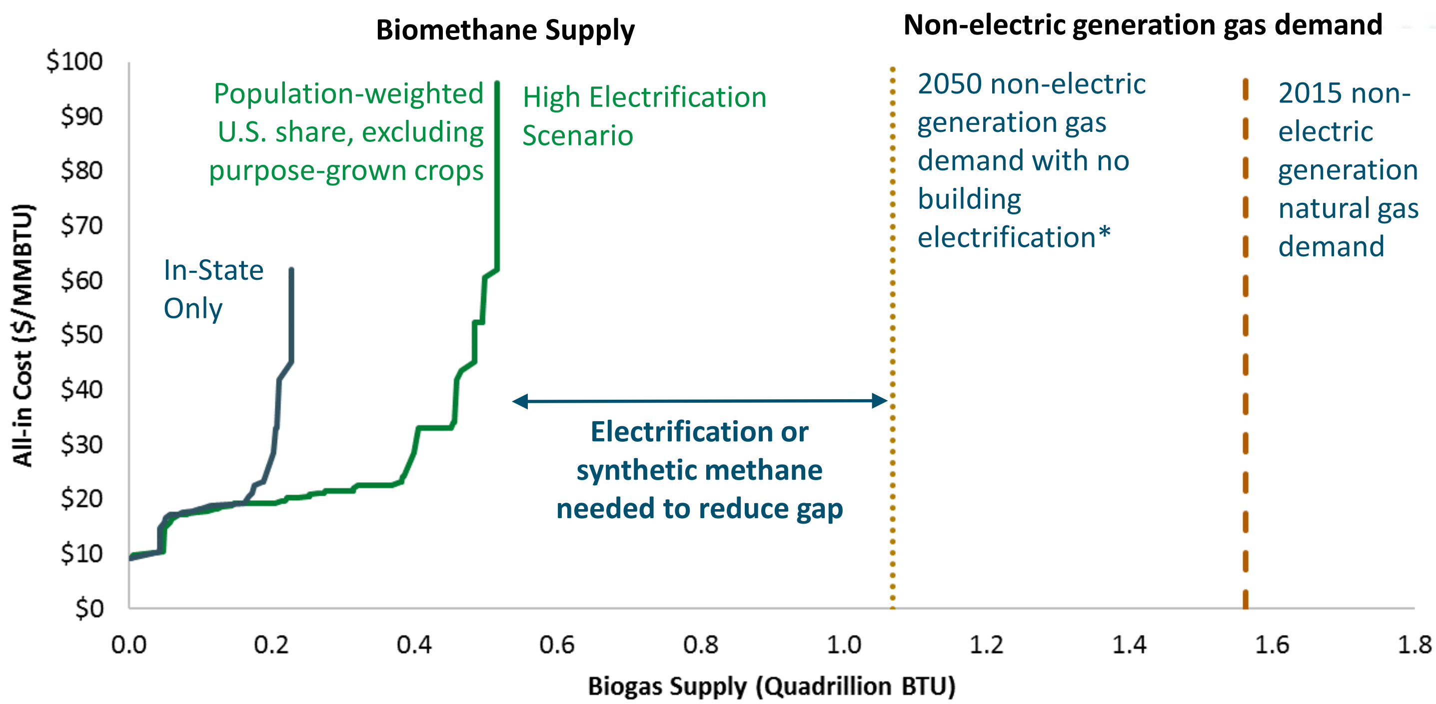
Biofuels



Biomethane may not be sufficient to displace industrial and building natural gas demand

+ **Without building electrification, gas demand from buildings & industry may exceed CA's population share of U.S. biomethane supply (excluding purpose-grown crops)**

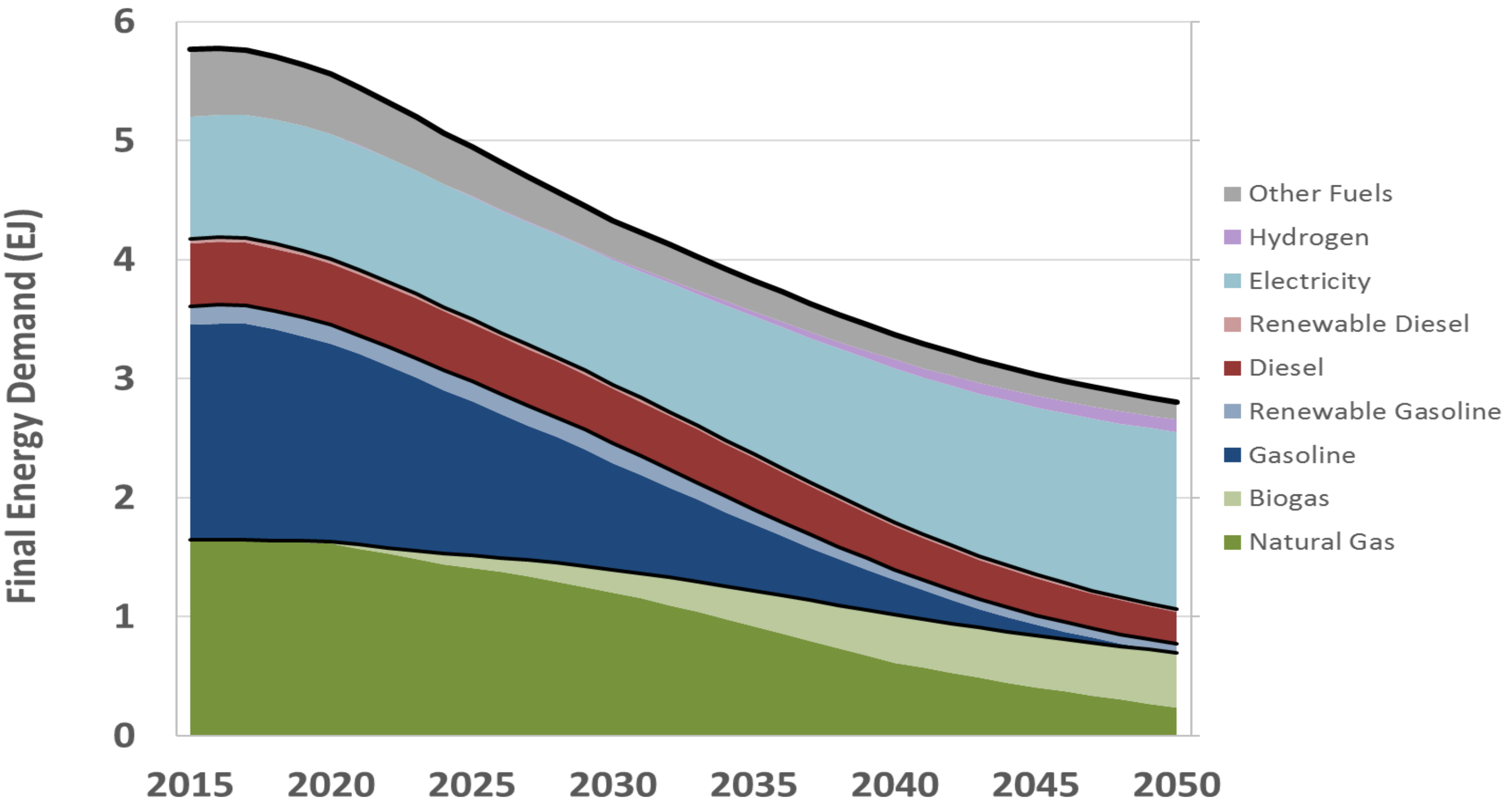
Estimated Cost and Available Biomethane Supply to California



* Includes high natural gas efficiency and petroleum industry demand reduction

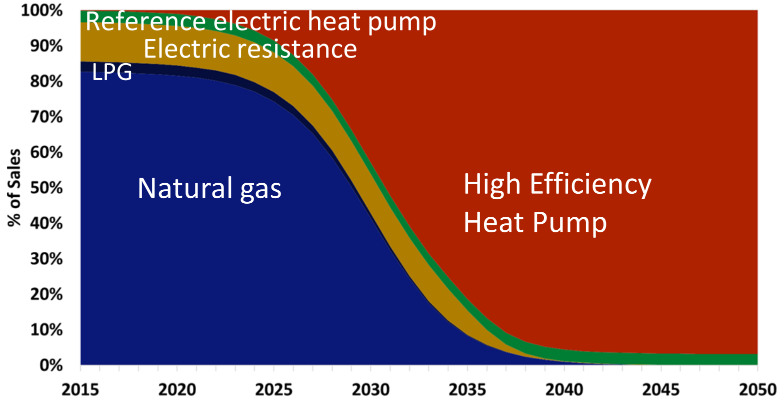
Energy Demand is Increasingly Met with Low-Carbon Electricity, Limited Biofuels Used for Hard to Electrify End-Uses

- Electricity increases due to electrification of transportation and buildings, all other fossil fuels decrease
- Biomethane is used in this scenario to decarbonize industry, could be directed to renewable diesel to decarbonize trucking and off-road instead

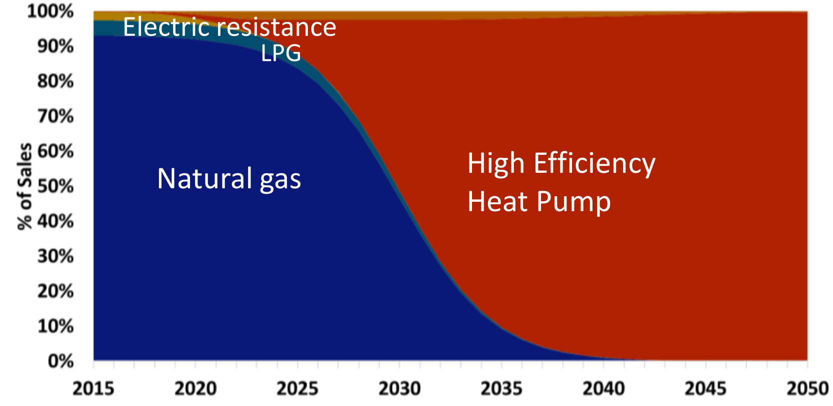


Buildings and vehicle sales shift to low emissions alternatives

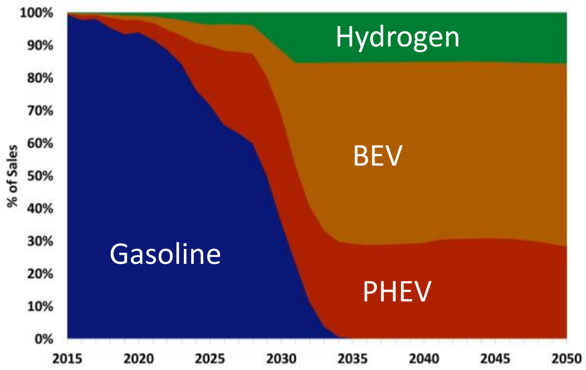
Space Heating (Residential, similar for Commercial)
% of new sales in High Electrification Scenario



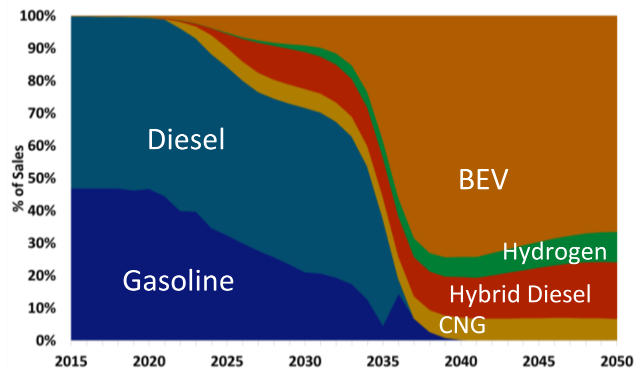
Water Heating (Residential, similar for Commercial)
% of new sales in High Electrification Scenario



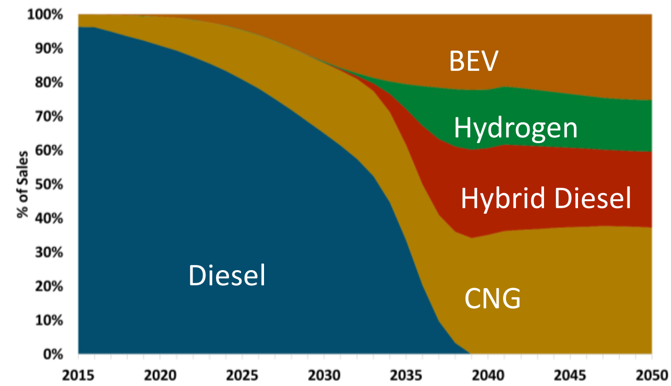
Light Duty Vehicles
% of new sales in High Electrification Scenario



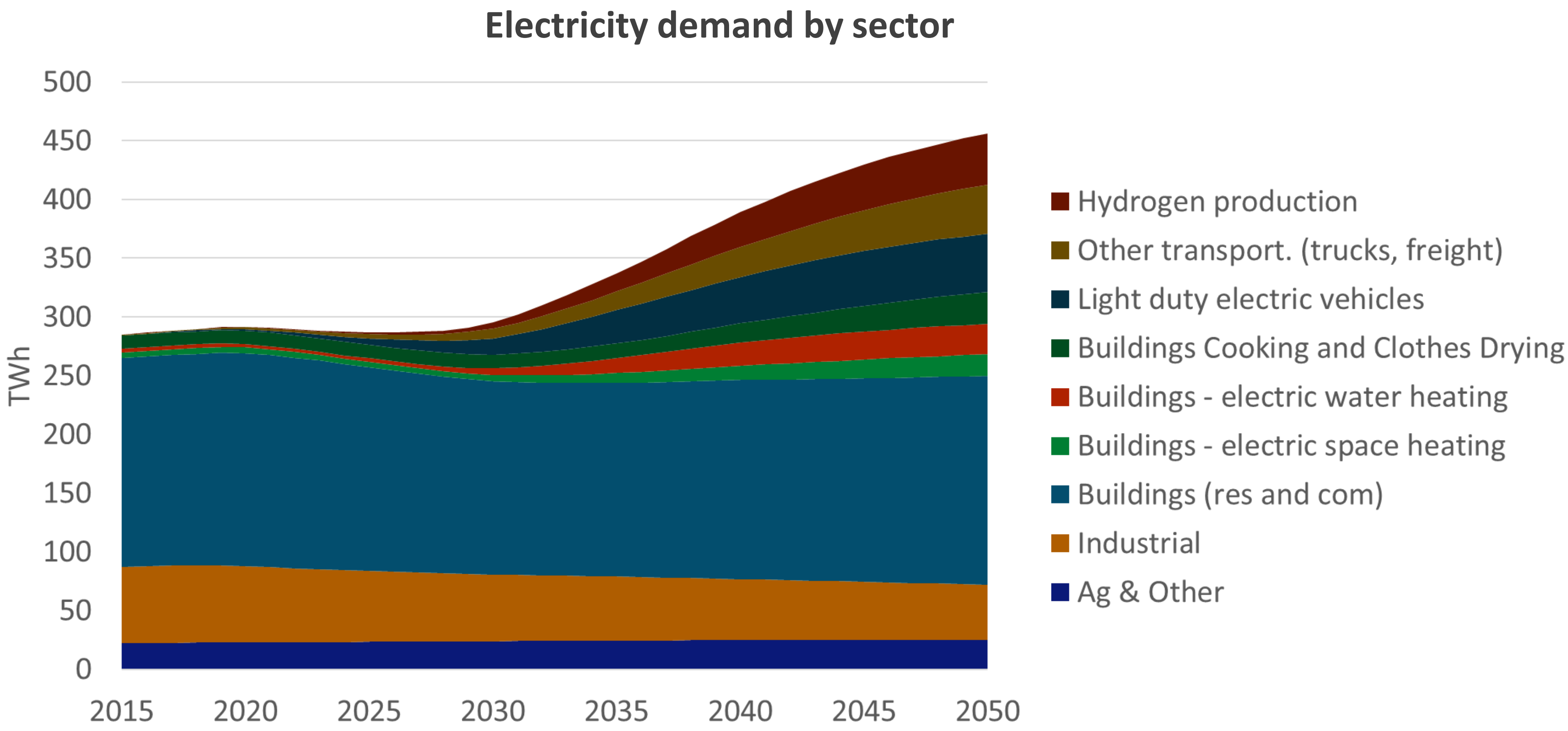
Medium Duty Vehicles
% of new sales in High Electrification Scenario



Heavy Duty Vehicles
% of new sales in High Electrification Scenario

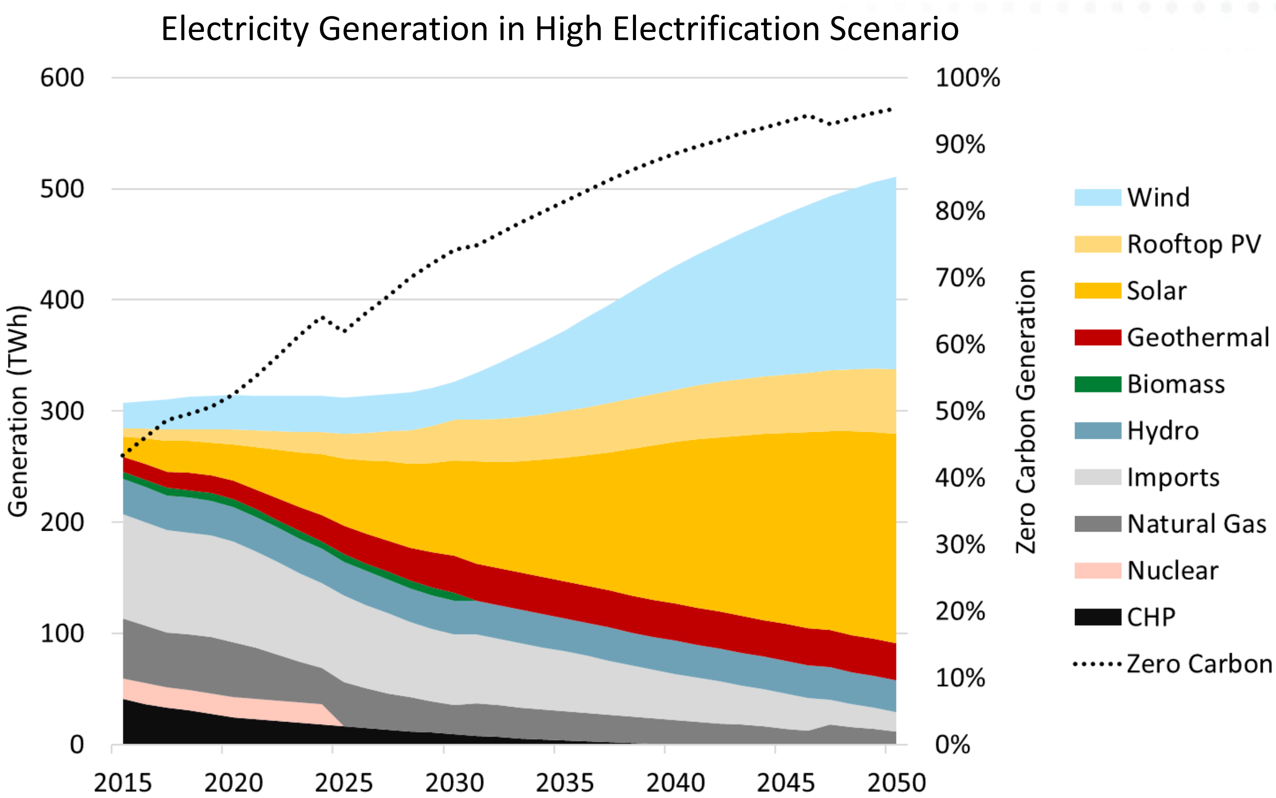


Fuel switching drives rapid growth in electric generation after 2030



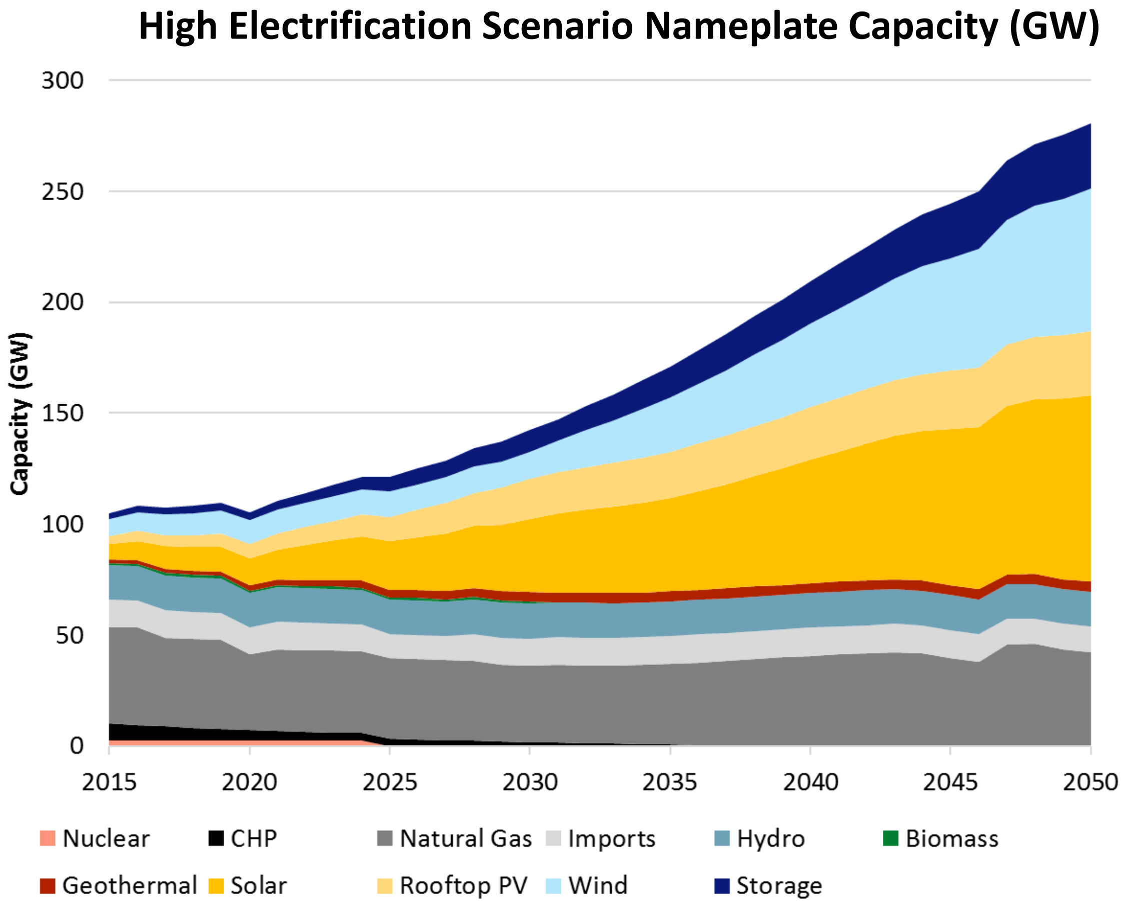
Electricity generation mix is increasingly renewables

- **95% of electricity generation is renewables (in-state and out-of-state) and hydro, 5% is gas generation (in-state and imports) in High Electrification Scenario by 2050**
  - High out-of-state wind helps to balance in-state solar



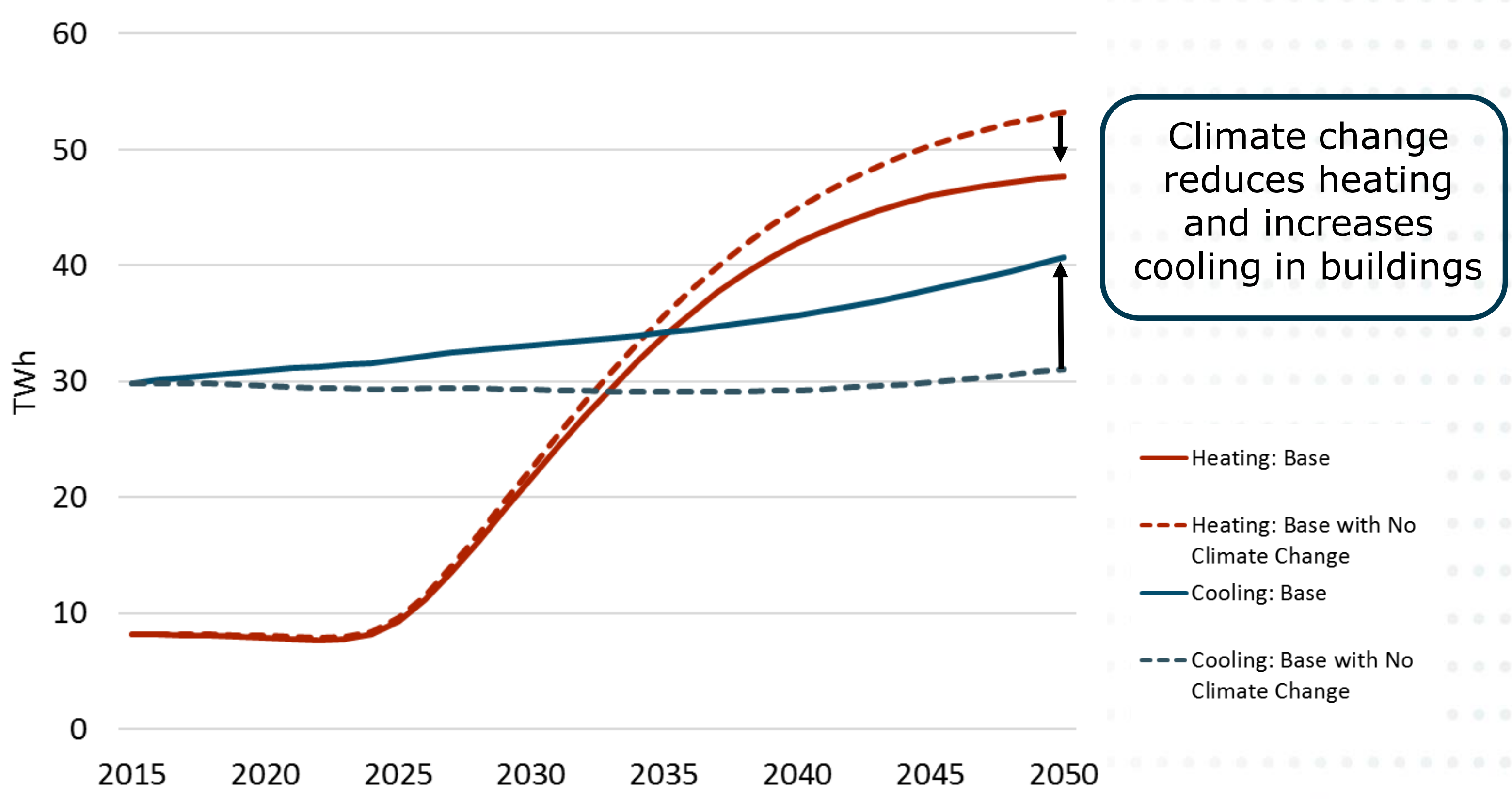
Total Gas Capacity is Relatively Unchanged Through 2050

+ **Gas generation is relied up occasionally for reliability during Winter and Fall months when solar, wind and storage are depleted; little used in Spring and Summer**



Modeled climate change impacts do not impede electric sector GHG mitigation

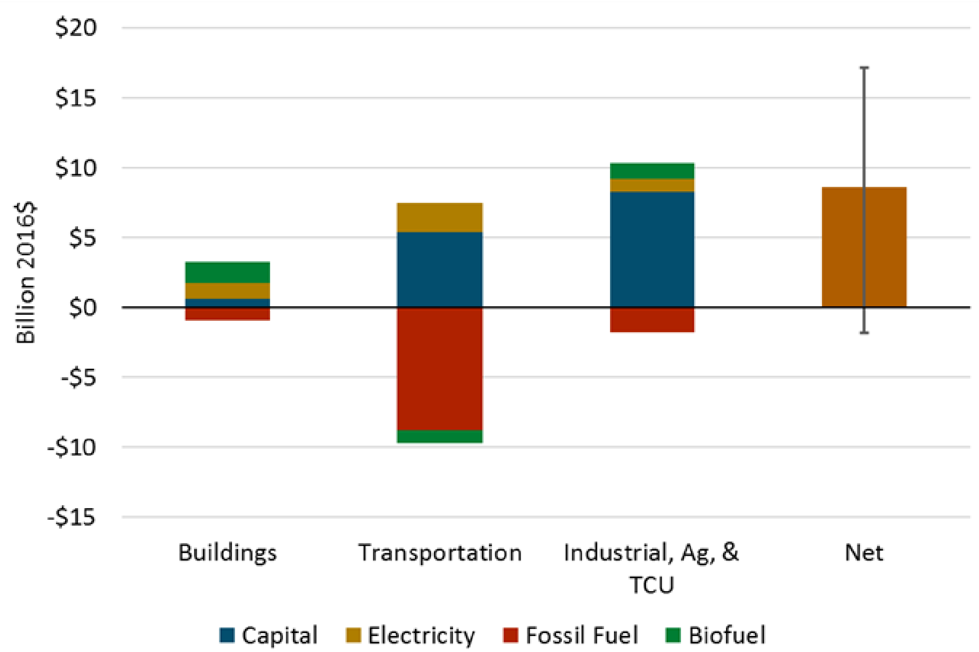
Changes in Building Electricity Demand due to GHG Mitigation & Climate Change (TWh)



2030 GHG abatement cost estimated at <1% of California gross state product

+ **2030 High Electrification Scenario annual total cost relative to Reference case: savings of $2B - cost of $17B (base is $9B)**
+ **Equivalent to -0.1% to 0.5% of California Gross State Product in 2030**
+ **Sensitivity ranges reflect lower/higher cost of capital assumption and higher/lower fossil fuel price assumptions (see table)**

2030 High Electrification Scenario Costs, Excluding Climate Benefits ($2016, billion)



2030 Mid Case and High/Low Sensitivity Assumptions ($2016)

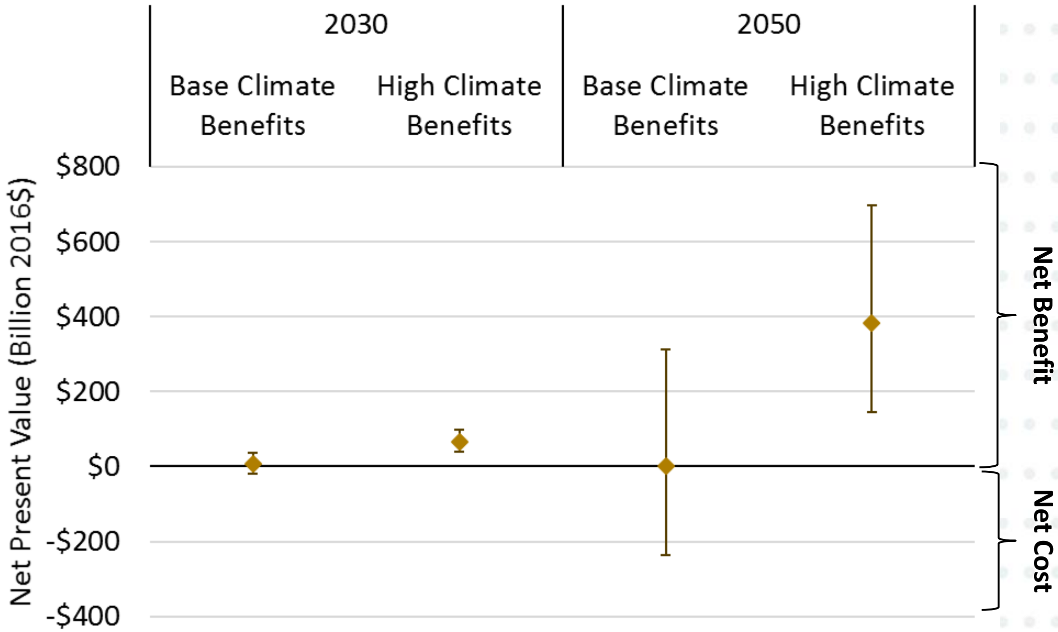
2030	Mid	Low	High
Consumer cost of capital (non-electric gen.)	5%	3%	10%
Gasoline price (2016$/gallon)*	$2.77	$5.01	$1.62
Diesel price (2016$/gallon)*	$3.49	$6.19	$1.96
Natural gas price ($/MMBTU)	$5.00	$7.95	$3.75

*Retail price excluding taxes

Estimated climate benefits of avoided CO_2 are generally larger than direct costs

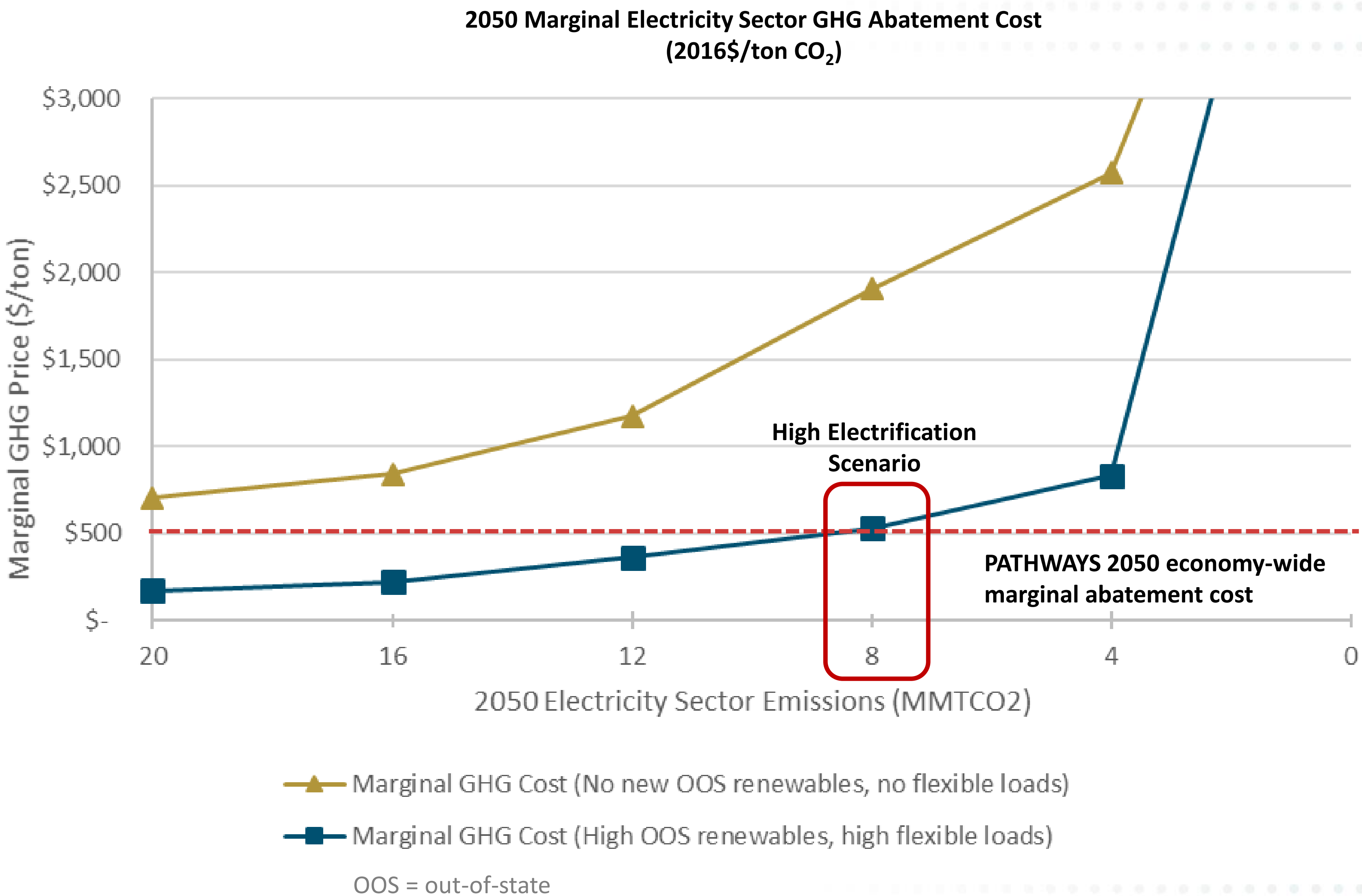
- **Net present value of emissions savings through 2030 and through 2050 exceed the direct costs modeled in PATHWAYS using the 2016 EPA Social Cost of Carbon**
- **Social costs of carbon are highly uncertain and depend strongly on discount rate and assumptions about climate damages**
- **Direct costs accrue in California, whereas social benefits of avoided emissions accrue globally**

Net Present Value of High Electrification Case, Including Climate Benefits ($2016, Billion)



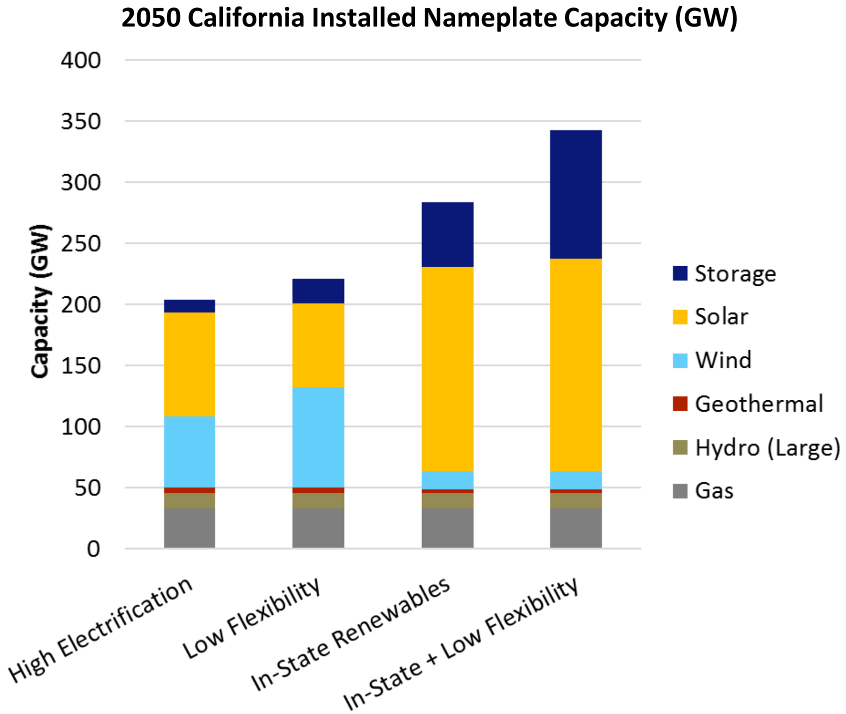
Assumes 3% discount rate. "Base climate benefits" is based on average social cost of carbon using 3% discount rate. "High climate benefits" is based on 95th percentile in ensemble of modeled climate benefits using 3% discount rate. Uncertainty ranges are based on PATHWAYS high/low fossil fuel price and financing cost sensitivities.

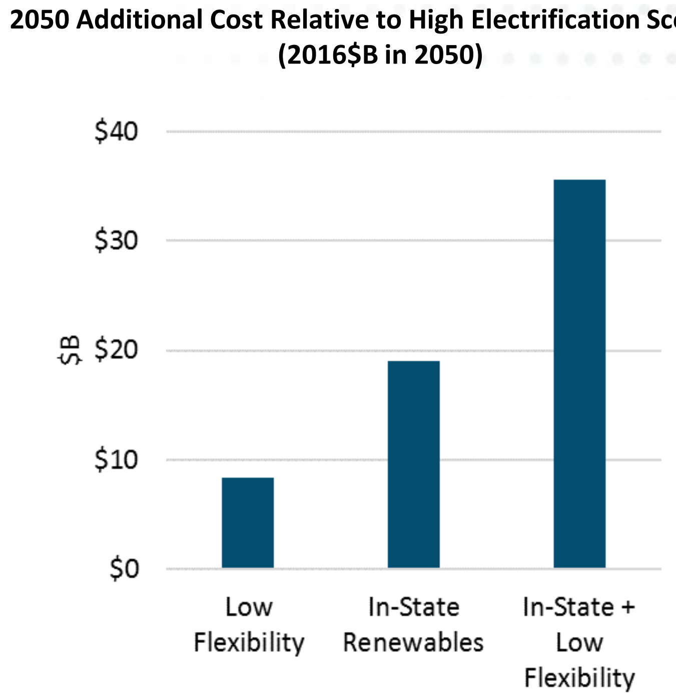
Renewable diversity & flexible loads enable lower-cost GHG reductions in electricity compared to other sector's mitigation costs



Without renewable integration solutions, 2050 electricity costs are 9% – 40% higher

2050 High Electrification Case with 95% zero-carbon electricity sector emissions (8 MMT CO2) RESOLVE model results:



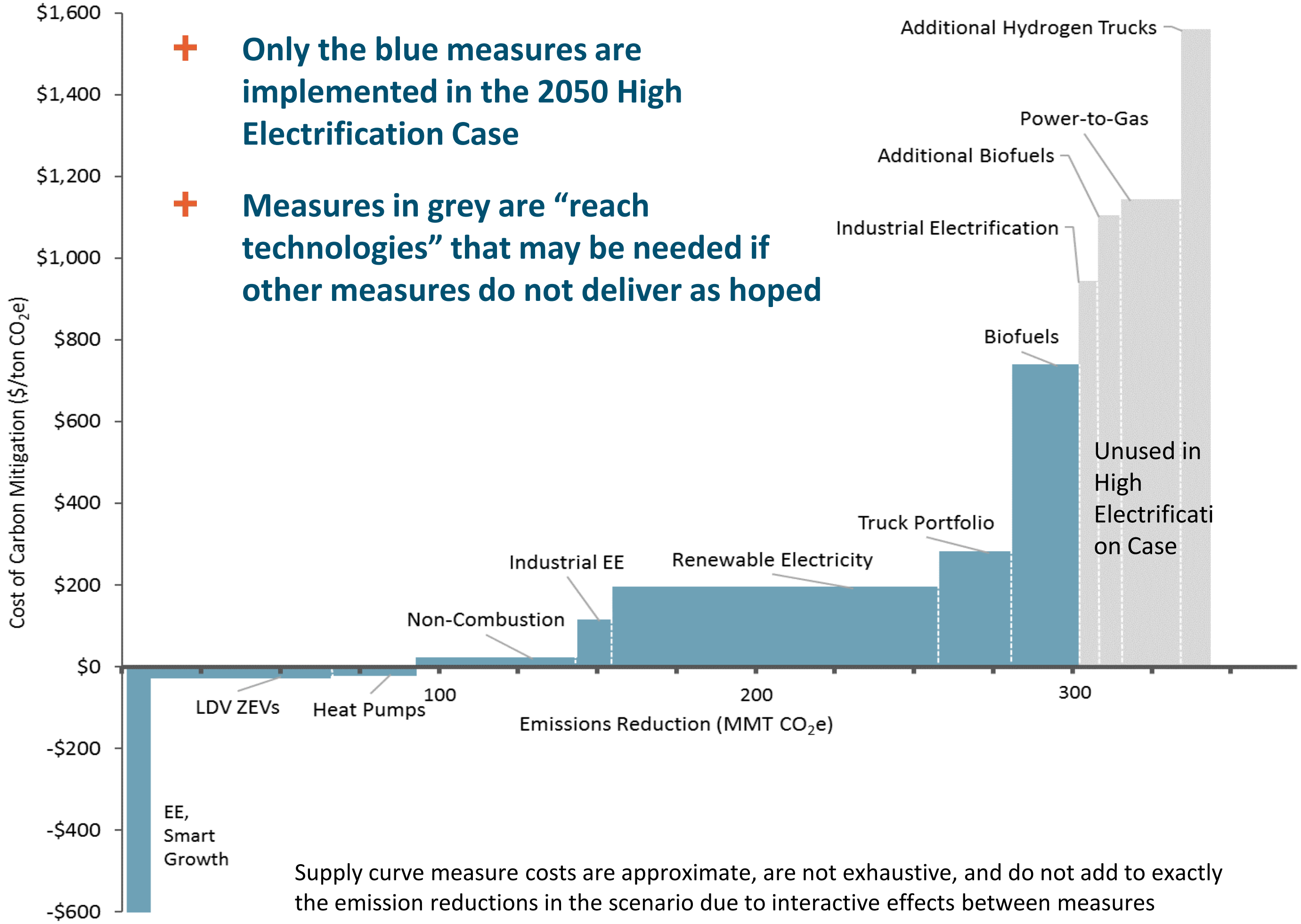


- High Electrification includes "best case" renewable integration solutions including a diverse renewable portfolio (44 GW of OOS wind)
- The land area required for new utility-scale solar PV in the "In-state + Low Flexibility" scenario exceeds ~1700 square miles (~1% of state land) vs. ~600 square miles in the High Electrification case

Future abatement costs are very uncertain but establish a rough "loading order" for the mitigation scenarios

2050 $/ton in High Electrification Scenario relative to Reference (2016$)

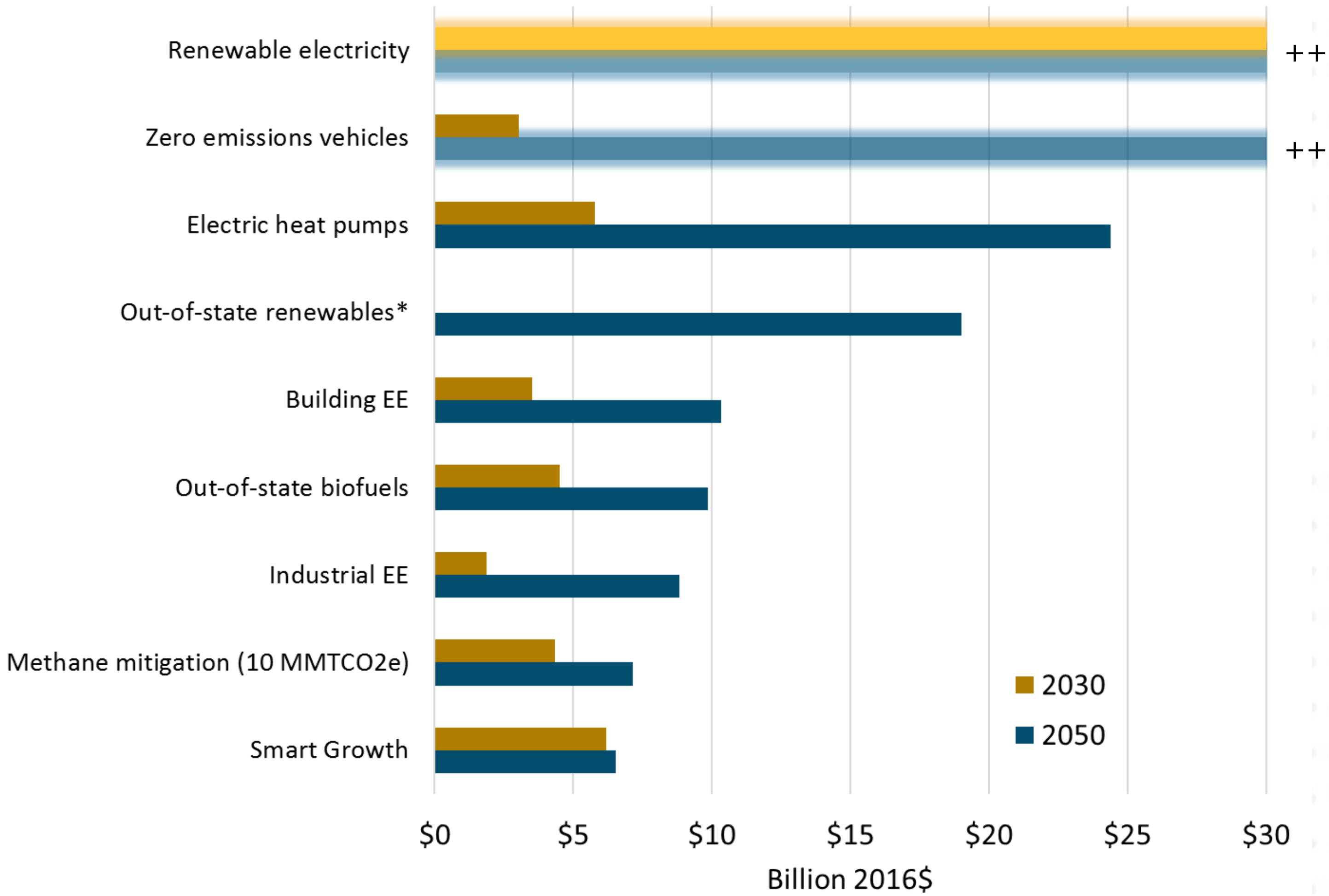
- Only the blue measures are implemented in the 2050 High Electrification Case
- Measures in grey are "reach technologies" that may be needed if other measures do not deliver as hoped



Supply curve measure costs are approximate, are not exhaustive, and do not add to exactly the emission reductions in the scenario due to interactive effects between measures

Renewables & ZEVs are critical to meeting GHG goals, electric heat pumps may reduce 2050 GHG compliance costs

Cost Savings Associated with Each Strategy Relative to Reference (2016$, Billions)

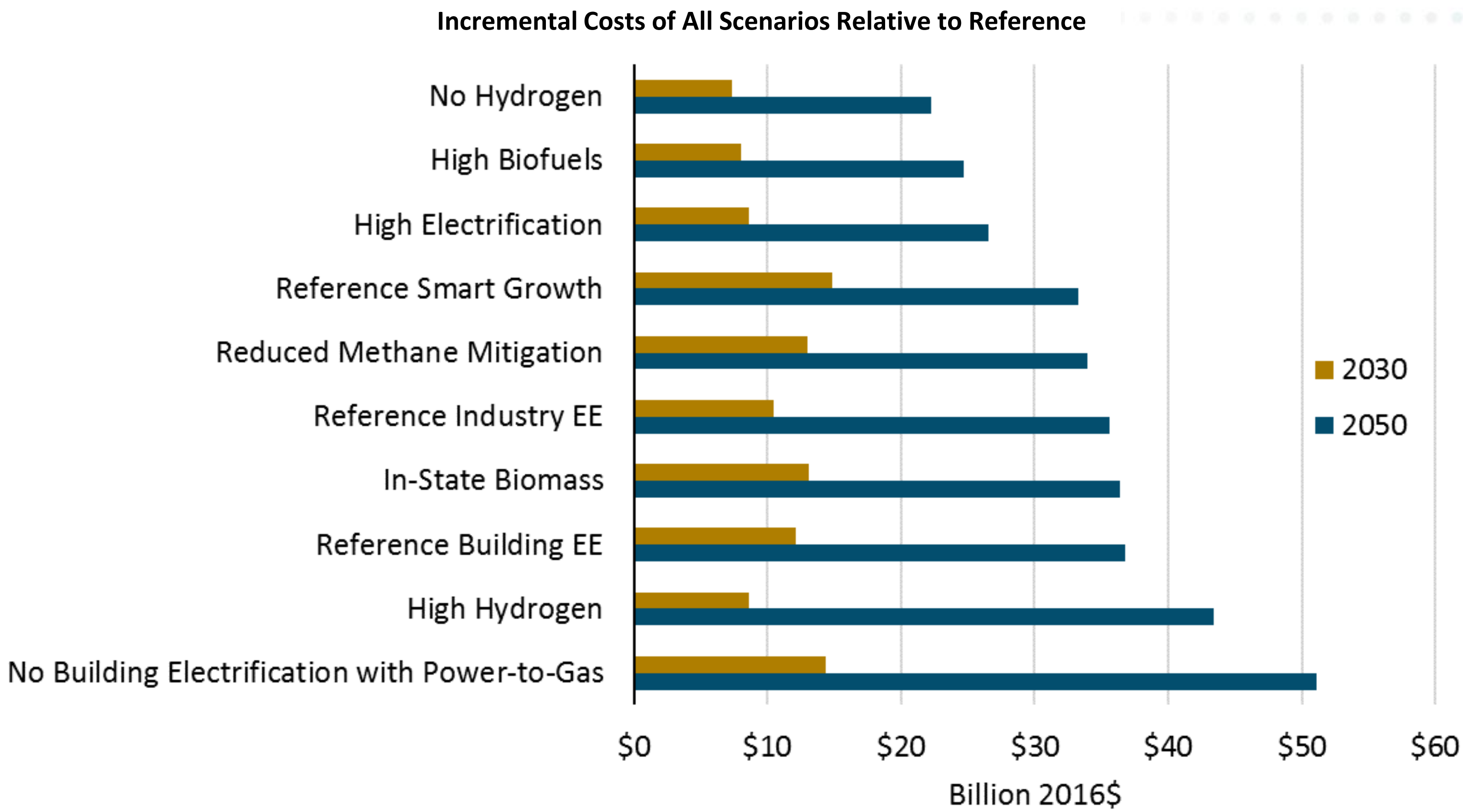


* Estimates for out-of-state renewables is based on RESOLVE model results, rather than PATHWAYS model

ALTERNATIVE MITIGATION SCENARIOS

Incremental Cost of Scenarios Relative to Reference Scenario

- **The High Electrification Scenario is among the lower cost scenarios. The "No Hydrogen" scenario replaces hydrogen fuel cell vehicles with more speculative industry electrification, and the "High Biofuels" scenario includes speculative purpose-grown crops**



What could change the rank order of the cost savings by technology?

- **Lower cost ZEV trucks, particularly hydrogen fuel cell trucks**
  - Lower-cost hydrogen fuel could also be significant
- **Lower cost biofuels: first mover advantage / high reliance on energy crops**
- **Cost of building retrofits for electrification**
- **Many other uncertainties (unexpected innovation progress, etc.)**

Potential game changing technologies and disruptions not modeled here

- **Clean tech innovations would make goals easier and cheaper to achieve**
  - Long-duration energy storage, long-range electric trucks, lower cost hydrogen, algal biofuels, offshore wind, high altitude wind, advanced geothermal, fusion, small modular nuclear reactors, carbon capture and storage, etc.
- **Autonomous transportation (self-driving cars, drones) would likely speed transition to electrified transportation**
- **Complete disconnection from the grid due to low-cost solar and storage**
- **Very low-cost fossil fuels due to reduced demand**
- **Dramatic changes in consumer and household preferences and price responsiveness could lead to higher conservation**
- **Synthetic/cultured meat & dairy to reduce agricultural & methane emissions**
- **Extreme events related to climate change, war & natural disasters: Mega-drought, The Big One earthquake, etc.**
- **Increased computing needs and artificial intelligence**
- **Global and national economic and political forces**

This is not meant to be a comprehensive list

CONCLUSIONS

High Priority GHG Mitigation Strategies & Key Challenges

Scale Up & Deploy	Key Challenges
Energy efficiency in buildings & industry	Consumer decisions and market failures
Renewable electricity	Implementation of integration solutions
Smart growth	Consumer decisions and legacy development
Market Transformation	**Key Challenges**
Zero-emission light-duty vehicles	Consumer decisions and cost
Advanced efficiency/ building electrification	Consumer decisions, equity of cost impacts, cost and retrofits of existing buildings
F-gas replacement	Standards needed to require alternatives
Methane capture	Small and diffuse point sources
Reach technologies	**Key Challenges**
Advanced sustainable biofuels	Cost and sustainability challenges
Zero-emissions heavy-duty trucks	Cost
Industrial electrification	Cost & technical implementation challenges
Electrolysis hydrogen production	Cost

Key Conclusions

+ ***Consumer decisions*** **are the lynchpin to meeting 2030 GHG target**
  - Investing in energy efficiency improvements in existing buildings
  - Purchasing and driving zero-emission vehicles
  - Installing electric heat pumps for HVAC and water heating
  - *Carbon pricing, incentives, and business and policy innovations* could all drive the needed *market transformation to* reduce costs, improve performance and increase choices for these key consumer-facing strategies
+ ***85% - 95% zero-carbon electricity*** **is needed by 2050**
  - Renewable diversity and integration solutions are needed to reduce costs
+ ***At least one "reach technology"*** **that has not been commercially proven is needed to help meet the longer-term 2050 GHG goal, and to mitigate risk of other solutions falling short**
  - A "reach technology" should address difficult to electrify end-uses (e.g. heavy-duty trucking, industry)

APPENDIX

SCENARIO DETAILS

Reference Scenario Assumptions

Pillar of GHG Reductions	Sector & Strategy	Reference Scenario assumptions
Efficiency	Building electric & natural gas efficiency	Approximately 26,000 GWh of electric efficiency, and 940 million therms of natural gas efficiency in buildings, relative to baseline load growth projections (approximately equal to the 2016 CEC IEPR additional achievable energy efficiency (AAEE) mid-scenario)
	Transportation smart growth and fuel economy	Federal vehicle efficiency standards (new gasoline auto averages 40 mpg in 2030). Implementation of SB 375 (2% reduction in vehicle miles traveled (VMT) relative to 2015)
	Industrial efficiency	CEC IEPR 2016 AAEE mid-scenario
Electrification	Building electrification	None
	Zero-emission light-duty vehicles	Mobile Source Strategy from the Vision Model Current Control Program scenario: 3 million light-duty vehicle (LDV) zero-emission vehicles (ZEVs) by 2030, 5 million LDV ZEVs by 2050
	Zero-emission and alternative fueled trucks	Mobile Source Strategy from the Vision Model Current Control Program scenario: 20,000 alternative-fueled trucks by 2030
Low carbon fuels	Zero-carbon electricity	Current RPS procurement achieves ~35% RPS by 2020, declining to 33% RPS with retirements post-2030. Includes current deployment of pumped storage and the energy storage mandate (1 GW by 2030)
	Advanced biofuels	10% carbon-intensity reduction Low Carbon Fuel Standard including corn ethanol (1.2 billion GGE advanced biofuels in 2030 and 0.7 billion GGE corn ethanol in 2030)
Non-combustion GHGs	Reductions in methane and fluorinated gases	No mitigation: methane emissions constant after 2015, fluorinated gases increase by 56% in 2030 and 72% in 2050

SB 350 Scenario Assumptions

Pillar of GHG Reductions	Sector & Strategy	Reference Scenario assumptions
Efficiency	Building electric & natural gas efficiency	Approximately 46,000 GWh of electric energy efficiency and 1,300 million therms of natural gas energy efficiency in buildings, relative to baseline load growth projections (reflecting targets under California SB 350, statutes of 2015)
	Transportation smart growth and fuel economy	New gasoline auto averages 45 mpg, implementation of SB 375 (2% reduction in VMT relative to 2015)
	Industrial efficiency	Approximate doubling of efficiency in Reference scenario
Electrification	Building electrification	None
	Zero-emission light-duty vehicles	Mobile Source Strategy: Cleaner Technologies and Fuels scenario (4 million LDV ZEVs by 2030, 24 million by 2050)
	Zero-emission and alternative fueled trucks	Mobile Source Strategy: Cleaner Technologies and Fuels scenario (140,000 alternative-fueled trucks)
Low carbon fuels	Zero-carbon electricity	50% RPS by 2030, Same energy storage as Reference, 10% of some building end uses and 50% of LDV EV charging is flexible
	Advanced biofuels	Same biofuel blend proportions as Reference, less total biofuels than Reference due to higher adoption of ZEVs
Non-combustion GHGs	Reductions in methane and fluorinated gases	34% reduction in methane emissions relative to 2015, 43% reduction in F-gases relative to 2015, 19% reduction in other non-combustion GHGs relative to 2015.

2030 GHG Mitigation Strategies in High Electrification Scenario

	Sector	2030 GHG reduction strategy
Efficiency	Buildings	10% reduction in total building energy demand relative to 2015
	Transportation	12% reduction in per capita light-duty vehicle miles traveled relative to 2015
	Industry	30% reduction in total industrial energy demand relative to 2015
Electrification	**Buildings**	**50% new sales of water heaters and HVAC are electric heat pumps**
	Light-duty vehicles	**6 million ZEVs (20% of total) and >60% of new sales are ZEVs**
	Trucks	4% of trucks are BEVs or FCEVs (6% of trucks are hybrid & CNG) 32% electrification of buses, 20% of rail, and 27% of ports
Low carbon fuels	**Electricity**	**74% zero-carbon electricity, including large hydro and nuclear (~70% RPS)**
	Advanced Biofuels	10% of total (non-electric power generation) fossil fuels replaced with advanced biofuels
Non-combustion GHGs	Reductions in methane and F-gases	37% reduction in methane and F-gas emissions relative to 2015 19% reduction in other non-combustion emissions relative to 2015

2050 GHG Mitigation Strategies in High Electrification Scenario

	Sector	2050 GHG reduction strategy
Efficiency	Buildings	34% reduction in total building energy demand, relative to 2015
	Transportation	24% reduction in per capita light-duty vehicle miles traveled relative to 2015
	Industry	30% reduction in total industrial energy demand relative to 2015 90% reduction in refinery and oil & gas extraction energy demand
Electrification	**Buildings**	**100% new sales of water heaters and HVAC are electric heat pumps**
	Light-duty vehicles	**35 million ZEVs (96% of total) and 100% of new sales are ZEVs**
	Trucks	47% of trucks are BEVs or FCEVs (31% of trucks are hybrid & CNG) 88% electrification of buses, 75% of rail, and 80% of ports
Low carbon fuels	**Electricity**	**96% zero-carbon electricity (including large hydro)**
	Advanced Biofuels	46% of total (non-electric power generation) fossil fuels replaced with advanced biofuels
Non-combustion GHGs	Reductions in methane and F-gases	62% reduction in methane and F-gas emissions relative to 2015 42% reduction in other non-combustion GHGs relative to 2015

2030 High Electrification Scenario Detailed Summary

Pillar of GHG Reductions	Sector & Strategy	2030 metric
Efficiency	Building electric & natural gas efficiency	10% reduction in total building energy demand relative to 2015. Same level of non-fuel substitution energy efficiency as the SB 350 Scenario in non-heating sub-sectors. Additional efficiency is achieved through electrification of space heating and water heating.
	Transportation smart growth and fuel economy	New gasoline ICE light-duty autos average 45 mpg, 12% reduction in light-duty vehicle miles traveled relative to 2015, 5-6% reduction in shipping, harbor-craft & aviation energy demand relative to Reference
	Industrial efficiency	20% reduction in total industrial, non-petroleum sector energy demand relative to 2015, additional 14% reduction in refinery output relative to 2015
Electrification	Building electrification	50% new sales of water heaters and HVAC are electric heat pumps
	Zero-emission light-duty vehicles	6 million ZEVs (20% of total): 1.5 million BEVs, 3.6 million PHEVs, 0.8 million FCEVs, >60% of new sales are ZEVs
	Zero-emission and alternative fueled trucks	10% of trucks are hybrid & alternative fuel (4% are BEVs or FCEVs), 32% electrification of buses, 20% of rail, and 27% of ports; 26% electric or hybrid harbor craft
Low carbon fuels	Zero-carbon electricity	74% zero-carbon electricity, including large hydro and nuclear (70% RPS), Storage Mandate + 6 GW additional storage, 20% of key building end uses and 50% of LDV EV charging is flexible
	Advanced Biofuels	2.8 billion gallons of gasoline-equivalent (10% of gasoline, diesel, jet fuel and other non-electric energy demand); 49 million Bone Dry Tons of biomass: 57% of population-weighted share excluding purpose-grown crops
Non-combustion GHGs	Reductions in methane, F-gases and other non-combustion GHGs	34% reduction in methane emissions relative to 2015, 43% reduction in F-gases relative to 2015, 19% reduction in other non-combustion CO_2 & N_2O

2050 High Electrification Scenario Detailed Summary

Pillar of GHG Reductions	Sector & Strategy	2050 metric
Efficiency	Building electric & natural gas efficiency	34% reduction in total (natural gas and electric) building energy demand, relative to 2015. Savings are achieved via conventional efficiency and building electrification.
	Transportation smart growth and fuel economy	24% reduction in per capita light-duty vehicle miles traveled relative to 2015, plus shipping, harbor-craft & aviation energy demand 2030 measures
	Industrial efficiency	20% reduction in total industrial, non-petroleum sector energy demand relative to 2015, 90% reduction in refinery and oil & gas extraction energy demand
Electrification	Building electrification	100% new sales of water heaters and HVAC are electric heat pumps; 91% of building energy is electric (no building electrification is possible, but requires higher biofuels or power-to-gas), Moderate electrification of agriculture HVAC
	Zero-emission light-duty vehicles	35 million ZEVs (96% of total): 19 million BEVs, 11 million PHEVs, 5 million FCEVs, 100% of new sales are ZEVs
	Zero-emission and alternative fueled trucks	47% of trucks are BEVs or FCEVs (31% of trucks are hybrid & CNG); 88% electrification of buses, 75% of rail, 80% of ports; 77% of harbor craft electric or hybrid
Low carbon fuels	Zero-carbon electricity	95% zero-carbon electricity (including large hydro), 84 GW of utility scale solar, 29 GW of rooftop solar, 52 GW out-of-state wind, 26 GW incremental storage above storage mandate, 80% of key building end-uses is flexible and 90% flexible EV charging; H_2 production is flexible
	Advanced Biofuels	4.3 billion gallons of gasoline-equivalent (46% of gasoline, diesel, jet fuel and other non-electric energy demand); 64 million Bone Dry Tons of biomass: 66% of population-weighted share excluding purpose-grown crops
Non-combustion GHGs	Reductions in methane, F-gases and other non-combustion GHGs	42% reduction in methane emissions relative to 2015 83% reduction in F-gases relative to 2015 42% reduction in other non-combustion CO_2 & N_2O

Supply Curve Measures: 2050 High Electrification Scenario as compared with Reference unless otherwise noted

Measure	Description	Emissions Reduction (MMT CO_2e)	2050 Cost (2016$ / ton CO_2e)
Smart Growth	21% LDV VMT reduction relative to Reference	2	-$2500
Building EE	~2.5 x AAEE vs. 1 x AAEE	6	-$1000
LDV ZEVs	35 million ZEVs (96% of vehicle stock) as compared with 5 million ZEVs	57	$0
Heat Pumps	Nearly 100% building electrification as compared with none in Reference	27	$0
Non-combustion GHGs	59% reduction relative to Reference	51	$0
Industrial EE	30% reduction in energy demand plus high electric efficiency	11	$100
Renewable Electricity	95% zero-carbon including out-of-state wind and storage with high flexible loads; as compared with 33% RPS; last 10% of zero-carbon requires storage and is most expensive: more detailed electricity analysis in RESOLVE	103	$200
Truck Portfolio	78% of trucks are alternative-fuel as compared with 5% (HDVs) and 0% (MDVs) in Reference	23	$300
Biofuels	4.3 billion gallons gasoline-equivalent of advanced biofuels as compared 0.4 billion	21	$700
Industrial Electrification	35% of industrial non-electric end use energy is electrified in In-State Biofuels Only Scenario	6	$900
Additional Biofuels	Additional biofuels relative to biofuels in Base Mitigation Case	7	$1100
Power-to-Gas	7% of pipeline hydrogen and 25% of pipeline synthetic methane in No Building Electrification Scenario	19	$1100
Additional Hydrogen Trucks	58% hydrogen HDVs and 57% MDVs in the High Hydrogen Scenario as compared with 14% of HDVs and 7% of MDVs in the Base Mitigation Case	9	$1600

Supply curve measures are not exhaustive and do not add to exactly the emission reductions in the scenario due to interactive effects

Non-Combustion GHG Mitigation Assumptions (% change relative to Reference 2030 & 2050)

Category	% reduction relative to Reference	
	2030	2050
Cement (CO_2)	10%	20%
Waste (CH_4)	15%	26%
Refining (CH_4)	47%	80%
Oil Extraction (CH_4)	47%	80%
Electricity Generation (CO_2, CH_4)	42%	80%
Pipeline Fugitive (CH_4)	47%	80%
Agriculture: enteric fermentation (CH_4)	16%	16%
Agriculture: soil emissions (CO_2, N_2O)	23%	52%
Agriculture: manure (CH_4)	65%	65%
Agriculture: other (CO_2, CH_4)	0%	0%
F-gases	64%	90%

COST SENSITIVITIES

Future costs are very uncertain; some key drivers of cost

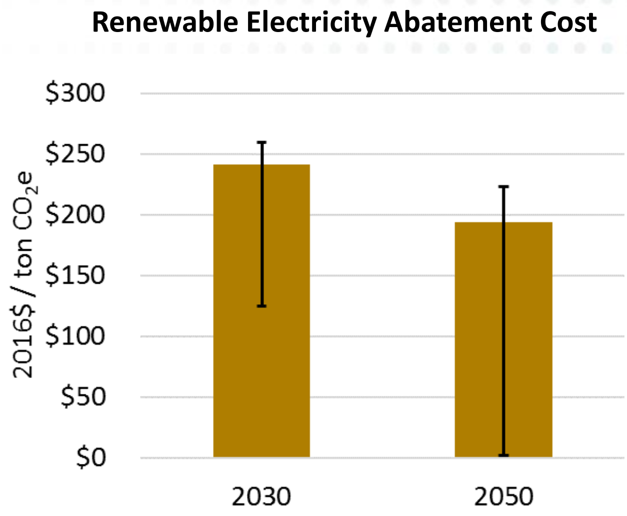
2030 Cost Driver	Base Assumptions
Consumer cost of capital (non-electric gen., % real)	5% (real)
Gasoline price (2016$/gallon)[1]	$2.77
Diesel price (2016$/gallon) [1]	$3.49
Natural gas commodity price (2016$/MMBTU) [1]	$5.00
Biomethane commodity price (2016$/MMBTU)[2]	$21
Incremental cost of a light duty battery electric auto[3]	$0
Cost of solar PV (2016$/kW, >20 MW single axis tracker)[4]	$2080
Incremental cost of industrial energy efficiency (2016$/MMBTU)[5]	$15-30
Avg. incremental cost of residential heat pump space heater (heating only) [2016$/unit]	$2100
Avg. incremental cost of commercial heat pump space heater (heating only) [2016$/(kBTU/hr)]	$107

[1]EIA AEO 2017, excluding state and local taxes
[2]Estimated in PATHWAYS
[3]Based on Ricardo analysis
[4]CPUC IRP assumptions
[5]ARB Scoping Plan Assumptions

Renewable electricity cost sensitivity

- **Base utility-scale PV and battery storage costs based on CPUC RPS Calculator and appear conservative relative to current trends, lower solar/storage cost tested with high/low natural gas prices**
- **$/ton estimate represents average incremental cost of:**
  - 74% zero-carbon portfolio vs. 35% RPS in 2030
  - 95% zero-carbon portfolio vs. 33% RPS in 2050

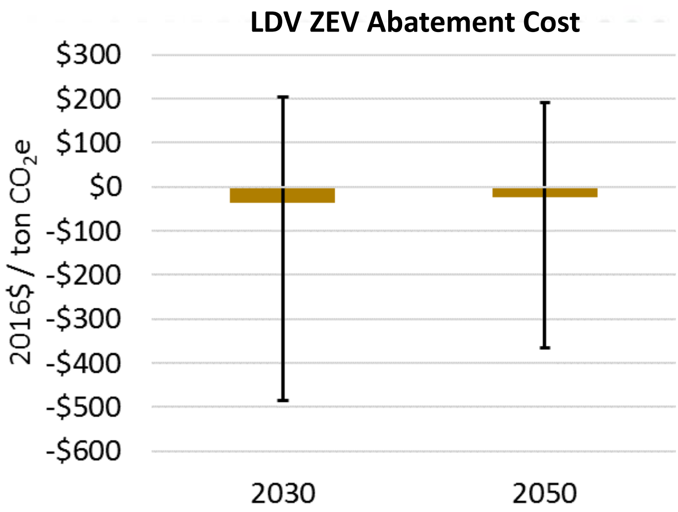
2030 Cost Driver	Base	Low Sensitivity case	High Sensitivity case
Utility-Scale PV Capital Costs (2016$/kW)	$2,080	$1,040	$2,080
Grid-scale Storage Capital Costs (2-hr batteries; 2016$/kW-yr)	$134	$33	$134
Natural gas price ($/MMBTU)	$5.00	$7.95	$3.75



LDV ZEV cost sensitivity

- **Base EV costs based on an analysis by consulting firm Ricardo (2017)**
  - Low-cost sensitivity tests assumption of cost parity with conventional ICE vehicle by 2025 (based on Bloomberg), along with high gasoline price and low financing rate
  - High-cost sensitivity uses base vehicle prices along with low gasoline price and high financing rate

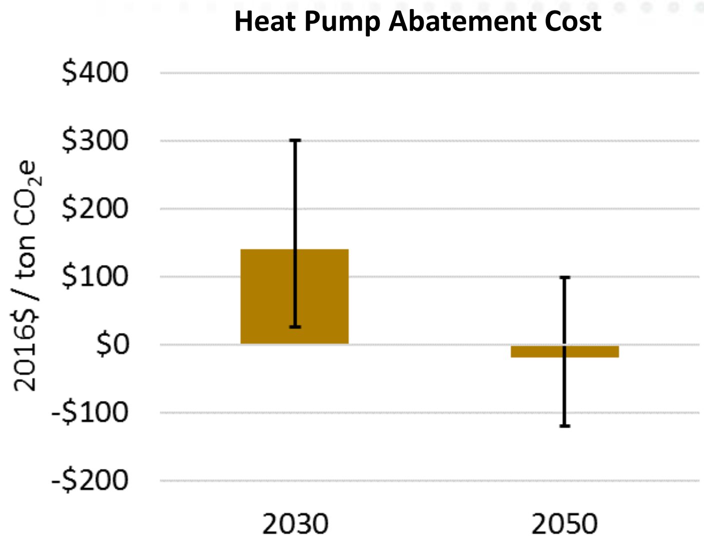
2030 Assumptions	**Base**	**Low Sensitivity case**	**High Sensitivity case**
Light-duty auto BEV, *year reaching capital cost parity with gasoline vehicle*	*2029*	*2025*	*2029*
Light-duty auto 40-mile PHEV, *year reaching capital cost parity*	*2036*	*2025*	*2036*
Gasoline price (2016$/gallon)	$2.77	$5.01	$1.62
Consumer cost of capital (non-electric gen.)	5%	3%	10%



Heat pump cost sensitivity

- **Cost sensitivity applies to residential and commercial electric heat pump HVAC and water heaters**
- **Base HVAC and water heater costs based on DOE NEMS (2013)**
  - Low-cost sensitivity uses high natural gas price and low financing rate
  - High-cost sensitivity uses low natural gas price and high financing rate
- **Installation costs associated with retrofitting existing buildings to electric heat pump HVAC and water heating are not included in these estimates**

2030 Assumptions	**Base**	**Low** Sensitivity case	**High** Sensitivity case
Consumer cost of capital (non-electric gen.)	5%	3%	10%
Natural gas price ($/MMBTU)	$5.00	$7.95	$3.75

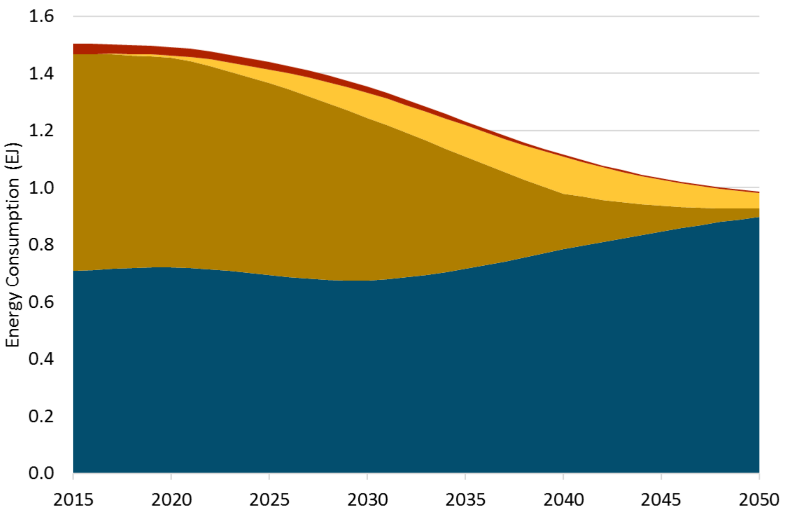


BUILDINGS

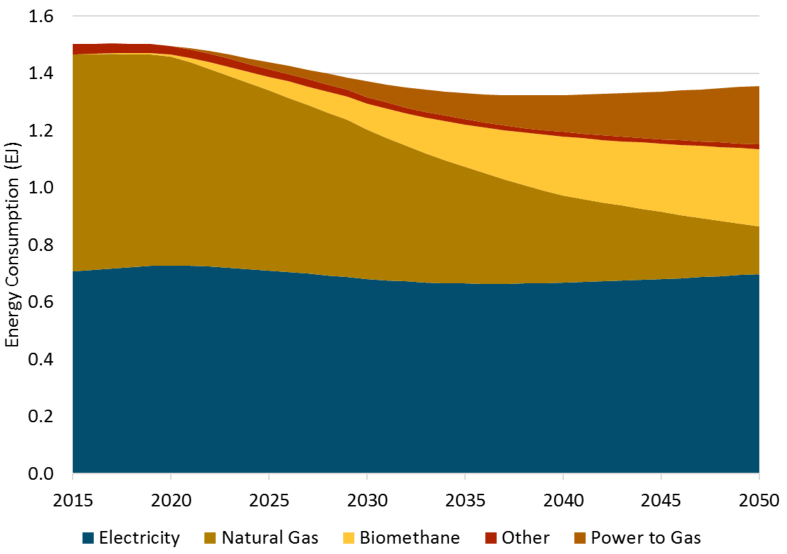
Building Energy Transition

- Efficiency reduces building energy demands through 2030
- After 2030, electricity supplies most building energy demand, also enhancing total energy efficiency
- Base mitigation case requires near-complete electrification of space & water heating, cooking, and clothes drying by 2050
- No building electrification Scenario requires higher biofuels and/or power-to-gas (modeled here as power-to-gas)

Building Energy Consumption in the High Electrification Scenario



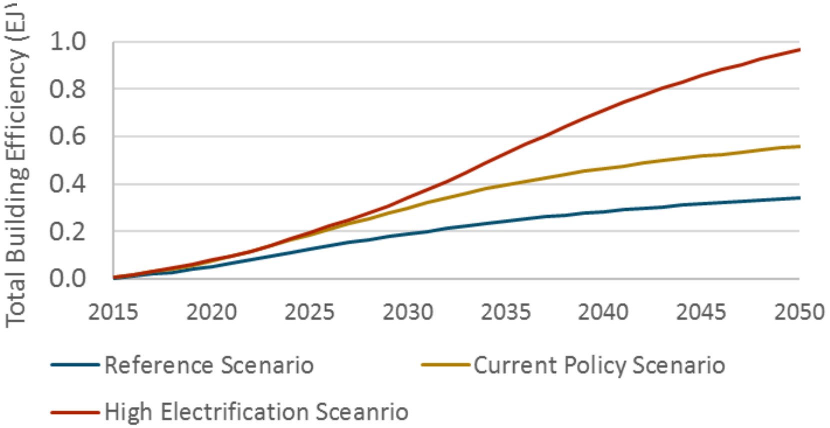
Building Energy Consumption in No Electrification Scenario



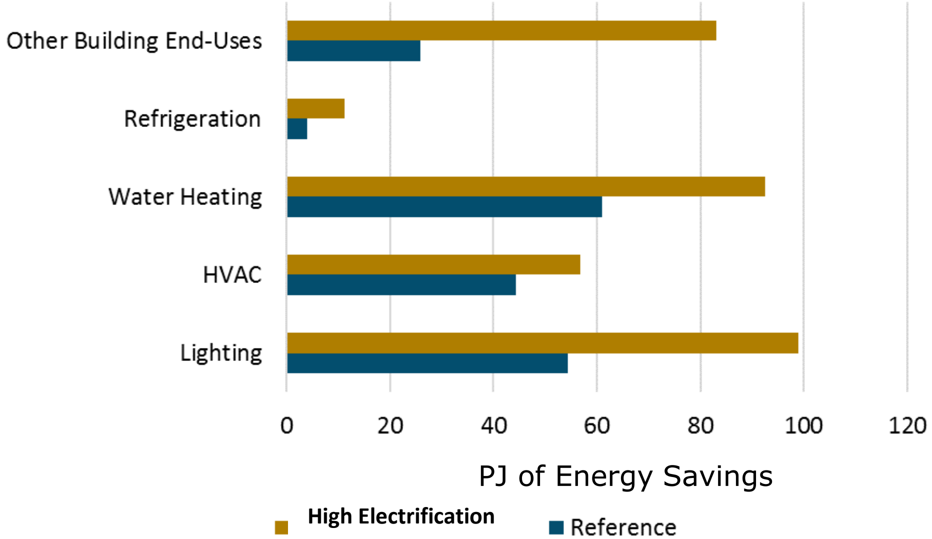
Building Energy Efficiency

+ **High energy efficiency is included in all scenarios:**
    - Reference scenario: 26 TWh electricity savings relative to Baseline in 2030
    - Current Policy Scenario: 46 TWh electricity savings relative to Baseline in 2030
    - High Electrification Scenario includes electrification of building end-uses, requiring a total building energy efficiency metric, rather than a focus on electricity savings vs. gas savings
+ **Incremental electric building electric energy efficiency in the High Electrification Scenario saves $3B in 2030 and $10B in 2050 due to reduced electricity costs and avoided additional abatement measures**

Total Building Energy Efficiency (including Electrification) Energy Savings Relative to Baseline (Exajoules, EJ) 2015 - 2030



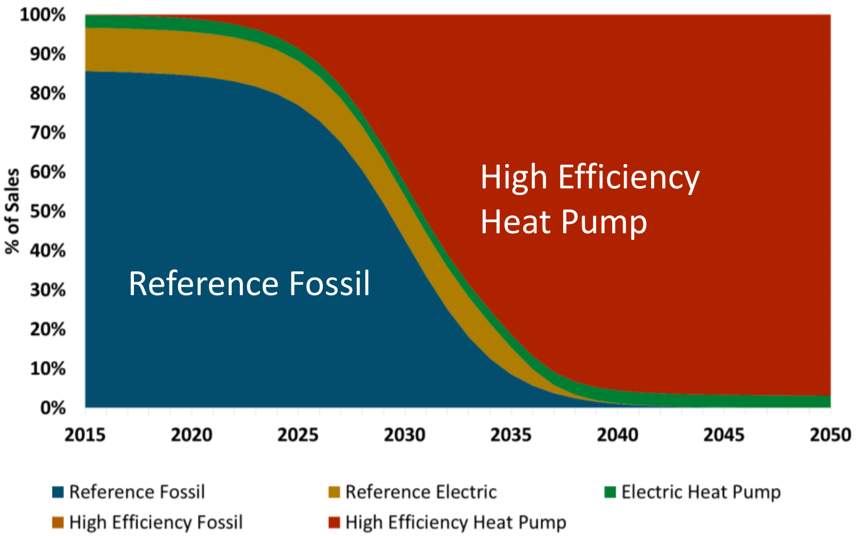
Total Building Energy Efficiency (including Electrification) Energy Savings Relative to Baseline (electricity and natural gas demand savings), 2030



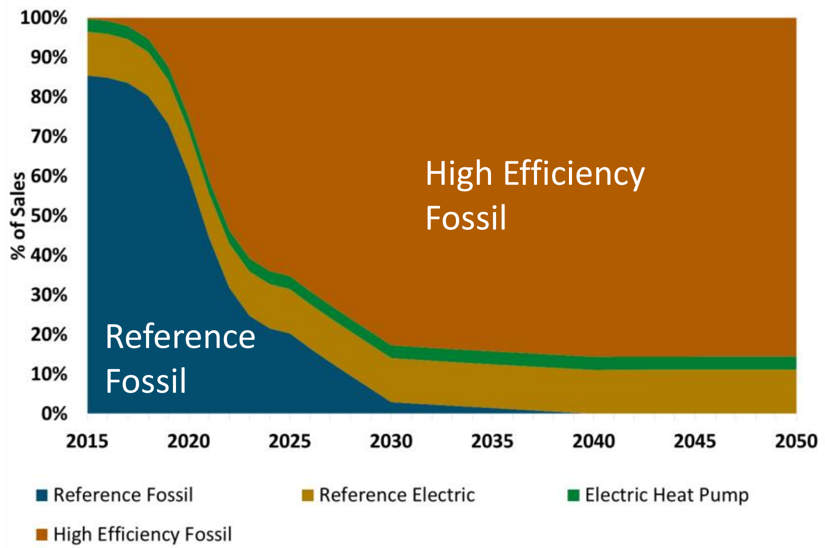
Building electrification is projected to reduce economy-wide mitigation cost

- No Building Electrification with Power-to-Gas Scenario requires higher utilization of hydrogen trucks, out-of-state biofuels including purpose-grown crops, industry electrification, and/or power-to-gas; extensive gas efficiency is also required
- In 2050, No Building Electrification with Power-to-Gas Scenario is estimated at a cost $24B relative to the High Electrification Case. Costs of building retrofits to electrification are not included, and could close this cost differential between scenarios.

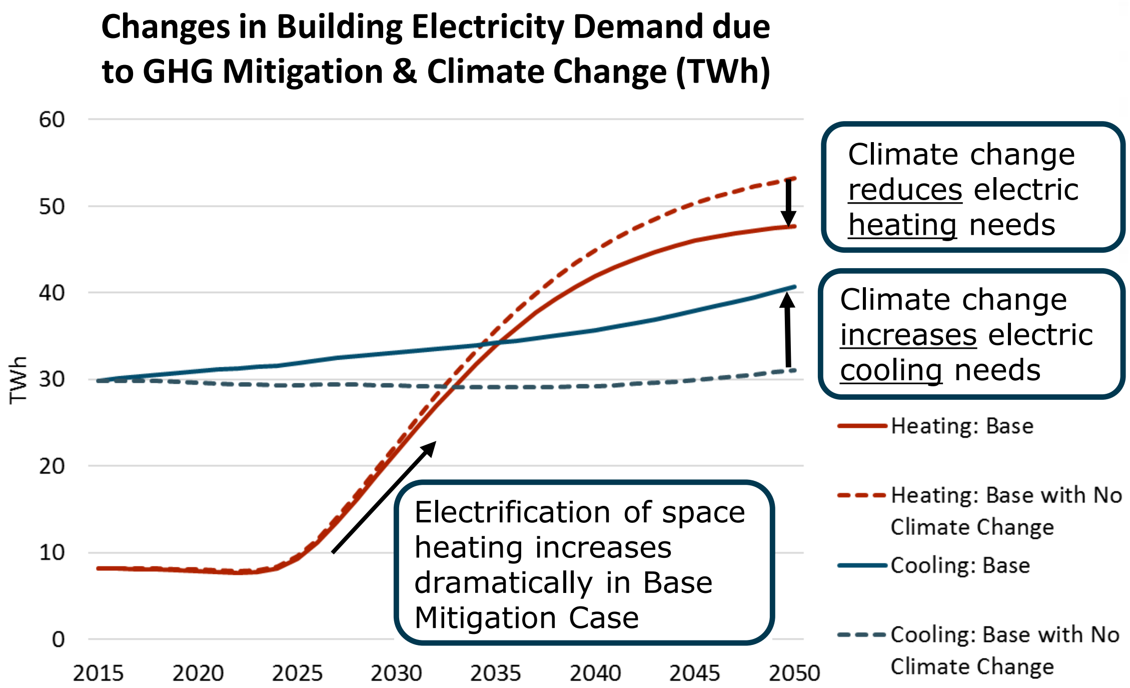
Residential Space Heating, % of new sales in High Electrification Scenario



Residential Space Heating, % of new sales, No Building Electrification Scenario



Climate change is not expected to be a major impediment to reducing electricity sector emissions



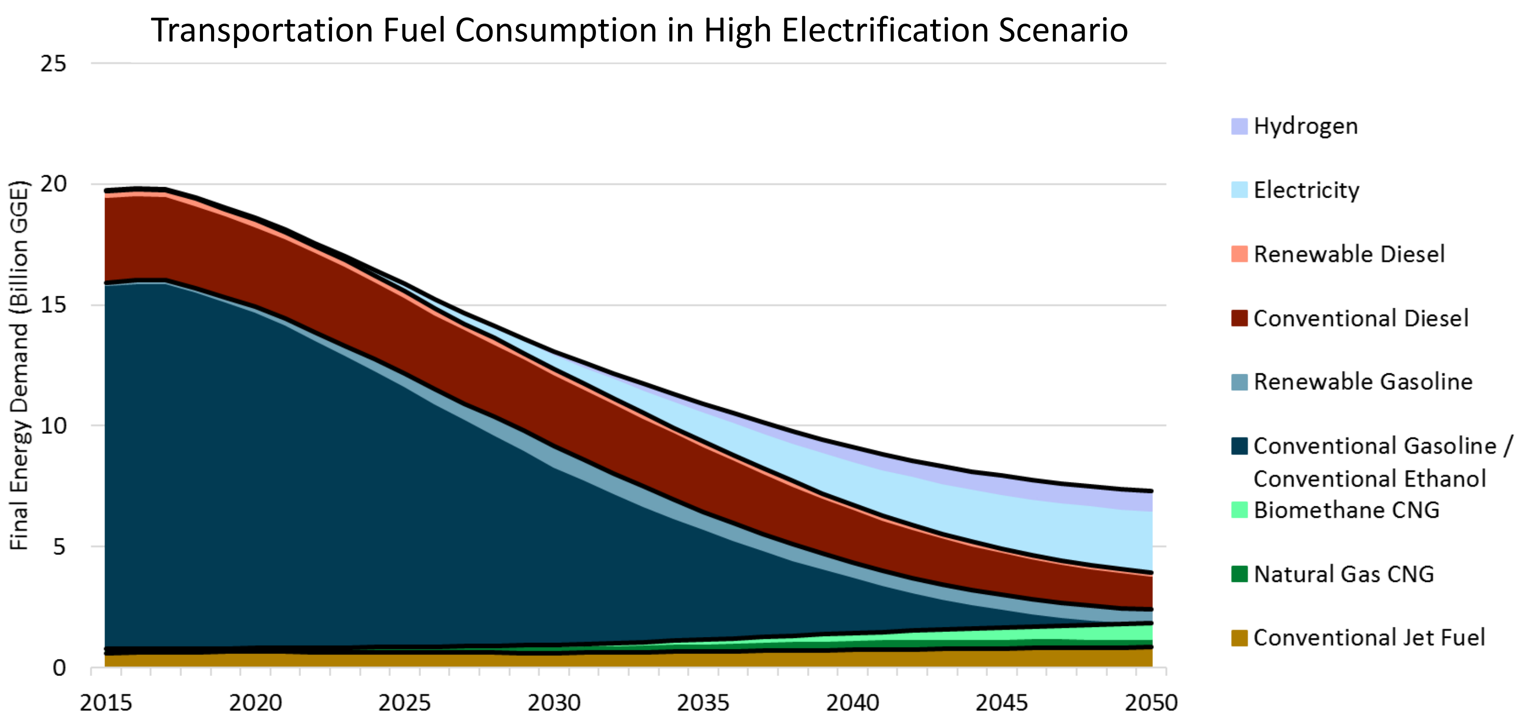
- **The threat of extreme events and other effects of climate change could have large consequences for the energy system and economy which are not modeled here**
- **The direct effect of climate change on the electric sector by 2050 is modeled as negligible compared to the changes necessitated by GHG mitigation goals**

- **This model incorporates changes in typical heating and cooling needs, and hydroelectric availability due to climate change. The impact of extreme events is not modeled. The net effect of climate change on building energy demands and hydroelectric availability is modeled as minimal in the context of climate mitigation: <1 MMT CO_2/yr and <$1B/yr for the Base Mitigation Case**
  - Given that heating is electrified in the Base Mitigation Case, climate change reduces the burden of this additional load on the grid

TRANSPORTATION

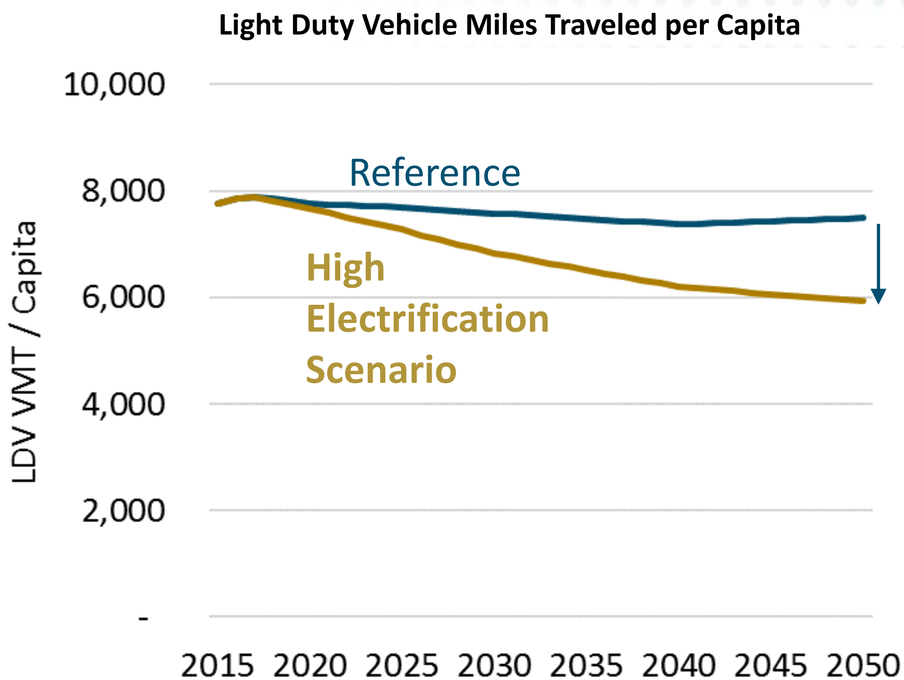
Transportation Energy Transition

- 44% reduction in gasoline and diesel fuel consumption by 2030, relative to 2015 (on-road and off-road)
- 92% reduction in gasoline and diesel fuel consumption by 2050, relative to 2015 (on-road and off-road)
- In the High Electrification Scenario, economy-wide costs were reduced by using limited biomass supply primarily to satisfy pipeline gas demand in industry rather than liquid transportation fuel demand, but this result is sensitive to uncertain biofuel assumptions.



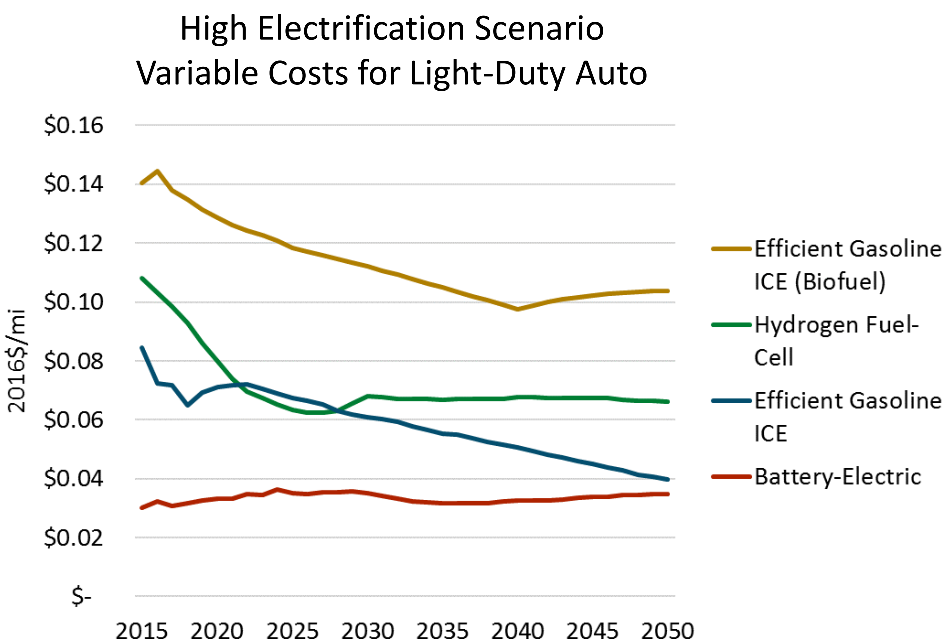
Transportation Conservation: Smart Growth Needed to Reduce VMT

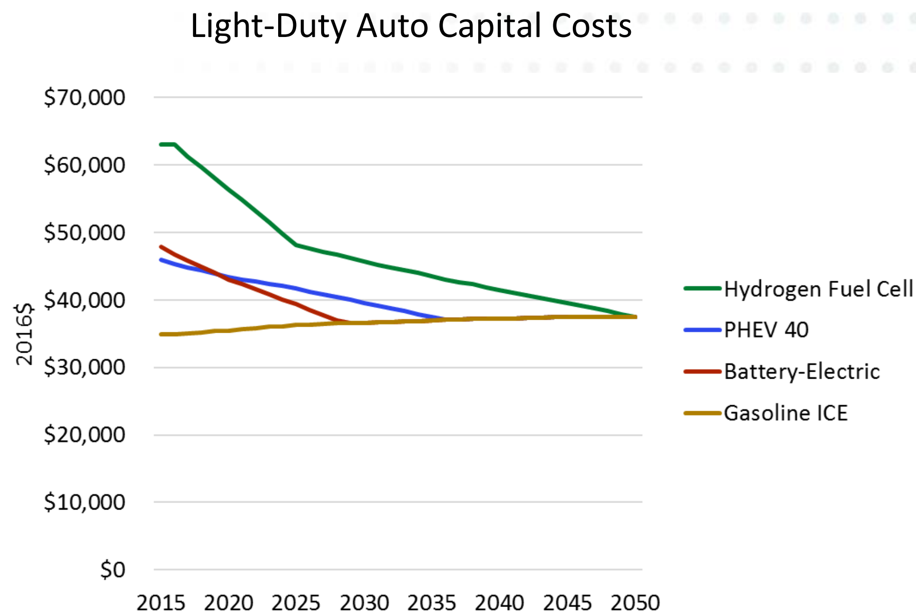
+ **12% reductions in per capita light duty vehicle miles traveled (VMT) in 2030, 24% per capita reduction in 2050, relative to 2015**
  - Reference scenario reflects smart growth VMT reductions required by SB 375, based on interpretation in 2016 prior to release of final Scoping Plan Update
  - Smart growth saves $2.5B in 2030 and $4.1B in 2050 from direct fuel savings
+ **Scenarios also assume 5-6% reductions in energy demand for off-road sectors**



The Low Cost of Driving a Light Duty Electric Vehicle

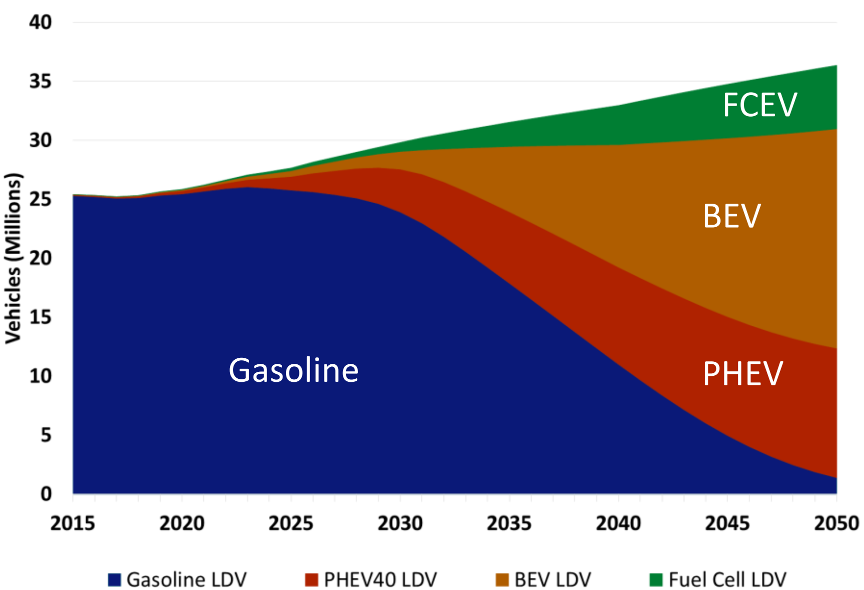
- **The cost of driving an all-electric vehicles is expected to remain lower than alternatives, while biofuel-supplied ICE vehicles are the most expensive to operate (variable fuel costs only)**
- **Up-front capital costs of all-electric vehicles are projected to reach parity with efficient internal combustion engine (ICE) vehicles around 2030**



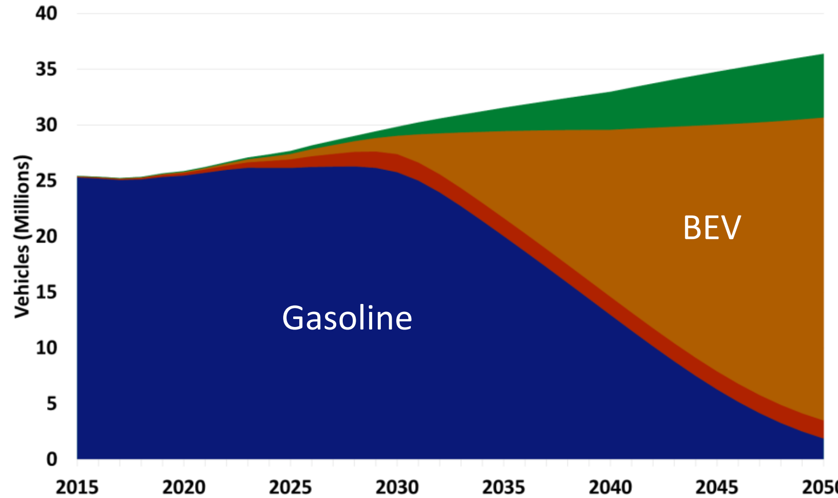


Light-Duty Vehicle Stocks by scenario

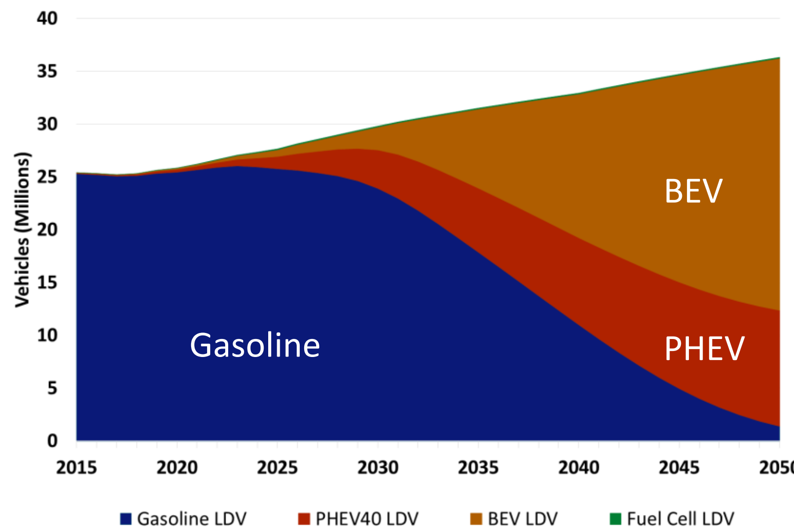
Light duty vehicle (LDV) stocks, High Electrification Scenario



LDV Stocks, In-State Biofuels Case



LDV Stocks, No Hydrogen Case



Medium & heavy duty trucks are diverse in duty requirements, may require a diverse decarbonization strategy

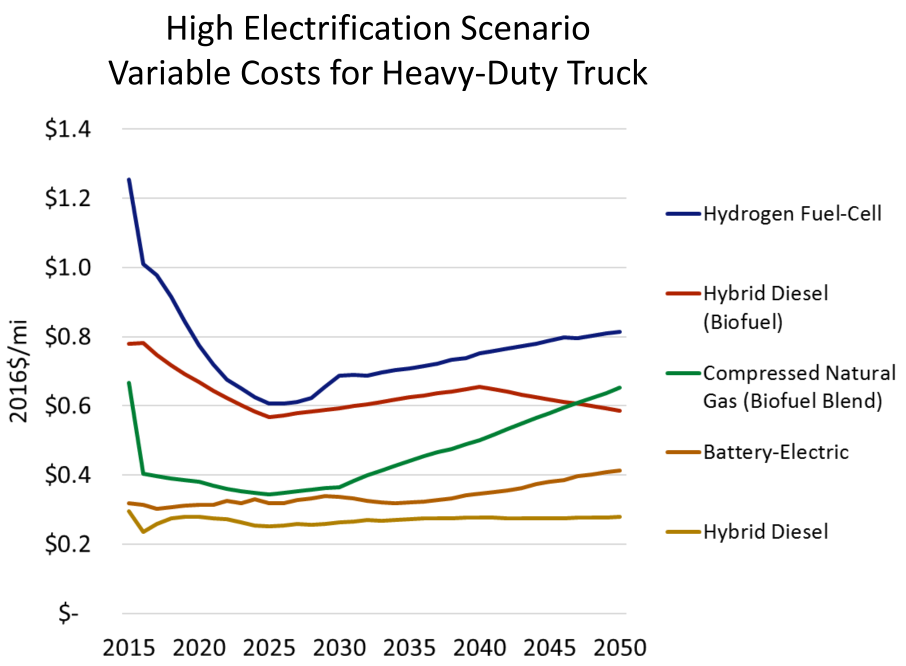
- Shorter distance trucking and lower weight requirements may be amenable to fully electric trucks or CNG
- Long-haul and higher weight requirements may be better suited to hydrogen fuel cell trucks or hybrid truck
- PATHWAYS scenarios model a diverse trucking fleet, reflecting uncertainty in future economics around zero-emission technologies

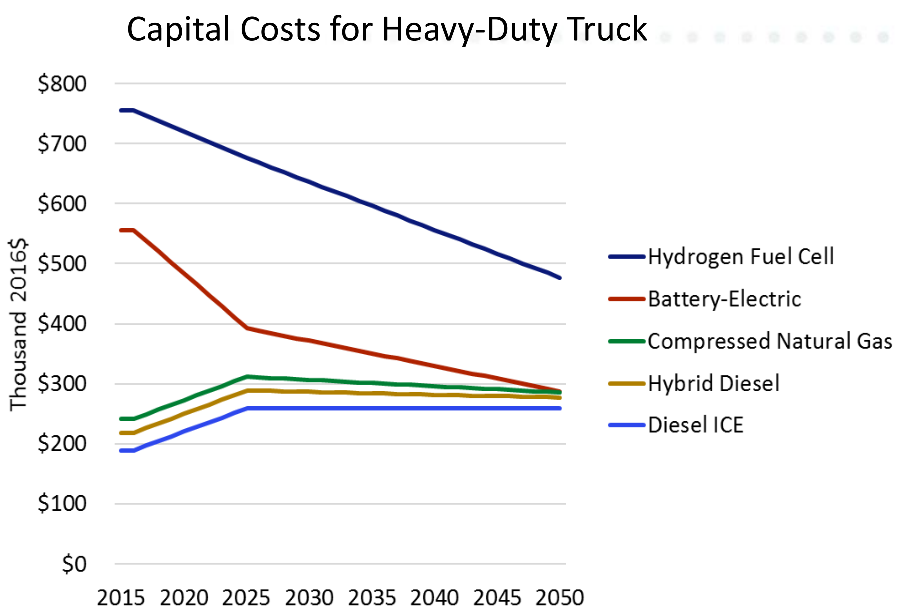
		Vans					Work Vehicles						Freight			Other
Class	Weight (1,000 lbs)	Step	Enclosed	Insulated	Open top	Other	Flatbed	Dump	Concrete	Tow	Utility	Garbage	Tank	Beverage	Tractor	Other
8	60+	2	4	2	6	1	33	203	122	2	2	32	19	0	2,670	29
8	50-60	1	4	3	22	1	41	160	49	4	7	73	28	0	314	21
8	40-50	1	14	4	69	2	81	187	17	7	11	49	51	2	279	24
8	33-40	2	18	6	38	1	100	101	2	11	31	26	41	8	131	15
7	26-33	5	87	40	78	4	203	181	0	16	73	20	130	46	64	40
6	19.5-26	127	294	60	89	20	475	315	0	78	106	14	96	32	31	104
5	16-19.5	101	175	23	19	7	157	80	0	31	70	6	14	5	0	49
4	14-16	98	80	7	12	11	185	114	2	36	46	2	13	3	0	69
3	10-14	234	256	21	11	43	[illegible]	[illegible]	0	65	117	5	13	4	0	151
Total		572	933	167	345	90	1,617	1,546	193	249	465	229	405	100	3,489	502

Source: Kast,J.,etal.,Designing hydrogen fuel cell electric trucks in a diverse medium and heavy duty market, Research in Transportation Economics (2017), http://dx.doi.org/10.1016/j.retrec.2017.07.006

Heavy-duty trucking may require a portfolio approach

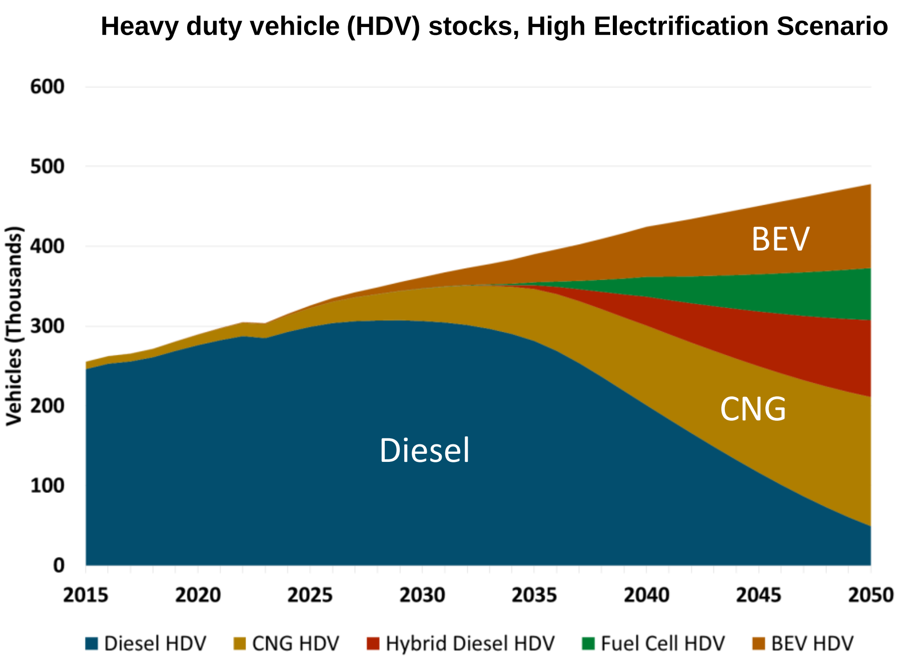
- **Different solutions may be optimal for short-haul vs. long-haul and in-state vs. out-of-state trucks**
  - Cost and performance of alternative fuel trucking options are highly uncertain
- **Hydrogen vehicles are the most expensive to operate and purchase, but they may be more feasible than battery electric for heavy-duty long-haul**

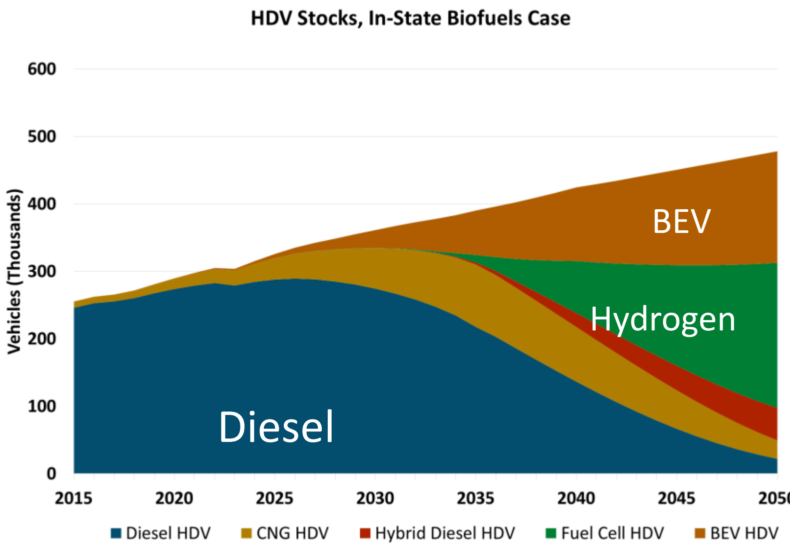


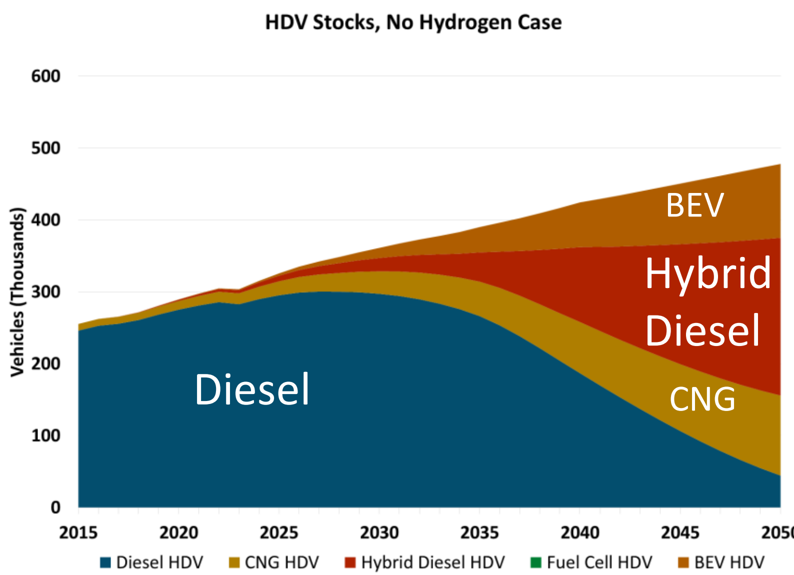


Note: Hydrogen fuel cell truck capital costs may be overestimated. Lack of commercial deployments of ZEV trucks makes cost-estimates difficult to forecast.

Heavy-Duty Vehicle Stocks by scenario



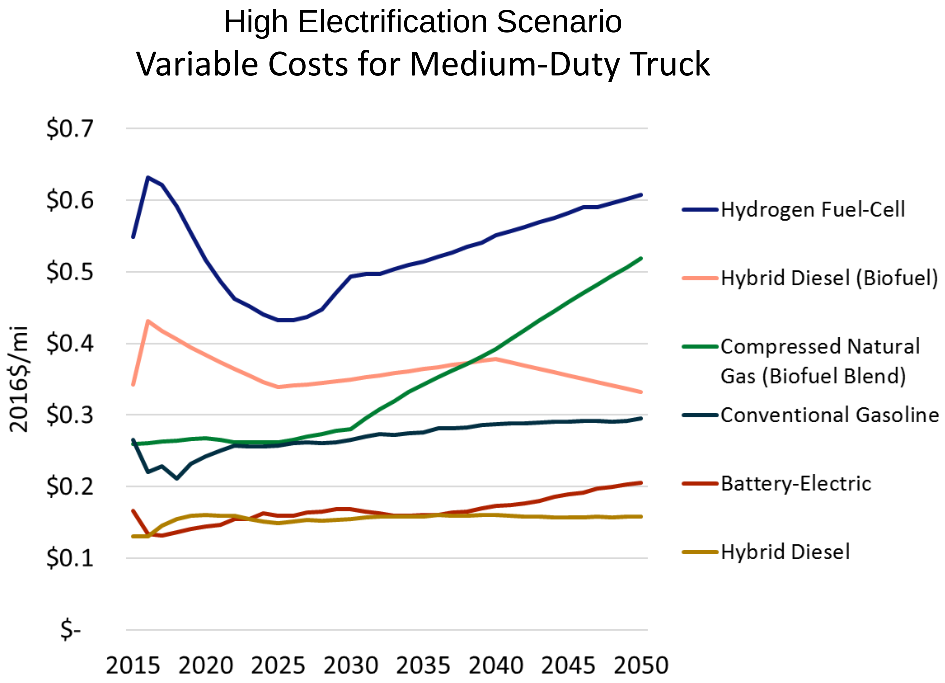


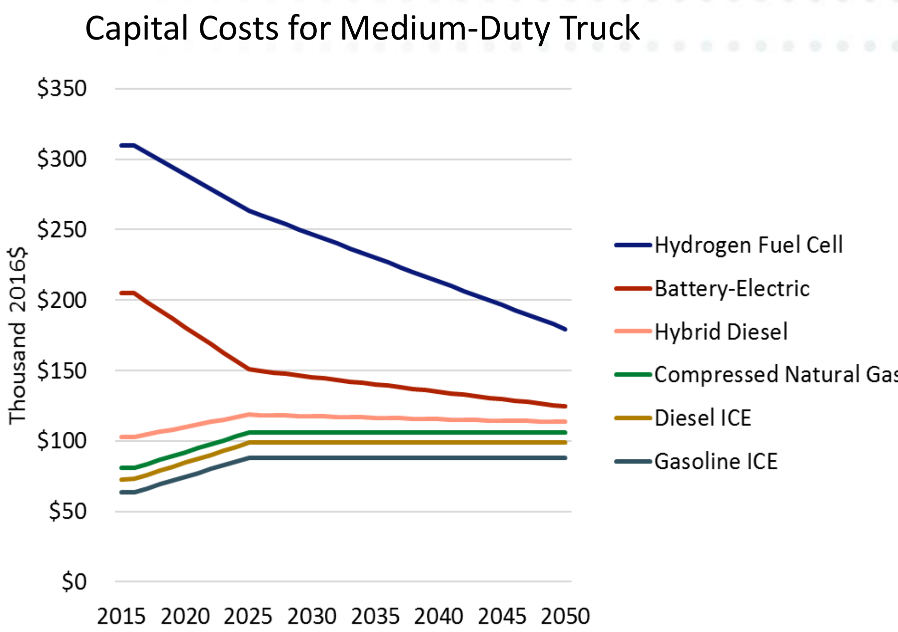


Note: Heavy-duty trucks represent class 7 and 8 trucks.

Portfolio strategy dominated by electric vehicles chosen for medium-duty trucks

+ **Battery-electric vehicles provide the lowest-cost GHG mitigation option for medium-duty vehicles in our cases**

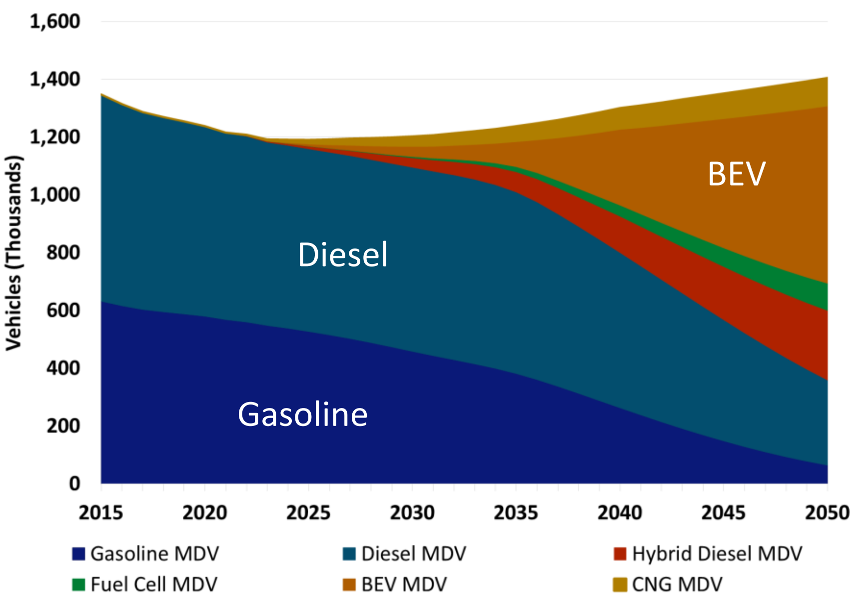




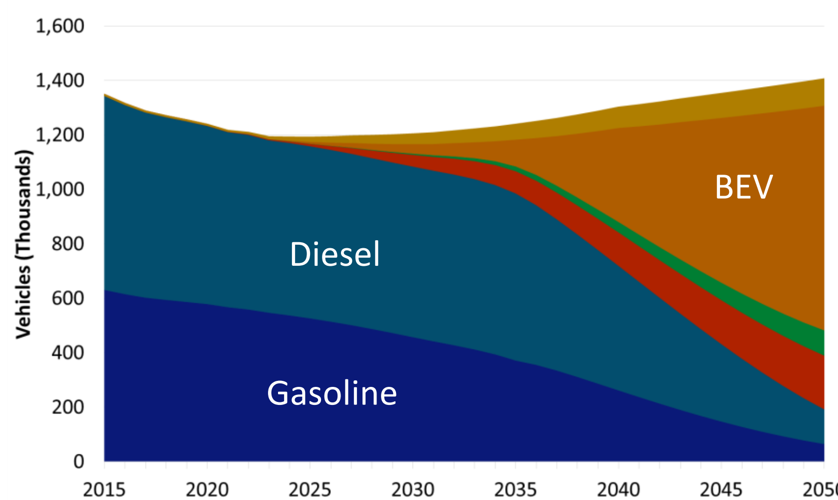
Note: Hydrogen fuel cell truck capital costs may be overestimated. Lack of commercial deployments of ZEV trucks makes cost-estimates difficult to forecast.

Medium-Duty Vehicle Stocks by scenario

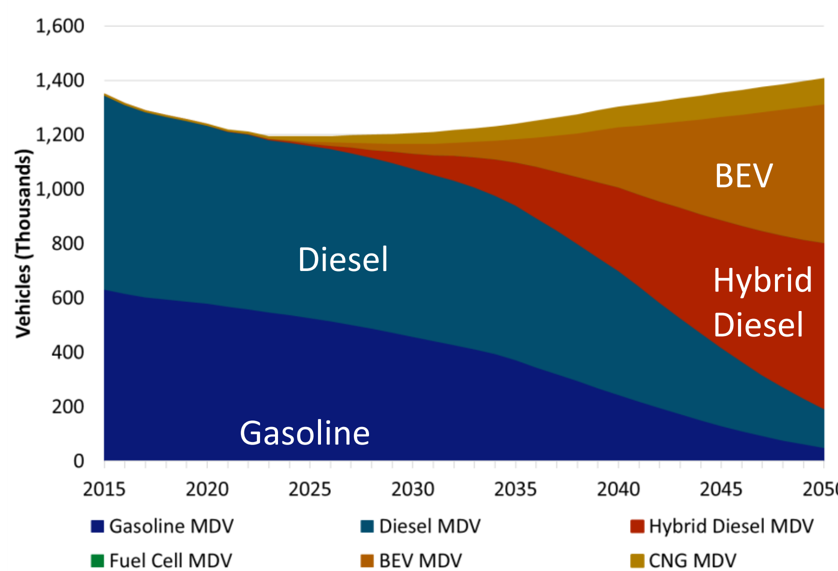
Medium duty vehicle (MDV) stocks, High Electrification Scenario



MDV Stocks, In-State Biofuels Case

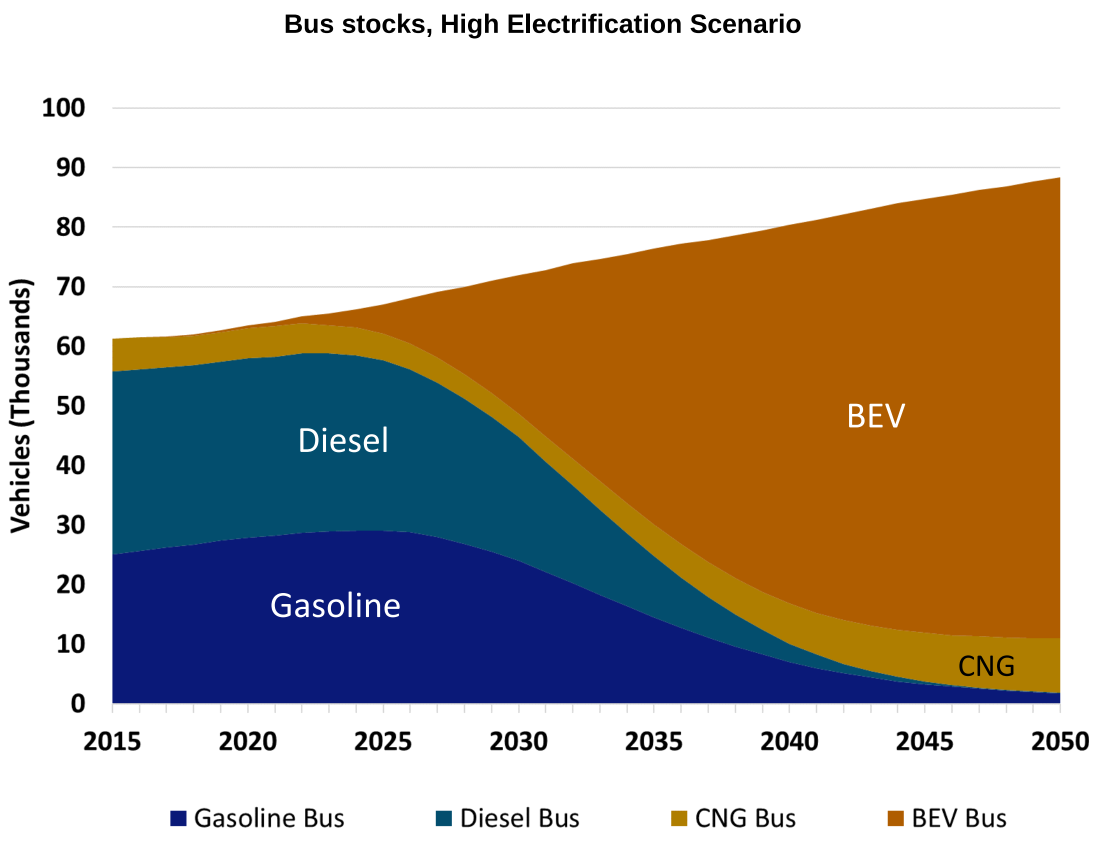


MDV Stocks, No Hydrogen Case

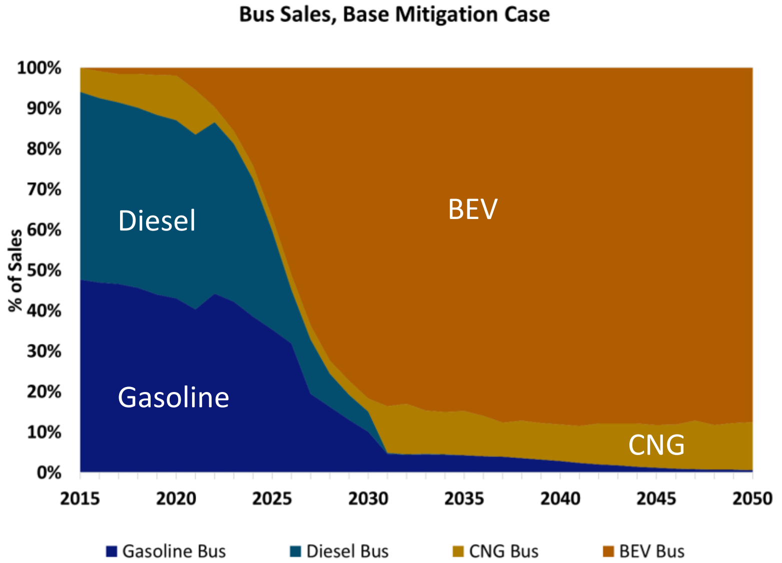


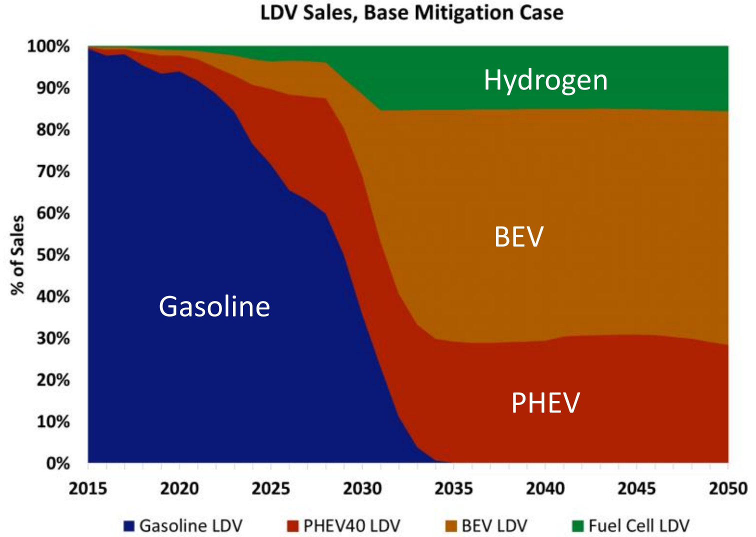
Note: Medium-duty trucks represent class 6 trucks and smaller, excluding light-duty trucks.

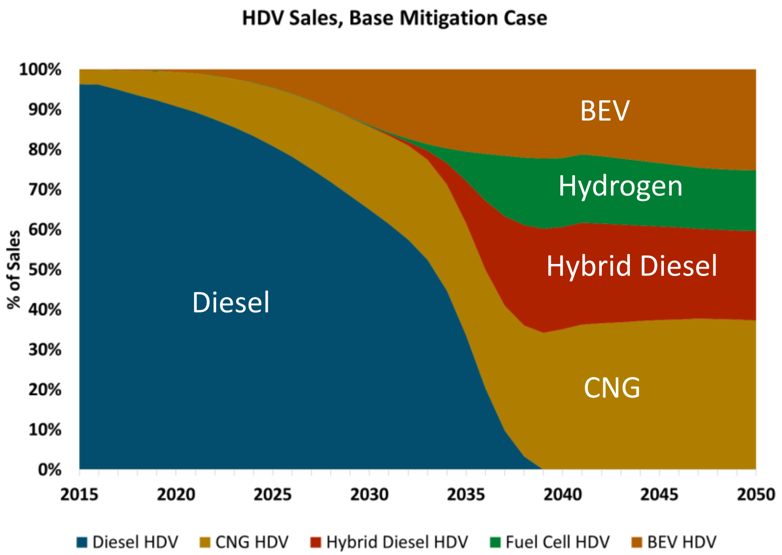
Bus Stocks: High Electrification Scenario

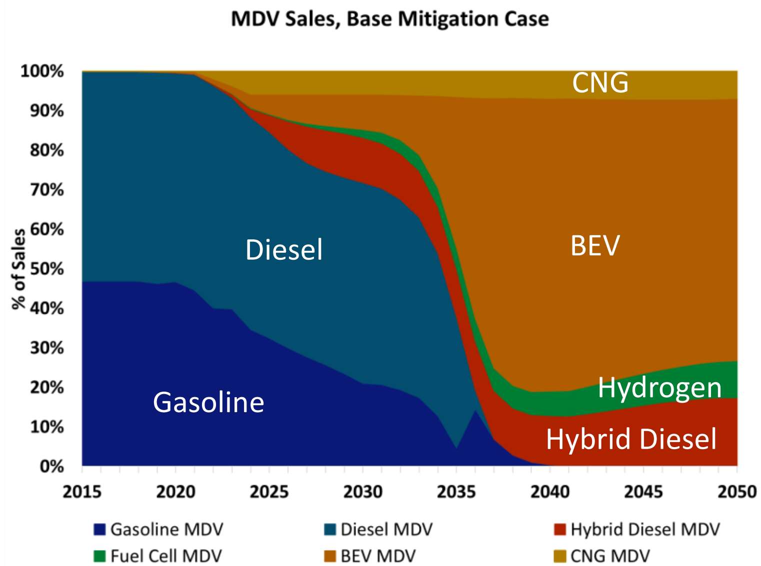


High Electrification Scenario Equipment as a % of new sales



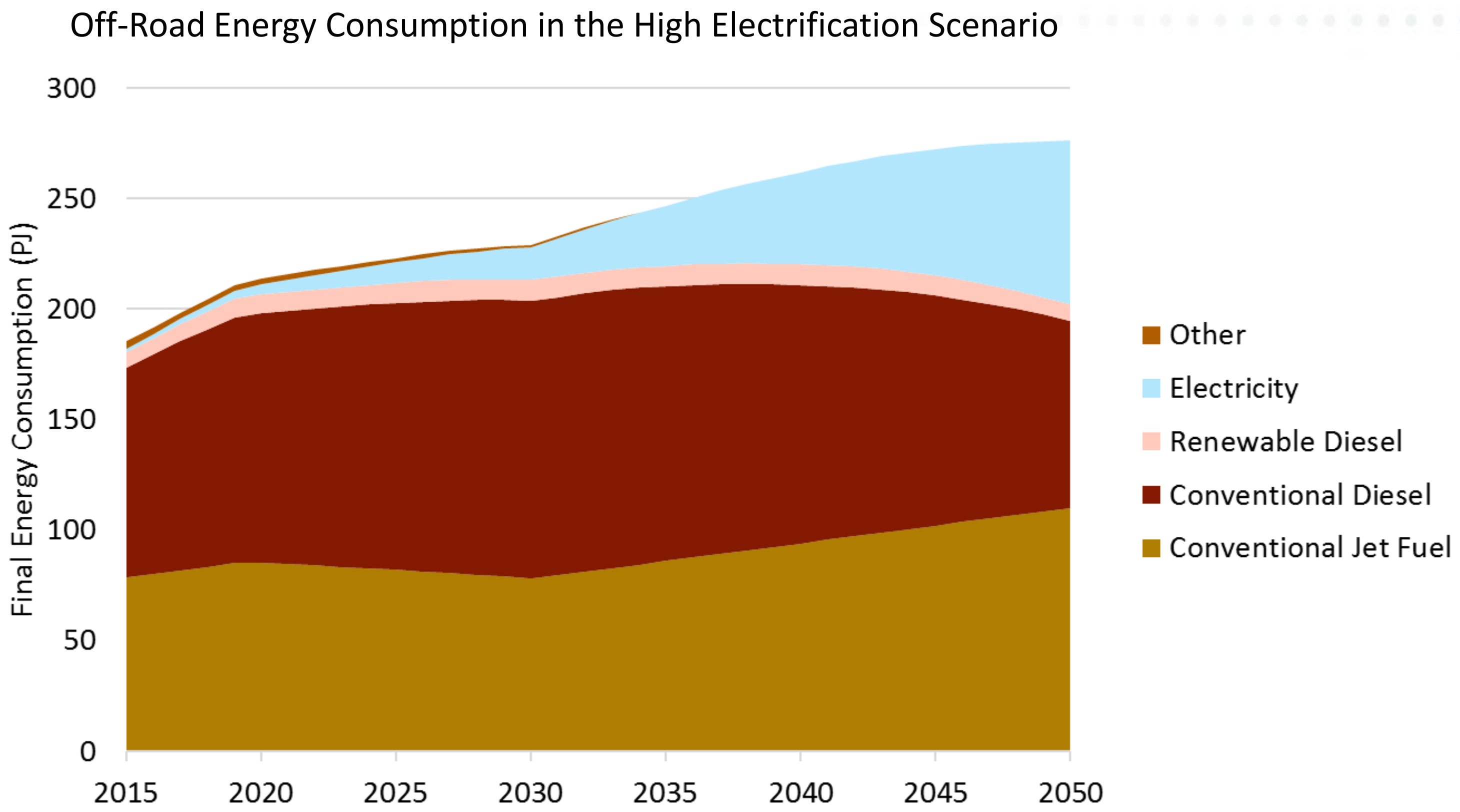






Off-road transportation GHGs may be difficult to mitigate

+ High electrification of rail and ports, moderate aviation efficiency through 2030
+ Remaining conventional diesel use is mostly used in shipping
+ Off-road transportation sector (shipping, aviation & rail) is responsible for 28% of total GHG emissions in 2050 (14 MMT CO_2e in 2050 out of total energy emissions budget of 50 MMT)

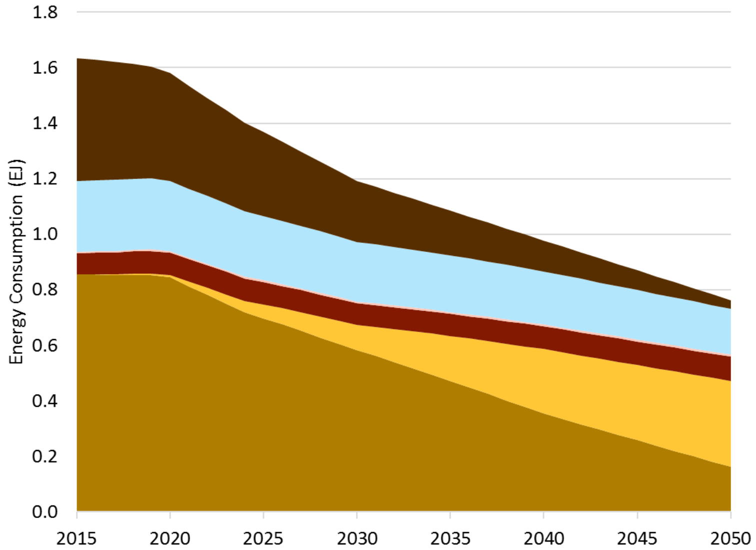


INDUSTRY & AGRICULTURE

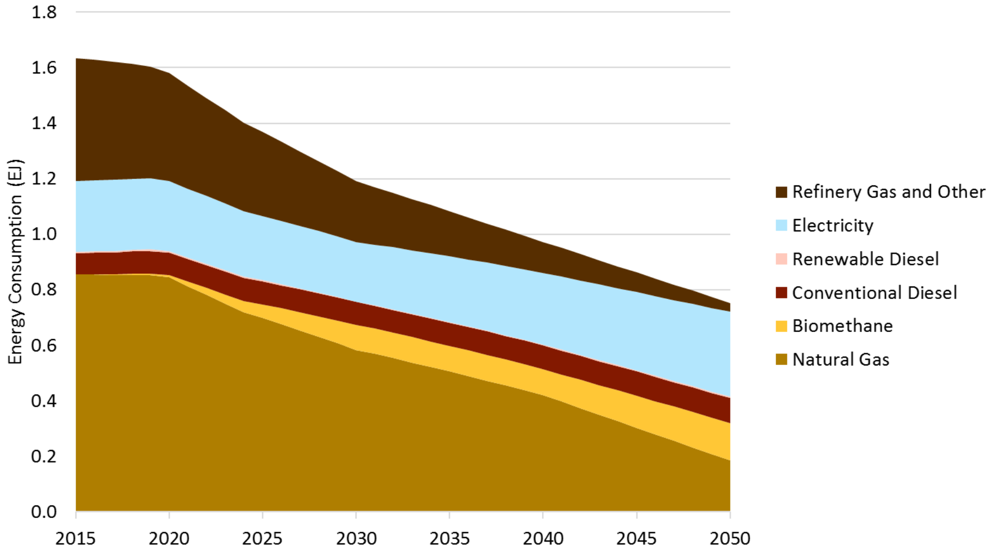
Industrial & agriculture energy consumption

- 20-30% energy efficiency by 2030 in industrial subsectors, moderate energy efficiency in agriculture
- Additional 14% reduction in petroleum refining output by 2030
- 90% reduction in oil and gas extraction & refining energy demand by 2050
- Responsible for 17 MMT CO_2e remaining in 2050 (out of total energy emissions budget of 50 MMT)

Industry and Agriculture Final Energy Consumption in High Electrification Scenario

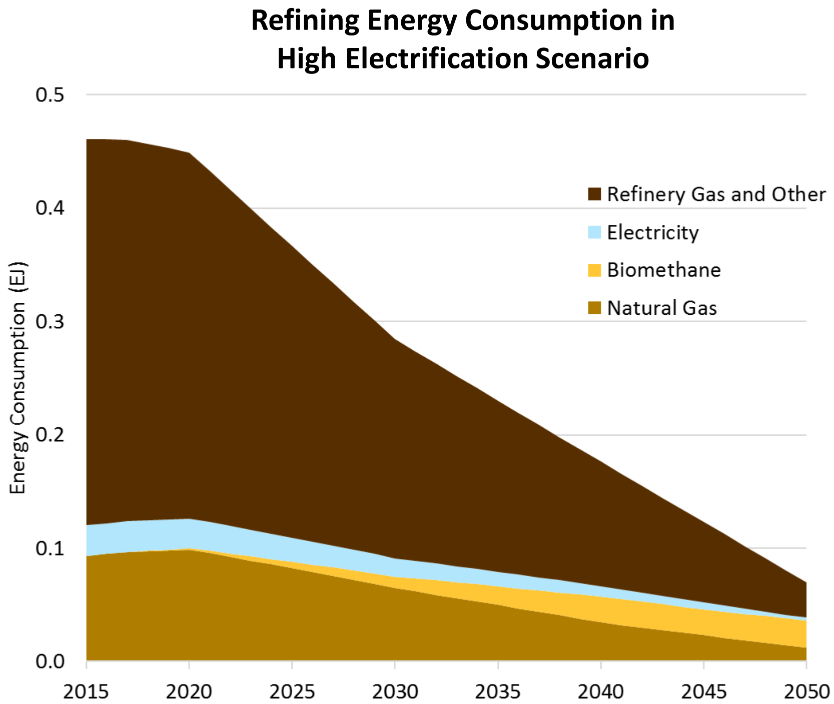


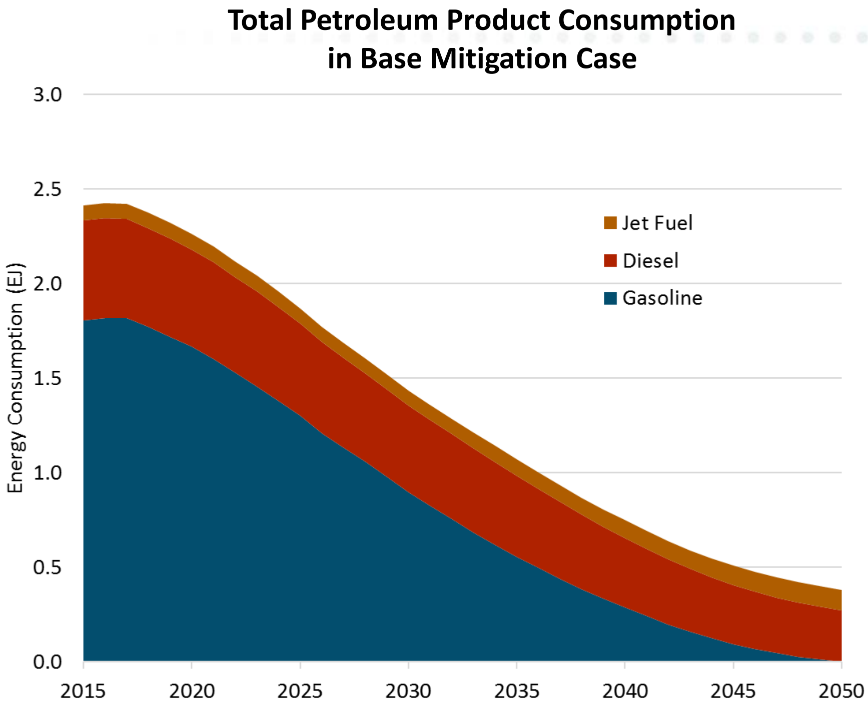
Industry and Agriculture Final Energy Consumption in In-State Biomass Case



Refining Sector

+ **Refining energy declines rapidly due to assumed efficiency (2020-2030) and reduced production (2020-2050)**
+ **Energy emissions decline from 34 MMT CO_2e in 2015 to 3 MMT CO_2e in 2050**

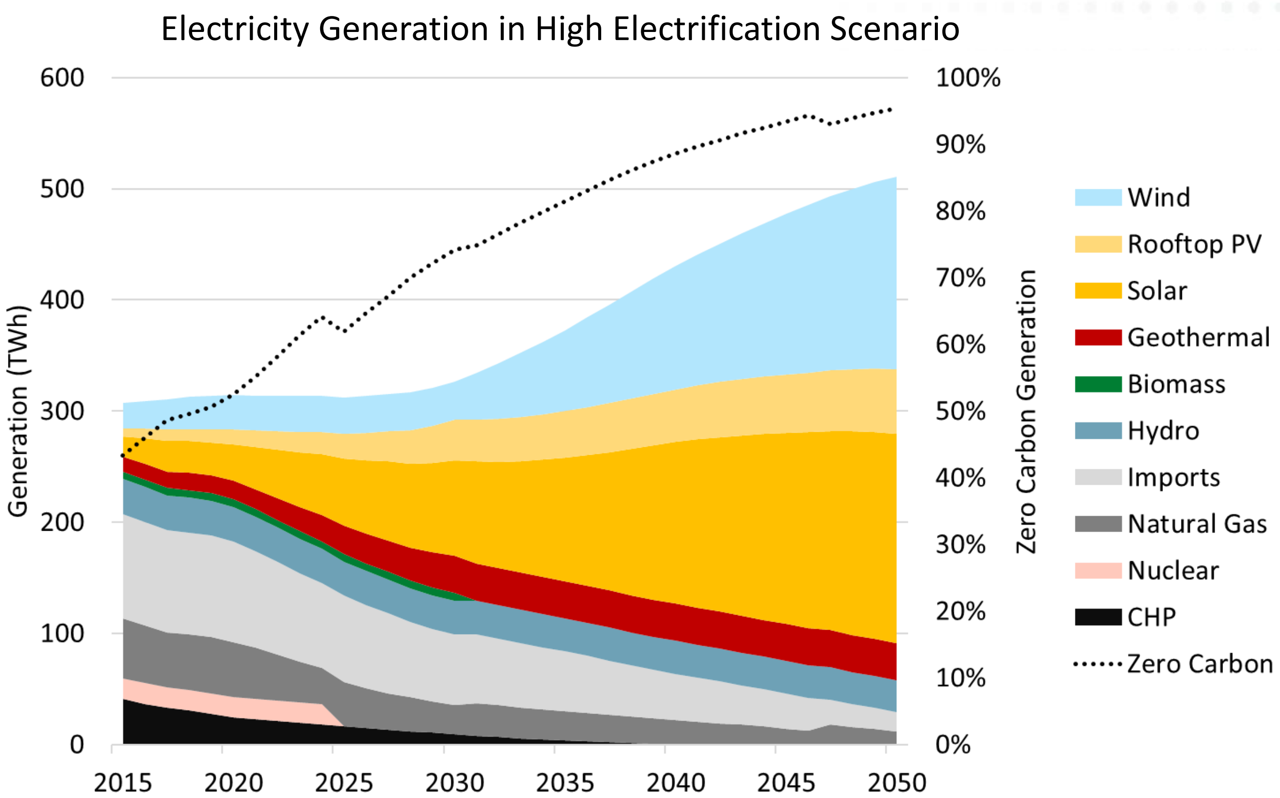




ELECTRICITY

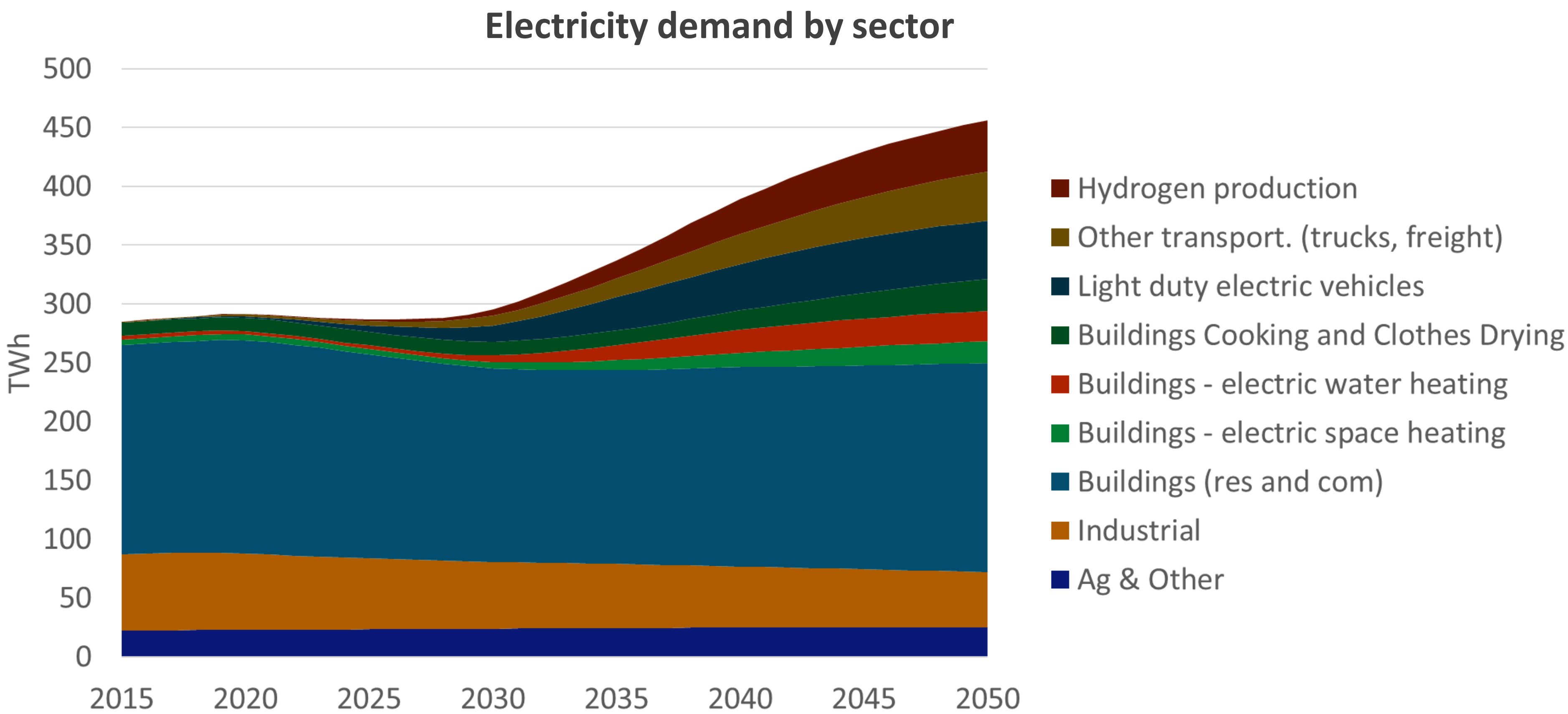
Electricity Generation Mix is Increasingly Renewables

- **Renewables and hydro constitute 95% of electricity generation by 2050 in the High Electrification Scenario**



Fuel switching drives rapid growth in electric generation after 2030

- **Energy efficiency offsets impact of electrification through 2030**
- **Beyond 2030 new loads offer potential for flexibility to help integrate solar and wind generation**



All Mitigation Scenarios include high levels of flexible loads

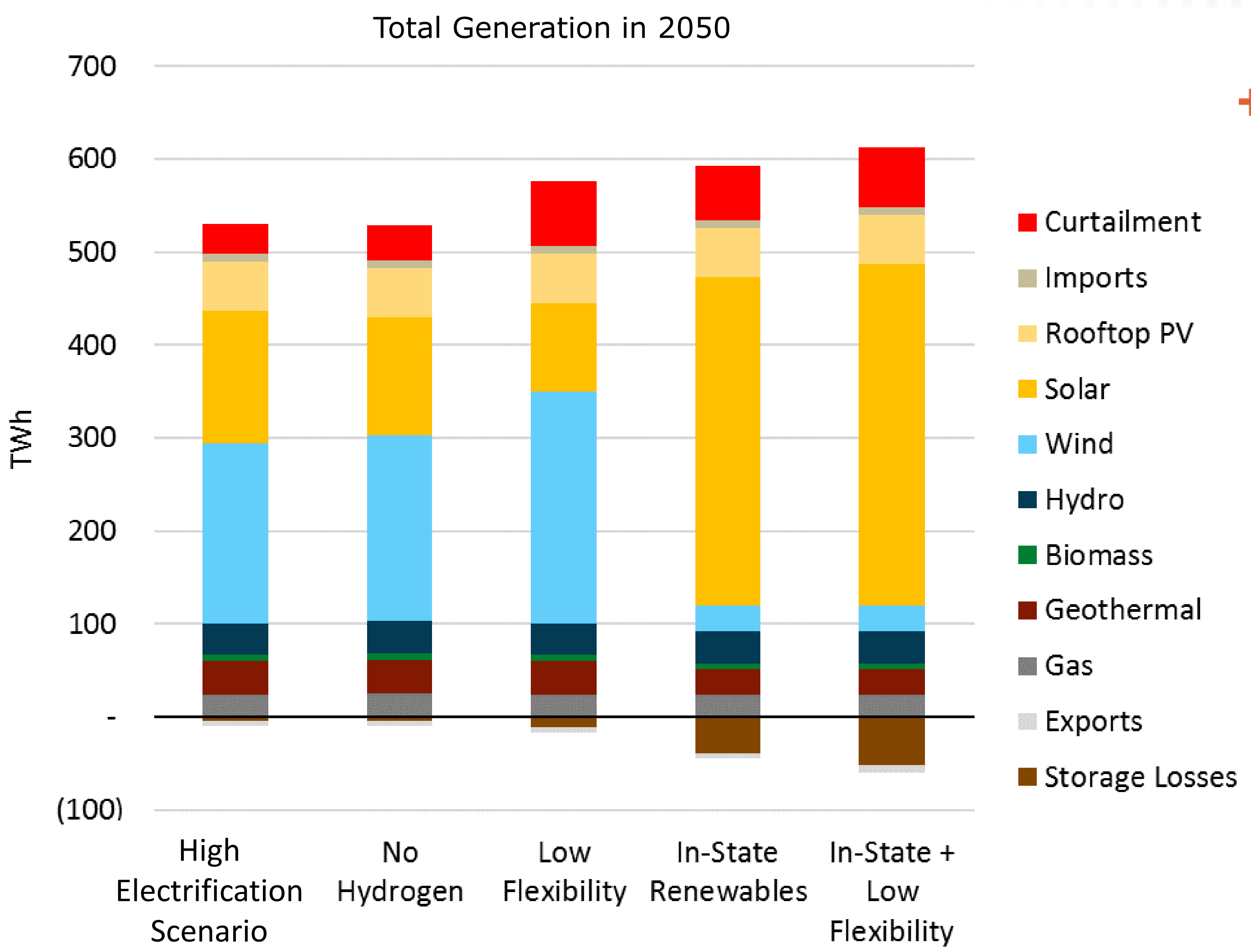
+ **Flexible loads ("shift DR") in PATHWAYS is modeled as a % of load by end use that can be shifted (advanced or delayed) by a specified number of hours each day.**

	% Flexible		
Subsector	**2030**	**2050**	**Hours Shift-able**
Commercial Water Heating	20%	80%	3
Commercial Space Heating	20%	80%	2
Commercial Air Conditioning	20%	80%	3
Commercial Refrigeration	20%	80%	2
Residential Water Heating	20%	80%	3
Residential Space Heating	20%	80%	2
Residential Central Air Conditioning	20%	80%	3
Residential Room Air Conditioning	20%	80%	3
Residential Refrigerators	20%	80%	2
Light Duty Vehicles	50%	90%	12

Electric Sector Analysis Using the RESOLVE Model

- **PATHWAYS High Electrification Scenario electricity demands by type, and electric sector GHG limit, was input into the Renewable Integration Solutions (RESOLVE) model**
  - Used determine electricity sector costs, capacity expansion and energy storage needs, with a focus on 2050
- **For this project, RESOLVE was updated to reflect statewide geographic footprint and 2050 analysis timeframe**
- **RESOLVE was developed by E3 to investigate need and timing for renewable integration solutions**
  - Used in CAISO SB 350 regional integration study & CPUC IRP to select renewable portfolios
  - Performs optimal dispatch over a representative set of operating days
  - Selects least-cost combination of renewable integration solutions, subject to power system constraints
  - Meets energy and capacity needs & subject to a GHG constraint (RPS constraint was not used in this analysis)
  - Investment decisions minimize NPV of investment + operational costs

Scenario results: Generation in 2050

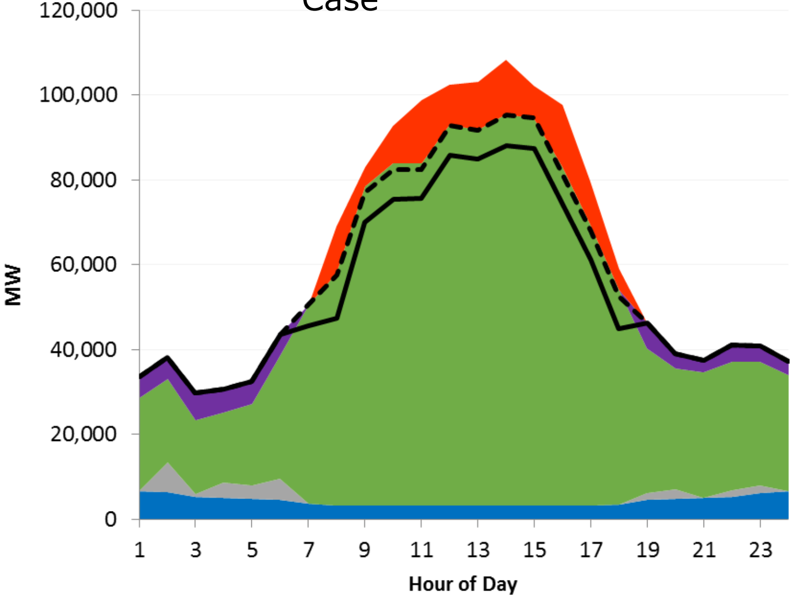


- **Without out-of-state wind and flexibility, costly storage and solar overbuild are required.**

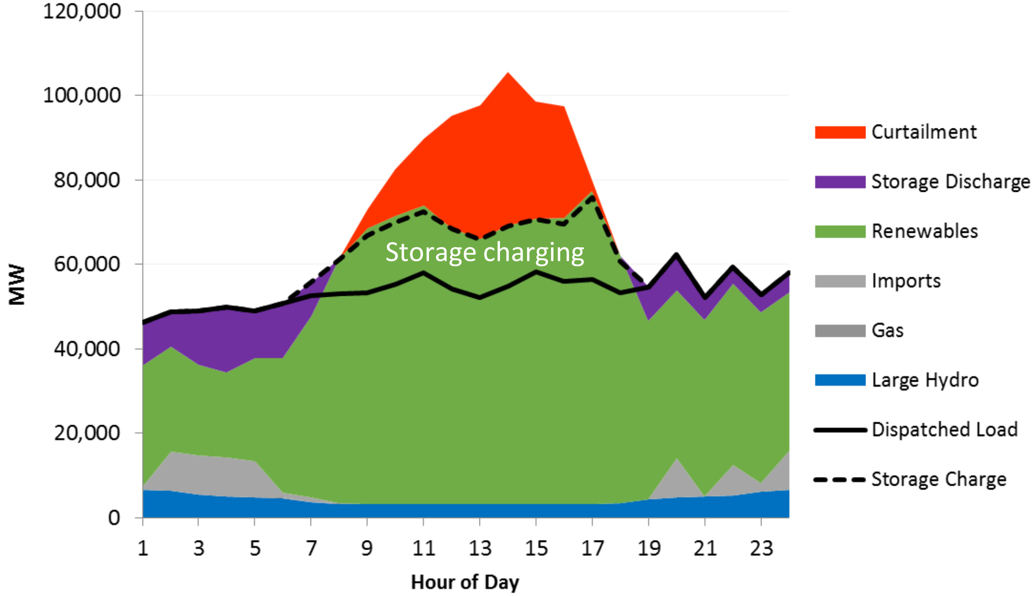
Impact of flexible loads

+ **High flexibility of building loads, EV charging loads, and hydrogen production loads avoids costly need for additional storage and overbuild.**

Spring Day in 2050, High Electrification Case



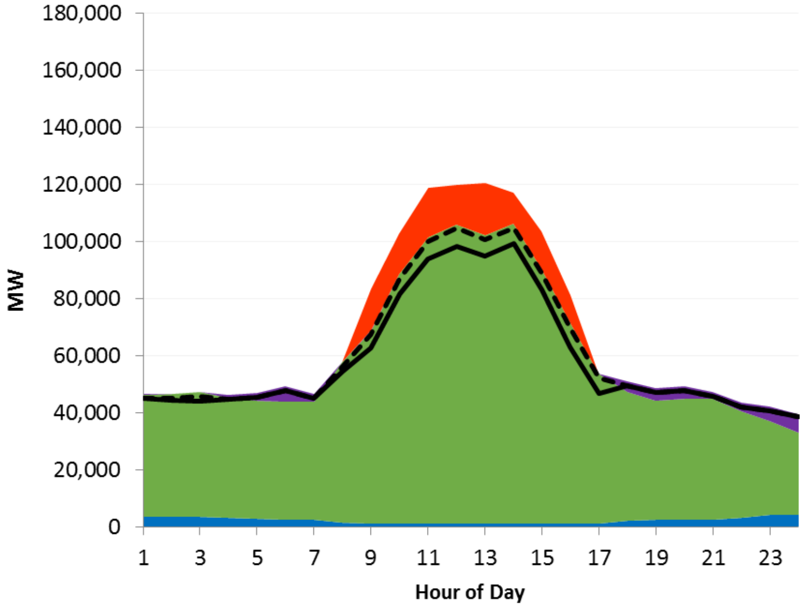
Spring Day in 2050, Low Flexibility



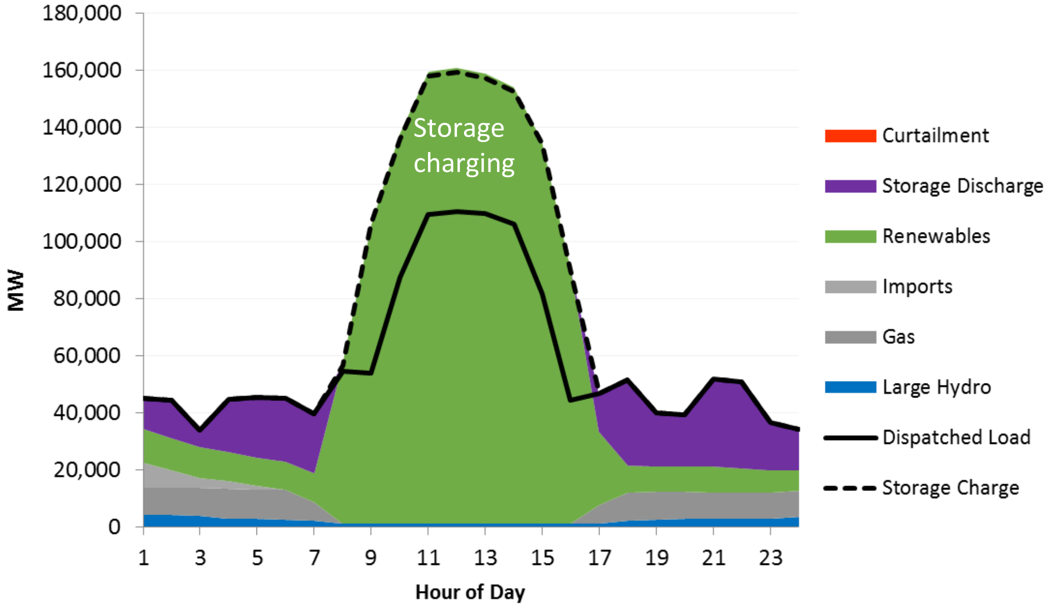
Impact of Out-of-State Wind

+ **Renewable diversity avoids costly dependence on storage and solar overbuild, particularly in winter**

December Day in 2050,
High Electrification Case



December Day in 2050,
In-State Renewables



Curtailment in 2050

- 9% curtailment in High Electrification Case in 2050
- 22% curtailment in In-state, Low Flexibility case in 2050

High Electrification Case

Average GW of Curtailment by Month-Hour												
HE/Month	1	2	3	4	5	6	7	8	9	10	11	12
1	-	-	1	1	2	1	-	1	-	-	1	-
2	-	-	1	1	1	1	-	1	-	-	1	-
3	-	3	0	0	4	1	-	1	-	-	0	-
4	-	-	1	0	1	1	-	1	-	-	1	-
5	-	-	1	0	1	1	-	1	-	-	1	-
6	-	0	1	0	1	0	-	1	-	-	0	-
7	-	-	1	1	1	0	-	-	-	-	0	-
8	-	1	9	3	17	0	-	1	0	21	3	-
9	-	16	23	7	7	0	-	2	0	19	11	12
10	0	13	21	6	14	0	-	5	0	32	12	12
11	0	16	27	8	10	-	-	2	0	36	6	15
12	0	9	23	9	15	-	-	1	0	11	5	12
13	0	11	19	7	10	-	-	4	-	27	6	15
14	0	19	29	6	14	0	-	2	-	20	10	9
15	0	15	20	6	10	0	-	3	-	9	6	11
16	0	9	19	6	16	1	-	5	-	39	5	8
17	-	5	14	5	14	1	-	2	-	17	1	-
18	-	2	5	1	6	1	-	3	-	-	1	-
19	-	0	1	1	2	1	-	-	-	-	-	-
20	-	0	1	1	1	1	-	1	-	-	0	-
21	-	0	1	1	1	1	-	-	-	-	2	-
22	-	0	1	1	1	1	-	1	-	-	1	-
23	-	0	2	1	1	1	-	1	-	-	0	-
24	-	0	6	1	1	1	-	1	-	-	0	-

In-State, Low Flexibility

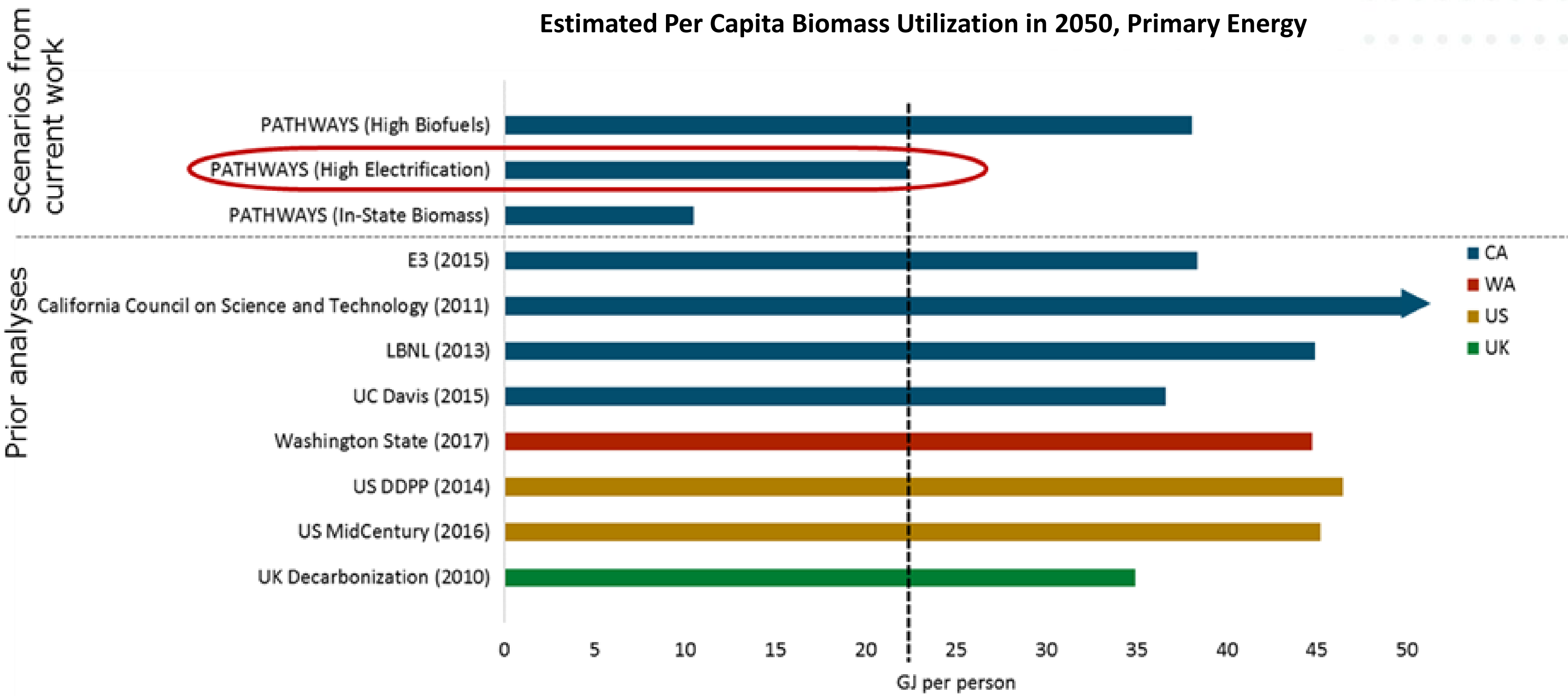
Average GW of Curtailment by Month-Hour												
HE/Month	1	2	3	4	5	6	7	8	9	10	11	12
1	-	-	0	1	0	2	0	2	-	-	-	-
2	-	-	0	1	1	1	0	2	0	-	-	-
3	-	-	0	1	0	1	0	1	0	-	-	-
4	-	-	0	1	0	2	0	1	0	-	-	-
5	-	-	0	1	1	1	0	2	0	-	-	-
6	-	-	0	1	7	6	4	7	-	-	-	-
7	-	-	0	2	16	21	9	8	2	-	-	-
8	-	0	8	3	23	15	17	8	3	9	0	-
9	2	0	18	11	17	37	9	40	10	45	0	-
10	0	0	27	16	66	26	9	45	5	50	0	0
11	4	0	22	24	34	36	26	28	0	27	1	0
12	13	0	24	19	50	42	12	30	13	51	3	1
13	12	0	36	21	56	28	14	56	6	17	3	1
14	11	3	39	13	46	26	17	26	10	21	5	0
15	6	0	20	16	37	29	16	35	16	20	1	0
16	2	0	11	8	37	17	7	33	1	23	0	-
17	-	-	10	9	24	19	8	20	5	-	-	-
18	-	-	3	3	16	16	1	7	2	-	-	-
19	-	-	1	1	6	5	2	6	-	-	-	-
20	-	-	1	1	1	2	0	3	0	-	-	-
21	-	-	0	1	1	2	0	1	-	-	-	-
22	-	-	1	1	1	1	0	1	-	-	-	-
23	-	-	1	1	3	2	0	2	-	-	-	-
24	-	-	2	1	2	1	0	1	-	-	-	-

Climate change is not expected to be a major impediment to reducing electricity sector emissions

- **The threat of extreme events and the indirect effects of climate change could have large consequences for the energy system and economy which are not modeled here**
- **Without modeling extreme climate events, on average, climate change is expected to have small direct impacts on a very low-carbon electricity system in the 2050 timeframe**
  - Climate change will cause hydroelectric availability will fall, and seasonality will shift, but reduced hydro availability has less impact in 2050 due to higher total loads from electrification, and as the system becomes increasingly dominated by wind, solar and new energy storage
  - Climate change will increase air conditioning demand more than heating demand decreases, but AC demand is easier to integrate with solar, so effects on electricity are mitigated in a low-carbon future
  - Climate change will reduce the thermal efficiency of power plants due to hotter temperatures, but in a low-carbon electricity system, this has no noticeable effect as total gas generation in 2050 is small, and would mostly run during the winter
  - Excluding extreme climate events, the net effect of climate change on building energy demands and reduced hydroelectric output is modeled minimal in the context of climate mitigation costs: < 1 MMT CO_2/yr and < $1B/yr for the Base Mitigation Case.

BIOFUELS & HYDROGEN

High Electrification Scenario Assumes Fewer Biofuels than Prior Studies

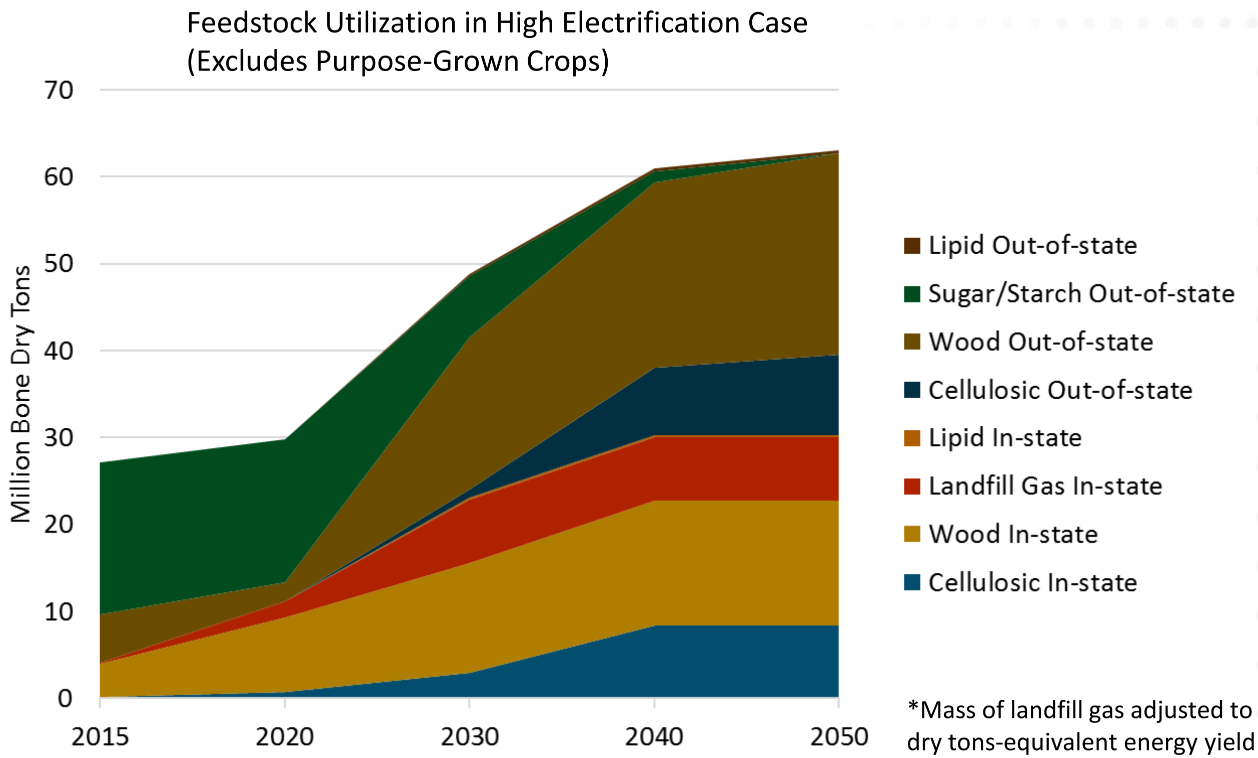


Estimated per capita biomass primary energy utilization in 2050 shown for selected deep decarbonization scenarios. The comparison assumes 18 GJ per bone dry ton primary energy yield, corresponding to the average yield assumed in the US analysis for the Deep Decarbonization PATHWAYS Project (Williams, 2014).

References: E3. 2015. California State Agencies' PATHWAYS Project: Long-term GHG Reduction Scenarios; California Council on Science and Technology (CCST). 2011. California's Energy Future - The View to 2050; LBNL. 2013. Scenarios for Meeting California's 2050 Climate Goals (see cited reference Wei et al., 2014); U.C. Davis: Yang et al. 2015. Achieving California's 80% Greenhouse Gas Reduction Target in 2050; Washington State: Haley, et al. 2016. Deep Decarbonization Pathways Analysis for Washington State; U.S. DDPP: Williams, J.H., et al. (2014). Pathways to deep decarbonization in the United States. U.S. Mid-Century: The White House. 2016. United States Mid-Century Strategy for Deep Decarbonization; U.K. Decarbonization: European Climate Foundation. 2010. Roadmap 2050

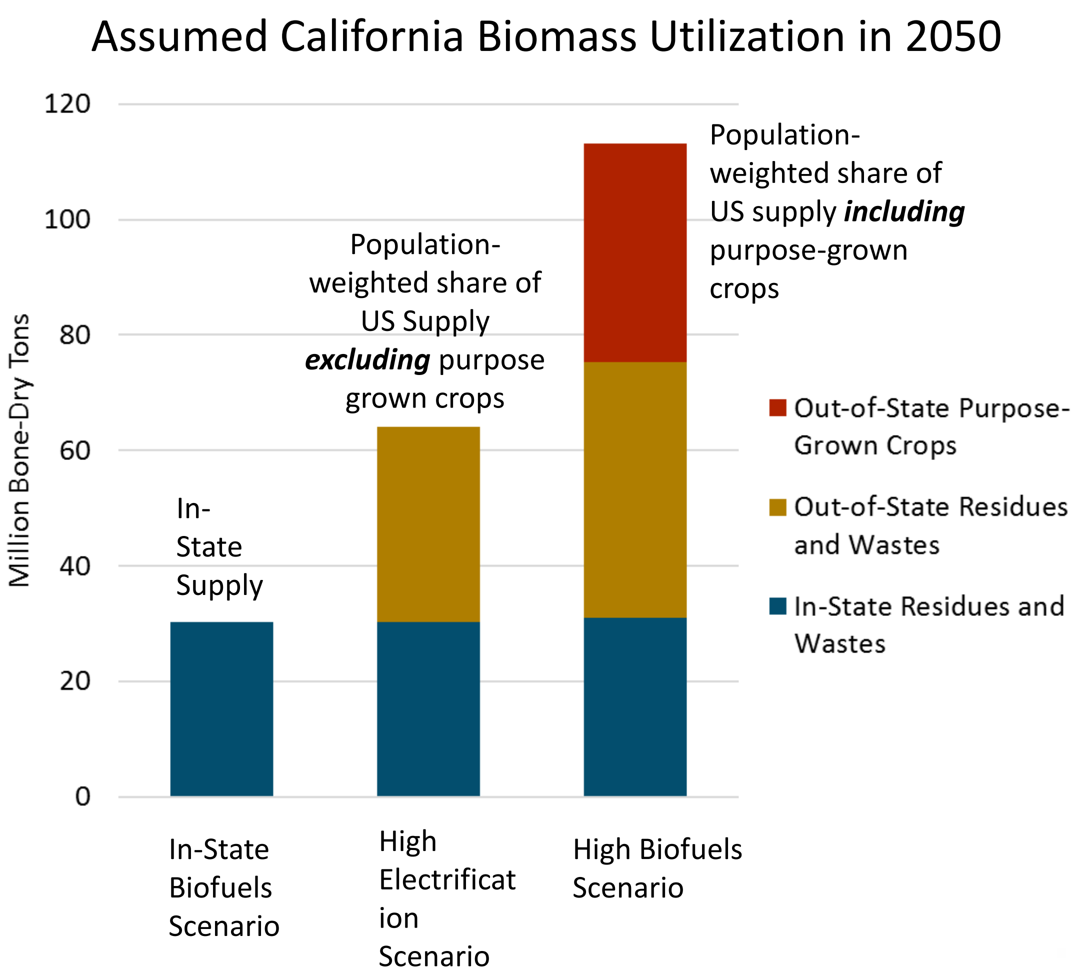
California Biomass Feedstock Supply in High Electrification Case

+ **Out-of-state corn ethanol feedstocks (sugar) dominate present-day biomass supply**
+ **Out-of-state wood and cellulose dominate 2050 biomass supply**



*Mass of landfill gas adjusted to bone dry tons-equivalent energy yield

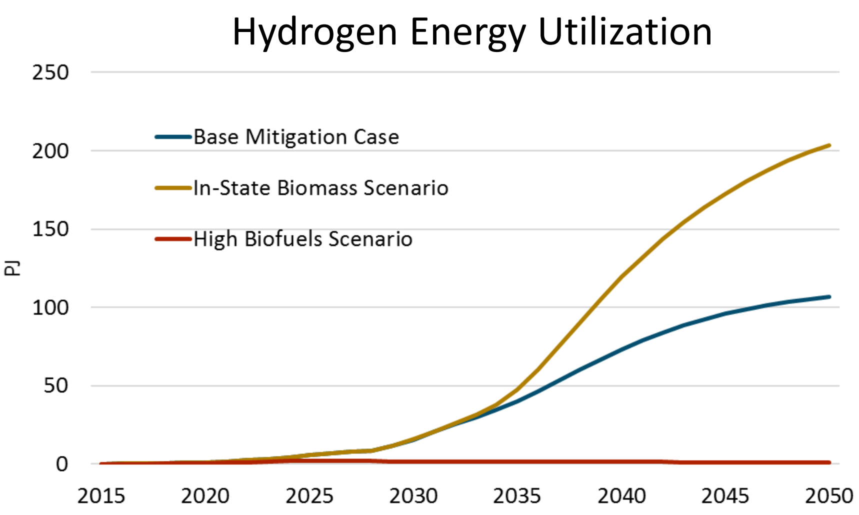
High Electrification Case Assumes Lower Biomass Utilization Than E3's Prior Work

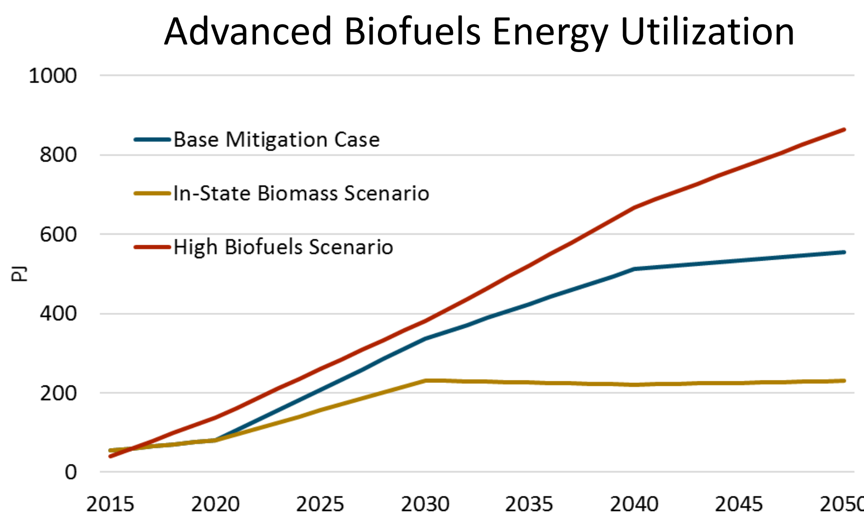


- **In High Electrification scenario biomass is used to produce biofuels for transportation and in the gas pipeline**
  - Pipeline biomethane costs and GHG savings can be attributed to any sector based on policy assumptions
  - High Electrification case assumes biomethane is ***not*** used in electric sector
- **E3's prior work reflected biomass assumptions similar to High Biofuels Case**

Low-Carbon Biofuels and Hydrogen

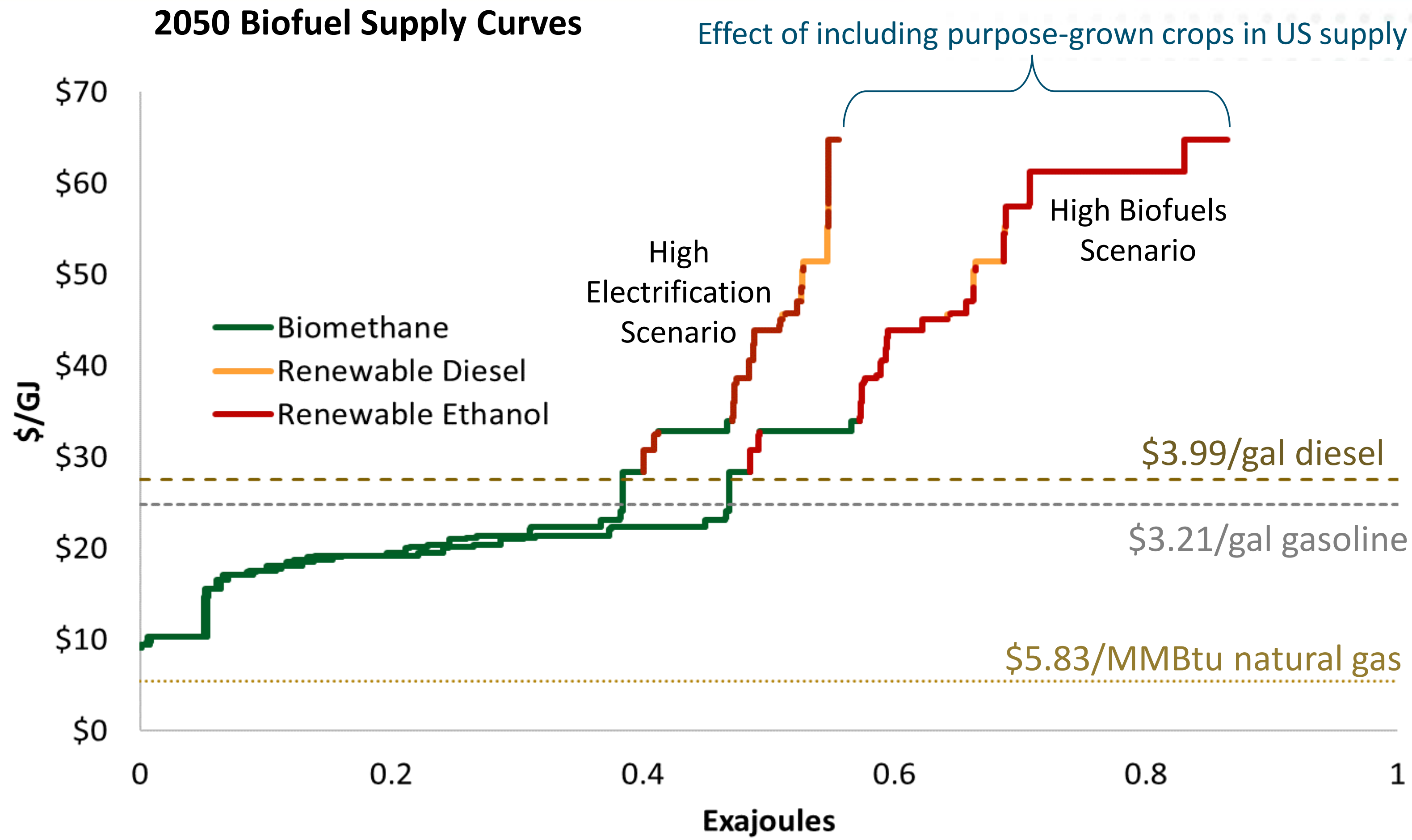
- **Hydrogen and advanced biofuels can be substitute GHG mitigation options**
  - H_2 is assumed to be produced via central-station PEM electrolysis
- **Large increase in advanced biofuels are found to lower total economy-wide mitigation costs**





Note the difference in scale between the two charts.

High Biofuels Scenario extends the biofuel supply used in the High Electrification Scenario, allowing displacement of more expensive measures



+ Some biofuels are cheaper than marginal measures in other sectors (e.g., electricity storage, hydrogen trucks)

High Electrification Case includes US population-weighted share of biomass supply *without* advanced purpose-grown crops (e.g., switchgrass); High Biofuels case includes share of biomass supply *with* purpose-grown crops.

Power-to-Gas Assumptions: Hydrogen

- **Delivered compressed hydrogen costs $62/GJ in 2050 in PATHWAYS (2016$) for transportation**
- **Commodity price for pipeline blending is $49/GJ**
- **Produced via grid electrolysis by 2050**
  - Production efficiency (excluding compression/liquefaction): 78%
  - Capital costs: $0.65/kg/yr (2012$)
  - Flexible production at 25% load factor, dispatched to reduce renewable curtailment, hydrogen can be stored over 1 week
  - Delivered electricity rate for production in 2050: $0.09/kWh, assuming grid-connected, power-to-gas production. Assumes a portion of the total electricity revenue requirement is allocated to fuel production loads (e.g. lower electricity rate applied to power-to-gas would increase other electricity rates)

* Based on assumptions in the “No Building Electrification with Power-to-Gas” Scenario

Power-to-Gas Assumptions: Synthetic Methane

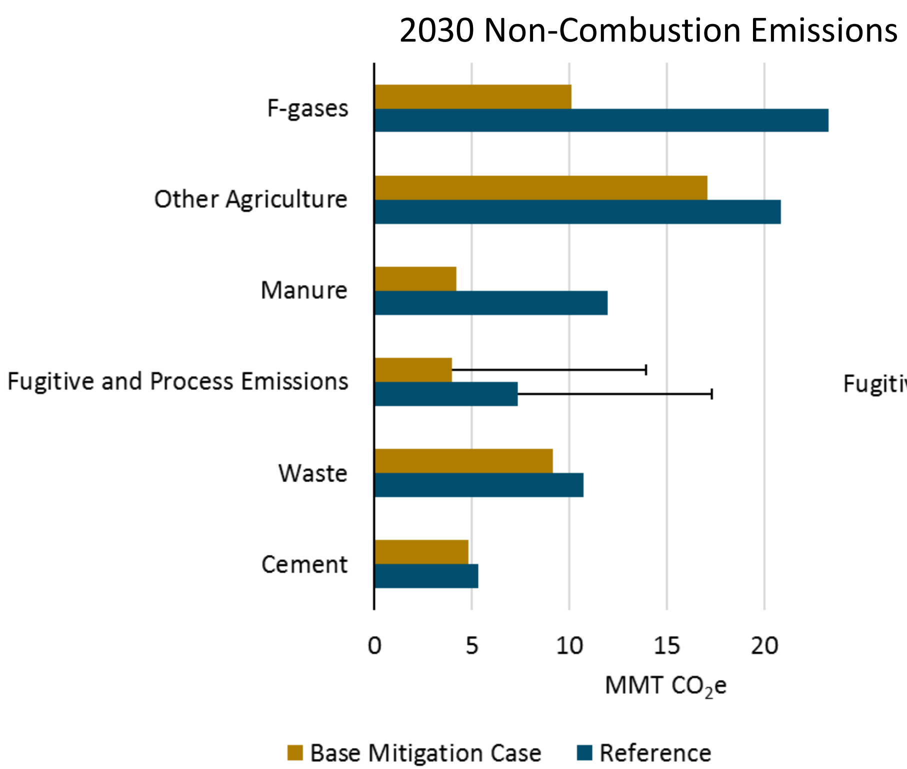
+ **Assumes air- or sea-capture of CO_2 reduced to methane (CH_4) with electrolytically-produced hydrogen, powered by grid electricity**
+ **Delivered synthetic methane costs $81/GJ in 2050 in PATHWAYS (2016$)**
  - Total production efficiency: 63%
  - Capital costs: $7.6/MMBTU/yr (2012$)
  - Non-energy variable operating costs: $6.5/MMBTU
  - Flexible production at 25% load factor, dispatched to reduce renewable curtailment, methane can be stored over 1 yr
  - Delivered electricity rate for production in 2050: $0.09/kWh. Assumes a portion of the total electricity revenue requirement is allocated to fuel production loads (e.g. lower electricity rate applied to power-to-gas would increase other electricity rates)

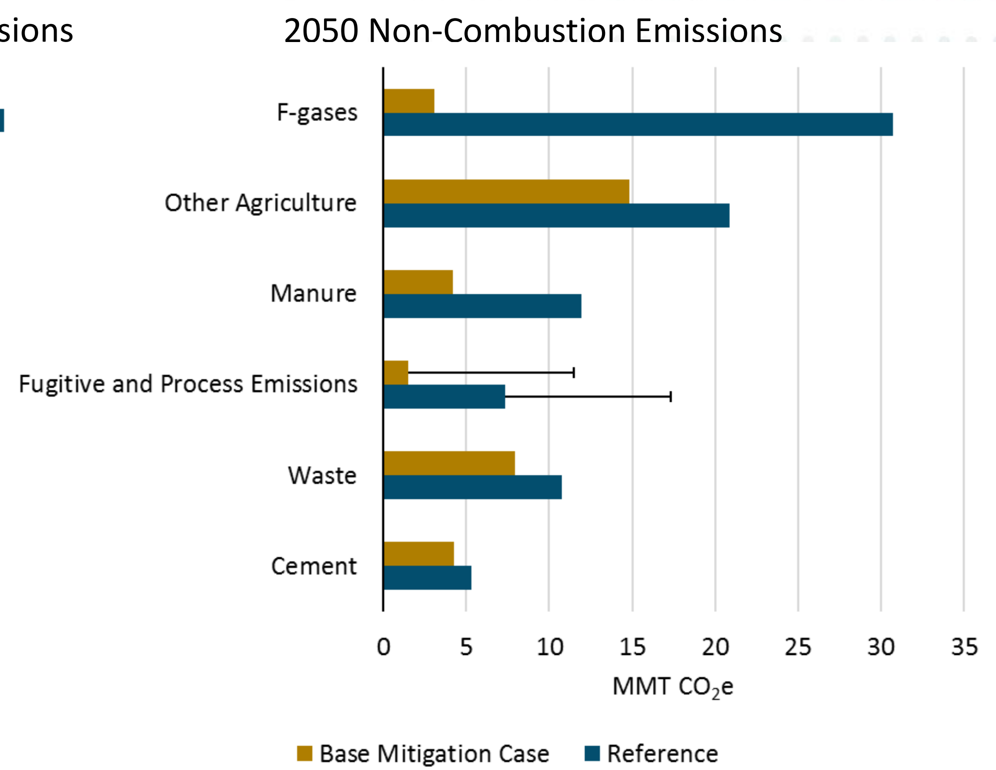
* Based on assumptions in the "No Building Electrification with Power-to-Gas" Scenario

NON-COMBUSTION GREENHOUSE GASES

Reductions in Non-Combustion GHG Emissions

+ **The Short-Lived Climate Pollutant Strategy and SB 1383 (2016) calls for reductions in non-combustion emissions. These cases exceed a 40% reduction of F-gases in 2030, but do not quite achieve a 40% reduction of methane emissions due to assumed challenges mitigating methane emissions from waste and enteric fermentation in cows**



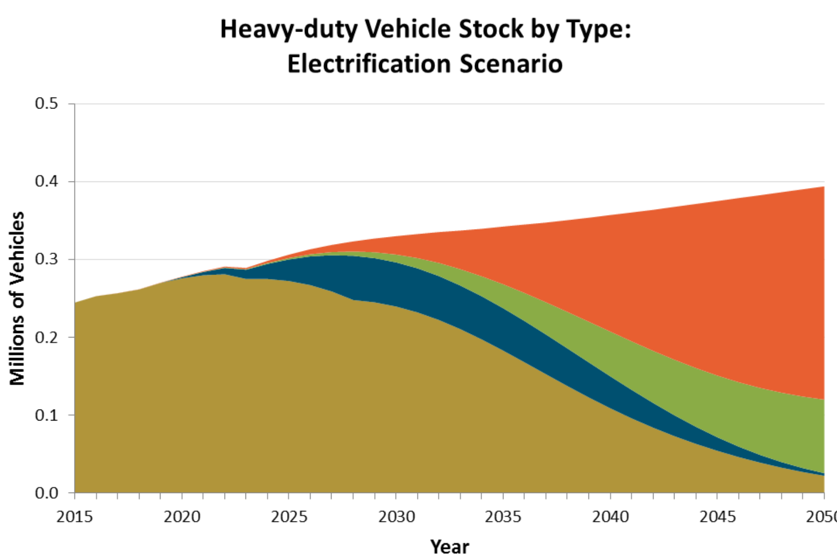


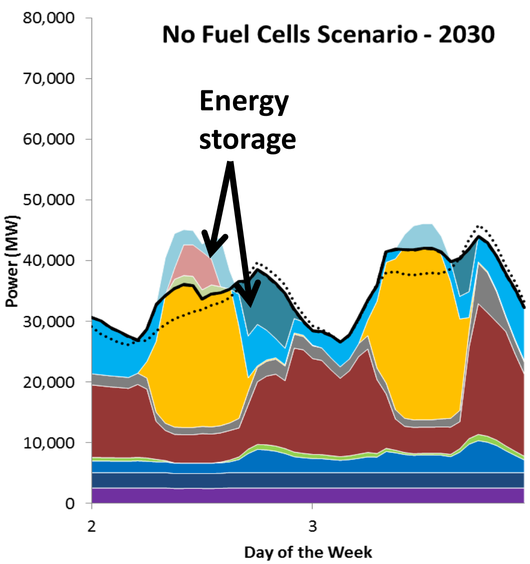
Note: Error bars bracket potential underestimate in fugitive methane emissions from the California Greenhouse Gas Emissions Inventory: see, e.g., Wunch et al. (2016). The IPCC estimates a ~20% uncertainty in global fossil methane emissions (2013).

METHODS

E3's California PATHWAYS model

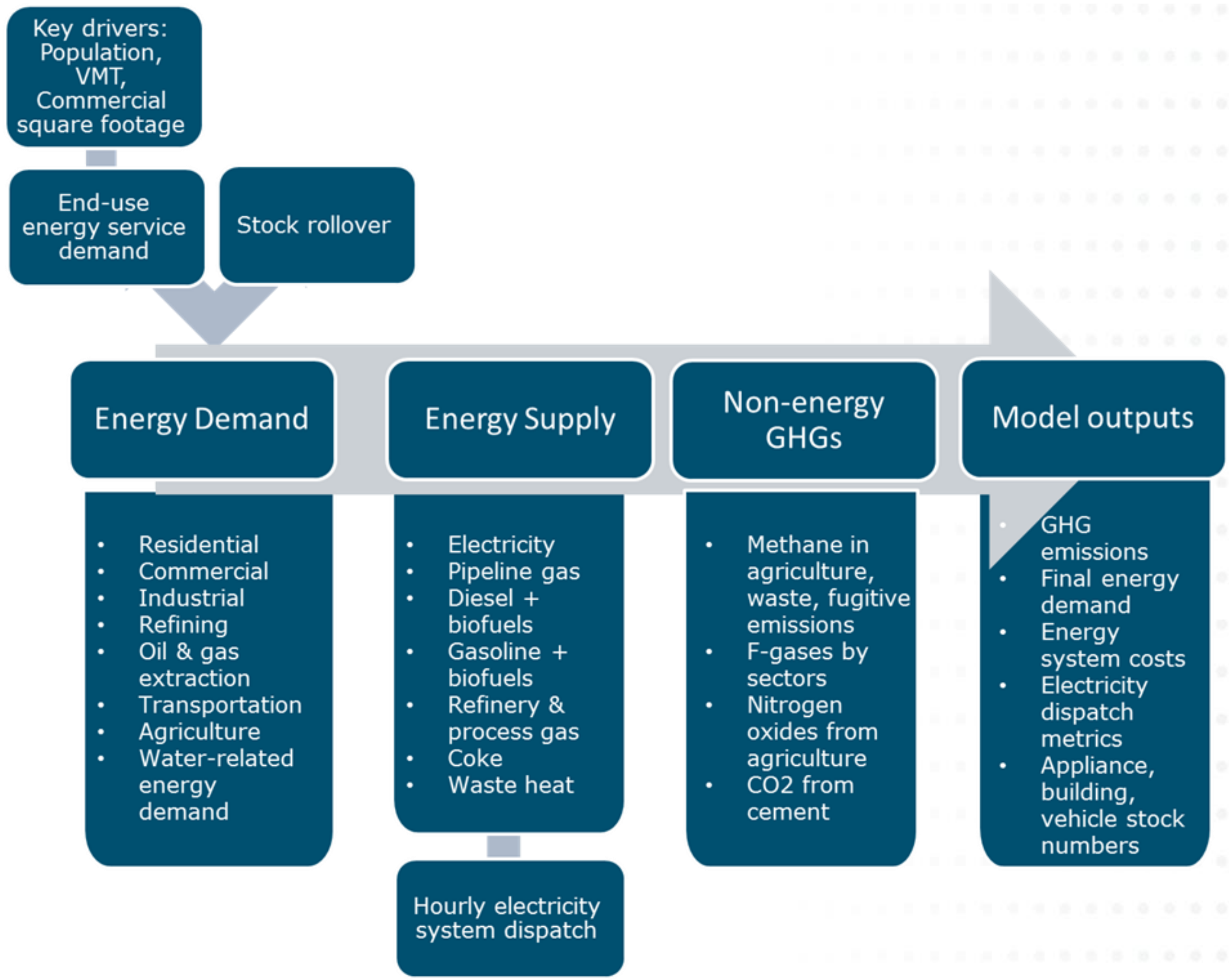
- Bottom-up, user-defined, non-optimized scenarios test "what if" questions
- Economy-wide model captures interactions between sectors & path-dependencies
- Annual time steps for infrastructure-based accounting simulates realistic stock roll over
- Hourly treatment of electric sector
- Tracks capital investments and fuel costs over time





Allows for development of realistic & concrete GHG reduction roadmaps

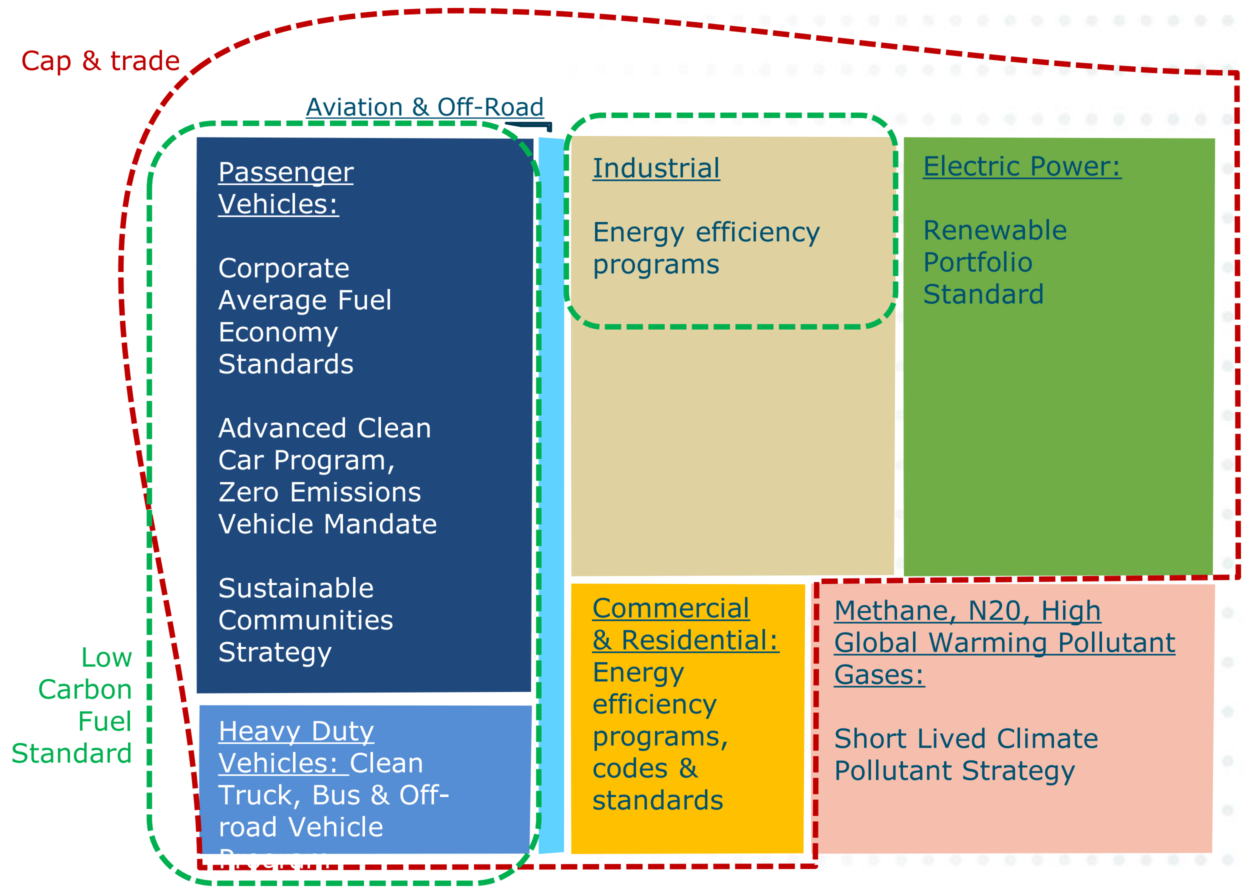
PATHWAYS modeling framework



How does PATHWAYS reflect the impact of policies and Cap and Trade?

- **The impacts of Cap and Trade depend on carbon price and program details still to be determined and is not explicitly modeled in these scenarios. Carbon pricing will help to reduce the cost differential between fossil fuels and lower-emissions alternatives**
- **Carbon pricing may help to speed adoption of key techs by closing the fuel cost gap for:**
  - Electric vehicles
  - Heat pumps
  - Industrial efficiency
  - Other market innovations, hard to predict
- **Additional market transformation may be needed to overcome upfront capital cost barriers and other market failures, i.e. improve customer awareness & contractor experience**

California GHG Emissions by sector (2015)



Scale based on California GHG Inventory for 2015 Tree Map: https://www.arb.ca.gov/cc/inventory/data/graph/treemap/scopingplan_2000-15.htm

PATHWAYS model enhancements

+ **Inclusion of climate impacts on electricity system**
  - Warmer temperatures: reduction in building space heating & increase in space cooling by 2050 (varies by climate zone and sector, magnitudes range from 10 to 60%)
  - 11% reduction in hydroelectric generation output by 2050 relative to historical average
  - Reduced efficiency of thermal power plants tested as a sensitivity
+ **Biofuel supply curves**
  - Option to remove out-of-state biomass and/or purpose-grown crops from biomass supply
  - Updated biofuel resource potential in California to include better resolution on landfill gas, manure, and municipal solid waste biogas feedstocks based on research from UCD (Jaffe)
  - Optimization of biofuel selection
  - Updated process costs, conversion efficiencies, transportation/delivery costs
+ **Benchmarked to least-cost electricity system capacity expansion based on results from RESOLVE model runs**
  - Lower in-state wind resource potential estimates based on updated information about environmental exclusions
+ **Updated performance and capital cost assumptions for advanced trucks, heat pumps, renewable energy technologies**

How does PATHWAYS measure costs?

Included:

+ **Annualized incremental cost of energy infrastructure**
  - Transportation: light-, medium- & heavy duty vehicles
  - Building end uses: lighting, water heaters, space heaters, etc.
  - Industrial equipment
  - Electricity production: revenue requirement of all electric assets
+ **Annual fuel & avoided fuel cost**
  - Electricity, hydrogen, gasoline, diesel, natural gas, biofuel
+ **Net present value of climate benefits of GHG mitigation are reported separately**

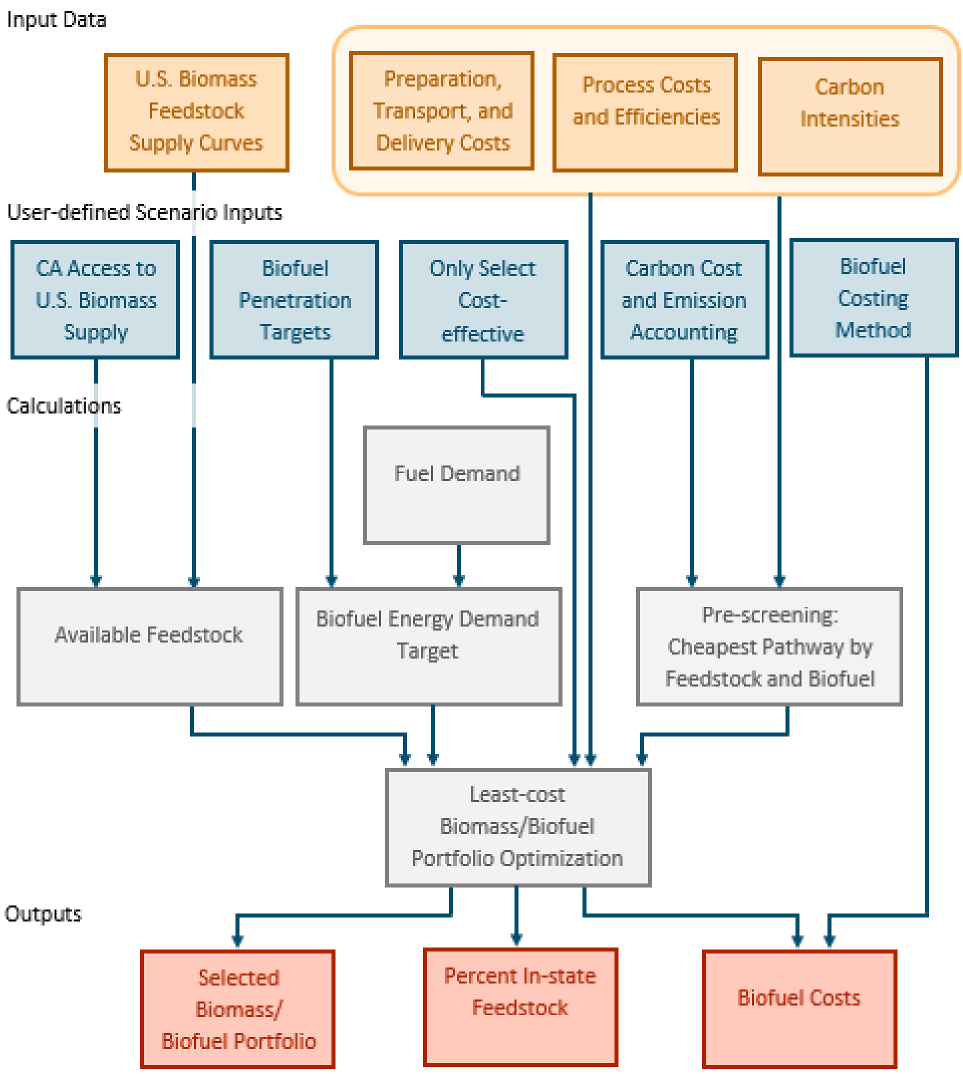
Excluded:

+ **Macroeconomic impacts**
  - Changes in the costs of goods and services, jobs, structural changes to economy
  - Price response of customers to changing fuel prices
  - Cap and trade is not explicitly modeled
+ **Health benefits of reduced criteria pollutants**

Note: Costs are reported in 2016$ unless otherwise noted.

Biofuels Module

- Starts with DOE BTS (2011), supplemented with ARB and UC Davis (2016)
- User-defined final demands by sector (including electricity as an option, though not selected in Base Mitigation case)
- Least-cost portfolio optimization over feedstocks and conversion pathways
- Feedstock limited granularly to % of US share for both in-state and out-of-state
- Average or marginal (market-based) costs



Conversion pathways

- **Generally preferred pathways with base assumptions:**

1. **Anaerobic digestion of biogas feedstocks (landfill gas, manure)**
2. **Hydrolysis of cellulose for renewable ethanol**
3. **Gasification of wood to biogas**
4. **Pyrolysis of remaining wood and cellulose to diesel or jet fuel**

Feedstock Conversion Category	Biofuel Process	Biofuel
Cellulosic	Pyrolysis (thermochemical)	Renewable Diesel
		Renewable Gasoline
		Renewable Jet Fuel
	Hydrolysis (hydrotreating)	**Renewable Ethanol**
Woody Cellulosic	Pyrolysis (thermochemical)	Renewable Diesel
		Renewable Gasoline
		Renewable Jet Fuel
	Hydrolysis (hydrotreating)	**Renewable Ethanol**
	Gasification	**Biomethane**
Lipid	Hydrolysis (hydrotreating)	Renewable Diesel
	FAME	Biodiesel
Manure	Anaerobic Digestion	Biomethane
Landfill Gas	**Anaerobic Digestion**	**Biomethane**
Municipal Solid Waste	Gasification	Biomethane
Starch	Fermentation	Conventional Ethanol

Energy+Environmental Economics

Thank You!