Energy+Environmental Economics

Achieving Carbon Neutrality in California Report

Final Presentation

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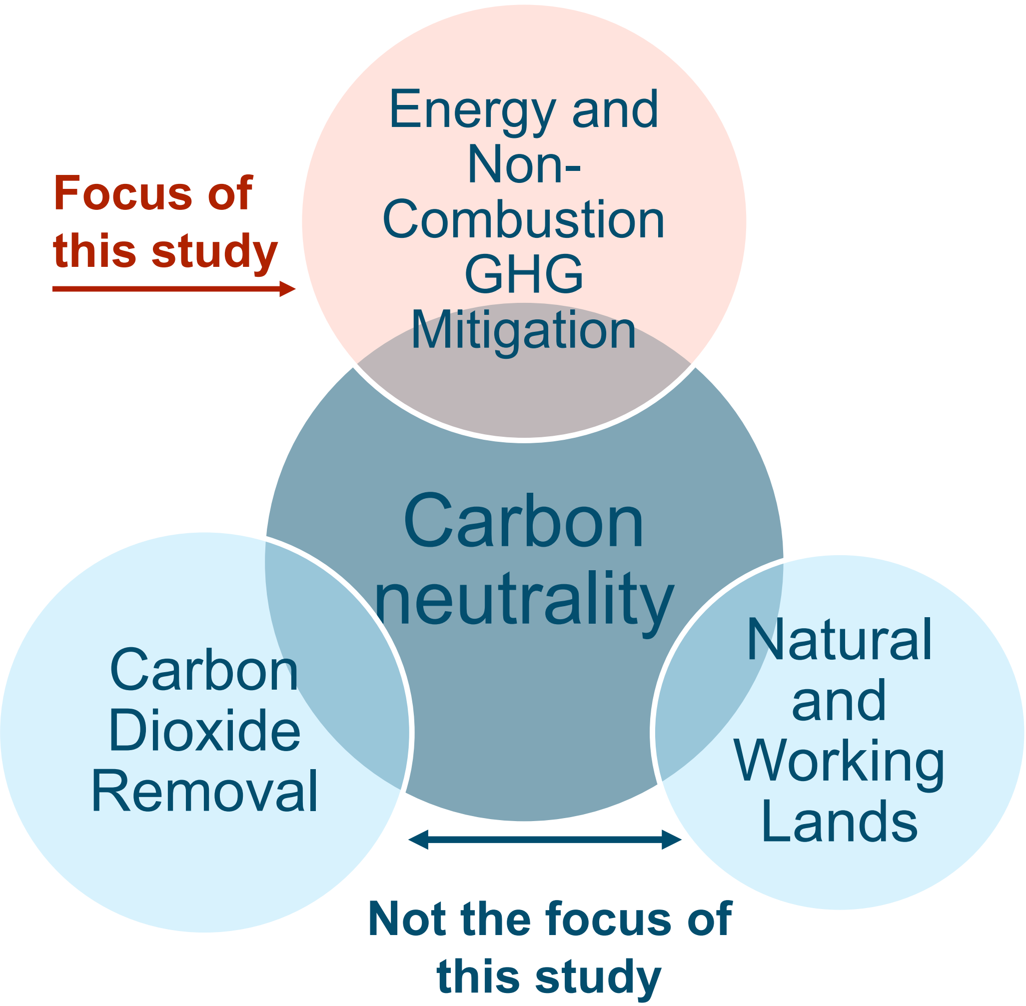
Outline

- Study purpose and background
- Scenarios
- Key findings
- Next steps

- Appendix
  - sector-by-sector assumptions & results

Study purpose and background

- Executive Order B-55-18: **carbon neutrality by 2045**
- This study examines potential **energy system and technology transformations** to achieve carbon neutrality

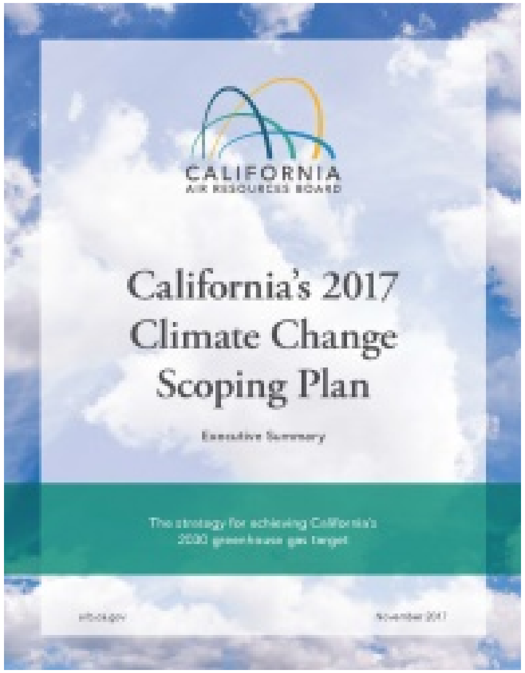


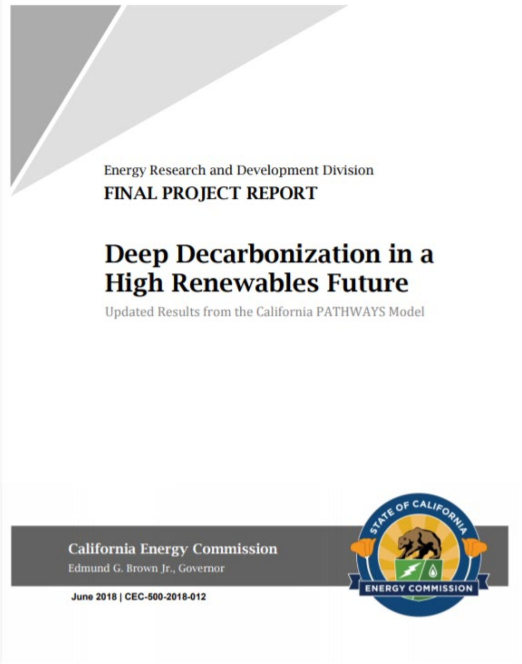
Key questions

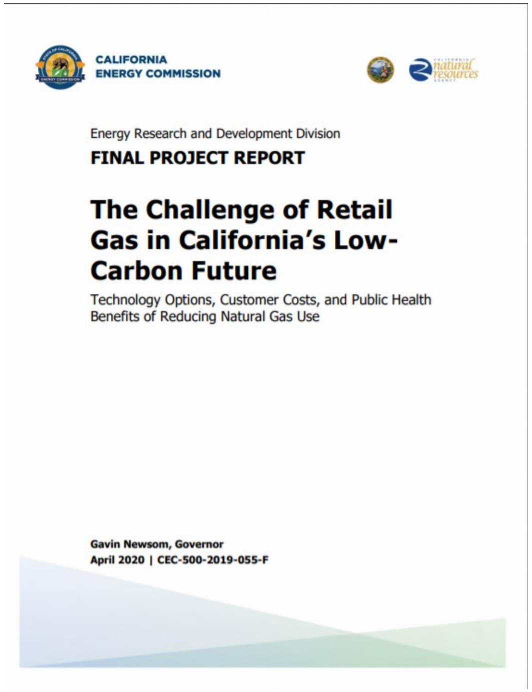
1. What are the available energy and non-combustion GHG mitigation strategies to help achieve carbon neutrality by 2045?
2. How should California consider the tradeoffs between achieving additional energy-sector greenhouse gas reductions, versus relying on carbon dioxide removal?
3. How do different mitigation strategies compare on the basis of fuel combustion (implying air quality and health impacts), climate change mitigation risk, and technology adoption and implementation risk?
4. What are least regrets strategies that are likely to be indispensable in working towards carbon neutrality?

Project Context

+ **Carbon neutrality study builds on a literature review of deep decarbonization studies in the U.S. and Europe, and prior E3 research into decarbonization strategies in California, using the PATHWAYS model**

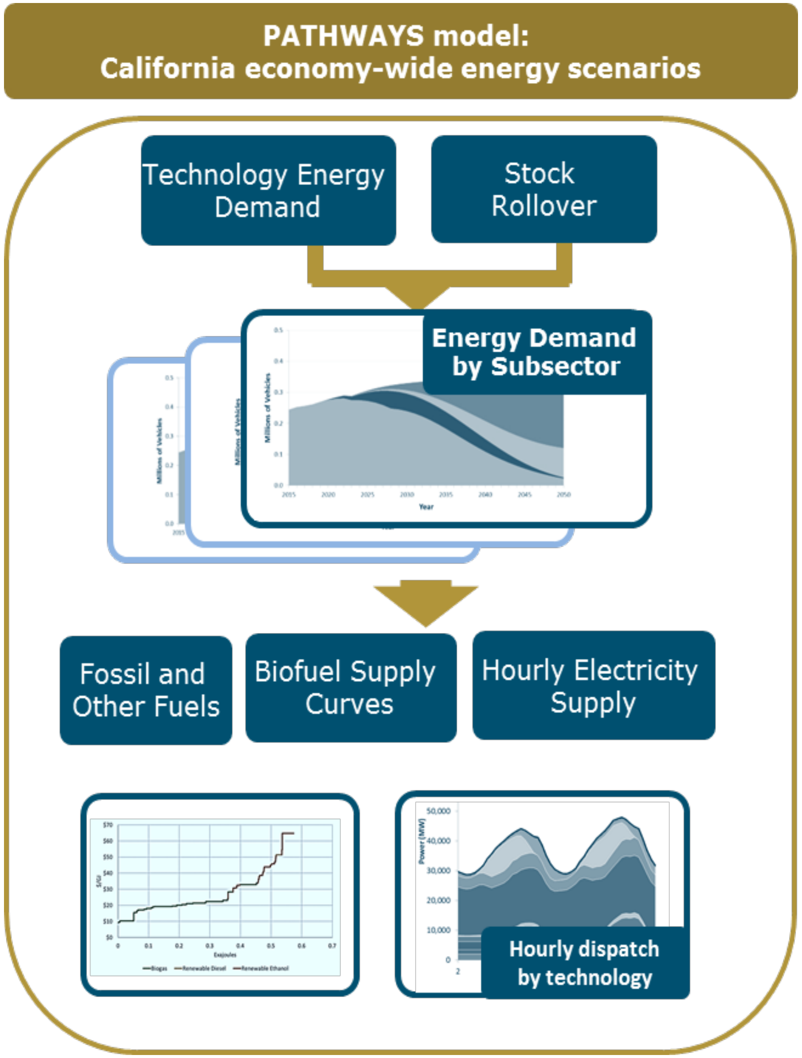






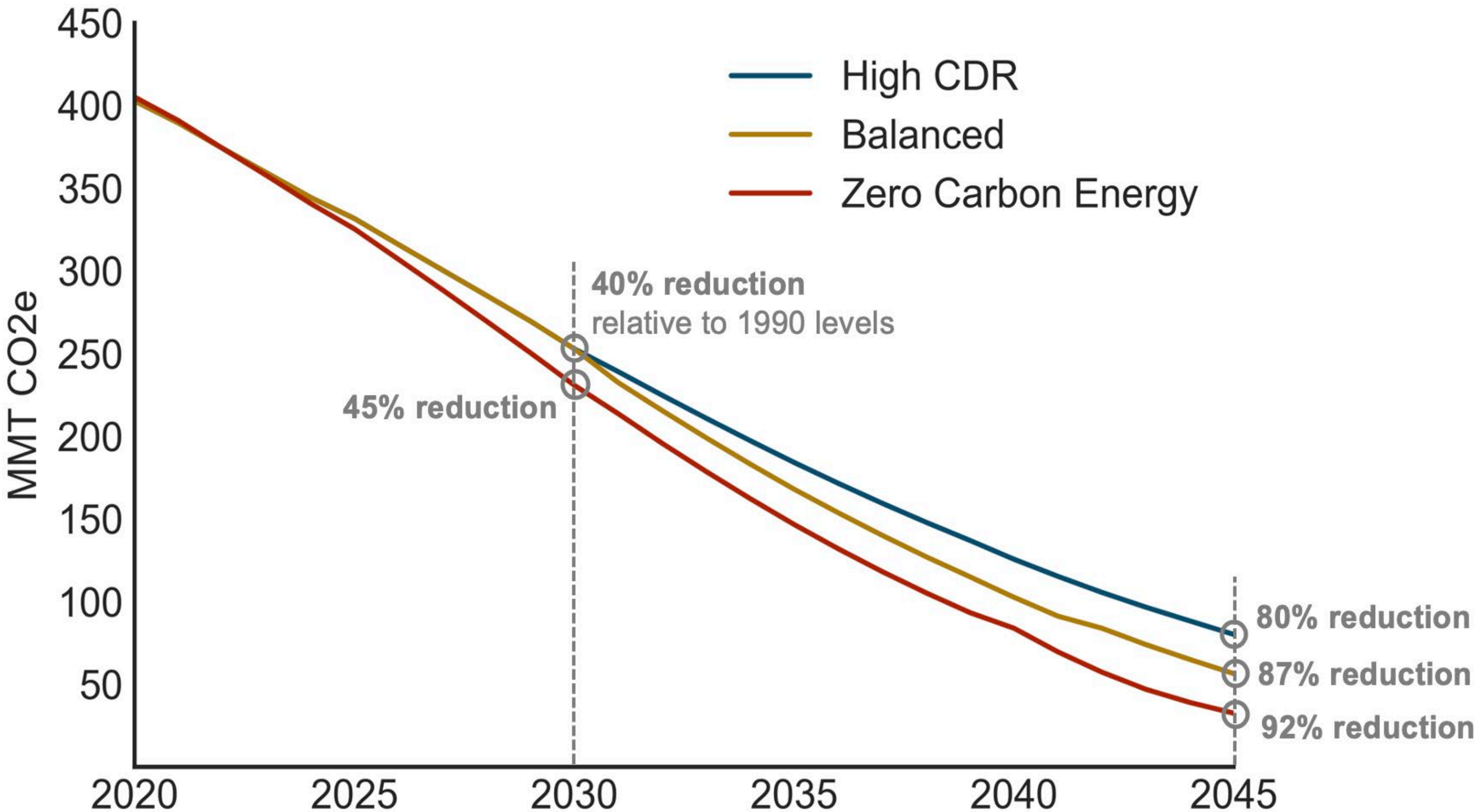
About the PATHWAYS model

+ Covers California, economy-wide energy consumption and non-energy GHG emissions based on the CARB AB 32 Annual GHG Inventory
+ Stock-roll over treatment of building equipment and vehicles in transportation provides realistic timeframes for technology adoption
+ Biofuels, hydrogen, synthetic fuels, electricity sector representations reflect potential abatement opportunities from energy supply options



Three Scenarios

+ Scenarios examine **80% to 92% reductions in direct emissions** (energy and non-combustion GHGs) by 2045, using a "high electrification" scenario as the starting point for each

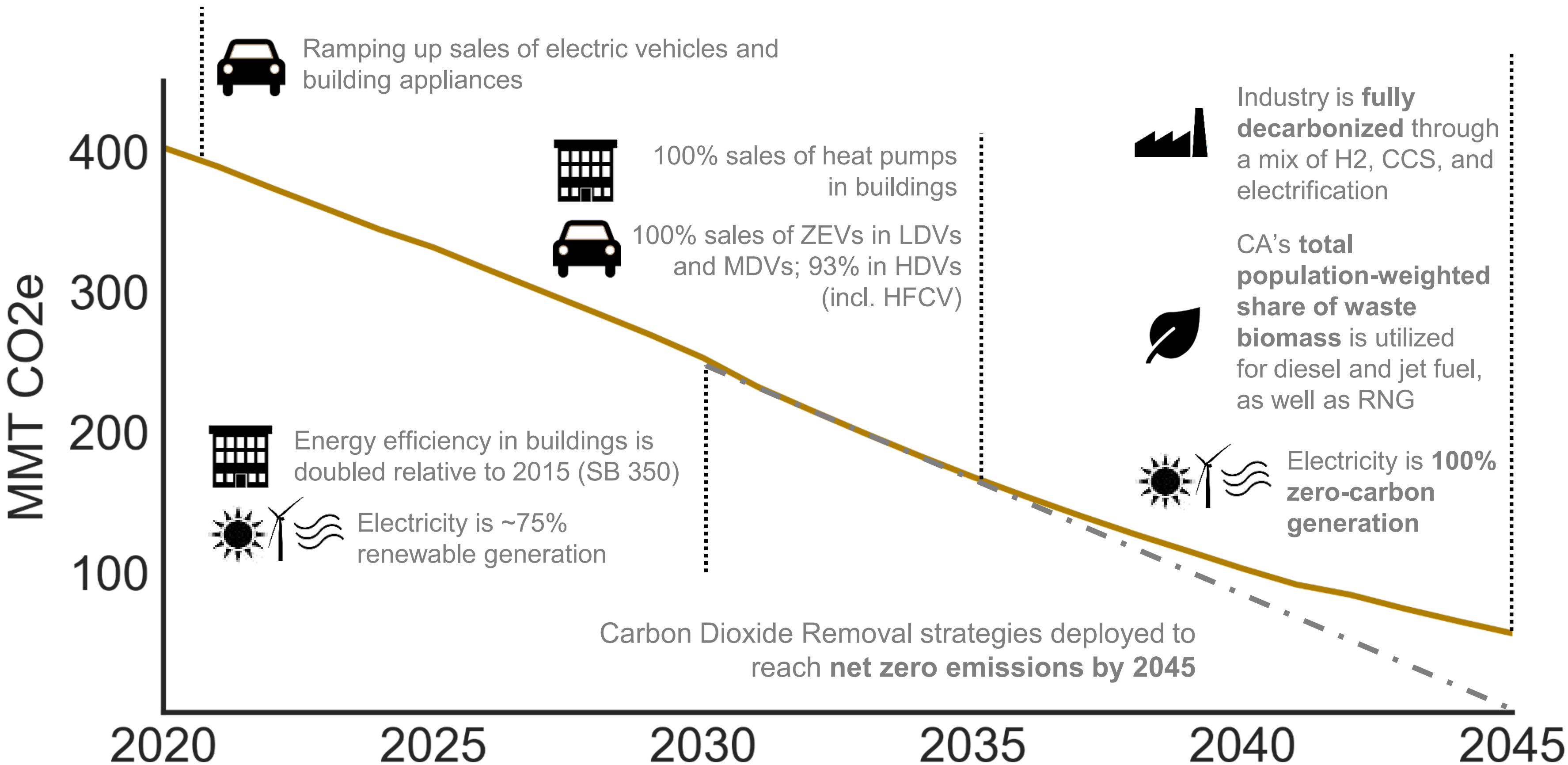


Scenario Descriptions

+ **"High Carbon Dioxide Removal (CDR)" scenario:** broad range of deep decarbonization strategies, similar to E3's prior "high electrification" scenario, including energy efficiency, electrification, low-carbon fuels, zero-carbon electricity, and reductions in non-energy GHG emissions. ***Highest reliance on CDR of all three scenarios.***
+ **"Zero-Carbon Energy" scenario:** similar set of decarbonization strategies as the High CDR scenario but electrification is deployed ***earlier*** and ***more completely***. Emerging emission reduction technologies, including synthetic natural gas in the gas pipeline, electric aviation, and fuel-cell trains in off-road transportation ***eliminate all fossil fuel emissions by 2045***.
+ **"Balanced" scenario:** less reliance on CDR compared to the High CDR scenario; slower electrification and less reliance on emerging emission reductions technologies included in the Zero-Carbon Energy scenario, i.e. less electric aviation and hydrogen fuel-cell trains. ***Intermediate direct GHG reductions between other two scenarios.***

Balanced Scenario: Key Assumptions

+ The “Balanced” scenario includes widespread efficiency and electrification paired with zero-carbon electricity, as well as zero-carbon fuels for hard-to-decarbonize sectors



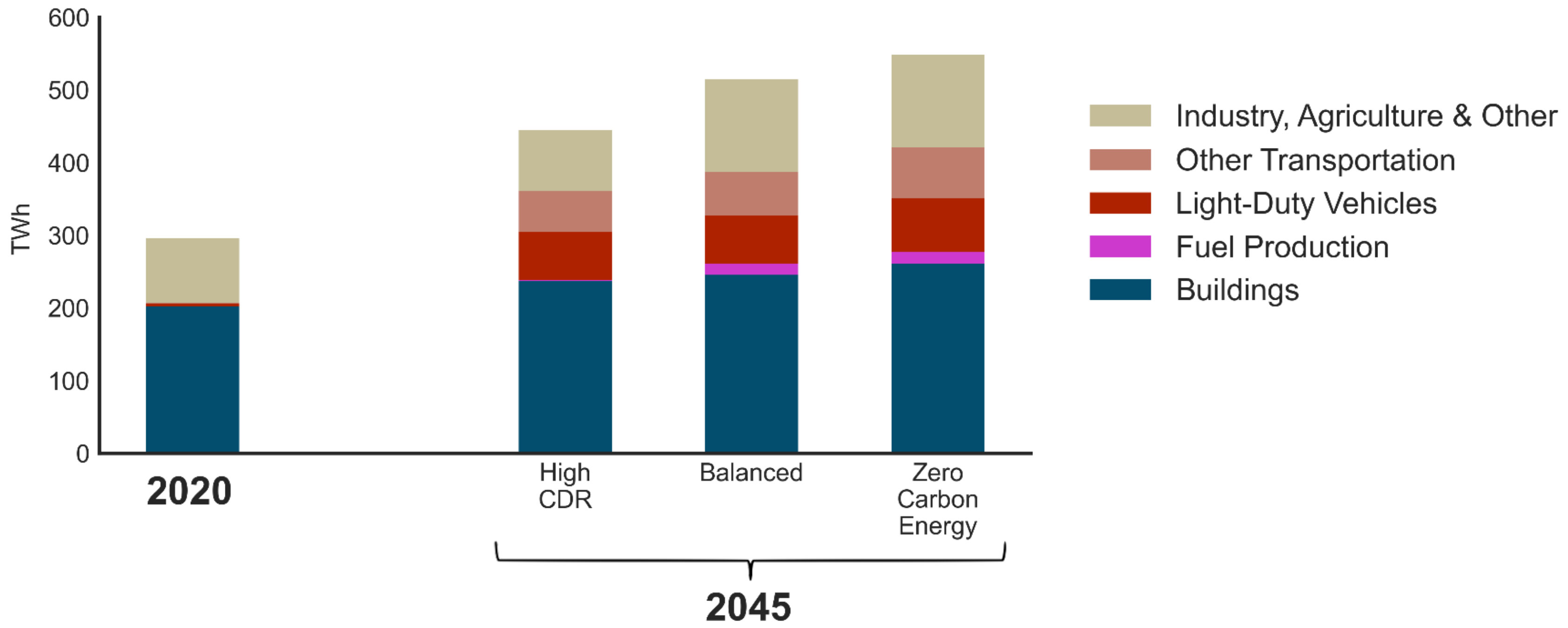
Scenario Details

Sector	High CDR	Balanced	Zero Carbon Energy
Low-Carbon Fuels	*All scenarios utilize CA's **full population-weighted share of US waste biomass** to produce liquid and gaseous biofuels, plus **5% electrolytic H2 blend** in pipeline*		
	No additional H2	Widespread use of **H2 in industry and HDV trucks**	Widespread use of **H2 in industry and HDV trucks**
Buildings	*All scenarios achieve **SB 350 doubling of additional achievable energy efficiency by 2030** (Scoping Plan interpretation): 46 TWh of electric EE in 2030 relative to 2015; 67 TWh in 2045*		
	100% sales of all-electric appliances in buildings **by 2040**	**100% sales** of all-electric appliances in buildings **by 2035**	**100% sales** of all-electric appliances in buildings **by 2030,** with **gas distribution grid retirement** in **2045**
Transportation	**100% LDV ZEV** sales by 2035; **100% MDV ZEV** sales by 2040; **45% HDV ZEV** sales by 2035	**100% LDV ZEV** sales by 2035; **100% MDV ZEV** sales by 2035; **93% HDV ZEV** sales by 2035	**100% LDV ZEV** sales by 2030; **100% MDV ZEV** sales by 2030; **100% HDV ZEV** sales by 2030
Industry and Agriculture	High industry EE; **Minimal** industry decarbonization; 90% reduction in O&G emissions	High industry EE; **High** industry decarbonization (H2+CCS+electrification); 90% reduction in O&G emissions	High industry EE; **High** industry decarbonization (H2+CCS+electrification); **100%** reduction in O&G emissions
Electricity	**95% zero carbon** electricity	**100% zero carbon** electricity (~5% firm dispatchable generation provided by zero carbon fuels)	**100% zero carbon** electricity (~5% firm dispatchable generation provided by zero carbon fuels)
High GWP and Non-Combustion	***~50% reduction** in high GWP and non-energy emissions relative to 2020 (~33 MMT remaining in 2045)*		

Electric Loads: Scenario Comparison

- Electric loads increase by 50-90% relative to today by 2045
- Loads for direct air capture (up to ~50-100 TWh) and hydrogen production to serve industry (~90 TWh in Balanced and ZCE scenarios) are assumed to be provided by off-grid renewables, and are not included in this graphic

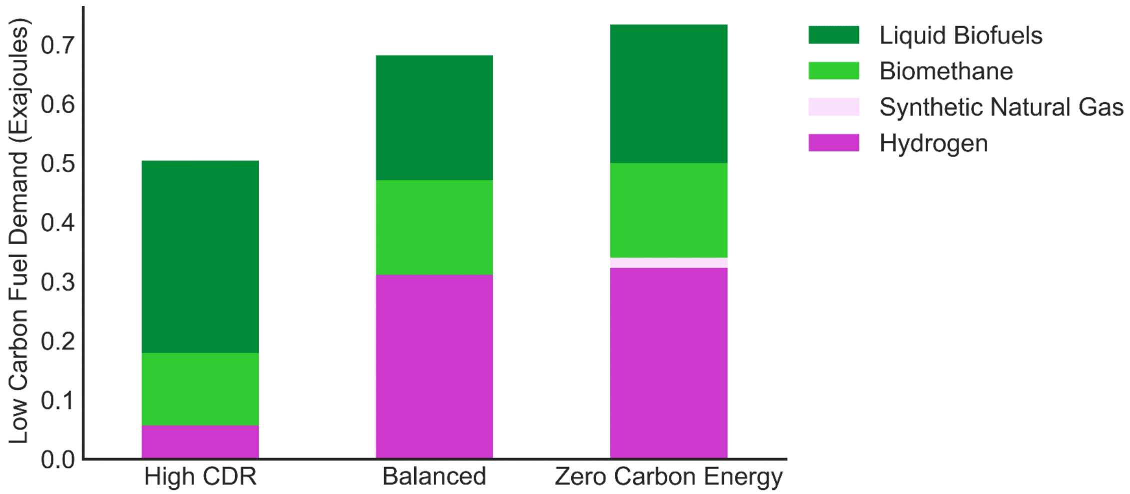
Electric loads by category: today, and in 2045 across scenarios



Low-Carbon Fuels: Scenario Comparison

+ All scenarios assume similar **total quantity of waste & residues biomass for biofuels**, based on CA's population-weighted share of waste biomass
+ All scenarios include hydrogen, Balanced and Zero Carbon Energy scenarios assume **widespread use of hydrogen** in HDV trucks & industry

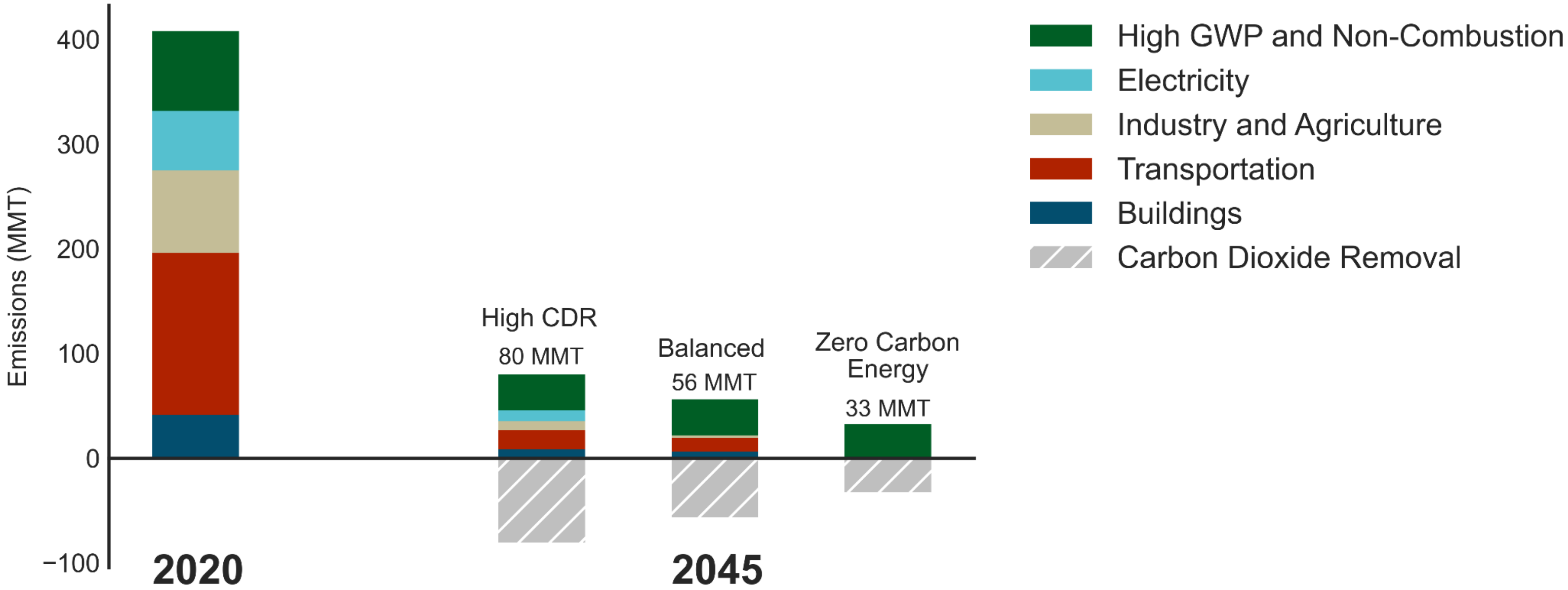
Low Carbon Fuel Demand by Scenario in 2045



GHG Emissions: Scenario Comparison

+ **Largest source of remaining GHG emissions in all scenarios is from high global warming potential gases (GWP), e.g. fluorinated refrigerant gases and non-combustion emissions, e.g. fugitive methane from agriculture**

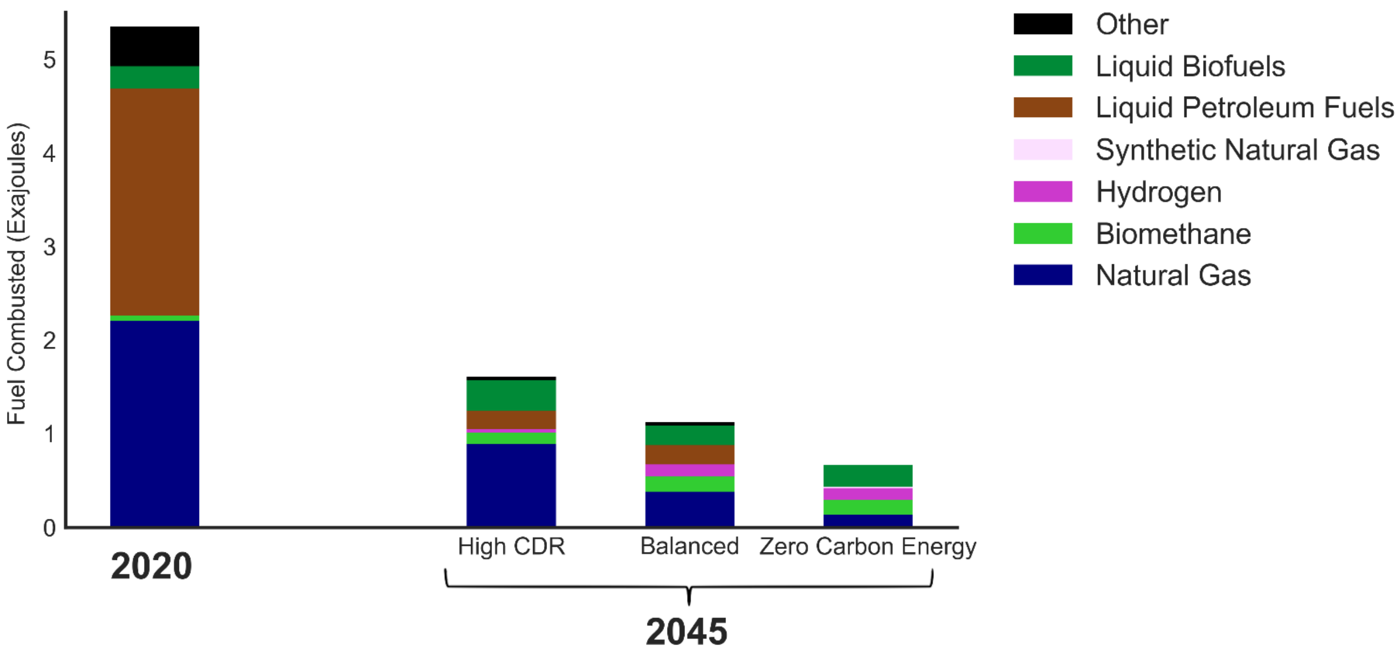
AB 32 emissions: today, and in 2045 across the three scenarios



Scenario comparison: air quality and human health

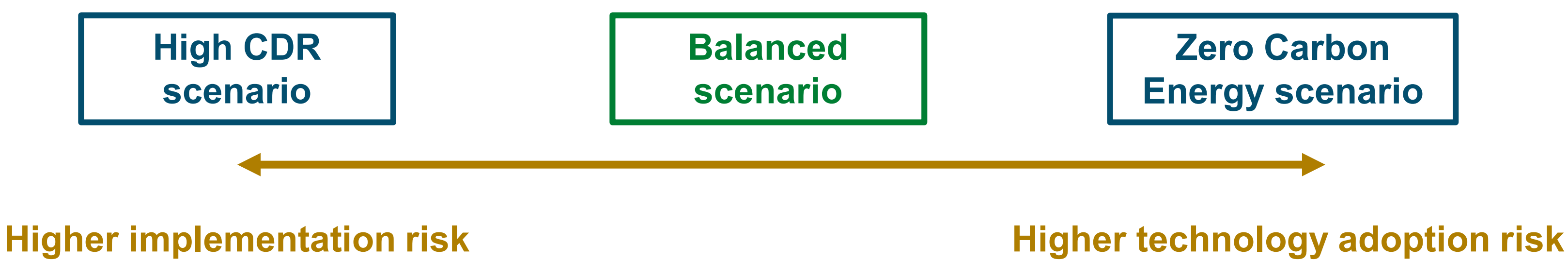
- **All scenarios include a significant reduction in fuel combustion relative to today, implying potential co-benefits for air quality and human health could be significant**
- **This study does not perform a detailed air quality analysis, but rather uses total statewide fuel combustion as a proxy for potential human health impacts**
  - High CDR scenario has the highest relative risk for air quality and human health (although air quality would be significantly improved relative to today), while Zero Carbon Energy is the lowest risk. Fossil fuels in the Zero Carbon Energy scenario are associated with Carbon Capture and Sequestration.

Total statewide fuel combustion: today, and in 2045 across scenarios



Scenario comparison: technology adoption and implementation risk

- **All scenarios involve risk trade-offs in the categories of technology adoption risk and implementation risk**
  - Technology adoption risk includes the risk that consumers will be able to feasibly transition to buying electric technologies by a certain timeline
  - Implementation risk includes the risk that certain technologies will be commercialized and cost-effective by 2045, such as hydrogen and biofuel production
- **The balanced scenario represents the lowest risk scenario in both of these categories, by minimizing reliance on non-commercialized technologies such as CDR, while also minimizing the technology adoption risk of rapidly transitioning to all-electric technologies**

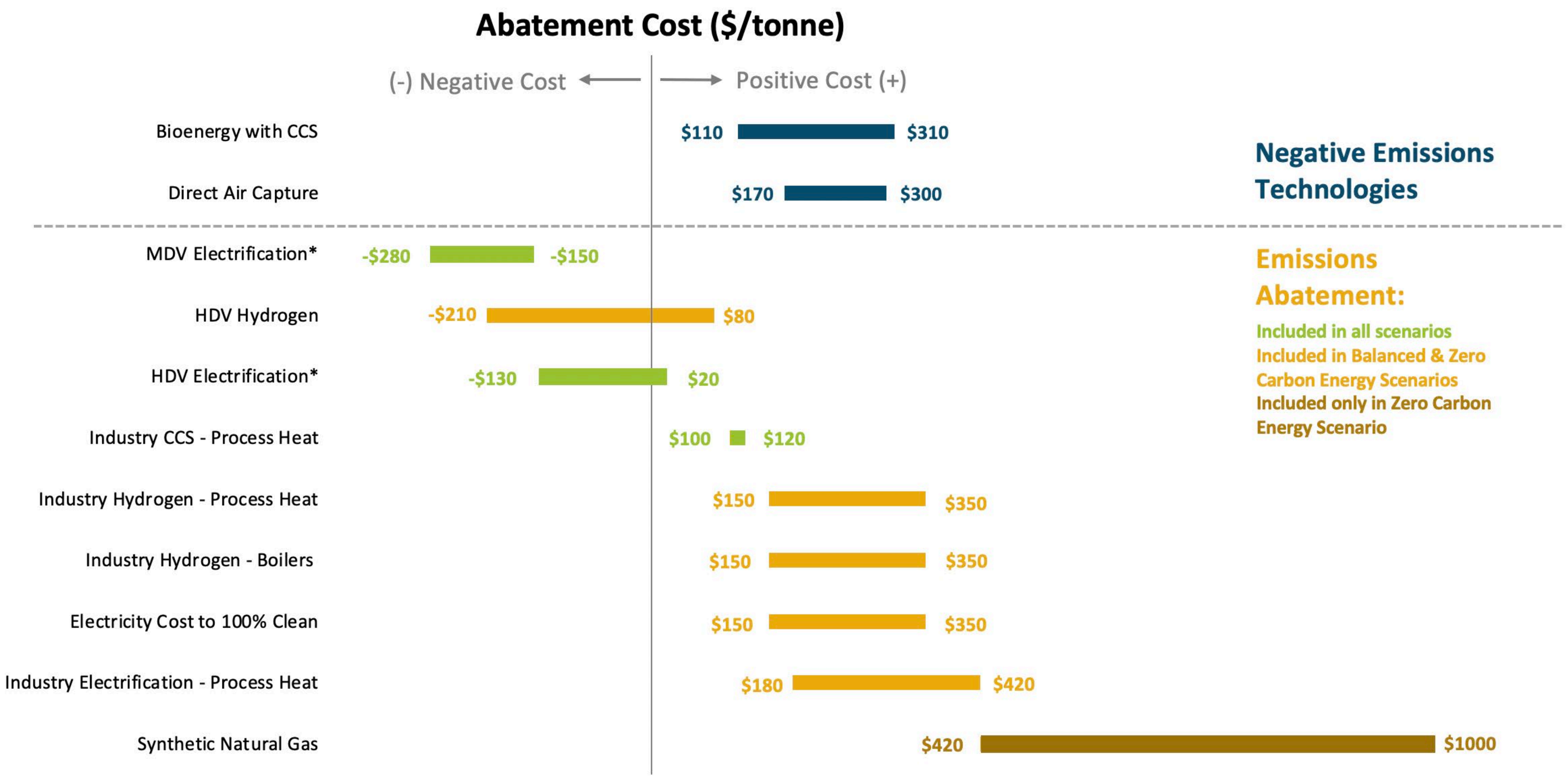


Scenario risk framework

+ **"Balanced" scenario falls between the other two scenarios across key risk categories**

Cost comparison:
Estimated 2045 $/metric ton of CO2e abatement

+ **Cost difference between scenarios is uncertain**



*Included in lower penetrations in the High CDR scenario than in other scenarios.

Key findings

+ **Least-regrets strategies** for getting to carbon neutral include:
  - **Energy efficiency in buildings, industry, and agriculture**
  - **Widespread transportation and building electrification**
  - **Zero-carbon electricity**
  - **Investment in zero-carbon fuel options for hard-to-decarbonize sectors where electrification is not practical**
  - **Pursuing reductions in non-combustion emissions**
  - **Investment and research into carbon dioxide removal (CDR) technologies**

Next steps

- **Receive comments on draft report & finalize report for consideration by CARB**
- **Areas for further study include:**
  - **Maximizing co-benefits** for heavily burdened communities with respect to environmental justice issues and equity;
  - **The impact of large infrastructure development** associated with renewable energy development, hydrogen production, and/or DAC with CCS on land use compared to the use of natural and working lands as a carbon sink;
  - **A better understanding of the adoption challenges** that vehicle and building electrification strategies might face as well as the practical infrastructure rollout needed, e.g. distribution and transmission upgrades to match growth in electric loads
  - **Strategies to incentivize the development of advanced mitigation strategies,** in particular low carbon fuel production, CCS, and NETs and to bring down their costs

Workshop Materials

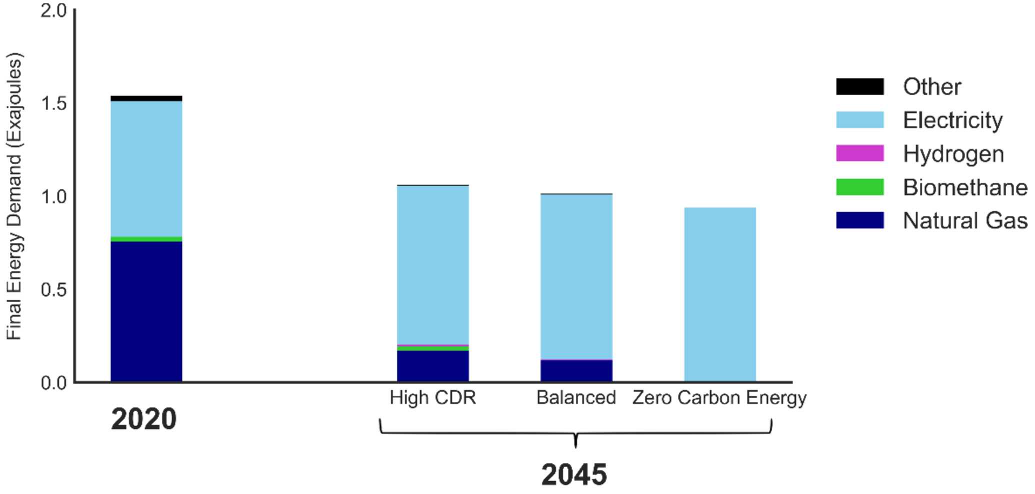
- **Link to view workshop materials from the August 19, 2020 Public Workshop to Discuss Achieving Carbon Neutrality in California**
  - Presentations, final report, cost supplement data spreadsheet, webinar recording, and informal comments submitted on draft report are available:
- https://ww2.arb.ca.gov/our-work/programs/carbon-neutrality/carbon-neutrality-meetings-workshops

Appendix: Additional Slides

Buildings

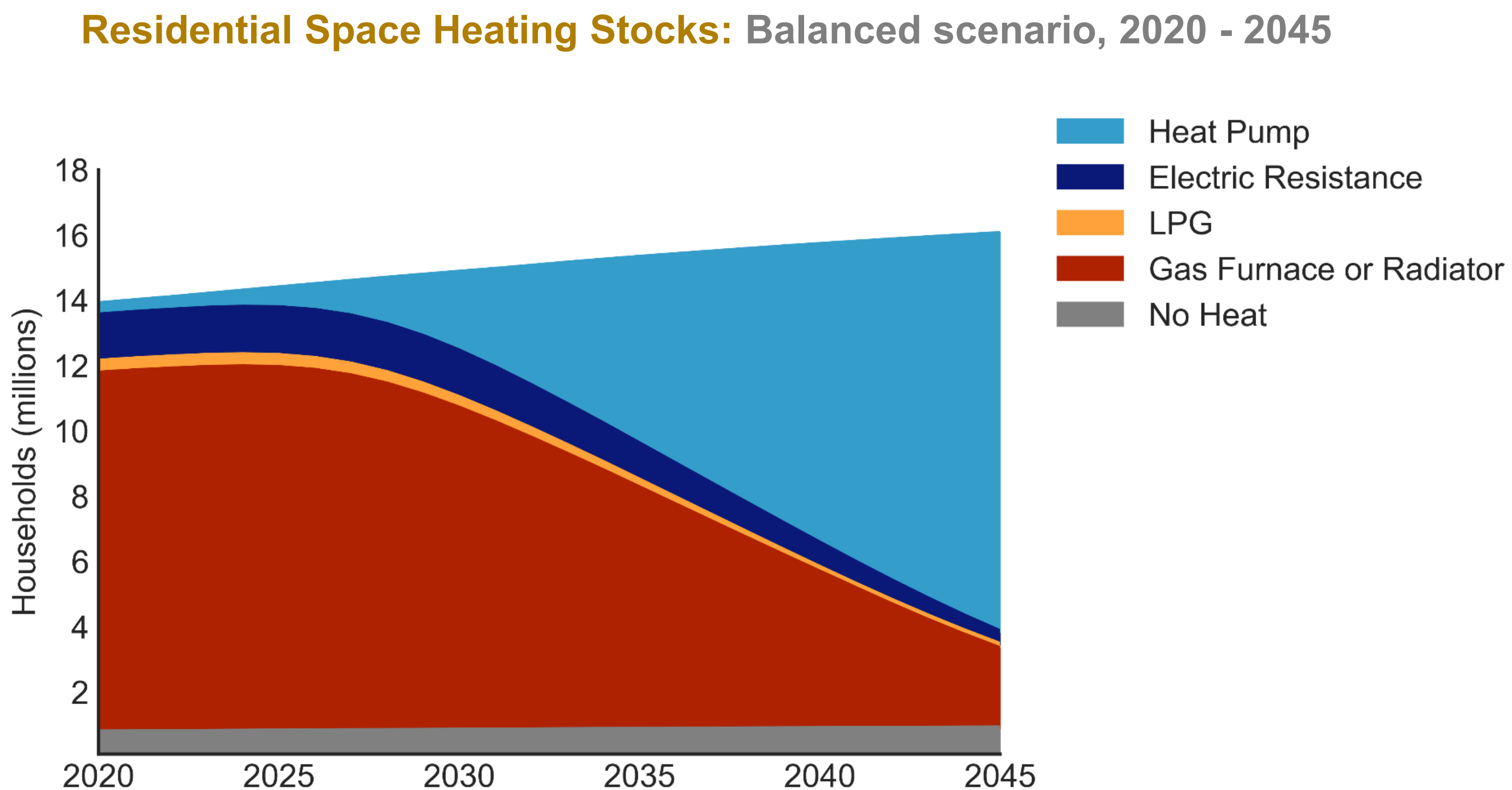
- All scenarios employ **high levels of efficiency and a transition to 100% all-electric buildings**, with the date of 100% electric appliance sales varying by scenario
- Significant reduction in final energy demand occurs mainly due to the **3-4x efficiency gain** from heat pumps

Final energy demand in buildings: today, and in 2045 across scenarios



High CDR	Balanced	Zero Carbon Energy
100% sales of all-electric appliances by **2040**	**100% sales** of all-electric appliances by **2035**	**100% sales** of all-electric appliances by **2030**; with **gas distribution grid retirement** in **2045**

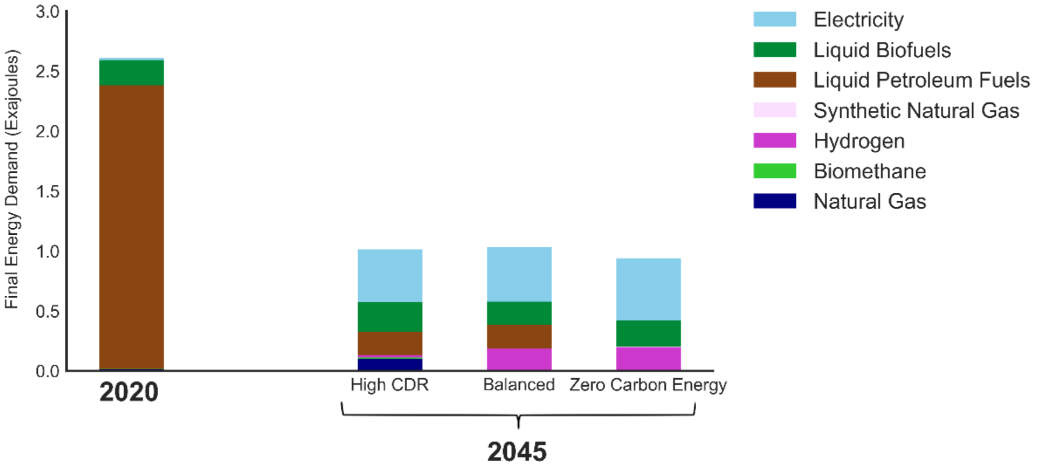
Residential Space Heating: Balanced Scenario



Transportation

- All scenarios employ **significant VMT reductions and a widespread transition to zero-emission vehicles**, with the level of ambition varying by scenario
- Significant reduction in final energy demand occurs mainly due to the **2-3x efficiency gain** from electric drivetrains

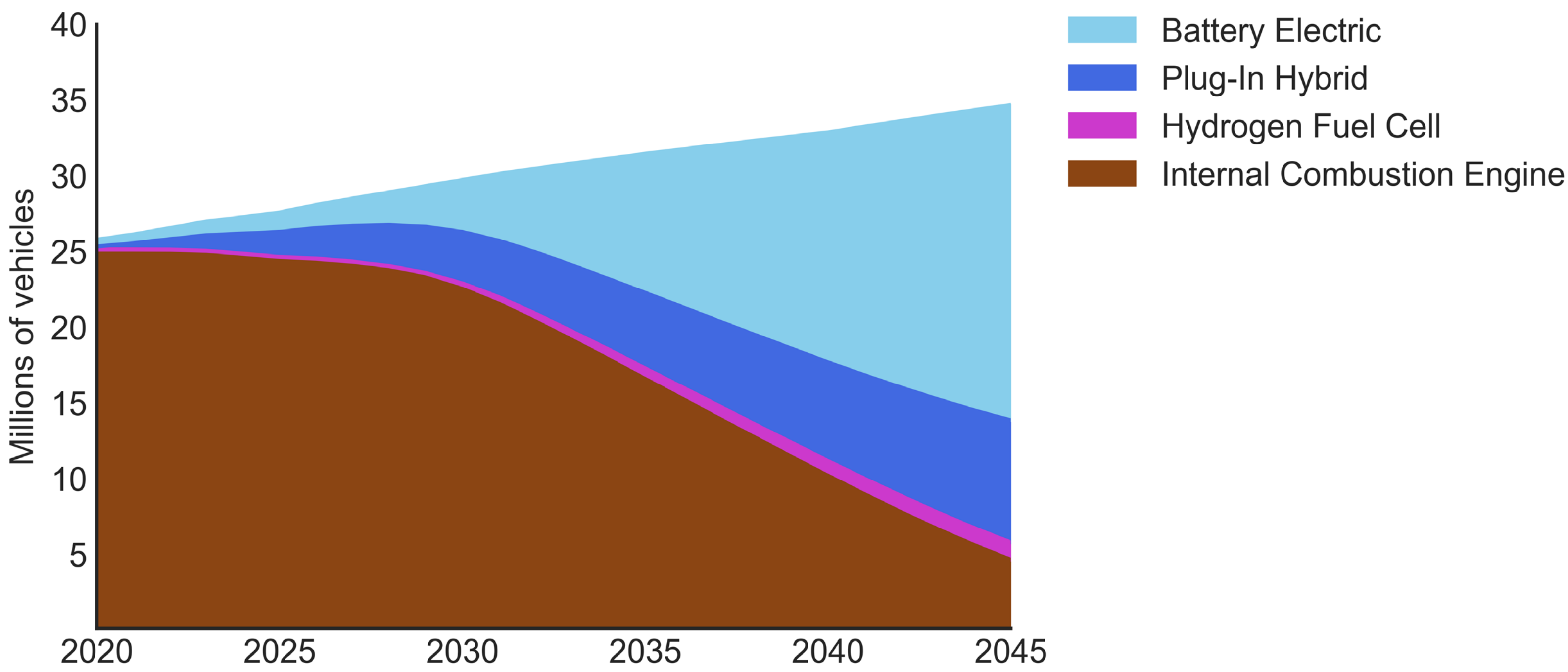
Final energy demand in transportation: today, and in 2045 across scenarios



High CDR	Balanced	Zero Carbon Energy
100% LDV ZEV sales by 2035; **100% MDV ZEV** sales by 2040; **45% HDV ZEV** sales by 2035	**100% LDV ZEV** sales by 2035; **100% MDV ZEV** sales by 2035; **93% HDV ZEV** sales by 2035 (**50/50 H2/BEV**)	**100% LDV ZEV** sales by 2030; **100% MDV ZEV** sales by 2030; **100% HDV ZEV** sales by 2030 (**50/50 H2/BEV**)

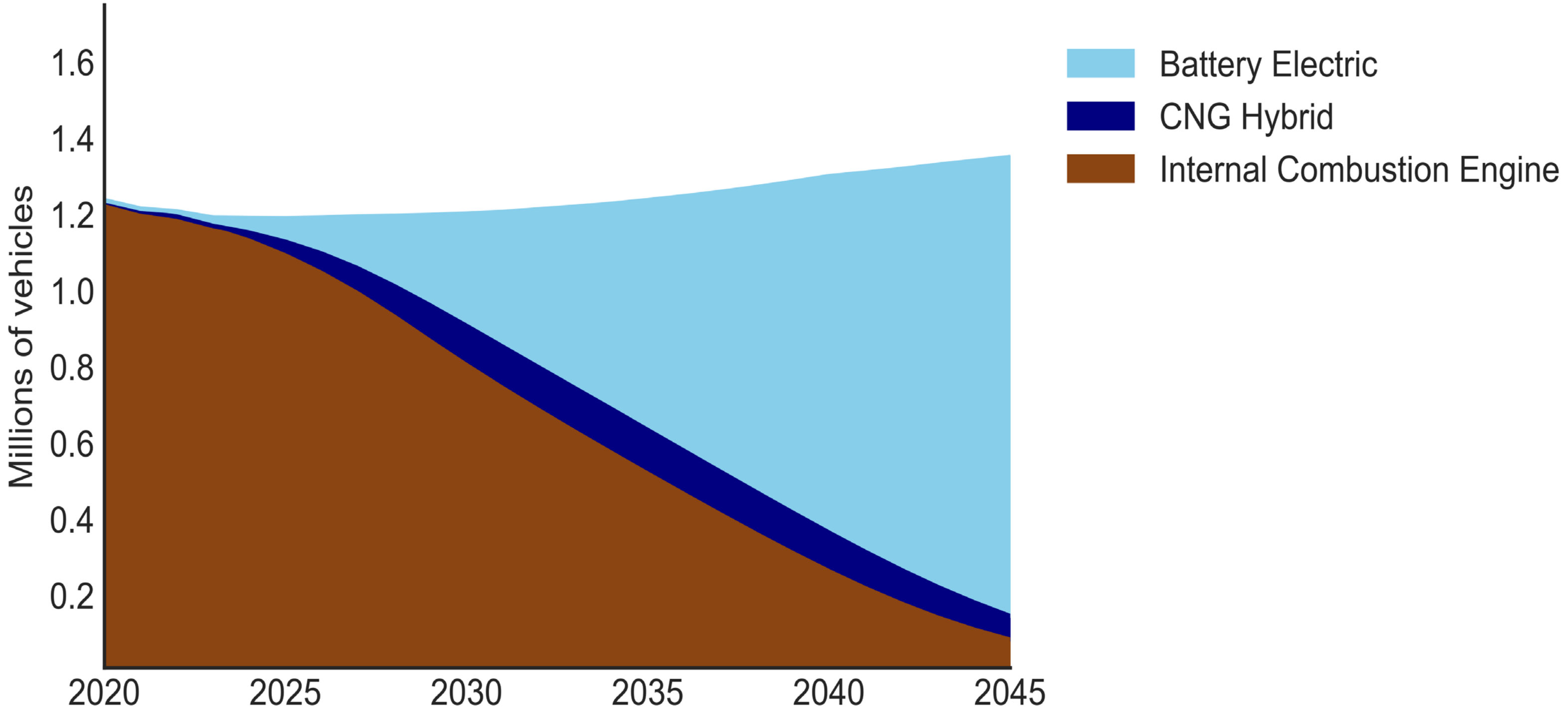
Light Duty Vehicles: Balanced Scenario

Light Duty Vehicle Stocks (Millions): Balanced scenario, 2020 - 2045



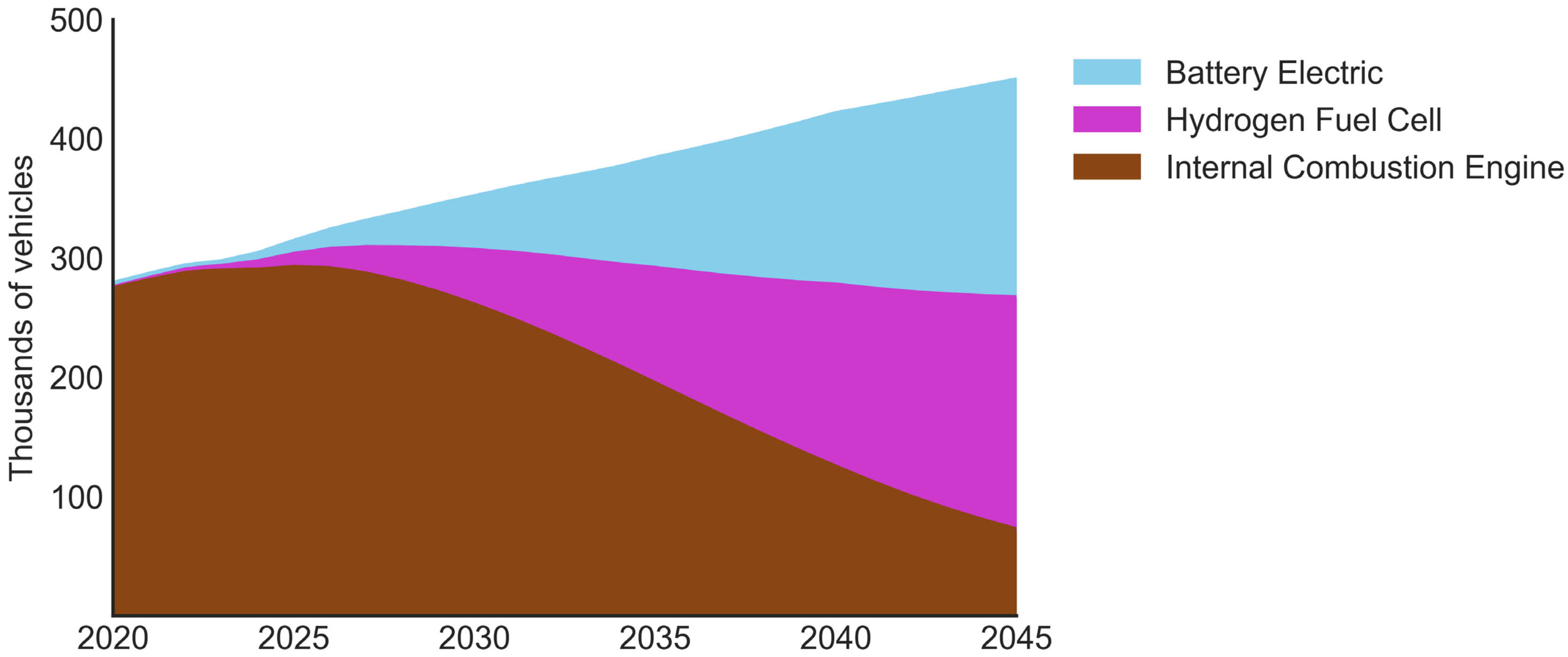
Medium Duty Vehicles: Balanced Scenario

Medium Duty Vehicle Stocks (Millions): Balanced scenario, 2020 - 2045



Heavy Duty Vehicles: Balanced Scenario

Heavy Duty Vehicle Stocks (Thousands): Balanced scenario, 2020 - 2045



Industry and Agriculture

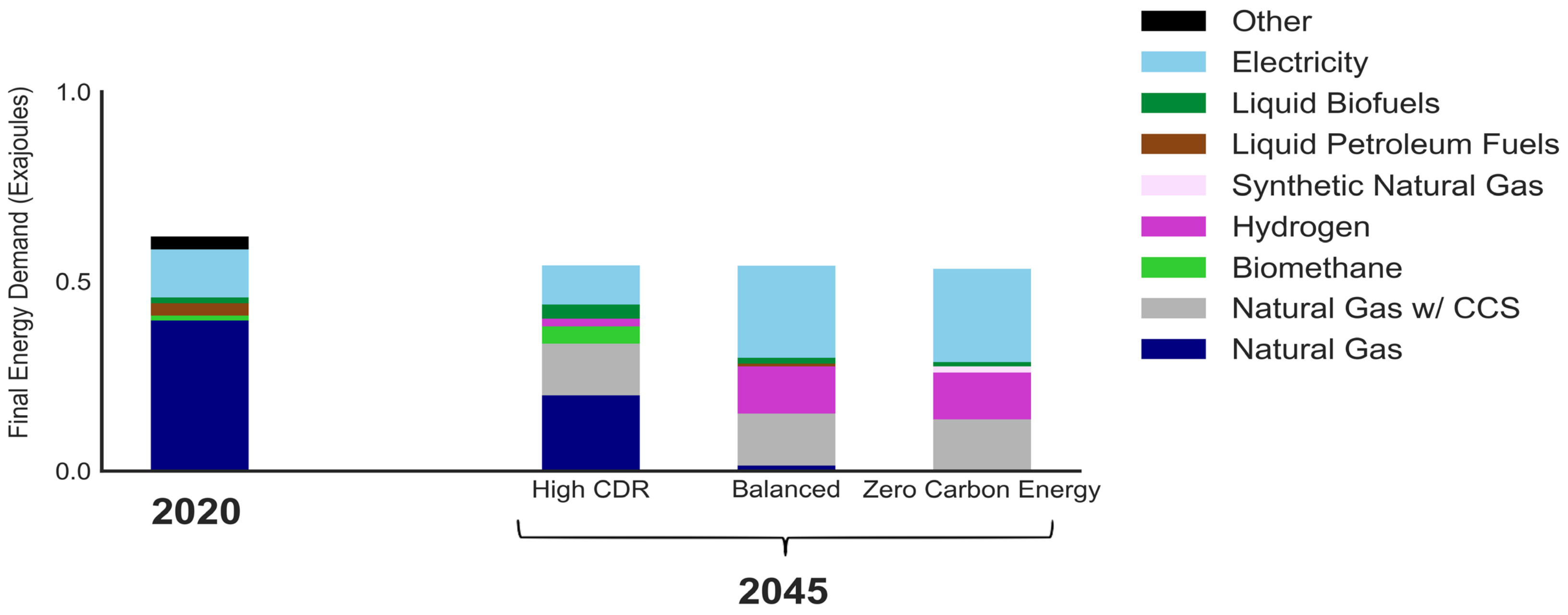
+ **All scenarios include high levels of EE in industry and a near to complete phase-out of oil & gas extraction and petroleum refining**
+ **High CDR scenario includes industrial CCS measures, while the other two scenarios assume full industry decarbonization via a variety of strategies:**
  - Electrification for low temperature heat
  - Hydrogen for medium temperature heat, including all boilers, assuming dedicated hydrogen pipelines delivering 100% blends
  - Natural gas with CCS for high temperature heat and non-combustion CO2 emissions, including cement production, glass and primary metals production

Decarbonization strategies assumed for industrial manufacturing, by end use
(percentages indicate share of final energy demand for each fuel)

End Use	Renewable Diesel	Natural Gas with CCS	Electricity	Hydrogen
Conventional Boiler Use	0%	0%	0%	100%
Lighting	0%	0%	100%	0%
HVAC	0%	0%	100%	0%
Machine Drive	0%	0%	100%	0%
Process Heating	0%	53%	47%	0%
Process Cooling & Refrigeration	0%	0%	100%	0%
Other	7%	31%	31%	31%

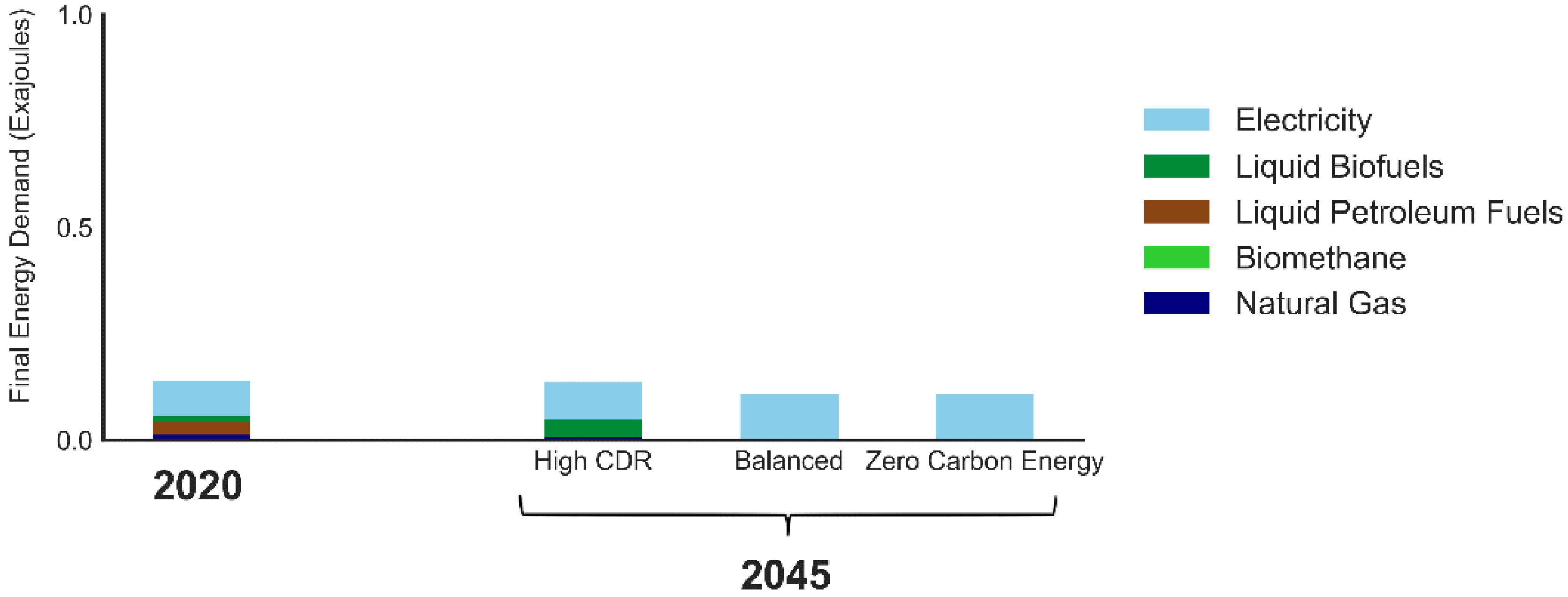
Industrial Manufacturing

Final energy demand in industrial manufacturing: today, and in 2045 across scenarios



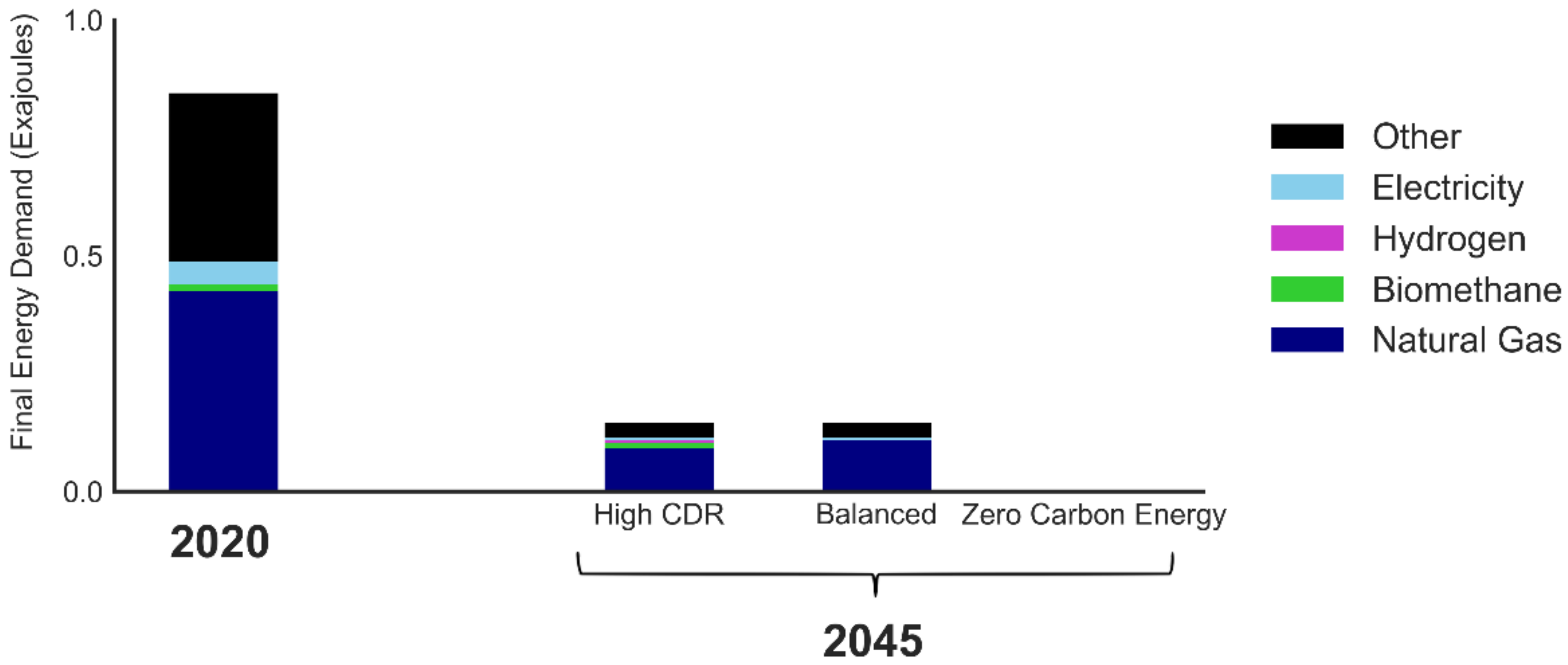
Agriculture

Final energy demand in agriculture: today, and in 2045 across scenarios



Oil & Gas Extraction & Petroleum Refining

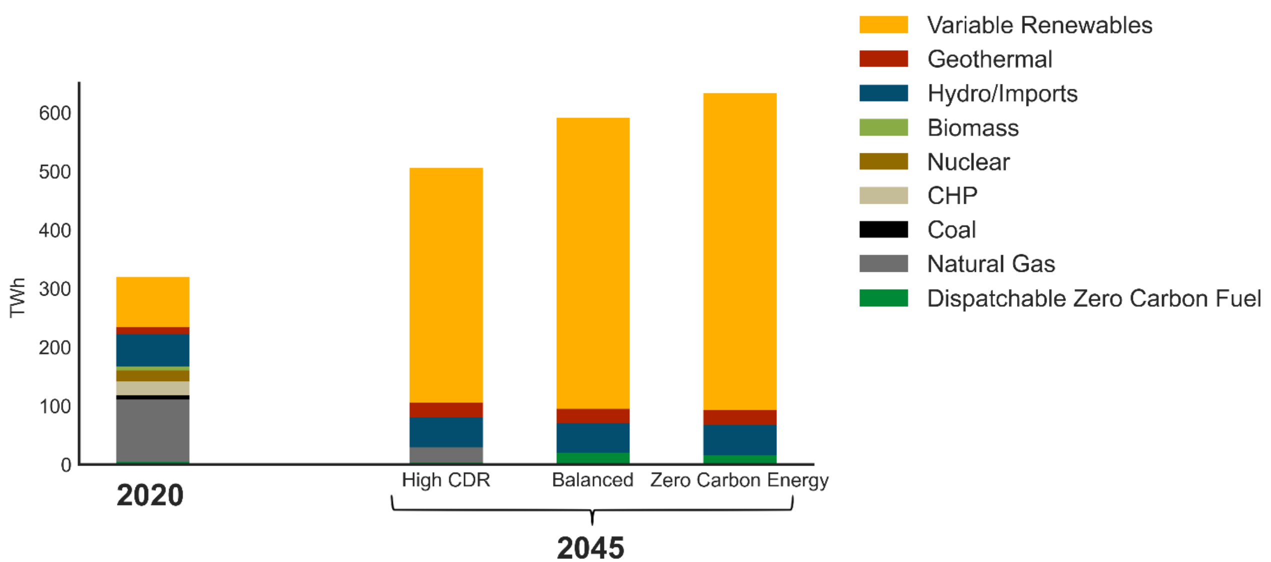
Final energy demand in oil & gas extraction and petroleum refining: today, and in 2045 across scenarios



Electricity Generation

- All scenarios assume a near or complete transition to zero-carbon electricity generation
- In Balanced and Zero Carbon Energy scenarios, zero-carbon dispatchable resources are used for about 5% of generation to reach 100% zero carbon electricity (dispatchable generation could be provided by any mix of Hydrogen, RNG, and long-duration energy storage)

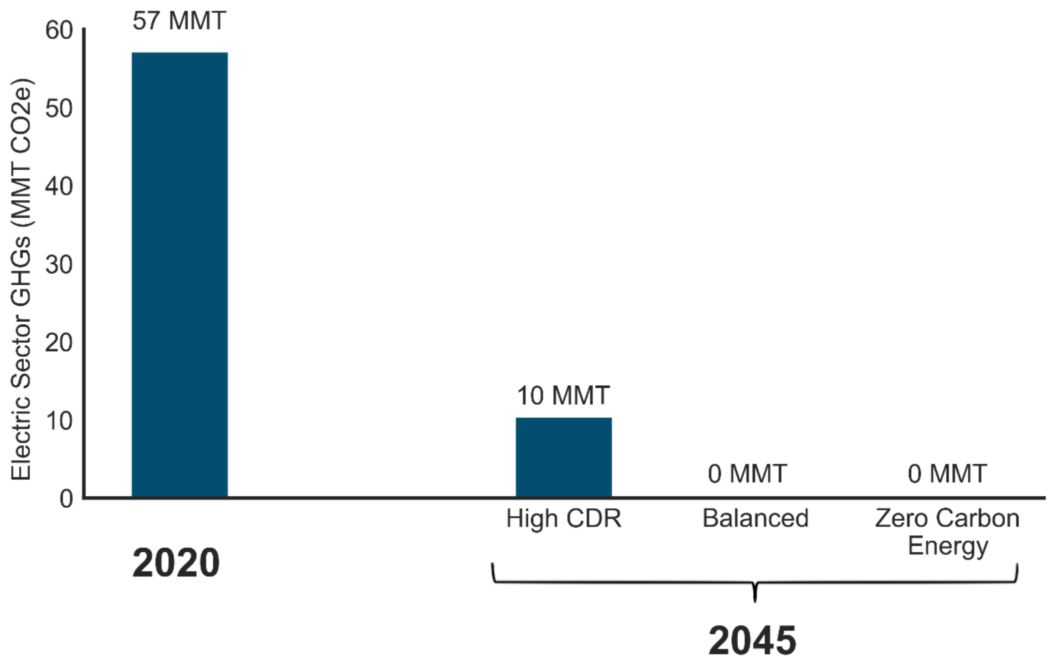
Electricity generation by resource: today, and in 2045 across scenarios



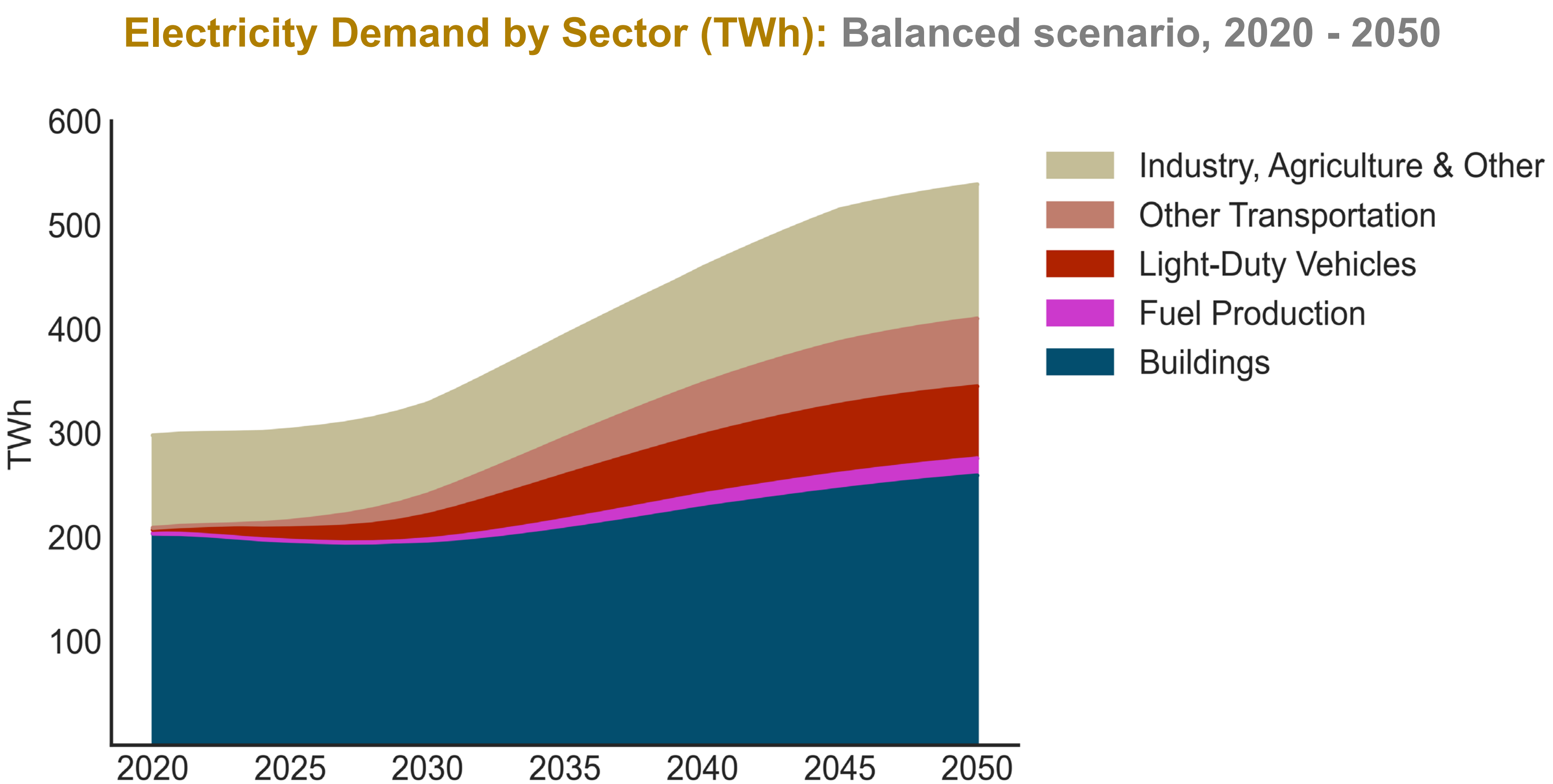
Electricity GHGs

- Natural gas serves 5% of generation in the High CDR scenario, leaving 10 MMT of GHGs in 2045 in the electricity sector
- In the Balanced scenario and Zero Carbon Energy scenario, this 5% of generation is served with zero-carbon fuels

Electric sector GHGs: today, and in 2045 across scenarios



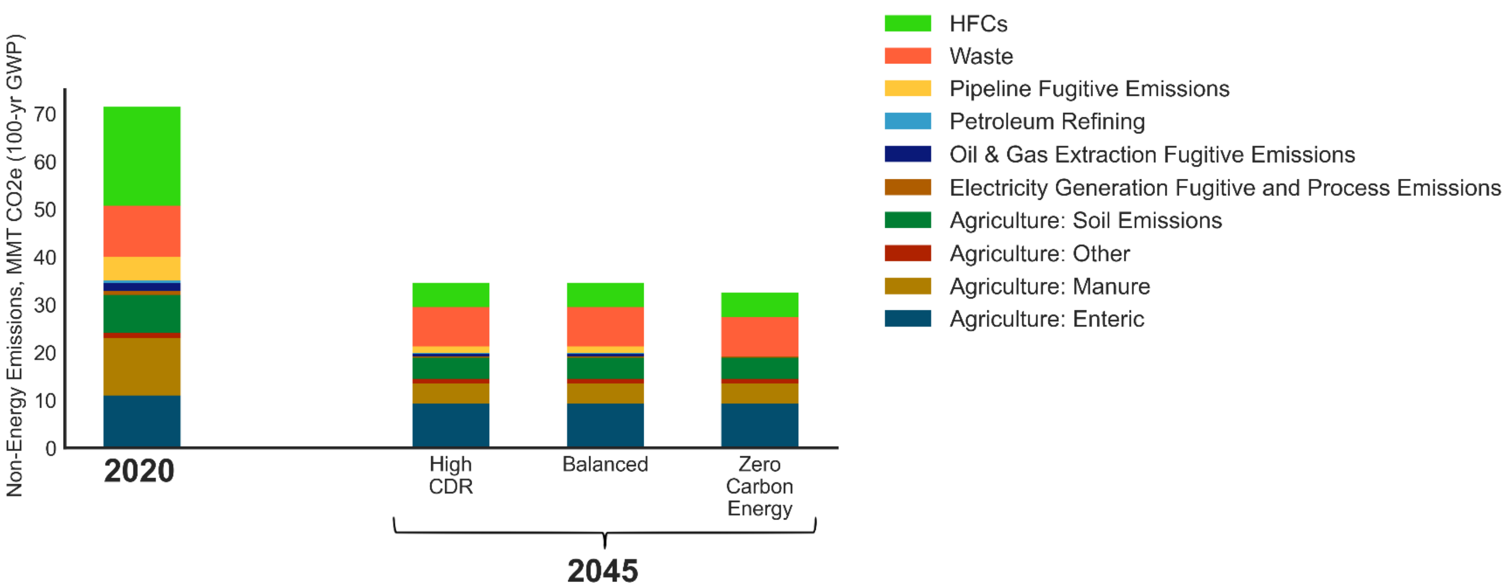
Electric Loads by Sector: Balanced Scenario



Non-Combustion, High Global Warming Potential Gases

+ **All scenarios assume a ~50% reduction in non-energy emissions by 2045 due to ongoing CARB efforts to address HFCs and methane emissions from agriculture, natural gas pipelines, and waste**
  - Retirement of natural gas distribution grid in Zero Carbon Energy scenario leads to near elimination of methane leakage in this scenario
  - Some of these emissions, particularly in agriculture, are unlikely to be possible to fully mitigate, meaning there are ~33 MMT of non-energy emissions remaining in all scenarios

Non-energy emissions by category: today, and in 2045 across scenarios



Carbon Dioxide Removal

+ **All scenarios require significant levels of carbon dioxide removal (CDR), with annual amount varying by scenario**
+ **This study does not prescribe specific recommendations on CDR strategies, but rather highlights the necessity for them and discusses the range of options, which includes direct air capture with storage (DACCS), bioenergy with carbon capture and storage (BECCS), and natural and working lands strategies (NWL)**
  - These strategies are all uncertain in their future commercialization potential and cost, meaning that relying on them is risky
  - Additionally, direct air capture in particular requires significant amounts of energy, with ~500 MW of solar nameplate capacity required if solar is the energy source

Carbon Dioxide Removal: amount required in 2045, by scenario

High CDR	Balanced	Zero Carbon Energy
80 MMT CDR required	**56 MMT** CDR required	**33 MMT** CDR required