# California's Route to Carbon Neutrality

Stanford | Doerr School of Sustainability | Stanford Center for Carbon Storage

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| Term | Description | Term | Description | Term | Description |
|---|---|---|---|---|---|
| **AC** | Air conditioner | **FCEV** | H2 fuel cell electric vehicle | **Remaining Electricity** | Load satisfied by distributed solar |
| **AD** | Anaerobic digestion | **LCFS** | Low carbon fuel standard | **Res** | Residential |
| **BAU** | Business as usual | **LDV** | Light Duty Vehicles | **RNG** | Renewable Natural Gas |
| **BEV** | Battery Electric Vehicle | **LEAP** | Low Emissions Analysis Platform | **RPS** | Renewable Portfolio Standard |
| **CA** | California | **F-Gas** | Fluorinated gas (e.g., refrigerant) | **SH** | Space heater / Space heating |
| **CARB** | California air resources board | **GWP** | Global warming potential | **SMR** | Steam methane reforming plant |
| **CCS** | Carbon capture & sequestration | **H2** | Hydrogen | **T&D** | Transmission and distribution (electricity) |
| **CDR** | Carbon dioxide removal | **HDV** | Heavy Duty Vehicles | **D&S** | Distribution and storage (hydrogen) |
| **CGC** | Clean generation constraint | **HP** | Heat pump | **VMT's** | Vehicle miles traveled |
| **CI** | Carbon Intensity | **Li Ion** | Lithium-Ion Batteries | **WH** | Water heater / Water heating |
| **Comm** | Commercial | **LPG** | Liquid propane gas | **ZEV's** | Zero emission vehicles |
| **CO2e** | Carbon dioxide equivalent | **Mfg** | Manufacturing<br>Small: <25kt co2e/ yr<br>Large: >25kt co2e/ yr | **45Q** | Federal program incentivizing CCS & DAC |
| **DAC** | Direct air capture | **NGCCS** | Natural gas power plant with CCS | **% Blend** | Blend percentage of specified fuel (RD, Biodiesel, RNG, Ethanol) |
| **DECAL** | Our model – Decarbonize California | **O&G** | Oil and Gas | | |
| **e-** | Electricity | **O&G Upstream** | Upstream oil and gas, including crude extraction | | |
| **E-Gen** | Electricity Generation | **PHEV** | Plug in hybrid electric vehicle | | |
| **EOL** | End of life | **PTC** | Production Tax Credit | | |
| **ER** | Electric resistance | **RD** | Renewable Diesel (diesel fuel made from a biofeedstock) | | |

# Agenda

- Motivation / Research Question
- Model Background
- Comparison between DECAL and the CARB Scoping Plan
- “What is it going to take to get to net-zero by 2045?”
  - Silver Bullets
  - Economy Wide Overview
  - Electricity Sector
  - Transportation Sector
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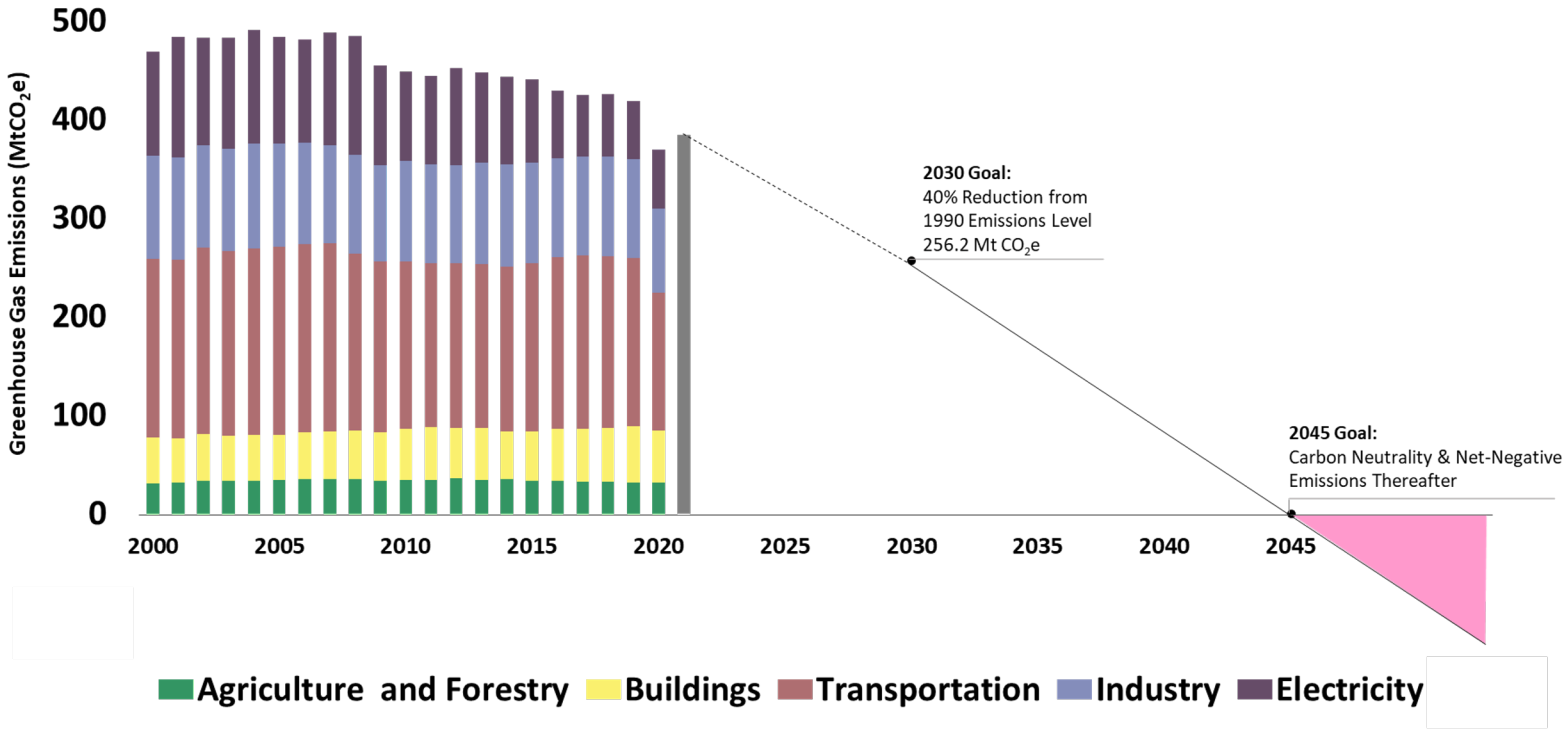
  - Direct Air Capture
- Sensitivity Analyses

# Motivation / Research Question



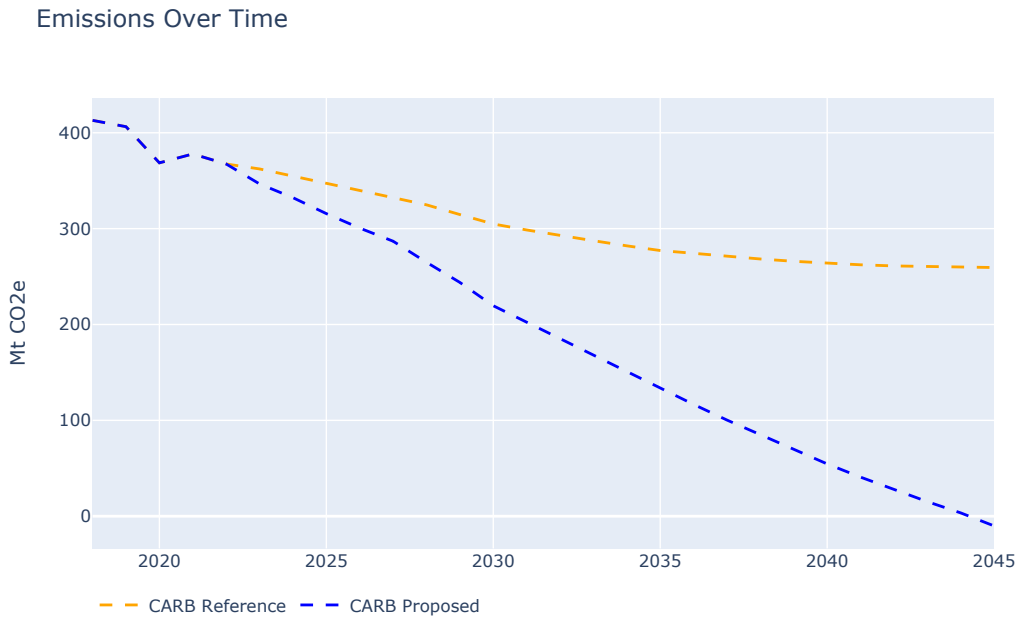

Source: Adapted from CARB (2022)

**What will it take to reach net-zero emissions by 2045?**

# CARB Scoping Plan

- Every five years, CARB creates a scoping to help meet climate goals
- CARB Reference Case – CARB's BAU forecast
- CARB Proposed Scenario – CARB's proposal for reaching net-zero by 2045

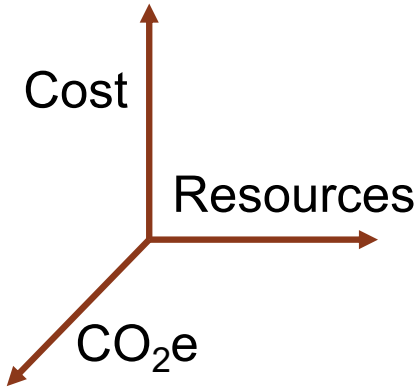
- CARB's key findings:
  - Triple amount of installed solar
  - Build 20 GW of offshore wind
  - Electrify 20 Million cars
  - Reduce fossil fuel consumption by 90%
  - 100 Mt of CCS (point source and CDR)

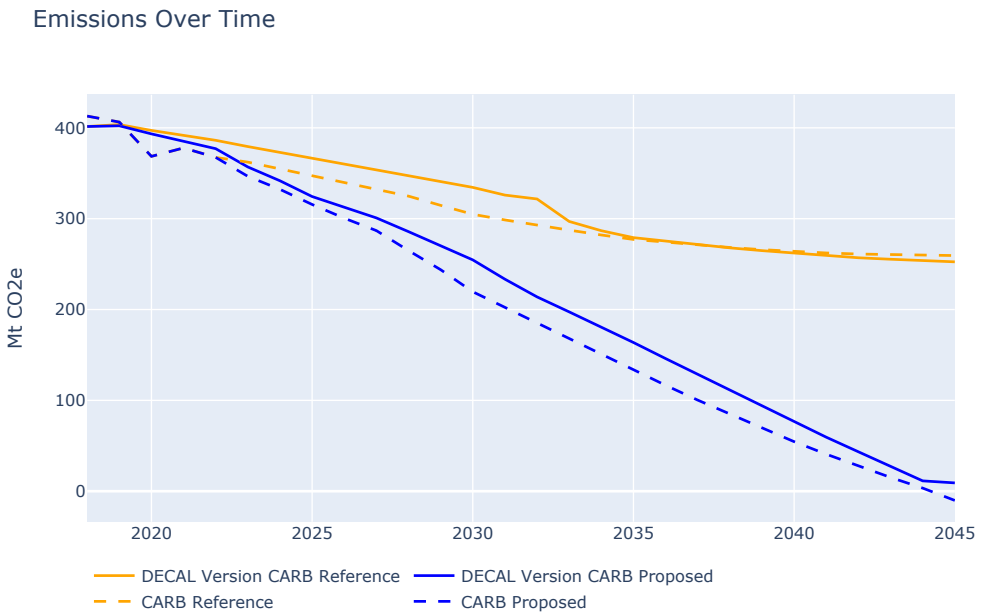


# Stanford DECAL Model

Stanford Model: DECAL (DEcarbonize CALifornia)

- Built using LEAP (Low Emissions Analysis Platform)
- 3 results we care about most: emissions, costs, & resources
- System boundary: CA, scope 1 & 2 emissions
- Total resource cost test
- Stock & flow in buildings and transportation sectors
- Optimization in electricity sector
- Driven by exogenously defined levers; not an equilibrium model




Comparison to Scoping Plan:

- Results broadly similar when run under same assumptions
- Goal is not to reinvent the CARB Scoping Plan, but to provide an independent analysis and inform the climate mitigation discussion

# DECAL Executive summary

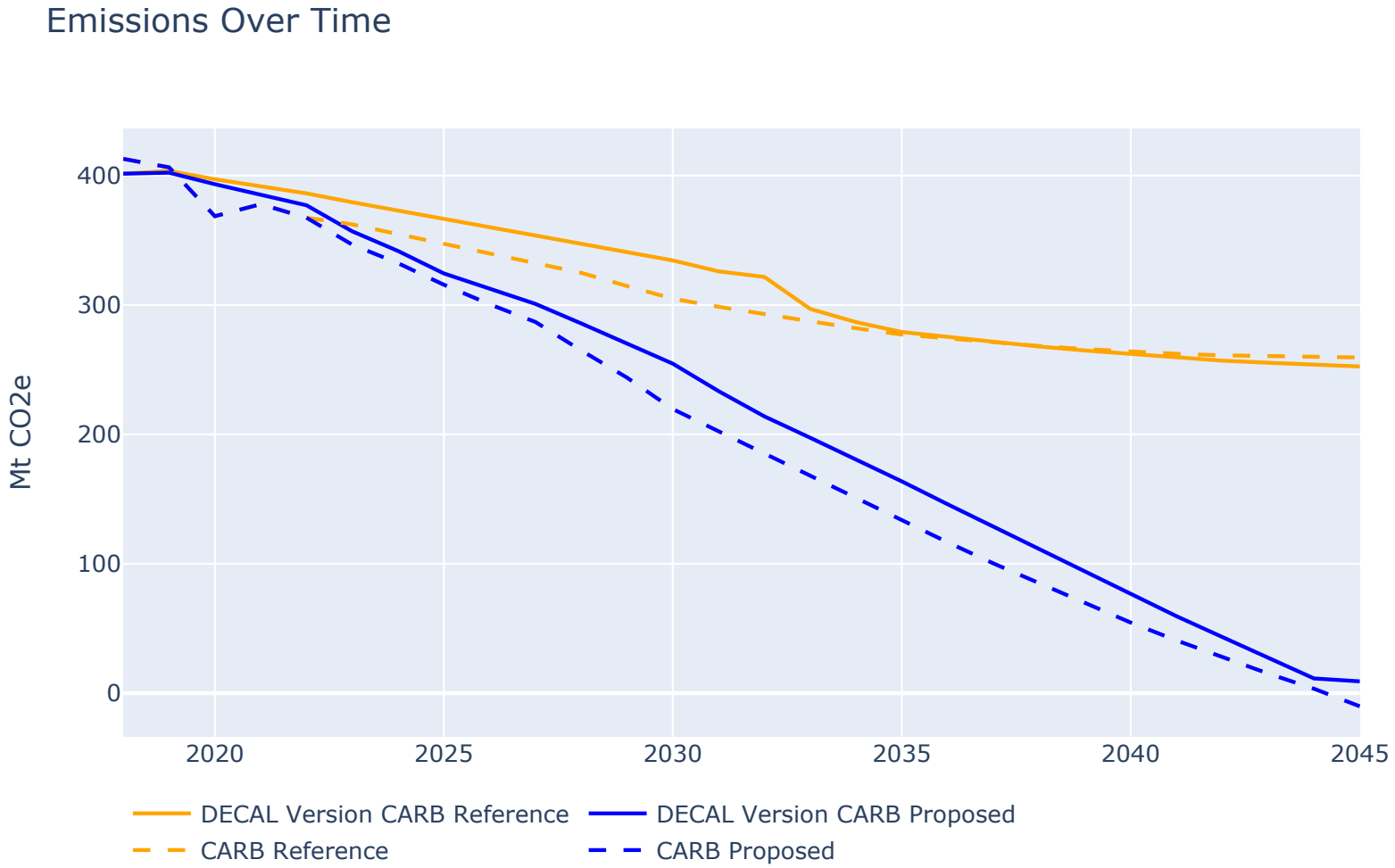
**What will it take to reach net-zero emissions by 2045?**

- All technologies and resources will be needed to get to net zero by 2045
- Electrification will require major expansion to the existing grid (approximately 225 – 400 GW of capacity depending on CGC)
- Going from 99% to 100% carbon-free electricity generation is very expensive
- Policies encouraging ZEV sales can be effective
- Point source CCS is effective and economically favorable for the industrial sector
- F-Gas mitigation requires innovation
- Expanding use of H2 may be very expensive, especially due to distribution & storage
- RNG and RD usage may be limited by feedstock availability
- It is very difficult to reach net-zero by 2045 without significant CDR (>35 Mt/yr by 2045)

# Comparison between DECAL and CARB Scoping Plan

**Question**: Do DECAL and CARB forecasts align?

**Method**: Convert CARB scenario descriptions into DECAL levers




- DECAL's economy-wide emission forecasts are similar to CARB's

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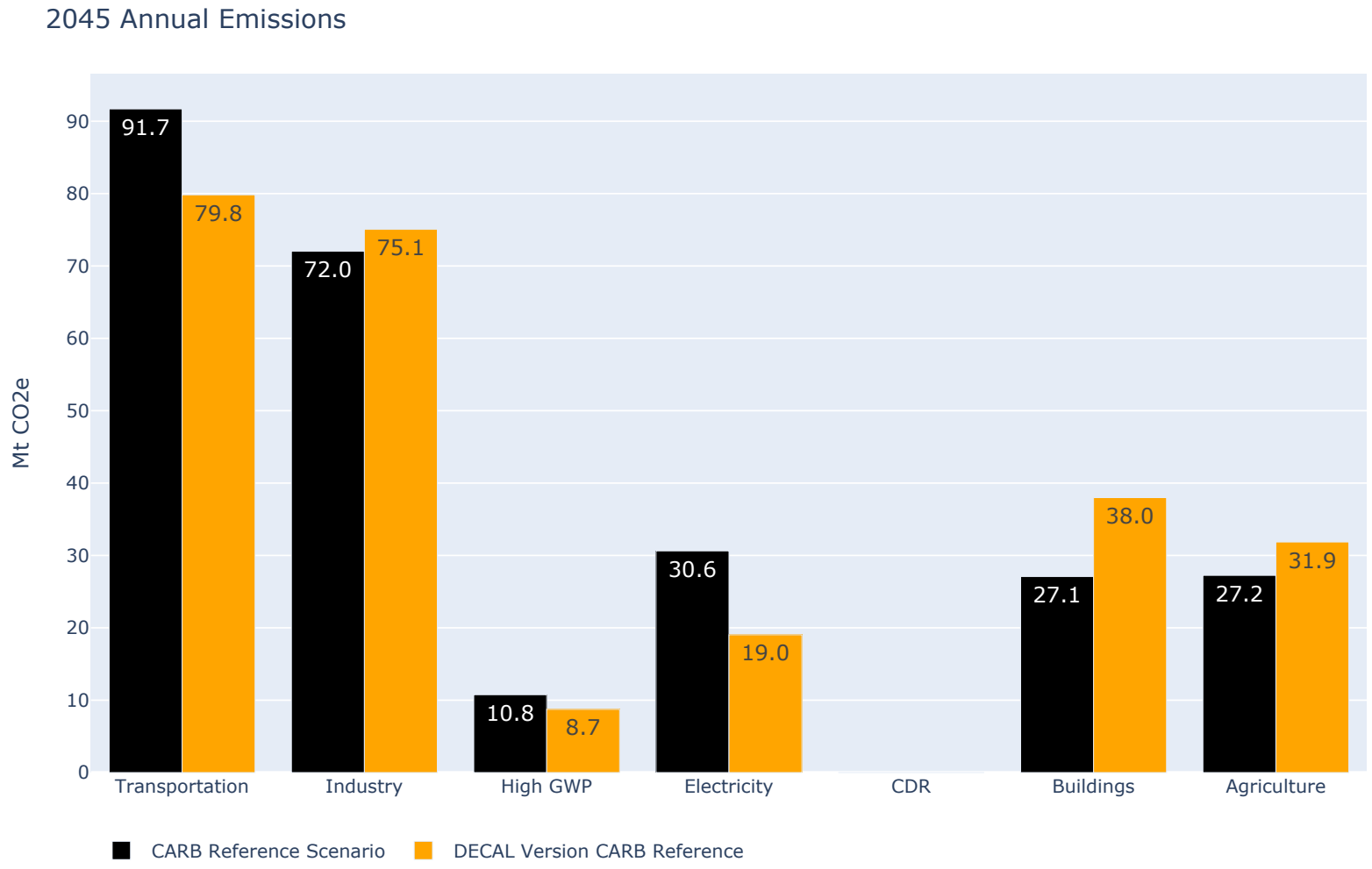

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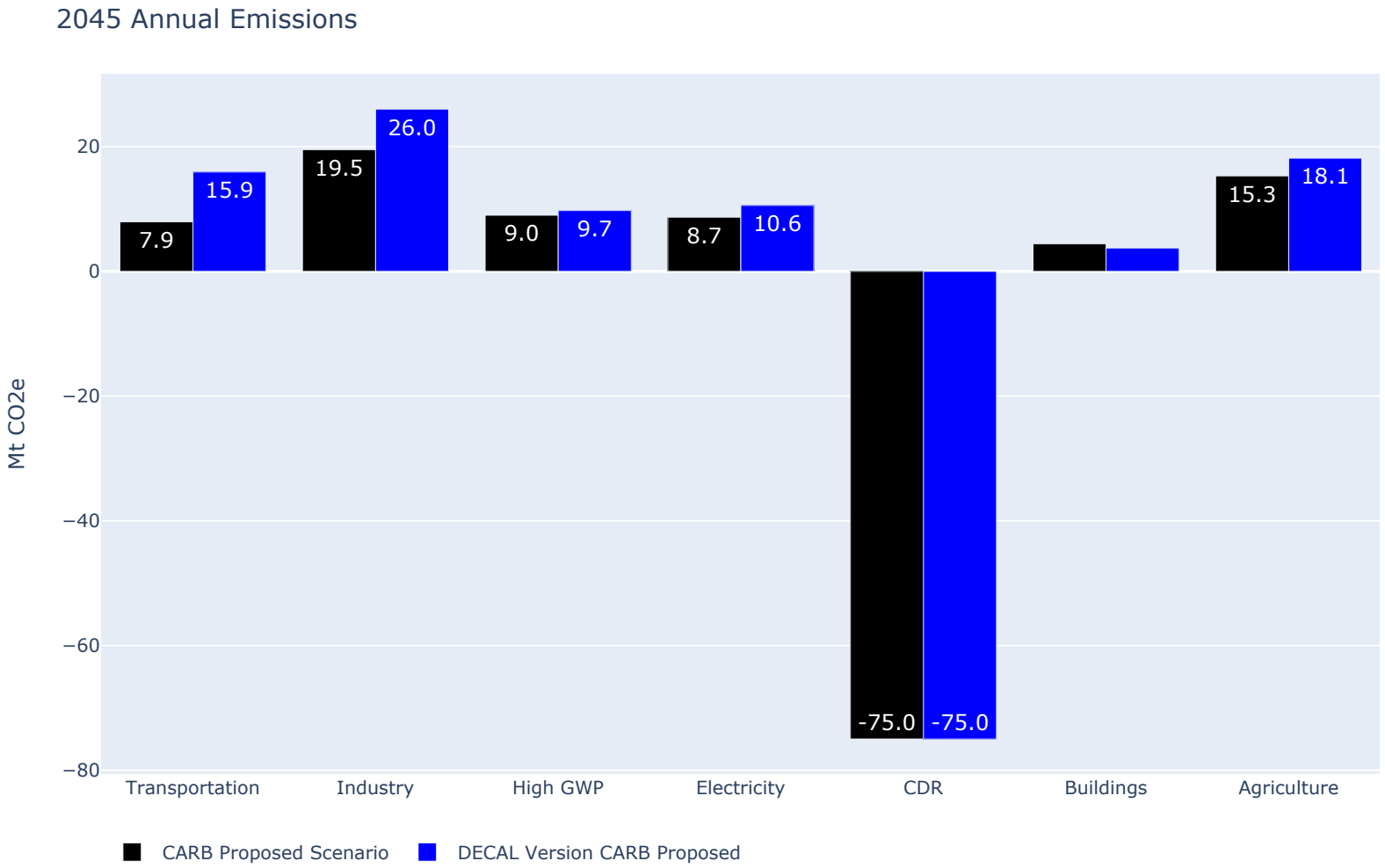

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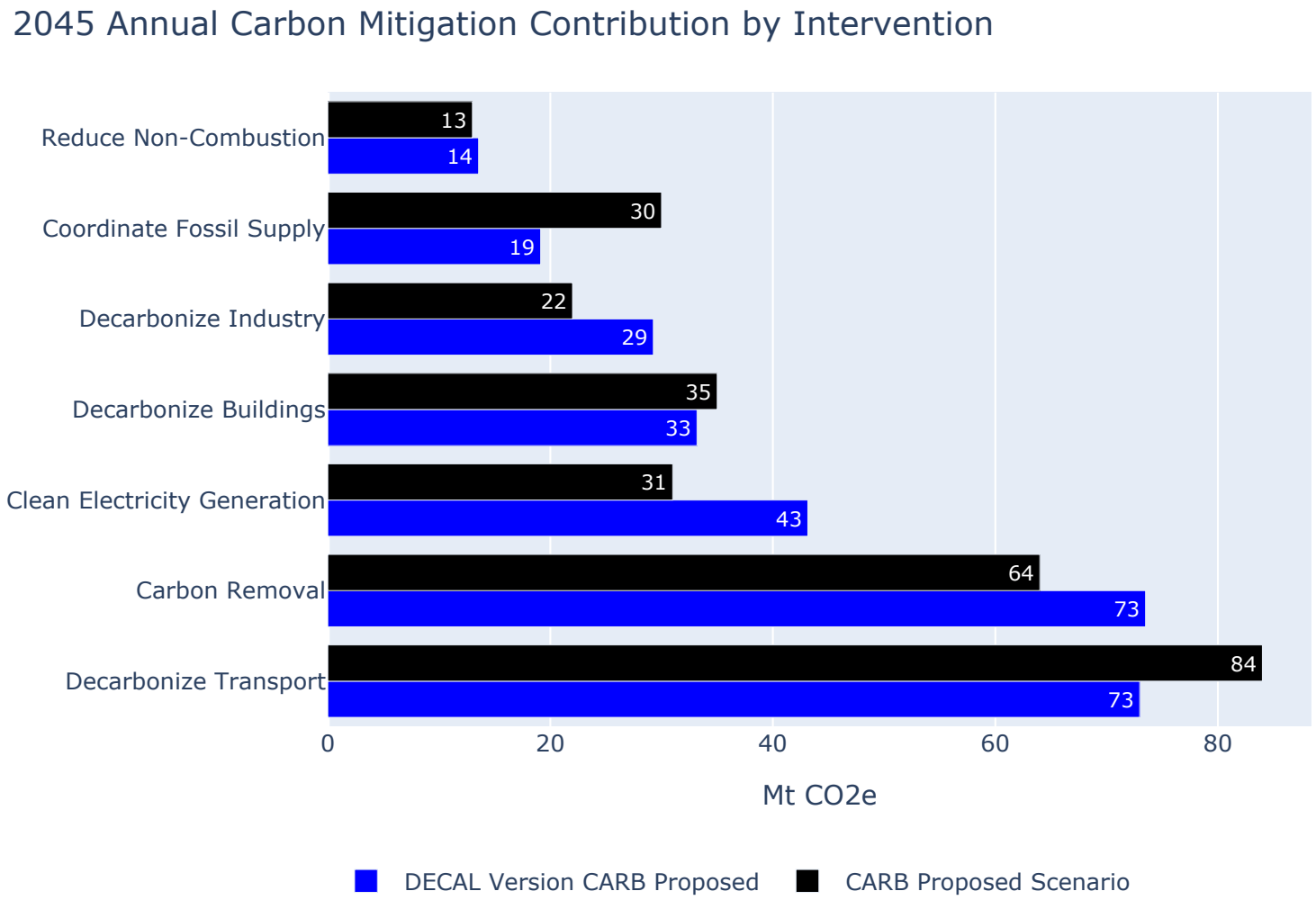


** Reduced refining emissions included in Decarbonize Transport instead of Coordinate Fossil Supply*

*** CARB Scoping Plan, Table 3-5*

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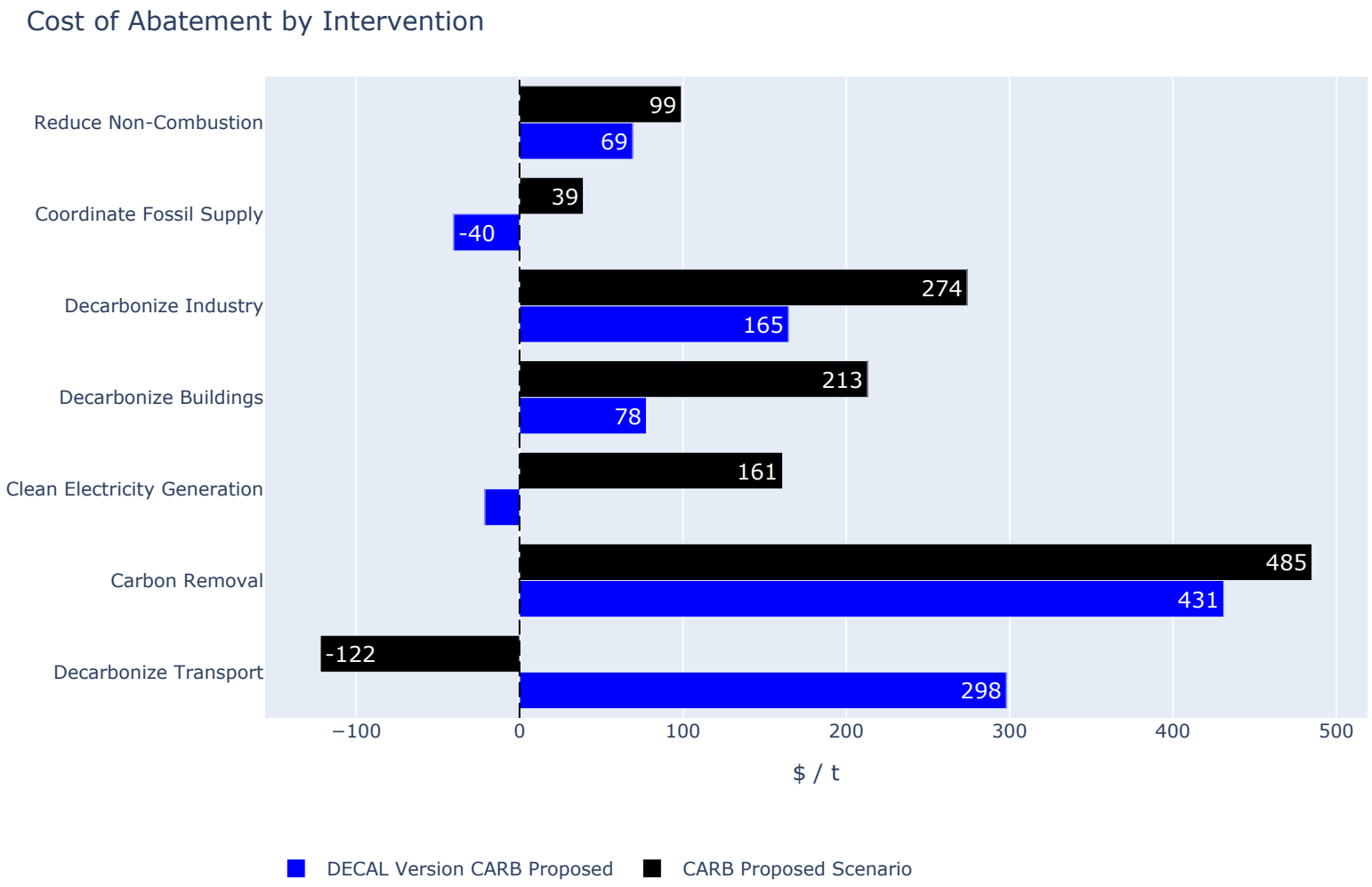
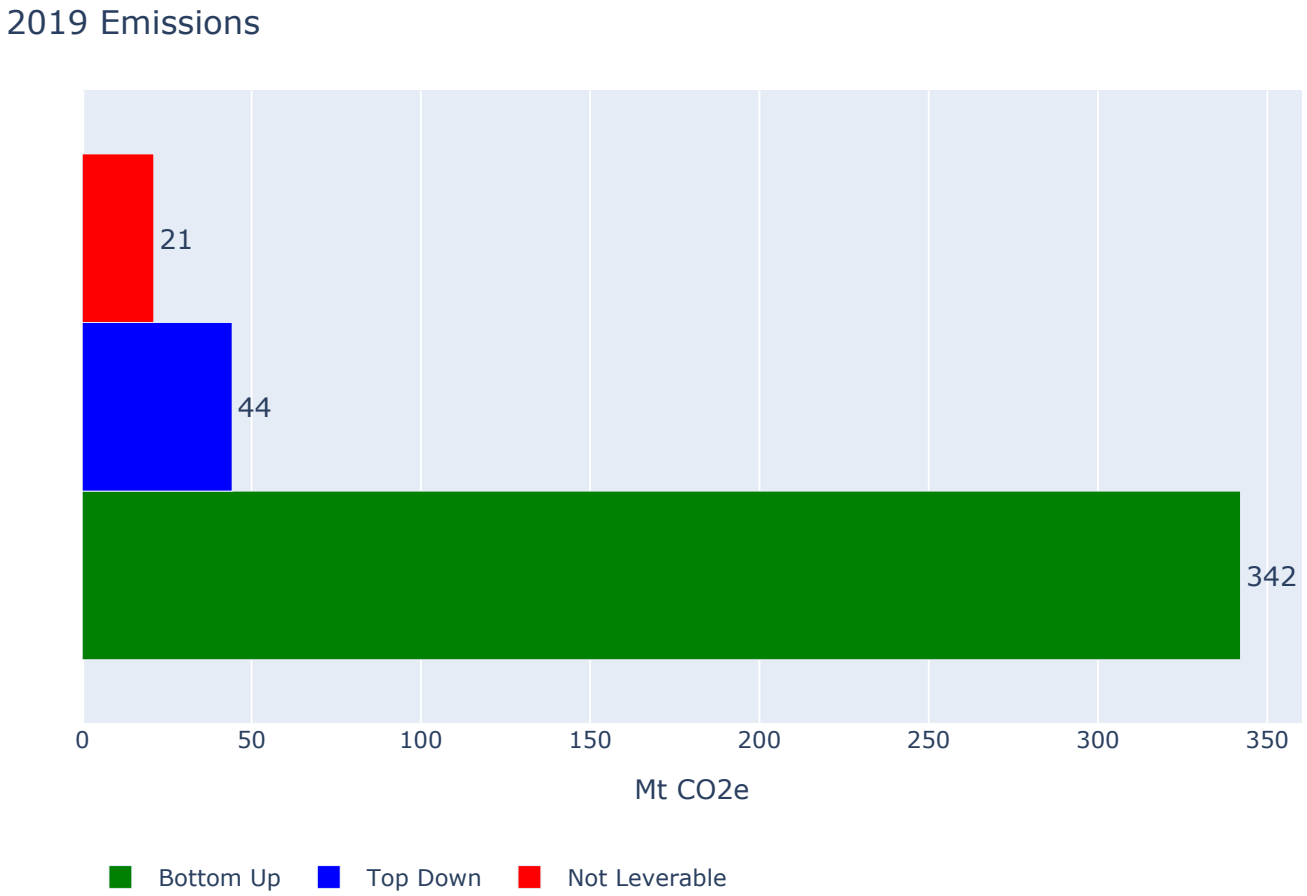



*CARB Scoping Plan, Table 3-11*

# DECAL Leverable Emissions




- Bottom up – detailed understanding of emissions and costs
  - e.g.: Automobiles, residential space heating, electricity generation, etc.
- Top down – superficial understanding of emissions and costs
  - e.g.: Residential-other emissions, trains/planes/boats, etc.
- Not leverable – unable to affect emissions in DECAL
  - Aerosols, foams, fertilizers, fire protection, solvents, waste, residue burning, crop residue, liming, histosol cultivation, manure, rice cultivation

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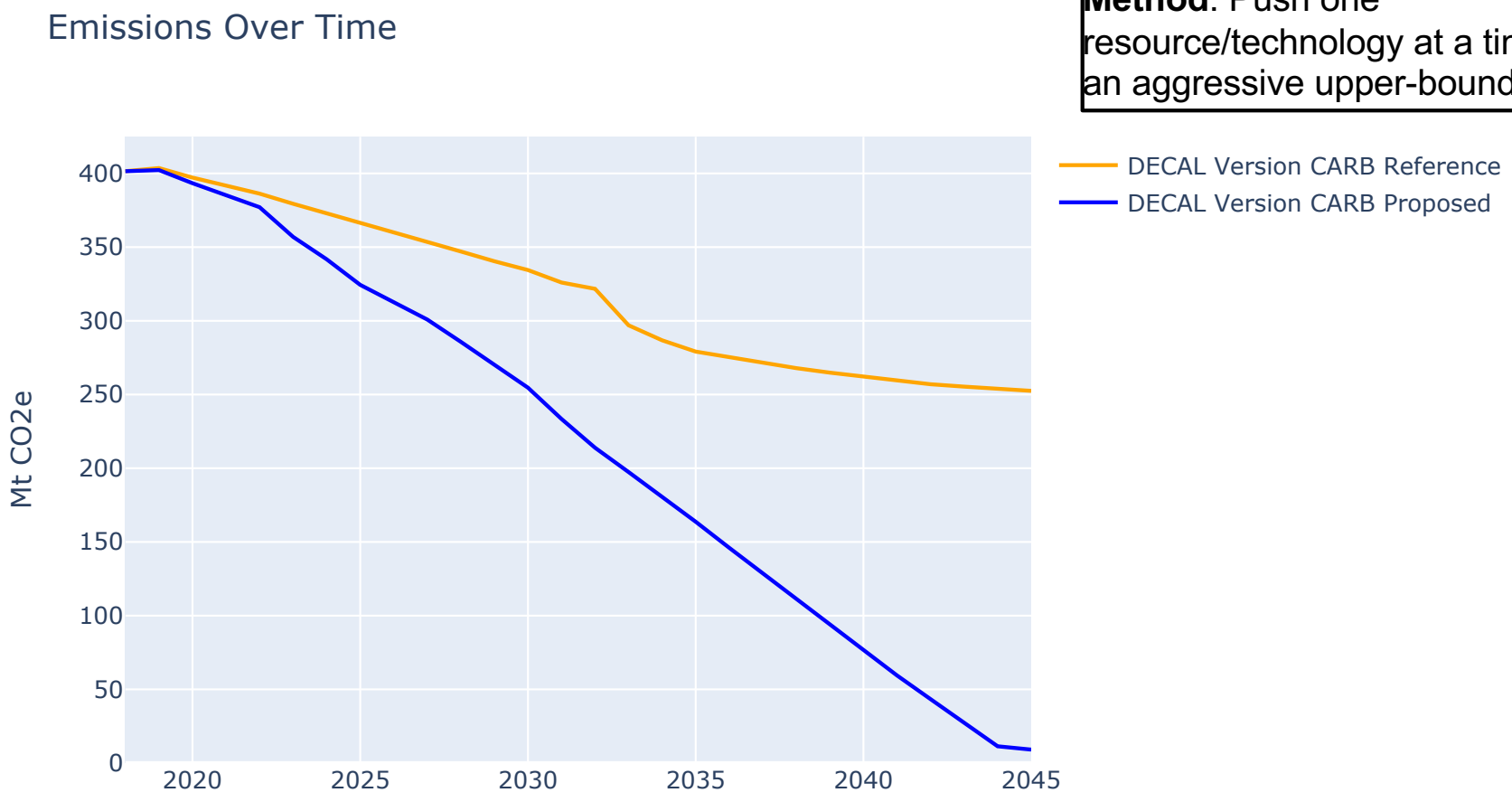
# Silver Bullets

## All resources and technologies will be needed

**Questions**: Can one resource or technology get us to net-zero by 2045? Is there a *silver bullet*?

**Method**: Push one resource/technology at a time to an aggressive upper-bound



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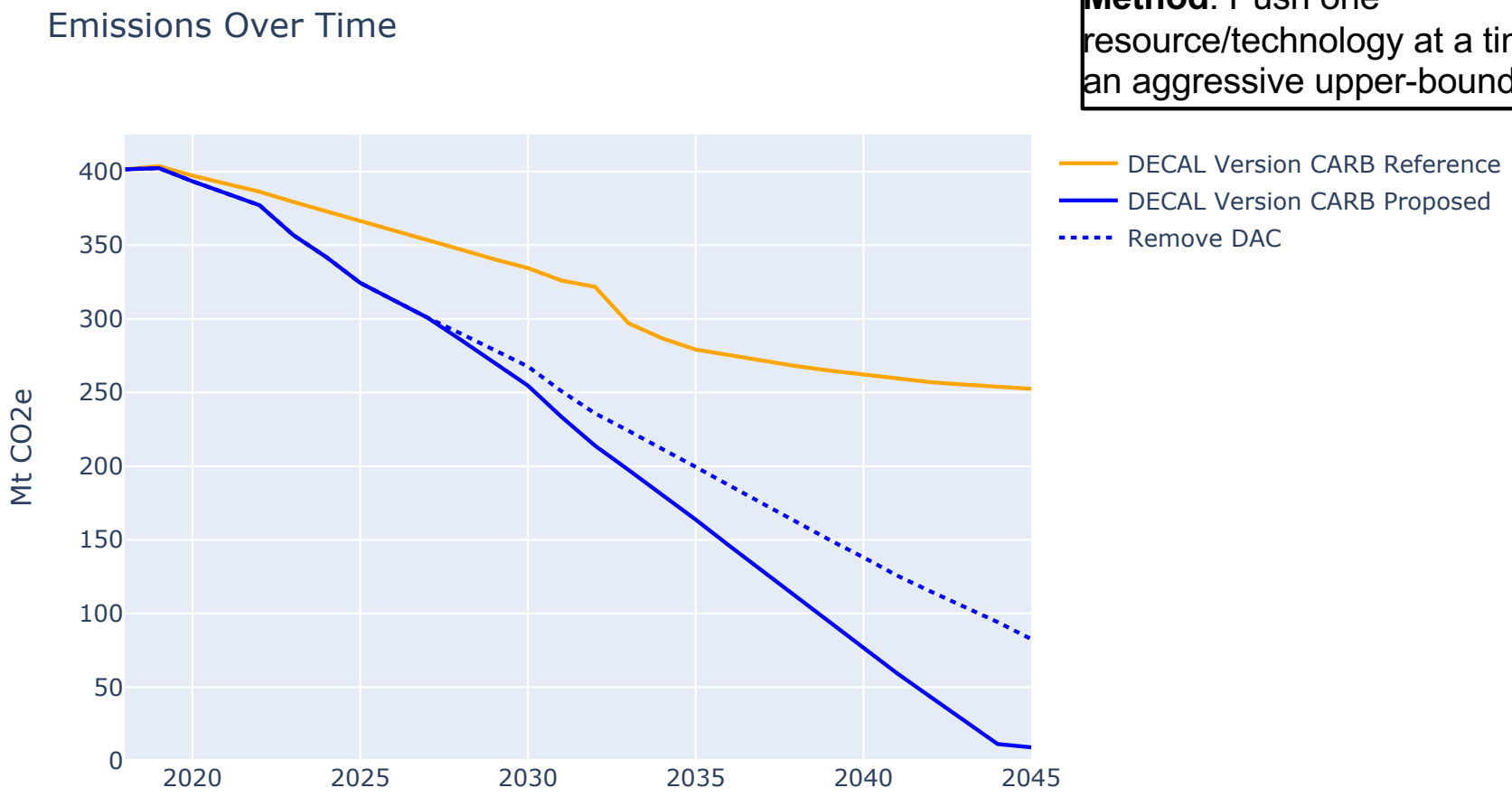


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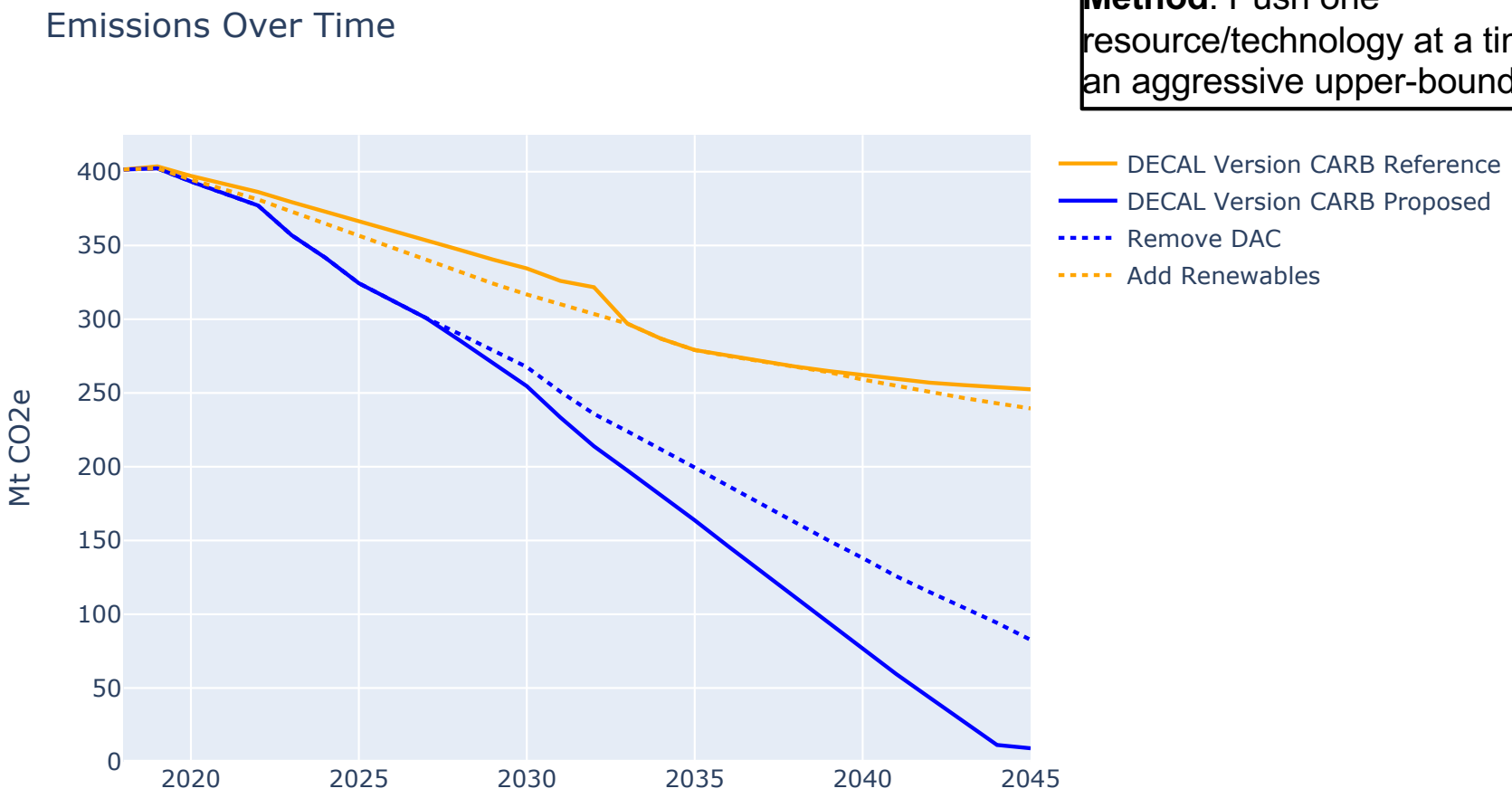


- CDR is critical component of CARB's scoping plan
- A clean grid is important

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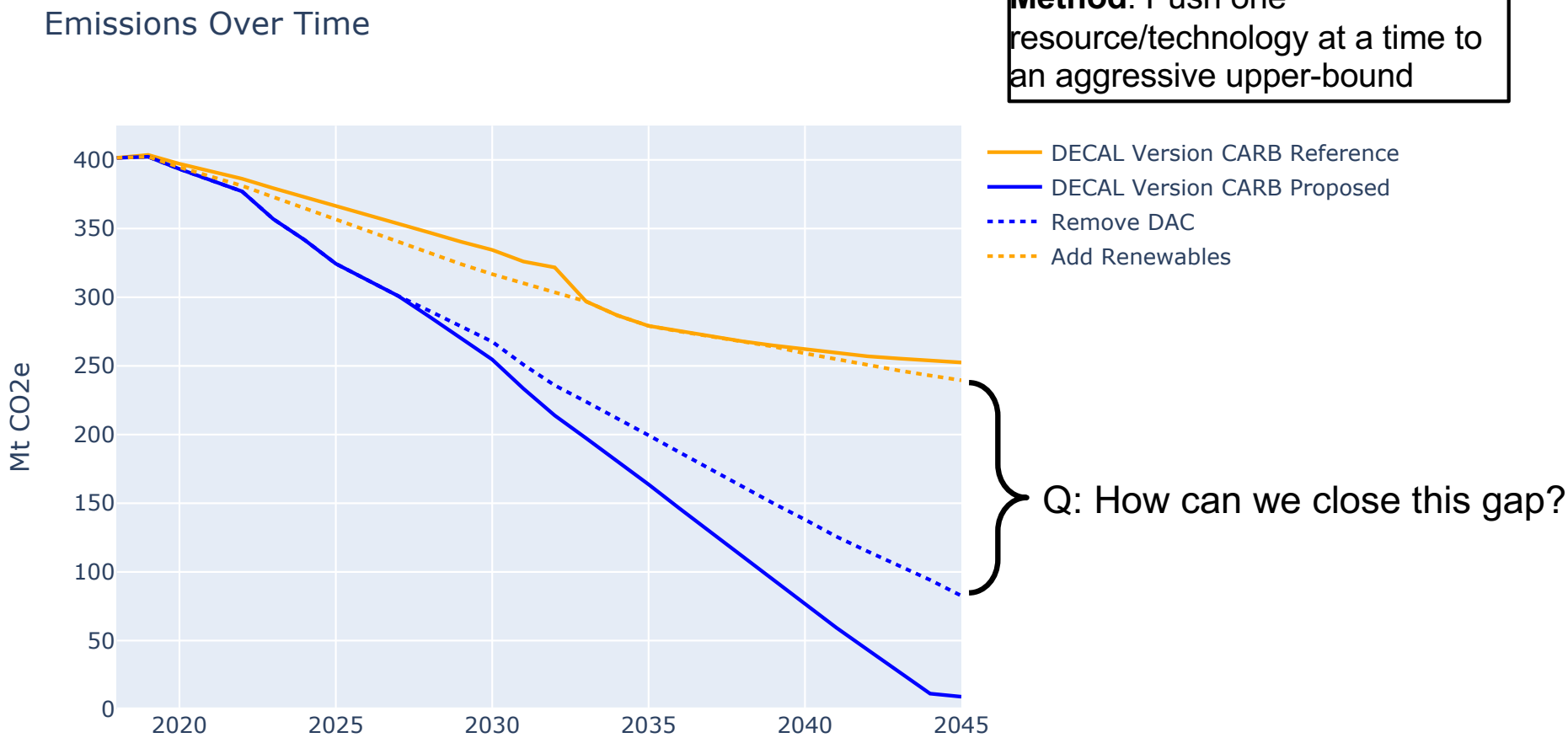


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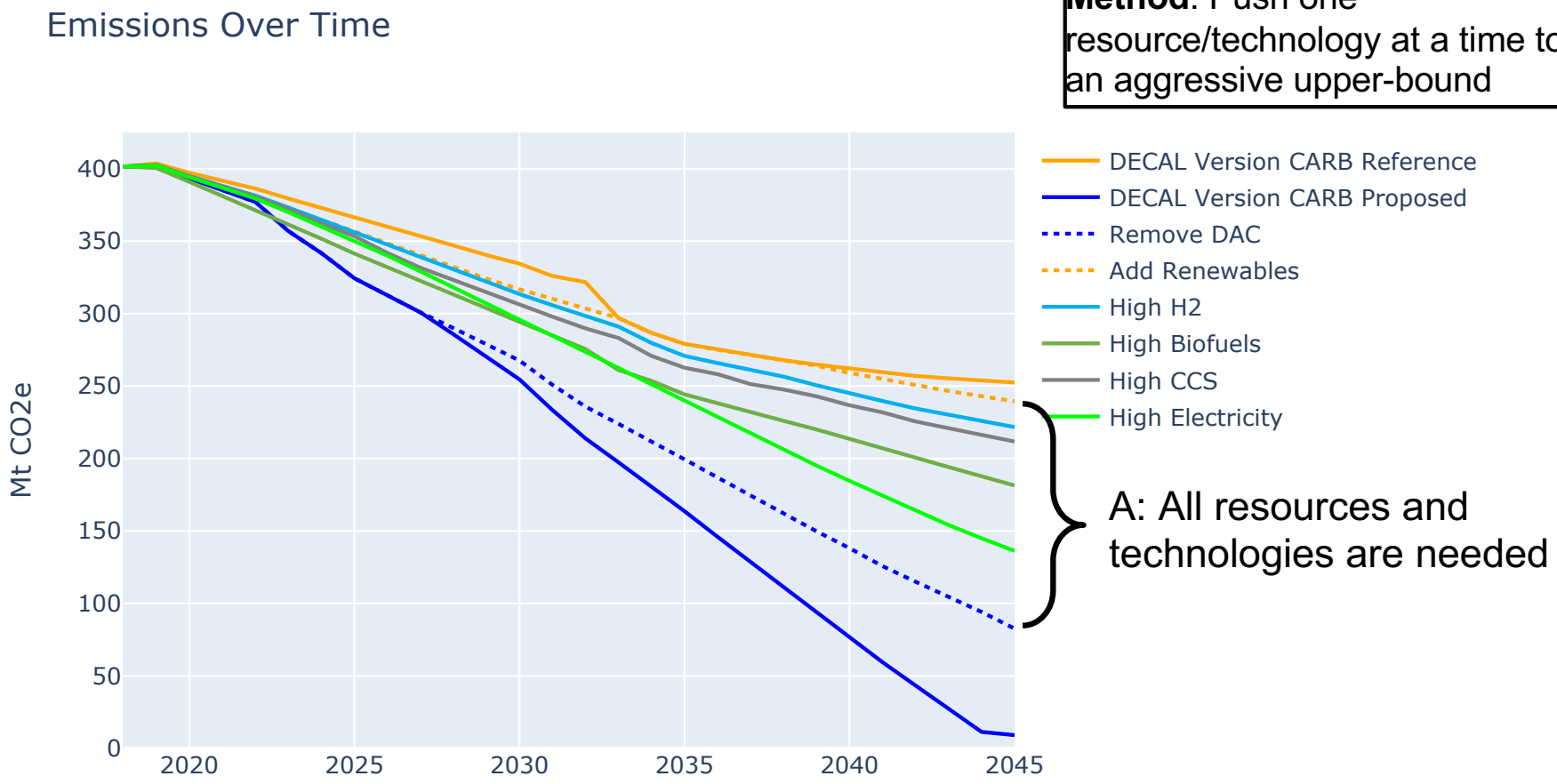
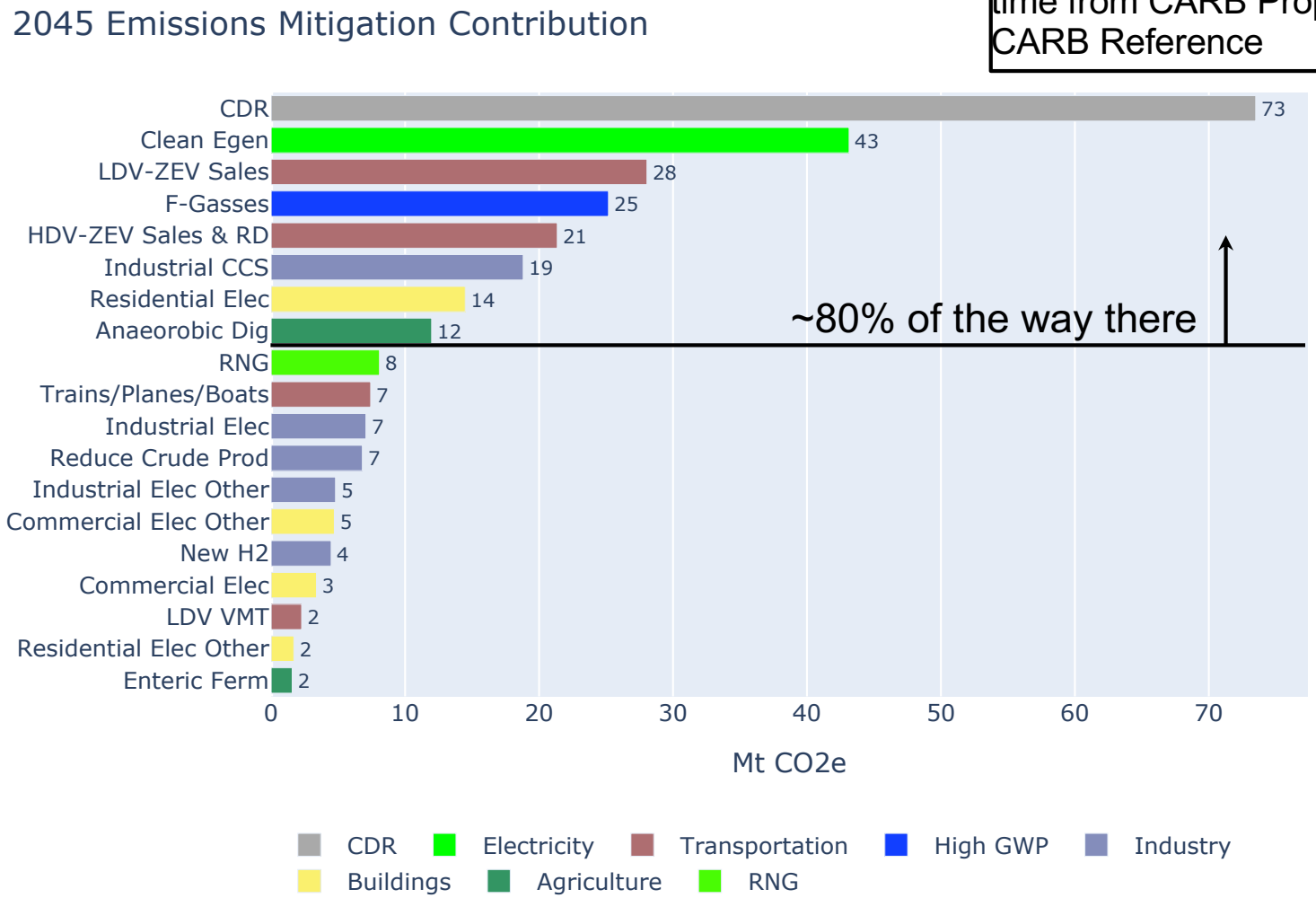



- CDR is critical component of CARB's scoping plan
- A clean grid is important
- **There is no silver bullet – resources and technologies must be combined to reach our goals**

# Economy Wide Overview
## A few policies/programs will be key

**Question**: What policies and technologies have the most impact on emissions reductions?

**Method**: Change levers one at a time from CARB Proposed to CARB Reference




**Refining emissions reductions not included*

- CARB highly reliant on CDR
- 80% of the way there with 7 key policies, many we already have programs for

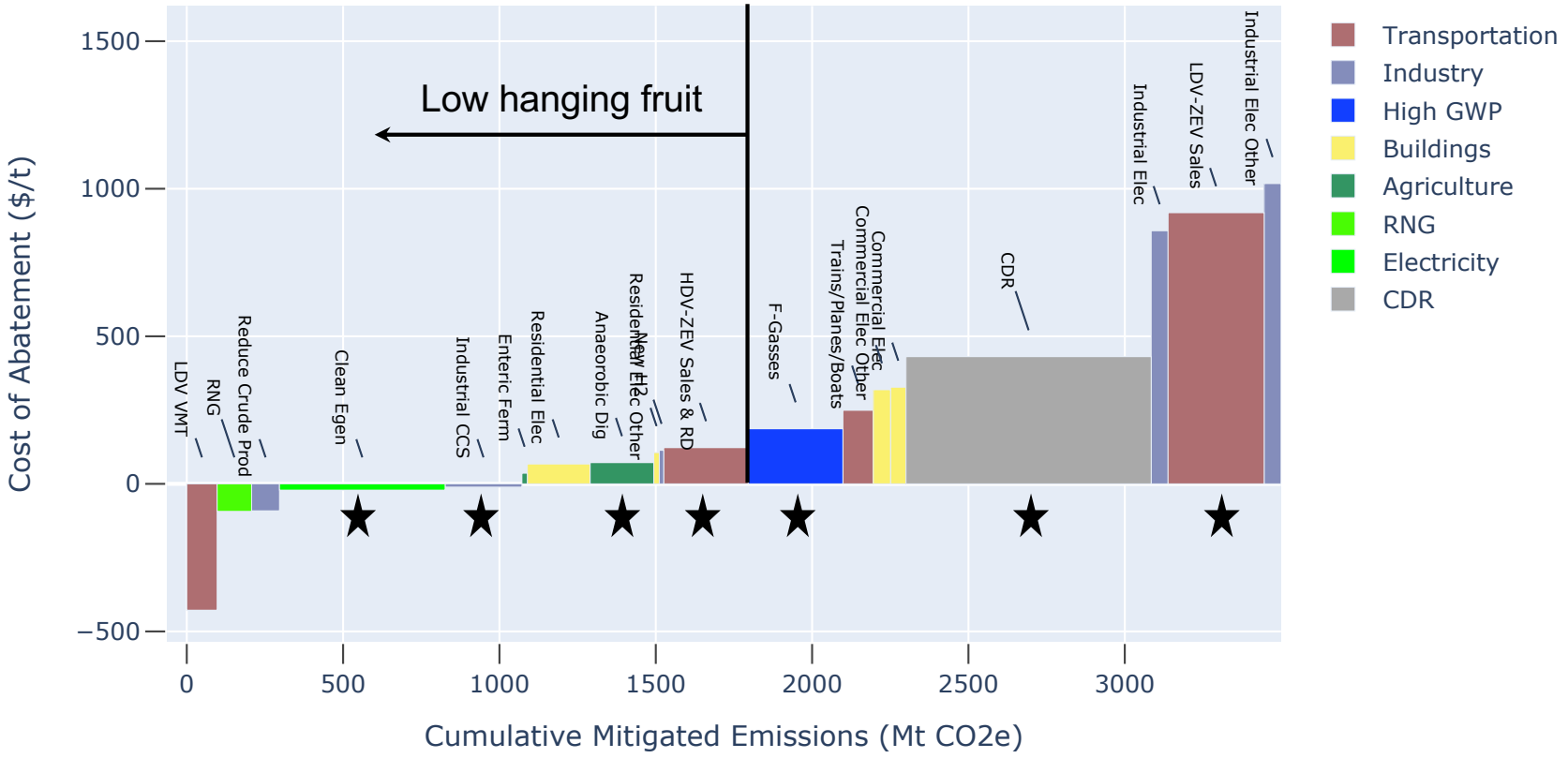
# Economy Wide Overview

## Some policies/programs are quite affordable... but these don't get us far

**Question**: What policies and technologies have the most impact on emissions and costs?

**Method**: Change levers one at a time from CARB Proposed to CARB Reference

DECAL CARB Proposed - MACC




DECAL version of CARB Proposed: $238/tonne

★7 areas noted on previous slide

# Economy Wide Overview
## Electric load will grow in every sector

**Question**: What policies and technologies have the most impact on electric load?

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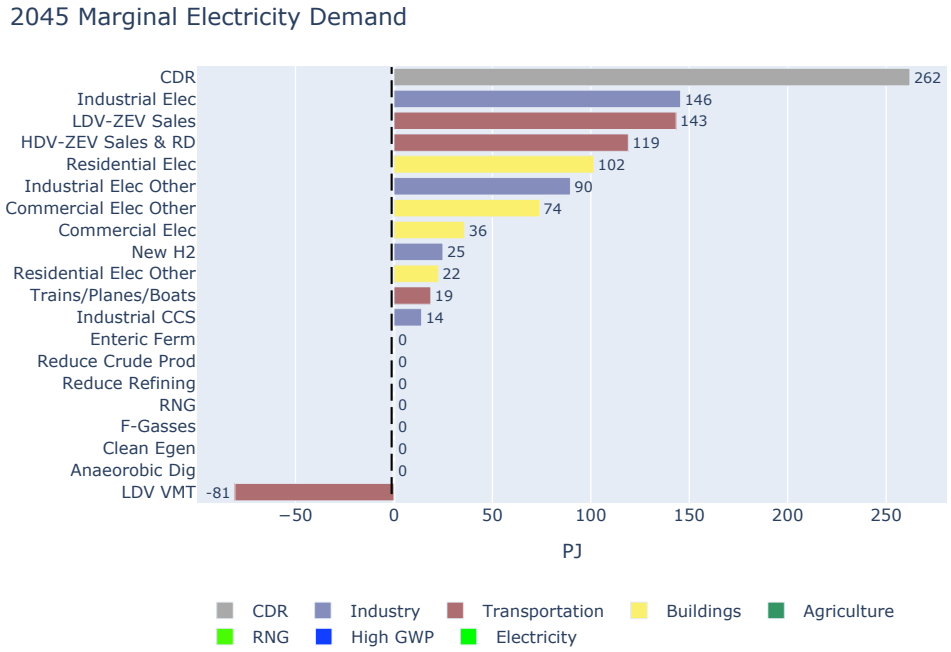


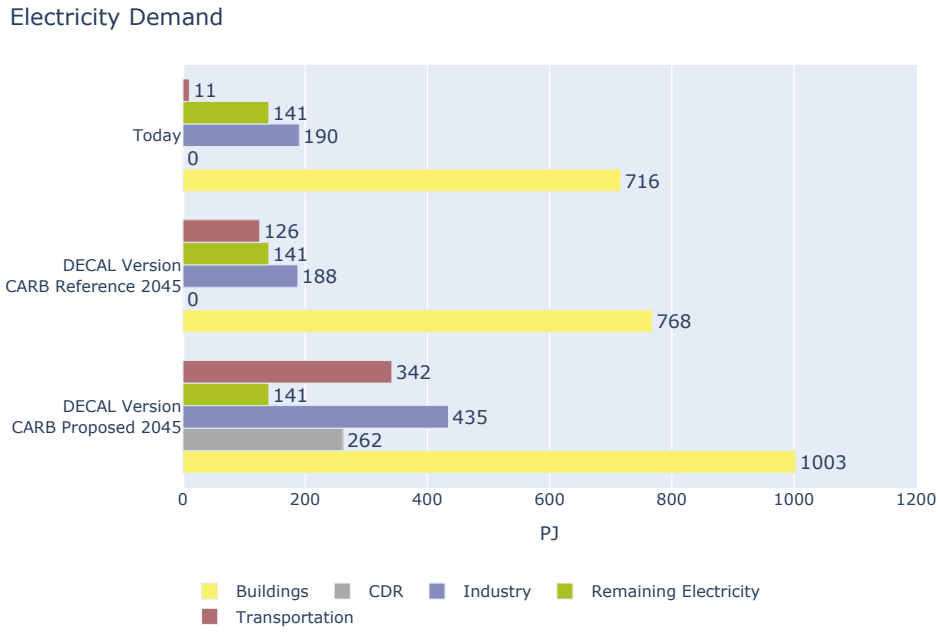


- 75Mt / yr of CDR has large impact on electric load
- Buildings are and will remain the largest sectoral electric load
- Growth in electric load in transportation, industry, and buildings are all similar

** Marginal electricity demand: DECAL Version CARB Proposed vs DECAL Version CARB Reference (2045)*

# Electricity Sector

## A clean grid will be required… but 100% clean may not be necessary

**Question**: What is the impact of the electricity clean generation constraint?

**Method**: Iterate on CGC in low/medium/high e- scenarios

*All scenarios reach similar 2045 emissions*

- *Low: Choose H2, biofuels, and CCS*
- *Med: CARB Proposed*
- *High: Choose electricity where possible*



- Going from 99% to 100% CGC requires enormous capacity installations, partially due to lack of NGCCS
- Going from 99% to 100% CGC has little impact on electricity emissions

** Due to using representative days of the month and perfect foresight, the capacity expansion results should be considered optimistic*

# Electricity Sector

## A clean grid will be required…
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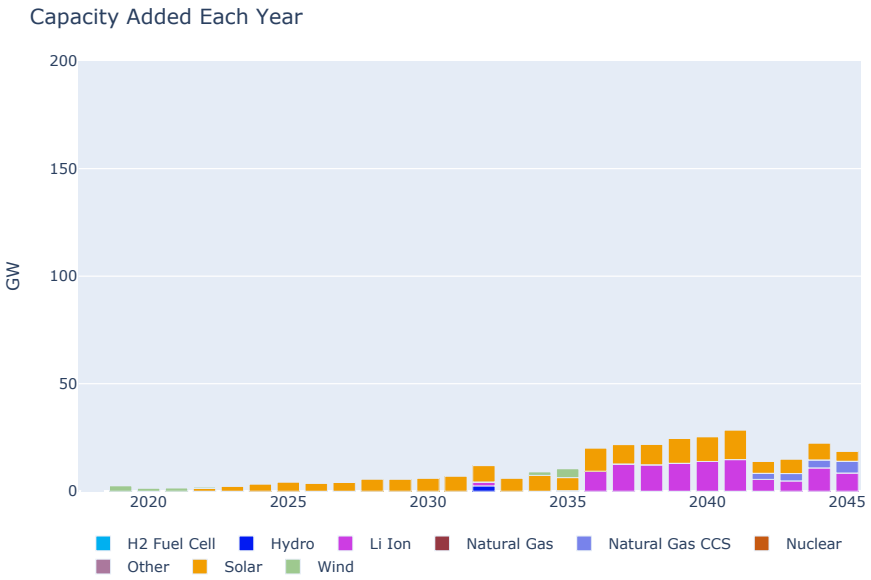
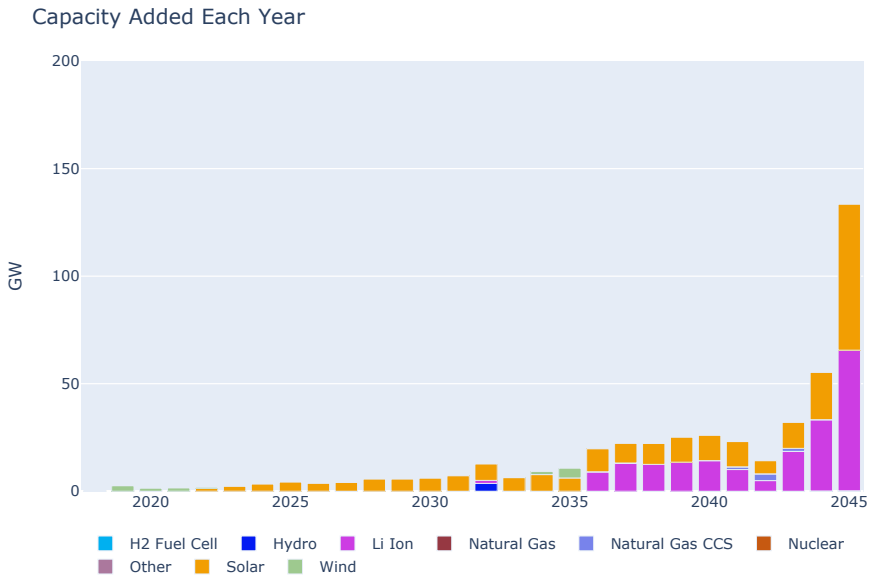
## Medium Electricity

CGC = 99% by 2045




CGC = 100% by 2045

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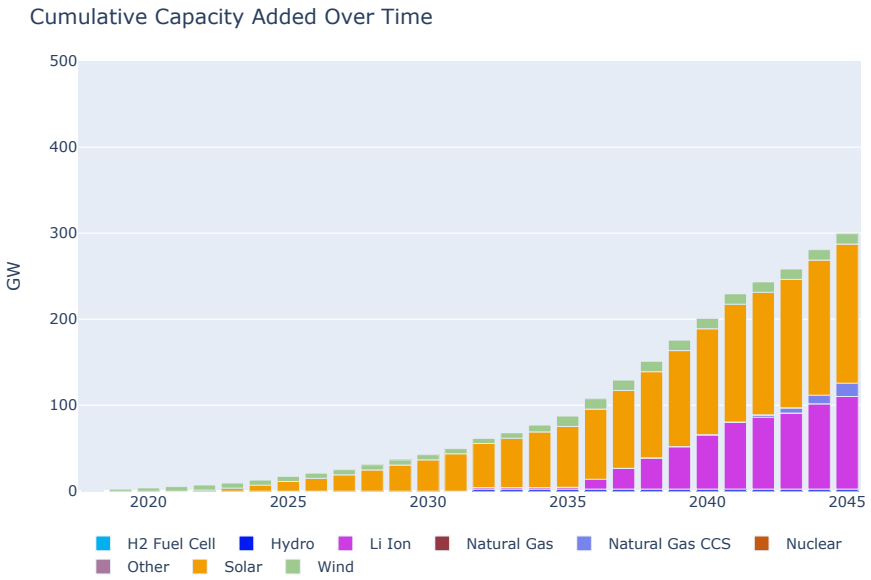


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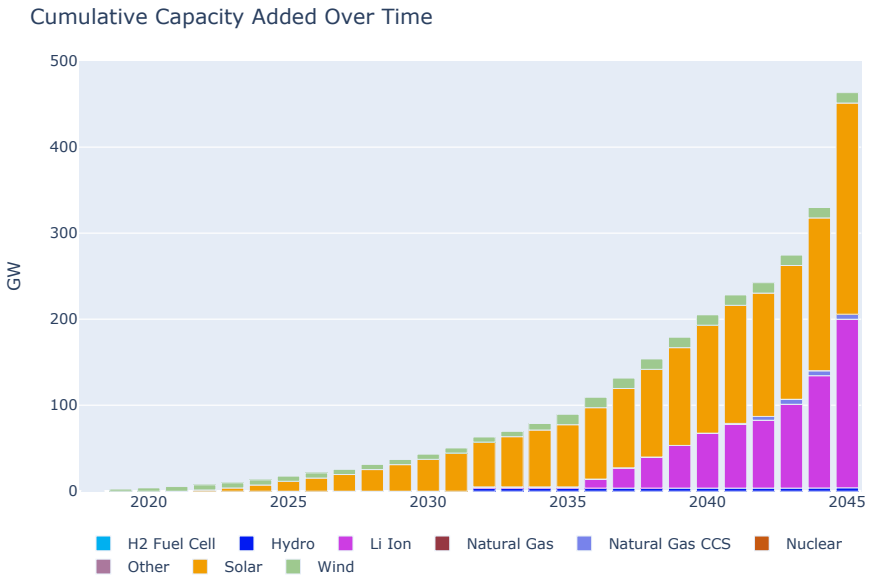


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- Going from 99% to 100% CGC has little impact on electricity emissions

# Electricity Sector
## We must be proficient at building e- infrastructure

**Question**: How much capacity needs to be added to the grid?

**Method**: Compare decarbonization pathways with varying degrees of electrification

*All scenarios reach similar 2045 emissions; 99% CGC by 2045*

- *Low: Choose H2, biofuels, and CCS*
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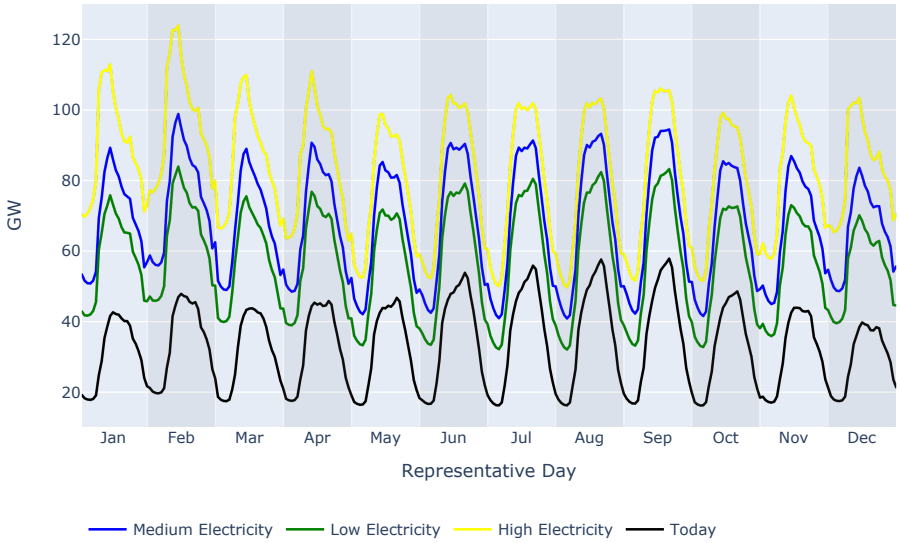
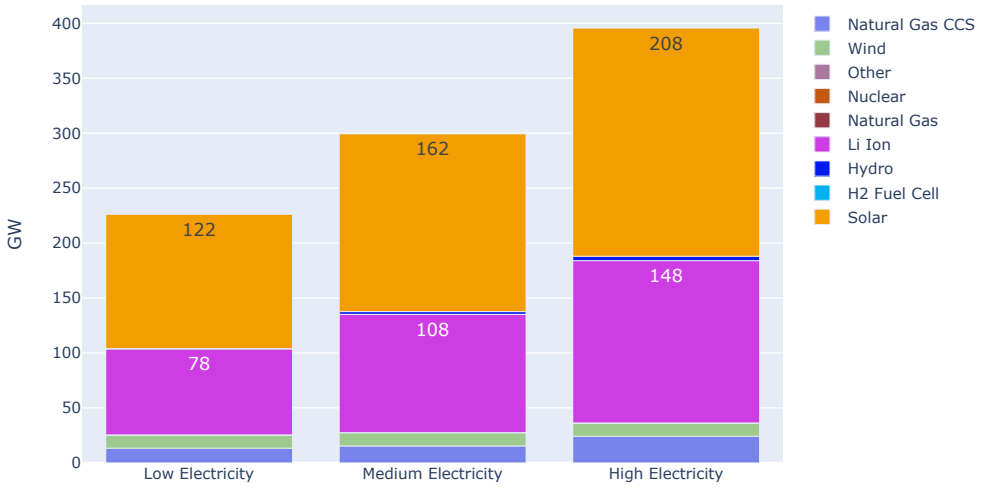
Load Shape by Scenario




Cumulative Capacity Added by Resource in 2045




- Between ~20 – 60 GW increase in peak load from the reference scenario
- Shift to a winter peaking system

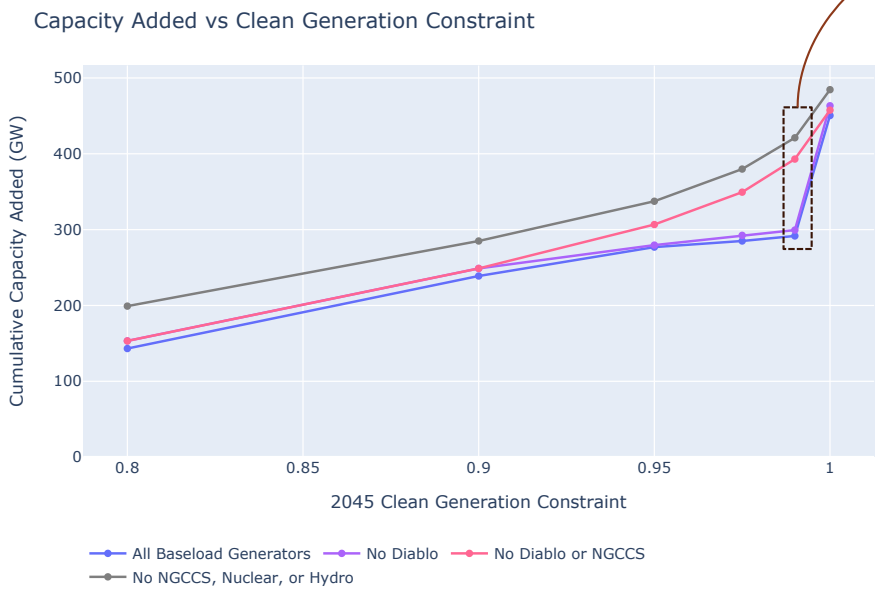
- Bounds of capacity addition for the decarbonized future: 225 – 400 GW
  - Current in-state capacity: 80 GW
  - We've added ~29GW since 2000
  - About 1-4% of CA acreage would be taken up by added solar capacity

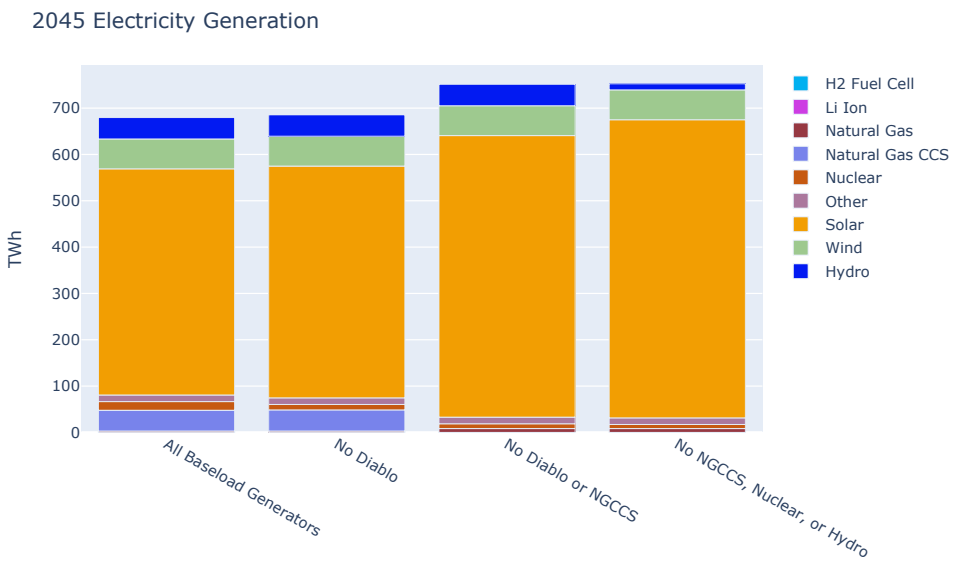
# Electricity Sector
## Clean baseload power limits overbuilding

**Question**: How important is clean baseload power?

**Method**: Stepwise remove 1) Diablo, 2) NGCCS, 3) Hydro & remaining Nuclear

99% CGC Case




- Diablo Canyon makes a small difference
- NGCCS makes a bigger difference
- Small amount of clean baseload power reduces required capacity expansion significantly

# Electricity Sector

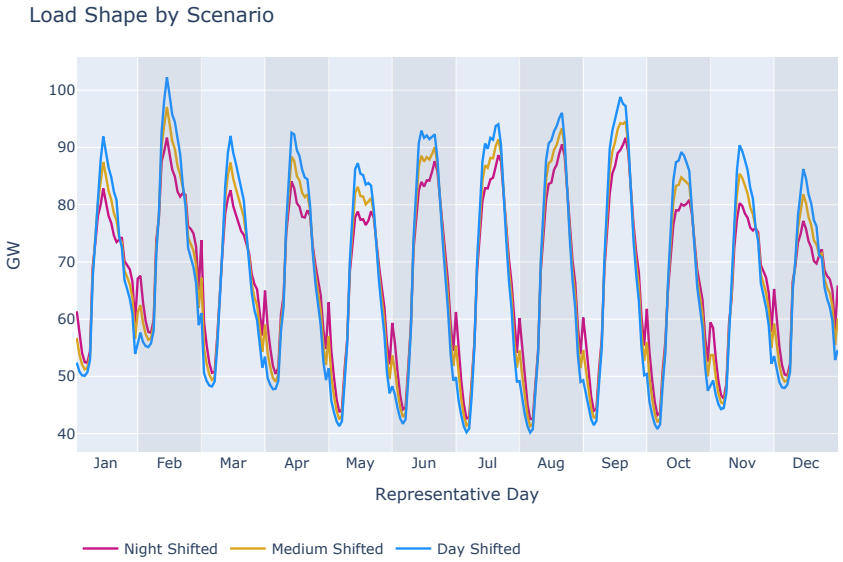
## Shiftable loads make some difference
## Deep shifting will be more challenging

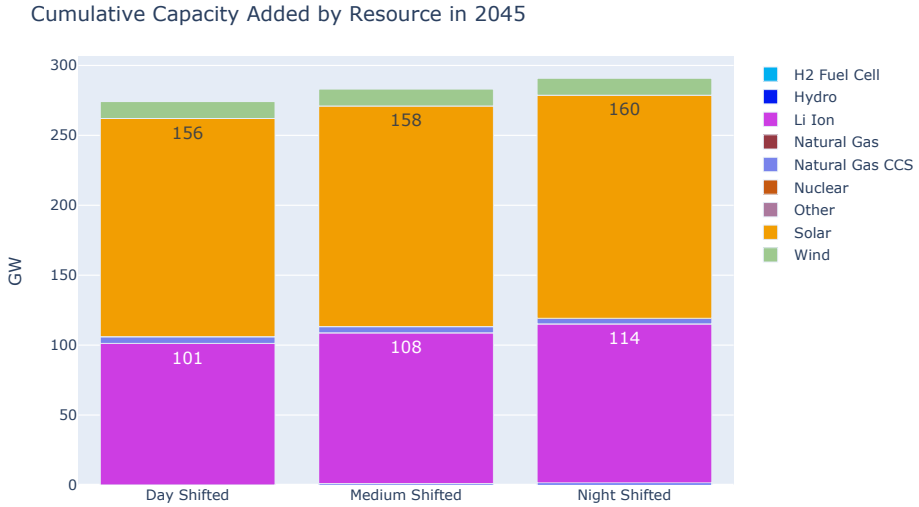
*Load shifting:*

- *Night Shifted: heavier night-time water-heating and BEV charging*
- *Medium Shifted: in between*
- *Day Shifted: heavier day-time water-heating and BEV charging*

**Question**: What is impact of temporally shifting LDV charging and residential water heating?

**Method**: Change load profiles for residential water heating and LDV-BEV charging




- Load shifting can significantly impact daytime load
- By shifting load to day-time, less solar and battery storage are required

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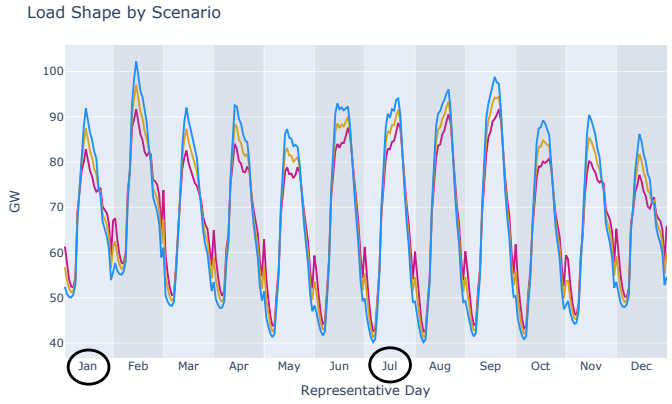


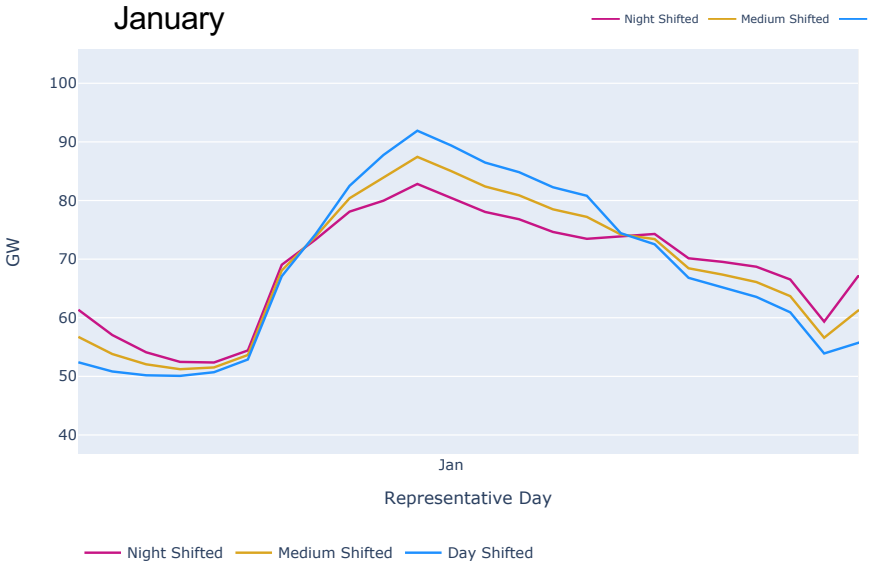


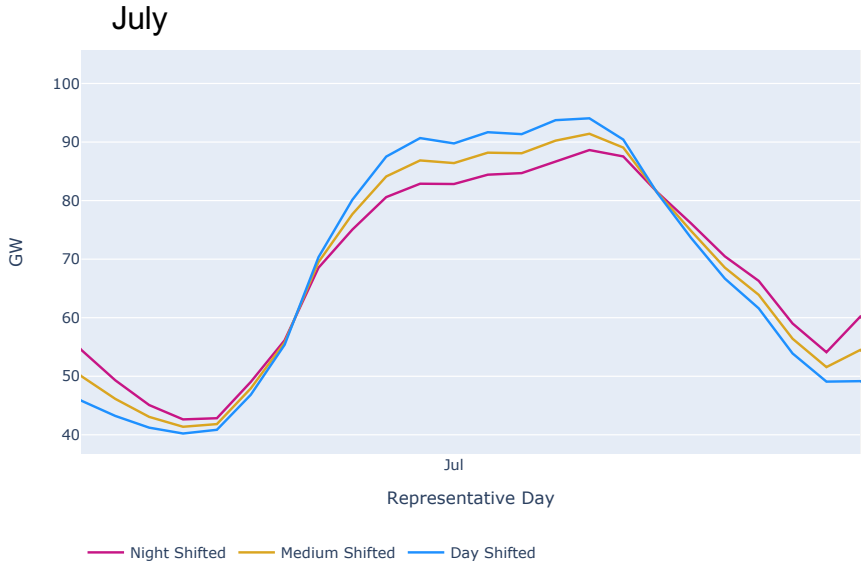

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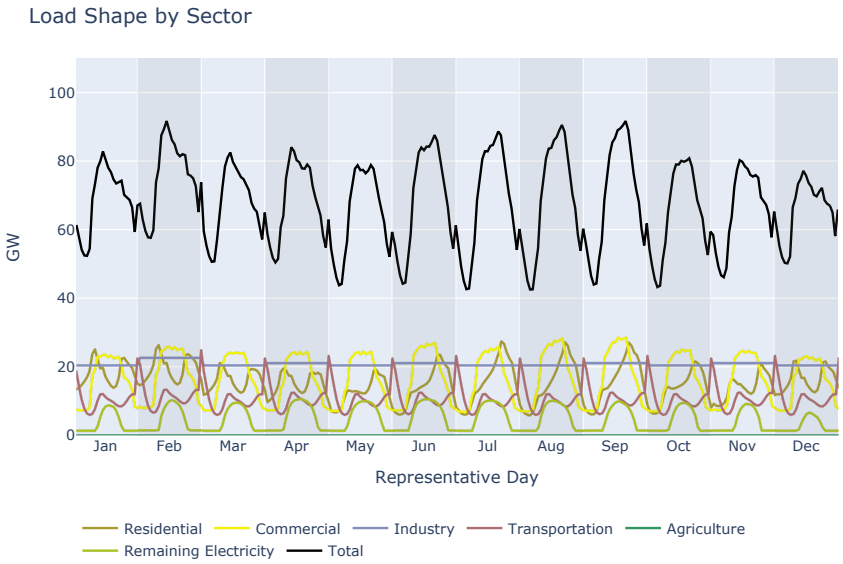
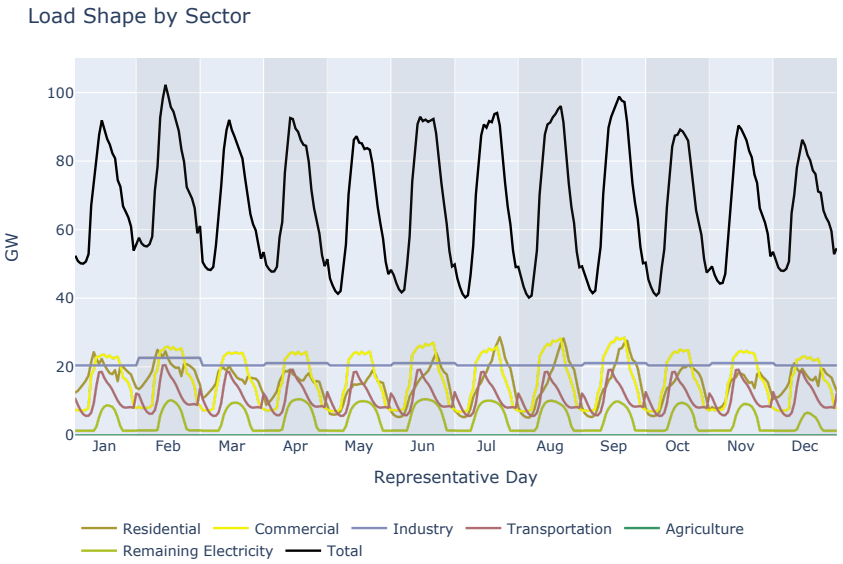
**Method**: Change load profiles for residential water heating and LDV-BEV charging

### Night-Shifted




### Day-Shifted




- Able to shift some load from night to day, but little change to nighttime load
- Deep shifting will require changes beyond residential water heaters and LDVs

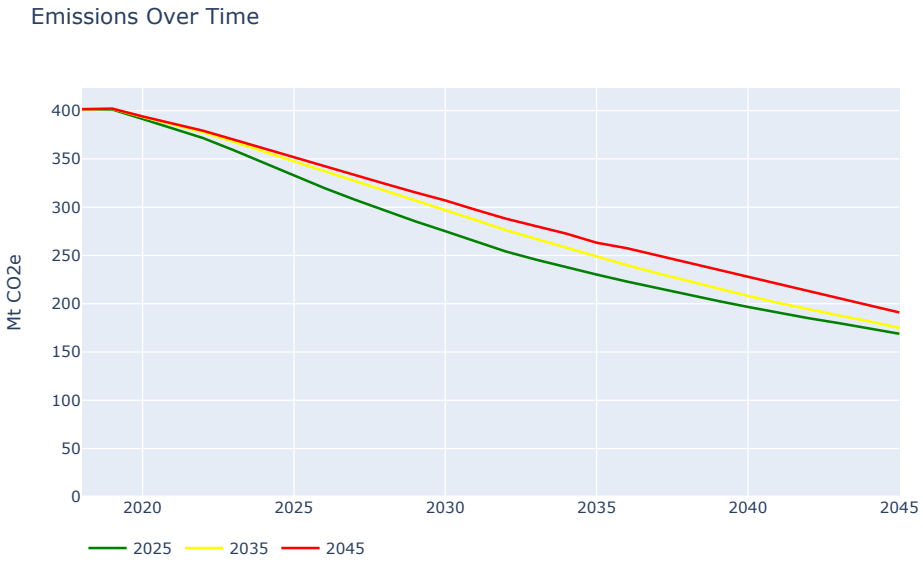
** Demand response can provide additional benefits to the grid (e.g., reliability) that DECAL cannot represent well*

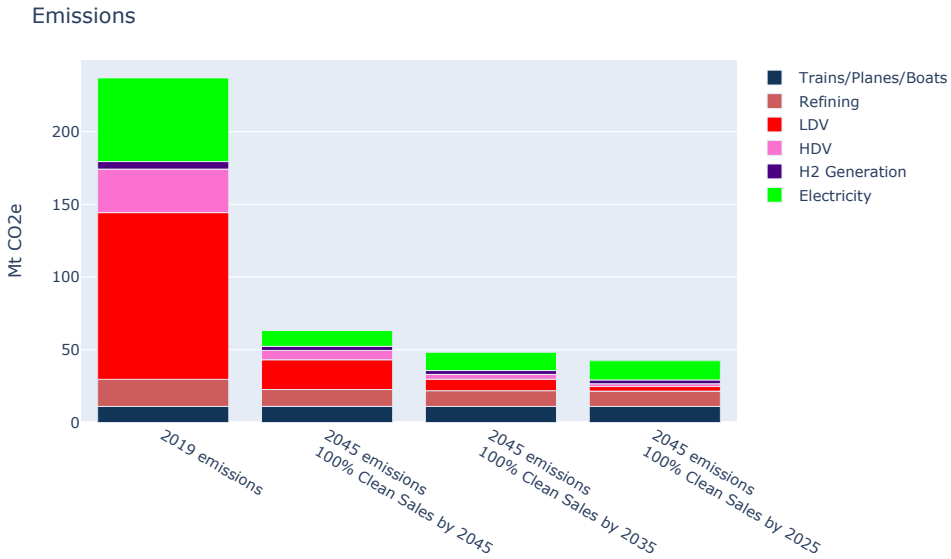
# Transportation Sector
## Policies encouraging ZEV sales can be effective

**Question**: What is the effect of ZEV adoption rate on transport emissions?

**Method**: Modify ZEV sales rates to reach 100% by 2025, 2035, and 2045 (linear interpolation)

100% ZEV sales by:




- There is currently very low ZEV penetration
- Having a policy that continually drives ZEV sales is clearly beneficial
- Existing 2035 policy will substantially reduce, but not eliminate, transport emissions

**These scenarios assume 95% CGC by 2045*

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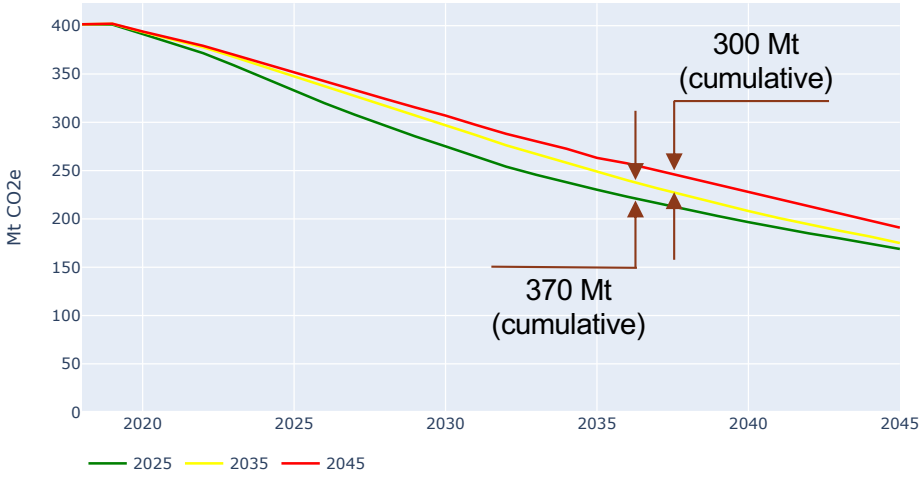
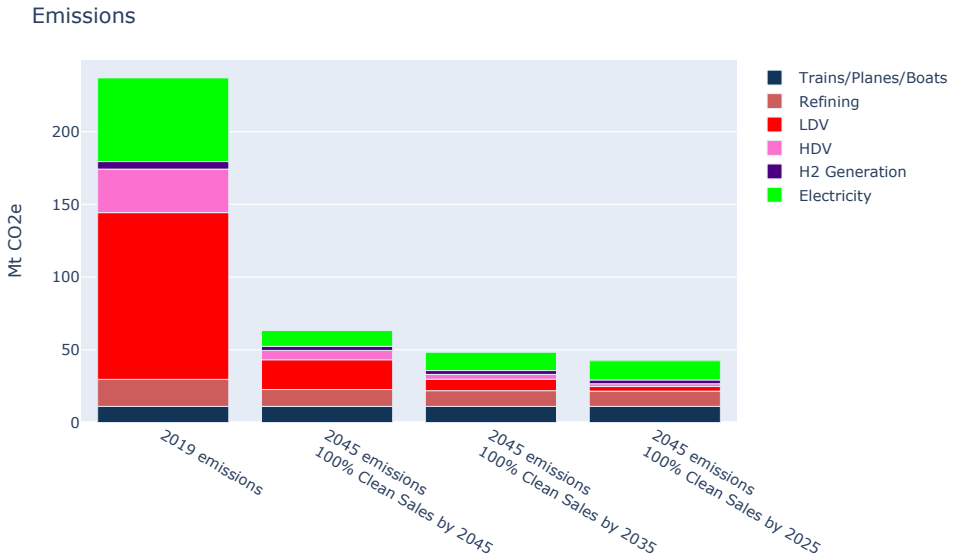
CARB Prop Cumulative Abatement: ~2860 Mt



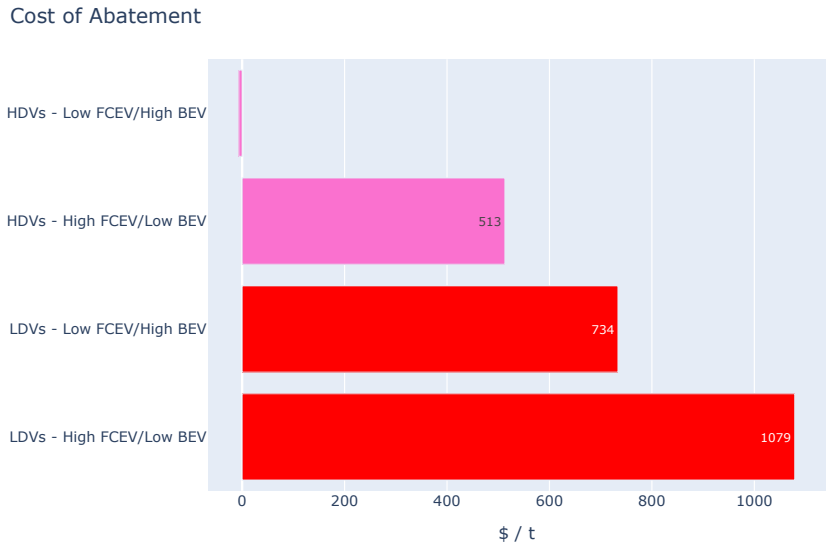

- There is currently very low ZEV penetration
- Having a policy that continually drives ZEV sales is clearly beneficial
- Existing 2035 policy will substantially reduce, but not eliminate, transport emissions
- Cumulative emissions are important to consider
  - This decision can sway cumulative marginal emissions by ±10%

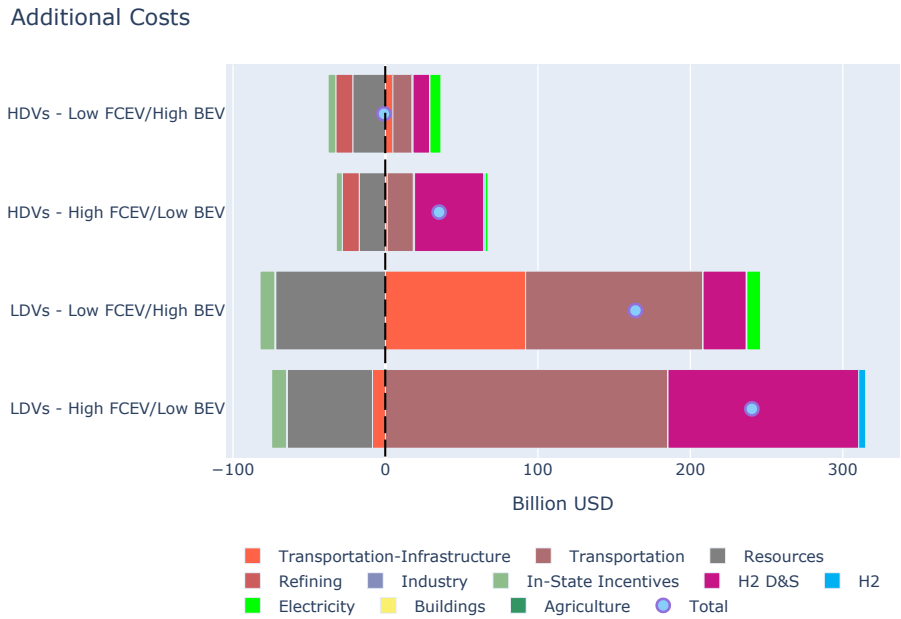
**These scenarios assume 95% CGC by 2045*

# Transportation Sector
## BEVs are an effective option

**Question**: How do costs and emissions of BEVs and FCEVs compare?

**Method**: Evaluate low/high BEV and FCEV scenarios



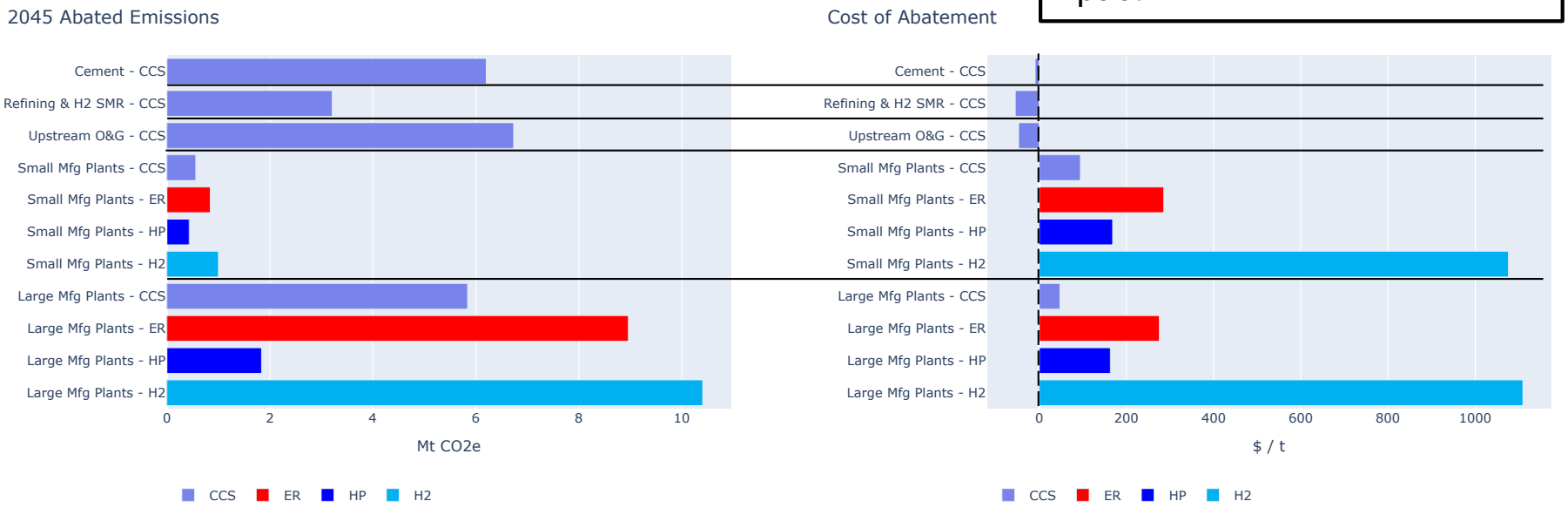

- HDVs are a less costly problem than LDVs:
  - There are fewer HDVs than LDVs
- Cost breakdown:
  - BEVs are cheaper than FCEVs
  - For BEVs, costs due to added electricity generation are relatively small
  - BEV chargers and H2 delivery and storage are both expensive

** Particularly for HDVs, many externalities (e.g., charge time, vehicle reliability, payload, etc.) are not captured*

# Industrial Sector
## CCS is an effective and affordable option

**Question**: Which decarbonization technology is preferrable for the industrial sector?

**Method**: Evaluate technology options for emissions and cost impact




- For cement, upstream O&G facilities, and refineries & SMRs, CCS is the only option
- For all facilities, CCS is an affordable option
- CCS may be logistically difficult for small manufacturing plants, even if cost effective
- Petrochemical and mineral plants cannot use HPs for process heating due to temp constraints
- Fuel switching to H2 is not a cost-effective solution

** Economics evaluated from perspective of the state; marginal cost of electricity is significantly lower to the state than to the ratepayer.*

# Industrial Sector

## Incentives have a large impact on CCS technoeconomics

**Question**: What is the impact of incentives on CCS technoeconomics?
**Method**: Evaluate CCS with incentives on, off, or 45Q start date extended through 2045


45Q applicable
45Q & LCFS applicable

Mistake applying 45Q to small mfg plants. Will fix

- Extending 45Q start date or accelerating CCS can have an impact on technoeconomics

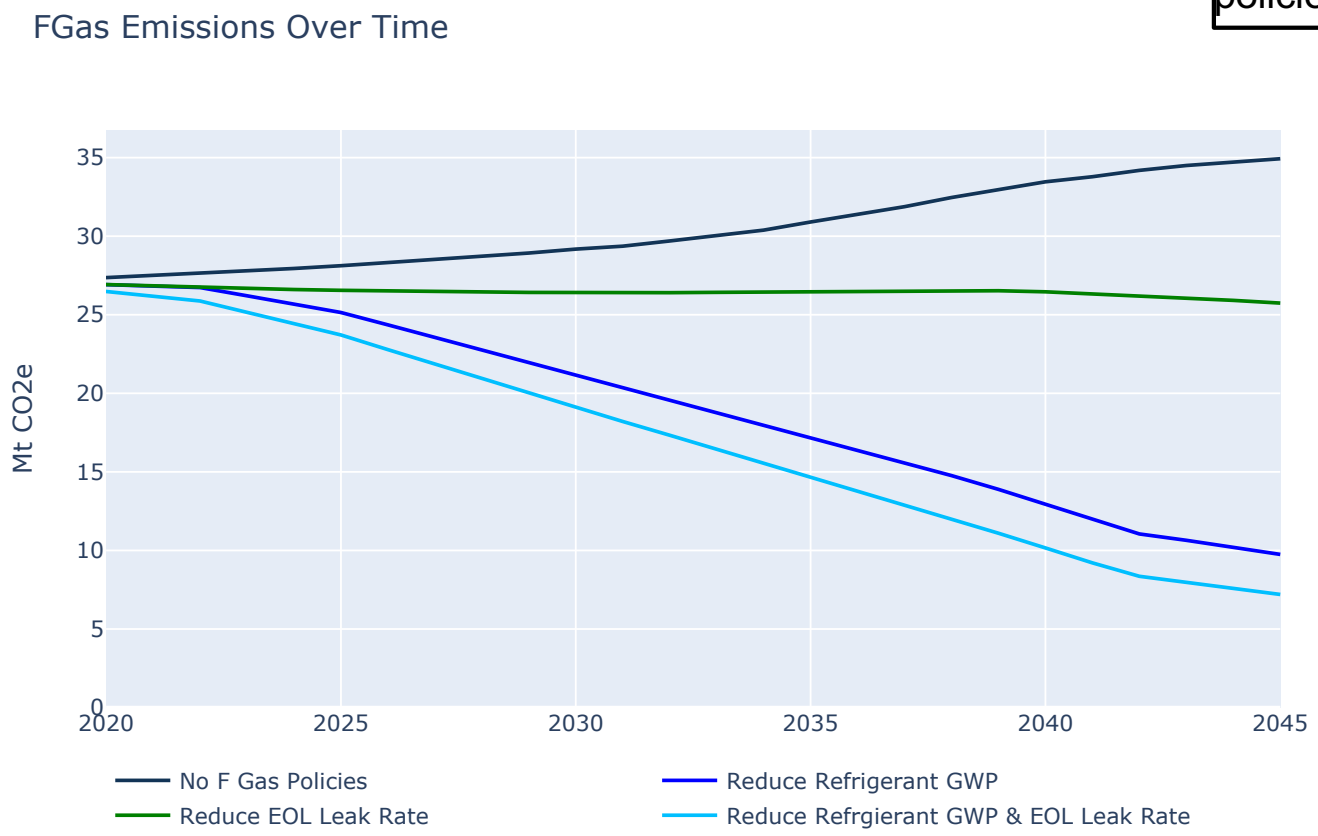
**Economics evaluated from perspective of the state; marginal cost of electricity is significantly lower to the state than to the ratepayer.*

# F-Gases

## Existing solutions are helpful
## Innovation is needed for deep reductions

**Question**: What is the impact of various F-gas policies?

**Method**: Evaluate the effect of EOL and annual F-gas policies on emissions.




- EOL F-Gas strategies can help keep F-Gas emissions constant, despite installing millions of heat pumps
- Deep reductions will require low GWP refrigerants, like $CO_2$ or propane

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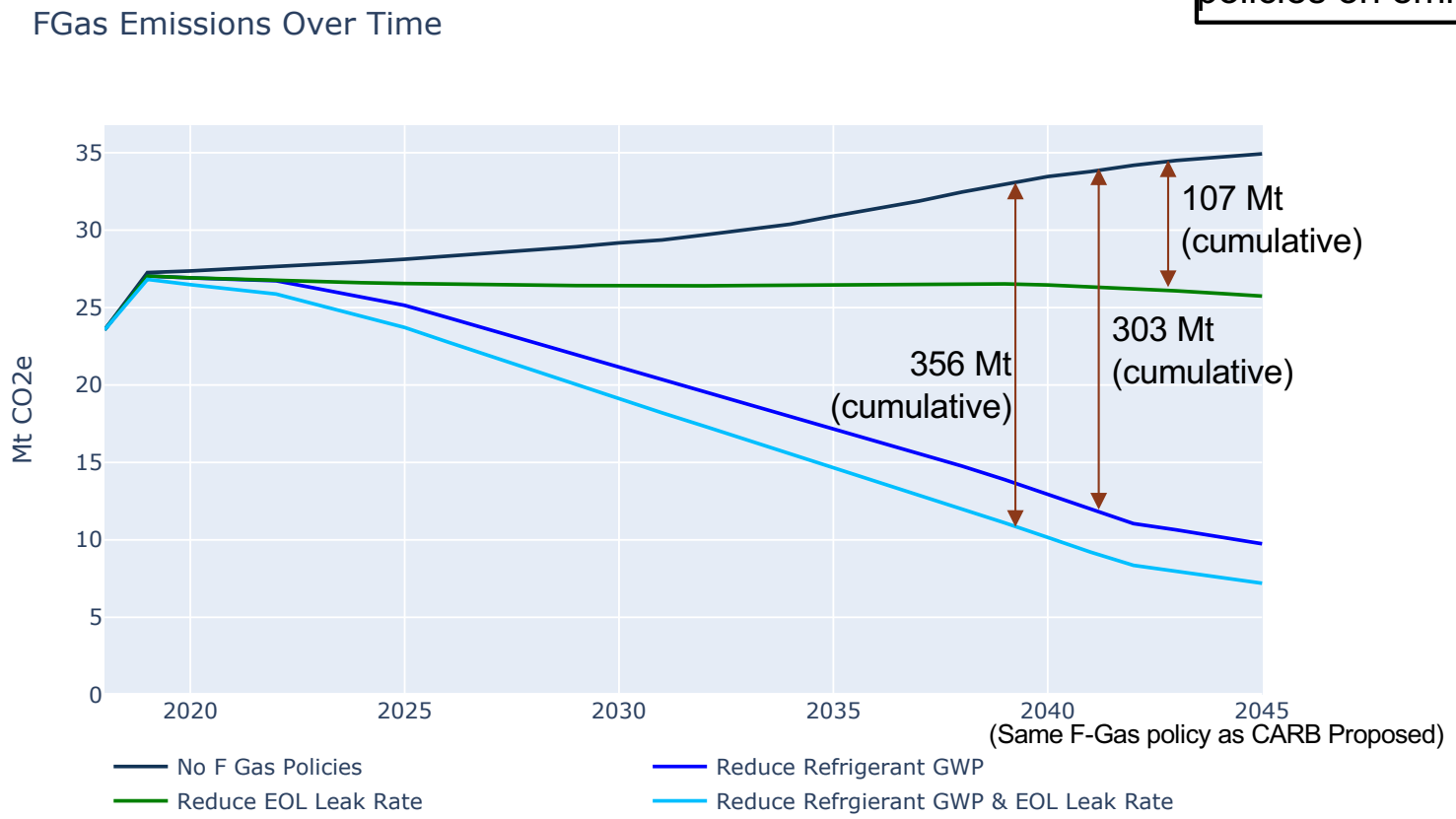


CARB Prop Cumulative Abatement: ~2860 Mt

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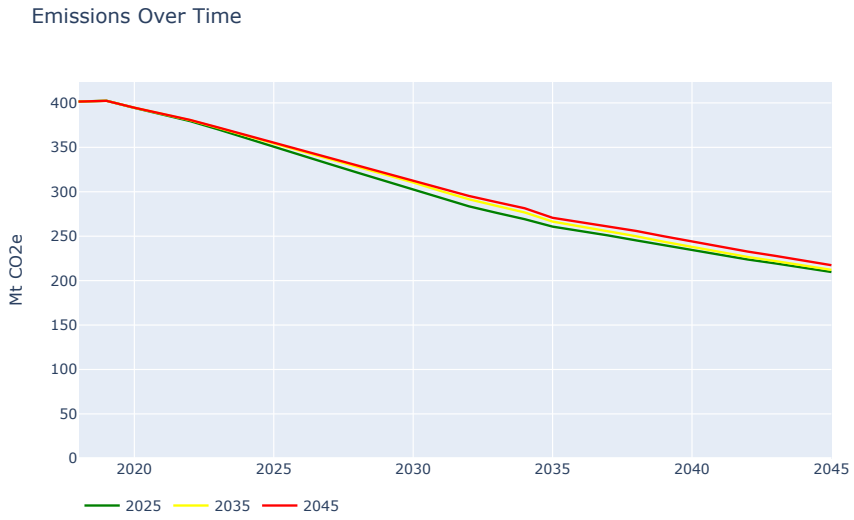
- Deep reductions will require low GWP refrigerants, like $CO_2$ or propane

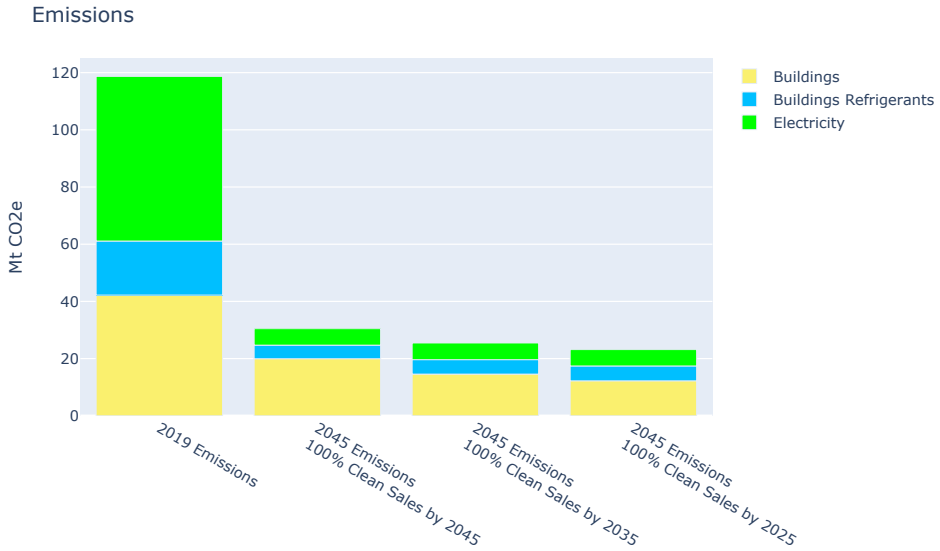
# Buildings Sector
## Policies encouraging HP adoption can be effective

**Question**: What is the effect of heat pump adoption rate on buildings sector emissions?

**Method**: Evaluate heat pump sales rates reaching 100% by 2025, 2035, and 2045 (linearly interpolate).

100% clean sales by:




- There is currently very low HP penetration
- Having a policy that continually drives HP sales is clearly beneficial
- CARB's proposed 2030 policy (banning sale of NG furnaces and water heaters) would substantially reduce, but not eliminate, buildings sector emissions

**Remaining building sector emissions are classified as 'other' and are not impacted by this scenario*
***These scenarios assume 95% CGC by 2045*

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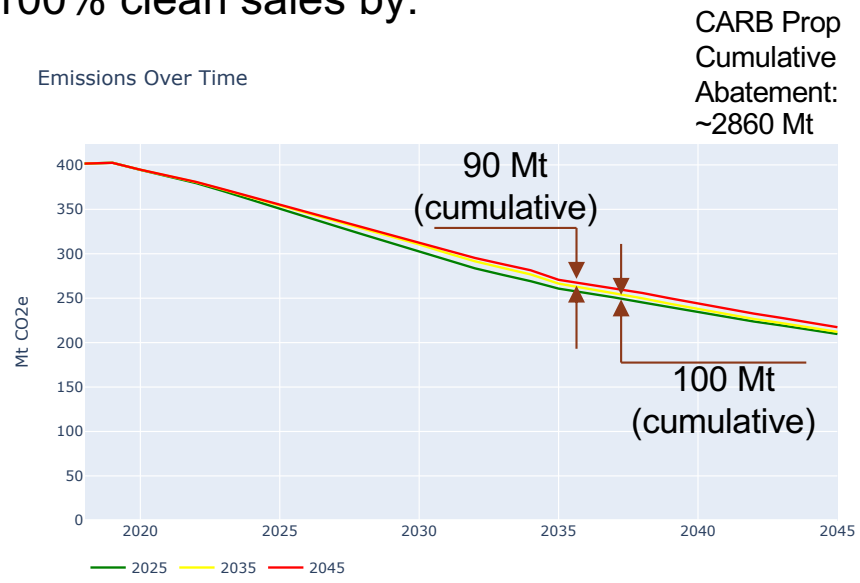


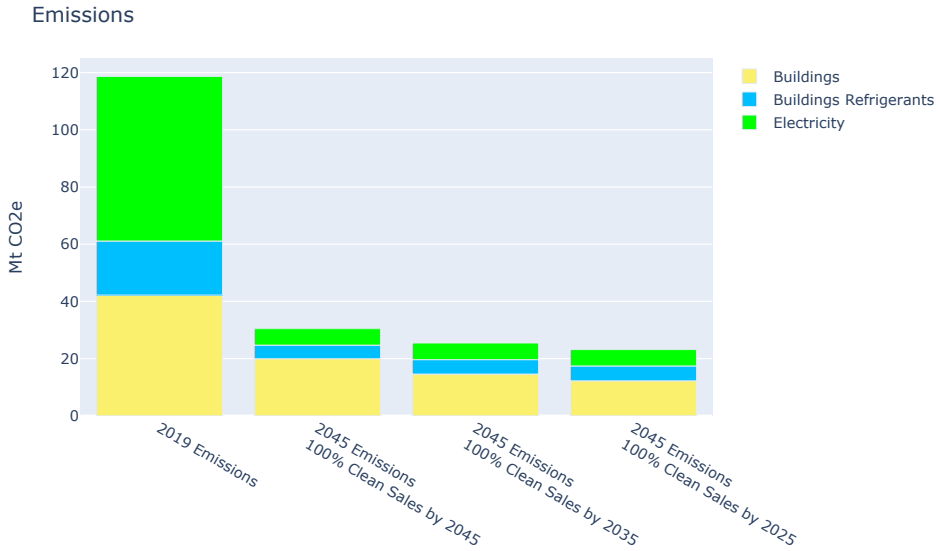


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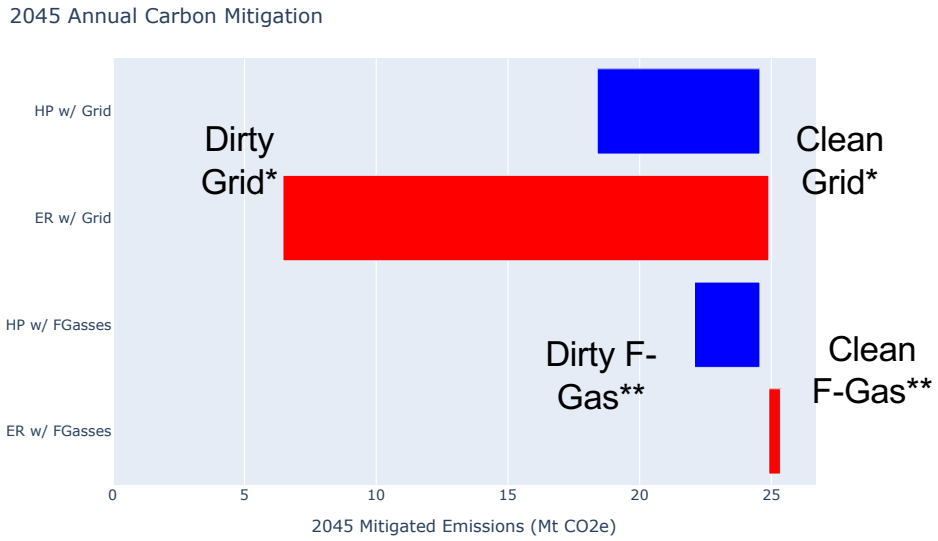
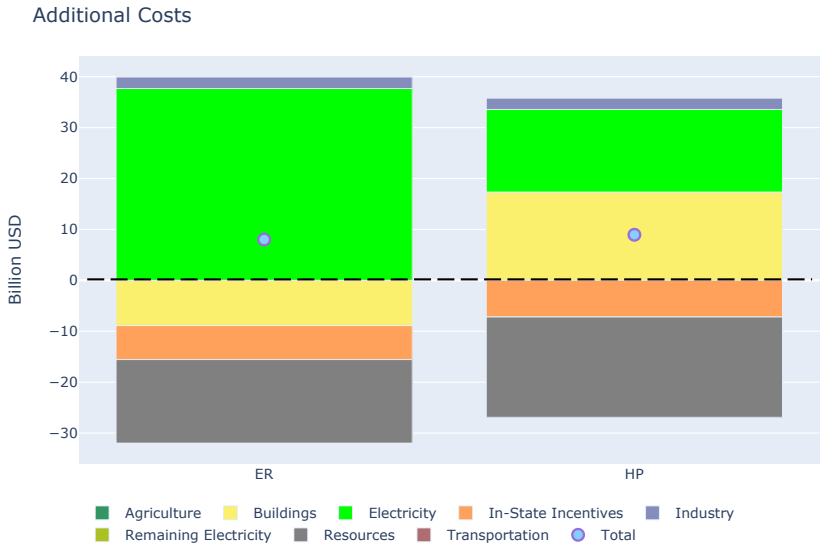
**Remaining building sector emissions are classified as 'other' and are not impacted by this scenario*
***These scenarios assume 95% CGC by 2045*

# Buildings Sector
## ER & HP are both effective options

**Question**: How do costs and emissions of different building electrification options compare?

**Method**: Evaluate ER vs HP under different grid and F-Gas assumptions.




- ER is less effective with a dirty grid
- ACs and HPs have F-gas emissions, while ERs do not
- Whether choosing ER or HPs, the F-Gas stock will remain relatively similar because HPs replace ACs, while ERs still require ACs

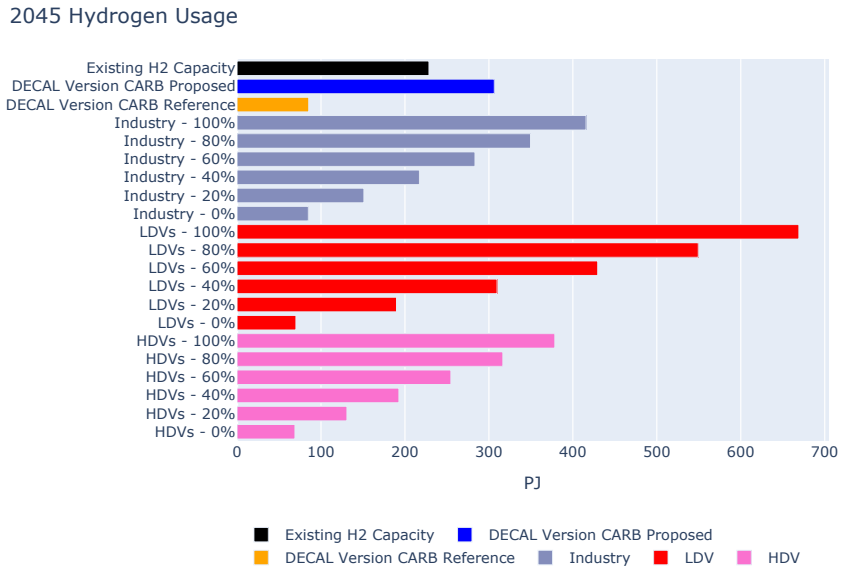
- HPs are more efficient than ERs
- HP - higher upfront costs, lower e- costs
- ER - lower upfront costs, higher e- costs

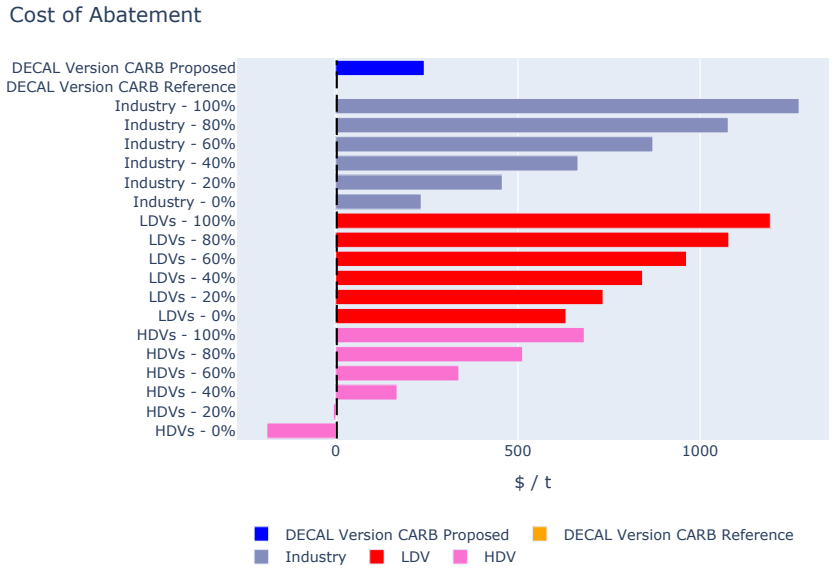
**Assumes clean F-Gases; **Assumes clean grid*

# Hydrogen Usage
## H2 will require careful planning

**Question**: What role can H2 play in decarbonizing CA?

**Method**: Change adoption of H2 technologies in industry and transportation (where applicable)



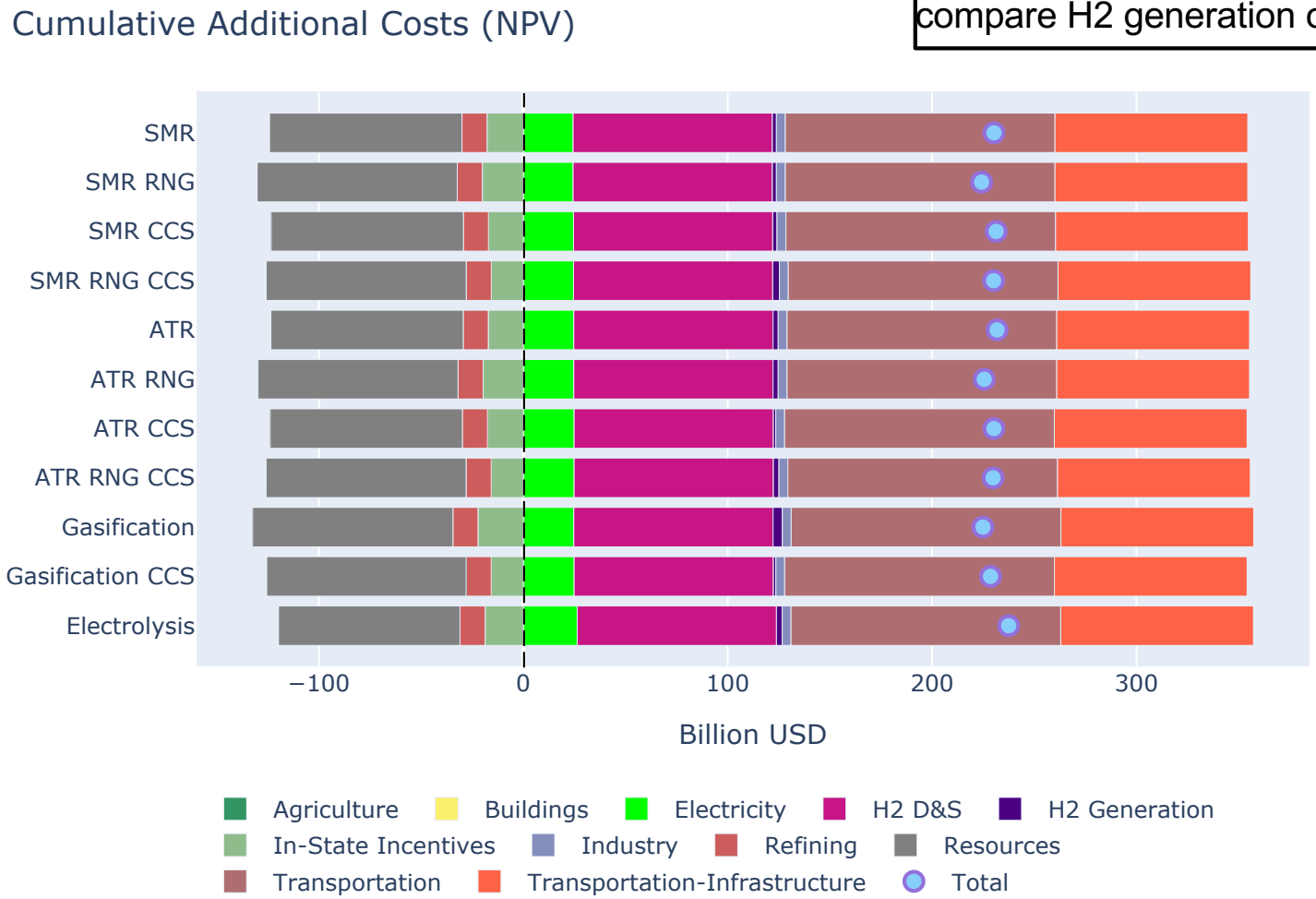




- Left plot provides helpful guideposts as to “how much” H2 can be used in each sector
  - Ex: DECAL Version CARB Proposed requires build out
- H2 is expensive; cost should play into planning as well
- H2 may be best prioritized in HDVs

# Hydrogen Generation
## H2 Delivery and Storage drive costs

**Question**: What is the impact of different H2 generation methods on costs?

**Method**: Using a high H2 scenario, compare H2 generation options



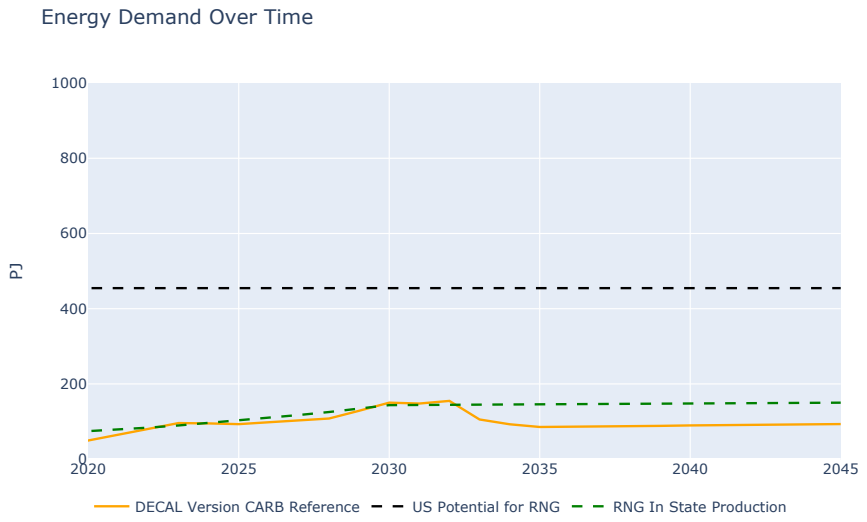

- H2 generation is a very small fraction of these scenarios' marginal costs
- Scenario marginal costs vary <6% between scenarios

# Renewable Natural Gas
## RNG will require careful planning

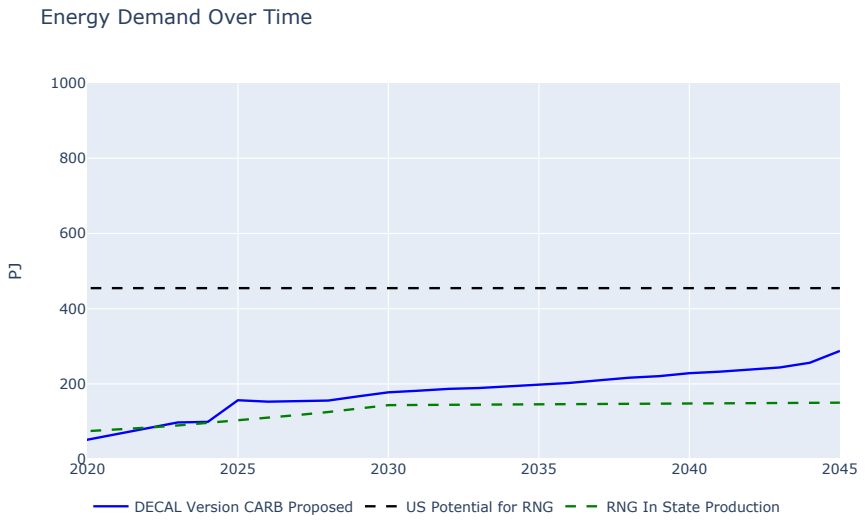
**Question**: What role can RNG play in decarbonizing CA?

**Method**: Evaluate RNG use in DECAL versions of CARB Reference and Proposed scenarios

DECAL Version CARB Reference




DECAL Version CARB Proposed




- CARB Proposed strategy may pose risk to resource constraints

** US Potential for RNG - https://www.nrel.gov/docs/fy14osti/60178.pdf*

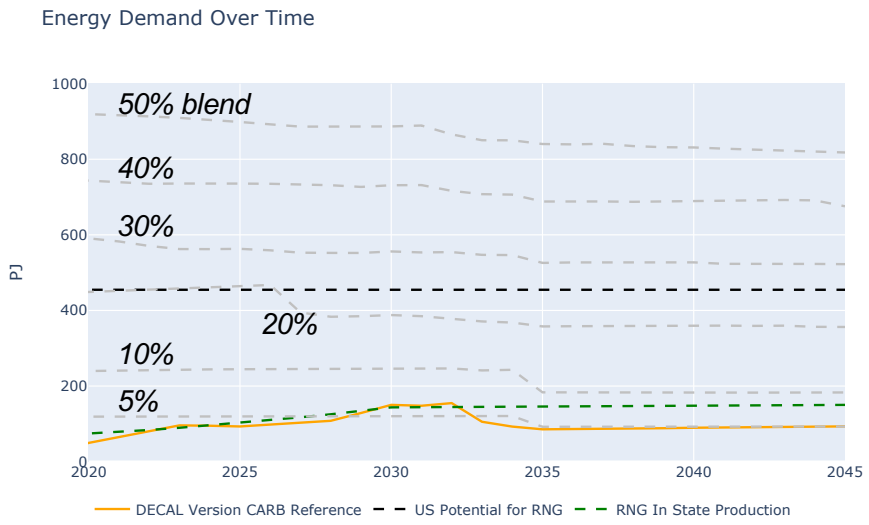
*** RNG In State Production – Arifi et. al, 2022 (assumes food waste used for AD instead of compost)*

# Renewable Natural Gas
## RNG will require careful planning

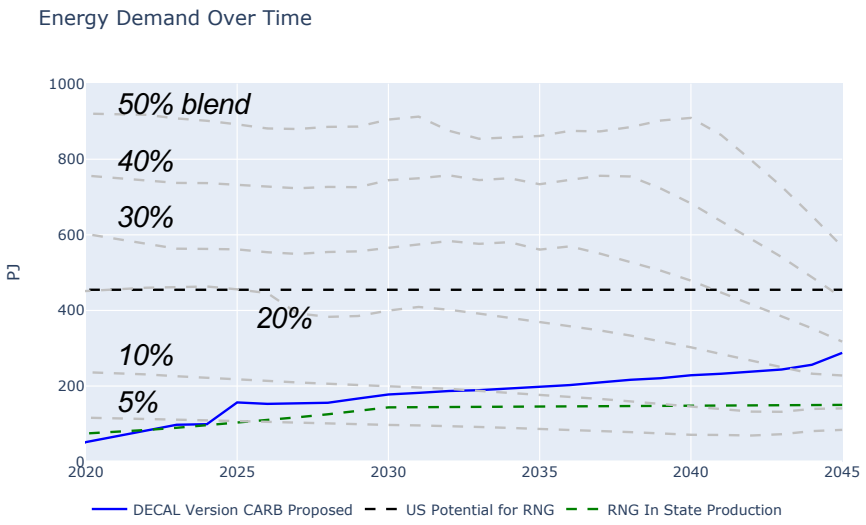
**Question**: What role can RNG play in decarbonizing CA?

**Method**: Change the blend level of RNG.

### DECAL Version CARB Reference




### DECAL Version CARB Proposed



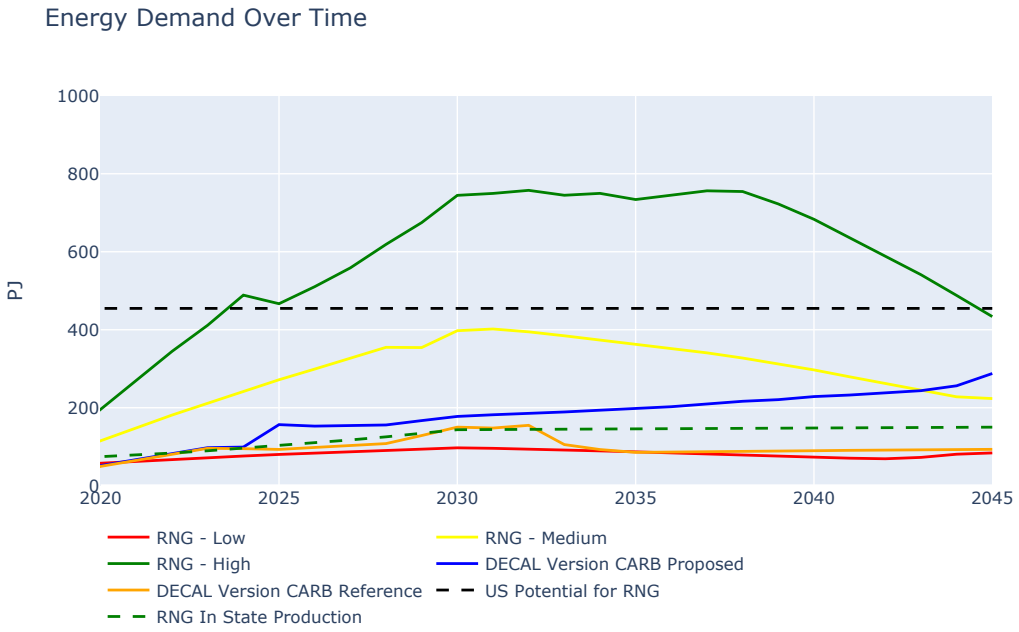

- CARB Proposed strategy may pose risk to resource constraints
- Contour maps show RNG use with different blends assuming unlimited supply and can help guide planning

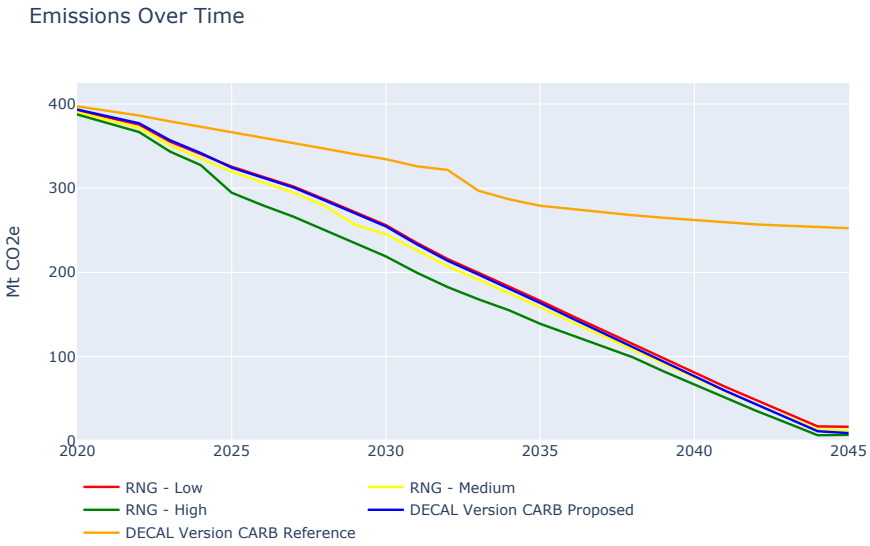
# Renewable Natural Gas
## RNG will require careful planning

**Question**: What role can RNG play in decarbonizing CA?

**Method**: Evaluate Low, Medium, and High RNG blends.

### Emissions Compared to DECAL Version of CARB Proposed



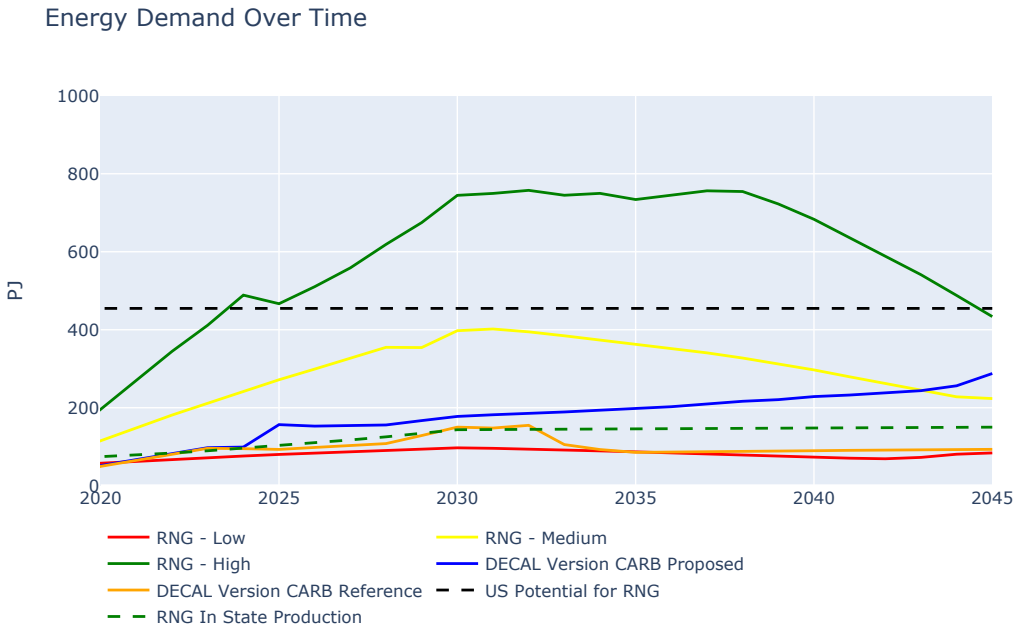

- High RNG blend fractions can have an immediate and significant impact on emissions
- Given that there is more NG used earlier in the scoping plan period, high blend fractions have greater impact earlier on
- Resource constraints need to be carefully considered

# Renewable Natural Gas
## An 'immediate' decarbonization opportunity

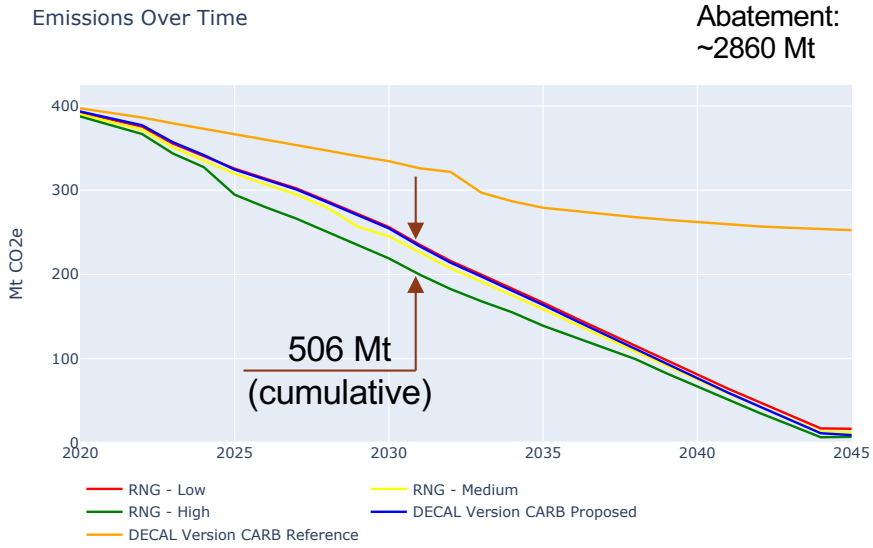
**Question**: What role can RNG play in decarbonizing CA?

**Method**: Evaluate Low, Medium, and High RNG blends.

### Emissions Compared to DECAL Version of CARB Proposed




CARB Prop Cumulative Abatement: ~2860 Mt



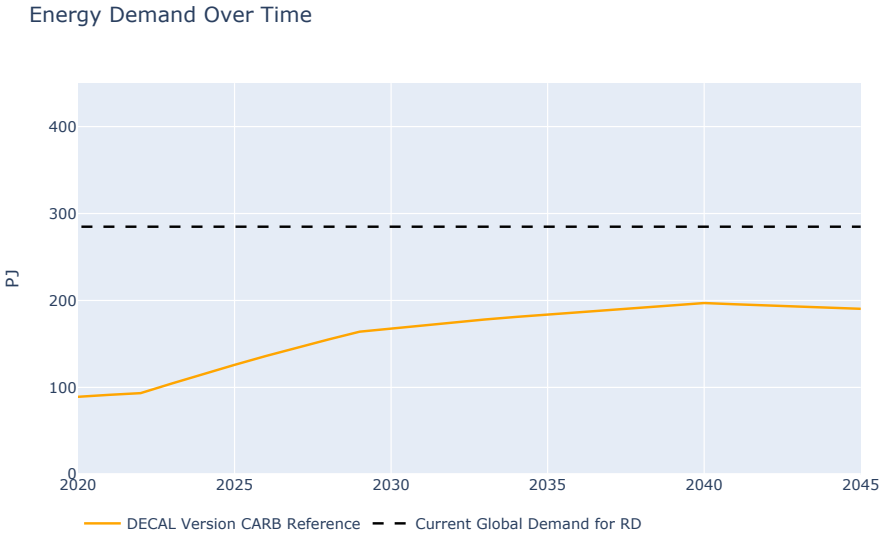

- High RNG blend fractions can have an immediate and significant impact on emissions
- Given that there is more NG used earlier in the scoping plan period, high blend fractions have greater impact earlier on
- Resource constraints need to be carefully considered

# Renewable Diesel
## RD will require careful planning

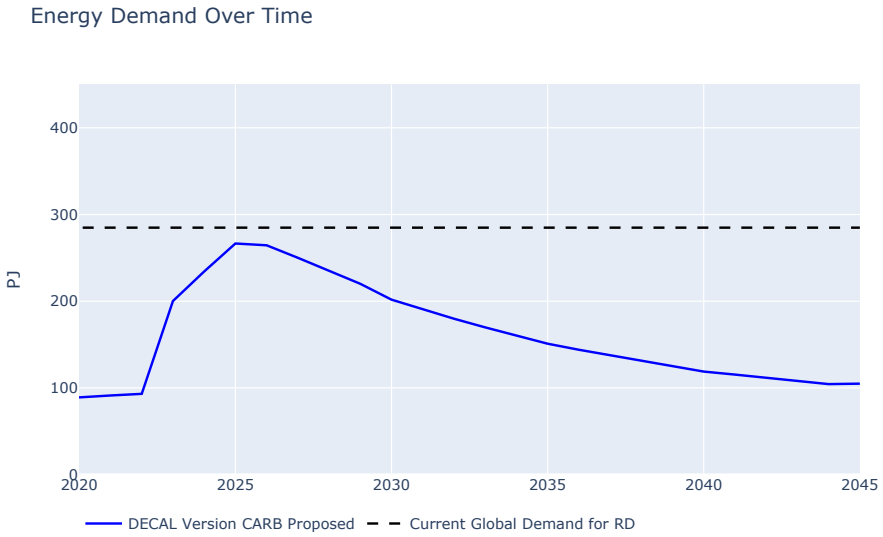
**Question**: What role can RD play in decarbonizing CA?

**Method**: Evaluate RD use in DECAL versions of CARB Reference and Proposed scenarios

DECAL Version CARB Reference




DECAL Version CARB Proposed




- CARB Proposed strategy may pose risk to resource constraints

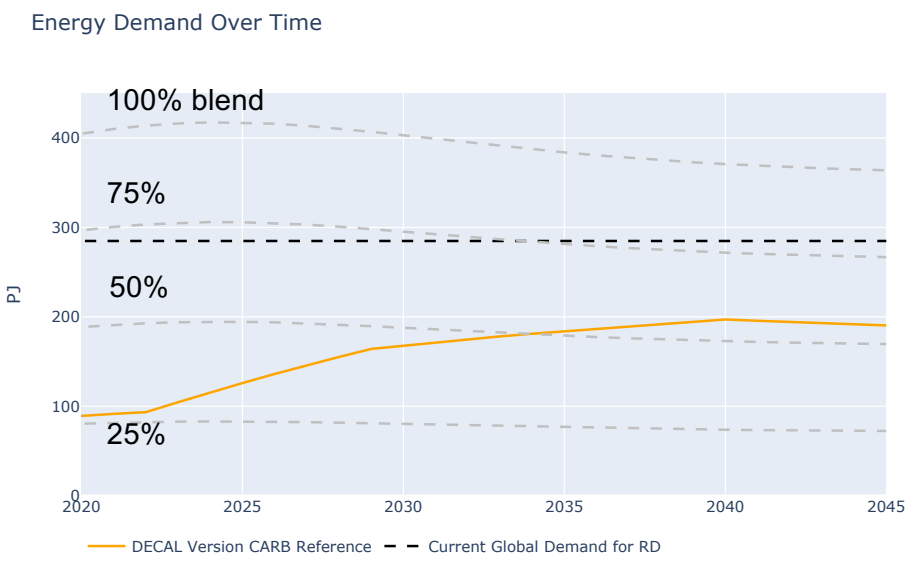
** Current Global Demand for RD - https://www.iea.org/reports/renewables-2021/biofuels*

# Renewable Diesel
## RD will require careful planning

**Question**: What role can RD play in decarbonizing CA?

**Method**: Change the blend level of RD.

DECAL Version CARB Reference

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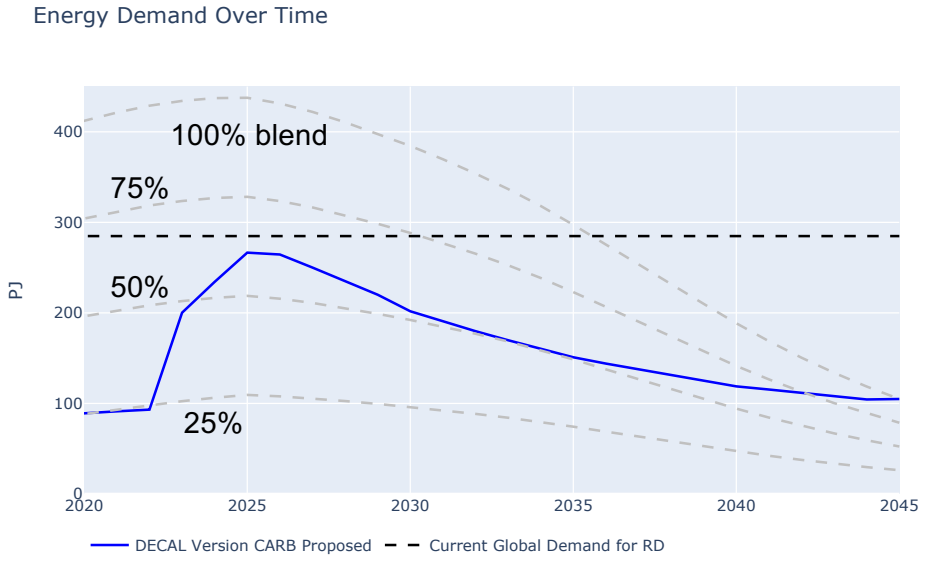



- CARB Proposed strategy may pose risk to resource constraints
- Contour maps show RD use with different blends assuming unlimited supply and can help guide planning
- The blend level that can be supported increases as ZEVs penetrate the fleet

# Renewable Diesel

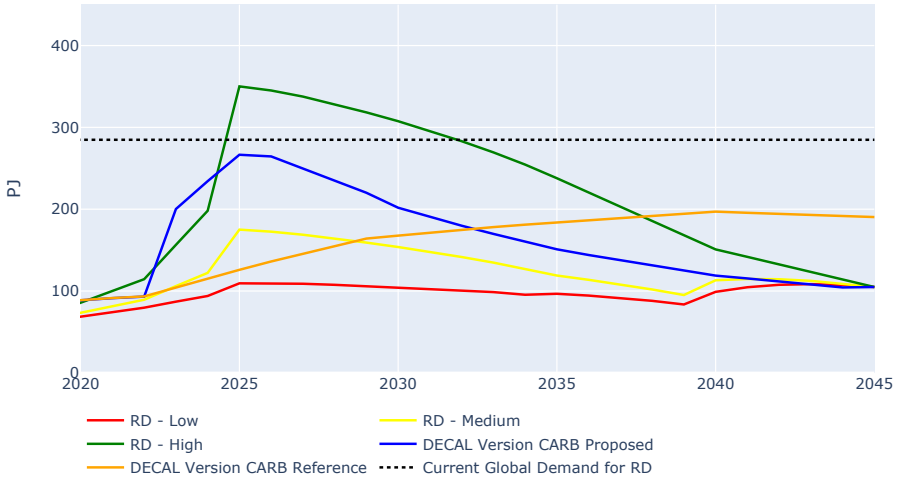
## RD provides an immediate opportunity
## ZEV sales are a long-term solution

**Question**: Even if ZEVs are the future, what role can low CI fuels play now?

**Method**: Evaluate High, Medium, and Low RD blends

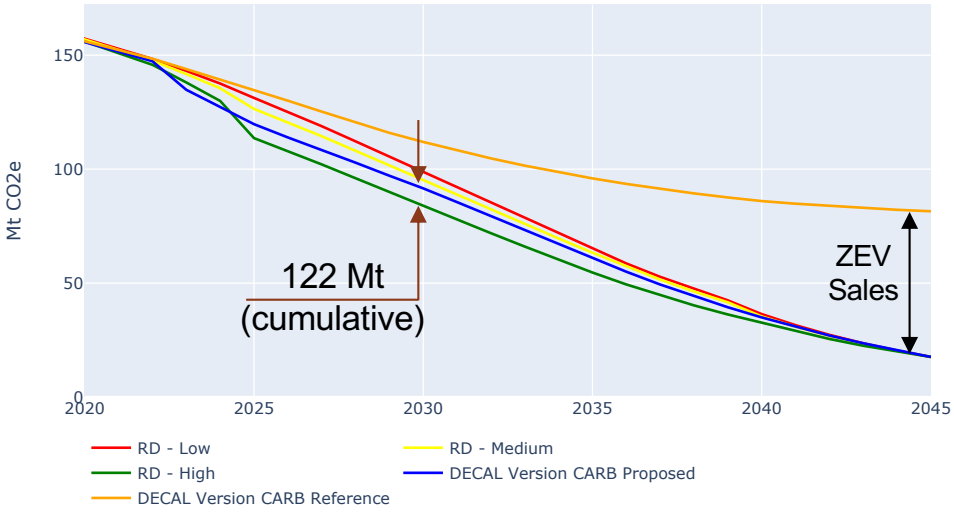
### Emissions Compared to DECAL Version CARB Proposed

Energy Demand Over Time




Transportation Emissions Over Time

CARB Prop Cumulative Abatement: ~2860 Mt



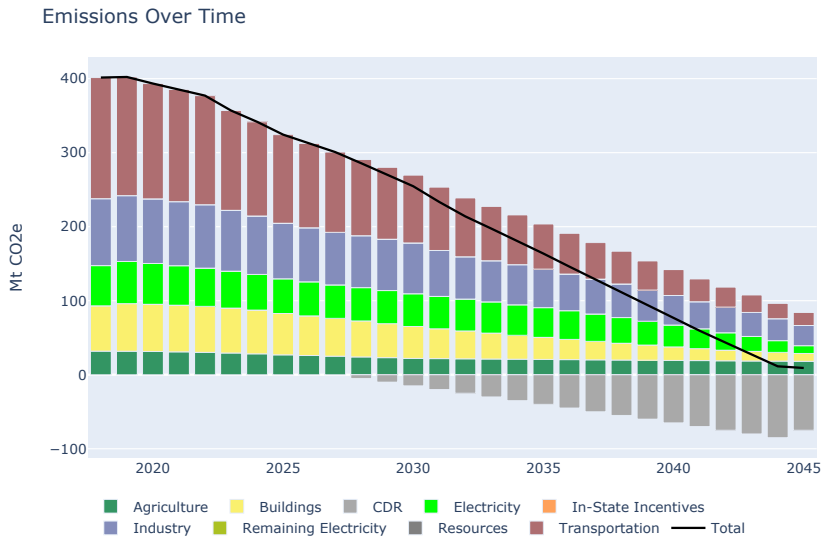

- Deep decarbonization of the transportation sector will ultimately rely on ZEV sales

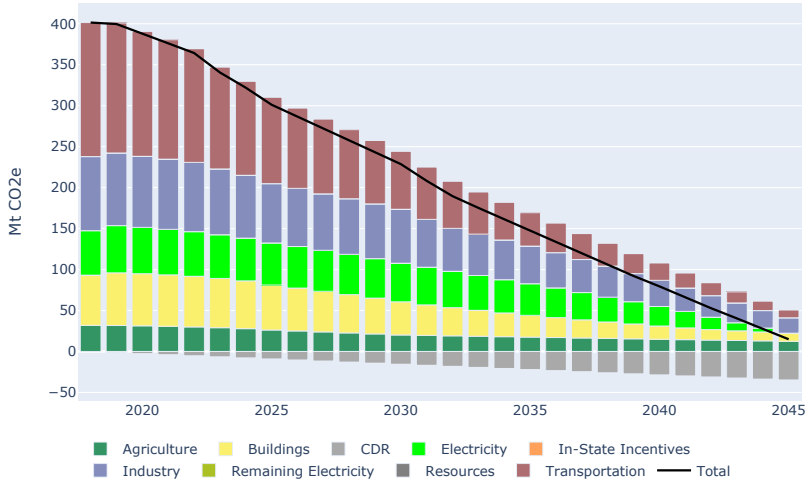
# Direct Air Capture

## Net-zero will be difficult without DAC and/or other innovations

**Question**: What is the minimal amount of CDR/DAC that can be used while still meeting net-zero goal?

**Method**: Deep deployment of all decarbonization technologies




| | DECAL Version of CARB Proposed | Minimal DAC Scenario |
|---|---|---|
| **CDR** | • 75Mt in 2045 | • 35Mt in 2045 |
| **Electricity** | • 95% clean generation by 2045 | • 99% clean generation by 2045 |
| **Transport** | • 100% LDV sales ZEV by 2035<br>• 100% HDV sales ZEV between 2035-2040<br>• 100%/50%/25% reduction planes/trains/boats | • 100% LDV sales ZEV by 2030<br>• 100% HDV sales ZEV by 2030-2035<br>• 100% reduction planes/trains/boats |
| **Buildings** | • 100% clean sales by 2035/2045 Res/Comm | • 100% clean sales by 2030 |
| **Industry** | • ~50% deployment of CCS where applicable | • Deep deployment of CCS where applicable<br>• Electrify Industry – Other |
| **Agriculture** | • Seaweed : 50% eligibility, 30% reduction rate | • Seaweed : 85% eligibility, 60% reduction rate |

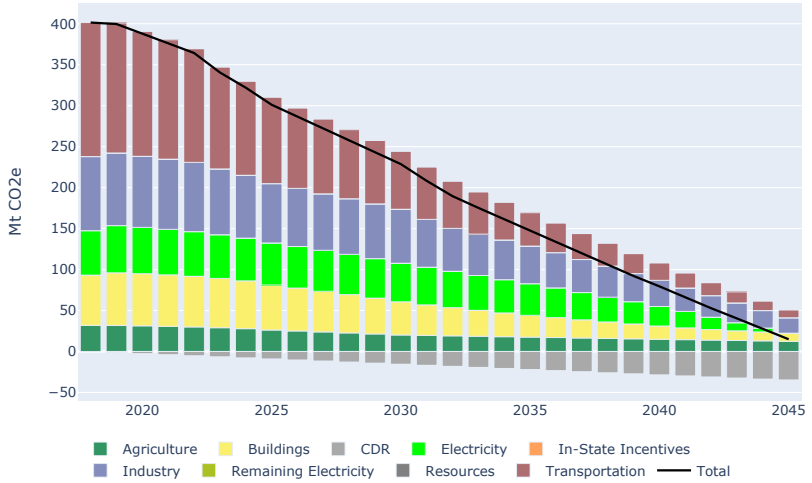
# Direct Air Capture

## Net-zero will be difficult without DAC and/or other innovations

**Question**: What is the minimal amount of CDR/DAC that can be used while still meeting net-zero goal?

**Method**: Deep deployment of all decarbonization technologies

- Even with (beyond) extreme decarbonization assumptions, reaching net-zero emissions still requires 35 Mt/yr of CDR in 2045

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# Conclusions: What will it take to reach net-zero emissions by 2045?

| Category | Conclusion |
|---|---|
| **Silver Bullet** | • All resources will be needed |
| **Economy Wide Overview** | • A few policies are key<br>• Only some are affordable<br>• Electric load will grow in every sector |
| **Electricity Sector** | • We must be proficient at building electric infrastructure<br>• A clean grid is key, but 100% clean may not be needed<br>• Clean baseload power reduces cost<br>• Some load can be shifted, but deep shifting will be challenging |
| **Transportation Sector** | • Policies encouraging ZEV sales can be effective<br>• BEVs are an effective and affordable option |
| **Industrial Sector** | • CCS is an effective and affordable option<br>• Incentives have a large impact on CCS technoeconomics |
| **F-Gasses** | • EOL programs are helpful but not enough on their own<br>• Innovation is needed for deep reductions |
| **Buildings** | • Policies encouraging electric heating can be effective<br>• ER and HP are both effective options |
| **Hydrogen** | • H2 is expensive, but is most cost-effective in HDVs<br>• H2 delivery and storage costs far outweigh generation costs |
| **Renewable Natural Gas** | • Careful resource planning will be required<br>• Fast adoption is beneficial |
| **Renewable Diesel** | • Careful resource planning will be required<br>• Fast adoption is beneficial<br>• Deep decarbonization of the transportation sector will ultimately rely on ZEV sales |
| **Direct Air Capture** | • Net-zero will be difficult without DAC |

# Action Items

**R&D Focus Areas**

- CDR – cost and parasitic load reduction for DAC technologies
- F-Gases – low GWP F-Gases (e.g.: CO2, propane)
- Biofuel feedstocks – identifying additional feedstocks
- H2 Distribution and Storage cost reductions
- Li Ion battery costs for vehicles

**Policy Implications**

- NG water and space heating sales reductions are needed
- Electricity generation – 99% CGC is more cost effective than 100%; clean baseload power can help reduce costs
- Streamline building electricity, BEV charging, CDR, CCS, and biofuel infrastructure

# Future Opportunities

DECAL can be used to address a number of additional questions:

- xxx

Thank you! Questions?

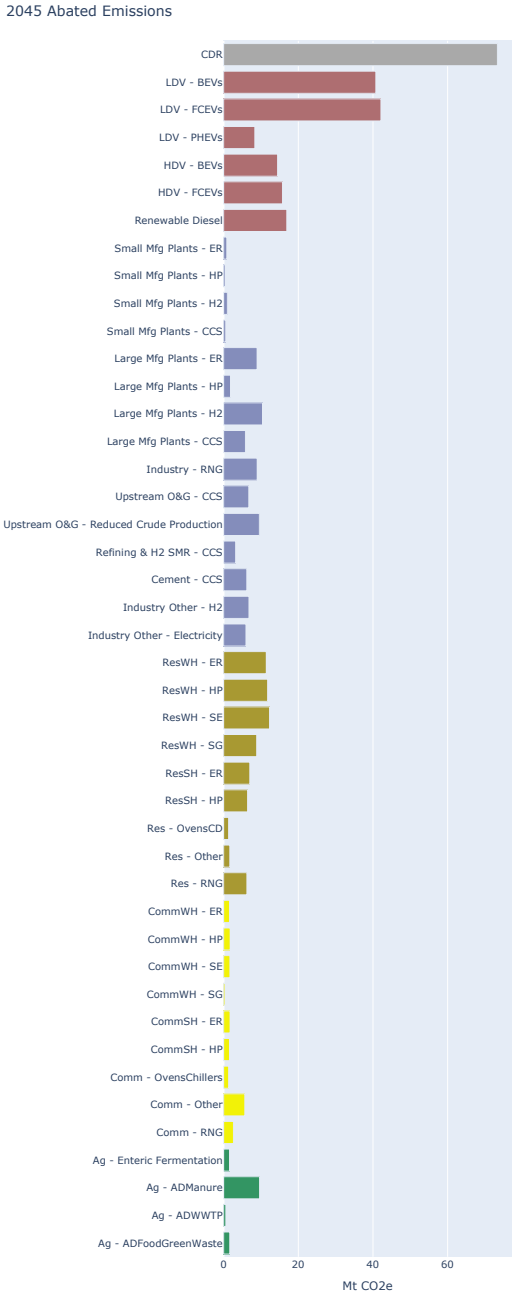
# Sensitivity Analyses

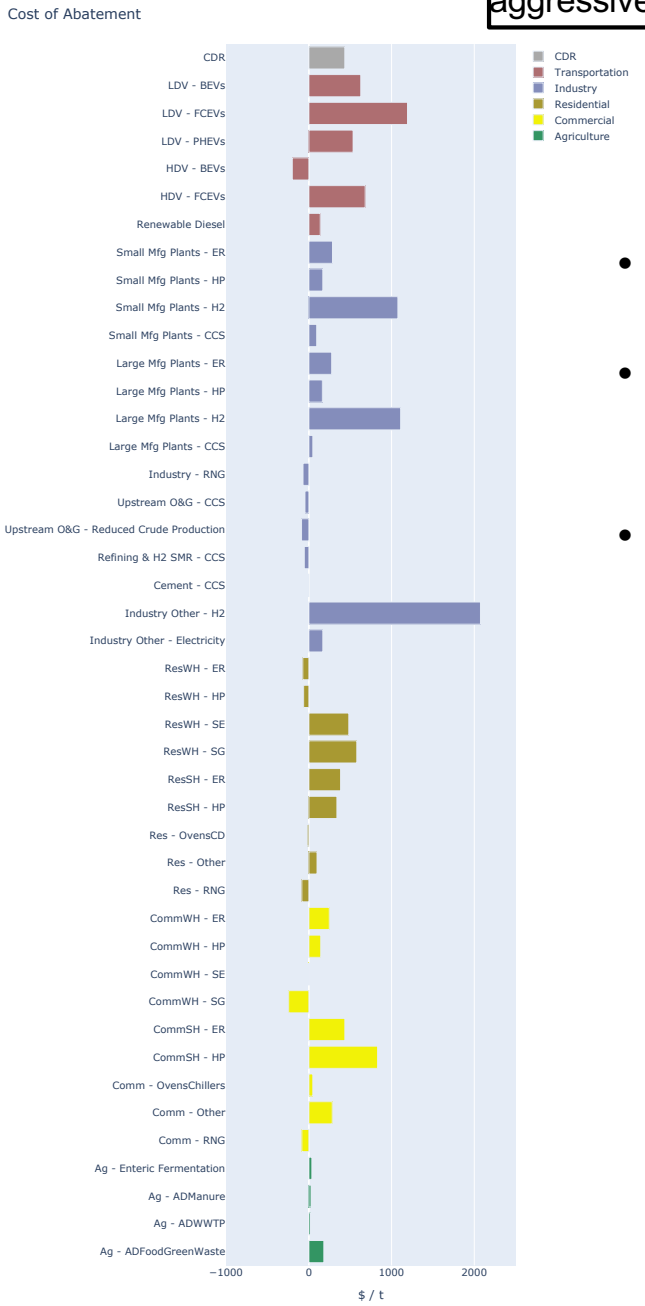
# Tech-Choice Sensitivity Whole Economy



**Question**: Where a choice is available, which technology is most effective? What are the 'next best' options in case the first fails?

**Method**: Adopt various technologies at aggressive rate on top of CARB Reference Case



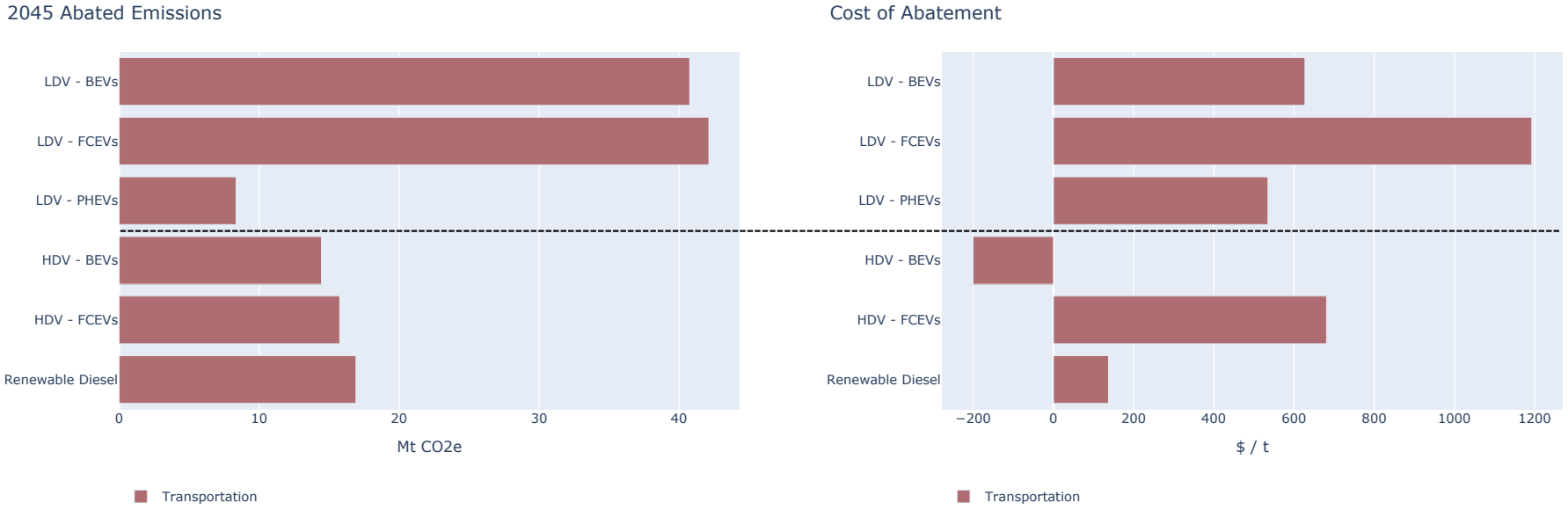

- CARB Proposed Scenario is highly reliant on CDR
- Decarbonizing transportation, especially LDVs, is critical but expensive
- Hydrogen is expensive

# Tech-Choice Sensitivity Transportation



**Question**: Where a choice is available, which technology is most effective? What are the 'next best' options in case the first fails?

**Method**: Adopt various technologies at aggressive rate on top of CARB Reference Case



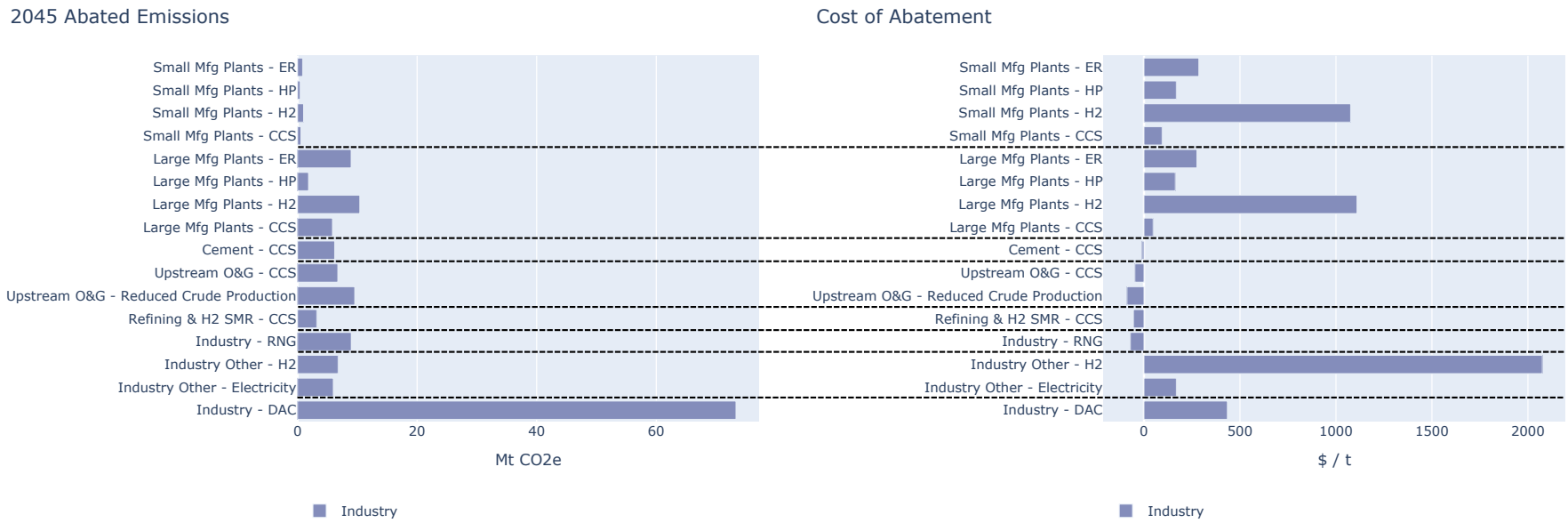

- LDVs are a larger source of emissions than HDVs, but also more expensive to decarbonize
- BEVs and FCEVs lead to more emissions reductions than PHEVs
- BEVs and FCEVs have similar emissions reductions, but BEVs are significantly cheaper

# Tech-Choice Sensitivity Industry



**Question**: Where a choice is available, which technology is most effective? What are the 'next best' options in case the first fails?

**Method**: Adopt various technologies at aggressive rate on top of CARB Reference Case



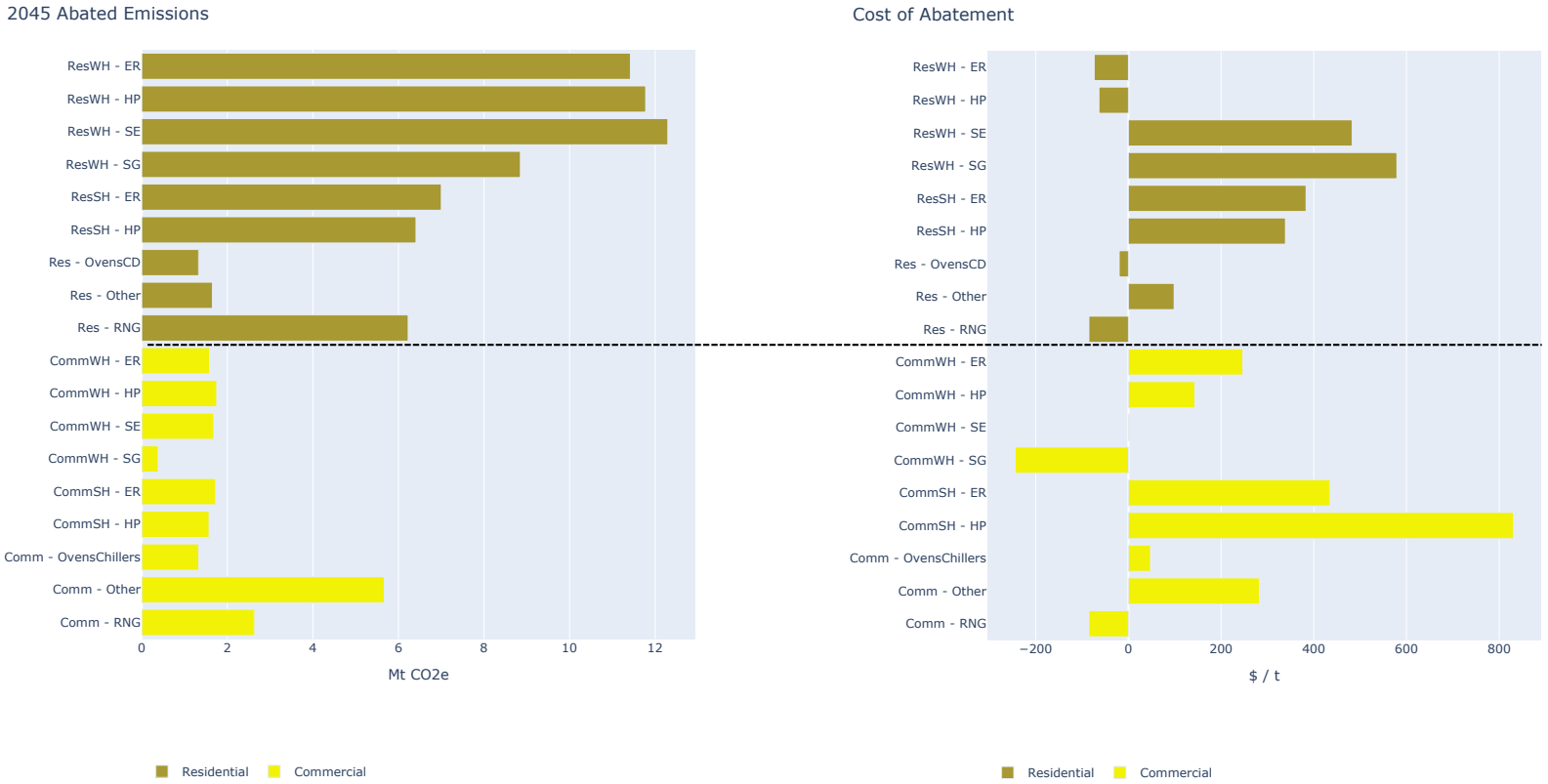

- CARB highly reliant on CDR/DAC
- Some plants cannot use heat pumps for heating
- CCS is effective in both emissions reductions and cost
- Hydrogen is expensive

# Tech-Choice Sensitivity Buildings



**Question**: Where a choice is available, which technology is most effective? What are the 'next best' options in case the first fails?

**Method**: Adopt various technologies at aggressive rate on top of CARB Reference Case




Residential

- Residential emissions are larger than commercial
- Water and space heating have higher emissions than ovens and clothes dryers
- Water heating more important than space heating
- Water heating is cheaper than space heating
- Solar water heating very expensive

Commercial

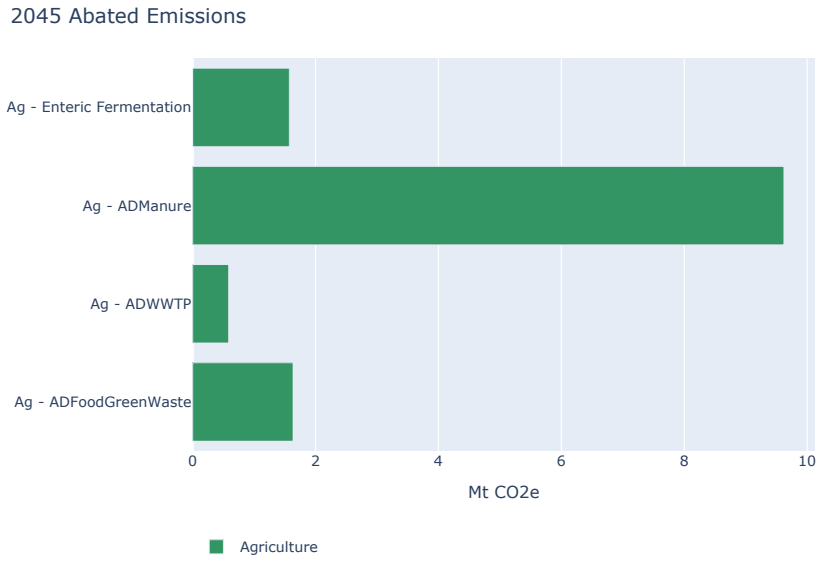
- Water heating is cheaper than space heating
- Solar water heaters are more economical

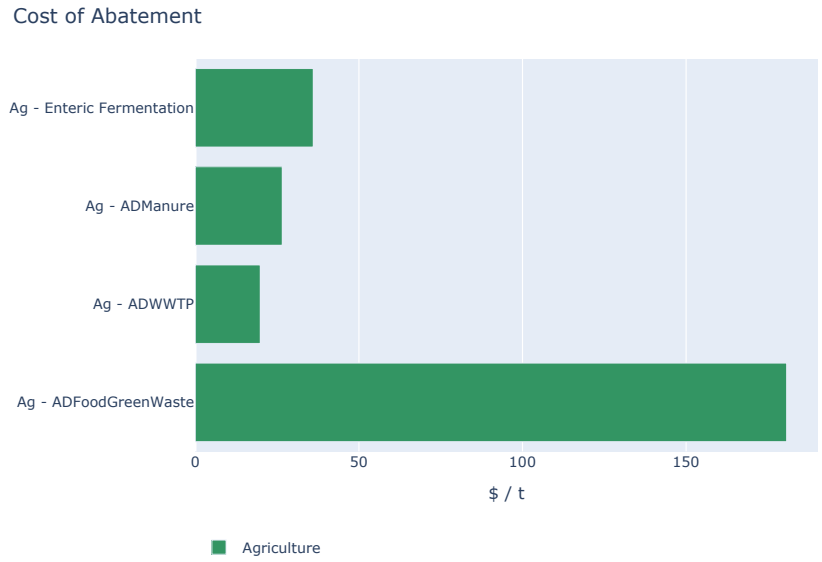
# Tech-Choice Sensitivity Agriculture



**Question**: Where a choice is available, which technology is most effective? What are the 'next best' options in case the first fails?

**Method**: Adopt various technologies at aggressive rate on top of CARB Reference Case




- Methane reductions are generally cost effective on $/t basis
- AD Manure has highest potential emissions savings

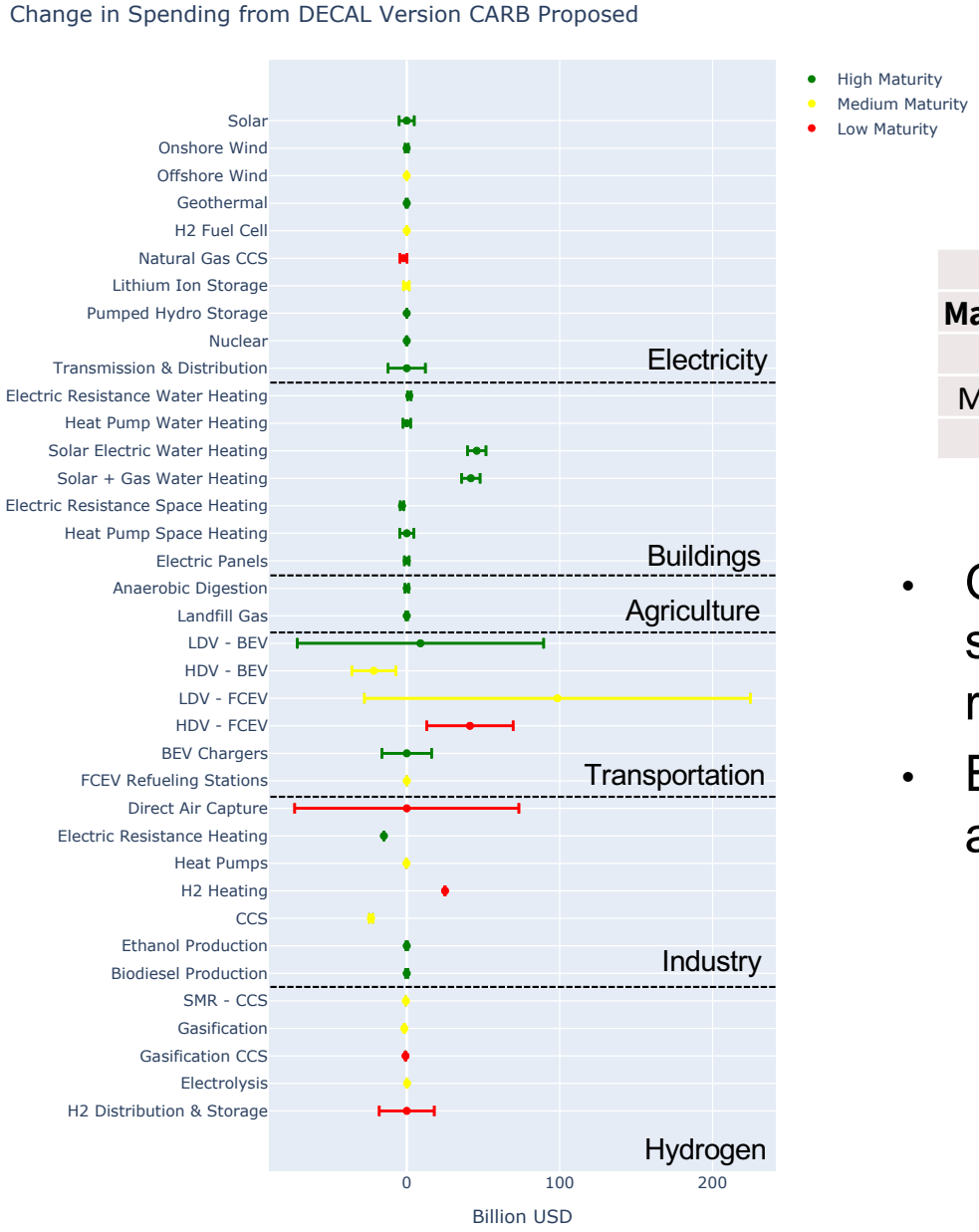
** Cost of Abatement evaluated as $ / t CO2e*

Stanford University

# Cost Sensitivity – Whole Economy

**Question**: How will cost reductions over time affect overall costs?

**Method**: Fully adopt technology and evaluate anticipated cost range




| 2045 Cost Reduction | | | |
|---|---|---|---|
| **Maturity** | **Low** | **Medium** | **High** |
| High | 0% | 15% | 30% |
| Medium | 10% | 30% | 50% |
| Low | 20% | 50% | 80% |

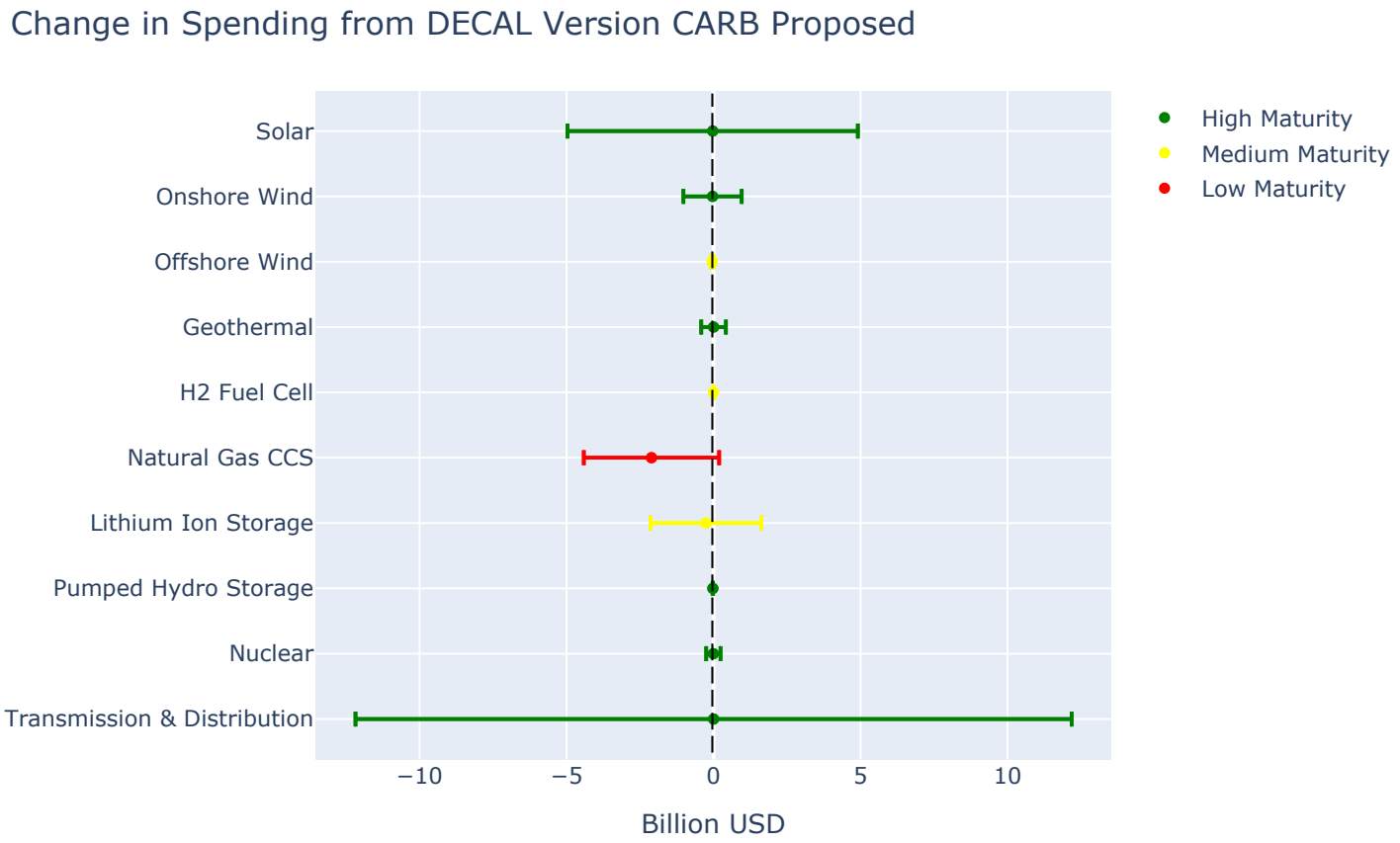
- Overall system costs are most sensitive to LDV & CDR cost reductions
- Electricity T&D, H2 D&S, and HDVs are next most significant drivers

CARB Prop Cost: 363 $B

# Cost Sensitivity – Electricity

**Question**: How will cost reductions over time affect overall costs?

**Method**: Fully adopt technology and evaluate anticipated cost range



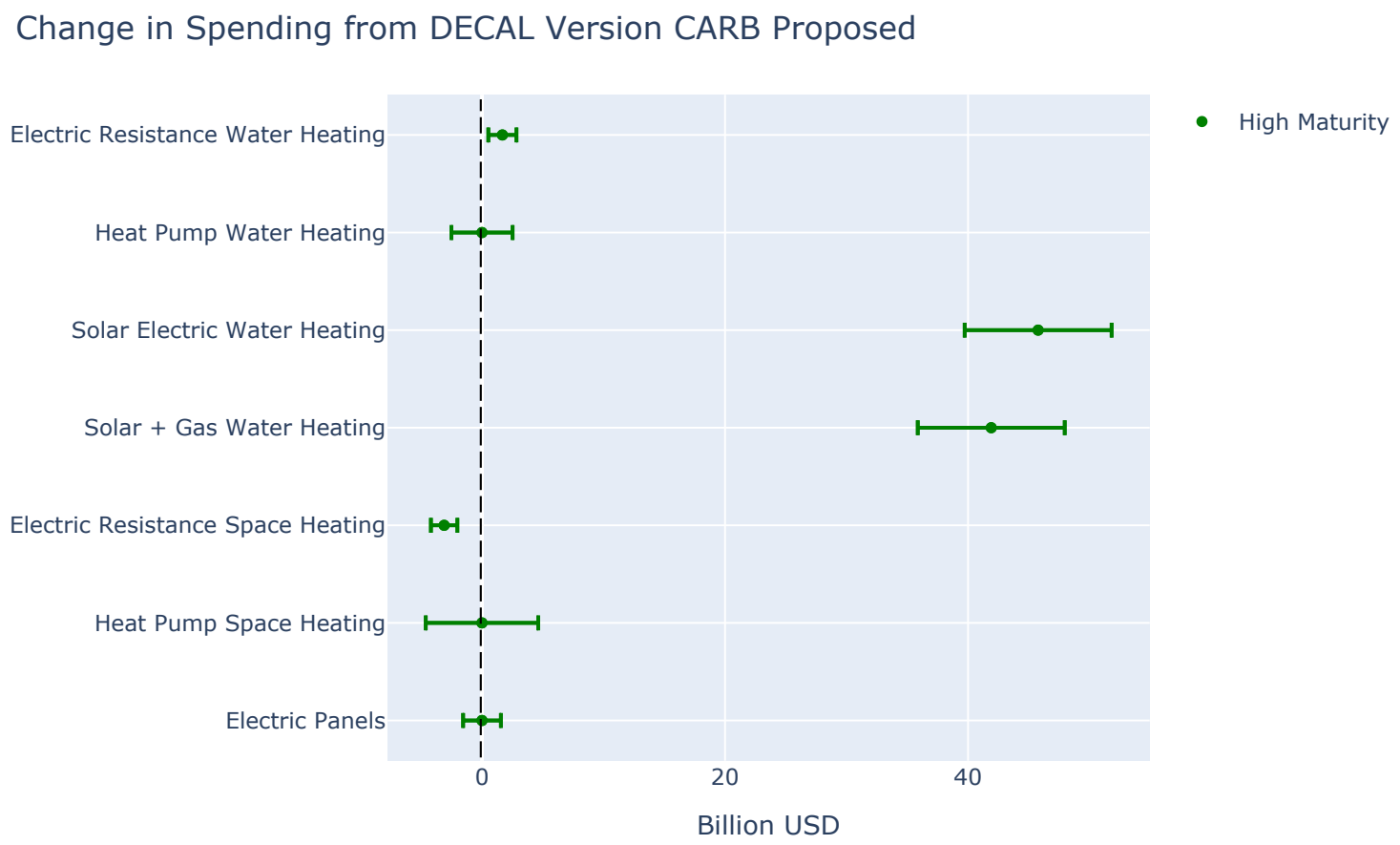

- Overall system costs are most sensitive to T&D costs
- Next most sensitive are Solar, NGCCS, and Li Ion

** Due to optimization, we cannot control how much of each resource is used*
*** Different learning rates used in electricity sector*

# Cost Sensitivity – Buildings

**Question**: How will cost reductions over time affect overall costs?

**Method**: Fully adopt technology and evaluate anticipated cost range

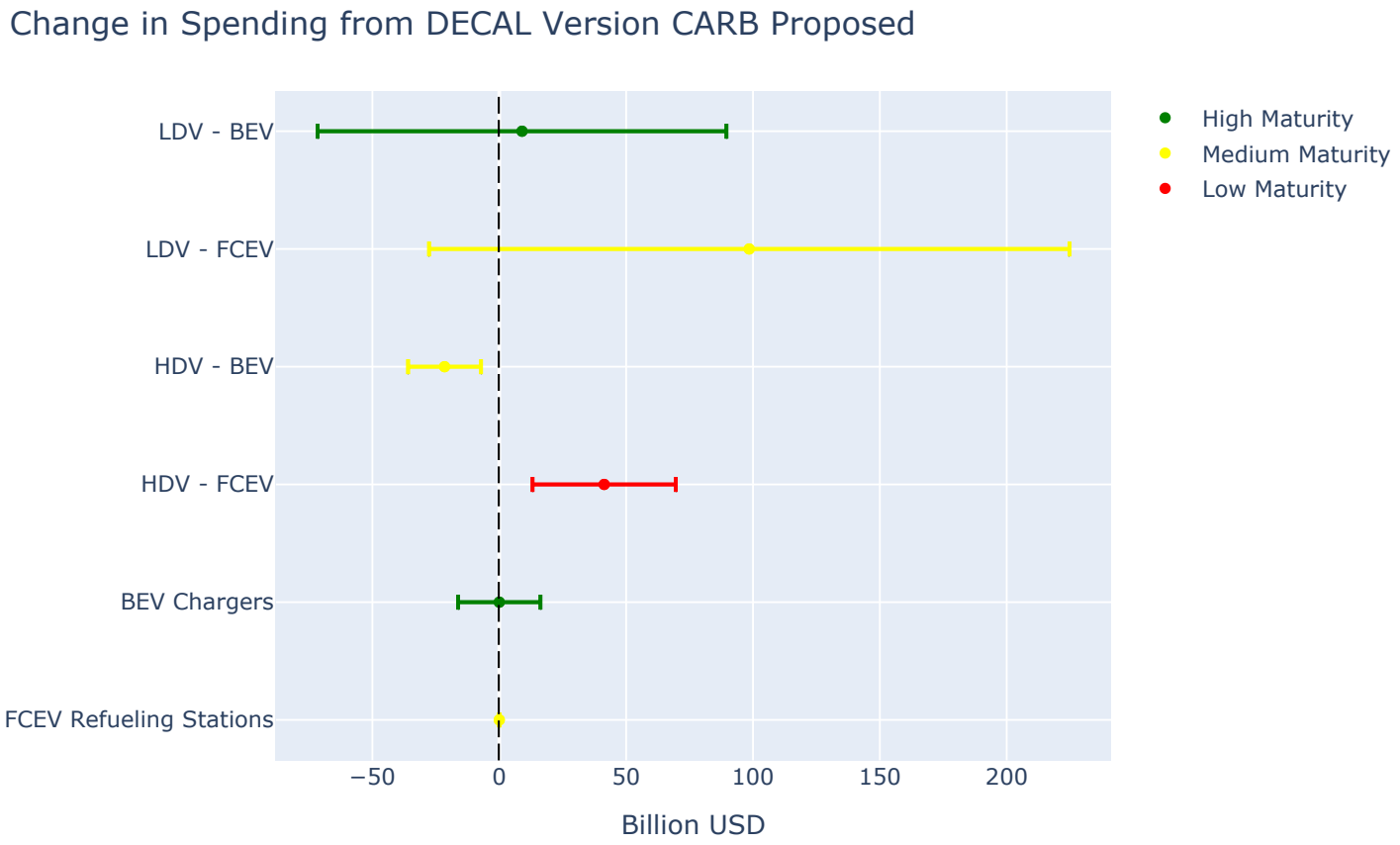



- Solar thermal water heating is expensive
- Electric resistance and heat pumps are both viable options
- Overall system costs not too dependent on electric panel costs

# Cost Sensitivity – Transportation

**Question**: How will cost reductions over time affect overall costs?

**Method**: Fully adopt technology and evaluate anticipated cost range

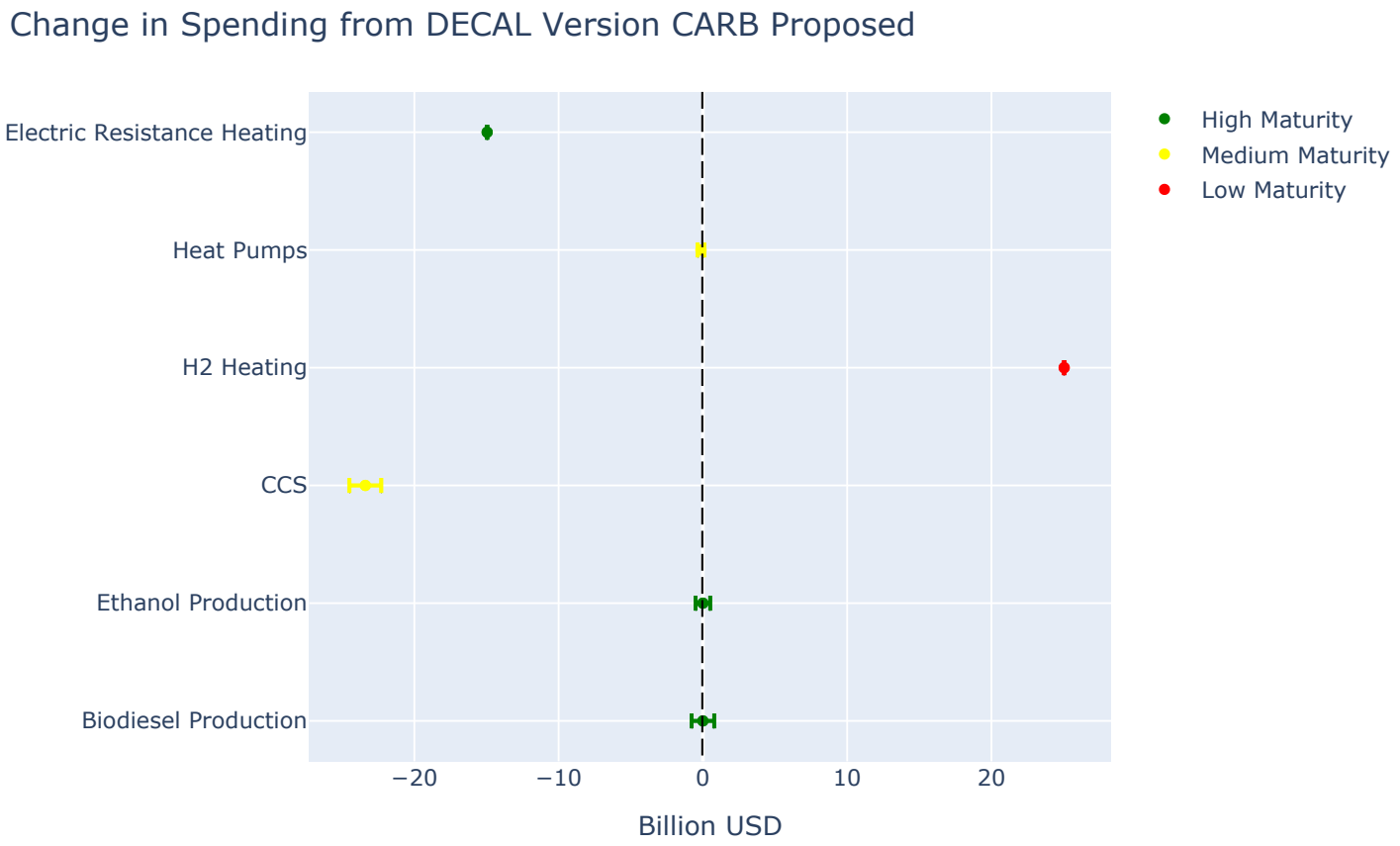



- FCEVs are more expensive than BEVs, even given uncertainty
- Overall system costs are driven significantly by the cost of BEVs or FCEVs
- BEV charger costs are moderately significant

# Cost Sensitivity – Industry

**Question**: How will cost reductions over time affect overall costs?

**Method**: Fully adopt technology and evaluate anticipated cost range

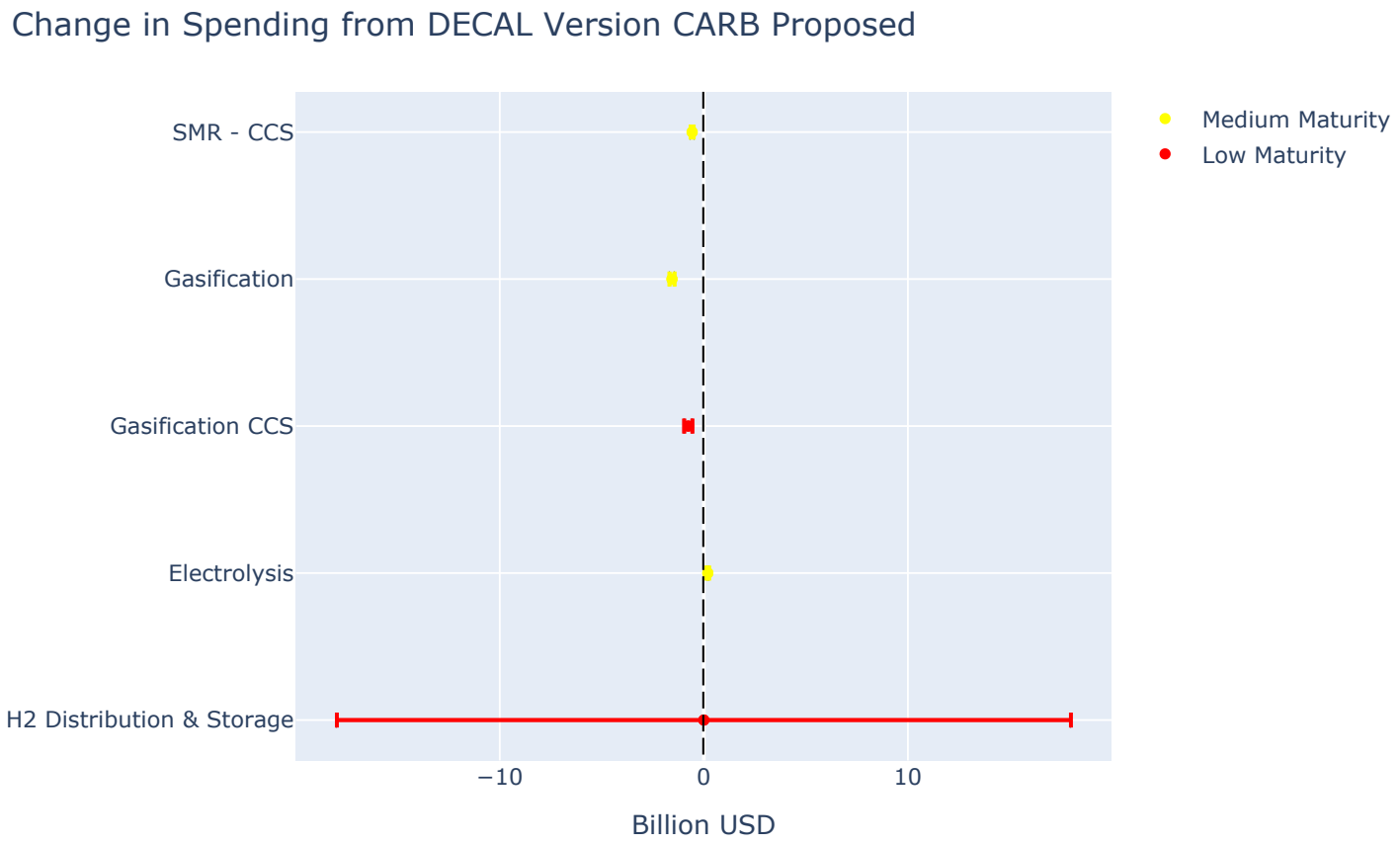



- Uncertainty bounds are far less than gaps in technology costs
- CCS and ER are cheaper options compared to HP
- H2 is expensive

# Cost Sensitivity – Hydrogen

**Question**: How will cost reductions over time affect overall costs?

**Method**: Fully adopt technology and evaluate anticipated cost range

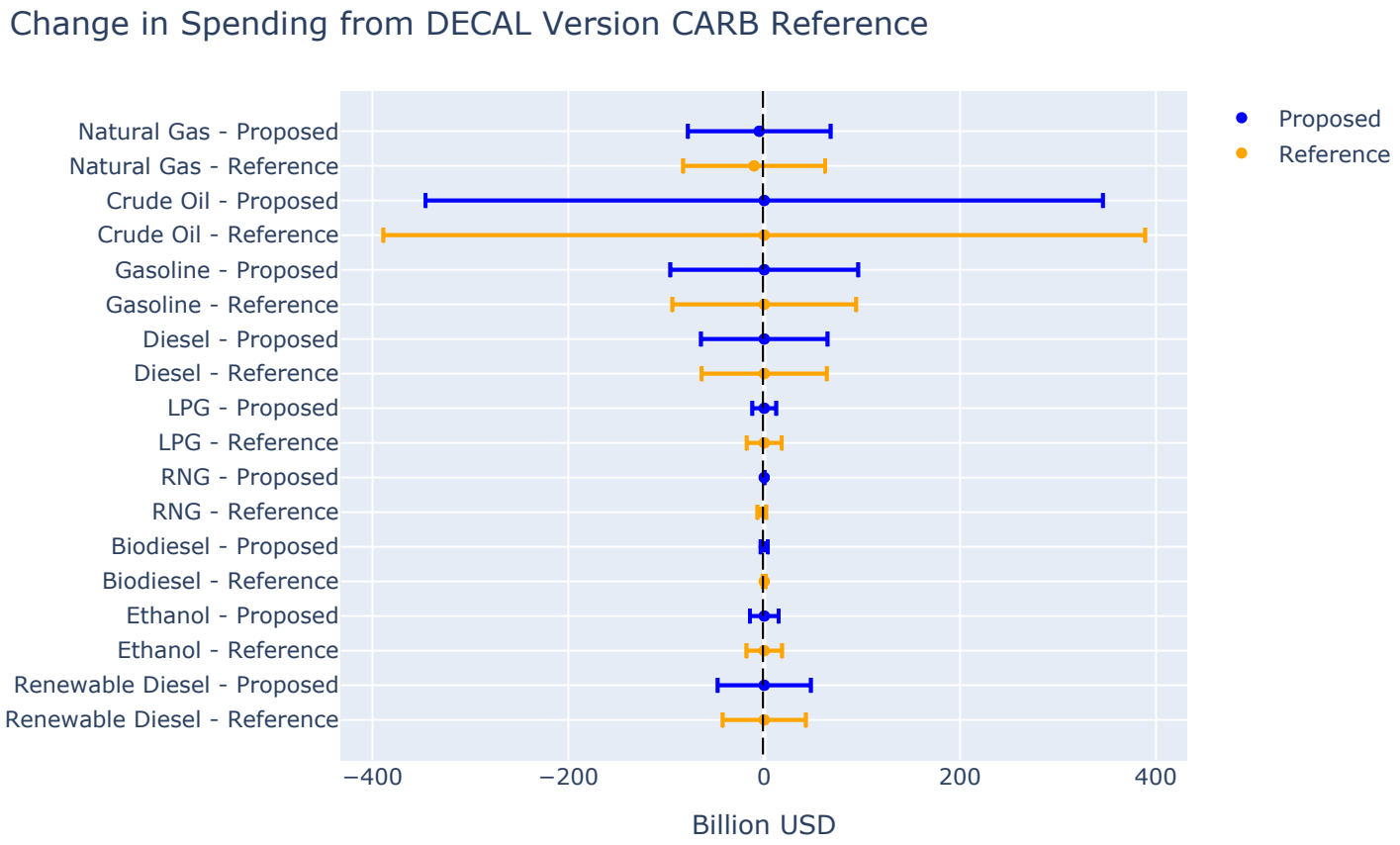



- H2 Distribution & Storage drives costs

# Cost Sensitivity - Fuels

**Question**: How sensitive are overall system costs to fuel prices?

**Method**: Evaluate sensitivity of reference and proposed scenario costs to changes in fuel prices

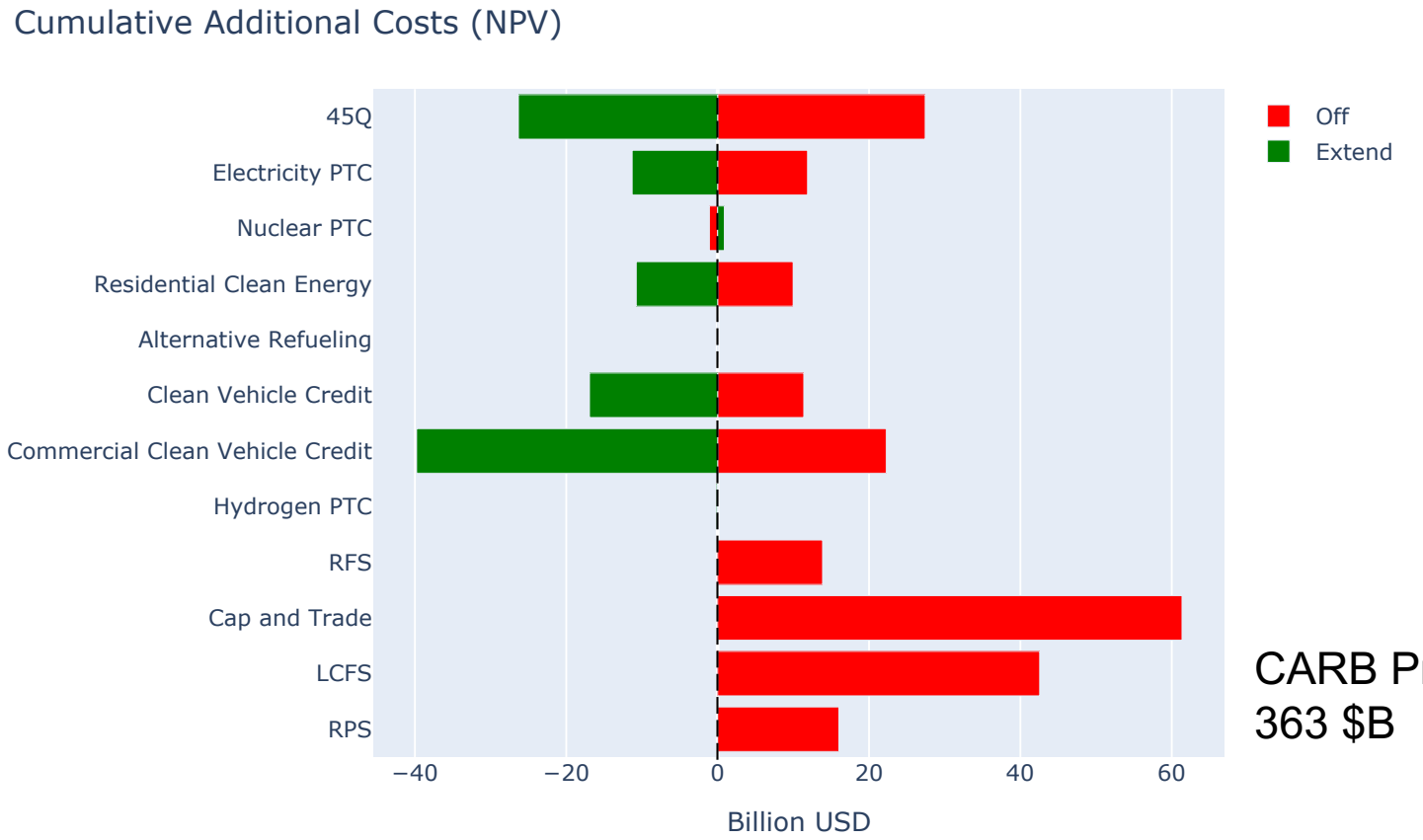



- Fossil fuel price important for both reference and proposed
- Price of crude oil has largest impact on LEAP Version CARB Proposed Costs
  - Larger than even CDR
- Next most are Gasoline, Diesel, and Renewable Diesel

# Cost Sensitivity - Incentives

**Question**: How important are incentives?

**Method**: Evaluate CARB Proposed with incentives off/extended




CARB Prop Cost:
363 $B

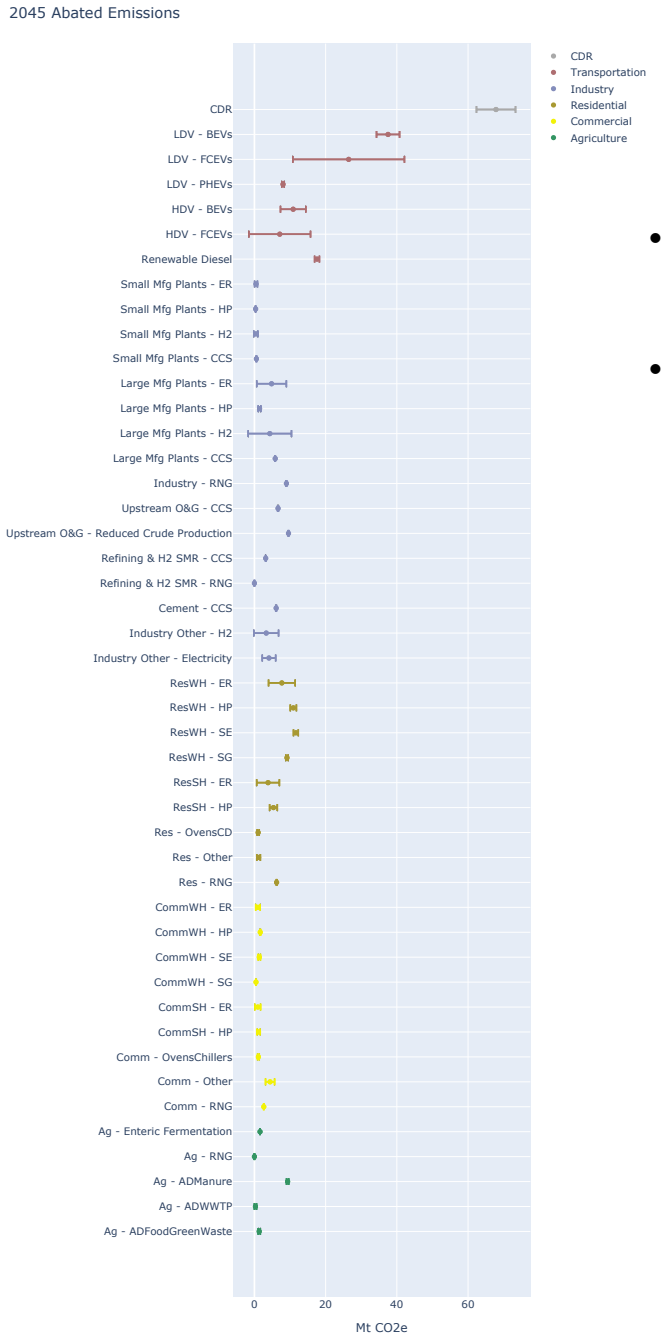
- Incentives are significant
- Largest drivers: 45Q, Commercial Clean Vehicle, Cap & Trade, LCFS
- In state incentives are included as a price on ‘externalities’
- H2 PTC guidelines are too stringent

# Clean Fuels / Dirty Fuels Sensitivity Whole Economy



**Question**: Which technologies are most reliant on clean fuels?

**Method**: Fully adopt technology, evaluate effect of clean / dirty fuels

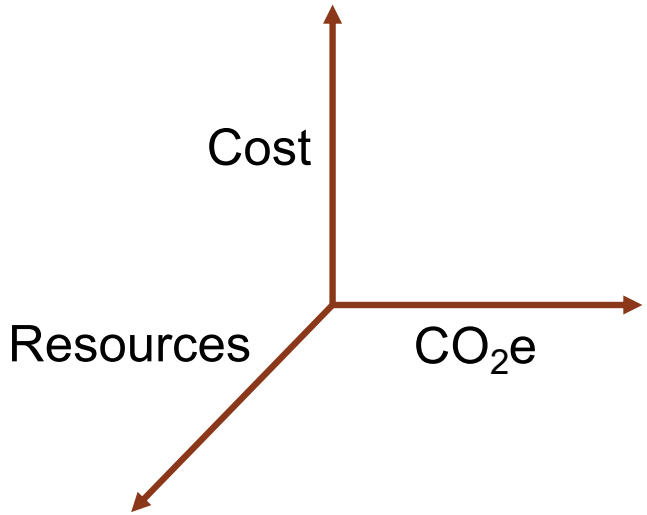



- Technologies that use electricity or hydrogen are dependent on clean fuels
- Transportation and CDR are most sensitive

# Backup Slides

# Model Background

- We've developed a "What-if" model that allows us to run economy-wide decarbonization experiments
- 3 results we care about most: cost, emissions, resource constraints




- Model details
  - Platform: LEAP (Low Emissions Analysis Platform)
  - System boundary: California, scope 1 & 2 emissions
  - Total resource cost test
  - Demand & Supply; mostly bottom-up in both
  - Stock & flow in buildings and transportation sectors
  - Optimization in electricity sector
  - Driven by exogenously defined levers
  - Not an equilibrium model

# Electricity Sector

## A clean grid will be required… but 100% clean may not be necessary

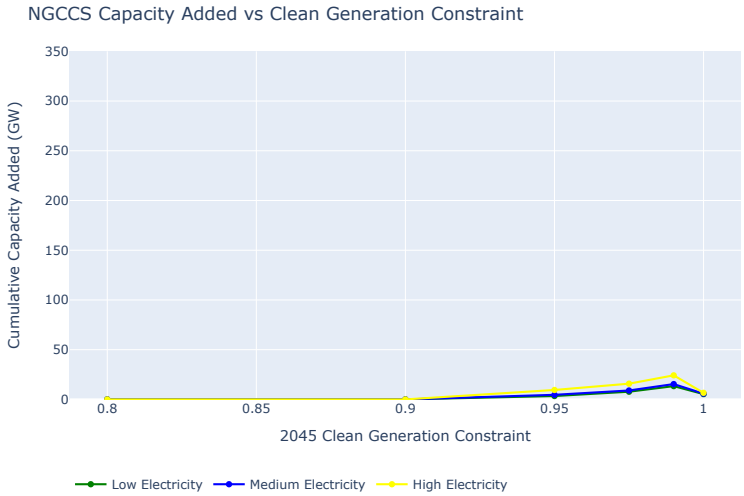
**Question**: What is the impact of the electricity clean generation constraint?

**Method**: Iterate on CGC in low/medium/high e- scenarios

*All scenarios reach similar 2045 emissions*

- *Low: Choose H2, biofuels, and CCS*
- *Med: CARB Proposed*
- *High: Choose electricity where possible*



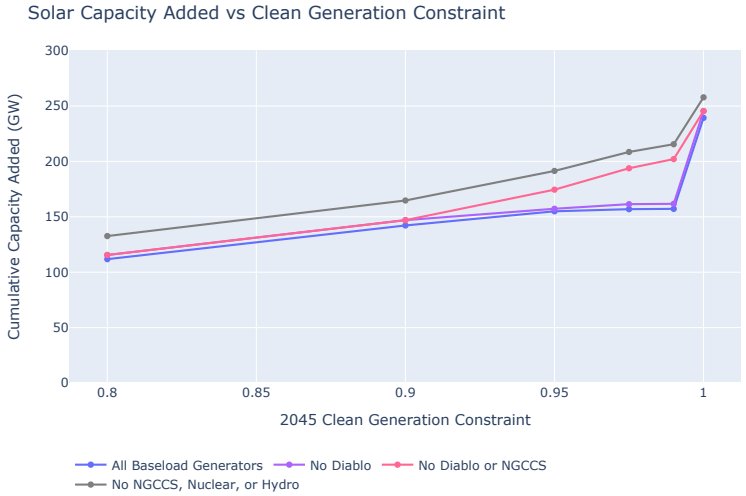


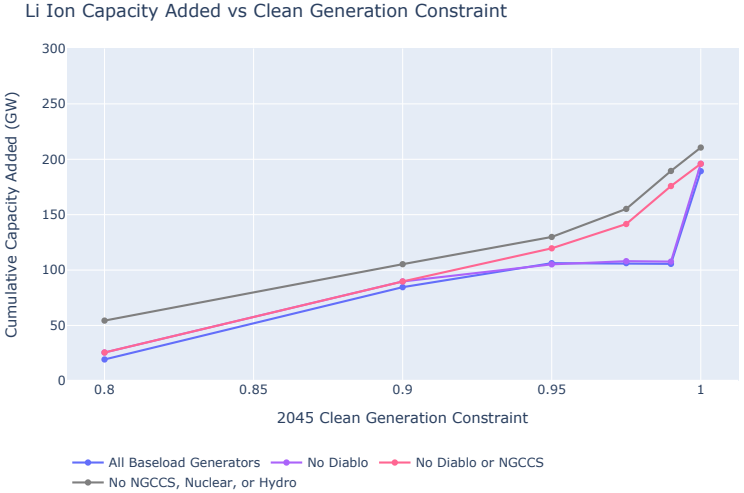

- 99% → 100% clean generation requires much more solar & batteries, largely because NGCCS must be used less
- A small amount of NGCCS can help prevent significant overbuild

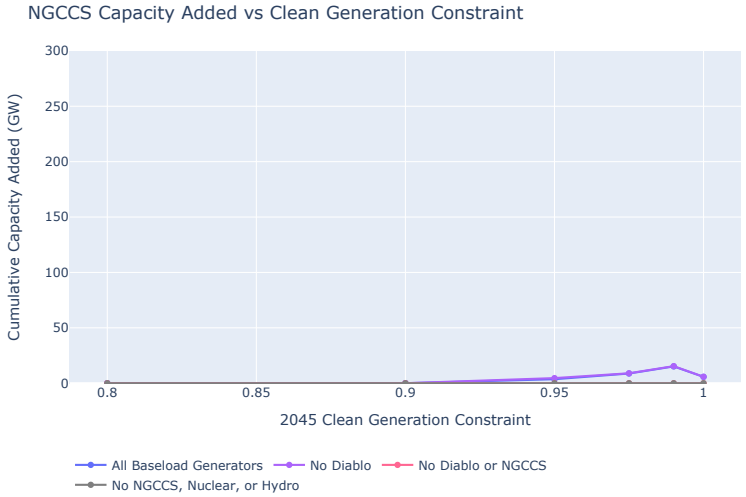
# Electricity Sector
## Clean baseload power limits overbuilding

**Question**: How important is clean baseload power?

**Method**: Stepwise remove 1) Diablo, 2) NGCCS, 3) Hydro & remaining Nuclear




- Diablo Canyon makes a small difference
- NGCCS makes a bigger difference
- Nuclear & Hydro also significant