California PATHWAYS: GHG Scenario Results

California Climate Policy Modeling Dialogue
UC Davis
February 23rd, 2015

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Agenda

+ Overview of California PATHWAYS
+ Scenario results
  - 2030 greenhouse gas emissions
  - Commonalities across scenarios
  - Forks in the road
  - Costs impacts of the energy transformation
About the California state agencies’ PATHWAYS project

+ **Purpose**

- To evaluate the feasibility and cost of a range of greenhouse gas reduction scenarios in California

+ **Project sponsors**

- Collaboration between CARB, CAISO, CPUC, CEC
- Additional funding provided by the Energy Foundation

+ **Team**

- Energy & Environmental Economics with support from LBNL
+ PATHWAYS is a California-wide, economy-wide infrastructure-based GHG and cost analysis tool

  • Adoption rates of technologies are defined by user, stock turn-over rates are based on lifetime of equipment
  • Energy & infrastructure costs are tracked
  • Not a macroeconomic model, costs & technologies are not endogenously defined, not an optimization model

+ “Bottom up” forecast of energy demand by end use, driven by:

  • Population, residential & commercial square footage, space heating/cooling, water heating, lighting, etc.

+ Hourly electricity demand & supply detail simulates planning, system operations, and cost
Key conclusions

+ GHG reductions of 25 – 36% below 1990 levels (324 - 274 MMTCO2e) appears achievable in 2030 with significant increase in GHG reduction efforts, mitigation of key risks

+ 2030 “straight line” scenario ranges from net savings of $4B to net cost of $11B (in real 2012$)

+ Critical to success of long-term GHG goals:

  1. Significant increase in energy efficiency and conservation in buildings, vehicles & industry
  2. Fuel-switching away from fossil fuels in buildings & vehicles
  3. Sustained pace of low-carbon electricity development (~50% renewables in 2030 in CA)
  4. Decarbonize liquid or gas fossil fuels with sustainable biofuels and/or synthetic decarbonized fuels
  5. Reductions of non-energy GHGs (methane & F-gases)
     More data are needed on forestry & land-use GHG emissions
Key scenario assumptions

- Continuation of current lifestyle & growth of economic activity
- Technological conservativism, plus key emerging technologies
- Natural retirement of equipment (not early replacement)
- Biomass use is limited based on DOE estimate of sustainable supply
- Advanced biofuels are assumed to have net-zero carbon emissions
- Electricity planning and operational assumptions maintain hourly balance of electricity supply & demand
Multiple scenarios are on a consistent trajectory to meet 2050 GHG goal.
A range of potential targets in 2030 are consistent with 2050 goals

Initial scenarios achieve a 25% – 36% reduction in GHGs by 2030, relative to 1990 GHG levels (33% - 43% below 2005 levels)
Decarbonizing CA’s economy depends on four energy transitions

1. Efficiency and Conservation

2. Fuel Switching

3. Decarbonize electricity

4. Decarbonize fuels (liquid & gas)

Energy use per capita (MMBtu/person)

Share of electricity & H₂ in total final energy (%)

Emissions intensity (tCO₂e/MWh)

Emissions intensity (tCO₂/EJ)
1. Doubling of current energy efficiency goals & reduced vehicle miles traveled

+ Higher Efficiency in Buildings & Industry
  - Approximate doubling of current plans for EE savings
  - Largest EE savings assumed to come from commercial LED lighting, more efficient equipment & appliances

+ Higher Efficiency of Vehicles and Reduced Demand for Transportation Services
  - 8% reduction in vehicles miles traveled through smart growth policies and demographic trends by 2030
  - Sustained vehicle efficiency improvements
  - Petroleum refining and oil & gas extraction energy use decline proportionally with demand for liquid fossil fuels
2. Greater reliance on electricity in buildings & zero emission vehicles

- Switching to electric space conditioning & water heating in buildings
- Electric processes in industry
- Rapid ramp up of battery electric and/or fuel cell vehicles

- 6-7 million ZEVs and PHEVs on the road by 2030

Share of New Vehicle Sales by Year and Technology

<table>
<thead>
<tr>
<th>Year</th>
<th>2015</th>
<th>Reference</th>
<th>Straight Line</th>
<th>High BEV</th>
<th>Early Deployment</th>
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<td>2030</td>
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FCV | BEV | PHEV
3. Renewables account for 50-60% of annual energy use by 2030

Average renewable additions are ~2,400 MW/year (plus rooftop PV) through 2030, mostly solar and wind resources.

Integration solutions are needed in all high renewables cases:
- regional coordination, renewable diversity, flexible loads, more flexible thermal fleet, curtailment energy storage, flexible fuel production for ZEVs

![Annual Energy Chart]

![2030 Renewable Generation by Type (%) – Straight Line]

- Renewable
- Nuclear
- Hydro
- Imports
- CA CCGT/CT
- CHP
- Geothermal
- Wind
- Solar thermal
- Grid solar
- Rooftop PV
4. Limits to sustainable biomass: insufficient to replace both liquid and gaseous fuels

Share of Final Energy Demand by Fuel Type: 2030

Low Carbon Gas Scenario

- Biogas
- Renewable Diesel

Biofuels used in gaseous form in buildings & industry

- Natural Gas
- Renewable Gasoline
- Electricity
- Biogas
- Diesel
- Hydrogen

Straight Line Scenario

- Gasoline
- Renewable Diesel
- Other Fuels

Biofuels used for liquid transportation fuels
Mitigation potential is high for F-gases, methane leaks and some types of waste & manure. Difficult to mitigate cement, enteric fermentation, other agricultural non-energy GHG emissions. Places higher burden on mitigating energy GHGs.

Notes: Does not include land-use GHGs; Emissions inventory accounting protocol changed between 6th and 7th edition, resulting in higher estimate of historical non-energy GHG emissions.
Two forks in the road

1. Fuel production for ZEVs impacts electric grid needs
   - Flexible production of hydrogen fuels using 9,000 MW of grid electrolysis can balance 50% renewables, eliminating need for other storage (straight line)
   - Without flexible hydrogen fuel production, ~5,000 MW of long-duration energy storage is needed at 50% renewables in 2030 (high BEV scenario)

2. Use of biofuels impacts need to electrify buildings
   - If biomass is used for liquid transportation fuels, over 50% of new sales of space conditioning & water heating are electric in 2030 (straight line)
   - If biomass is used to produce biogas to replace over 50% of natural gas use in buildings & industry in 2030, no electrification in buildings and industry is needed (low carbon gas scenario)
WHAT ARE THE COST IMPACTS?
How does PATHWAYS measure costs?

Included:

- Incremental cost of energy infrastructure
  - Transportation: light-, medium- & heavy duty vehicles
  - Building & end uses: lighting, hot water heaters, space heaters, air conditioners, washer/dryer, etc.
  - Industrial equipment: boilers, motors, etc.
  - Electricity production: revenue requirement of all electric assets

- Fuel & avoided fuel cost
  - Electricity, hydrogen, gasoline, diesel, natural gas, biofuel

Excluded:

- Societal cost impacts
  - Climate benefits of GHG mitigation
  - Health benefits of reduced criteria pollutants

- Structural/macroeconomic impacts
  - Changes in the costs of goods and services, jobs, structural changes to economy

Note: All costs are reported in real, levelized 2012 dollars
Cost impacts of timing decisions

- 2030 scenarios & sensitivities span savings of $8B to costs of $24B/year
- 2030 Straight Line scenario equivalent to $50/yr/capita total net cost
- Delaying deployment of some high cost measures until post-2030 reduces cost in near-term, but may increase cost in long-run; Early deployment increases near-term costs (but reduces criteria pollutants)
Average household sees significant savings in gasoline/diesel costs, offset by increases in electric bill, car payments and cost of ZEV fuel (doesn't include changes to cost of goods & services)

2030 Household Costs - Straight Line

- Appliances & Building EE
- Vehicles
- Vehicle Electricity & Hydrogen Fuel
- Vehicles Gas, Diesel, & Biofuels
- Natural Gas Bill
- Electricity Bill

Net Total: $8/mo/household
0.8% increase over Reference Scenario energy-related costs
($12/mo/household if assume all com. & industrial energy system costs flow through to households)
Thank You!

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APPENDIX
PATHWAYS: Model framework

Energy Demand
- Residential
- Commercial
- Industrial
- Refining
- Oil & gas extraction
- Transportation
- Agriculture
- Water-related energy demand

Energy Supply
- Electricity
- Pipeline gas
- Diesel + biofuels
- Gasoline + biofuels
- Refinery & process gas
- Coke
- Waste heat

Model outputs
- GHG emissions
- Final energy demand
- Energy system costs
- Electricity dispatch metrics
- Appliance, building, vehicle stock numbers
Key Scenario Assumptions

+ **Continuation of current lifestyle & growth of economic activity**
+ **Technological conservativism with key emerging technologies**
  - Use commercial, or near-commercial technologies with conservative cost and performance assumptions. Key emerging technologies include: advanced biofuels, decarbonized gas, electrolysis, long-duration energy storage, and CCS.
+ **Natural retirement of equipment (not early replacement)**
+ **Limitations on use of biomass**
  - Based on DOE estimate of sustainable U.S.-based supply of biomass
  - Advanced biofuels are assumed to have net-zero carbon emissions
+ **Electricity planning and operational heuristics**
  - Hourly demand derived from flexible end use loads; resources built to RPS requirement and planning reserve margin requirement; hourly supply simulated; import/export capability, & operational heuristics benchmarked to production simulation and historical data; all renewables are assumed to be balanced with in-state resources
WHAT IS AN ACHIEVABLE 2030 GHG GOAL?
Scenarios evaluate GHG reduction timing and energy pathways to 2030 and 2050

### Timing Scenarios (achieve 80% below 1990 by 2050)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Straight Line</td>
<td>distinguished by high renewable energy, fuel cell and battery electric vehicles, energy efficiency and electrification</td>
</tr>
<tr>
<td>3. Early Deployment</td>
<td>similar to Straight Line scenario but with more focus on near-term air quality &amp; GHG actions</td>
</tr>
<tr>
<td>4. Slower Commercial Adoption</td>
<td>delay some higher-cost measures in commercial and trucking until post-2030, accelerate adoption post-2030 to hit 2050 goal</td>
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### Alternate Technology Scenarios (achieve 80% below 1990 by 2050)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. Low Carbon Gas</td>
<td>no building electrification, decarbonized pipeline gas</td>
</tr>
<tr>
<td>6. Distributed Energy</td>
<td>achieves zero-net energy building goals w/ DG PV and grid storage</td>
</tr>
<tr>
<td>7. CCS</td>
<td>phase-in of CCGTs with CCS post-2030</td>
</tr>
<tr>
<td>8. High BEV</td>
<td>no fuel cell vehicles, focus on BEVs</td>
</tr>
</tbody>
</table>
## Summary of Timing Scenarios: Key Input Assumptions in 2030

<table>
<thead>
<tr>
<th></th>
<th>Slower Commercial Adoption Scenario</th>
<th>Straight Line Scenario</th>
<th>Early Deployment Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electricity</strong></td>
<td>50% qualifying renewables in 2030</td>
<td>50% qualifying renewables in 2030</td>
<td>60% qualifying renewables in 2030</td>
</tr>
<tr>
<td><strong>Biomass &amp; Biofuels</strong></td>
<td>Ramp up of renewable diesel is delayed until after 2030</td>
<td>Significant imported renewable diesel</td>
<td>Same as Straight Line Scenario</td>
</tr>
<tr>
<td><strong>Electricity balancing services</strong></td>
<td>Same as Straight Line Scenario</td>
<td>Mix of 2 to 8 hour battery storage, flexible loads and smart charging of EVs. Increasing reliance on grid electrolysis for H2 production after 2030.</td>
<td>Same as Straight Line Scenario plus additional pumped hydro in 2020 timeframe.</td>
</tr>
</tbody>
</table>

### End-uses and fuel choices

<table>
<thead>
<tr>
<th></th>
<th>Slower Commercial Adoption Scenario</th>
<th>Straight Line Scenario</th>
<th>Early Deployment Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Buildings</strong></td>
<td>Commercial electric heat pump adoption is postponed until 2030, then sees faster adoption post-2030. Residential buildings are unchanged from Straight Line scenario.</td>
<td>Significant energy efficiency though out, electric heat pump HVAC &amp; water heating large part of new appliance sales starting in 2020, no early replacement of equipment.</td>
<td>Electric heat pumps for nearly all new sales of hot water &amp; HVAC in South Coast region by 2030</td>
</tr>
<tr>
<td><strong>Transportation</strong></td>
<td>Postponed adoption of BEVs &amp; FCVs until 2030, faster adoption post-2030. Faster adoption of LNG for HDVs &amp; CNG buses through 2030.</td>
<td>Significant increase in H2 fuel cell vehicles (FCV) and electric vehicles + biodiesel</td>
<td>CNG &amp; LNG for all new MDVs and HDVs in South Coast, more rapid adoption of ZEVs than Straight Line Scenario</td>
</tr>
<tr>
<td><strong>Industry</strong></td>
<td>Delayed electrification of industrial end uses until post-2030.</td>
<td>Increase in energy efficiency, electrification</td>
<td>Same as Straight Line Scenario</td>
</tr>
</tbody>
</table>
Multiple scenarios are on a consistent trajectory to meet 2050 GHG goal

Initial scenarios achieve a 25% – 36% reduction in GHGs by 2030, relative to 1990 GHG levels (33% - 43% below 2005 levels)
A range of potential targets in 2030 are consistent with 2050 goals

Initial scenarios achieve a 25% – 36% reduction in GHGs by 2030, relative to 1990 GHG levels (33% - 43% below 2005 levels).
CA scenarios in 2025 are similar to U.S. administration’s 2025 goal on a percent reduction basis, although CA has lower per capita GHG emissions.
KEY COMMONALITIES ACROSS SCENARIOS
Decarbonizing CA’s economy depends on four energy transitions

1. Efficiency and Conservation
2. Fuel Switching
3. Decarbonize electricity
4. Decarbonize fuels (liquid & gas)

Energy use per capita (MMBtu/person)
Share of electricity & H₂ in total final energy (%)
Emissions intensity (tCO₂e/MWh)
Emissions intensity (tCO₂/EJ)
Decarbonizing CA’s economy depends on four energy transitions:

1. **Efficiency and Conservation**
   - Energy use per capita (MMBtu/person)
   - Common strategies applied across all scenarios

2. **Fuel Switching**
   - Share of electricity & H₂ in total final energy (%)
   - Forks in the road:
     1) Electrification vs. biogas in buildings
     2) All-electric vehicles vs. fuel cell

3. **Decarbonize electricity**
   - Emissions intensity (tCO₂e/MWh)
   - Common strategies applied across all scenarios (except CCS scenario)

4. **Decarbonize fuels (liquid & gas)**
   - Emissions intensity (tCO₂/EJ)
   - Forks in the road:
     1) Liquid biofuels in vehicles vs. biogas & synthetic gas in buildings
**Electric energy efficiency** is nearly double in the straight line scenario compared to current policy, mostly due to LED lighting and more efficient appliances.

Fuel switching from natural gas appliances to high efficiency electric heat pumps (not shown at right) achieves additional EE in the Straight line scenario; increases electric loads.

Natural gas efficiency also increases through 2030; but in the straight line scenario it falls post-2030 due to fuel switching to electricity.
Conventional energy efficiency savings are driven by residential & commercial lighting, HVAC and commercial plug-loads and appliances, additional efficiency from fuel-switching to heat pumps are not shown.

Natural gas efficiency is driven by water heating, space heating and agriculture and industrial measures.
Energy Efficiency & Smart Growth in Transportation

**Significant reduction in vehicle-miles-traveled (VMT) & transportation energy demand in all compliant scenarios**

**Vehicle Miles Traveled**

![Graph showing Vehicle Miles Traveled and Transportation Energy Demand over time.](image)

- **Reference**
- **Straight Line**
- **Low Carbon Gas**
- **High BEV**
Increase in Building Electrification

Transition toward electric heat pumps in buildings in Compliant Scenarios begins in 2020

Early deployment scenario assumes *all* new building space heating and water heating in the South Coast is electric starting in 2020

**Residential Electrification: 2030**

**Commercial Electrification: 2030**
Light duty fuel cell vehicles (FCV), battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) as % of new vehicle sales in 2025 and 2030.
Light Duty Vehicles – Number (#) of ZEVs & PHEVs in Fleet by Year

Number of light duty fuel cell vehicles (FCV), battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) on the road in CA in 2025 and 2030

- FCV
- BEV
- PHEV

2025

2030

Millions of Vehicles

Number of medium and heavy duty zero-emission vehicles

- LNG
- CNG
- FCV
- BEV
- Diesel Hybrid

Thousands of Vehicles

- Reference
- Straight Line
- High BEV
- Early Deployment
- Low Carbon Gas
- Slower Com. Adopt.

2025
2030
All scenarios except CCS rely on renewables to decarbonize electricity

+ **Straight line scenario targets 50% renewables in 2030**
  - 75 – 86 % renewables in 2050, except for CCS scenario
+ **Renewable capacity needs increase dramatically post-2030 due to higher electric loads and higher renewable goals**

**Integration solutions needed:**
+ Hydro & thermal generation
+ Renewable diversity, regional coordination, renewable curtailment
+ Increased reliance on flexible loads, especially flexible fuel production (grid electrolysis) in scenarios with fuel cell vehicles
+ 4-8hr stationary storage is needed in high BEV scenario due to no flexible grid electrolysis

**Renewable Capacity (MW)**

Note: In-state and out-of-state renewable development is assumed, including new transmission to deliver renewable resources.
Electricity generation increases significantly due to fuel switching

- Low-carbon electricity is primarily provided by solar and wind resources, natural gas generation continues to provide energy when solar and wind are not available.

- Electric loads increase significantly between 2030 – 2050 due to fuel switching in buildings, industry & transportation.

Generating capacity by fuel type

Annual Generation by fuel type
CCS Scenario

- Meets capacity needs post-2030 with dispatchable natural gas CCGT with CCS, limited new renewables
- Lower total demand because natural gas reformation with CCS replaces grid electrolysis to produce hydrogen
Key Results:

- CCS runs at high capacity factor, reducing capacity build of renewables.
- CCS is higher risk strategy since technology is not yet commercialized but opportunity for cost savings.
Distributed Energy Scenario

+ Meets zero net energy goal (ZNE) by 2020 for new residential & ZNE by 2030 for all new commercial
Distributed Energy Scenario

- Rooftop PV vs. ground-mounted PV is not a critical GHG policy decision
- High DG scenario is not very different than straight line scenario in terms of GHG and cost metrics
- Key questions in this scenario are who pays for the rooftop solar & cost uncertainty around upgrades to the grid.
California is assumed to import biofuels from U.S. resource

Compliant scenarios assume California imports population weighted share of U.S. sustainable biomass supply for biofuels.

Biomass supply is assumed to increase over time, up to 75% of U.S. estimated resource potential, based on DOE’s “Billion Tons Study Update”.
Pipeline gas demand & emissions intensity varies with future policy & technology options

- **Bi-modal scenarios evaluated on pipeline gas:**
  - Enable a switch to low-carbon fuels and sustain gas distribution grid (i.e. through a renewable fuels standard for biogas and synthetic methane) or;
  - Enable electrification and phase out gas distribution grid

![Pipeline gas demand and emissions intensity graphs](image)
Liquid fuel demand falls in all scenarios, but emissions intensity depends on policy choices.

+ Low-emissions and zero-emissions vehicles are needed in all scenarios, dramatically reducing demand for liquid fossil fuels.

+ If natural gas sector is decarbonized (low carbon gas scenario), then liquid fuel supply doesn’t need low-carbon fuels through 2050, otherwise, large amounts of liquid biofuels are needed.
Reduction in non-energy GHGs is essential, but mitigation measures are limited

Mitigation potential is high for F-gases, methane leaks and some types of waste & manure. Difficult to mitigate cement, enteric fermentation, other agricultural non-energy GHG emissions. (Does not include Forestry/lands GHGs due to data limitations)

Note: Emissions inventory accounting protocol changed between 6th and 7th edition, resulting in higher estimate of historical non-energy GHG emissions.
Sensitivities in Straight Line scenario reveal consequences of failure or achievement in 2030

Ex: ZEVs in 2030 contribute \~16 MMTCO2 reductions, given electricity portfolio
Sensitivities in 2050 show relative importance of carbon reduction strategies in long-term.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Contribution to GHG Reductions (% of 1990 GHG levels)</th>
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</thead>
</table>
| Zero-Emission Vehicles           | ![Graph showing contribution](image)
| Forestry/land GHGs              | ![Graph showing contribution](image)
| Reduction in non-energy GHGs     | ![Graph showing contribution](image)
| Biofuels production              | ![Graph showing contribution](image)
| Grid electrolysis                | ![Graph showing contribution](image)
| Building EE & electrification    | ![Graph showing contribution](image)
| Reduction in refining GHGs       | ![Graph showing contribution](image)
| Building electrification         | ![Graph showing contribution](image)
| ZEVs in Trucking                 | ![Graph showing contribution](image)
| Industrial EE & electrification  | ![Graph showing contribution](image)
| Additional 10% RPS in 2030       | ![Graph showing contribution](image)
| Additional Smart Growth          | ![Graph showing contribution](image)
| Relicence Diablo                 | ![Graph showing contribution](image)
GHGs in compliant strategies range from 25% - 36% below 1990 levels by 2030 (i.e. 33% - 43% below 2005 levels by 2030)
WHAT ARE THE COST IMPACTS?
Other studies attempt to quantify the costs of climate change

Other studies have shown that the costs and risks of climate change exceed expected investment cost in low-carbon solutions.

PATHWAYS does NOT evaluate whether carbon mitigation is cost-effective relative to the costs of climate change.

PATHWAYS evaluates trade-offs between carbon mitigation pathways & investment need in low-carbon solutions.

How does PATHWAYS measure costs?

**Included:**

- **Incremental cost of energy infrastructure**
  - Transportation: light-, medium- & heavy duty vehicles
  - Building & end uses: lighting, hot water heaters, space heaters, air conditioners, washer/dryer, etc.
  - Industrial equipment: boilers, motors, etc.
  - Electricity production: revenue requirement of all electric assets

- **Fuel & avoided fuel cost**
  - Electricity, hydrogen, gasoline, diesel, natural gas, biofuel

**Excluded:**

- **Societal cost impacts**
  - Climate benefits of GHG mitigation
  - Health benefits of reduced criteria pollutants

- **Structural/macroeconomic impacts**
  - Changes in the costs of goods and services, jobs, structural changes to economy

Note: All costs are reported in real, levelized 2012 dollars
Cost sensitivities are asymmetric; focus on technology, fuels & financing costs

<table>
<thead>
<tr>
<th>Key uncertainties</th>
<th>Low cost sensitivity</th>
<th>High cost sensitivity</th>
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<tbody>
<tr>
<td><strong>Technologies</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Solar PV</td>
<td>-50%</td>
<td>...</td>
</tr>
<tr>
<td>• Electric heat pumps</td>
<td>-20%</td>
<td>...</td>
</tr>
<tr>
<td>• LED lighting</td>
<td>-20%</td>
<td>...</td>
</tr>
<tr>
<td>• Grid electrolysis</td>
<td>-20%</td>
<td>...</td>
</tr>
<tr>
<td>• Wind power</td>
<td>-5%</td>
<td>...</td>
</tr>
<tr>
<td>• Fuel Cell Vehicles</td>
<td>-5%</td>
<td>...</td>
</tr>
<tr>
<td>• Battery Electric Vehicles &amp; PHEVs</td>
<td>-5%</td>
<td>...</td>
</tr>
<tr>
<td>• Electric boilers</td>
<td>-5%</td>
<td>...</td>
</tr>
<tr>
<td>• Biofuels</td>
<td>...</td>
<td>High cost</td>
</tr>
<tr>
<td><strong>Fossil fuel prices</strong></td>
<td>+50%</td>
<td>-50%</td>
</tr>
<tr>
<td><strong>Financing cost</strong></td>
<td>5% (real)</td>
<td>10% (real)</td>
</tr>
</tbody>
</table>

Technology costs are not modified in the high cost sensitivity because base cost assumptions are already conservative. All cost sensitivities modify both the Reference and Straight Line scenario assumptions.
Fossil and renewable fuel prices projections range from high to low, reflecting future price uncertainties.
Cost impacts of timing decisions

- 2030 scenarios & sensitivities span savings of $8B to costs of $24B/year
- 2030 Straight Line scenario equivalent to $50/yr/capita total net cost
- Delaying deployment of some high cost measures until post-2030 reduces cost in near-term, but may increase cost in long-run; Early deployment increases near-term costs (but reduces criteria pollutants)

Error bars represent high & low cost sensitivity analysis
Average household sees significant savings in gasoline/diesel costs, offset by increases in electric bill, car payments and cost of ZEV fuel (doesn't include changes to cost of goods & services)

Net Total:
$8/mo/household

0.8% increase over Reference Scenario energy-related costs

($12/mo/household if assume all com. & industrial energy system costs flow through to households)
Average commercial enterprise sees significant savings in gasoline/diesel costs, offset by increases in other costs.

**2030 Commercial Costs - Straight Line**

- **Net Total:** $10/mo/1,000 sf
- **1.7% increase over Reference Scenario energy-related costs**

- Appliances & Building EE
- Vehicles
- Vehicle Electricity & Hydrogen Fuel
- Vehicles Gas, Diesel, & Biofuels
- Natural Gas Bill
- Electricity Bill

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**Average Incremental Cost (2012$/mo/1,000sqft)**
**Total cost / Household (including change in goods and services costs)**

**Monthly Cost: 2030 Straight Line Scenario**

Total costs/# households: average household sees savings in gasoline/diesel costs, offset by increases in electric bill, ZEV costs and increases in the cost of goods & services

2030 Household Costs - Straight Line

- Net Total
- Appliances & Building EE
- Vehicles
- Vehicle Electricity & Hydrogen Fuel
- Vehicles Gas, Diesel, & Biofuels
- Natural Gas Bill
- Electricity Bill

Net Total: $12/mo/household

0.7% increase over Reference Scenario energy-related costs

*Assumes all cost impacts on commercial and industrial sectors flow through to California households
Medium & heavy duty trucks & buses low-carbon alternatives are expected to be costly relative to current technologies.

2030 Trucking & Busing Costs - Straight Line

Net Total: $26/mo/vehicle
1.7% increase over Reference Scenario energy-related costs

Average Incremental Cost (2012$/mo/vehicle)
2030 average industrial costs are relatively modest. Higher electricity bills are due largely to higher cost of electricity rather than electrification.

**2030 Industrial Costs - Straight Line**

- **Net Total**: 0.4% of MFG output
- **2.4% increase over Reference Scenario**
- **Net Total**
- **Industrial EE**
- **Natural Gas Bill**
- **Electricity Bill**
Key Uncertainties Affecting Reference & All Scenarios

Climate change (warmer summers, colder winters and less hydro availability) and unexpected increases in population growth represent two uncertainties that would increase the cost of all future scenarios, including the Reference scenario.

These uncertainties have little impact on net costs or GHGs relative to Reference scenario, but large impact on total costs and GHGS.
FORKS IN THE ROAD
How to use limited supply of biofuels?

- **Biomass supply is limited**: assume CA imports population-share (12%) of U.S. total supply (61-69 million bone dry tons in 2030)

- **Current policy directs biomass into liquid fuels** (Straight Line scenario assumptions); Alternate pathway could direct biomass into biogas (Low carbon gas scenario assumptions); or a blend of different biofuels options (not tested here)

### Final Energy Demand by Major Fuel Type

- **Straight Line**
- **Low Carbon Gas**

![Graphs showing final energy demand by major fuel type](image)

- **Renewable Diesel**
- **Biogas**
- **Natural Gas**
- **Other Fuels**
- **Hydrogen**
- **Electricity**
- **Renewable Diesel**
- **Diesel**
- **Gasoline**
- **Pipeline Hydrogen**
- **Synthetic Gas**
Biofuel pathways require different low-carbon strategies in buildings

**Biomass Utilization**

- Use renewable liquid fuels for transport.

**Building Electrification**

- Electrify new sales of water and space heating

---

**Straight Line**

By 2030:
Biomass serves 24% of liquid fuels; 60% of new water heaters, 50% of new residential space heaters are electric

---

**Low Carbon Gas**

By 2030:
Biogas serves 53% of natural gas demand; no building electrification

---

**OR**

- Produce biogas for buildings & industry

- No building electrification

---

(new appliance sales)
ZEV pathways require different electricity infrastructure

**Zero Emissions Vehicles**

- Mix of fuels cell (FCVs) and battery electric vehicles (BEVs)
- By 2030: New sales are 29% PHEV/BEVs, 27% FCVs; Flexible electrolysis balances renewables (assuming 25% load factor)
- OR
- Focus on BEVs if FCVs don’t materialize

**New Infrastructure**

- Electric vehicle charging load: 7,000 MW
- Flexible grid electrolysis: 9,000 MW
- H₂ fueling stations
- No new energy storage

**Straight Line**

- By 2030: New sales are 29% PHEV/BEVs, 27% FCVs; Flexible electrolysis balances renewables (assuming 25% load factor)

**High BEV**

- By 2030: New sales are 57% PHEV/BEVs; Energy storage balances renewables
- Electric vehicle charging load: 20,000 MW
- New 4-8 hr energy storage: 5,000 MW
- No grid electrolysis
- No H₂ fueling stations
Cost implications of forks in the road

- Low Carbon Gas scenario vs. Straight Line scenario costs are driven by assumptions about biofuel availability and cost (very uncertain).
- Cost differences between Straight Line and High BEV scenario are minor and are driven by cost assumptions for FCVs vs. BEVs.
## Technology commercialization risks vary by scenario

The table below illustrates the technology risks across different scenarios, combining importance and the degree of commercialization.

<table>
<thead>
<tr>
<th>Technology Category</th>
<th>Straight Line</th>
<th>High BEV</th>
<th>Low Carbon Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability of low-carbon, sustainably-sourced biomass</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Hydrogen production using renewable electrolysis</td>
<td>High</td>
<td>n/a</td>
<td>High</td>
</tr>
<tr>
<td>Fuel cells in light-duty &amp; heavy duty vehicles</td>
<td>High</td>
<td>n/a</td>
<td>High</td>
</tr>
<tr>
<td>Production of low-carbon, drop-in liquid biofuels</td>
<td>High</td>
<td>High</td>
<td>n/a</td>
</tr>
<tr>
<td>New long duration grid storage</td>
<td>n/a</td>
<td>High</td>
<td>n/a</td>
</tr>
<tr>
<td>Production of low-carbon biogas</td>
<td>n/a</td>
<td>n/a</td>
<td>High</td>
</tr>
<tr>
<td>Production of synthetic low-carbon gas</td>
<td>n/a</td>
<td>n/a</td>
<td>High</td>
</tr>
<tr>
<td>High efficiency heat pumps</td>
<td>Medium</td>
<td>Medium</td>
<td>n/a</td>
</tr>
<tr>
<td>Electrification of industrial end uses</td>
<td>Medium</td>
<td>Medium</td>
<td>n/a</td>
</tr>
<tr>
<td>Light duty &amp; heavy duty electric vehicles</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>LED lighting</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Energy efficiency in vehicles</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
ELECTRICITY SECTOR DETAILS
In near-term, renewables balanced largely by natural gas and hydro
Electricity Balancing 2030 in Straight line Scenario

Additional renewables built for and absorbed by flexible grid electrolysis to fuel FCVs

Straightline Scenario - 2030

Winter

Summer

Graph showing power generation sources and load for Winter and Summer scenarios.
Lower loads, some balancing provided by workplace charging, additional balancing required from storage
Integration solutions are needed in all high renewable scenarios

In all renewable scenarios:

+ Continued role for hydro & thermal generation
+ Renewable diversity, regional coordination, renewable curtailment
+ Increased reliance on flexible loads, especially flexible fuel production (grid electrolysis)

More 4-8hr stationary storage is needed in high BEV scenario due to no flexible grid electrolysis

Renewable Curtailment (% of available renewable energy)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Curtailment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight Line</td>
<td>0.7%</td>
</tr>
<tr>
<td>High BEV</td>
<td>0.8%</td>
</tr>
<tr>
<td>Low Carbon Gas</td>
<td>1.9%</td>
</tr>
</tbody>
</table>

*Storage balancing capability = charging + discharging capacity
Renewable curtailment relatively low in all scenarios due to integration solutions.

+ Straight Line scenario assumes grid electrolysis (producing hydrogen for fuel cell vehicles) will provide grid balancing services. With no fuel cell vehicles or grid electrolysis, renewable curtailment and/or dedicated electricity energy storage needs increase substantially.

+ **Important Note:** Storage needed for integration and system-wide renewable curtailment are highly sensitive to input assumptions in PATHWAYS. Additional integration studies would be needed to precisely determine adequate storage capacity for each PATHWAYS scenario.
Electricity Costs by Scenario

+ Average cost of electricity generation (revenue requirement divided by total generation) increase in Compliant Scenarios relative to Reference scenario.
+ Increases in reference case cost assumptions are driven by assumptions about “business-as-usual” escalation rates of existing generation, transmission & distribution costs.
KEY INPUT ASSUMPTIONS
Vehicle Costs - Low Cost Sensitivity

LDV - Autos

HDVs

MDVs

Buses
Vehicle Efficiency

- LDV - Autos
  - Gasoline
  - PHEV
  - BEV
  - FCV

- MDVs
  - Gasoline
  - Diesel
  - Diesel Hybrid
  - BEV
  - FCV
  - CNG

- HDVs
  - Diesel
  - Hybrid Diesel
  - FCV
  - CNG

- Buses
  - Gasoline
  - Diesel
  - CNG
  - LNG
Heat Pump Water Heaters - Costs

- Residential WH - Base
- Residential WH - Low Cost
- Commercial Water Heating - Base
- Commercial Water Heating - Low Cost

Graph showing the cost trends from 2010 to 2050 for residential and commercial water heaters.
Grid Electrolysis and Batteries – Costs

Levelized Cost of Grid Electrolysis ($/kg·yr)

- Base Cost
- Low Cost

Capital Cost of Battery Storage ($/kW)

- 2010
- 2020
- 2030
- 2040
- 2050
Renewable capital costs and trajectories through 2030 are based on Black & Veatch 2013 study of renewable capital costs used in CPUC RPS Calculator update, beyond 2030 B&V’s learning curves are applied.

<table>
<thead>
<tr>
<th>All-in capital cost ($/kW – 2012$)</th>
<th>2015</th>
<th>2030</th>
<th>2050</th>
<th>% reduction from 2015 by 2050</th>
<th>% reduction from 2050 cost in low cost sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biogas - Distributed</td>
<td>$9,700</td>
<td>$9,700</td>
<td>$9,700</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Biomass - Distributed</td>
<td>$6,000</td>
<td>$6,000</td>
<td>$6,000</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Biomass - Large</td>
<td>$5,600</td>
<td>$5,600</td>
<td>$5,600</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Geothermal</td>
<td>$5,522</td>
<td>$5,522</td>
<td>$5,522</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Hydro - Small</td>
<td>$3,960</td>
<td>$3,960</td>
<td>$3,960</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Solar Thermal - No Storage</td>
<td>$5,908</td>
<td>$5,217</td>
<td>$4,297</td>
<td>-27%</td>
<td>-50%</td>
</tr>
<tr>
<td>Solar Thermal - Storage</td>
<td>$8,074</td>
<td>$7,034</td>
<td>$5,584</td>
<td>-31%</td>
<td>-50%</td>
</tr>
<tr>
<td>Utility PV - Res Roof</td>
<td>$5,255</td>
<td>$4,445</td>
<td>$3,785</td>
<td>-28%</td>
<td>-50%</td>
</tr>
<tr>
<td>Utility PV - Distributed</td>
<td>$3,774</td>
<td>$3,193</td>
<td>$2,719</td>
<td>-28%</td>
<td>-50%</td>
</tr>
<tr>
<td>Utility PV - Fixed Tilt - 1MW</td>
<td>$3,822</td>
<td>$3,233</td>
<td>$2,753</td>
<td>-28%</td>
<td>-50%</td>
</tr>
<tr>
<td>Utility PV - Fixed Tilt - 5MW</td>
<td>$3,545</td>
<td>$2,999</td>
<td>$2,553</td>
<td>-28%</td>
<td>-50%</td>
</tr>
<tr>
<td>Utility PV - Fixed Tilt - 10MW</td>
<td>$3,258</td>
<td>$2,756</td>
<td>$2,347</td>
<td>-28%</td>
<td>-50%</td>
</tr>
<tr>
<td>Utility PV - Fixed Tilt - 20MW+</td>
<td>$3,134</td>
<td>$2,651</td>
<td>$2,257</td>
<td>-28%</td>
<td>-50%</td>
</tr>
<tr>
<td>Utility PV - Tracking - 1MW</td>
<td>$4,000</td>
<td>$3,527</td>
<td>$3,088</td>
<td>-23%</td>
<td>-50%</td>
</tr>
<tr>
<td>Utility PV - Tracking - 5MW</td>
<td>$3,752</td>
<td>$3,308</td>
<td>$2,896</td>
<td>-23%</td>
<td>-50%</td>
</tr>
<tr>
<td>Utility PV - Tracking - 10MW</td>
<td>$3,485</td>
<td>$3,072</td>
<td>$2,690</td>
<td>-23%</td>
<td>-50%</td>
</tr>
<tr>
<td>Utility PV - Tracking - 20MW+</td>
<td>$3,380</td>
<td>$2,980</td>
<td>$2,609</td>
<td>-23%</td>
<td>-50%</td>
</tr>
<tr>
<td>Wind</td>
<td>$2,341</td>
<td>$2,277</td>
<td>$2,190</td>
<td>-6%</td>
<td>-5%</td>
</tr>
<tr>
<td>Wind - Distributed</td>
<td>$2,890</td>
<td>$2,809</td>
<td>$2,703</td>
<td>-6%</td>
<td>-5%</td>
</tr>
</tbody>
</table>
Thank You!

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