The Clean Power and Electrification Pathway

Realizing California's Environmental Goals

Appendices

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APPENDIX I: Pathway Analysis

Development Approach

The scope of the SCE Pathways Analysis was to identify the most feasible and economical pathway to realizing California's greenhouse gas (GHG) policy target in 2030, reducing emissions from all economic sectors by 180 million metric tons (MMT) — from 440 MMT in 2015 to 260 MMT in 2030 — and reducing air pollution to support achievement of health-based air quality standards.

The analysis resulted in the development of the Clean Power and Electrification Pathway. The Pathway includes the 132 MMT[1] of GHG abatement from the California Air Resources Board (CARB) Proposed Scoping Plan, in addition to 12 MMT of abatement obligations projected to be met by cap-and-trade offsets (4 percent of CARB's allotment for 2030). (See **Table 1.**) The GHG abatement from most of the current and expected policies identified in the CARB Proposed Scoping Plan are listed in **Table 2**.

Table 1. California GHG Accounting from CARB Policy

	GHG Accounting
2015 California Emissions (Economy Wide)	**440 MMT**
CARB Scoping Plan Update 2017	(132 MMT)
Cap-and-Trade Offsets	(12 MMT)
Cap-and-Trade Market / Incremental Abatement	(36 MMT)
2030 Emissions Target (40% below 1990 levels)	**260 MMT**

SCE used four criteria to select the GHG abatement measures for the Clean Power and Electrification Pathway (see **Table 3**) to abate the remaining 36 MMT needed to reach the 2030 GHG goal:

1. GHG abatement potential;
2. Marginal abatement costs[2];
3. Measure feasibility (availability of technology, infrastructure requirements, economies of scale, consumer preference, timing of deployment); and
4. Technologies that will continue to support GHG reductions beyond 2030 and help California achieve the 2050 GHG target (i.e., technologies with low risk of stranded investment by 2050).

The analysis to develop the Clean Power and Electrification Pathway, and alternative pathways, details the combination of measures (**see Table 4**) that could be implemented to achieve the 36 MMT of incremental abatement, incented by cap-and-trade.

This analysis used the Energy + Environmental Economics (E3) PATHWAYS model for deep decarbonization scenarios (https://www.ethree.com/tools/pathways-model/), as well as internally-developed economic adoption and renewable generation optimization models. These models produced an economy-wide view of the expected GHG abatement from existing and expected policies and forecasted economic adoption of low-carbon technologies and fuels. Results are in **Table 5**.

[1] The CARB Proposed Scoping Plan calls for a number of initiatives and policies that would achieve 135 MMT of GHG abatement. However, AB 398 (2017) removed refinery efficiency improvements, accounting for 3 MMT of abatement. AB 398 also authorized the use of offsets to account for up to 12 MMT of emissions abatement.

[2] Marginal abatement costs refer to the cost of an additional unit of abatement, whereas incremental costs in this appendix refer to the cost of abating the final 36 MMT of GHG to meet California's 2030 climate goals.

Table 2. CARB-Identified Policy Impacts by Sector

Sectors	Initiatives and Policies	High-Level Description of Key Elements
Transportation	Low Carbon Fuel Standard	- 18% reduction in carbon intensity in fuel by 2030
	Mobile Source Strategy	- 1.5 million light-duty Zero Emission Vehicles (ZEV*) and Plug-in Hybrid Electric Vehicles (PHEV) by 2025 and 4.2 million ZEVs by 2030 - Medium- and heavy-duty GHG Phase 1 and 2 to reduce new vehicle emissions by 4 to 5% per year starting 2014 - Advanced Clean Transit: starting in 2018, 20% of new buses sold must be zero emission, increasing to 100% in 2030 - Last Mile Delivery: requirement to purchase low-NOx engines and phase-in zero emission trucks starting in 2020
	SB 375 Sustainable Community Strategies and Climate Protection Act of 2008	- Reduce Vehicle Miles Traveled (VMT) through greater access to alternative forms of transportation
	California Sustainable Freight Action Plan	- Improve freight system efficiency by 25% by 2030 - Deploy >100,000 freight vehicles and equipment capable of zero emission operation and maximize near-zero emission freight vehicles and equipment powered by renewable energy by 2030
	CARB Advanced Clean Cars	- By 2025, new vehicles will emit 75% less smog-forming pollutants and about one-half the GHG of the average new car sold today - Beyond 2025, 5% additional GHG emissions reductions are projected through new vehicle emissions standards - Zero Emission Vehicle Regulation requires ~15% of new cars sold in CA in 2025 to be PHEV, battery electric vehicles (BEV) or fuel cell vehicles
	Alternative Transportation	- Large Scale High Speed Rail
	Caltrans Complete Streets Implementation Action Plan	- Sustainable transportation facility for all users in rural, suburban, and urban areas
Electric Power	SB 350	- Increase the Renewables Portfolio Standard (RPS) to 50% by 2030 - Double additional achievable energy efficiency in electricity and natural gas end uses by 2030
	CPUC Rulemaking 13-09-011	- Improve Demand Response reliability and utility, in order to replace quick-start fossil-fueled generation
	AB 2514 and AB 2868	- AB 2514 requires investor-owned utilities (IOUs) to procure 1325 MW of energy storage by 2024, and AB 2868 requires an additional 500 MW
	SB 338	- Utilities are to identify carbon-free alternatives to gas generation for meeting peak demand in their integrated resources plans
Industrial	Governor Brown's Clean Energy Jobs Plan	- 6,500 MW of additional capacity from combined heat and power systems by 2030
Residential / Commercial	CPUC Long-term Energy Efficiency Strategic Plan	- Set policy goals to achieve zero net energy building (ZNE) in all new residential buildings by 2020, and all new commercial buildings by 2030
	Executive Order B-18-12	- State agencies to reduce grid-based energy purchases by at least 20% by 2018 - State agencies to reduce the GHG emissions associated with the operating functions of their buildings by 20% by 2020
	AB 758	- Requires CEC to develop and implement a comprehensive energy efficiency plan for all of California's existing buildings
Agriculture	SB 1383	- 40% reduction in methane & hydrofluorocarbon emissions by 2030 - 50% reduction in black carbon emissions by 2030
Total Scoping Plan GHG Reduction	**Combined effect of policies with cross-sector impacts**	**Approximately 132 MMT GHG Abatement**

*Zero emission vehicles primarily include Plug-in Hybrid Electric Vehicles, Hydrogen Fuel-cell Vehicles, and Battery Electric Vehicles.

GHG Abatement Methodology

Potential measures for additional GHG abatement from each economic sector were assessed across four key criteria and weighted based on their suitability for an optimized pathway to achieve the 2030 GHG goal.

Table 3 Legend

Marginal Cost	Low	Medium	High
Abatement	Low	Medium	High
Feasibility			
Enables 2050 Target			

Table 3. GHG Abatement Pathway Selection Criteria

Sectors	Measure	Marginal Cost †	Abatement Potential ‡	Feasibility	Enables 2050 Target Δ
Transportation	Light-Duty Hydrogen Fuel-Cell Trucks				
	Light-Duty Hydrogen Fuel-Cell Autos				
	Medium-Duty Hydrogen Fuel Cell Vehicles				
	Electric Light-Duty Autos				
	Electric Light-Duty Trucks				
	Heavy-Duty Hydrogen Fuel Cell Vehicles				
	Light-Duty Plug-in Hybrid Autos				
	Light-Duty Plug-in Hybrid Trucks				
	Heavy-Duty Electric Vehicles				
	Medium-Duty Electric Vehicles				
	Medium-Duty Natural Gas Vehicles				
	Aviation Efficiency				
Electric Power	Hydrogen Pipeline Injection ¶				
	Rooftop Photovoltaic (PV)				
	Renewable Diesel Production				
	Large-Scale Renewable Generation				
	Biogas				
Industrial	Process Cooling Efficiency				
	Boiler Efficiency				
	Process Heating Efficiency				
	HVAC Efficiency				
	Lighting Efficiency				
	Machine Drive Efficiency				
Residential	Air Conditioning Efficiency				
	Clothes Washer Efficiency				
	Clothes Drying Efficiency				
	Refrigeration Efficiency				
	Dishwasher Efficiency				
	Heat Pump Water Heaters				
	Other Efficiency #				
	Air Source Heat Pumps				
	Lighting Efficiency				
	Freezer Efficiency				
Commercial	Water Heating Electrification				
	Space Heating Electrification				
	Ventilation Efficiency				
	Other Efficiency				
	Lighting Efficiency				
	Refrigeration Efficiency				

† An average Marginal Cost abatement curve represents a snapshot in time and a relative cost ranking of measures.
‡ Abatement potential represents total technical potential, rather than feasible potential.
Δ Likelihood that technology will enable California to meet its 2050 GHG emissions reduction goal.
¶ Restricted by a technical limit of 7 percent natural gas replacement.

Table 4. The Clean Power and Electrification Pathway Assumptions by Sector

	Measures	Measure Assumptions	Incremental GHG Abatement Contribution*	Full Path GHG Abatement Contribution*
Transportation	**Electric Light-Duty Autos** **Electric Light-Duty Trucks** **Light-Duty Plug-in Hybrid Autos** **Light-Duty Plug-in Hybrid Trucks** **Heavy-Duty Electric Vehicles** **Medium-Duty Electric Vehicles** **Medium-Duty Natural Gas Vehicles**	• Economic adoption alone drives 2MM of the 7 MM EVs necessary in 2030, requiring state and federal support for charging infrastructure and vehicles. • Increased EV adoption to at least 7 MM vehicles requires the extension of existing state and federal subsidies. EV growth will be driven by improved technology/lower costs, purchase incentives, charging infrastructure availability, consumer education and other measures. • Ridesharing is projected to grow by 20% through 2030. Policies that encourage the electrification of rideshare services can drive increased vehicle turnover and greater EV adoption. • On a per-vehicle basis, converting an ICE vehicle to an EV has significant air quality impacts, reducing NOx emissions by 98% for light duty and medium duty vehicles, and 84% for heavy duty vehicles, in addition to having no tailpipe emissions.	15 MMT	**58 MMT**
Electric Power	**Large-Scale Renewable Generation, Energy Storage, Energy Efficiency and Distributed Solar**	• Adding up to 30 GW of large scale renewable generation combined with existing large hydro facilities can enable 80% carbon-free electricity (determined through 2030 demand forecasts, less existing renewable generation contracts). • Expanding transmission and distribution infrastructure to accommodate large-scale and distributed generation. Adding up to 10 GW of energy storage for grid balancing, in addition to current mandates. • Full pathway abatement includes the doubling of energy efficiency and additional distributed solar as defined in CARB's Proposed Scoping Plan.	15 MMT	**56 MMT**
Industrial	**Reduction in Refinery (Calculated outside of Pathways)**	• Increase in EV adoption reduces petroleum demand and associated refining.	4 MMT	**30 MMT**
Residential **Commercial**	**Heat Pump Water Heaters** **Air Source Heat Pumps** **Space Heating Electrification**	• Updating market costs and efficiency data, SCE calculated consumer adoption based on total cost of ownership. • Updated market data on cost plus policy-driven adoption in new construction leads to an increased adoption of high efficiency space and water heaters for residential buildings, totaling over 5 million units by 2030. Commercial space and water heating is also electrified and comprises 24% of thermal load. These represent up to 30% of space and water heaters expected in California in 2030.	2 MMT	**12 MMT**
Agricultural	**(Same as CARB Proposed Scoping Plan)**			**11 MMT**
Total			36 MMT	**180 MMT**

* **Incremental GHG Abatement Contribution** represents the GHG reductions from the identified technologies to meet the incremental 36 MMT of reductions after offsets to achieve California's 2030 GHG target. This 36 MMT reduction is incentivized by the cap-and-trade market under CARB's Proposed Scoping Plan. **Full Path GHG Abatement Contribution** represents both current and expected measures in CARB's Proposed Scoping Plan and the additional identified technologies used to meet the total 2030 GHG emission reduction goal.

Results Summary

Table 5 summarizes the three pathways. All scenarios include significant new electrification, in addition to major market transformations. (More information on the alternative pathways is detailed on page 6.)

Table 5. Comparing Decarbonization Pathways

	Clean Power and Electrification	Renewable Natural Gas (RNG)	Hydrogen (H2) Pathway
Carbon-Free Electricity Delivered	80%	60%	80%
Renewable Energy Over Generation	Managed through up to 10 GW of battery storage	Used to produce synthetic methane through "power to gas"	Used for hydrogen production from steam reforming and electrolysis
Transportation: Light-Duty Passenger Vehicles (EVs)	7MM EVs 24% of LDV stock	7MM EVs 24% of LDV stock	2MM EVs 4MM H2 fuel cell vehicles 22% of LDV Stock
	~13% reduction in transportation-related refinery throughout		
Transportation: Medium-Duty (MDV) and Heavy-Duty (HDV) Vehicles (Buses and Trucks)	9% MDVs, 6% HDVs are compressed natural gas (CNG)	12% MDVs, 12% HDVs are CNG	4% HDVs are H2 7% MDVs, 6% HDVs are CNG
	15% MDVs and 6% HDVs are EVs	7% MDVs and 1% HDVs are EVs	
Space and Water Heating (Residential and Commercial buildings)	Up to 30% electrification of space and water heating end uses	42% of natural gas replaced by RNG, 7% of natural gas replaced by H2	Up to 30% electrification of space and water heating end uses
Fuels and Other End Uses	7% of natural gas replaced by RNG		7% of natural gas replaced by H2 (technical limit)
Risks	- Most feasible pathway as technology already exists - Dependent on broad adoption of electrified technologies	- Power to gas not yet commercially available - A large biogas market requires expensive imports	- Most expensive pathway - Requires significant H2 adoption outside CA - Lack of sufficient delivery infrastructure
Average Abatement Cost (180 MMT)	**$37/metric ton**	**$47/ metric ton**	**$70/metric ton**
Incremental Abatement Cost (last 36 MMT)	**$79/metric ton**	**$137/metric ton**	**$262/metric ton**

Alternative Pathway 1: Renewable Natural Gas (RNG)

The RNG pathway includes the same assumptions as the CARB Proposed Scoping Plan with a few notable differences, which include:

- Higher percentage of MDV and HDV vehicles using compressed natural gas;
- Natural gas replaced in pipeline with RNG primarily from landfill capture and conversion, including the injection of hydrogen into the pipeline; and
- Renewable power over-generation is balanced on the grid through production of synthetic methane (power to gas), a technology that is not yet commercially available.

The RNG case requires less large-scale renewable generation because a large segment of the natural gas pipeline is replaced with RNG. Consequently, the cost per ton of abatement is higher due to the cost to procure and produce RNG, which would likely require significant imports into California.

Alternative Pathway 2: Hydrogen

The hydrogen pathway builds on the CARB Proposed Scoping Plan assumptions with the following differences:

- Hydrogen Fuel Cell Vehicles have higher adoption rates across two classes (light duty vehicles, medium duty vehicles);
- Hydrogen replaces pipeline natural gas for end uses up to the technical potential of 7 percent by volume (mid-range of 5-15 percent hydrogen concentration level defined in NREL's "Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues"); and
- The addition of large-scale renewable generation in the hydrogen pathway is consistent with the generation capacity called for in the Clean Power and Electrification Pathway. Excess renewable generation during peak generation periods can be used in electrolysis to produce hydrogen, helping to balance the grid and reducing the need for energy storage.

The abatement cost of the Hydrogen Pathway is the highest among all three cases, due to the need for construction of hydrogen production infrastructure not currently present in California. Additionally, hydrogen production is energy intensive and its energy storage potential is limited. Infrastructure and production costs are embedded in the cost per ton.

APPENDIX II: Additional Information and Resources

Relevant Policies

Action	Authorization	Reference
Renewables Portfolio Standard (RPS): 20% by 2010 and then 33% by 2020	SB 1078 (2002)	Sen. Bill 1078, 2001-2002 1st Ex. Sess., ch. 516, *California State Legislatur*e, Sept 12, 2002. http://www.energy.ca.gov/portfolio/documents/documents/SB1078.PDF
	SB 107 (2006)	Sen. Bill 107, 2005-2006 1st Ex. Sess., ch. 464, *California State Legislature*, September 26, 2006. http://www.energy.ca.gov/portfolio/documents/documents/sb_107_bill_20060926_chaptered.pdf
	SB X1-2 (2011)	Sen. Bill X1 2, 2010-2011 1st Ex. Sess., ch. 1, *California State Legislature*, April 12, 2011. http://www.leginfo.ca.gov/pub/11-12/bill/sen/sb_0001-0050/sbx1_2_bill_20110412_chaptered.html
Target established to reduce GHG emissions 80% below 1990 levels by 2050	Executive Order S-3-05 (2005)	California Executive Order S-3-05, June 2005. https://www.gov.ca.gov/news.php?id=1861
GHG emissions target of 1990 levels by 2020 is codified and economy-wide cap-and-trade program is created	AB 32 (2006)	Assem. Bill 32, 2005-2006 1st Ex. Sess., ch. 488, *California State Legislature*, Sept 27, 2006. http://www.leginfo.ca.gov/pub/05-06/bill/asm/ab_0001-0050/ab_32_bill_20060927_chaptered.pdf
Established RPS of 50% by 2030 and new requirements for doubling energy efficiency and wide-scale transportation electrification deployment	SB 350 (2015)	Sen. Bill 350, 2015-2016 1st Ex. Sess., ch. 547, *California State Legislature*, Oct 07, 2015. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB350
GHG target of reducing emissions 40% below 1990 levels by 2030 is codified	SB 32 (2016)	Sen. Bill 32, 2015-2016 1st Ex. Sess., ch. 249, *California State Legislature*, Sept 08, 2016. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB32
Cap-and-trade program extended to 2030 and new offset levels are defined	AB 398 (2017)	Assem. Bill 398, 2017-2018 1st Ex. Sess., ch. 398, *California State Legislature*, July 25, 2017. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180AB398
CARB Proposed Scoping Plan to achieve the 2030 GHG target	CARB (2017)	AB 32 Scoping Plan, *California Air Resource Board*, last modified Jul 14, 2017, accessed Sept 13, 2017. https://www.arb.ca.gov/cc/scopingplan/scopingplan.htm
Low Carbon Fuel Standard to encourage the production and use of cleaner low-carbon fuels	Executive Order S-1-07 (2007)	*California Air Resource Board*, last modified Sept 8, 2017, accessed Sept 21, 2017. https://www.arb.ca.gov/fuels/lcfs/lcfs.htm
Zero Emission Vehicle (ZEV) Program	CARB (1990)	*California Resource Board*, last modified August 16, 2017, accessed Sept 21, 2017. https://www.arb.ca.gov/msprog/zevprog/zevprog.htm
"The Partnership for Sustainable Communities	U.S. Department of Housing and	*Sustainable Communities*, accessed Sept 21, 2017. https://www.sustainablecommunities.gov/partnership-resources/community-planning

Action	Authorization	Reference
(PSC) works to coordinate federal housing, transportation, water, and other infrastructure investments to make neighborhoods more prosperous, allow people to live closer to jobs, save households time and money, and reduce pollution. The partnership agencies incorporate six principles of livability into federal funding programs, policies, and future legislative proposals."	Urban Development (HUD), U.S. Department of Transportation (DOT), U.S. Environmental Protection Agency (EPA) 2009	

Additional Sources

CARB Scoping Plan

The 2017 climate change scoping plan update establishes a proposed framework of action for California to achieve a 40 percent GHG emissions reduction by 2030 compared to 1990 levels. The key programs under the proposed plan are the Cap-and-Trade market, the Low Carbon Fuels standard, movement toward cleaner vehicles, increasing electricity generation from renewable sources and strategies for methane emission reduction from agriculture.
https://www.arb.ca.gov/cc/scopingplan/scopingplan.htm

Energy Costs of GHG Emissions: National Pathway Clean Energy Study (NRDC)

NRDC's analysis shows that the United States can achieve 80 percent GHG emission reduction by 2050 from 1990 levels with only 1 percent cost increase compared with current U.S. energy cost. The key actions under the NRDC plan are: implement energy efficiency technologies to reduce energy demand by 40 percent, expand renewable energy to achieve 70 percent RPS by 2050, employ near-zero carbon electricity to displace fossil fuel usage in transportation, residential and commercial buildings and industry, and decarbonize remaining fuel use in transportation and industry.
https://www.nrdc.org/sites/default/files/americas-clean-energy-frontier-es.pdf

EV Market Trends

Electric cars sales are forecasted to surpass internal combustion engine sales by 2038 because electric cars could be cost competitive with gasoline models by 2025, battery manufacturing capacity will continue to grow, and lithium-ion cell cost will decline significantly. The global shift toward electric vehicles will create upheaval for the auto industry, will increase EV electricity consumption from 6 terawatt-hours in 2016 to 1800 terawatt-hours in 2040, and will affect the oil industry through gasoline demand reduction.
https://www.bloomberg.com/news/articles/2017-07-06/the-electric-car-revolution-is-accelerating

Electric vehicles are becoming increasingly common, with automakers indicating that about 70 EV passenger models will likely be available within five years. Key factors driving additional purchases of electric cars are that electric cars use far less energy than gasoline-powered cars, cost less to run and have lower maintenance costs. Limited variety among electric vehicles, high price premium and limited range are among the barriers that prevent people from purchasing EVs.
https://www.consumerreports.org/hybrids-evs/electric-cars-101-the-answers-to-all-your-ev-questions/

Mass-produced electric vehicles first entered the market late in 2010, with the benefit of high performance, safety, versatility and ability to conveniently charge at home at a low cost. Displacing gasoline with electricity also lowers emissions and decreases petroleum use. The challenge to consumers is to understand their own driving needs and how each vehicle option can meet their specific requirements as more options become available.
https://www.epri.com/#/pages/product/1023161/

Job Creation

The Bureau of Labor Statistics projects that solar PV installers and wind turbine service technicians will be the fastest growing occupations in the US from 2016 to 2026.
https://www.bls.gov/news.release/pdf/ecopro.pdf?utm_source=newsletter&utm_medium=email&utm_campaign=newsletter_axiosgenerate&stream=politics

According to a UC Berkeley report, 10,200 job years (one full time job for one year) have been created in the solar industry in California in the five years ending in 2014; in 2014, the average salary for these jobs was $78,000 per year plus benefits.
http://laborcenter.berkeley.edu/environmental-and-economic-benefits-of-building-solar-in-california-quality-careers-cleaner-lives/

CAISO's Senate Bill (SB) 350 report concluded that an additional 90,000 – 110,000 statewide jobs would be created from the 50% Renewables Portfolio Standard and also projected higher statewide gross product, real output, and state revenue across all the scenarios studied.
http://www.caiso.com/Documents/SB350Study-Volume8EconomicImpacts.pdf

The Southern California Association of Governments 2016-2040 Regional Transportation Plan is projected to create 351,000 additional jobs (in part from transportation electrification strategies).
http://scagrtpscs.net/Documents/2016/final/f2016RTPSCS.pdf

A report issued by the Union for Concerned Scientists and Greenlining Institute, reports that "California's heavy-duty EV sector is an emerging job market," and that family-supporting jobs will be available in maintenance, charging infrastructure and truck and bus manufacturing.
http://www.ucsusa.org/sites/default/files/attach/2016/10/UCS-Electric-Buses-Report.pdf

NRDC research finds that "today's automotive sector provides a powerful example of how we can simultaneously meet the nation's environmental, economic, and job-creation goals." Currently, 288,000 American workers are "building technologies that reduce pollution and improve fuel economy for today's innovative vehicles, from family sedans to long-haul tractor trailers."
https://www.nrdc.org/sites/default/files/supplying-ingenuity-clean-vehicle-technologies-report.pdf