U.S.-China Energy Efficiency and Air Quality Strategies: A Review of Best Practices in Buildings, Transportation, and Industry

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REPORT AUTHORS:

California-China Climate Institute:
Dr. Robert B. Weisenmiller, Hae Jeong Cho, Jenn Perron, Dr. Fan Dai

Lawrence Berkeley National Laboratory:
Hongyou Lu, Nina Khanna, Dr. Nan Zhou, Lynn Price

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ABOUT THE CALIFORNIA-CHINA CLIMATE INSTITUTE

The California-China Climate Institute was launched in September 2019 and is a University of California-wide initiative housed jointly at UC Berkeley's School of Law (through its Center for Law, Energy & the Environment) and the Rausser College of Natural Resources. It is Chaired by Jerry Brown, former Governor of the State of California, and Vice-Chaired by the former Chair of the California Air Resources Board Mary Nichols. The Institute also works closely with other University of California campuses, departments and leaders. Through joint research, training and dialogue in and between California and China, this Institute aims to inform policymakers, foster cooperation and partnership and drive climate solutions at all levels.

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1. Acronyms and Abbreviations

AB	Assembly Bill
AMP	alternative maritime power
APCD	Air Pollution Control District
AQMD	Air Quality Management District
AQMP	Air Quality Management Plan
BAAS	battery as a service
BAT	best available technology
BESS	battery energy storage system
BTM	behind-the-meter
BTO	Building Technologies Office
CAA	Clean Air Act
$CACO_3$	calcium carbonate
CAFÉ	Corporate Average Fuel Economy
CAMx	Comprehensive Air Quality Model with extensions
CARB	California Air Resources Board
CAISO	California Independent System Operator
CalEPA	California Environmental Protection Agency
CAO	calcium oxide
CCS	carbon capture and sequestration
CCUS	carbon capture, utilization, and storage
CEC	California Energy Commission
CEIDARS	California Emission Inventory Development and Reporting System
CEPA	Controlled Emissions Projection Algorithm
CEPAM	California Emission Projection Analysis Model

CEQA	California Environmental Quality Act
CHP	combined heat and power
CH_4	Methane
CMAQ	Community Multiscale Air Quality
CNBM	China National Building Materials
CO	carbon monoxide
CO_2	carbon dioxide
CPUC	California Public Utilities Commission
DOE	Department of Energy
DPF	Diesel particulate filters
DREAM	Demand, Resources Energy Analysis Model
DV	Design value
EE	Energy efficiency
EPD	Environmental Product Declarations
ETS	Emissions trading system
EU	European Union
EV	Electric vehicle
EERE	Department of Energy's Office of Energy Efficiency and Renewable Energy
EPIC	Electric Program Investment Charge Program
EPRI	Electric Power Research Institute
F-gases	fluorinated gases
FYP	Five-Year Plan
GHG	greenhouse gas
GWP	global warming potential
HERS	Home Energy Rating System
HFC	Hydrofluorocarbons
HVAC	heating, ventilation, and air conditioning

ICE	internal combustion engine
IEA	International Energy Agency
IEPR	Integrated Energy Policy Report
IOU	investor-owned utility
ITC	Investment tax credit
Lb.	Pound
LCFS	Low Carbon Fuel Standard
LNG	Liquid natural gas
MCE	Marin Clean Energy
MOU	Memorandum of Understanding
MSW	Municipal solid waste
MUA	Multi-use application
NAAQS	National Ambient Air Quality Standards
NEV	New Energy Vehicle
NEM	net energy metering
NF_3	nitrogen trifluoride
NH_3	Ammonia
NHTSA	National Highway Safety Administration
NOx	nitrogen oxides
NSP	New suspension preheater-precalciner rotary kilns
PFC	Perfluorocarbons
PG&E	Pacific Gas & Electric (PG&E)
PM2.5	fine particulate matter 2.5 microns in width
PM10	Fine particulate 10 microns in width
POU	Publicly-owned utility
PPB	Parts per billion
Pv	Photovoltaic

REES	Regional Energy Efficiency Strategy
ROG	reactive organic gas
RPS	Renewable Portfolio Standard
SB	Senate Bill
SCC	social cost of carbon
SCE	Southern California Edison
SCG	Southern California Gas Company
SDG&E	San Diego Gas & Electric
SF_6	sulfur hexafluoride
SGIP	Self-Generation Incentive Program
SIP	State Implementation Plan
SO_2	sulfur dioxide
SMOKE	Sparse Matrix Operator Kernel Emissions
TAP	Technology Advancement Program
TOU	time-of-use
U.S.	United States
USD	United States dollars
U.S. EPA	U.S. Environmental Protection Agency
VOC	volatile organic compound
V2B	vehicle-to-building
V2G	Vehicle-to-grid
WHR	Waste to heat recovery
ZEV	zero emission vehicles
ZNE	zero net energy

2. Introduction

California and China have long battled air quality issues, but now must increasingly address greenhouse gas (GHG) emissions. Last September, China's President Xi Jinping set a zero net carbon target for China by 2060 and peaking GHG emissions before 2030 target. California's Assembly Bill (AB) 32 established a goal for 2020 of reducing its GHG emissions to 1990 levels (which was achieved by 2017), while Senate Bill (SB) 32 established a goal of reducing GHG emissions to 40% below 1990 levels by 2030 and Governor Jerry Brown signed an Executive Order (B-55-18) establishing the goal of zero net carbon by 2045.

Similar control policies address air quality and GHG emissions in both China and California, although they can be different control technologies. Since the 1960s, California has realized its air quality issues are linked to transportation (along with the atmospheric chemistry and frequent thermal inversions in the Los Angeles basin), and now realizes that more than 50% of its GHG emissions also come from transportation. China has relied on coal for power production, fueling industry and heating some of its cities, which accounted for 58% of the country's primary energy consumption in 2019[1] and has resulted in air quality issues (particularly, when there are thermal inversions such as in Beijing), and also now realizes that coal combustion is responsible for the bulk of its GHG emissions. Thus, both California and China can find substantial co-benefits by reducing GHG emissions with some additional improvement in air quality.

Both pollutants are multi-dimensional: air quality issues arise from fine particulate matter (PM2.5), nitrogen oxides (NOx), volatile organic compounds (VOCs) and ozone, while GHG emissions include not just carbon dioxide (CO_2), but also methane (CH_4), black carbon, and other short-lived climate pollutants. Indeed, a fundamental issue for controlling traditional air pollutant emissions is the nature of the control strategy and the question of whether to focus on individual pollutants or to take a multi-pollutant approach.[2] A multi-pollutant strategy, while more difficult to devise, would have lower costs.[3] Traditional air quality regulations usually start with tailpipe control technologies but strategies must ultimately become more sophisticated as tailpipe control technologies approach saturation. For example, in the 1970s, California Air Resources Board (CARB) pursued catalytic controls on automobiles, while its current strategy builds on catalytic controls accompanied with vehicle electrification, improved vehicle efficiency, Low Carbon Fuel Standard (LCFS), and land use policies. Similarly, CARB is now trying to develop and implement a strategy for not only air quality control over multi-pollutants but also to address climate change multi-pollutants.

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[1] Energy Information Agency. (n.d.). *International—China.* United States Energy Information Administration (EIA). Retrieved May 5, 2021, from https://www.eia.gov/international/analysis/country/CHN.

[2] Wang, A., Shen, S., & Pettit, D. (2020). *Coordinated Governance of Air & Climate Pollutants: Lessons from the California Experience*. UCLA Law. https://law.ucla.edu/news/coordinated-governance-air-climate-pollutants-lessons-california-experience

[3] Wang, L., Chen, H., & Chen, W. (2020). Co-control of carbon dioxide and air pollutant emissions in China from a cost-effective perspective. *Mitigation and Adaptation Strategies for Global Change*, *25*(7), 1177–1197. https://doi.org/10.1007/s11027-019-09872-7

While this study is entitled best practices, the reality is that the reference is towards the overall approach of pursuing co-benefits for the regulation of GHG and air pollutant emissions and considering energy efficiency measures. In general, energy efficiency measures provide the same level of energy services (such as light, heating, cooling and cooking) but with fewer energy inputs. For purposes of this study, we are also considering energy storage technologies. The specific emission control approaches must be tailored to local circumstances. A good complementary study to this current report was prepared by Alex Wang, Siyi Shen and David Pettit entitled "Coordinated Governance of Air & Climate Pollutants: Lessons from the California Governance" (2020) which is an excellent primer on California's governance of both air and climate pollutants. For air pollutants there are a number of federal and state laws which establish the regulatory relationships and boundaries between the federal Environmental Protection Agency (U.S. EPA), CARB, and the local air districts, such as the South Coast Air Quality Management District (AQMD), San Joaquin Valley Air Pollution Control District (APCD), and Bay Area AQMD. A. Wang et al. make the point that while all three of these AQMDs use coordinated planning to address traditional air pollutants, they can have different strategies. For example, South Coast and San Joaquin AQMDs have emphasized NOx pollution control (relative to the control of VOCs) because of the greater co-benefits for ozone and PM2.5 control associated with NOx control, while the Bay Area AQMD emphasizes VOC control in the near term since it has relatively lower concentrations of ozone and PM2.5. The "best" strategy for air pollutant control has to consider local pollution levels and sources, geography, economics, atmospheric chemistry, co-benefits, and other factors. While there are best practices on how to approach these issues, there is not a single solution for all cases.

A. Wang et al. also discuss California's governance strategy for climate pollutants—the Scoping Plan—developed by CARB. Since its first adoption in 2008, the Scoping Plans have established a pathway that would achieve California's GHG targets. As can be seen from Figure 1 in the 2017 Scoping Plan, the Scoping Plans involve almost all sectors of the state's economy and, accordingly, a broad range of state agencies. Actual implementation requires coordinated actions by not only CARB, but also the California Energy Commission (CEC), the California Public Utilities Commission (CPUC), the California Independent System Operator (CAISO) and a host of other environmental control agencies as well as federal agencies, particularly in the regulation of automobile technology.

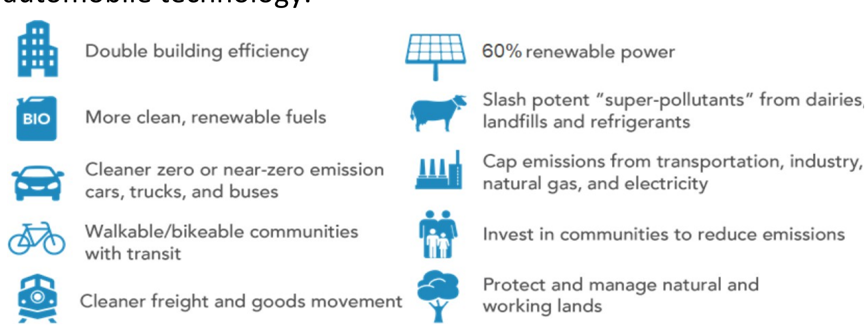

Figure 1: CARB's Climate Portfolio
Source: CARB (2020) [4]

[4] California Air Resources Board. (2020, October 28). *California's Climate Change Scoping Plan*. (Presentation)

Figure 2 demonstrates that California has managed to both grow its economy (to the fifth largest in the world in pre-COVID days), while at the same time reducing its GHG emissions (below 1990 levels).

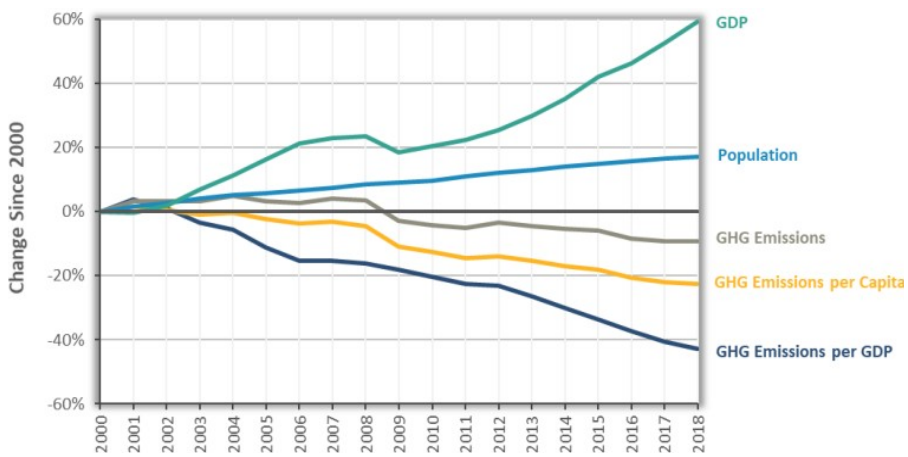

Figure 2. Results of California's Efforts to Reduce GHG Emissions
Source: CARB (2020) [5]

As the nexus of California's climate and air quality regulation, CARB is well positioned to consider the interaction between control of air pollutants and climate regulation to minimize control costs and maximize the efficiency of the regulation.

In addition, climate and air quality issues are starting to have feedback loops in California. Millions of trees have died from the combination of multi-year droughts, higher temperatures, and bark beetle infections. Climate change further increased California's vulnerability to wildfirerisks. The resulting fires lead to a substantial increase in both GHG and PM2.5 emissions. In 2020,California had roughly 9,600 fires which burned nearly 4.2 million acres, killed 31 people, and emitted an estimated 112 million metric tons of carbon dioxide equivalent (MMTCO2e).[6] This is equivalent to the GHG emissions of 24.2 million cars driving for a single year.[7] The fires also destroyed tens of thousands of households which resulted in increased emissions of not only

[5] California Air Resources Board. (2020). *California Greenhouse Gas Emissions for 2000 to 2018: Trends of Emissions and Other Indicators*. California Air Resources Board. https://ww3.arb.ca.gov/cc/inventory/pubs/reports/2000_2018/ghg_inventory_trends_00-18.pdf
[6] California Air Resources Board. (2020). *Public Comment Draft—Greenhouse Gas Emissions of Contemporary Wildfire, Prescribed Fire, and Forest Management Activities*. California Air Resources Board. https://ww3.arb.ca.gov/cc/inventory/pubs/ca_ghg_wildfire_forestmanagement.pdf
[7] Dooley, E.C. (2021, January 5). *California's 2020 Wildfire Emissions Akin to 24 Million Cars.* Bloomberg Law. https://news.bloomberglaw.com/environment-and-energy/californias-2020-wildfire-emissions-akin-to-24-million-cars

PM2.5 but also of toxics.[8] Wildfires accounted for half of the particulate matter emissions in the Western United States (U.S.)[9] Thus, California's progress in air quality improvement is being eroded by climate change.

At the same time, California's climate strategy has rested on a very holistic approach. The centerpiece of the Scoping Plan is putting a price on carbon through its cap-and-trade program. This program establishes a decreasing cap on GHG emissions in the state and raises a substantial amount of revenue that has been used to provide funding for innovative programs to reduce GHG emissions as shown in Table 1. However, California's carbon price is relatively low compared to other emissions trading systems because of the impact of complementary energy programs like building standards and the procurement of renewables, which have resulted in much of California's reductions of GHG emissions in the past ten years.[10]

Administering Agency	Program	Appropriations ($M)[4,5]		
		Cumulative Appropriations, Prior to FY 19–20	FY 19–20	Cumulative Total
California Air Resources Board	Community Air Protection	$556	$291	$847
	Fluorinated Gases Emission Reduction Incentives	–	$1	$1
	Funding Agricultural Replacement Measures for Emission Reductions	$197	$65	$262
	Low Carbon Transportation	$1,724	$492	$2,216
	Prescribed Fire Smoke Monitoring	$6	$2	$8
	Woodsmoke Reduction	$8	–	$8
California Coastal Commission	Coastal Resilience Planning	$3	$2	$5
California Conservation Corps	Training and Workforce Development	$27	$14	$41
California Department of Community Services and Development	Low-income Weatherization	$202	$10	$212
California Department of Fish and Wildlife	Wetlands and Watershed Restoration	$46	<$1	$47
California Department of Food and Agriculture	Dairy Methane	$260	$34	$294
	Healthy Soils	$13	$28	$41
	Renewable Alternative Fuels	$3	–	$3
	State Water Efficiency and Enhancement	$66	–	$66
California Department of Forestry and Fire Protection	Community Fire Planning and Preparedness	–	$10	$10
	Fire Prevention	$107	$85	$192
	Forest Carbon Plan Implementation	$25	$35	$60
	Sustainable Forests	$454	$170	$624
California Department of Resources Recycling and Recovery	Waste Diversion	$134	$25	$159

[8] Aquilera, R. Corringham, T., Gershunov, A., & Benmarhia, T. (2021). Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California. *Nature Communications, 12, 1493.* https://doi.org/10.1038/s41467-021-21708-0

[9] Barboza, T. (2021, January 13). *Wildfire smoke now causes up to half the fine-particle pollution in Western U.S., study finds.* LA Times. https://www.latimes.com/california/story/2021-01-13/wildfire-smoke-fine-particle-pollution-western-us-study

[10] Abrell, J., Betz, R. Kosch, M., Kardish, C. Mehling, M. (2020, December). The Californian Emissions Trading System and Electricity Market: Influence of market structures and market regulation on the carbon market, *Climate Change*, 49

Administering Agency	Program	Appropriations, Prior to FY 19–20	FY 19–20	Cumulative Total
California Department of Transportation	Active Transportation	$10	–	$10
	Low Carbon Transit Operations	$459	$66	$525
California Department of Water Resources	State Water Project Turbines	$20	–	$20
	Water-Energy Grant	$50	–	$50
California Energy Commission	Food Production Investment	$124	–	$124
	Low-Carbon Fuel Production	$13	–	$13
	Renewable Energy for Agriculture	$10	–	$10
California Environmental Protection Agency	Transition to a Carbon-Neutral Economy	–	$3	$3
California Governor's Office of Emergency Services	Wildfire Response and Readiness	$50	$1	$51
California High-Speed Rail Authority	High-Speed Rail Project[6]	$2,523	$330	$2,853
California Natural Resources Agency	Regional Forest and Fire Capacity	$20	–	$20
	Urban Greening	$127	$30	$157
California State Coastal Conservancy	Climate Ready	$7	–	$7
California State Transportation Agency	Transit and Intercity Rail Capital	$1,029	$132	$1,161
California State Water Resources Control Board	Safe and Affordable Funding for Equity and Resilience Drinking Water	–	$100	$100
California Strategic Growth Council	Affordable Housing and Sustainable Communities Sustainable Agricultural Lands Conservation	$1,877	$263	$2,140
	Climate Change Research	$29	$5	$34
	Technical Assistance	$4	$2	$6
	Transformative Climate Communities	$190	$60	$250
California Wildlife Conservation Board	Climate Adaptation and Resiliency	$20	–	$20
California Workforce Development Board	Low Carbon Economy Workforce	–	$35	$35
San Francisco Bay Conservation and Development Commission	Climate Resilience Planning	$1	$2	$3
	Total	$10,395	$2,292	$12,687

Table 1. Cumulative Appropriations for California Climate Investments
Source: California Climate Investments (2020) [11]

In China, both climate and air quality issues have becoming increasingly important at the national and subnational levels of policymaking with multiple national strategies and plans released within the last decade. On climate mitigation specifically, China has committed to important domestic and international commitments, including goals for CO_2 peaking, CO_2 intensity reduction, non-fossil share of energy consumption and most recently, carbon neutrality by 2060. Its climate strategies have focused on building upon decades of energy efficiency improvements across all sectors, and increasing the adoption of renewable energy through power sector reform and fuel switching in end-use sectors to replace dirtier fuels such as coal. At the same time, as air quality concerns are exacerbated in some of China's largest and most densely populated regions, there have also been increasing focus on phasing out the use of heavily polluting, dispersed coal, particularly used for rural heating and some industrial boilers, and adopting end-of-pipe measures to reduce air pollutants from mobile point sources.

In the transport sector, China has concurrently adopted increasingly stringent fuel economy standards and vehicle emission standards to improve vehicle energy efficiency and to limit the air pollutants emitted by both light-duty and heavy-duty vehicles. At the same time, there have also been concerted efforts to promote the adoption of cleaner plug-in hybrid, battery electric and hydrogen fuel cell New Energy Vehicles (NEV) through pilot programs and

[11] Annual Report to the Legislature on California Climate Investments Using Cap-and-Trade Auction Proceeds. California Climate Investments, March 2020. p. iv-v.

various supporting policies including financial incentives, preferential tax policies, and infrastructure support. As a result, China is now a global leader in light-duty NEV sales and some cities such as Shenzhen have fully electrified its municipal fleets in a very short time. Air quality strategies for heavy-duty vehicles have focused on phasing-out older, inefficient and heavily polluting diesel trucks that do not meet more stringent emission standards, while climate strategies have recognized the need to both tap into remaining energy efficiency gains for new vehicles and increasing the deployment of clean NEVs based on the latest available technologies.

In the cement sector, China's cement industry has improved its energy efficiency through a combination of adopting energy-efficient technologies (e.g., new suspension preheater-pre-calciner rotary kilns and waste heat recovery) and supply-side policies (e.g., phasing out small and inefficient capacities and production curtailment). These actions have resulted in a positive impact on air quality improvement, reducing key pollutants of SOx, NOx, and PM emissions in targeted regions. Looking forward, China's cement industry continues to face multifaceted challenges, not only to reduce energy intensity, phase out outdated capacity, increase utilization rates, but also to continue reducing key air pollutants and decreasing carbon dioxide emissions to support China's carbon peaking and carbon neutral goals.

3. Overview of Co-benefits of Energy Efficiency Measures

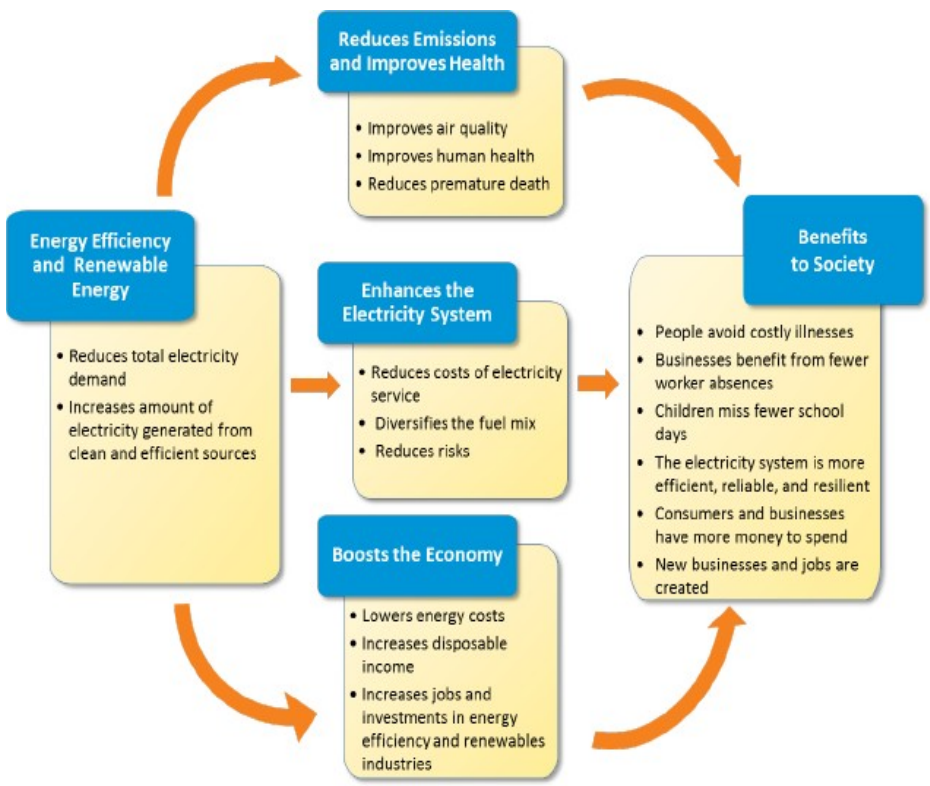

Figure 3. Multiple Benefits of Energy Efficiency and Renewable Energy

Source: EPA (2018) [12]

Figure 3 demonstrates both the direct and indirect benefits of energy efficiency, renewables, and storage. The benefits of energy efficiency are multifold: it reduces GHG and pollutant emissions, helps the economy by reducing residents' and businesses' utility bills, provides jobs, and saves money by avoiding the need to build new power plants and transmission lines. Storage can shift electricity production either in time and/or space so that it can prevent curtailment of renewables and drive electric motors in automobiles.

Below is a summary of the benefits of energy efficiency combined with renewable energy generation illustrated above and identified in the 2018 edition of *Quantifying the Multiple Benefits of Energy Efficiency and Renewable Energy: A Guide for State and Local Governments* released by the U.S. EPA.[13]

- "Electricity system benefits: Energy efficiency and renewable energy initiatives—in combination with demand response measures—can help **protect electricity producers and consumers from the costs of adding new capacity to the system and from energy supply disruptions, volatile energy prices, and other reliability and security risks**.

- Emissions and health benefits: Fossil fuel-based electricity generation is a source of air pollution that poses risks to human health, including respiratory illness from fine-particle pollution and ground-level ozone. The burning of fossil fuels for electricity is also the largest source of GHG emissions from human activities in the United States, contributing to global climate change. Improving energy efficiency and increasing the use of renewable energy can **reduce fossil fuel-based generation and its associated adverse health and environmental consequences**.

- Economic benefits: Many of the electricity system, emissions, and health benefits yield overall economic benefits to the state. These benefits include **savings** in energy and fuel costs for consumers, businesses, and the government; **new jobs in, profits for, and tax revenue from companies** that support or use energy efficiency and renewable energy, such as construction, manufacturing, and services; and **higher productivity from employees and students** taking fewer sick days." (Excerpt from U.S. EPA (2018))

A 2019 International Energy Agency (IEA) report similarly lays out multiple benefits of energy efficiency. Energy efficiency, according to the IEA, is the "first fuel" that you do not have to use and is cheap to extract.[14] Of its multiple benefits, this report focuses on those related to GHG and

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[12] United States Environmental Protection Agency. (2018). *Quantifying the Multiple Benefits of Energy Efficiency and Renewable Energy: A Guide for State and Local Governments - Part One: The Multiple Benefits of Energy Efficiency and Renewable Energy*. p. 1-7.

[13] *Id.*

[14] International Energy Agency. (2019, December 19). *Energy Efficiency is the First Fuel, and Demand for It Needs to Grow*. International Energy Agency. www.iea.org/commentaries/energy-efficiency-is-the-first-fuel-and-demand-for-it-needs-to-grow.

air pollutant emissions reduction. In California there is a "loading order" for resource additions that starts with energy efficiency, then moves to renewable resources and finally considers fossil fueled resources starting with natural gas and only at the very bottom considers coal.[15] The section below summarizes the studies that estimate the size of GHG emissions reduction and air quality benefits to be achieved by energy efficiency and electrification measures in California.

4. Air Quality Benefits from Energy Efficiency and Electrification in California

California's long-term air quality and climate strategy is basically complete electrification - to combine a much cleaner grid (100% renewable by 2045) to power not only its residential and commercial buildings, but also its transportation fleet.

California has studied the air quality benefits and economic costs of scenarios where substantial electrification occurs throughout the economy along with a renewable powered grid. Electrification results in substantial air quality benefits in both the South Coast and inland Central Valley, the state's two worst nonattainment areas.

A study of the energy efficiency programs implemented by seven investor-owned utilities (IOUs) (electricity and natural gas providers) in California from 2013-2015 found substantial reductions in CO_2, NOx, and other traditional air pollutants from efficiency improvements in the electric and natural gas sectors. These energy efficiency programs were estimated to have reduced CO_2 and NOx emissions substantially over a three-year period (2013-15), avoiding more than 4.1 million tons of CO_2 and 1.6 million pounds of NOx emissions.[16]

Zhao et al. (2019) found that the deep decarbonizing pathway that reduces GHG emissions by 80% (by 2050 from 1990 levels) using electrification and renewable energy would also reduce PM2.5 by 33%, NOx by 34%, sulfur dioxide (SO_2) by 37%, ammonia (NH_3) by 34%, and reactive organic gases (ROG) by 18%.[17]

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[15] Earthjustice. (2012, January 12). *California Regulators Add Teeth to Landmark Clean Energy Policy.* This release summarizes a decision adopted in the CPUC's Long-Term Procurement Plan (Rulemaking 10-05-006). This decision reinvigorates a CEC policy adopted in 1980.

[16] California Public Utilities Commission. (2018, May). *Energy Efficiency Portfolio Report.* https://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=6442459323

[17] Zhao, B., et al. (2019). Air Quality and Health Cobenefits of Different Deep Decarbonization Pathways in California. *Environmental Science & Technology 53*(12), 7163-7171. https://doi.org/10.1021/acs.est.9b02385.

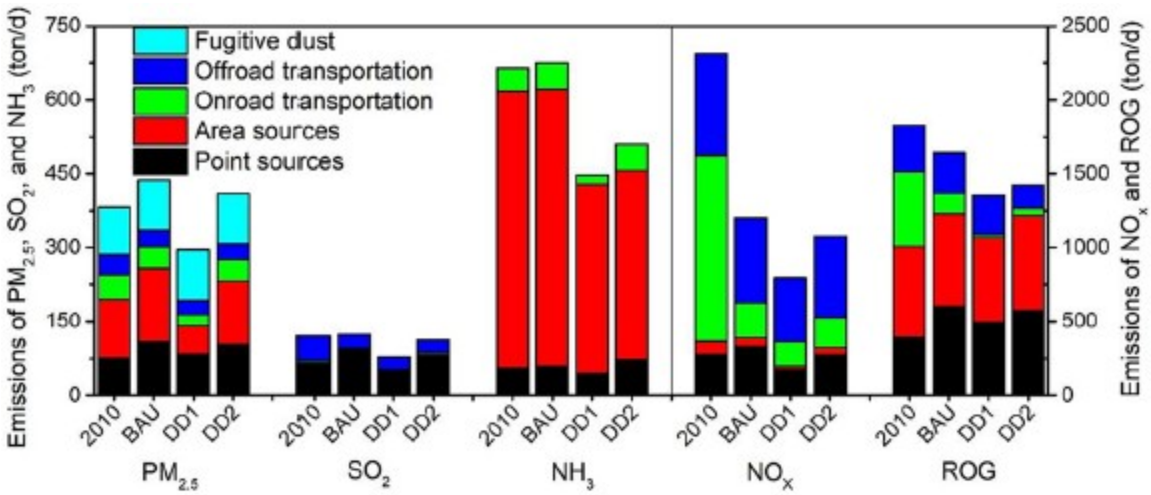

Figure 4. California Statewide Emissions of Major Air Pollutants in 2010 and under Different Scenarios in 2050. DD1 is a pathway with higher electrification rates.
Source: Zhao et al. (2019)

Zhu et al. (2020) found that an electrification scenario in which 100% of residential gas appliances are replaced with clean-energy electric appliances would reduce the ambient PM2.5 concentration by an average of 0.11 microns per cubic meter (µg/m3) per county. The resulting improvement in outdoor air quality would reduce approximately 354 deaths (all-cause mortality), 304 cases of chronic bronchitis, and 596 cases of acute bronchitis in California.[18]

A 2020 study by the Electric Power Research Institute (EPRI) analyzed the air quality co-benefits of the efficient electrification scenario that meets California's decarbonization targets (40% by 2030 and 80% by 2050) and 100% clean electricity targets by 2045, under which electricity reaches 55% of the final energy share in California by 2050 (Figure 5).[19]

[18] Zhu et al. (2020 April). *Effects of Residential Gas Appliances on Indoor and Outdoor Air Quality and Public Health in California*. UCLA Fielding School of Public Health. https://ucla.app.box.com/s/xyzt8jc1ixnetiv0269qe704wu0ihif7

[19] Knipping, E., Bistline, J., Blanford, G. (2020). *Efficient Electrification in California: Assessment of Energy System and Air Quality Impacts*. Electric Power Research Institute. https://www.epri.com/research/products/3002019494

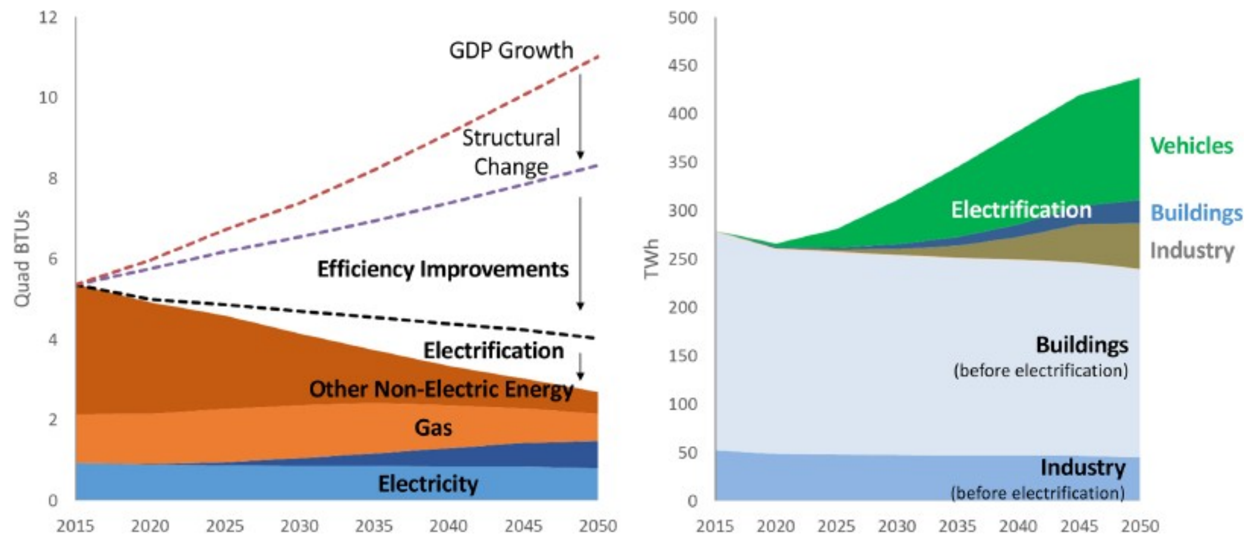

Figure 5. California's Final Energy Demand by Fuel (left) and Electricity Demand by Sector (right) Source: EPRI (2020)

The study found that CO, NOx, and SO2 emissions would decrease from 2015 to 2050, NH_3, PM10, and PM2.5 emissions increase from 2015 to 2050, and VOC emissions decrease from 2015 to 2035, then increase from 2035 to 2050. Emission increases would result from increased non-combustion activity in industrial facilities, road dust, and agricultural dust source categories. A more detailed air quality modeling for ozone and PM2.5 in the South Coast Air Basin, one of the nonattainment areas in the state, suggested that electrification can substantially improve air quality by lowering ozone due primarily to lower NOx emissions (Figure 6). Electrification would also lower the formation of secondary PM2.5, but growing activity from non-electrified sources could offset the benefits if not controlled (Figure 7).

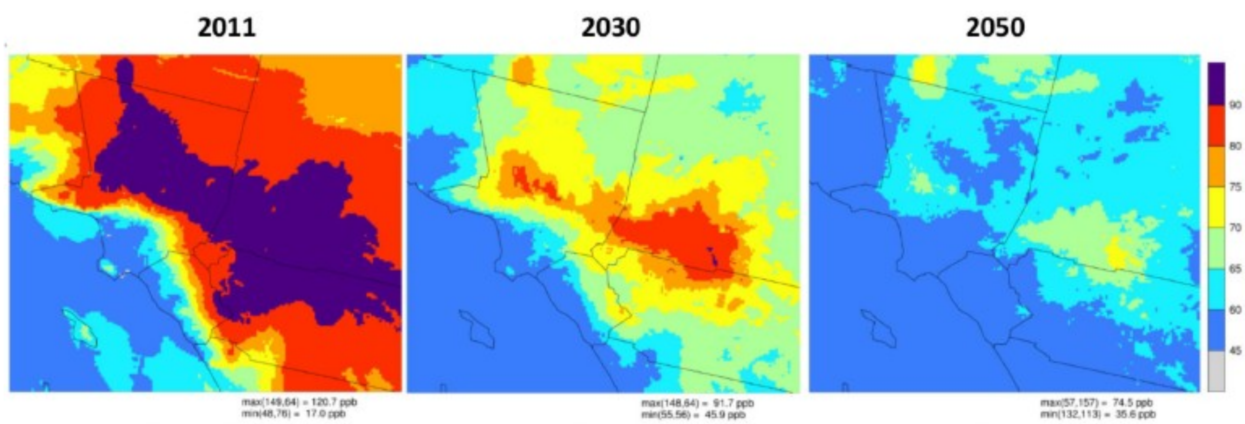

Figure 6. Estimated Ozone design values (DVs)20 (ppb) throughout the South Coast Air Basin Source: EPRI (2020)

[20] The annual fourth-highest daily maximum 8-hour average concentration averaged over three years.

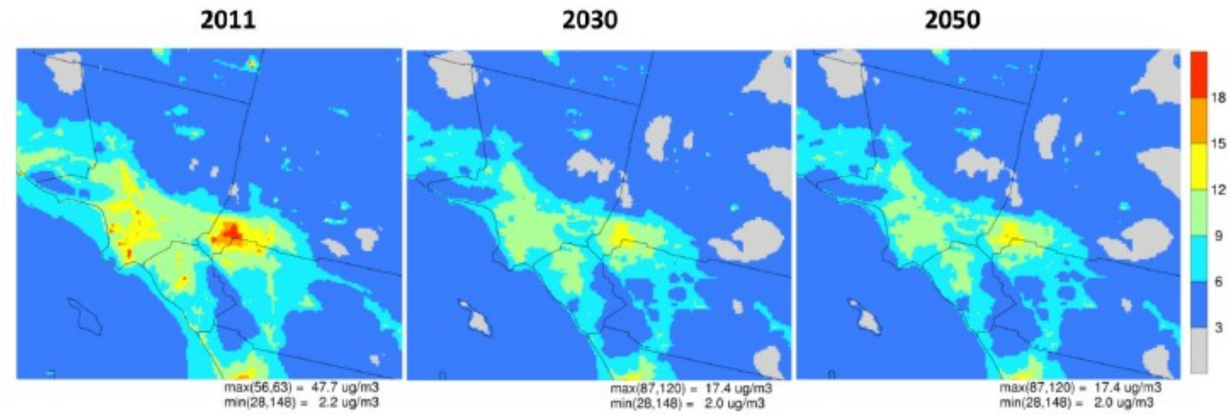

Figure 7. Estimated PM2.5 DVs(μg/m3) throughout the South Coast Air Basin
Source: EPRI (2020)

5. Energy Efficiency and Air Quality Strategies in the U.S.

6.1 Federal Energy Efficiency and Air Quality Strategies

6.1.1 Overview

The federal Clean Air Act (CAA) is the main framework of both air pollution and GHG emissions in the U.S. The law authorizes the U.S. EPA to establish the National Ambient Air Quality Standards (NAAQS) for six air pollutants ("criteria pollutants''): particulate matter (PM2.5, PM10), ozone, SO_2, NO_2, carbon monoxide (CO), and lead. The U.S. EPA periodically updates the standards based on the latest scientific evidence.[21] As discussed above, A. Wang et al. provides a comprehensive assessment of Federal, state, and local air quality regulation in California. In 2009, EPA concluded that GHG including CO_2, methane, N_2O, and f-gases endanger public health and welfare, making itself responsible for the regulation of GHG emissions.[22] This finding allowed the U.S. EPA to develop GHG emission standards for light-duty vehicles jointly with the National Highways Traffic Safety Administration (NHTSA), in addition to the existing Corporate Average Fuel Economy (CAFE) standards.[23]

The Department of Energy (DOE)'s Office of Energy Efficiency and Renewable Energy (EERE) leads efforts to improve energy efficiency and increase renewable generation at the federal level. It provides funding to research, especially early-stage research, on emerging energy technologies

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[21] Wang, A., Shen, S. and Pettit, D. (2020). *Coordinated Governance of Air & Climate Pollutants: Lessons from the California Experience.* UCLA School of Law Emmett Institute of Climate Change & the Environment. https://law.ucla.edu/news/coordinated-governance-air-climate-pollutants-lessons-california-experience
[22] United States Environmental Protection Agency. *Air Pollution: Current and Future Challenges.* https://www.epa.gov/clean-air-act-overview/air-pollution-current-and-future-challenges
[23] United States Environmental Protection Agency. *Regulations for Greenhouse Gas Emissions from Passenger Cars and Trucks.* https://www.epa.gov/regulations-emissions-vehicles-and-engines/regulations-greenhouse-gas-emissions-passenger-cars-and

in transportation, renewable energy, and energy efficiency. Much of this research is performed at the national laboratories, such as Lawrence Berkeley National Laboratory and the National Renewable Energy Laboratory. The Building Technologies Office (BTO) within EERE implements federal energy conservation standards for more than 60 categories of appliances and equipment. According to EERE, the products covered by the standards represent about 90% of home energy use, 60% of commercial building use, and 30% of industrial energy use.[24] As will be discussed below, the federal standards preempt state and local appliance standards in order to reduce regulatory burden for manufacturers.

The Federal government also provides a variety of tax credits for energy investments, including a solar investment tax credit (ITC) for both commercial and residential buildings. Storage devices installed with solar equipment are also eligible for this solar investment tax credit. The amount of benefit was 30% of the cost for residential and commercial solar photovoltaic (PV) projects installed in 2019. The amount of tax benefit started decreasing annually from 2020 and was set to expire for residential properties in 2022.

As part of the second COVID-19 relief bill passed in December 2020, the solar deadlines were extended by two years. Solar projects that start construction in 2020, 2021, or 2022 will qualify for a 26% investment tax credit. This tax credit drops to 22% for projects starting construction in 2023. A project placed in service after 2025 qualifies for only a 10% investment tax credit.[25] [26]

The Biden infrastructure plan proposes additional extensions of the solar tax credit and a standalone storage tax credit among other things.[27] This is an area to monitor as legislative language is developed and debated.

6.1.2 Changes during the Trump Administration (2017 - 2021)

According to the Washington Post, as of October 2020, the Trump administration rolled back more than 125 environmental regulations, 42 of which affected air pollution and GHG emissions.[28] Some of the rollbacks that would negatively affect air quality, GHG emissions, and energy efficiency were as follows:

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[24] United States Department of Energy. (2017, January). *Saving Energy and Money with Appliance and Equipment Standards in the United States.* https://www.energy.gov/sites/default/files/2017/01/f34/Appliance%20and%20Equipment%20Standards%20Fact%20Sheet-011917_0.pdf

[25] Martin, K. Esq. (2020, December). *Renewable energy tax credits extended*. Norton Rose Fulbright. https://www.projectfinance.law/publications/2020/december/renewable-energy-tax-credits-extended/

[26] United States Department of Energy (2015, May 15). *Residential and Commercial ITC Factsheets.* https://www.energy.gov/eere/solar/downloads/residential-and-commercial-itc-factsheets

[27] Martin, K. Esq. (2021 April). *Infrastructure Plan: Outlook in Congress.* Norton Rose Fulbright. https://www.projectfinance.law/publications/2021/april/infrastructure-plan-outlook-in-congress/

[28] Eilperin, J., Dennis, B., and Muysken, J. (2020, October 20). *Trump has rolled back 125 climate and environmental policies. It would take Biden years to restore them*. The Washington Post. https://www.washingtonpost.com/graphics/2020/climate-environment/trump-climate-environment-protections/

- Replaced the Clean Power Plan, which would have set strict limits on carbon emissions from coal- and gas-powered plants, with the Affordable Clean Energy rule.[29]

- Slashed the social cost of carbon (SCC) for assessing regulatory costs and benefits by using domestic rather than global damages from climate change and using a higher range of discount rates. The Trump estimates for SCC ranged from 1 to 7 in 2018 U.S. dollars per ton of carbon dioxide (tCO_2) emitted in 2020.[30] (Figure 8)

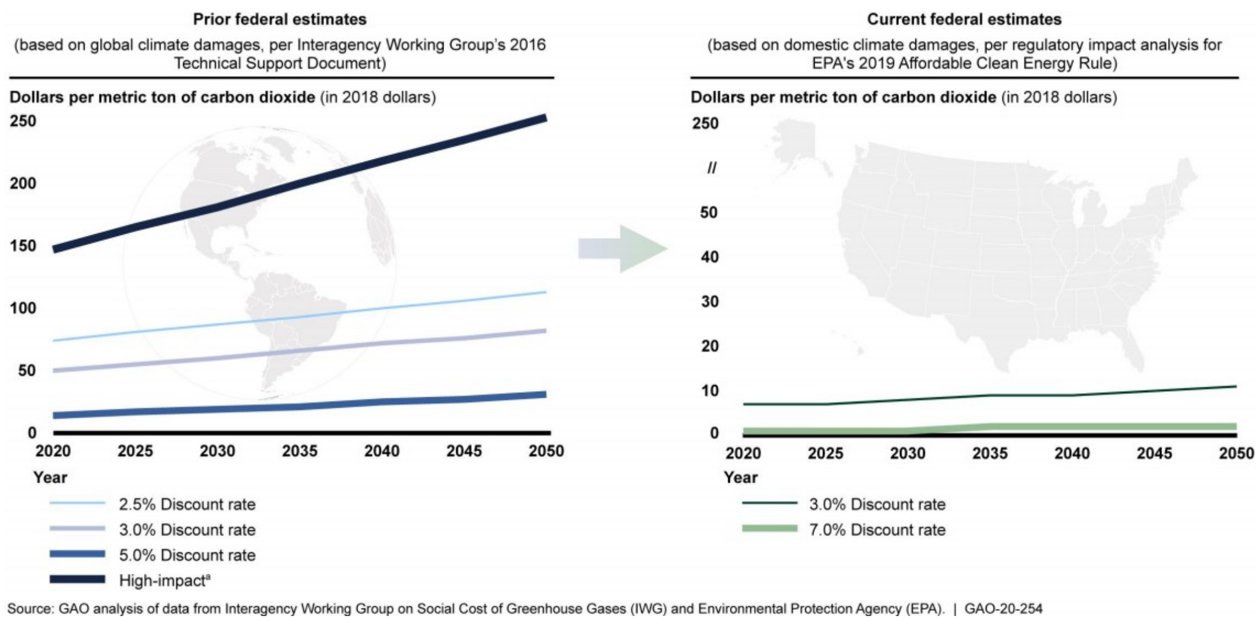

Figure 8. Federal Estimates of the SCC before and during the Trump Administration
Source: GAO (2020)

- Made a rule to require the U.S. EPA to break out expected health gains to make clear the difference between the benefits of pollutant reductions directly targeted by the planned regulations and other indirect "co-benefits." [31]

[29] See the Affordable Clean Energy Rule, United States Environmental Protection Agency, https://www.epa.gov/stationary-sources-air-pollution/affordable-clean-energy-rule. On January 19, 2021, the D.C. Circuit vacated the Affordable Clean Energy rule and remanded to the Environmental Protection Agency for further proceedings consistent with its opinion.
[30] United States Government Accountability Office. (2020). *Social Cost of Carbon: Identifying a Federal Entity to Address the National Academies' Recommendations Could Strengthen Regulatory Analysis p. 16.* United States Government Accountability Office. https://www.gao.gov/assets/710/707871.pdf.
[31] Reilly, S. (2020, December 9). *Trump's new cost-benefit rule will curb EPA's regulatory power.* Science Magazine. https://www.sciencemag.org/news/2020/12/trump-s-new-cost-benefit-rule-will-curb-epa-s-regulatory-power

- Rolled back efficiency standards of showerheads, washers, dryers, dishwashers, and light bulbs.[32]

- Proposed substantial budget cuts for EERE and other applied energy R&D programs within DOE,[33] although these were generally refused by Congress.

- With the Safer Affordable Fuel-Efficient Vehicles rule, weakened fuel economy standards for light-duty vehicles and challenged California's right to set its own more stringent standards.[34]

- Moreover, on the topic of co-benefits in general the Trump EPA proposed to stop considering all indirect environmental and public health benefits when deciding whether to regulate mercury pollution from power plants. The Office of Management and Budget has defined a co-benefit as "a favorable impact of [a] rule that is typically unrelated or secondary to the statutory purpose of the rulemaking."[35] In the cost-benefit analyses for the mercury rule the direct monetizable benefits from reducing mercury emitted from power plants range from USD 4 to 6 million per year (the value of many other public health benefits cannot be readily monetized). The estimated annual co-benefits of reducing particulate matter emissions are USD 36 to 89 billion. The costs of the control technologies are estimated to range from USD 7.4 to 9.6 billion per year.[36] Even though the U.S. EPA's historic practice was to include co-benefits, the Trump EPA concluded that if the point of the Clean Air Act and the regulation was to reduce mercury, then the co-benefits from reducing particulate matter should not be counted. At the same time, the Trump NHTSA argued in the Safer Affordable Fuel-Efficient Vehicle rule that reducing auto fuel economy standards would reduce the costs of new cars, thereby resulting in the replacement of less safe older cars which would in turn improve safety. These Trump rules were primarily supported by consideration of the safety co-benefit. Overall, it was the Trump approach to include or exclude co-benefits or costs if it would justify fewer regulations.[37]

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[32] Delaski, A. (2021, March 8). *Biden, States Kick Off Pivotal Year for Appliance Efficiency Standards* | American Council for an Energy Efficient Economy. https://www.aceee.org/blog-post/2021/03/biden-states-kick-pivotal-year-appliance-efficiency-standards

[33] American Institute of Physics. (2020, March 26). *FY21 Budget Request: DOE Applied Energy R&D.* American Institute of Physics. https://www.aip.org/fyi/2020/fy21-budget-request-doe-applied-energy-rd

[34] United States National Highway Safety Administration. (2021). SAFE The Safer Affordable Fuel-Efficient 'SAFE' Vehicles Rule. United States National Highway Safety Administration. https://www.nhtsa.gov/corporate-average-fuel-economy/safe

[35] Circular A-4, "Regulatory Impact Analysis: A Primer" (reginfo.gov). p. 7. (Definition of "ancillary benefits")

[36] Raso, C. (2019, April 1). *Examining the EPA's Proposal to Exclude Co-Benefits of Mercury Regulation*. The Brookings Institution. https://www.brookings.edu/research/examining-the-epas-proposal-to-exclude-co-benefits-of-mercury-regulation/

[37] Raso, C. (2019, April 1). *Examining the EPA's Proposal to Exclude Co-Benefits of Mercury Regulation*. The Brookings Institution. https://www.brookings.edu/research/examining-the-epas-proposal-to-exclude-co-benefits-of-mercury-regulation/

6.1.3 Changes in the Biden Administration (starting in 2021)

On the day of his inauguration, President Biden signed an executive order that required the immediate review of all agency actions, including the fuel economy standards for light-duty vehicles, taken during the Trump administration that are or may be inconsistent with the protection of public health and environment.[38] The same executive order reinstated the Interagency Working Group on the Social Cost of Greenhouse Gases, which shall publish a final SCC, social cost of nitrous oxide, and social cost of methane by January 2022. The interim value of SCC published in February 2021 ranged from 51 to 76 in 2020 U.S. dollars per tCO2 emitted in 2020.[39] We anticipate the Biden Administration returning to the traditional co-benefits policy if not strengthen it.[40]

The new administration's budget request for fiscal year 2022 included a significant increase in proposed budgets for the U.S. Department of Energy (DOE) and U.S. EPA. Its 2022 discretionary request for DOE was USD 46.1 billion with a USD 4.3 billion or 10.2% increase from the 2021 enacted level, including: USD 1.9 billion towards new energy efficiency and clean electricity standards and clean energy workforce development; U.S. dollars (USD) 8 billion towards clean energy technologies such as advanced nuclear energy, electric vehicles, green hydrogen, and innovative air conditioning and refrigeration technologies; USD 1 billion for advanced research projects; and USD 7.4 billion for foundational research on climate change and clean energy technologies. Its request for the U.S. EPA was USD 11.2 billion with a USD 2 billion or 21.3% increase from the 2021 level, including USD 110 million to restore staff capacity and USD 1.8 billion in programs that would help reduce GHG emissions.[41]

Moreover, Biden rejoined the Paris accord, is incorporating climate considerations into his entire administration, and proposed a multi-trillion dollar infrastructure plan with significant climate elements.

6.2 Energy Efficiency and Air Quality Strategies in California

6.2.1 Energy Efficiency in California's Climate Policies

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[38] The White House. (2021, January 20). *Executive Order on Protecting Public Health and the Environment and Restoring Science to Tackle the Climate Crisis*. Executive Office of the President. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/20/executive-order-protecting-public-health-and-environment-and-restoring-science-to-tackle-climate-crisis/

[39] The White House. (2021, February). *The White House Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under Executive Order 13990*. Interagency Working Group on Social Cost of Greenhouse Gases, United States Government. https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf

[40] Friedman, L. (May 14, 2021). *Biden Administration to Repeal Trump Rule Aimed at Curbing E.P.A.'s Power*. The New York Times. https://www.nytimes.com/2021/05/13/climate/EPA-cost-benefit-pollution.html

[41] The White House. (2021, April 9). *Summary of the President's Discretionary Funding Request*. Executive Office of the President. https://www.whitehouse.gov/wp-content/uploads/2021/04/FY2022-Discretionary-Request.pdf.

Energy efficiency has a long-standing presence in California's policies, with its first appliance and building efficiency standards dating back to 1976 and 1978, respectively. California's loading order identifies energy efficiency and demand response as the state's preferred means of meeting growing energy needs. The unmet energy needs will then be met by renewable energy and distributed generation.[42] The state also decoupled the IOUs' revenues from sales in order to remove their disincentive to encourage energy saving.[43] Figure 9 below shows the timeline of the state's major energy efficiency and climate policy measures from the 1970s to date.

[42] California Public Utilities Commission. (2013, July). *Energy Efficiency Policy Manual, p 1*. California Public Utilities Commission. https://www.cpuc.ca.gov/uploadedfiles/cpuc_public_website/content/utilities_and_industries/energy_-_electricity_and_natural_gas/eepolicymanualv5forpdf.pdf

[43] California Public Utilities Commission. *(2016). Actions to Limit Utility Cost and Rate Increases - Public Utilities Code Section 913.1 Report to the Governor and Legislature, p. 5*. California Public Utilities Commission. https://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=6442457283

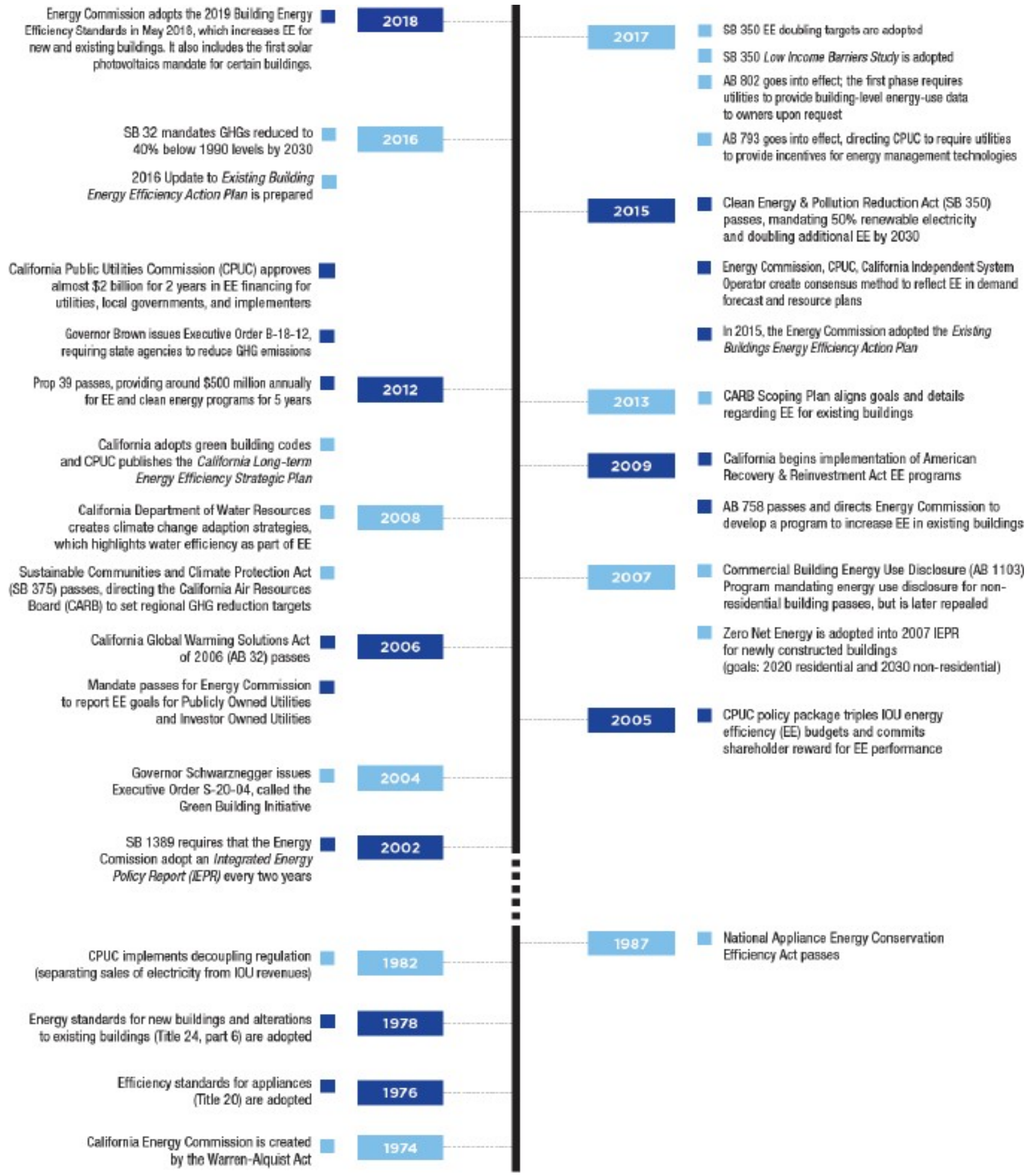

Figure 9. Timeline of California's Major Energy Efficiency Policies. Source: CEC (2018) [44]

[44] California Energy Commission. (2018, September). *Tracking Progress: Energy Efficiency, p 4*. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-12/energy_efficiency_ada.pdf

As a result of these energy efficiency measures, especially building and appliance efficiency standards, per capita energy consumption in California has leveled since the 1980s (Figure 10), and the state now ranks 48th in energy consumption per capita.[45]

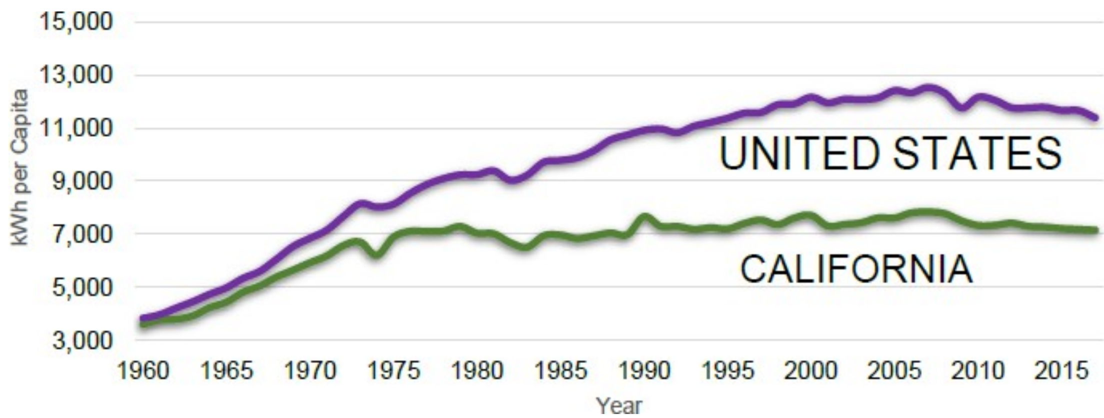

Figure 10. Electricity consumption per Capita in US and California
Source: CEC (2019) [46]

In 2015, the Clean Energy and Pollution Reduction Act of 2015 (SB 350, De León, Chapter 547, Statutes of 2015) set an ambitious goal to achieve a statewide cumulative doubling of energy efficiency savings and demand reductions in electricity and natural gas end uses by January 1, 2030, relative to the 2015 level, which was then incorporated into the 2017 Scoping Plan.

6.2.2 Scoping Plan

Pursuant to AB 32, CARB is responsible for developing a Scoping Plan to identify and make recommendations to achieve the "maximum feasible and cost-effective reductions of GHG emissions"[47] and is required to update it at least every five years. The Scoping Plan has been updated twice since its first adoption in 2008. CARB is now developing the 2022 Scoping Plan focused on carbon neutrality.[48] The state's GHG inventory (Figure 11), also maintained by CARB, helps track progress of its measures, make adjustments as necessary, and draft the next Scoping Plan.

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[45] United States Energy Information Agency. (2021). *California State Profile and Energy Estimates.* United States Energy Information Agency. https://www.eia.gov/state/data.php?sid=CA#ConsumptionExpenditures.
[46] California Energy Commission. (2019, November). *2019 California Energy Efficiency Action Plan*, *p. 16.* California Energy Commission. https://www.energy.ca.gov/filebrowser/download/1900
[47] AB-32.
[48] California Air Resources Board presentation on October 28, 2020.

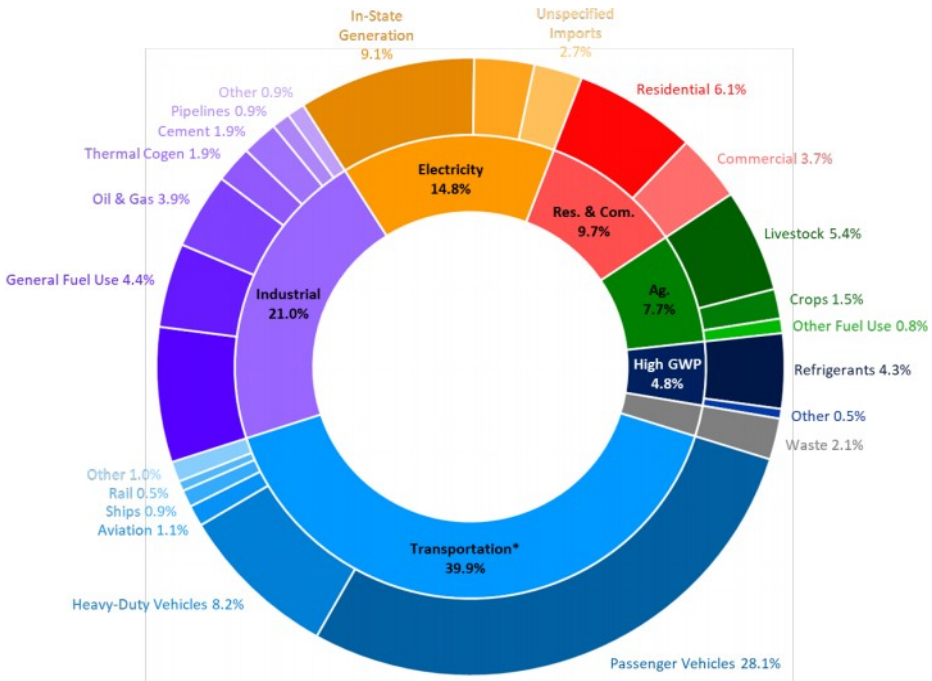

Figure 11. California's 2018 GHG Emissions Inventory [49]
Source: CARB (2020)

The initial Scoping Plan in 2008 identified specific measures across the sectors that would help the state achieve its goal of reducing GHG emissions to 1990 levels by 2030.[50] The first update in 2014 described the progress to date as well as the sector-specific recommended actions to meet a longer-term goal of limiting GHG emissions 80% below 1990 levels by 2050.[51] The part on energy discusses energy efficiency, demand response, and energy storage as the three measuresthat reduce the need for the state to develop new energy resources, reduce peak demand, and increase the state's capabilities to manage frequent and wide variations in solar and wind energy. It recommended the following action items in the energy sector:

- "Develop criteria and rules for flexible demand response resources to participate in wholesale markets and integrate variable renewable resources, reducing the need for new flexible fossil generation.

[49] California Air Resources Board. (2020). *California Greenhouse Gas Emission Inventory: 2000 - 2018*. California Air Resources Board. p. 6. https://ww2.arb.ca.gov/ghg-inventory-data
[50] California Air Resources Board. (2008, December). *Climate Change Scoping Plan: A Framework for Change*. California Air Resources Board. https://ww2.arb.ca.gov/sites/default/files/classic//cc/scopingplan/document/adopted_scoping_plan.pdf pp. ES-3-4.
[51] California Air Resources Board. (2014, May). *First Update to the Climate Change Scoping Plan*. California Air Resources Board. https://ww2.arb.ca.gov/sites/default/files/classic//cc/scopingplan/2013_update/first_update_climate_change_scoping_plan.pdf p. 5.

- Expand participation of regional balancing authorities in the CAISO Energy Imbalance Market and other potential methods of balancing authority cooperation, which provide low-cost, low-risk means of achieving real-time operational efficiency and flexibility needed for greater penetration of variable renewable resources, while ensuring support for GHG emission reduction programs.

- Through the AB 758 process, CEC will develop a plan to encourage energy assessments—particularly when done at the time a building or unit is sold by a predetermined date—as well as energy use disclosure requirements.

- Enhance energy efficiency and demand response programs, including development of education/outreach programs, and develop robust methodologies to monitor and evaluate the effectiveness of these programs. Methodologies developed by the end of 2015 with the enhanced program proceedings completed by the end of 2016.

- A CPUC proceeding to continue to streamline state jurisdictional interconnection processes to create a ministerial low-cost interconnection process for distributed generation completed by the end of 2015. The CEC to explore similar streamlined processes for interconnecting distributed generation in POU systems. The CPUC and CEC consult as appropriate with the CAISO as part of these proceedings.

- CARB will assess existing barriers to expanding the installation of combined heat and power (CHP) systems and propose solutions (in consultation with the State's energy agencies) to achieve the Governor's objectives and that of the initial Scoping Plan for CHPto reduce GHG emissions. A future CHP measure could establish requirements for new orupgraded efficient CHP systems.

- Evaluate the potential for carbon capture and sequestration (CCS) in California to reduce emissions of CO_2 from energy and industrial sources. Working with the Division of Oil, Gas & Geothermal Resources, CEC and CPUC, CARB will consider a CCS quantification methodology for use in California by 2017." [52] (Excerpt from the 2014 Scoping Plan)

CARB developed the 2017 Scoping Plan to identify pathways to achieve an updated California GHG reduction target of 40% below 1990 levels by 2030 as established in Executive Order B-30-15.[53] The Plan includes a range of additional measures developed or required by the recent legislation with 2030 as their target date including extending the LCFS to an 18% reduction in carbon intensity beyond 2020 and the requirements of SB 350 to increase renewables to 50%

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[52] California Air Resources Board. (2014, May). *First Update to the Climate Change Scoping Plan*. California Air Resources Board. https://ww2.arb.ca.gov/sites/default/files/classic//cc/scopingplan/2013_update/first_update_climate_change_scoping_plan.pdf

[53] California Air Resources Board. (2017). *California's 2017 Climate Change Scoping Plan*. California Air Resources Board. https://ww2.arb.ca.gov/sites/default/files/classic//cc/scopingplan/scoping_plan_2017.pdf p. 2.

and to double energy efficiency savings. Figure 12 shows the measures included in the 2017 Scoping Plan scenario and their forecasted impacts on GHG emissions reduction.

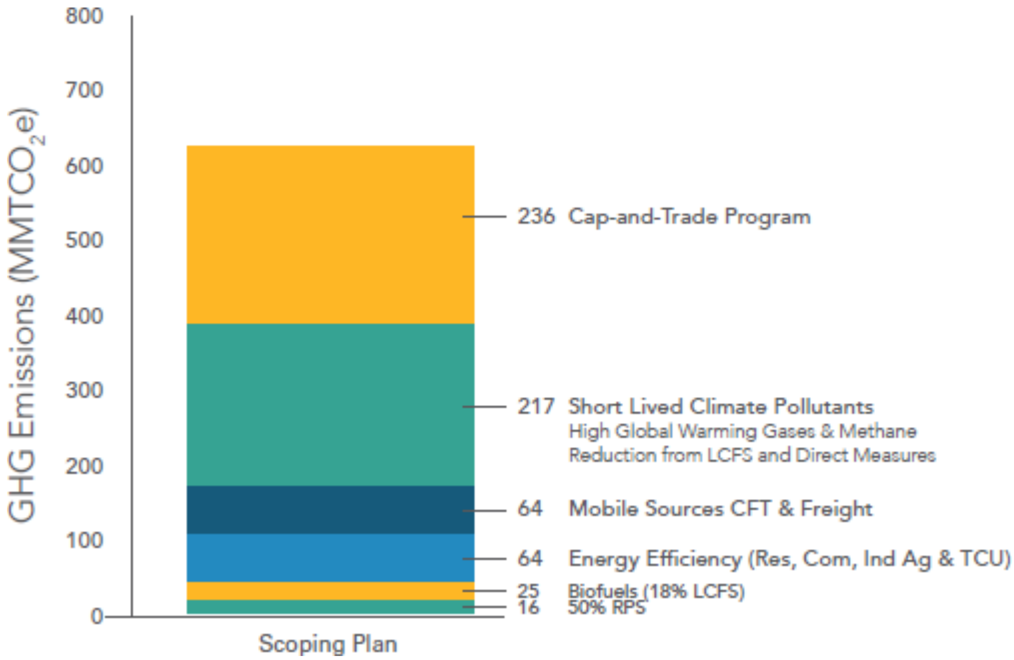

Figure 12. Forecasted Impacts of the 2017 Scoping Plan
Source: CARB (2017) [54]

The Scoping Plan is also required to estimate the range of projected air pollution reductions that result from the measures in order to understand if any of the measures would increase criteria pollutant or toxic air contaminant emissions. For the Scoping Plan measures, CARB estimates air quality benefits by using reductions in GHGs to assign similar reductions for criteria and toxic pollutants (i.e., 1:1 relationship in changes between pollutants).[55]

The measures included in the 2017 Scoping Plan are expected to reduce 48-73 tons/day of NOx, 5.1-7.3 tons/day of VOCs, 1.4-2.4 tons/day of PM2.5, and 5-10 tons/day of diesel particulate matter emissions, most of which are achieved through the Mobile Source Strategy. Reductions from doubling the energy efficiency savings are estimated at 0.4-0.5 tons/day of NOx and 0.5-0.7 tons/day of VOCs. [56]

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[54] California Air Resources Board. (2017). *California's 2017 Climate Change Scoping Plan*. California Air Resources Board. https://ww2.arb.ca.gov/sites/default/files/classic//cc/scopingplan/scoping_plan_2017.pdf p. 28.

[55] California Air Resources Board. (2017). *California's 2017 Climate Change Scoping Plan*. California Air Resources Board. https://ww2.arb.ca.gov/sites/default/files/classic//cc/scopingplan/scoping_plan_2017.pdf p. 38.

[56] *Id.*

CARB also recognizes the potential health benefits of the Scoping Plan measures, which mainly come from reductions in PM emissions and increased physical activity from active transportation. Moving forward, CARB is initiating a process to better understand how to integrate health analysis broadly into the design and implementation of its climate change programs with the goal of maximizing the health benefits.[57]

6.2.3 State Implementation Plans

State Implementation Plans (SIPs) are comprehensive plans that describe how a nonattainment area with unhealthy levels of ozone, PM, carbon monoxide (CO), NOx, and SOx will attain the NAAQS. SIPs are not a single document, but a compilation of plans, programs, district rules, state regulations and federal controls. Regional APCDs and AQMDs develop air quality management plans (AQMPs), which, upon review and approval of CARB and the U.S. EPA, become part of the SIPs.

In California, there are 35 local APCDs and AQMDs. Air pollution from stationary sources is regulated by these local air basin agencies and air pollution from mobile sources (both on- and off-road sources such as passenger cars, motorcycles, trucks, busses, heavy-duty construction equipment, recreational vehicles, marine vessels, lawn and garden equipment, and small utility engines) by CARB. AQMPs would include measures to regulate both stationary and mobile sources but need to work closely with CARB and the U.S. EPA to ensure the attainment from mobile source emissions. Their revenues mainly come from permit-related fees, vehicle registration fees, and state and federal grants, with which they fund education, financial and other incentives, and public procurement.

The following section looks at three major AQMD/APCDs in the state: South Coast AQMD, San Joaquin Valley APCD, and Bay Area AQMD. All three monitor the activities of California's energy agencies and attempt to incorporate the impacts of these activities into their State Implementation Plan by relying on the estimates of these agencies for the impact of their programs. The most recent plans of all these agencies are from 2016 or 2017, although all are preparing updates now. As discussed throughout this paper, California's energy law and regulations have had major impacts upon the operation of the power grid along with buildings, industry, and transportation. Changes have been most dramatic for the power grid, which saw renewables and energy efficiency significantly reduce the consumption of fossil fuel in the power grid and thus the emissions from the grid of both GHG and criteria pollutants.

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[57] California Air Resources Board. (2017). *California's 2017 Climate Change Scoping Plan*. California Air Resources Board. https://ww2.arb.ca.gov/sites/default/files/classic//cc/scopingplan/scoping_plan_2017.pdf, p. 50.

South Coast AQMD

This air district is responsible for managing air quality of Orange County and the urban portions of Los Angeles, San Bernardino, and Riverside counties, including the Coachella Valley. The region is not in attainment of the national ozone and PM2.5 standards and its AQMPs include both stationary and mobile source strategies to comply with the standards, with a focus on NOx measures.

The 2016 AQMP lists all stationary source NOx measures, stationary source VOC measures, and mobile source measures, as well as their projected emission reductions where applicable. The measures numbered with "CMB" (combustion sources) and "MOB" (mobile sources) in the plan entail replacing old, fossil fuel-powered appliances and vehicles. Accordingly, the South Coast AQMD has various incentive programs supporting replacement of vehicles and equipment and installation of EV chargers.[58] Those numbered with "ECC" (Energy and Climate Change Programs) recognize co-benefits from other programs targeting GHG emissions reduction and energy efficiency.[59] The ECC measures included in the 2016 AQMP are in Appendix 1.

These measures demonstrate how the South Coast AQMD seeks to encourage and maximize the co-benefits from the continued transformation in the energy sector: integrating additional renewable resources into the grid; widespread adoption of zero emission vehicle (ZEV) technologies; development and implementation of energy storage technologies; increased energy efficiency measures; use of alternative low-emission fuels; and launch of new energy markets to ensure these new technologies flourish.[60]

Appendix III of the 2016 AQMP describes in detail the methodology by which the South Coast AQMD estimates the current emissions as well as the controlled emissions after the proposed measures are implemented.[61] To project emission reductions and remaining emissions from the implementation of the proposed control measures, the South Coast AQMD uses a mathematical algorithm called Controlled Emissions Projection Algorithm (CEPA). CEPA is developed to calculate projected remaining emissions and/or emission reductions for specified control scenarios.[62] CEPA estimates emission reductions and remaining emissions for future years by pollutant (i.e., summer VOC and NOx; winter CO and NO_2; and average annual day for VOC, NOx, CO, SOx and PM10) based on the control factor profile and projected baseline emissions. The

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58 Incentives & Programs (aqmd.gov).

59 South Coast Air Quality Management District. (2016) Final 2016 Air Quality Management Plan. South Coast Air Quality Management District. https://www.aqmd.gov/home/air-quality/clean-air-plans/air-quality-mgt-plan/final-2016-aqmp

60 South Coast Air Quality Management District. (2016) Final 2016 Air Quality Management Plan. South Coast Air Quality Management District. https://www.aqmd.gov/home/air-quality/clean-air-plans/air-quality-mgt-plan/final-2016-aqmp p. 10-30.

61 South Coast Air Quality Management District. (2016) Final 2016 Air Quality Management Plan. South Coast Air Quality Management District. https://www.aqmd.gov/home/air-quality/clean-air-plans/air-quality-mgt-plan/final-2016-aqmp p. III-2-89.

62 *Id.*

control factor is an indicator of the level of control on a specific source category resulting from adopted air quality regulations and is calculated based on estimates projected during rulemaking.[63]

San Joaquin Valley APCD

The air district is made up of eight counties in the state's Central Valley: San Joaquin, Stanislaus, Merced, Madera, Fresno, Kings, Tulare and the San Joaquin Valley Air Basin portion of Kern County, all primarily driven by agricultural activities. Its geography and meteorology (e.g., high temperatures, atmospheric stagnation, temperature inversions), summer wildfires, and rapid population growth contribute to the formation and retention of its air pollution.[64] The area is not in attainment of the national ozone and PM2.5 standards, largely due to mobile emissions from agricultural equipment and heavy-duty vehicles. According to the air district's *2018 Plan for the 1997, 2006, and 2012 PM2.5 Standards*, mobile source emissions represent over 85% of the air basin's NOx emissions.[65] As such, many of its incentive programs target switching of agricultural equipment, off-road equipment, and heavy-duty trucks.[66]

While the air quality co-benefits of energy efficiency programs or the GHG co-benefits of air pollutant control measures are not quantified, they are both part of the air district's two recent AQMPs (*2016 Plan for 2008 8-Hour Ozone Standard* and *2018 Plan for the 1997, 2006, and 2012 PM2.5 Standards*). The GHG benefits largely come from CARB's Mobile Source Strategy, the framework for statewide emissions from mobile sources, which aims not only to meet federal air quality standards but also to achieve GHG emission reduction targets and to reduce petroleum consumption.[67] In addition, the San Joaquin Valley APCD implements the Technology Advancement Program (TAP) in order to identify and accelerate the deployment of innovative clean air technologies through grant funding, outreach programs, and local capacity building. Its three focus areas are renewable energy, waste solutions, and mobile sources, which all have GHG co-benefits as well.[68]

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[63] South Coast Air Quality Management District. (2016) Final 2016 Air Quality Management Plan. South Coast Air Quality Management District. https://www.aqmd.gov/home/air-quality/clean-air-plans/air-quality-mgt-plan/final-2016-aqmp p. III-2-6.

[64] San Joaquin Valley Air Pollution Control District. (2016) *2016 Plan for 2008 8-Hour Ozone Standard*, *Chapter 2*. San Joaquin Valley Air Pollution Control District. 2016. http://www.valleyair.org/Air_quality_Plans/Ozone-Plan-2016.htm

[65] San Joaquin Valley Air Pollution Control District. (2018). *2018 Plan for the 1997, 2006, and 2012 PM2.5 Standards.* San Joaquin Valley Air Pollution Control District. http://valleyair.org/pmplans/documents/2018/pm-plan-adopted/2018-Plan-for-the-1997-2006-and-2012-PM2.5-Standards.pdf p. 4-9.

[66] San Joaquin Valley Air Pollution Control District. (2021) *Grant and Incentive Programs*. San Joaquin Valley Air Pollution Control District. https://valleyair.org/grants/

[67] California Air Resources Board. (2016). *2016 Mobile Source Strategy*. California Air Resources Board. https://ww2.arb.ca.gov/resources/documents/2016-mobile-source-strategy

[68] San Joaquin Valley Air Pollution Control District. (2018). *2018 Plan for the 1997, 2006, and 2012 PM2.5 Standards.* San Joaquin Valley Air Pollution Control District. http://valleyair.org/pmplans/documents/2018/pm-plan-adopted/2018-Plan-for-the-1997-2006-and-2012-PM2.5-Standards.pdf p. F-1.

The air quality co-benefits are recognized in its Regional Energy Efficiency Strategy (REES)adopted in January 2010. The REES is a non-regulatory approach to encourage and incentivize energy efficiency and conservation in residential, commercial, municipal, and industrial sectors throughout the aid district.[69] According to the REES, the potential for energy saving is significant as the region experiences more heating and cooling days than others in California and, as of 2010, more than half of the homes were built before the introduction of Title 24 building codes. The strategy would consist of outreach, education and information programs; effective energy decision-making tools and programs; and grants and incentive funding.[70]

Appendix J of the air district's two recent AQMPs describe its methodology for estimating current and future emissions inventory. For both ozone and PM2.5, the California Emission Inventory Development and Reporting System (CEIDARS), a database of emissions and other useful information maintained by CARB to generate aggregate emission estimates at the county, air basin, and district level, provides a foundation for the development of a more refined (hourly, grid cell-specific) set of emission inputs that are required by air quality models. The CEIDARS base year inventory is a primary input to the state's emission forecasting system, known as the California Emission Projection Analysis Model (CEPAM). CEPAM produces the projected emissions that are then gridded and serve as the emission input for the air quality models.

The reductions from control measures (by sources) are implemented as reduction factors in the Sparse Matrix Operator Kernel Emissions (SMOKE) model. Reduction factors for each source are specified separately for NOx and PM2.5 in the years 2024 and 2025. Specific reduction factors are input to a program nested in SMOKE, which applies the reductions uniformly across the district to the sources by their emission inventory code number.[71]

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[69] San Joaquin Valley Air Pollution Control District. (2010, January 21). *Re: Approval of the District's Regional Energy Efficiency Strategy*. San Joaquin Valley Air Pollution Control District. http://www.valleyair.org/Board_meetings/GB/agenda_minutes/Agenda/2010/January/Agenda_Item_7_Jan_21_2010.pdf p. 3.

[70] San Joaquin Valley Air Pollution Control District. (2010, January 21). *Re: Approval of the District's Regional Energy Efficiency Strategy*. San Joaquin Valley Air Pollution Control District. http://www.valleyair.org/Board_meetings/GB/agenda_minutes/Agenda/2010/January/Agenda_Item_7_Jan_21_2010.pdf. p. 7.

[71] San Joaquin Valley Air Pollution Control District. (2018). *2018 Plan for the 1997, 2006, and 2012 PM2.5 Standards.* San Joaquin Valley Air Pollution Control District. http://valleyair.org/pmplans/documents/2018/pm-plan-adopted/2018-Plan-for-the-1997-2006-and-2012-PM2.5-Standards.pdf Appendix.

Bay Area AQMD

The air district covers nine counties that surround the San Francisco Bay: Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, southwestern Solano, and southern Sonoma counties. The area is out of attainment for some state and national ozone and PM2.5 standards. Unlike the two other AQMDs, the Bay Area AQMD focuses on reducing VOC and ROG emissions based on different geographical conditions (no thermal inversions) and main sources of emissions (large refineries).

Its air quality management plan, the *2017 Clean Air Plan*, explicitly links two goals of protecting air quality and health through air pollutant control and protecting the climate through GHG emissions reduction. More specifically, the Bay Area AQMD's control measures have the following four key themes:

- Reduce emissions of criteria air pollutants and toxic air contaminants from all key sources;
- Reduce emissions of "super-GHGs" such as methane, black carbon and fluorinated gases;
- Decrease demand for fossil fuels (gasoline, diesel and natural gas) through increased efficiency and reduced demand for vehicle travel and high-carbon consumption; and
- Decarbonize our energy system through carbon-free generation and electrification.[72]

As such, energy efficiency measures in the transportation, energy, and buildings sectors are incorporated into the AQMP as targeting "all pollutants." Appendix 2 lists selected energy efficiency-related measures for the three sectors as well as for super-GHGs.[73]

The Bay Area AQMD uses two air quality models that are publicly available: U.S. EPA's Community Multiscale Air Quality (CMAQ) model and Ramboll Environ US Corporation's Comprehensive Air Quality Model with extensions (CAMx). Both are capable of handling multiple pollutants, including ozone, toxics and PM. For the 2017 AQMP, the air district used CAMx for simulating air toxics, and CMAQ for simulating ozone and PM2.5 simultaneously.

Emissions inventory and meteorological inputs to these models are prepared using several specialized computer programs. The U.S. EPA's Sparse Matrix Operator Kernel Emissions (SMOKE) program is used to prepare anthropogenic emissions as inputs to air quality models.

Appendix H in the report discusses estimated emission reductions for each control measure, but not how they are calculated.[74]

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[72] Bay Area Air Quality Management District. (2017, April). *Final 2017 Clean Air Plan p. ES-5*. Bay Area Air Quality Management District. https://www.baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/attachment-a_-proposed-final-cap-vol-1-pdf.pdf p. ES-5.

[73] Note: 1. For some measures, emissions could not be estimated, but all measures are expected to reduce emissions of air pollutants and/or GHGs, either directly or indirectly. 2. GHG emissions are estimated using 100-year time horizons.

[74] Bay Area Air Quality Management District. (2017, April). *Final 2017 Clean Air Plan p. ES-5*. Bay Area Air Quality Management District. https://www.baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/attachment-a_-proposed-final-cap-vol-1-pdf.pdf Appendix D, p. D-1.

6.2.4 Energy Efficiency Being Rethought in the Context of GHG Emissions Reduction

The California Energy Commission's *2019 California Energy Efficiency Action Plan* emphasizes that a new paradigm is needed that targets energy savings and demand flexibility during specific hours of the day when GHG emissions are relatively high. California has added substantial amounts of intermittent wind and solar renewable resources, and indeed there are periods when it must curtail renewables or pay neighboring regions to take renewable power. As shown in Figure 13 below, there are monthly and hourly variations in the carbon content of grid supply as renewable resources are increasingly integrated into the grid. The state's energy policy is increasingly looking toward GHG emission reductions, and the lack of progress from efficiency programs speaks to the way programs have historically been designed.[75]

2019 System Average Metric Ton CO_2 per MWh

24-hour cycle

2020	January	February	March	April	May	June	July	August	September	October	November	December
1	0.23	0.22	0.20	0.17	0.17	0.18	0.23	0.26	0.26	0.25	0.24	0.24
2	0.23	0.23	0.20	0.17	0.17	0.18	0.23	0.26	0.26	0.25	0.24	0.24
3	0.23	0.22	0.20	0.17	0.17	0.18	0.23	0.26	0.26	0.25	0.24	0.24
4	0.23	0.22	0.20	0.17	0.17	0.18	0.23	0.26	0.26	0.25	0.24	0.24
5	0.23	0.22	0.20	0.16	0.17	0.18	0.23	0.26	0.26	0.25	0.24	0.24
6	0.23	0.21	0.18	0.15	0.16	0.17	0.23	0.25	0.25	0.24	0.23	0.23
7	0.22	0.20	0.18	0.15	0.15	0.17	0.22	0.25	0.24	0.23	0.22	0.22
8	0.21	0.19	0.17	0.15	0.15	0.15	0.20	0.23	0.24	0.23	0.21	0.22
9	0.20	0.17	0.16	0.13	0.13	0.13	0.19	0.20	0.21	0.21	0.19	0.20
10	0.18	0.14	0.13	0.12	0.11	0.12	0.17	0.18	0.19	0.18	0.17	0.18
11	0.16	0.13	0.12	0.10	0.11	0.11	0.16	0.17	0.18	0.17	0.16	0.17
12	0.16	0.13	0.11	0.10	0.10	0.10	0.15	0.17	0.17	0.16	0.16	0.16
13	0.16	0.13	0.11	0.10	0.10	0.10	0.15	0.16	0.17	0.16	0.16	0.16
14	0.16	0.13	0.12	0.10	0.10	0.10	0.14	0.16	0.17	0.17	0.16	0.17
15	0.17	0.14	0.12	0.10	0.10	0.10	0.14	0.16	0.18	0.17	0.18	0.18
16	0.20	0.17	0.14	0.11	0.10	0.10	0.14	0.16	0.18	0.19	0.20	0.21
17	0.20	0.19	0.16	0.13	0.10	0.11	0.14	0.16	0.18	0.19	0.20	0.21
18	0.19	0.18	0.16	0.13	0.11	0.12	0.15	0.17	0.19	0.19	0.19	0.19
19	0.18	0.17	0.15	0.13	0.12	0.13	0.16	0.18	0.19	0.19	0.19	0.19
20	0.19	0.18	0.15	0.13	0.13	0.14	0.17	0.19	0.20	0.20	0.19	0.19
21	0.19	0.18	0.16	0.14	0.14	0.15	0.19	0.21	0.22	0.21	0.20	0.20
22	0.20	0.19	0.17	0.14	0.15	0.16	0.20	0.22	0.23	0.23	0.21	0.21
23	0.22	0.20	0.18	0.16	0.15	0.17	0.21	0.24	0.24	0.24	0.22	0.22
24	0.23	0.21	0.19	0.16	0.16	0.17	0.22	0.25	0.26	0.25	0.23	0.23

Figure 13. Hourly Carbon Content Heat Map in California
Source: CEC (2020)

6.2.5 Buildings and Appliances

In 2017, the state's building stock accounted for 24% of statewide GHG emissions, including fossil fuel consumed onsite (for example, gas or propane for heating) and electricity consumption (for example, for lighting, appliances, and cooling).[76] Natural gas accounts for 78% and 50% of direct GHG emissions from residential and commercial building sectors, respectively (Figure 14), most

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[75] California Energy Commission. (2019, November). *2019 California Energy Efficiency Action Plan*, *p. 70.* California Energy Commission. https://www.energy.ca.gov/filebrowser/download/1900

[76] California Energy Commission. (2020). *Adopted 2019 Integrated Energy Policy Report*, *p. 43*. California Energy Commission. https://efiling.energy.ca.gov/getdocument.aspx?tn=232922
p. 3.

of which is used for water and space heating. Electrification of heating end uses can, therefore, significantly reduce CO_2 emissions through combustion and methane leakages. As gas appliances emit air pollutants such as carbon monoxide, nitrous oxides, particulate matter, and formaldehyde, electrification in the building sector can also result in better indoor air quality and health benefits.[77]

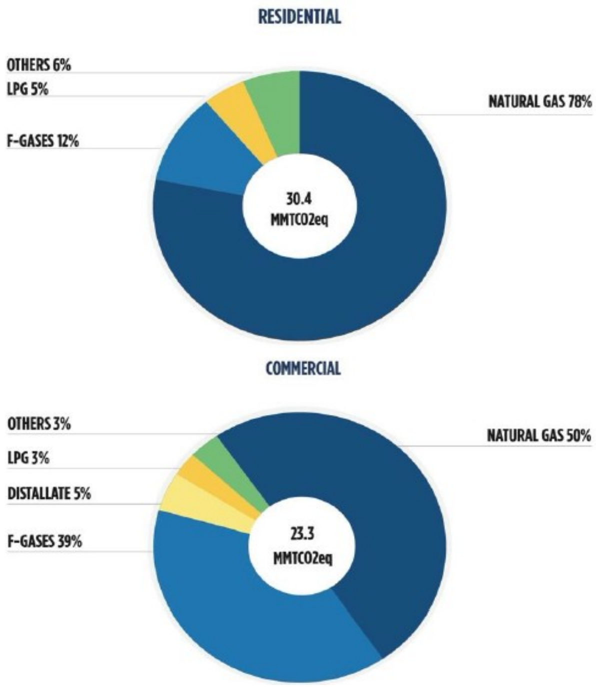

Figure 14. 2017 Direct GHG Emissions from the Residential and Commercial Sectors [78]
Source: CEC (2020)

This section describes California's efforts to reduce energy consumption and, increasingly, GHG emissions from the building sector through building energy efficiency standards, appliance efficiency standards, programs to encourage energy efficiency retrofits, and demand flexibility.

Building Energy Efficiency Standards (Title 24)

The Building Energy Efficiency Standards (Title 24 of California Code of Regulations), updated every three years by the CEC, set rules for new construction of, and additions and alterations to, residential and nonresidential buildings. Due to the diversity of its climate, California is divided

77 Zhu et al. (2020 April). *Effects of Residential Gas Appliances on Indoor and Outdoor Air Quality and Public Health in California*. UCLA Fielding School of Public Health. https://ucla.app.box.com/s/xyzt8jc1ixnetiv0269qe704wu0ihif7. p. 6.
78 California Energy Commission. (2020). *Adopted 2019 Integrated Energy Policy Report*, *p. 43*. California Energy Commission. https://efiling.energy.ca.gov/getdocument.aspx?tn=232922 p. 46.

into 16 climate zones (Figure 15), which dictates the energy budget[79] and several efficiency standards, such as those for envelope and fenestration (window and door) materials for the buildings in that specific zone. There are also mandatory requirements for all buildings (e.g., energy conservation, design, construction, safety, etc.).[80] The energy efficiency measures included in the standards must be cost-effective for the owners over the 30-year life of a building: savings from energy and maintenance costs must be greater than the increase in construction costs. Since 2005, nonresidential buildings are required to undergo acceptance testing, a process in which a field technician verifies if newly installed equipment or construction elements are operating as designed and in compliance with the standards.[81] While not mandatory, the Home Energy Rating System (HERS) program enables homeowners to have certified raters to verify compliance with the standards and rate the energy performance of their home.[82]

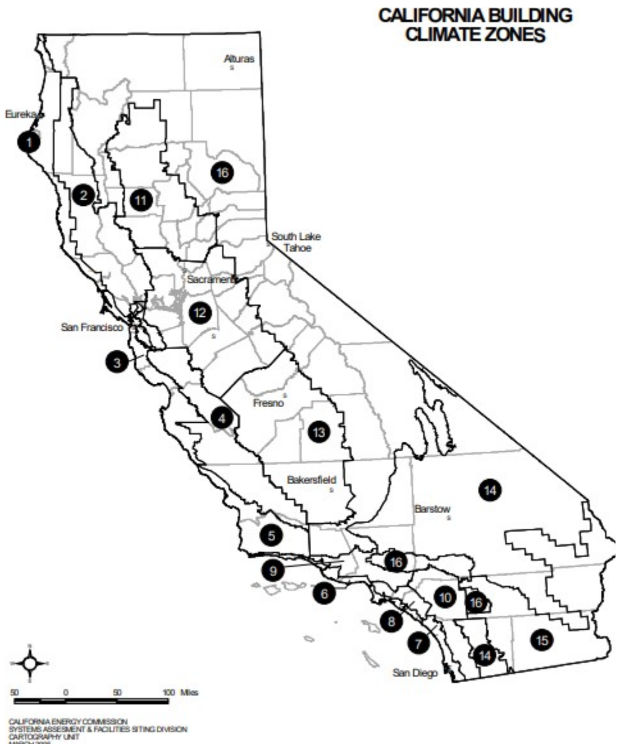

Figure 15. 16 Climate Zones in California
Source: CEC (2018)

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[79] Energy budget is the maximum energy consumption, based on Time Dependent Valuation (TDV) energy, that a proposed building, or portion of a building, can be designed to consume, calculated using Commission-approved compliance software as specified by the Alternative Calculation Method Approval Manual. (*2019 Building Energy Efficiency Standards for Residential and Nonresidential Buildings*. CEC, December 2018. p. 64)

[80] Center for Law, Energy and Environment. (2019). *California Climate Policy Fact Sheet: Building Energy Efficiency*. UC Berkeley. Accessed 23 February 2021 from www.law.berkeley.edu/wp-content/uploads/2019/12/Fact-Sheet-Building-Energy-Efficiency.pdf.

[81] California Energy Commission. (2021). *Acceptance Test Technician Certification Provider Program Frequently Asked Questions*. Accessed 5 April 2021 from https://www.energy.ca.gov/programs-and-topics/programs/acceptance-test-technician-certification-provider-program/acceptance-0

[82] California Energy Commission. (2021). *Home Energy Rating System Program – HERS*. California Energy Commission. Accessed 5 April 2021 from https://www.energy.ca.gov/programs-and-topics/programs/home-energy-rating-system-hers-program

The 2019 standards that took effect on January 1, 2020, mandated smart residential photovoltaic systems, high performance envelopes to prevent heat transfer from the interior to exterior and vice versa, residential and nonresidential ventilation requirements, and nonresidential lighting requirements. It required single-family houses and multifamily residences up to three stories to have solar panels installed or be powered by a solar array nearby.[83] As a result, a home built under the 2019 standards will use about 7% less energy and, with the solar mandate, 53% less grid energy than one built under the 2016 standards.[84] The solar mandate was an important step towards zero net energy (ZNE) goals.[85] The CEC projects that the new standards will reduce 700,000 tons of CO_2 emissions over three years, equivalent to taking 115,000 fossil fuel cars off the road.[86]

Currently, the 2022 Building Energy Efficiency Standards are being developed in an open and public process[87] in which the public can participate in the workshops or watch the recordings and submit comments. The next standards, taking effect on January 1, 2023, will focus on multifamily and commercial buildings.[88] They will also set the standard design requirements (baseline) for heat pumps. Heat pumps will be a key technology to achieve building decarbonization, replacing natural gas end uses for space and water heating. In addition, CEC aims to use an improved GHG-based metric to properly value the avoidance of GHG emissions in buildings.[89] It recognizes that ZNE buildings, which consume less energy than they produce on an annual basis, may not necessarily reduce emissions if the accounting ignores when energy is generated, consumed on site, and exported to the grid, due to the monthly and hourly variations in the carbon content of grid supply mentioned earlier.

One concern related to heat pumps is the leakage of the high global warming potential (GWP) refrigerant gases. Fluorinated gases (referred to as "F-gases") - hydrofluorocarbons (HFCs),

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[83] California Energy Commission. (2021). *California Clean Energy Almanac 2020*. California Energy Commission. Accessed 22 February 2021 from https://www.energy.ca.gov/sites/default/files/2021-02/2020%20-%20CEC%20-%20CCEA%2002.04.21%20ADA.pdf.

[84] California Energy Commission. (2020). *2019 Building Energy Efficiency Frequently Asked Questions*. California Energy Commission. Accessed 23 February 2021 from www.energy.ca.gov/sites/default/files/2020-03/Title_24_2019_Building_Standards_FAQ_ada.pdf.

[85] https://www.cpuc.ca.gov/ZNE/. A ZNE building is defined as an energy-efficient building where, on a source energy basis, the actual annual consumed energy is less than or equal to the on-site renewable generated energy.

[86] California Energy Commission. (2019, November). *2019 California Energy Efficiency Action Plan*, *p. 16.* California Energy Commission. https://www.energy.ca.gov/filebrowser/download/1900 p. A-14.

[87] California Energy Commission. (2021). *2022 Building Energy Efficiency Standards.* California Energy Commission. www.energy.ca.gov/programs-and-topics/programs/building-energy-efficiency-standards/2022-building-energy-efficiency

[88] On May 6, 2021, the CEC proposed 2022 Energy Code Changes. Some workshops have been held on these changes, and comments are due by June 21. The CEC will consider adoption of these changes in August which may be amended based on comments. For more details see California Energy Commission. (May, 2021). *2022 Building Energy Efficiency Standards.* www.energy.ca.gov/programs-and-topics/programs/building-energy-efficiency-standards/2022-building-energy-efficiency.

[89] California Energy Commission. (2019, November). *2019 California Energy Efficiency Action Plan*, *p. 16.* California Energy Commission. https://www.energy.ca.gov/filebrowser/download/1900 p. 14.

perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3) have GWPs of tens of thousands.[90] In particular, HFCs are commonly used in refrigerators and air conditioners and account for 17% and 6% of all commercial and residential building emissions, respectively.[91] The stock of HFCs in buildings is expected to grow as electric heat pumps using HFCs replace conventional heating systems. Management of HFCs and development of alternative refrigerants with lower GWPs will be important going forward. As in building and appliance efficiency standards, California has been a leader in regulating HFCs. California is required under Senate Bill 1383 to reduce HFC emissions by 40% below 2013 levels by 2030 and recently approved a regulation of establishing GWP limits for new refrigeration and air conditioning systems starting in 2022.[92] Another challenge for heat pumps would be achieving cost-effectiveness on a lifecycle basis, which would require more research and scale-up of production in both California and China.

Appliance Energy Efficiency Standards (Title 20)

The appliance efficiency standards (Title 20) apply to appliances sold in California and set minimum efficiency levels for energy and water consumption. California was the first state to establish appliance standards in 1976. The first national standards were introduced in 1987 under the National Appliance Energy Conservation Act based on the standards previously developed by California and other states.[93] Federal laws have since established efficiency standards for more than 50 products, which represent about 90% of home energy use, 60% of commercial building energy use, and about 30% of industrial energy use.[94] While states are preempted from adopting their own standards for the products covered by federal standards,[95] California continues to develop efficiency standards for other products. Some recent standards set by CEC include those for computers, computer monitors, portable electric spas, light-emitting diode (LED) light bulbs, sprinklers, and general service lamps.

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[90] United States Environmental Protection Agency. (2021). *Overview of Greenhouse Gases.* United States Environmental Protection Agency. https://www.epa.gov/ghgemissions/overview-greenhouse-gases#fluorinated-sources

[91] California Energy Commission. (2018, September). *Tracking Progress: Energy Efficiency*. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-12/energy_efficiency_ada.pdf

[92] California Air Resources Board. (2020, December 10). *California introduces groundbreaking program to reduce climate super pollutants*. California Air Resources Board. Retrieved 16 February 2020 from ww2.arb.ca.gov/news/california-introduces-groundbreaking-program-reduce-climate-super-pollutants.

[93] American Council for an Energy-Efficient Economy. (2020). *2020 State Energy Efficiency Scorecard*, *P. 117*. American Council for an Energy-Efficient Economy. https://www.aceee.org/research-report/u2011

[94] United States Environmental Protection Agency. (2017). *EPA Energy and Environment Guide to Action. Chapter 4. Energy Efficiency Policies: State Appliance Efficiency Standards,* p. 4-74. United States Environmental Protection Agency. https://www.epa.gov/sites/production/files/2017-06/documents/guide_action_chapter4.pdf

[95] State efficiency standards that were established before a product was covered under NAECA are preempted as of the effective date of the federal standard (i.e., the date that manufacturers must comply with that standard), although states can apply for waivers of such preemption. (*EPA Energy and Environment Guide to Action.* Chapter 4. Energy Efficiency Policies: State Appliance Efficiency Standards. EPA, 2017. p. 4-77.)

The "power of appliance standards is in the numbers."[96] After all, appliance standards have achieved more energy savings than the building energy standards and efficiency programs from utilities and public agencies in California.[97] The new standards for computers and monitors and those for general purpose LED lamps and small diameter directional lamps are expected to save 2,332 GWh and 3,144 GWh per year, respectively.[98] [99] Figure 16 below shows the energy savings from recent appliance efficiency standards.

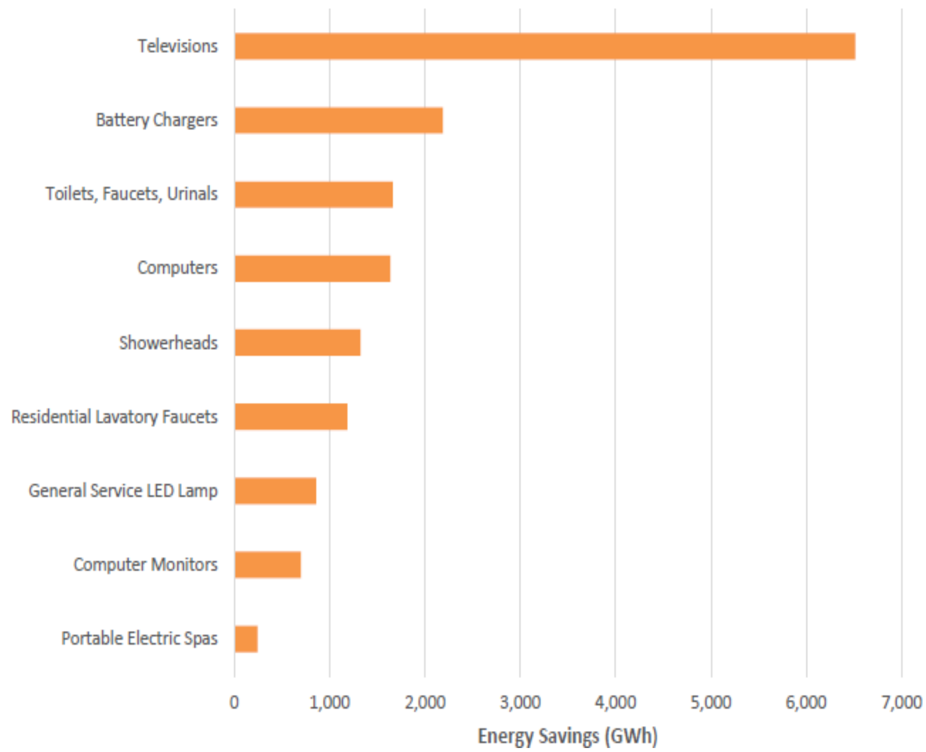

Figure 16. Recent Energy Savings from California's Appliance Standards
Source: CEC (2018) [100]

[96] American Council for an Energy-Efficient Economy. (2020). *2020 State Energy Efficiency Scorecard*, *P. 117*. American Council for an Energy-Efficient Economy. https://www.aceee.org/research-report/u2011
[97] California Energy Commission. (2018*) - Tracking Progress*, *p. 6*. California Energy Commission.
[98] California Energy Commission. (2019, November). *2019 California Energy Efficiency Action Plan*, *p. 16.* California Energy Commission. https://www.energy.ca.gov/filebrowser/download/1900 p. A-16.
[99] duVair, P.H. *Electricity Savings Figures - Title 20 Appliance Efficiency Standards*. Received by Robert Weisenmiller, 20 Apr. 2021.
[100] California Energy Commission. (2018*) - Tracking Progress*, *p. 6*. California Energy Commission.

Increasing Energy Efficiency in Existing Buildings

Nearly half of the 10 million single-family buildings and more than half of the 3.4 million multifamily buildings were constructed before there were building energy efficiency standards (pre-1978).[101] There is a great potential for energy efficiency gains from these existing buildings.

The building owners' lack of awareness of efficiency benefits is often a barrier to implementing deep energy efficiency retrofits. The Building Energy Benchmarking Program managed by the CEC tries to address this issue by requiring the building owners to report building characteristics, energy use data, and building usage information annually (Figure 17). Commercial (no residential unit) and multifamily buildings (17+ residential units) with more than 50,000 square feet of gross floor area are all required to publicly disclose their energy use.[102] Benchmarking helps measure the performance of a building and tells the owner how efficient or inefficient the building is. The information is eventually intended to help current and prospective building owners and occupants make better-informed decisions about purchasing, leasing, maintenance, and upgrades.[103]

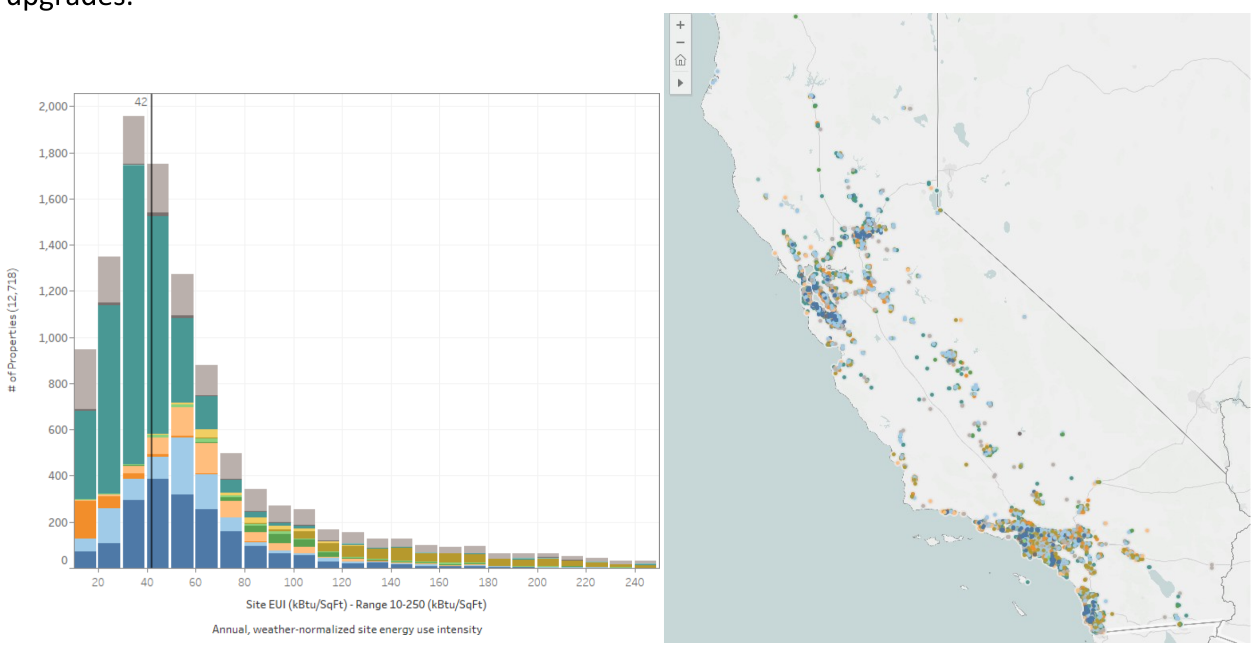

Figure 17. California Building Energy Benchmarking Program 2019 Data
Source: CEC [104]

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[101] California Energy Commission. (2019, November). *2019 California Energy Efficiency Action Plan*, *p. 16.* California Energy Commission. https://www.energy.ca.gov/filebrowser/download/1900 p. 23, p. 27.

[102] California Energy Commission. (2021). *Building Energy Benchmarking Program Frequently Asked Questions*. California Energy Commission. https://www.energy.ca.gov/programs-and-topics/programs/building-energy-benchmarking-program/building-energy-benchmarking

[103] California Energy Commission. (2021). *Building Energy Benchmarking Program Frequently Asked Questions*. California Energy Commission. https://www.energy.ca.gov/programs-and-topics/programs/building-energy-benchmarking-program/building-energy-benchmarking

[104] California Energy Commission. (2019). *California Building Energy Benchmarking Program.* California Energy Commission.

CPUC oversees ratepayer-funded programs administered by four IOUs - Pacific Gas & Electric (PG&E), Southern California Edison (SCE), Southern California Gas Company (SCG), and San Diego Gas & Electric (SDG&E) - as well as two regional energy networks, BayREN and SoCalREN, one community choice aggregation program,[105] Marin Clean Energy, and third-party administrators.[106] Publicly-owned utilities (POUs) must identify all feasible and cost-effective energy efficiency savings every four years and provide their customers and CEC with their investments in and the results of energy efficiency programs.[107] The programs encourage customers to switch to new technologies that exceed the standards and include financial incentives (e.g., energy savings assistance, rebates, loans), behavioral programs, and education and outreach. In 2019, 38% and 23% of CPUC's energy efficiency portfolio (USD 639 million in expenditures) was spent on the residential and commercial sectors, respectively (Table 2). CPUC notes the recent success with behavioral programs in which utilities offer customers home energy reports comparing one's energy use to that of their neighbors. These programs lead to savings ranging from less than 1% up to 3% per household and are expected to represent a large portion of savings in the future.[108]

2019 Energy Efficiency Portfolio Performance

Sector	2019 Expenditures	% of Total Expenditures	Total Portfolio First Year Savings			Portfolio TRC	CO_2 Reductions (tons)
			GWh	MW	Million Therms		
Residential	$243,930,367	38%	726	129.42	21	1.15	409,709
Commercial	$147,236,438	23%	166	35.37	6	0.71	109,714
Public	$80,122,476	13%	69	7.33	1	0.44	31,802
Industrial	$36,740,784	6%	44	3.29	6	1.17	56,425
Agricultural	$15,026,680	2%	21	6.83	0	0.54	11,592
Total	**$523,056,745**	**82%**	**1,026**	**182**	**35**	**n/a**	**619,242**
Cross-Cutting	$116,254,402	18%	1,712	372.45	49	1.81	1,060,035
Total	**$639,311,147**	**100%**	**2,738**	**555**	**84**	**1.44**	**1,679,277**

https://tableau.cnra.ca.gov/t/CNRA_CEC/views/EnergyEfficiencyBenchmarkingDashboard/BenchmarkingDashboard?iframeSizedToWindow=true&%3Aembed=y&%3AshowAppBanner=false&%3Adisplay_count=no&%3AshowVizHome=no&%3AshowShareOptions=false

[105] Community choice aggregation are programs that allow local governments to procure power on behalf of their residents, businesses, and municipal accounts from an alternative supplier while still receiving transmission and distribution service from their existing utility provider. (Community Choice Aggregation | Green Power Partnership | US EPA)

[106] California Public Utilities Commission. (2018, May). *Energy Efficiency Portfolio Report* p. 8. California Public Utilities Commission. https://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=6442459323.

[107] California Energy Commission. (2019, November). *2019 California Energy Efficiency Action Plan*, *p. 16.* California Energy Commission. https://www.energy.ca.gov/filebrowser/download/1900 p. A-1.

[108] California Energy Commission. (2019, November). *2019 California Energy Efficiency Action Plan*, *p. 16.* California Energy Commission. https://www.energy.ca.gov/filebrowser/download/1900 p. A-37.

Table 2. 2019 CPUC Energy Efficiency Portfolio Performance
Source: CPUC (2020) [109]

Public buildings owned by local and state governments play the role of living labs for energy efficiency and demand-flexible technologies. As of July 2019, 28 public buildings were approved as zero-net-energy.[110] In particular, CEC implements energy efficiency programs for schools such as Bright School Program, which provides technical assistance for schools planning to retrofit existing buildings, or School Energy Efficiency Stimulus Program, which will provide funding to upgrade heating, ventilation and air conditioning (HVAC) systems and replace non-compliant plumbing fixtures in public schools.

Demand Flexibility

Even with the most stringent energy efficiency measures, electrification in buildings as well as in transportation will pose a significant challenge to the existing electricity distribution system. At the same time, the grid needs to integrate rapidly growing renewable resources and accommodate the daily changes in the net load (total load minus solar and wind generation).[111] In this context, demand flexibility is one of the three key elements, along with clean energy supply and energy efficiency, in achieving the state's long-term building decarbonization.[112]

Pursuant to SB 49 (Skinner, Chapter 697, Statutes of 2019), CEC is developing flexible demand appliance standards. The standards aim to help schedule, shift, and curtail energy use from one time of day to another and eventually better align customer and electric system demand. Current utility demand response programs require participating customers to change their electricity usage (typically reducing use or shifting use to other times in the day) at certain times with high electricity demand in response to economic incentives, price signals, or other conditions.[113] Under the flexible demand appliance standards to be developed, such changes in electricity usage will occur on a daily basis, across many customers, and without an inconvenience to customers. For example, with customer consent and automated communication and control technologies, various end-use loads (e.g., pool pumps, space heating, ventilation and air-conditioning equipment, refrigeration, electric vehicle service equipment, electric clothes dryers, dishwashers, and electric hot water storage tank heaters) would automatically be shifted to off-

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[109] California Public Utilities Commission. (2020). *What is the Impact of CPUC Energy Efficiency Programs? 2019 Results and 2020 Look Ahead*, *p. 2*. California Public Utilities Commission. https://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=6442465530

[110] California Energy Commission. (2019, November). *2019 California Energy Efficiency Action Plan*, *p. 38.* California Energy Commission. https://www.energy.ca.gov/filebrowser/download/1900

[111] California Energy Commission. (2020). *Adopted 2019 Integrated Energy Policy Report*, *p. 2*. California Energy Commission. https://efiling.energy.ca.gov/getdocument.aspx?tn=232922

[112] California Energy Commission. (2020). *Adopted 2019 Integrated Energy Policy Report*, *p. 43*. California Energy Commission. https://efiling.energy.ca.gov/getdocument.aspx?tn=232922

[113] California Public Utilities Commission. (2021). *DR Information and FAQs for Consumers.* California Public Utilities Commission. https://www.cpuc.ca.gov/General.aspx?id=5923

peak hours and customers would benefit from lower rates.[114] China has a very active appliance standard group, and there has been significant coordination between the California and China efforts. Since California has been adopting appliance standards well before China, originally the Chinese looked to California's example. More recently, California's computer monitor standards were developed based upon the Chinese standards. California is hoping China helps develop low-cost communication and control technologies for California's load flexibility efforts.

SB 350 Doubling Energy Efficiency Savings by 2030

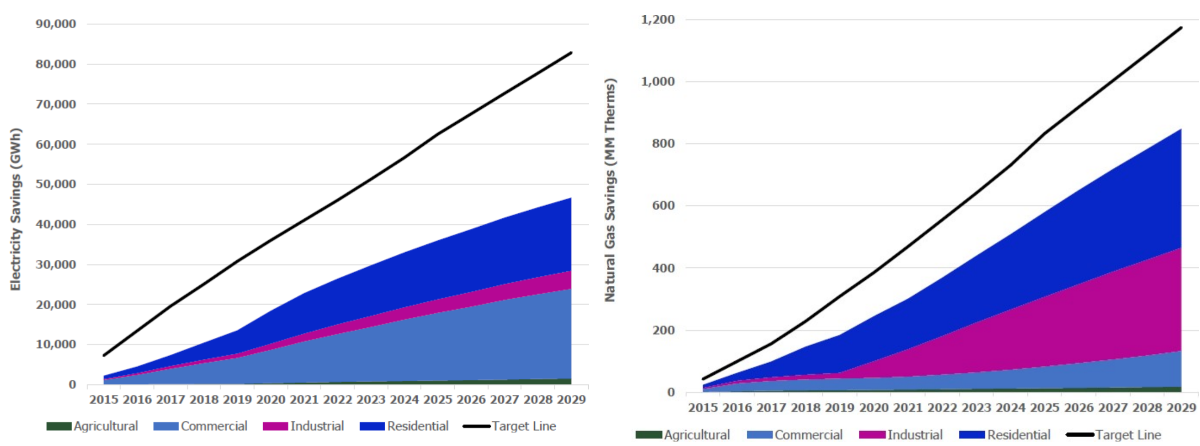

Figure 18. SB 350 Doubling Efficiency Targets for Electricity (Left) and Natural Gas (Right)
Source: CEC (2019) [115]

As mentioned above, SB 350 set the goal of doubling statewide energy efficiency savings in electricity and gas end uses, relative to the 2015 levels, by January 1, 2030, and the goal is assumed to be achieved under the 2017 Scoping Plan. However, it should be noted that, according to the CEC's 2019 California Energy Efficiency Action Plan, the state is expected to fall about 44% and 28% short of its goals for electricity and natural gas savings, respectively (Figure 18).[116] Given California's long-term efforts in energy efficiency since the 1970s and the lack of analysis behind the doubling goal, it is not surprising that achieving such a goal is very difficult. Therefore, the state is moving away from the singular focus on doubling energy efficiency and instead looking to GHG emissions reduction as the end goal. In addition, the 2019 Energy Efficiency Action Plan has two other goals in addition to doubling energy efficiency savings: equitable adoption of energy efficiency upgrades in low-income and disadvantaged communities and reducing GHG emissions from buildings.

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[114] California Energy Commission. (2020). *Introduction to Flexible Demand Appliance Standards, p. 5*. California Energy Commission. Accessed 9 December 2020 from https://efiling.energy.ca.gov/GetDocument.aspx?tn=235899

[115] California Energy Commission. (2019, November). *2019 California Energy Efficiency Action Plan*, *p. 2-3.* California Energy Commission. https://www.energy.ca.gov/filebrowser/download/1900

[116] California Energy Commission. (2019, November). *2019 California Energy Efficiency Action Plan*, *p. 2.* California Energy Commission. https://www.energy.ca.gov/filebrowser/download/1900

6.2.6 Energy storage solutions

Energy storage is another tool to integrate the increasing amount of solar and wind electricity generation into the grid. While renewable energy is outside the scope of this study, California has fundamentally reshaped the operation of its power grid through the addition of substantial quantities of intermittent renewable resources. In 2019, 36% of California's retail electricity sales came from renewable sources, with 62% coming from solar and wind, not including behind-the-meter (BTM) or off-grid solar generation (Figure 19).[117]

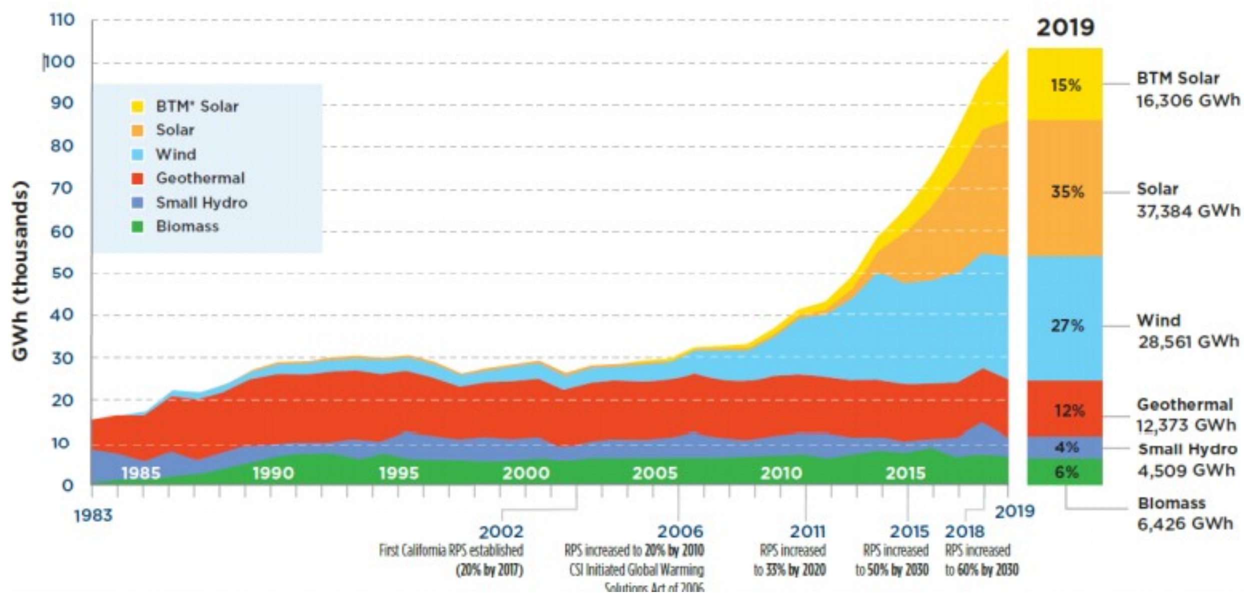

Figure 19. Total Renewable Generation Serving California Load
Source: CEC (2020) [118]

Storing excess renewable energy (when the sun shines and the wind blows) reduces or avoids the curtailment of renewable energy and displaces the use of fossil fuels, especially those used in "peaker" plants when energy demand is too high to be met by other resources. Reduced or avoided curtailment also make renewable energy projects more profitable. In California, energy storage can play an important role in addressing power outages from a soaring electricity demand as happened in August 2020 and, combined with solar PV installations onsite, power outages from fire danger.

Energy storage options vary greatly in technologies (batteries, flywheels, compressed air, pumped storage, and thermal energy), discharge duration (from minutes to days), power output (from watts to gigawatts), and location (interconnected at the transmission system, the

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[117] California Energy Commission. (2019). *Tracking Progress: Renewable Energy*. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-12/renewable_ada.pdf
[118] California Energy Commission. (2019). *Tracking Progress: Renewable Energy, p 5*. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-12/renewable_ada.pdf

distribution system, or behind the customer meter).[119] This section will cover California's energy storage solutions focusing on lithium-ion batteries for both utilities ("in front of the meter") and customers ("behind the meter").

Utility-scale Battery Storage

In 2013, authorized under AB 2514, the CPUC set an energy storage procurement target for the state's three IOUs of 1,325 MW by 2020.[120] AB 2868 further required the three IOUs to propose programs and investments to accelerate the widespread deployment of distributed energy storage systems[121] with the total capacity not exceeding 500 MW, at least 75% of which must be connected to the distribution system.[122]

The three IOUs have met the AB 2514 target of 1,325 MW. According to the CPUC, it has approved procurement of more than 1,533 MW of new storage capacity and 506 MW of the capacity are operational.[123] The world's largest lithium-ion battery energy storage system (BESS) began operation in Monterey County, California, in December 2020 with a 300 MW/ 1,200 MWh capacity. The second phase of the project will add an additional 100MW/ 400 MWh capacity by August 2021.[124] Under resource adequacy contracts, PG&E will pay the power generator, Vistra Energy, a fixed monthly resource adequacy payment to help maintain grid reliability. This is just one of several BESS projects under construction or in operation in the state. Figure 20 below shows the scale and speed at which California is building grid-scale batteries. The state plans to install 1.7 GW of battery storage in 2021 alone.[125]

[119] California Energy Commission. (2018, August). *Tracking Progress: Energy Storage*. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-12/energy_storage_ada.pdf

[120] California Public Utilities Commission. (2021). *Energy Storage*. California Public Utilities Commission https://www.cpuc.ca.gov/General.aspx?id=3462.

[121] "Distributed energy storage system" means an energy storage system with a useful life of at least 10 years that is connected to the distribution system or is located on the customer side of the meter. (AB 2868)

[122] State of California Legislature. (2016, September 26). *Assembly Bill No. 2868 Energy Storage*. State of California Legislature. https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160AB2868.

[123] California Public Utilities Commission. (2021). *Energy Storage*. California Public Utilities Commission https://www.cpuc.ca.gov/General.aspx?id=3462.

[124] Patel, S. (2020, January 14). *Vistra Energizes Massive 1.2-GWh Battery System at California Gas Plant.* Power Magazine. https://www.powermag.com/vistra-energizes-massive-1-2-gwh-battery-system-at-california-gas-plant/

[125] Baker, D. (2021, April 1). *California to Test Whether Big Batteries Can Stop Summer Blackouts.* Bloomberg. https://www.bloomberg.com/news/articles/2021-04-01/to-avoid-blackouts-california-s-installing-more-big-batteries-than-all-of-china

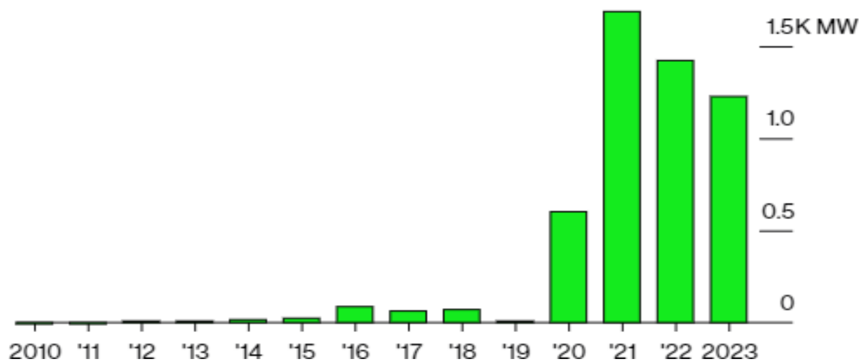

Figure 20. California's Battery Buildout through 2023
Source: BloombergNEF (2021)[126]

The rapid expansion of grid-scale systems was driven by the steeply falling lithium-ion battery prices, a spillover effect from the electric vehicle market. The prices have fallen 87% in real terms from USD 1,183 per kWh in 2010 to USD 156 per kWh in 2019 (Figure 21).[127] In 2020, the prices fell another 13% from 2019 to USD 137 kWh. BloombergNEF projects that the average prices will fall below USD 100 per kWh by 2024 and already observed the prices of less than USD 100 per kWh from batteries for e-buses in China.[128]

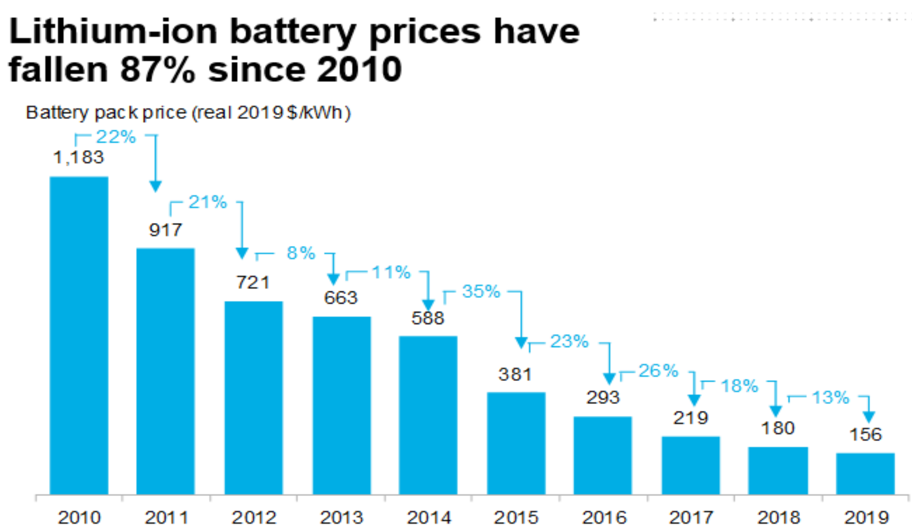

Figure 21. Lithium-ion Battery Prices from 2010 to 2019
Source: Bloomberg NEF (2020)

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126 Baker, D. (2021, April 1). *California to Test Whether Big Batteries Can Stop Summer Blackouts.* Bloomberg. https://www.bloomberg.com/news/articles/2021-04-01/to-avoid-blackouts-california-s-installing-more-big-batteries-than-all-of-china

127 BloombergNEF. (2019, December 3). *Battery Pack Prices Fall As Market Ramps Up With Market Average At $156/kWh In 2019*. BloombergNEF. https://about.bnef.com/blog/battery-pack-prices-fall-as-market-ramps-up-with-market-average-at-156-kwh-in-2019/

128 BloombergNEF. (2020, December 16). *Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh*. BloombergNEF. https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/

Behind-the-meter (BTM) Battery Storage

BTM battery storage is going to play an increasingly important role, especially when coupled with BTM solar resources which accounted for 15% of the state's renewable generation in 2019.[129] California has implemented financial incentives that reduce the cost of behind-the-meter storage installation and utility rate designs that encourage customers to install behind-the-meter storage systems.

Self-Generation Incentive Program (SGIP)

Established in 2001, SGIP incentivizes the development of emerging distributed energy resources by providing rebates for qualifying systems installed behind the meter. SGIP initially supported onsite solar PV but was allowed to support stand-alone energy storage systems as well in 2009. In 2018, the CPUC authorized the program to be extended for five more years with up to USD 830 million of funding. Nearly 80% of the funding (equity resiliency,[130] large-scale storage, and residential storage from Figure 22 below) is allocated to energy storage. SGIP has played an important role in increasing the penetration of onsite solar generation and storage.

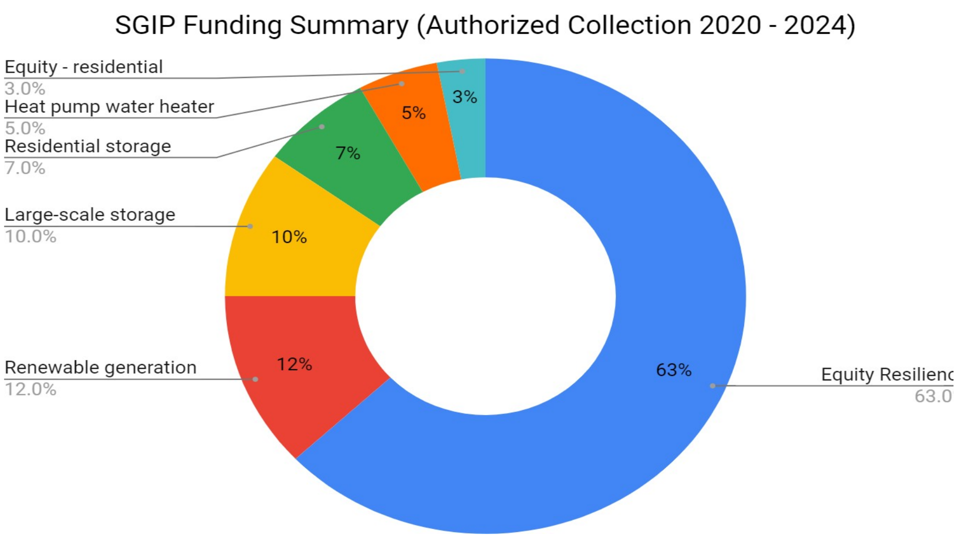

Figure 22. SGIP Funding Summary through 2024
Source: CPUC (2020) [131]

[129] California Energy Commission. (2019). *Tracking Progress: Renewable Energy, p. 5*. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-12/renewable_ada.pdf

[130] The funding allocated for equity resiliency covers the costs of energy storage systems for medically vulnerable people, low-income communities, and the communities with high fire and power shutoff risks.

[131] California Public Utilities Commission. (2020, January). *Self-Generation Incentive Program Revisions Pursuant to SB 700 and Other Program Changes*. California Public Utilities Commission. https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M325/K979/325979689.PDF

Utility rate design

There are three main utility rate designs that influence consumers' choice on whether to deploy solar PV and/or a storage system: time-of-use (TOU) rates, net energy metering (NEM), and demand rates.

- TOU is a rate plan in which rates vary according to the time of day, season, and day type (weekday or weekend/holiday). Higher rates are charged during the peak demand hours, usually weekday afternoons and evenings in California, and lower rates during off-peak demand hours.[132] All commercial, industrial and agricultural customers and residential customers entering into NEM (see below) with IOUs in California were required to be on a time-of-use plan between 2016 and 2017.[133] The rate plan provides an incentive for customers to produce and store solar power midday and use it during the peak demand hours as well as to implement energy efficiency and demand flexibility measures in general.
- Most utilities allow NEM although the detailed design might differ. NEM allows customers who generate their own energy ("customer-generators") to serve their energy needs directly onsite and to receive a financial credit on their electric bills for any surplus energy fed back to their utility.[134] As mentioned above, the three major IOUs require NEM customers to be on a time-of-use plan because a time-invariant financial credit would encourage solar installation but discourage storage installation.
- A demand rate charges customers a $/kW for their demand, which is highest during the peak demand hours, as well as a ¢/kWh rate for electricity consumed.[135] Demand charges are common for commercial, industrial and agricultural rates.[136] As with TOU rates, demand charges can incentivize customers to manage their load through solar PV and energy storage as well as energy efficiency and demand flexibility.

Research, Development and Deployment

The CEC has funded numerous energy storage demonstration projects with a focus on microgrids. With increasing risks of fires and power shutoffs, it is crucial for microgrids to be capable of

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132 California Public Utilities Commission. *What are TOU Rates?* California Public Utilities Commission. https://www.cpuc.ca.gov/General.aspx?id=12194.

133 *Id.*

134 California Public Utilities Commission. (2021). *Net Energy Metering (NEM)*. California Public Utilities Commission. https://www.cpuc.ca.gov/NEM/.

135 A kilowatt (kW) is the flow of electricity used at one moment in time. For example, if the one washing machine described above ran 10 loads, the household would use 10 kWh. If there were 10 washing machines all running at once, the household or business would be demanding 10 kW, even though the amount of electricity used would still be 10 kWh.

136 California Public Utilities Commission. (2021). *How is my bill calculated?* California Public Utilities Commission. https://www.cpuc.ca.gov/General.aspx?id=12188.

islanding and maintaining critical loads during grid outages through sophisticated control systems. Moreover, as battery and PV costs continue to fall, microgrids will become more widely applicable. As of August 2018, the CEC has funded 31 microgrid demonstration projects.[137] In 2018, the CEC announced the award of ten new microgrid demonstration projects and previously funded seven microgrid projects that can be broadly replicated (Table 3).[138]

Project Title	Location	Testing*
Existing (Seven)		
Blue Lake Rancheria Community	Blue Lake	Creates a community-scale system to support a Red Cross evacuation shelter in an islanded mode.
Borrego Springs	Borrego Springs	Develops an IOU-owned and -operated, front-of-the-meter system to improve grid resiliency for a community at the end of a distribution line affected by grid outages.
Bosch direct current building	Chino	Substantially reduces energy use for a distribution facility with direct current lighting, fans, and rechargeable forklifts.
City of Fremont Fire Station	Fremont	Enables building-scale functionality for three fire stations to reduce energy costs and provide resiliency.
Laguna Wastewater Treatment Plant**	Santa Rosa	Supports resiliency during a power outage and provides ancillary services to the grid and wholesale market.
Las Positas Campus (community college)	Livermore	Improve energy reliability, reduces demand, and provides ancillary services, while supporting critical loads during outages.
Kaiser Permanente Medical Center ***	Richmond	Supports life safety functions of the hospital in a grid outage and reduces electrical demand in grid operation.

137 California Energy Commission. (2018, August). *Tracking Progress: Energy Storage, p. 18*. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-12/energy_storage_ada.pdf

138 *Id*.

Project Title	Location	Testing*
Planned (Ten) – Ports, Tribes, Military, Disadvantaged Community, and Others		
Port of Long Beach***	Long Beach	Provides long-term islanding at the port's critical response facility and deploys a mobile battery for critical loads during grid outages or emergencies.
San Diego Port***	San Diego	Supports response to utility critical peak price events and maintains power to Department of Defense strategic port and jet fuel storage for the San Diego International Airport.
Miramar Marine Air Station	San Diego	Provides flight-line resilience through landfill gas generation and energy storage.
Camp Parks Army	Dublin	Creates a nested and modular system to modernize electric systems and meets critical loads with 100 percent renewables.
Port Hueneme Navy Server Farm Building	Port Hueneme	Addresses rapid electric instabilities during transition between grid-connected and islanding modes while supporting a critical military facility.
Redwood Coast Airport	McKinleyville	Develops a community-scale, front-of-the-meter system owned and operated by the local community choice aggregators and IOU to support an airport and U.S. Coast Guard Air Station.
Virtual Wide Area ***	Stockton, Fontana, Richmond	Provides virtual control of five distributed systems with a standard package with integrated DER to cover multiple customer segments, multiple meters, and different utility territories
Rialto ***	Bloomington	Creates a system to support a wastewater treatment plant with indefinite islanding potential using power generated from food waste and sewage sludge.
Chemehuevi Indian Reservation	Havasu Lake	Creates a community-scale system for 250 low-to-medium-income residents to provide power at the end of the IOU line.
Santa Rosa Junior College	Santa Rosa	Supports a resilient power system benefitting the campus and the community during emergencies and reduces electricity requirements during normal operation.

Source: California Energy Commission staff
* All microgrids at a minimum have solar PV, battery, and a controller
**The Laguna Wastewater Treatment Plant microgrid is expected to be on-line in late 2018.
***Disadvantaged Community

Table 3. Replicable Microgrid Projects in California
Source: CEC (2018)

The CEC has also supported numerous research and development projects through its Electric Program Investment Charge (EPIC) program. Examples include funding towards long-duration mechanical batteries (flywheel), flow batteries, zinc hybrid cathode batteries, vehicle-to-grid (V2G) and vehicle-to-building (V2B) services, and a storage value estimation tool. More information can be found in *Tracking Progress - Energy Storage* and *EPIC Annual Reports* published in the CEC website.

Challenges Ahead

Even with its rapidly increasing deployment, challenges remain for energy storage to play a key role in 100% clean grid as required by SB 100. First, there is a matter of sheer scale: to fully accommodate intermittent renewable energy sources, CEC, CPUC, and CARB estimate that the state will require additional 50 GW of battery storage to meet the SB 100 policy goal of 100% clean electricity by 2045.[139] Second, long-duration storage (100 or more hours of energy storage up to seasonal) will need to be developed in case of prolonged no-wind-no-solar periods. Pumped storage, flow batteries, or hydrogen could be the potential solutions. Third, there are concerns over the lifecycle environmental footprint of batteries. The mining of raw materials used in lithium-ion batteries - cobalt, lithium and rare earth elements - are linked to local soil/air/water pollution, intensive water use, and inhumane working conditions.[140] The lifespan of the batteries used in zero-emission vehicles (ZEVs) are estimated to be between 10-20 years.[141] Recycling or reusing the spent batteries will be a key challenge. AB 2832 requires CalEPA to convene an advisory group to recommend policies pertaining to the recovery and recycling of lithium-ion batteries used in vehicles.[142] Lastly, developing market rules by which storage systems can provide multiple services[143] (e.g., demand rate management, resource adequacy, time-of-use optimization) will enable energy storage to realize its full economic value. In 2018, the CPUC approved 11 rules to support multi-use applications (MUAs) for energy storage.[144] Achieving economic feasibility through stacking multiple services would have greater implications in other U.S. states and China where electricity retail rates are not as high as in California.

6.2.7 Transportation

Transportation results in over 50% of California's GHG emissions (including not just direct emissions but also indirect emissions for producing and refining the fuel), over 80% of the criteria pollutants and 97% of the diesel particulate emissions.[145] As such, emissions from transportation are a top priority for California's climate and air quality regulations: out of the ten climate policy portfolios laid out by CARB (Figure 1), five are related to transportation. California's transportation emissions are associated with 28 million automobiles and goods movement in heavy-duty vehicles, particularly from the Ports of Long Beach and Los Angeles across the South

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[139] California Air Resources Board, California Energy Commission, and California Public Utilities Commission. (2021, March). *2021 SB 100 Joint Agency Report, p 86*. California Air Resources Board, California Energy Commission and California Public Utilities Commission. https://efiling.energy.ca.gov/EFiling/GetFile.aspx?tn=237167&DocumentContentId=70349

[140] Tabuchi, H and Plumer, B. (2021 May 19). *How Green Are Electric Vehicles?* The New York Times https://www.nytimes.com/2021/03/02/climate/electric-vehicles-environment.html

[141] California Environmental Protection Agency. (2021) *Lithium-ion Car Battery Recycling Advisory Group.* California Environmental Protection Agency. https://calepa.ca.gov/climate/lithium-ion-car-battery-recycling-advisory-group/.

[142] *Id*.

[143] Rocky Mountain Institute. (2015, October). *The Economics of Battery Energy Storage, p. 6*. Rocky Mountain Institute. https://rmi.org/wp-content/uploads/2017/03/RMI-TheEconomicsOfBatteryEnergyStorage-FullReport-FINAL.pdf

[144] California Public Utilities Commission. (2021). *Energy Storage*. California Public Utilities Commission https://www.cpuc.ca.gov/General.aspx?id=3462.

[145] California Air Resources Board. (2013). *ARB Almanac 2013 - Chapter 2: Current Emissions and Air Quality 2-3 and 2-6*. California Air Resources Board. https://ww2.arb.ca.gov/our-work/programs/resource-center/technical-assistance/air-quality-and-emissions-data/almanac-2

Coast to every county in the United States. California is the gateway for goods moving from around the Pacific to the U.S. Both Ports are a key part of California's economy, indeed goods movement is responsible for about a third of the Southern California economy along with its single largest source of pollutants.[146] While California has achieved by 2017 its goal of reducing overall GHG emissions to 1990 levels by 2020, transportation emissions have continued to increase by 5% from 2013 through 2017.[147]

California's overall strategy is to target vehicles with greater efficiency and electrification, more appropriate fuels (reducing carbon intensity and incentivizing a shift away from fossil fuels) and improved mobility options (lowering miles traveled and building transportation infrastructure). In this section, we will discuss California's programs to clean up its transportation system, first for light-duty vehicles (cars and vans) and then for heavy-duty vehicles within the context of its ports. This discussion complements a working paper of the California-China Climate Institute.[148]

Light-duty Vehicles

California has been targeting air pollution from light-duty vehicles since at least the 1960s, and certainly reached saturation with some form of tailpipe emissions technology. California is pursuing a coordinated air quality and climate control approach. With the target of 100% clean electricity and 63% of its electricity coming from non-fossil sources[149] (Figure 23), it is natural for California to look to ZEVs.

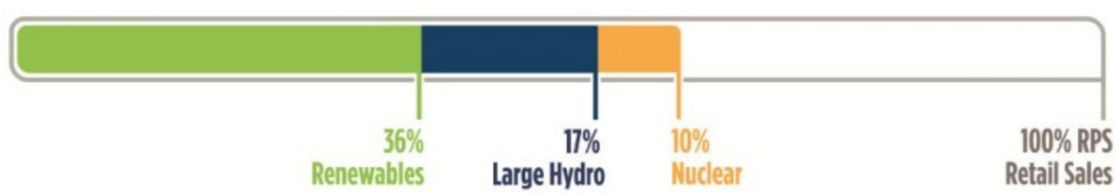

Figure 23. 63% of 2019 Electricity Retail Sales from Non-fossil Sources
Source: CEC (2020)[150]

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[146] California Energy Commission. (2020). *State Releases Final Plan to Transform Freight System.* California Energy Commission. Accessed May 20 2020 from https://calenergycommission.blogspot.com/2016/07/ state-releases-final-plan-to-transform.html

[147] California Air Resources Board. (2021, February 21). *Improved Program Measurement Would Help California Work More Strategically to Meet Its Climate Change Goals.* California Air Resources Board.

[148] California-China Climate Institute. (2020, September). *Driving to Zero: California and China's Critical Partnership on Zero Emission Vehicles*. California-China Climate Institute. https://ccci.berkeley.edu/sites/default/files/ZEV%20Paper%20-%20September2020.pdf

[149] California Air Resources Board, California Energy Commission, and California Public Utilities Commission. (2021, March). *2021 SB 100 Joint Agency Report, p 40*. California Air Resources Board, California Energy Commission and California Public Utilities Commission. https://efiling.energy.ca.gov/EFiling/GetFile.aspx?tn=237167&DocumentContentId=70349

[150] California Energy Commission. (2019). *Tracking Progress: Renewable Energy p. 2*. California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-12/renewable_ada.pdf

California has provided a variety of incentives for both the purchase of ZEVs and the development of charging/refueling infrastructure. California has almost half of the ZEVs in the United States, while China has almost half of the ZEVs in the world. Most of California's ZEVs are battery driven cars. The CEC is attempting to keep growing the charging and refueling infrastructure to match the expected growth of ZEVs.[151] In 2012, Governor Brown issued Executive Order B-16-12 which established a goal of 1.5 million ZEVs by 2025. In 2018, Governor Brown issued Executive Order B-48-14 which set a target of 5 million ZEVs by 2030, and installation of 250,000 publicly available electric vehicle (EV) charging ports and 200 hydrogen fueling stations by 2025, including 10,000 direct-current (DC) fast chargers. In 2020, Governor Newsom issued Executive Order N-79-20 that requires that all new passenger cars and trucks sold in the state be zero-emission by 2035 and all medium- and heavy-duty vehicles be zero-emission by 2045. Yet, plug-in vehicles represented only 8.26% of the state's annual new vehicle sales in 2019, and overall sales of these vehicles declined year-over-year by 12%, partly due to the expiration of federal tax credits for purchases from major manufacturers.[152]

In addition to the measures incentivizing the purchase of ZEVs, California has a variety of complementary transportation policies. First, there are the Corporate Average Fuel Economy (CAFE) standards which can reduce both air pollutants and GHG emissions.[153] Fuel economy or efficiency is a measure of the amount of fuel consumed by a vehicle over a set distance, expressed as "miles per gallon" in the U.S. NHTSA and U.S. EPA have set CAFE standards for passenger car and light-duty truck model years since 1975. California has a waiver to set its own tailpipe GHG emissions standards, which was very controversial and threatened during the Trump administration. These controversies are being resolved by the Biden administration.

Second, California's Low Carbon Fuel Standard (LCFS) reduces the carbon intensity of transportation fuels.[154] This standard not only reduces GHG emissions, but also reduces air pollutant emissions by requiring the development of lower carbon alternative fuels. The LCFS requires fuel suppliers to limit the carbon intensity of the fuels they sell (in terms of CO_2 equivalent per megajoule (MJ) of energy produced). Fuel suppliers comply either by limiting their fuel to the required intensity level or by purchasing credits to achieve compliance. Suppliers that produce fuels with low carbon intensity receive credits that may be sold to non-complying fuel suppliers or "banked" for future use by the supplier.

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[151] California Energy Commission. (2021, January). *Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment: Analysing Charging Needs to Support Zero-Emission Vehicles in 2030, 1.* California Energy Commission. https://efiling.energy.ca.gov/getdocument.aspx?tn=236237

[152] California-China Climate Institute. (2020, September). *Driving to Zero: California and China's Critical Partnership on Zero Emission Vehicles, p. 5*. California-China Climate Institute. https://ccci.berkeley.edu/sites/default/files/ZEV%20Paper%20-%20September2020.pdf

[153] Wang, A, Shen, S., Pettit, D. (2020, July). *Coordinated Governance of Air & Climate Pollutants: Lessons from the California Experience, p.52*. UCLA Law. https://law.ucla.edu/news/coordinated-governance-air-climate-pollutants-lessons-california-experience

[154] Wang, A, Shen, S., Pettit, D. (2020, July). *Coordinated Governance of Air & Climate Pollutants: Lessons from the California Experience, p. 53*. UCLA Law. https://law.ucla.edu/news/coordinated-governance-air-climate-pollutants-lessons-california-experience

Under LCFS, California's average fuel carbon intensity declines each year to 10% below the 2010 level in 2020 and then 20% below the 2010 level in 2030. (Figure 24) CARB uses a life-cycle assessment to determine the emissions associated with the fuel pathway, including extraction, production, processing, transportation and consumption.

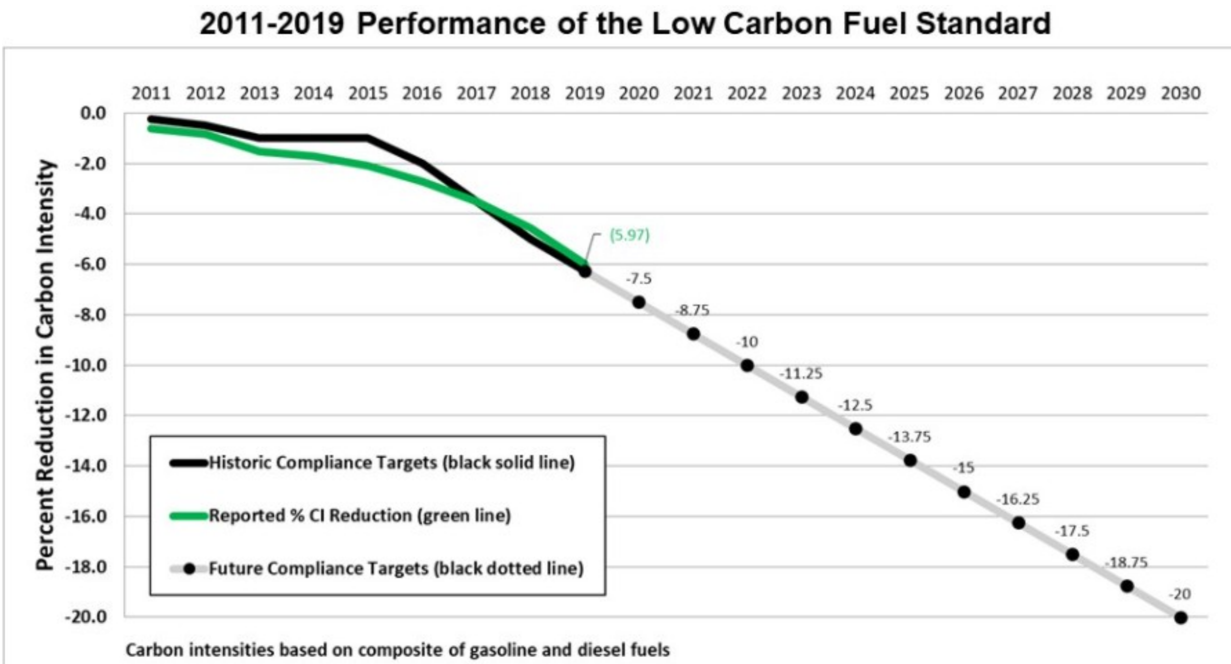

Figure 24. 2011-2019 Performance of the LCSF
Source: CARB (2020) [155]

The LCFS defines separate carbon intensity measures for gasoline and diesel. Fuels for light- and medium-duty vehicles are generally considered gasoline replacements, while replacement fuels for heavy-duty vehicles are considered diesel replacements. LCFS's alternative fuels include gas (natural gas and biogas), ethanol, bio-diesel, renewable diesel, electricity, hydrogen, etc.

As demonstrated in Figure 24 above, the LCFS has generated significant reductions in the overall carbon intensity of California's fuel markets through the expansion of alternative fuel supply. As of 2019, the LCFS has resulted in alternative fuel supplies displacing almost 3.3 billion gallons of petroleum diesel fuel.

Third, California has been using land use planning to attempt to reduce the vehicle miles traveled, which can reduce both GHG and air pollution emissions.[156] California's SB 375 attempts to align

[155] California Air Resources Board. (2021). *Data Dashboard*. California Air Resources Board. https://ww3.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm.

[156] Wang, A, Shen, S., Pettit, D. (2020, July). *Coordinated Governance of Air & Climate Pollutants: Lessons from the California Experience p. 53*. UCLA Law. https://law.ucla.edu/news/coordinated-governance-air-climate-pollutants-lessons-california-experience

land use and transportation planning with California's climate change goals. The goal would be building more housing close to jobs rather than in the suburbs since suburban housing would result in longer commutes. Local Metropolitan Planning Organizations are required to develop Sustainable Community Strategies as part of the federally-mandated Regional Transportation Plans. Projects consistent with the Sustainable Communities Strategies have streamlined procedures under the California Environmental Quality Act (CEQA).

Alternatively, the California Attorney General and others have used CEQA litigation to promote dense urban infill housing and discourage suburban sprawl. CEQA requires a full analysis of the environmental impacts of a proposed housing project, including GHG emissions. CEQA also requires the negative environmental impacts to be mitigated to the extent feasible. For new suburban housing developments, this can require the developer to make an enforceable commitment to build and maintain a "net zero" project. Net zero status can mean all electrical hookups for heating and cooking, wiring all houses for EV charging, having access to public transit, and increasing energy efficiency beyond building code requirements, among others.

Heavy-duty Vehicles and Goods Movement

The Ports of Los Angeles and Long Beach are the gateway for goods movement from around the Pacific, particularly from China, to the U.S.. Goods coming through these ports flow across the South Coast to every county in the U.S.. The Ports say they are responsible for some 190,000 jobs just within their own cities and as many as 3 million jobs nationwide connected to the goods flowing to and from these ports.[157] These ports are also the biggest single sources of air pollution within the greater Los Angeles area. These twin ports are major logistical operations serviced by a wide assortment of vehicles: cargo-laden container ships, oil tankers, tugboats, ship-to-shore cranes, rolling stacking cranes, container-lifting top-loaders, forklifts, tractors, freight trains and roughly 16,000 trucks. Almost all are run on diesel or petroleum-based fuels.[158]

In 2017, the mayors of Los Angeles and Long Beach set goals to make their ports zero emission. They committed to transitioning all of the cargo-handling equipment on the docks to zero-emission vehicles by 2030, and to do the same for the trucks servicing the terminals by 2035. These agreements call for reducing GHG emissions at the ports to 40% below 1990 levels by 2030 and 80% below 1990 levels by 2050.[159]

[157] Vock, D.C. (2019, May 20). *Governing the Future of States and Localities, Can America's Biggest Ports go Green, p. 5*. Governing.com. https://www.governing.com/archive/gov-california-ports-emissions-air-pollution.html
[158] Vock, D.C. (2019, May 20). *Governing the Future of States and Localities, Can America's Biggest Ports go Green, p. 5*. Governing.com. https://www.governing.com/archive/gov-california-ports-emissions-air-pollution.html
[159] Vock, D.C. (2019, May 20). *Governing the Future of States and Localities, Can America's Biggest Ports go Green, p. 6*. Governing.com. https://www.governing.com/archive/gov-california-ports-emissions-air-pollution.html

Port electrification

The biggest source of air pollution at the ports are the nearly 4,000 ships that call at the two ports every year. The Port of Los Angeles has been a leader in the use of alternative maritime power (AMP), sometimes called shore-side power or cold ironing, to reduce emissions of air pollutants and GHG. Ships plug into the AMP while its main and auxiliary engines are turned off. The Port of Los Angeles opened its first AMP network in August 2004. In 2007, CARB made this practice compulsory for all vessels calling at the Port of Los Angeles and Long Beach. As of 2020, the Port of Los Angeles has 79 AMP vaults and is working to expand its capacity to accommodate cruise vessels. CARB is considering raising the required percentage of container ships, refrigerated vessels and cruise ships using shore power from 70% to 80%. Plugging in one container ship for a day has the same pollution reduction impact as taking 33,000 cars off the road for that day.[160]

There are concerted efforts to develop zero emission cargo handling equipment and to step up the charging infrastructure at the ports. For example, the first portion of the Middle Harbor Project at Long Beach opened in 2016, and nearly all of it runs on electric equipment and is largely automated. Similarly, SCE is in the middle of a USD 356 million program to install charging infrastructure throughout its service territory (which includes the Port of Long Beach) for 8,500 medium- and heavy-duty vehicles through 2023. At least a quarter of the budget is earmarked towards ports and warehouses.[161]

There are 16,000 trucks at the two ports. There have been a variety of programs to encourage clean trucks. The ports need to move to zero-emission and near-zero emission trucks.[162]
The most appropriate technology is still under development, which will be comprehensively discussed in the next section. However, in June 2020, CARB adopted the first-in-the-world zero emission truck rule. It requires the manufacture of about 100,000 ZEV heavy-duty vehicles by 2030, and about 300,000 ZEVs by 2035.[163]

While there are numerous areas of technology challenges, there is an overall policy goal of transitioning the Ports of Los Angeles and Long Beach to zero emission ports.

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[160] Vock, D.C. (2019, May 20). *Governing the Future of States and Localities, Can America's Biggest Ports go Green, p. 8-9*. Governing.com. https://www.governing.com/archive/gov-california-ports-emissions-air-pollution.html

[161] Vock, D.C. (2019, May 20). *Governing the Future of States and Localities, Can America's Biggest Ports go Green, p. 14*. Governing.com. https://www.governing.com/archive/gov-california-ports-emissions-air-pollution.html

[162] Vock, D.C. (2019, May 20). *Governing the Future of States and Localities, Can America's Biggest Ports go Green, p. 5,10,11,12*. Governing.com. https://www.governing.com/archive/gov-california-ports-emissions-air-pollution.html

[163] California Air Resources Board

6. International Best Practices and Potential in China

7.1 Energy Efficiency and Potential Air Quality Co-Benefits in Heavy-Duty Trucks

Globally, heavy-duty freight trucks[164] account for only 10% of all vehicles but account for disproportionately higher shares of transport energy consumption and related CO_2 emissions. Heavy-duty trucks account for 70% of road freight activity and 50% of trucking energy consumption, and 40% of total transport CO_2 emissions.[165] Unlike medium and light-duty trucks that are often used for regional transportation and small-scale "last-mile" deliveries, heavy-duty trucks are generally used for long-distance delivery of goods with longer operating time. Partly as a result of heavier weight and payloads, and more rugged operations, heavy-duty trucks consume significantly more energy consumption on a per-kilometer basis than other classes of trucks. From a policy perspective, however, only five countries have developed fuel economy standards for this specific vehicle class and these standards were all developed within the last two decades. The disproportionately greater environmental impact of these heavy-duty trucks highlights significant opportunity for reducing energy consumption and CO_2 emissions while simultaneously achieving co-benefits through improved air quality. This is especially true in emerging and transition economies, where demand for road freight is expected to grow rapidly alongside continued economic development and where air pollution remains a key environmental challenge.

7.1.1 Current Market, Policy and Technology Landscape

Market Status

In China, road freight has grown significantly since the mid-2000s, with road freight turnover increasing by seven-fold from just under 1 trillion ton-kilometers (km) in 2006 to over 7 trillion ton-km in 2018.[166] By 2018, road freight accounted for 47% share of total freight activity. Within the road freight sector, heavy-duty trucks' share of total vehicles has also risen quickly in recent years, increasing its share from 18% in 2002 to 28% in 2018. Alongside this growth, China's transport sector now accounts for 58% of China's total petroleum use and China surpassed the U.S. as the world's largest crude oil importer in 2018. In addition to raising energy security and CO_2 emission concerns, heavy-duty trucks are also contributing to significant air quality and related health concerns. Diesel vehicles account for half of all on-road particulate matter (PM)

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164 Truck vehicle class weight specification schemes vary by country but heavy-duty trucks generally refer to gross vehicle weight equal to or greater than 15 tonnes.

165 Moultak, M., Nic, L, Hall, D. (2017). *Transitioning to zero-emission heavy-duty freight vehicles.* The International Council on Clean Transportation (ICCT) White Paper. https://theicct.org/publications/transitioning-zero-emission-heavy-duty-freight-vehicles; International Energy Agency. (2017). *The Future of Trucks.* International Energy Agency. https://doi.org/10.1787/9789264279452-en

166 National Bureau of Statistics (NBS). (2020). *China Statistical Yearbook 2019*. Beijing: China Statistics Press. National Bureau of Statistics. https://data.stats.gov.cn/easyquery.htm?cn=C01

and nitrogen oxide (NOx) emissions in China. For PM2.5, specifically, emissions from heavy-duty trucks can be 1-2 orders of magnitude greater than light-duty vehicles.

In China, heavy-duty trucks are classified as having gross vehicle weight of greater than 12 tonnes and include subcategories of tractor trucks, dump trucks, straight or pick-up trucks, and special trucks (Table 4). The total number of heavy-duty trucks has increased by five-folds to 7 million units in 2018 with an annual average growth rate of 10.3%, making it among the fastest growing segment in freight vehicles. Special trucks used for short-distances within urban areas, such as cement mixers, and tractor trucks used for long-distance transport dominate China's heavy-duty trucking sector, followed by dump trucks and straight trucks. In 2015, 98% of China's heavy-duty trucks were diesel-powered while another 2% of the vehicles were fueled by liquefied natural gas (LNG).[167] Since then, battery-electric and fuel cell trucks are also beginning to enter the heavy-duty trucking market, particularly for short-distance urban applications, as a result of national subsidy policies and the growth of electric vehicles. By 2016, about 2% of China's heavy-duty vehicles were electric.[168]

	Pick-up truck	**Tractor truck**	**Dump truck**	**Special truck**
				
Applications	Used by logistics companies; high-frequency operation	Fixed routes Transporting large quantities of goods and materials	Construction sites; transporting garbage; harsh working conditions	Short distances; used within a city
Annual average distance travelled (km)	200,000 – 250,000	150,000 – 200,000	80,000 – 100,000	30,000 – 60,000
Average lifetime (years)	10	8	3	10

Table 4. Heavy-Duty Vehicles Categorization and Characteristics
Sources: (China Automotive Technology and Research Center, 2018; Song et al., 2017; Xing et al., 2016)

[167] Song, H., Ou, X., Yuan, J., Yu, M., & Wang, C. (2017). Energy consumption and greenhouse gas emissions of diesel/LNG heavy-duty vehicle fleets in China based on a bottom-up model analysis. *Energy*, *140,* 966–978. https://doi.org/10.1016/j.energy.2017.09.011

[168] China Automotive Technology and Research Center. (2018). *China Green Freight Assessment.* China Automotive Technology and Research Center. https://www.ccacoalition.org/en/resources/china-green-freight-assessment

From a market perspective, China's heavy-duty trucking sector is also unique in that it is dominated by an individual ownership model where 71% of truck drivers own their vehicles.[169] As a result, 84% of truck purchases are also made through bank loans with a small down payment or through personal loans.[170] Combined with nearly 45% share of truck drivers operating independently rather than working for a specific company, these market conditions lead to rather decentralized and fragmented heavy-duty trucking ownership and operation.

Policy Status

Similar to other countries, China has introduced a mix of regulatory, fiscal and market-based policies to address the energy and broader environmental impacts of the heavy-duty trucking sector. As one of the few countries to have developed mandatory fuel economy standards for heavy-duty vehicles, China has since introduced three phases of heavy-duty vehicle fuel economy requirements that now cover straight, tractor and dump trucks. The specific requirements and increasing stringency of recent stages of fuel economy standards are shown for tractor trucks as an example in Figure 25 below.

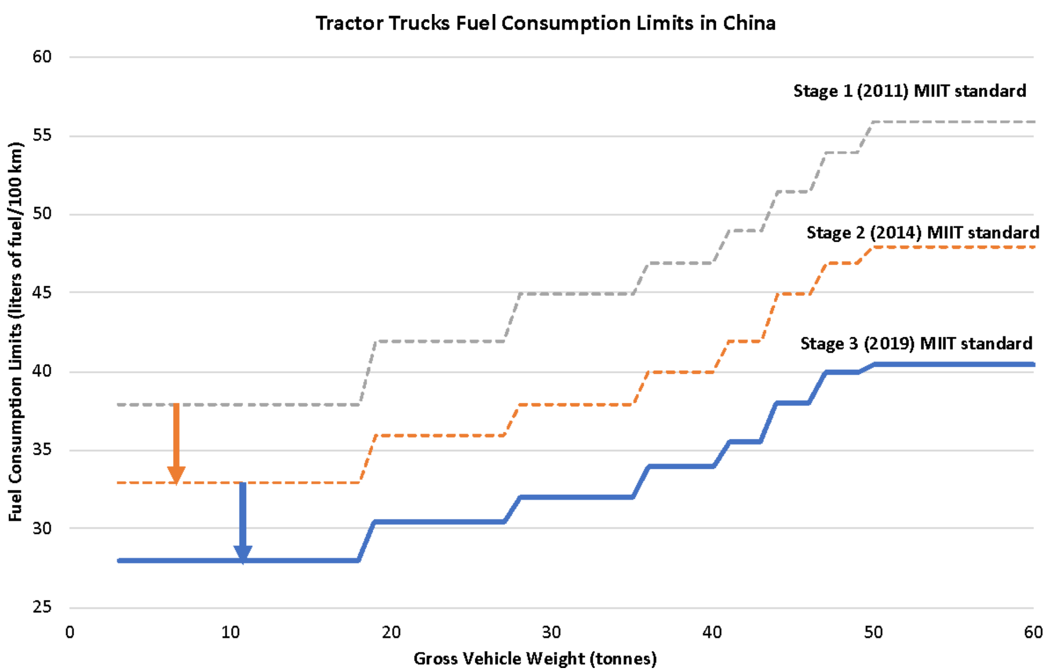

Figure 25. China's Fuel Economy Standards for Heavy-duty Tractor Trucks

In addition to increasing energy efficiency performance through fuel economy standards, another significant area of policy focus in China is to promote the development and deployment

[169] Chuanhua Charity Institute. (2018). *Group Characteristics and Labor Process of the Truck Drivers*. Social Sciences Academic Press.

[170] Id.

of New Energy Vehicles (NEV).[171] While NEV policy support initially focused on light-duty passenger vehicles, more attention has been paid recently to buses, urban special trucks and long-distance heavy-duty trucks. In the policy document on promoting NEVs issued in April 2020, exemption of purchase quota limits, exemption of traffic restrictions, strengthened environmental management of diesel trucks, and the business model of Battery as a Service (BaaS) were all included to support the development of new-energy heavy-duty trucks. In addition, the central government (and often with matching funding from local governments) has provided significant fiscal and financial support to the development of new energy trucks since 2015. The level of subsidies for heavy-duty trucks is also being gradually reduced by 10% and 20%, respectively, in 2021 and 2022, with plans for a complete phase-out by the end of 2022. Due to different paces of technological development in light versus heavy-duty vehicles, policies to promote NEV heavy-duty trucks are still emphasizing research and development, and manufacturing of key materials, components, and core technologies.

In terms of air pollution, China has adopted six phases of increasingly stringent heavy-duty vehicle emissions standards which limits the amount of NOx, PM, and CO emitted. The latest emission standard, known as the China VI emission standard for heavy-duty vehicles (GB17691-2018) was finalized in June 2018, and is being implemented in two phases between 2019 to 2021 for VI-a, and between 2021 and 2023 for new heavy-duty vehicles for VI-b. China VI-a introduces similar requirements as Euro VI emission standards, while China VI-b introduces more stringent testing requirements and a remote emission monitoring system.[172] Besides national emission standards, some subnational regions have adopted additional policies and programs to limit air pollution from heavy-duty trucks. The capital city of Beijing launched a low-emission zone in late 2017, banning heavy-duty trucks with emissions below China IV standards from entering the city. The city of Shanghai has started banning polluting China III diesel trucks from running on certain highways, with subsidies offered to truck operators for phasing out these polluting vehicles earlier than scheduled.

7.1.2 Technology Status

Compared to the U.S. and European Union (EU) heavy-duty trucking markets, Chinese heavy-duty trucks tend to have smaller and underpowered engines. Energy efficiency improvements are possible by adopting engine technologies such as such as advanced turbochargers, turbo-compounding, on-demand accessories, friction reduction, and high efficiency selective catalytic reduction systems.[173] Compared to similar vehicles on the global market, China's heavy-duty vehicles are also, on average, 10% heavier but key components such as vehicle frames and

[171] NEVs in China's context refers to plug-in hybrid, battery electric and fuel cell vehicles.

[172] Yang, L., He, H. 2018. *China's Stage VI emissions standard for heavy-duty vehicles (final rule).* International Council on Clean Transportation. https://theicct.org/publications/china%E2%80%99s-stage-vi-emissions-standard-heavy-duty-vehicles-final-rule

[173] Delgado, O., Zhao, L., Zheng, T., He, H., Yang, L., Muncrief, R. and Sharpe, B. (2017, July). *Market Analysis and Fuel Efficiency Technology Potential of Heavy-Duty Vehicles in China.* International Council on Clean Transportation. https://www.theicct.org/sites/default/files/publications/China-HDV-Market-Tech_ICCT-White-Paper_20072017_vF.pdf

suspension springs may be as much as 30-40% heavier.[174] This suggests that there is opportunity for adopting light-weighting technologies such as high-strength steel and aluminum to help reduce vehicle weight while increasing fuel efficiency. In addition, other efficiency technologies such as trailer side fairings and low rolling resistance tires are also commonly adopted in the U.S. and Canada to improve aerodynamics and increase fuel efficiency but are not yet widely used in China.

Besides vehicle efficiency improvements, there are also new developments in information communications technologies, big data, and automation with potential operational efficiency improvements for heavy-duty trucks. With recent global technological innovations, multiple systemic improvements in freight operations and logistics already exist that can reduce operational fuel use and related emissions. Examples of these freight operations and logistics improvements include optimized routing through global position systems and geographic information systems, automated truck platooning for reduced aerodynamic drag, fuel-efficient driving training and feedback, and co-loading by bundling shipments to improve economies of scale.[175] Yet most of these improvements have not been realized because of existing technical, economic, and/or political barriers and lack of enabling mechanisms or policies to overcome these barriers. In China where over- and under-loading still persist, back-hauling by delivering cargo on return trips can significantly improve vehicle utilization and decrease vehicle travel activity. Optimized routing and co-loading can further improve the operational efficiency of China's heavy-duty trucking fleets if widely adopted.

In terms of air pollutant emission control technologies, diesel particulate filters (DPF) are expected to become more widely deployed with the adoption of the China VI emission standards. Because China VI also sets emission limits on particle number emissions, DPF applications will be needed to remove diesel particulate matter such as soot and ash from exhaust gas for new diesel heavy-duty trucks to meet the new emissions limit. Similarly, to meet the China VI ammonia and NOx emission limits, advanced active emissions control technologies such as selective catalytic reduction systems will also be needed in new diesel heavy-duty trucks.[176]

7.1.3 Zero Emission Technologies Assessment

In addition to the existing commercialized technologies for improving heavy-duty trucking vehicle and operational energy efficiency, battery electric, hydrogen fuel cell, catenary and dynamic charging technologies are emerging as zero-emissions alternatives to conventional diesel trucks.

Unlike electric cars and light-duty vehicles that are already being commercially deployed, electrifying heavy-duty trucks faces specific technical constraints in terms of heavier weight and

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[174] *Id.*

[175] International Energy Agency. (2017). *The Future of Trucks.* International Energy Agency. https://doi.org/10.1787/9789264279452-en

[176] Li, G., Ying Y., Zhang M. et al. (2019). Key Technical Contents of the China VI Emission Standards for Diesel Fueled Heavy-duty Vehicles. *Johnson Matthey Technology Review 63* (1): 21 - 31. https://www.technology.matthey.com/wp-content/uploads/pdf/21-31-jmtr-jan19.pdf

larger vehicle sizes, more rugged operations, and longer travel distance and operating time common to this class of trucks. These defining characteristics in turn require batteries with greater energy densities, higher energy capacity on the order of 10 times that of electric cars, greater durability and more discharge cycles before battery performance begins declining, and temperature management requirements and safety. Globally, established multi-national manufacturers and start-ups have been developing electric HDT prototypes since 2016, with 10 battery electric truck models slated for commercial deployment by 2021. The batteries currently being used in these demonstration heavy-duty electric trucks are still based on technologies in the research and development stage, with uncertain timelines for production scale-up and deployment. For instance, there has been some recent improvements in expanding the limited range of most existing battery electric heavy-duty truck prototypes. Heavy-duty electric trucks, such as the Nikola Two and Tesla Semi, have recently demonstrated travel ranges of 400 to 550 miles compared to the 200-300 miles that has been typical until now. The costs of batteries for electric vehicle applications declined by 16% annually between 2007 and 2019, to an industry-wide average cost of USD 161 per kWh for lithium-ion battery packs.[177] There is general expectation that battery costs will continue to decline significantly over time to the range of USD 100/kWh for heavy-duty trucks with scaled-up production and economies of scale, and that battery electric heavy-duty trucks will reach cost parity with conventional diesel trucks around 2030.[178] However, there remains uncertainty over the forecasted decline because of an expected increase in demand for batteries for grid storage and electric vehicles. In addition to battery costs, there are additional infrastructure costs to support charging ranging from USD 71,000 to USD 189,000.[179]

An alternative to battery electric technologies is hydrogen fuel cell trucks that use hydrogen stored in a pressurized tank and equipped with fuel cells to convert hydrogen back into electricity for on-board power generation. As a much denser energy carrier than electric batteries, hydrogen's low volumetric energy density allows it to be stored as a compressed gas in hydrogen storage tanks to achieve higher ranges. Hydrogen refueling stations are co-located at gasoline stations and refilling for light-duty passenger cars can be completed in as short as 5 minutes. Currently, hydrogen is produced from natural gas through methane reforming, or electrolysis from coal or directly from electricity, with the hope that electrolysis from renewable electricity

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[177] Kapoor R., et al. (2020). *Analysis shows continued industry-wide decline in electric vehicle battery costs.* University of Pennsylvania. https://mackinstitute.wharton.upenn.edu/2020/electric-vehicle-battery-costs-decline/

[178] International Energy Agency. (2017). *The Future of Trucks.* International Energy Agency. https://doi.org/10.1787/9789264279452-en; Hall, D., & Lutsey, N. (2019). *Estimating the infrastructure needs and costs for the launch of zero-emission trucks*. The International Council on Clean Transportation (ICCT) White Paper. https://theicct.org/publications/zero-emission-truck-infrastructure; Phadke, A., Khandekar, A., McCall, M., Karali, N., & Rajagopal, D. (2019, September). *Long-haul battery electric trucks are technically feasible and economically compelling*. Lawrence Berkeley National Laboratory Working Paper. Retrieved from https://eta-publications.lbl.gov/sites/default/files/working_paper_005_battery_electric_trucks_906_0.pdf; ICF. (2019). *Comparison of Medium- and Heavy- Duty Technologies in California*. ICF. https://www.caletc.com/assets/files/ICF-Truck-Report_Final_December-2019.pdf

[179] Hall, D., & Lutsey, N. (2019). *Estimating the infrastructure needs and costs for the launch of zero-emission trucks*. The International Council on Clean Transportation (ICCT) White Paper. https://theicct.org/publications/zero-emission-truck-infrastructure

can provide a future clean source for hydrogen. Light-duty fuel cell vehicles are commercially available in limited quantities in localized markets in the U.S. and globally, but the technology and market are still being developed for medium- and heavy-duty vehicle applications with only four demonstration Class 8 truck prototypes manufactured by Hyundai, Toyota, Nikola, and Kenworth. Their ranges extend from a low of 249 miles for the Hyundai XCient Class 8 straight truck (small-scale production began in 2020), to a high of 1,000 miles for the Nikola One Class 8 tractor-trailer (production anticipated in 2022). In terms of cost, existing estimates of the capital costs for heavy-duty trucks with fuel cell systems total USD 256,000 to USD 480,000, but analysis suggest that this could decline to USD 150,000 to USD 200,000 by 2030 with declining fuel costs.[180] Additional infrastructure costs of USD 2 to USD 3 million per hydrogen refueling station and related infrastructure have been estimated based on California's experience.[181]

A third, but less common, alternative for electrifying heavy-duty trucks is through the use of in-road or dynamic charging infrastructure built into roads, such as through overhead catenary contact lines that can be connected or disconnected or through coils embedded in roads that can generate electromagnetic field with receiving coils for electricity generation on the truck. Three European companies including Siemens, Scania, and Volvo are working on pilot demonstrations of dynamically charging trucks using catenary lines, on-road rails, and induction for specialized applications such as short-distance routes connected to ports and airports.[182] The primary costs associated with dynamic or catenary charging is the investment costs needed for new on-road charging infrastructure, estimated at USD 0.8 to 1 million per kilometer of new road, with significantly higher costs if existing roads need to be retrofitted.[183]

7.1.4 International Best Practices

7.1.5 Fuel economy and CO2 emission standards

Globally, there are six mandatory energy or CO_2 emission standards programs that specifically cover heavy-duty trucks. Japan was the first to introduce heavy-duty vehicle fuel economy standards in 2006, and its recent second phase of standards was finalized in 2019. The new standard targets 13.4% efficiency improvement by 2025 from 2015 levels and includes requirements for efficient technologies such as improved aerodynamics and tires. India finalized

[180] Moultak, M., Nic, L, Hall, D. (2017). *Transitioning to zero-emission heavy-duty freight vehicles.* The International Council on Clean Transportation (ICCT) White Paper. https://theicct.org/publications/transitioning-zero-emission-heavy-duty-freight-vehicles ; ICF. (2019). *Comparison of Medium- and Heavy- Duty Technologies in California*. ICF. https://www.caletc.com/assets/files/ICF-Truck-Report_Final_December-2019.pdf

[181] ICF. (2019). *Comparison of Medium- and Heavy- Duty Technologies in California*. ICF. https://www.caletc.com/assets/files/ICF-Truck-Report_Final_December-2019.pdf

[182] Siemens. (2019). *eHighway- electrification of freight transport*. Siemens. https://new.siemens.com/global/en/products/mobility/road-solutions/electromobility/ehighway.html; International Energy Agency. (2017). *The Future of Trucks.* International Energy Agency. https://doi.org/10.1787/9789264279452-en

[183] International Energy Agency. (2017). *The Future of Trucks.* International Energy Agency. https://doi.org/10.1787/9789264279452-en

its heavy-duty vehicle fuel economy standards in 2017, with Phase 1 going into effect in 2018 and Phase 2 in 2021 and targeting average fuel reductions of 11%.

Similar to Japan and India, the U.S. greenhouse gas emission standards for heavy-duty vehicle are also based on two phases, with Phase 1 established for 2014 to 2018 model year vehicles, and Phase 2 for 2018 to 2027 model vehicles. The standards include separate efficiency and emission standards for engines and vehicles, and covers four major greenhouse gases including CO_2, methane, nitrous oxide and hydrofluorocarbons. Depending on the vehicle type and size, Phase 1 standard requires reductions of 6-23% compared to 2010 model base year in fuel consumption and CO_2 emissions. Phase 2 standards reduce fuel consumption and CO_2 emissions by 30%. Canada's standards for heavy-duty trucks are closely aligned to the U.S. standards.

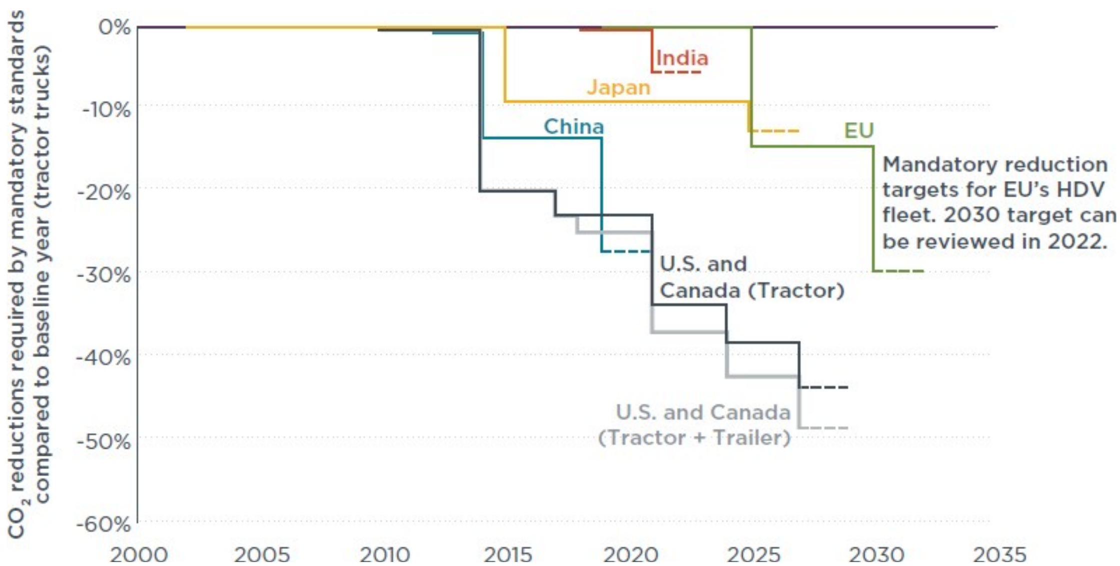

Figure 26. Comparison of CO2 Reduction Requirements for Global Mandatory Standards for Heavy-duty Vehicles
Source: ICCT, 2019

In 2019, the EU adopted its first CO_2 emission standards for heavy-duty vehicles that went into force in August 2019. The standard specifically regulates fleet-wide tailpipe CO_2 emissions by using average CO_2 emissions per ton-kilometer traveled and uses monitoring and reporting data from July 2019 through June 2020 as the baseline. It also includes two-phase limits: a 15% relative reduction from the baseline CO_2 emissions from 2025 to 2029, and a 30% reduction from the baseline level by 2030 that is subject to review in 2022.

In addition to the phased approach with increasingly stringent requirements that is common across existing international fuel economy and CO_2 emission standards, the EU regulation stands out in that it also includes a phased approach to incentivize the uptake of zero- and low-emission vehicles that are defined as having less than half of the average CO_2 emissions of all vehicles. From 2019 to 2024, the regulation introduces a super-credits system that rewards manufacturers for producing zero and low-emission vehicles with multipliers[184] to help reduce the fleet average emissions for complying with the 2025 target. Starting in 2025, a bonus only benchmark system will replace the super-credit system, where manufacturers that exceed a benchmark sales fleet threshold of 2% share for zero or low-emissions vehicle will benefit from a relaxed CO_2 emissions target,[185] up to a maximum of 3% decrease. The regulation also includes strict financial penalties for non-compliance, ranging from 4250 to 6800 euros per grams of CO_2 per tonne-kilometre (gCO_2/tkm) exceeding the target in 2025 and 2030, respectively.

7.1.6 Low emission zones

In addition to emission standards that directly control tailpipe air pollutant emissions from heavy-duty vehicles, Europe has developed a complementary policy of establishing low emission zones that concurrently incentivize the adoption of zero or low-emission zones while helping mitigate air pollution in primarily urban areas since 1996. These zero or low emission zones require vehicles entering the designated urban zone, such as heavy-duty construction or delivery trucks, to meet more stringent emission standards, which in turn helps accelerate the phase-out of older conventional vehicles. In some cases, vehicles that do not meet the more stringent emission standards in the designated zones may face retrofit requirements or higher tolls and additional road fees. Currently, low emission zones that cover trucks are in place or planned for over 250 cities in Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Italy, the Netherlands, Norway, Portugal, Sweden, and the United Kingdom.

Specific examples of low emission zones include the German city of Hamburg, which introduced partial access restrictions in April 2018 on specific city routes for trucks that fail to meet Euro VI standards. More restrictive access restrictions have also expanded to other major German cities including Berlin, Bonn, and Stuttgart. One successful case study of low emission zones is the city of London, which introduced low emission zones in its city center in 2008. London's low emissions zones have helped reduce black carbon by 40-50%, NOx emissions by 2.4%, and PM10 emissions by 1.9%.[186] More notably, a study found that the percentage of children living in areas exceeding the EU limit value for NO_2 fell from 99% in 2009 to 34% in 2013, indicating significant health benefits were achieved as a result of the low emission zones.[187]

Building on the benefits of low emission zones, major European cities including London, Oxford, Amsterdam, Madrid, Brussels and Paris are beginning to introduce zero emission zones that grant

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[184] Zero-emission vehicles receive a multiplier of 2 and low-emission vehicles receive a multiplier between 1 and 2 depending on the vehicle's specific emission levels; super-credits are capped at 3%.

[185] Each percentage point in excess of the benchmark threshold will decrease the manufacturer's average specific CO_2 emissions requirement by 1%, up to a maximum of 3%.

[186] Charging, Low Emission Zones, other Access Regulation Schemes (CLARS). (2021). *Urban Access Regulations in Europe*. Charging, Low Emission Zones, other Access Regulation Schemes (CLARS). https://urbanaccessregulations.eu/low-emission-zones-main/impact-of-low-emission-zones

[187] Mudway I., Dundas I., Wood H., et al. (2019). Impact of London's low emission zone on air quality and children's respiratory health: a sequential annual cross-sectional study. *The Lancet 4*(1): E28-E40. https://www.thelancet.com/journals/lanpub/article/PIIS2468-2667(18)30202-0/fulltext

access only to zero-emission vehicles or forms of mobility through a phased approach between 2019 and 2030.[188] London introduced its ultra-low emission zones in April 2019, covering the center-most part of the city, that requires vehicles entering the zone to meet Euro VI emission standards 24 hours a day/7 days a week or pay a penalty fee of 100 pounds per day. In October 2021, the ultra-low emission zone will be expanded to cover a larger portion of London outside of the city center. Preliminary results from the first six months of London's ultra-low emission zones have shown significant reductions of roadside NO_2 concentration by 29%-36%, road transport NOx emissions by 31% and road transport CO_2 emissions by 13%.[189]

7.1.7 Subnational leadership in target setting

At the subnational level, U.S. states have demonstrated leadership in ambitious target-setting to drive the adoption of zero emission vehicles, including for heavy-duty trucks. Following California's announcement of a target of 100% of medium and heavy-duty vehicle fleet transitioning to zero-emission vehicles by 2045 everywhere feasible, and for all drayage trucks to be zero emissions by 2035, 15 U.S. states signed a joint memorandum of understanding (MOU) pledging their own zero emission vehicle targets in late 2020. These 15 states committed to 100% zero emission vehicles for medium-duty and heavy-duty vehicle sales by 2050, with an interim goal of 30% zero emission vehicles by 2030. The MOU also establishes a joint task force that will help states develop and implement zero emission vehicle action plans including incentives, infrastructure, funding and financial models, outreach, uniform standards and data collection. This example demonstrates that in addition to national regulations and programs, more ambitious target-setting and collaboration at the subnational level can also help drive the zero-emission heavy-duty vehicle market.

7.1.8 Potential Benefits of Energy Efficiency Improvement and Air Quality Co-Benefits for ChineseHeavy-duty Trucks

Analysis Methodology

To understand the potential energy, CO_2 emissions and other air pollutant reductions from improved energy efficiency and adoption of New Energy Vehicle technologies for heavy-duty trucks, we used the bottom-up energy end-use model, China 2050 Demand, Resources Energy Analysis Model (DREAM), to conduct scenario analysis of the heavy-duty trucking sector out to 2030. As a national model that simulates energy demand, supply, and transformation sectors, the China 2050 DREAM model explicitly models intracity and inter-city heavy-duty trucks with macroeconomic drivers for freight transport activity. A stock turnover model is used to project the future sales and implied total stock of heavy-duty trucks, and tractor-trailers are used as a

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[188] Bannon, E. (2019, September 10). *Low emission zones are a success – but they must now move to zero-emission mobility*. Transport & Environment. https://www.transportenvironment.org/publications/low-emission-zones-are-success-%E2%80%93-they-must-now-move-zero-emission-mobility

[189] Charging, Low Emission Zones, other Access Regulation Schemes (CLARS). (2021). *Urban Access Regulations in Europe*. Charging, Low Emission Zones, other Access Regulation Schemes (CLARS). https://urbanaccessregulations.eu/low-emission-zones-main/impact-of-low-emission-zones

representative vehicle category for energy consumption analysis due to lack of data on other vehicle types.

Using the model, we developed three main sets of *energy strategies scenarios* to evaluate the potential impacts of energy efficiency improvement both in terms of vehicle technologies and operations and adoption of New Energy Vehicles (i.e., battery electric and hydrogen fuel cell) for heavy-duty trucks. These scenarios include:

1. **Reference Scenario**: A baseline scenario that assumes existing energy efficiency and some adoption of LNG trucks due to existing policies in place that will continue to have an incremental impact on heavy-duty trucks, with 0.6% - 0.7% of annual average efficiency improvements, but no electrification for heavy-duty trucks.
2. **Efficiency and Logistics Improvement Scenario**: Two sub-scenarios that assume the significant potential to capture additional vehicle and operational energy efficiency savings are realized, resulting in greater annual average efficiency improvements of 1.4-1.5%, and additional 15% reduction in heavy-duty turnover due to logistics improvements.
3. **Efficiency, Logistics plus NEV Adoption Scenario**: Two sub-scenarios that build on the Efficiency and Logistics Improvement Scenario, but with an additional assumption that the adoption of battery electric trucks will grow rapidly, reaching about 5% share of new sales and 2.5% of total stock in 2030. Because hydrogen fuel cell technologies are still in prototype development and face much higher and uncertain cost barriers, they are not considered for deployment before 2030 in this analysis.

While the three sets of energy strategies scenarios described above capture fleet-wide changes in energy efficiency and fuel-specific technology adoption and subsequent energy and CO_2 emission changes, they are not adequate in analyzing the air quality co-benefits of these energy strategies. Specifically, to address potential uncertainties in the future implementation and compliance of vehicle emission standards that could directly impact air quality co-benefits analysis, two *air quality pollution reduction sub-scenarios* were developed. These High and Low Air Pollution Reduction Potential sub-scenarios were developed for both the Efficiency and Logistics Improvement Scenario and the Efficiency, Logistics and NEV Adoption scenarios to represent two possible pathways of compliance with China's emission standards for heavy-dutytrucks.

Due to lack of data, we used a recent analysis of vehicle emissions of a representative middle-sized Chinese city[190] that includes simulation analysis of the implementation of different stages of emission standards for vehicles and its fleet turnover as a proxy for China's aggregate heavy-duty trucking fleet. We developed two sub-scenarios of stagnant and continuous implementation

[190] Sun S., Jin J., Xia M. et al. (2020, April). Vehicle emissions in a middle-sized city in China: Current status and future trends. *Environment International 137*: 105514. https://doi.org/10.1016/j.envint.2020.105514

of increasingly stringent emission standards across the heavy-duty trucking fleet to represent high and low ranges of air pollution reduction as co-benefits of energy efficiency improvement and NEV technology adoption. The energy and CO_2 implications of these two sub-scenarios are the same, as only the air pollutant emissions intensities differ between the sub-scenarios for a given energy strategy.

1. **High Air Pollution Reduction Potential sub-scenario**: Assumes that emission standard implementation remains stagnant at 2020 levels, resulting in counterfactual frozen stock-weighted average emission intensities for NOx and PM2.5 emissions per kilometers traveled. This translates into greater air pollutant emissions from the entire heavy-duty truck fleet, as more stringent China VI emission standards are assumed not to be in place to reduce air pollution from new vehicles, and thus greater reduction potential from efficiency improvement and NEV adoption. Although this scenario is not very realistic given China VI's planned implementation, it serves as an upper bound of air pollution reduction potential from energy strategies.
2. **Low Air Pollution Reduction Potential sub-scenario**: Assumes that emission standard implementation will continue with full enforcement, resulting in declining stock-weighted average emission intensities for NOx and PM2.5 emissions as more new vehicles meeting China VI are introduced to the fleet through 2030. For diesel vehicles, compared to China V emission standards, China VI reduces NOx emissions per kilometer by 77% and PM2.5 emissions by 67%. With the increasing adoption of China VI standards in new heavy-duty truck sales, the fleetwide air pollution levels are significantly reduced with much smaller remaining amount of total air pollutants that can be further reduced through efficiency improvement and NEV adoption.

Figure 27 compares the stock distribution by emission standard levels under these two scenarios of High and Low Air Pollution Reduction Potential, and Table 5 compares the calculated stock-weighted average emissions intensity under the two scenarios.

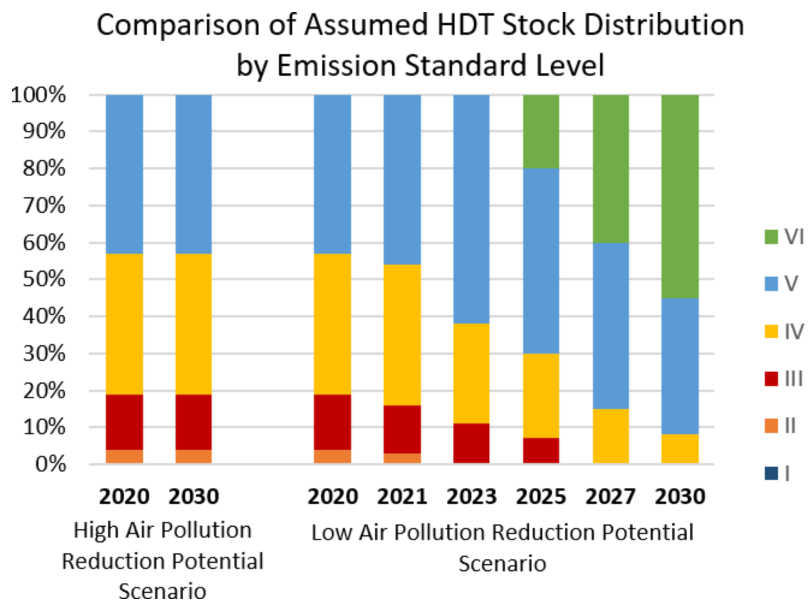


Figure 27. Comparison of Heavy-duty Trucking Fleet Distribution by Emission Standard Level by Scenario

g/km		Low Air Pollution Reduction Potential Scenario	High Air Pollution Reduction Potential Scenario		
		2020 – 2030	**2020**	**2025**	**2030**
Nox	**Diesel**	5.65	5.65	4.41	2.79
	LNG	6	6	4.76	3.95
PM2.5	**Diesel**	0.12	0.12	0.07	0.03
	LNG	0.04	0.04	0.04	0.04

Table 5. Comparison of Stock-weighted Average Emissions Intensity by Scenario

7.1.9 Potential Energy, CO_2 and Air Quality Co-benefits Results

Through the scenario analysis, the potential energy and CO_2 reductions and additional air quality co-benefits in terms of reduced NOx and PM2.5 pollution are quantified for the two energy strategies. Figure 28 compares the final energy consumption results by scenario for key years and shows that the energy reduction between Efficiency & Logistics Improvement and Efficiency Plus NEV Adoption scenarios compared to the Reference Scenario grows over time. In 2020, Efficiency and Logistics Improvement Scenario results in a 7% reduction in final energy demand of China's heavy-duty trucks, or a reduction of 16.8 million tonnes of oil equivalent (Mtoe). The reduction is primarily in heavy-duty trucks' diesel consumption, with 15.6 Mtoe less diesel consumed than under the Reference Scenario, and 1.2 Mtoe less LNG consumed. By 2030, the final energy demand reduction from efficiency and logistics improvement grows to 48 Mtoe annually, or the equivalent of 20% reduction from the Reference level, due to both greater efficiency gains and logistics improvement as well as a larger number of total vehicles. Total diesel demand is reduced by 60 Mtoe, but partially offset by an increase of 12 Mtoe in LNG for heavy-duty trucks in 2030.

NEV adoption contributes a very small incremental reduction in final energy demand due to its relatively small share of only 5% of new sales by 2030, with additional annual reductions of 2.3 Mtoe beyond what is achieved under the Efficiency and Logistics Improvement Scenario. Compared to the Reference Scenario, however, the total reduction in annual diesel demand as a result of efficiency, logistics improvement and NEV adoption totals 64 Mtoe, the equivalent of 28% of total diesel consumed by heavy-duty trucks and 20% of total diesel consumption for transport. Cumulatively from 2020 through 2030, diesel consumption is reduced by 446 Mtoe under the Efficiency Plus NEV Adoption Scenario when compared to the Reference Scenario, more than the equivalent of China's total annual diesel consumption.

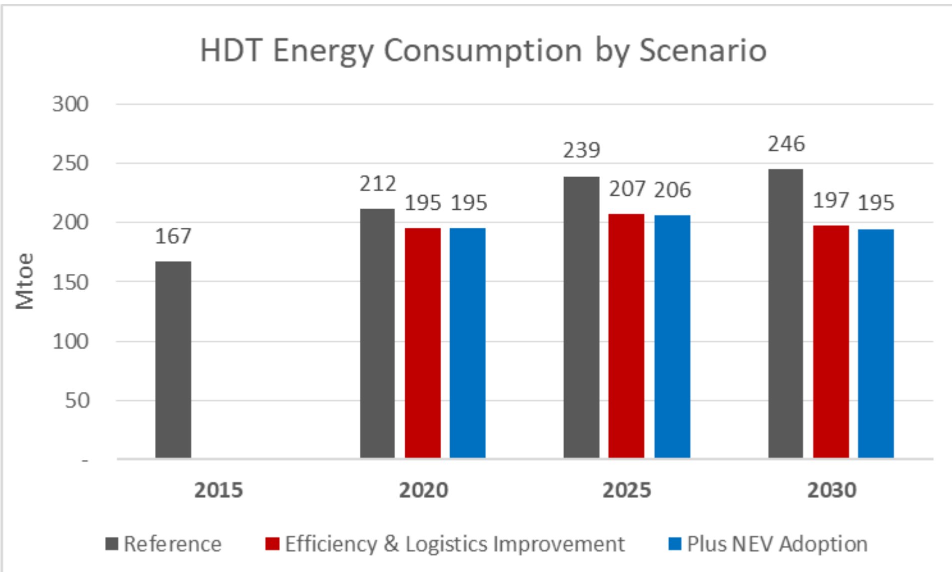


Figure 28. Comparison of Heavy-duty Truck Final Energy Demand by Scenario

Corresponding to reductions in final energy demand, energy efficiency and logistics improvement also contribute to reducing the total CO_2 emissions of heavy-duty trucks, with 8% (50.7 $MtCO_2$) annual reduction in 2030 rising to 22% (157 $MtCO_2$) reduction by 2030, when compared to the Reference scenario. The 2030 annual CO_2 emissions reduction from energy efficiency and logistics improvement equals nearly 10% of total transport CO_2 emissions today. If the indirect CO_2 emissions of electricity consumed by NEVs are not accounted for,[191] then the additional CO_2 emissions reduction impact of NEV adoption also becomes more apparent in later years as the number of NEV heavy-duty trucks increases. By 2030, NEV adoption contributes to an additional 2% CO_2 emissions reduction, or 14 $MtCO_2$ beyond the Efficiency & Logistics Improvement

[191] The CO_2 emissions results presented here only include the direct point emissions at the vehicles, and do not include indirect CO_2 emissions from the power sector that may be attributable to the electricity consumed by battery electric heavy-duty trucks. The total (direct + indirect) CO_2 emissions impact of electric trucks are closely linked to the power sector's average CO_2 emission intensity, which has been assessed elsewhere and not considered in this report due to uncertainty with future power generation fuel mix.

Scenario reductions. Cumulatively from 2020 to 2030, energy efficiency and logistics improvement to China's heavy-duty trucks reduces its CO_2 emissions by 1143 $MtCO_2$ compared to the Reference Scenario, while NEV adoption contributes to additional cumulative 75 $MtCO_2$ reduction during the same time period.

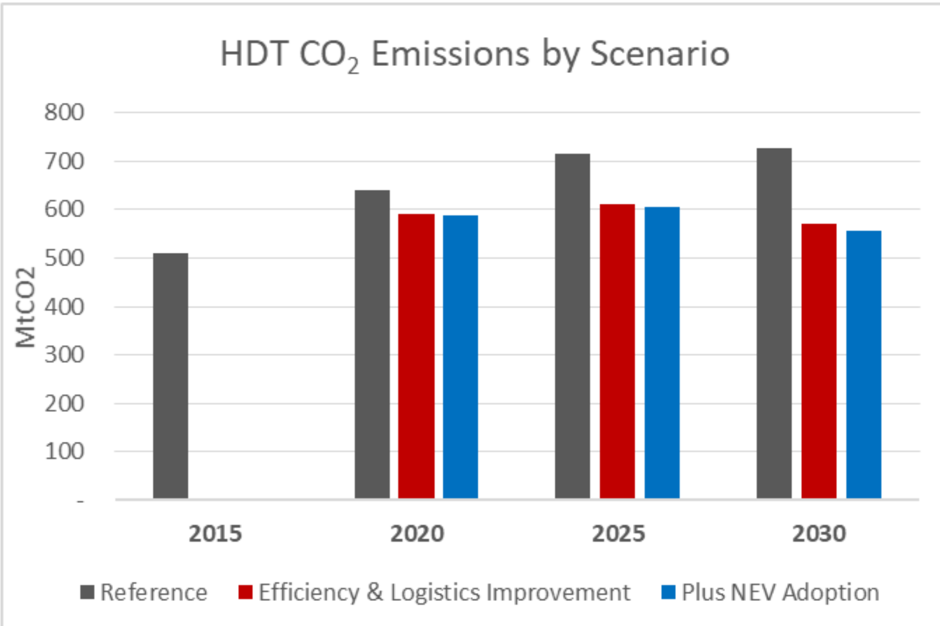


Figure 29. Comparison of Heavy-duty Truck CO2 Emissions by Scenario

Beyond the energy and CO_2 emissions reduction impacts, energy efficiency, logistics improvement and NEV adoption can concurrently reduce air pollutants such as NOx and PM that are emitted during diesel and natural gas combustion. The reduction potential is particularly significant for older heavy-duty trucks that do not meet the recent and more stringent emission standards, as these tend to also be less efficient, consume more diesel on a per unit basis, and do not have tailpipe emission control technologies in place. Using the two sub-scenarios to represent the high and low ranges of reduction potential from efficiency and logistics improvement and from NEV adoption, the projected NOx and PM2.5 reductions are shown in Figure 30 and Figure 31.

For NOx emissions, energy efficiency and logistics improvement in heavy-duty trucking alone can reduce annual NOx emissions by 131 kilotons (kt) to 167 kt in 2025, and by 122 kt to 238 kt in 2030. Compared to the estimated 2300 kt of annual NOx emissions reduction from fully implementing China VI emission standards in 2030, this suggests that energy efficiency and logistics improvement can contribute an additional 10% reduction in NOx emissions. Adopting NEVs on top of efficiency and logistics improvements can result in slightly greater NOx emission reductions of up to 327 kt annually in 2030, the equivalent of all NOx emissions from Beijing or 1% of all vehicle NOx emissions in China in 2015. Although not quantified here, the reduction of concentrations of NOx had additional health co-benefits in reducing human exposure that can aggravate respiratory illnesses and contribute to the development of asthma and increased susceptibility to respiratory infections.

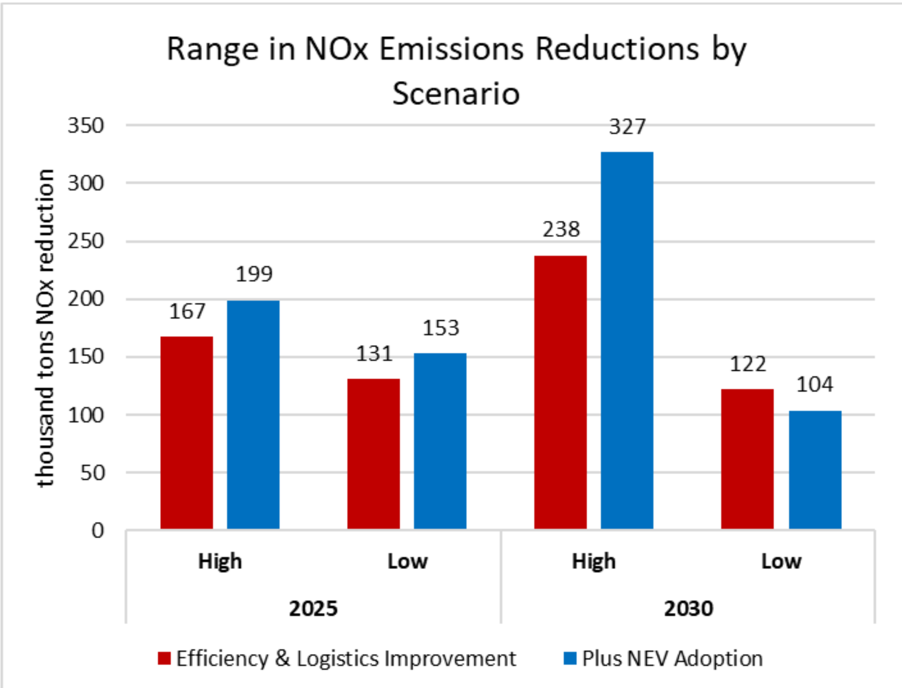


Figure 30. Range of Potential Heavy-duty Trucking NOx Emissions Reductions by Scenario

For PM2.5 emissions, heavy-duty trucking energy efficiency and logistics improvement can also result in nearly 10% greater annual emissions reductions when compared to emission standards implementation alone in both 2025 and 2030. The total annual PM2.5 reduction potential from heavy-duty trucks alone (ranging from 1.9 to 3.4 kt PM2.5 in 2025, to 1.2 to 4.7 kt PM2.5 in 2030) is also comparable in scale to Beijing-Tianjin-Hebei area's total PM2.5 emissions in 2015. NEV adoption can provide additional PM2.5 reductions, with more than doubled the reduction potential of efficiency and logistics improvement on the higher end by 2030. The 2030 annual reduction of 12.1 kt PM2.5 with NEV adoption is 17% greater compared to emission standards alone, highlighting that NEV adoption in addition to efficiency and logistics improvement can result in significant reductions of a key air pollutant. Reducing the PM2.5 pollution of heavy-duty trucks can help reduce PM2.5 concentrations, which helps reduce the associated health impacts of increased hospital admissions for heart or lung causes, and respiratory illnesses such as bronchitis and asthma attacks.

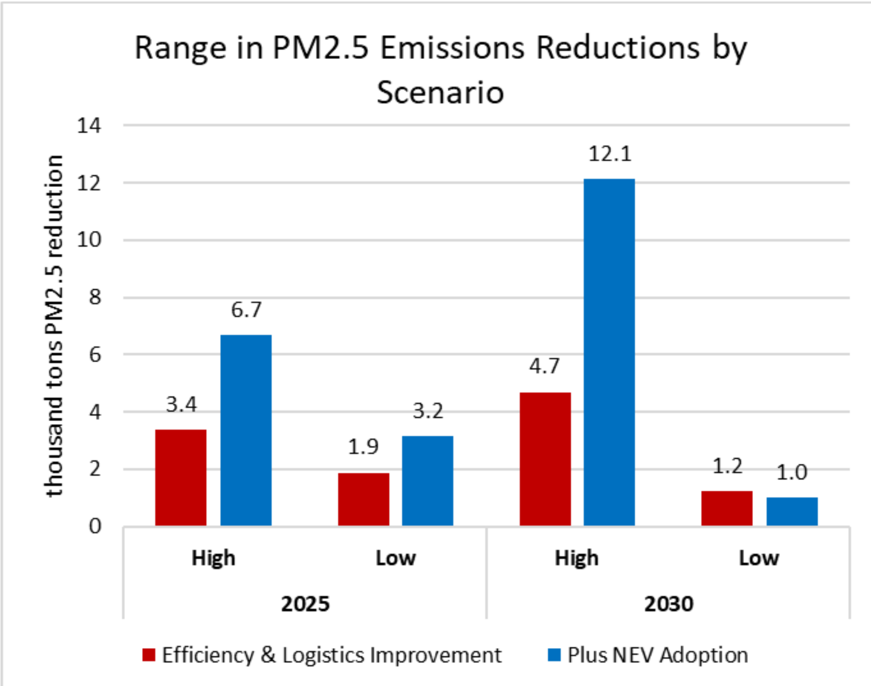


Figure 31. Range of Potential Heavy-duty Trucking PM2.5 Emissions Reductions by Scenario

7.2 Cement Industry

7.2.1 Overview of the cement industry in China

7.2.1.1 Market landscape

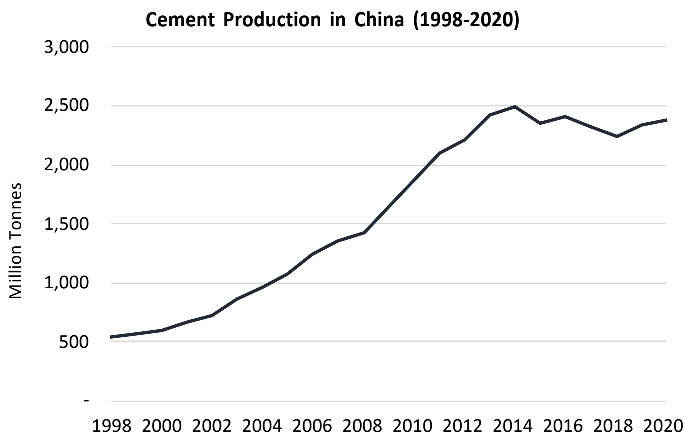
China has been the world's largest cement producer since 1986.[192] In 2020, due to COVID-19 impacts, cement production in the first quarter of 2020 dropped significantly, 25% lower than cement production in the first quarter of 2019 (Figure 32). However, cement production in China started to rebound since April 2020.[193] Annual cement production in 2020 reached to a record high of 2,380 million tonnes, exceeding 2019 production by 1.5% (Figure 33). The COVID-19 impacts on cement industry's energy consumption and CO_2 and air pollutant emissions are limited.

In comparison, just in the last two years, 2019 and 2020, China consumed more than 4,700 million tonnes of cement, which is equivalent of what the United States had consumed in the entire 20th

[192] Lu, H., Price, L., Zhang, Q. (2015). Capturing the Invisible Resource: Analysis of Waste Heat Potential in Chinese Industry. *Applied Energy 161*. http://doi:10.1016/j.apenergy.2015.10.060

[193] National Bureau of Statistics (2021). China Statistical Yearbook 2020. Beijing: China Statistics Press. National Bureau of Statistics. http://www.stats.gov.cn/tjsj/ndsj/2020/indexeh.htm

century (from 1900 to 2000). Globally, China's cement production accounted for about 56% of the world's total cement production.[194]



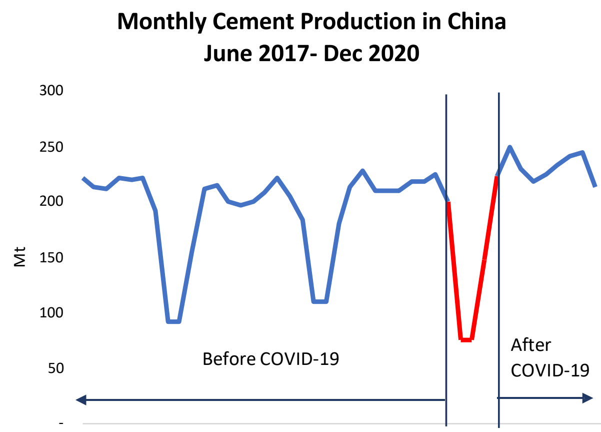


Figure 32: Cement Production in China 1998-2020
Source: National Bureau of Statistics of China, various years.

Figure 33: Monthly Cement Production in China

Domestically, the Chinese cement industry is comprised of a large number of enterprises. Since 2010, the Chinese government has been encouraging sectoral consolidation in the Five-Year Plans, leveraging policies such as "phasing-out outdated capacities" and differential electricity pricing. As a result, the number of Chinese cement enterprises has decreased from 7,000 in 1997 to 5,130 in 2006, to 3,507 in 2012, and further decreased to 2,800 enterprises by 2019.[195]

By the end of 2020, China had a total of 1,846 million tonnes of clinker production capacity. The Top 50 cement companies in China accounted for 76% of China's total clinker productioncapacity. The Top 10 cement companies represented for 57% of China's total clinker productioncapacity, led by companies such as China National Building Materials (CNBM), Anhui Conch, Jidong Cement, China Resources Cement, and Huaxin Cement.

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[194] United States Geological Survey. 2020. *Mineral Commodity Summary: Cement*. United States Geological Survey. https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-cement.pdf

[195] Sina Financial News. (2020, July 29). *Beginning of cement industry consolidation; can the traditional industry revive itself?* Sina Financial News. https://finance.sina.com.cn/chanjing/cyxw/2020-07-29/doc-iivhvpwx7987772.shtml; China Cement Association. (2014, March). *China Cement Almanac 2012-2013.* China Building Materials Industry Press. Beijing, China; China Cement Association. (2008, March). *China Cement Almanac 2007*. China Building Materials Industry Press. Beijing, China.

Top 10 Largest Chinese Cement Companies by Clinker Production Capacity in 2020 (Mt)

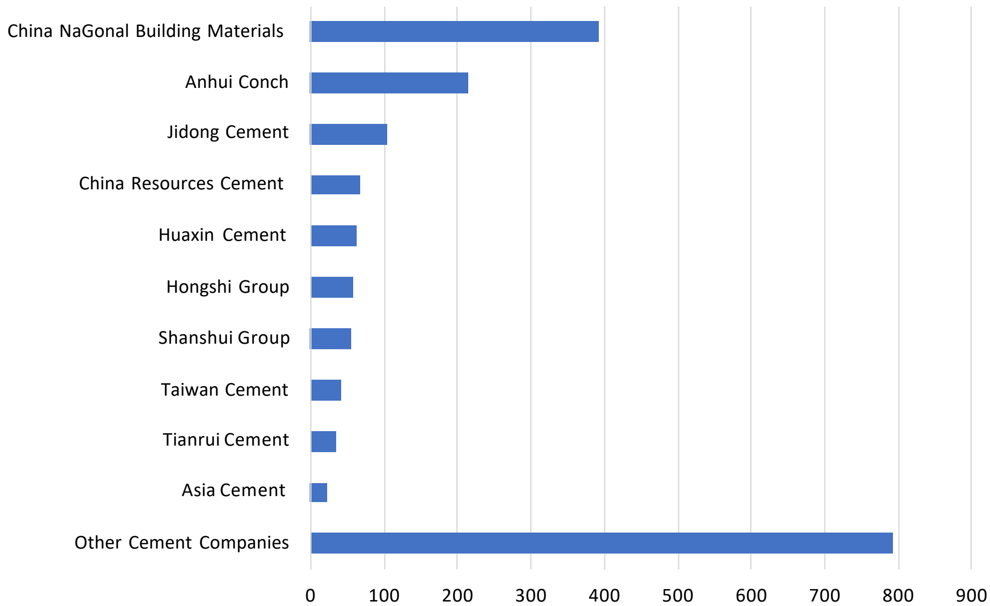

Figure 34. Top 10 largest cement companies by clinker production capacity in 2020
Source: Digital Cement, 2021.

7.2.1.2 Technology transition

In the last 20 years or so, China's cement industry has transformed technologically, mainly through building new facilities and installing new equipment. The technology shift has been from shaft kilns to dry kilns, and then to new suspension preheater-precalciner rotary kilns (NSP). As of today, clinker-production[196] in China is dominated by NSP kilns. The share of suspension rotatory kilns has increased from 40% in 2005 to 95% in 2015, with the expectation of continuing to increase to almost 100% by 2020,[197] as shown in Figure 35.

[196] Clinker, the key ingredient of cement, is the most energy-intensive and carbon-intensive to make, normally accounting 90% of total cement industry energy use (Worrell and Galitsky, 2008).
[197] China Cement Association (CCA). (2017). *13th Five-Year Plan for Cement Industry.* China Cement Association. http://www.ccement.com/news/content/9012415094564.html#top; China Cement Association. (2014, March). *China Cement Almanac 2012-2013.* China Building Materials Industry Press. Beijing, China; Ministry of Industry and Information Technology of China. (2011, November 8). *Cement Industry Development Plan during the Twelfth Five-Year (2011-2015).* Ministry of Industry and Information Technology of China. http://www.gov.cn/zwgk/2011-11/29/content_2005593.htm; Sui, T. Personal communication. 2021.

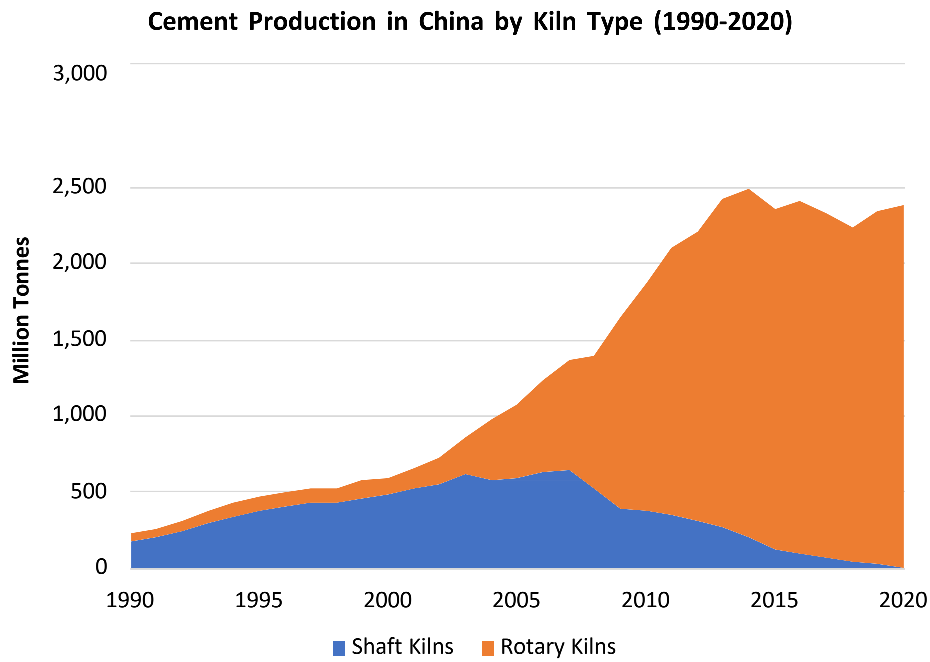

Figure 35. Cement production in China by kiln type
Sources: CCA, 2017; CCA, 2014; MIIT, 2011b; Sui, 2021

Many cement facilities have also installed precalciners and/or preheaters to utilize waste heat from the limestone calcination to pre-combust and/or preheat fuel and raw materials. Specifically, waste heat to power generation technologies been promoted in China's cement industry. Initiated with tax incentives and Clean Development Mechanism revenues, later supported with a national mandate on new clinker capacities, the penetration rate of waste heat recovery (WHR) technologies in the Chinese cement industry has reached over 80%.[198] In comparison, the U.S. cement industry has a much smaller adoption rate of WHR.[199] As of 2008, only four plants in the U.S. had installed waste heat to power generation technologies.[200]

In addition, key energy-saving technologies, such as multi-channel coal burners, high-efficiency coolers, optimization for energy-saving grinding, vertical mills for finish grinding, and energy-saving monitoring and optimization systems for NSP kilns played significant roles in improving energy efficiency in China's cement industries.

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[198] Ministry of Industry and Information Technology. (2020, July 14). *MIIT: China's green manufacturing is gradually being developed; industry and information technology industry saved 400 billion yuan in energy costs over four years.* http://sme.miit.gov.cn/cms/news/100000/0000000224/2020/7/14/3d8b92fcbb9447c393e46f2a48bd08a3.shtml

[199] Institute for Industrial Productivity and International Finance Corporation. (2014, June). *Waste Heat Recovery for the Cement Sector: Market and Supplier Analysis*. Institute for Industrial Productivity and International Finance Corporation. https://www.ourenergypolicy.org/wp-content/uploads/2014/06/cement.pdf

[200] Ilona, J., Choate, W.T., Davidson, A. (2008). *Waste Heat Recovery: Technology and Opportunities in U.S. Industry*. BCS Incorporated. https://doi.org/10.2172/1218716

7.2.1.3 Policy guidance

The Chinese government has implemented a number of policy measures to guide the development of the cement industry, ranging from supply side reforms, energy efficiency improvements, environmental regulations, to technology promotion and financial incentives.

The section below highlights the latest cement production curtailment policy (in supply side reforms) and the latest minimum energy performance standards and the provincial rolling out of ultra-low air pollution emissions standards (in energy-saving and environmental protection).

Supply side reform

The purpose of the supply side reform is to limit the growth of excess production capacity, mostly clinker production capacity in the cement industry, and guide the industry to grow stronger in producing higher quality and higher value-added products. The Chinese government has issued several policy measures to guide the development of the cement industry, such as phasing out outdated capacity, capacity swaps for building new plants, and cement industry access regulation.

Most recently, the Ministry of Industry and Information Technology and the Ministry of Ecology and Environment jointly announced on December 28, 2020 that cement production curtailment plans will continue and be normalized.[201] The cement production curtailment policy was implemented by the State Council at a large scale in 2016, and requires clinker production to be stopped in heating regions during the heating season in order to control air pollution in key regions. For non-heating regions, the policy requires that clinker production should also avoid Chinese Spring Festival season and hot summer days.

Under the 2020 new guidelines, the curtailment regions and timeline are normalized. Specifically, Liaoning, Jilin, Heilongjiang, and Xinjiang provinces are to implement curtailment production from November 1 to March 31 (i.e., five months, 150 days); Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Shandong, and Henan Provinces are to implement curtailment production from November 15 to March 15 (i.e., four months, 120 days); Shaanxi, Gansu, Qinghai, and Ningxia are to implement the policy from December 1 to March 10 (i.e., about three months, 90 days); while other provinces are to implement the policy during Chinese Spring Festival season, hot summer days, rainy seasons, and key events. The policy requires all clinker production kilns to be included. Production lines that dispose of municipal solid wastes and hazardous wastes during the full year are not subjected to this policy, but the policy indicates these production lines also need to reduce cement production load.[202]

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[201] Ministry of Industry and Information Technology (MIIT) and the Ministry of Ecology and Environment (MEE). (2020, December 28). *Two ministries issuing notice on continue to normalize cement production curtailment.* Ministry of Industry and Information Technology and the Ministry of Ecology and Environment. https://www.miit.gov.cn/zwgk/zcwj/wjfb/yclgy/art/2020/art_6bff7f6bd055439ebd806b7fb230bc37.html

[202] Ibid.

The key purpose of this policy is to avoid the air pollution of clinker production coinciding with air pollution from district heating, and also to reduce clinker production capacity. Enforcement and monitoring of the curtailment policy often relies on cement companies themselves, and lack of a proper reward and penalty system. It is reported that some cement companies did not implement the policy in order to increase their production.[203] The issue of overcapacity in China is still present, especially in northern regions. The latest data shows that China produced 2,377 million tonnes of cement in 2020, increased 1.6% from 2019.[204]

7.2.1.4 Energy saving and environmental protection

On the energy-savings and environmental protection front, the Chinese government has established targets to reduce energy and carbon dioxide emissions intensity, as well as reduce the absolute amount of air pollutant emissions. In the 13th Five-Year Plan (FYP), the national goals were to reduce 15% of energy use per unit of GDP, 18% CO_2 emissions per unit of GDP, and reduce the emissions of SO_2 and NOx by 15% and 15%, respectively, compared to 2015 levels.[205] In the 14th FYP, the energy intensity reduction target was reduced to 13.5%, while the carbon intensity reduction target was kept the same. While the 14th FYP has not specifically set targets for SO_2, NOx and PM reductions, it called for "continuing to improve environmental quality," "enhancing coordinated control of multiple air pollutants and carbon emissions reduction," "refining the management of environmental protection, energy conservation and emissions reduction," as well as to "actively participate in and lead international cooperation on ecological and environmental protection, including addressing climate change."[206] Based on the 13th and 14th FYPs, it is clear that the Chinese government are simultaneously pursuing three goals: improving energy efficiency (energy conservation), improving air quality, and reducing greenhouse gas emissions. As illustrated in Figure 36, the intersection of all three goals highlights the air quality co-benefits as well as the CO_2 emission reductions through adopting and scaling up energy efficiency measures in key industries, such as the cement industry.

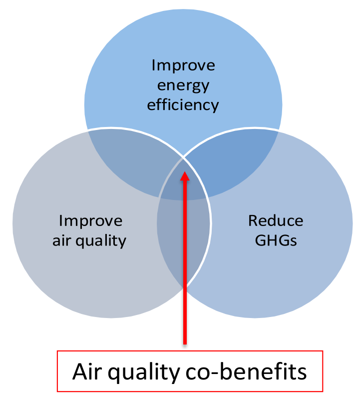

Figure 36. China's Energy and Environmental Goals

At the cement industry level, the government set the goal of reducing clinker energy intensity by 7% from 2015 levels to 105 kilograms of coal equivalent (kgce)/tonne by 2020.[207] Other policies, such as promoting the use of waste heat recovery, implementing differential electricity pricing,

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203 Xinhua. (2021, January 29 (a)). *Cement quality and price are stable, need to continue to implement cement production curtailment*. Xinhua. http://www.xinhuanet.com/energy/2021-01/29/c_1127039953.htm

204 National Bureau of Statistics (2021). China Statistical Yearbook 2020. Beijing: China Statistics Press. National Bureau of Statistics. http://www.stats.gov.cn/tjsj/ndsj/2020/indexeh.htm

205 State Council. (2016, January 5). *13th Five-Year Energy Conservation and Emission Reductions Comprehensive Working Plan*. State Council. http://www.gov.cn/zhengce/content/2017-01/05/content_5156789.htm

206 Xinhua. (2021 March 5 (b)). *14th Five-Year Plan and development context, guiding policy, and main targets of 2035 Long-term goals*. Xinhua. http://www.xinhuanet.com/politics/2021-03/05/c_1127172897.htm

207 Ibid.

and increasing the co-processing of municipal solid wastes in cement kilns were also encouraged and promoted.[208]

The current minimum energy performance standard for the cement industry is *The Norm of Energy Consumption per Unit of Product of Cement (GB16780-2012*), which was revised upon the 2007 version of the standard and has been implemented since 2012. The 2012 standard is currently being revised and seeking public comments. The upcoming new standard revised the levels of energy efficiency, and the Level 1 (used to be called "advanced level") energy efficiency for clinker production is now reduced to 103 kgce/t (as proposed), instead of 110 kgce/t in the 2012 version of the standard.

In addition, ultra-low air pollution emission standards for the cement industry are also rolling out in provinces. For example, starting in March 2020 Hebei province set maximum concentrations of $PM_{2.5}$, SO_2, and NOx emissions from cement kilns to be 10, 35, and 100 mg/m3.[209] Hebei province also set ultra-low emissions standards for flat glass industry and boilers. In April 2021, the China Cement Association launched the standard development meeting for a group standard on ultra-low emissions standards for the cement industry.[210] A summary of the key policy measures that are relevant to China's cement industry are presented in Table 6.

Policies	Supply Side Reform	Energy Saving	Environmental Protection	Technology Promotion	Financial Incentives
National	Phasing out backward Capacity	National energy intensity reduction targets	National emission reduction targets	Energy conservation and low carbon technology promotion catalogues	Energy-saving and emission reduction retrofits rewards
	Production curtailment policy				Tax incentives from CDM
Cement Industry	Cement industry access regulation	Sectoral energy intensity targets	Clean production of cement	Clean production technologies promotion plan for cement	Differential pricing
		Minimum energy performance standards			

Table 6. Key policy measures for China's cement industry
Source: Tan et al., 2016.

[208] Xinhua. (2021 March 5 (b)). *14th Five-Year Plan and development context, guiding policy, and main targets of 2035 Long-term goals*. Xinhua. http://www.xinhuanet.com/politics/2021-03/05/c_1127172897.htm
[209] Tangshan Bureau of Ecology and Environment. (2020, March 13). *Explanation of three standards, including cement industry ultra-low emissions standards*. Tangshan Bureau of Ecology and Environment. https://sthjj.tangshan.gov.cn/cms/jsp/site001/article.jsp?fchannelidenty=zhengcexiedu&articleId=8a8d825b710600b501710a589f4000be&a1b2dd=7xaac
[210] Digital Cement, 2021.

7.2.1.5 Energy use and emissions impact

China's cement industry consumed about 188 million tonnes of coal equivalent (Mtce) in 2017, accounting for 9% of China's manufacturing energy use, or 4% of China's total energy use.[211] China's current cement manufacturing is predominately coal-based. From 2008 to 2020, coal represented more than 90% of the total fuel input,[212] or 80% of total energy input in the cement industry (Figure 37). Municipal solid waste and biomass (e.g., agricultural residues, biomass crops, etc.) accounted for about 10% of total fuel input.[213]

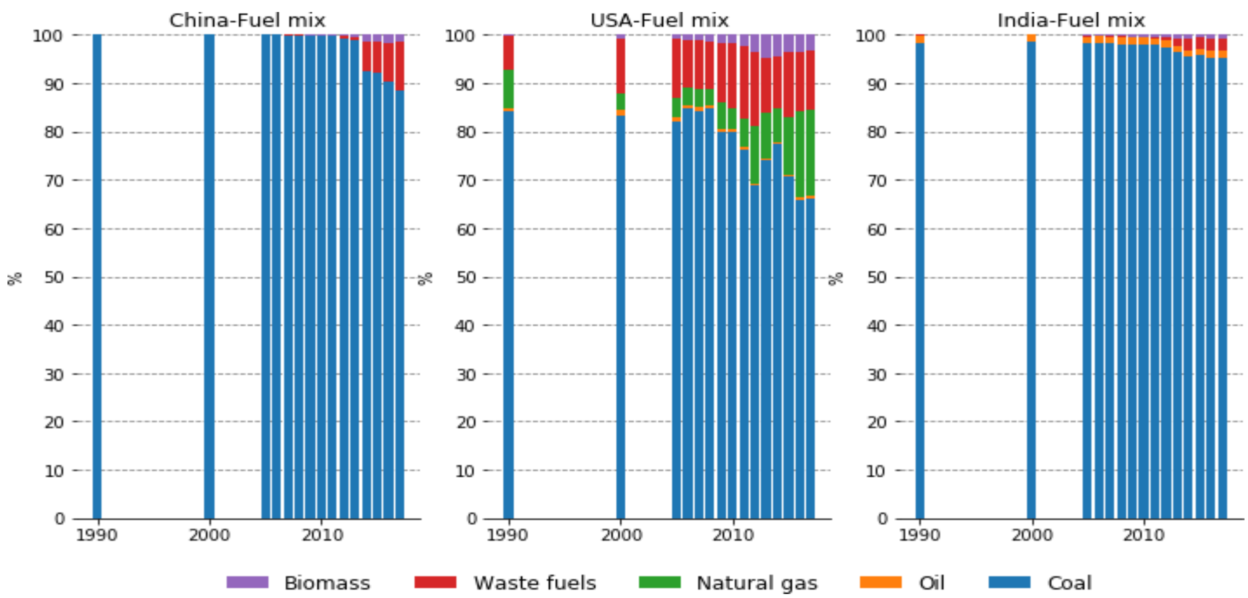

Figure 37. Fuel mix of cement industry in China, United States, and India
Source: Masanet and Cao, 2021.

Carbon dioxide emissions are from two sources: 1) from the use of fossil fuels, mostly burning of coal in the cement industry to generate significant amounts of energy to heat the raw materials to 1450°C; and 2) from limestone calcination, where CO_2 emissions emitted as carbonates (largely $CaCO_3$ found in limestone) are decomposed into oxides (largely lime, CaO) and CO_2.[214]

Even though the Chinese government has implemented a number of key policies measures (as shown in Table 7), carbon dioxide (CO_2) emissions and air pollutant emissions from the Chinese cement industry are still very high. Energy-related (fuel-based) CO_2 emissions from the cement

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[211] National Bureau of Statistics. (2019). *China Energy Statistical Yearbook 2018*. China Statistics Press. Beijing, China.

[212] Masanet, E. and Cao, Z. (2020). *Decarbonizing Concrete: Deep decarbonization pathways for the cement and concrete cycle in the United States, India, and China*. Northwestern University Technical Report. https://www.climateworks.org/wp-content/uploads/2021/03/Decarbonizing_Concrete.pdf

[213] Cement Sustainability Initiative. (2018). *GNR Project.* Cement Sustainability Initiative. https://gccassociation.org/gnr/

[214] Andrew, R.M. (2019). Global CO_2 emissions from cement production, 1928–2018. *Earth System Science Data, 11*, 1675–1710. https://doi.org/10.5194/essd-11-1675-2019

industry accounted for 8% of China's CO_2 emissions in the manufacturing sector, or 6% of the national energy-related CO_2 emissions in China. If including process-related CO_2 emissions, total CO_2 emissions of the cement industry represented 16% of China's total manufacturing CO_2 emissions or 12% of the national CO_2 emissions from fossil fuels and process-related emissions (Table 8).

The cement industry also produces significant amounts of sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matters (PM). SO_2 emissions come from oxidation of sulfur content in coal. It is worth noting that 70-80% of SO_2 emissions are absorbed by reaction with calcium oxide (CaO) in precalciners; but much less in other rotary kilns or shaft kilns (30%).[215]

NOx emissions are from two potential sources. One source is from the oxidation of molecular nitrogen in combustion air, or the thermal NOx formation. The other source is from the oxidation of nitrogen compounds in fuel, or fuel NOx formation. NOx emissions from cement kilns are highly dependent on combustion temperature and oxygen availability. PM emissions from the cement industry are from multiple sources, including raw material quarrying and crushing, raw material storage, grinding and blending (dry process only), clinker production, finish grinding, packaging, and loading. Clinker production (calcination and cooling) is the largest source of PM.[216]

Specifically, China's cement industry represented about 9%, 16%, and 40% of the manufacturing sector's total SO_2, NOx, and PM emissions, respectively. At the national level, it contributed to 3-4%, 8-12%, and 17-27% of the national SO_2, NOx, and PM emissions, respectively (Table 7). The cement industry is the largest source of PM emissions in China.[217]

In addition, the cement industry also emits small amount of volatile organic compounds (VOCs), ammonia (NH_3), chlorine, hydrogen chloride, heavy metals (as particulates or vapor), residual materials from fuel and raw materials, as well as other hazardous pollutants that are released as products of incomplete combustion.[218]

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[215] Liu, H.Q. (2006). Control of SO_2 from cement kiln systems. *China Cement 11*, 74-77. (in Chinese).

[216] Hasanbeigi, A., Lobscheid, A., Dai, Y., Lu, H., Price, L., (2012). *Quantifying the Co-benefits of Energy-Efficiency Programs: A Case Study of the Cement Industry in Shandong Province, China* (LBNL-5949E). Lawrence Berkeley National Laboratory. https://eta-publications.lbl.gov/sites/default/files/shandong_co-benefit_full_report_english.rev_.pdf

[217] Lei, Y., Zhang, Q., Nielsen, C., and He, K. (2011). An inventory of primary air pollutants and CO2 emissions from cement production in China, 1990–2020. *Atmospheric Environment 45*, 147-154. https://doi.org/10.1016/j.atmosenv.2010.09.034

[218] Hasanbeigi, A., Lobscheid, A., Dai, Y., Lu, H., Price, L., (2012). *Quantifying the Co-benefits of Energy-Efficiency Programs: A Case Study of the Cement Industry in Shandong Province, China* (LBNL-5949E). Lawrence Berkeley National Laboratory. https://eta-publications.lbl.gov/sites/default/files/shandong_co-benefit_full_report_english.rev_.pdf

Indicator	Energy Use	Indicator	CO_2	Indicator	SO_2	NOx	PM
Share of manufacturing energy use	9%	Share of industrial energy-related CO_2 emissions	8%	Share of industrial air pollutant emissions	9%	16%	40%
		Share of industrial energy and process-related CO_2 emissions	16%				
Share of national energy use	4%	Share of national energy-related CO_2 emissions	6%	Share of national air pollutant emissions	3-4%	8-12%	17-27%
		Share of national energy and process-related CO_2 emissions	12%				

Table 7. Energy and emissions impact of China's cement industry
Sources: NBS, 2021; NBS, 2017; Liu et al., 2017; Tan et al., 2016; Lei et al., 2011; Zhang et al., 2007; NDRC, 2004; and author estimates.

7.2.2 International best practice programs in cement industry

7.2.2.1 Cap-and-trade programs

Cap-and-Trade Program

Cap-and-trade emission trading programs focus on reducing GHG emissions in society, including the cement industry, through a cap and trade system. This type of program is often mandatory to join.

In California, the cap-and-trade program covers 80% of the state's greenhouse gas emissions. Industrial facilities track, report, and reduce GHG emissions. The program allocates allowances to cement facilities with a declining cap adjustment factor each year.

In the EU, the Emissions Trading System (ETS) covers 40% of the EU's GHGs. Industry, such as cement manufacturing receives free allocations due to the concerns over carbon leakage risks. However, this allocation of free allowances reduces cement plant incentives to actively seeking actions to reduce its GHG emissions.

7.2.2.2 Green procurement

Green procurement programs are when government agencies have mandates to procure products that are environmentally sustainable. There are already several existing government programs, such as Buy Clean California, U.S. Environmental Protection Agency (EPA) Environmentally Preferable Purchasing Program, Smart Procurement in the Netherlands, and Green Public Procurement in the EU.

BUY CLEAN

These programs set requirements on government agencies to procure sustainable products, which often carry third-party certifications for higher efficiency or reduced environmental impacts.

For example, the Buy Clean California program currently covers steel, flat glass, and mineral wool (insulation). Producers must submit Environmental Product Declarations (EPDs) and eligible materials to meet required Global Warming Potential (GWP) thresholds. The U.S. EPA Environmentally Preferable Purchasing Program provides a buying green guide, and recommended Cradle to Cradle Certified standards. The Smart Procurement in Netherlands monetizes CO_2 reduction and other environmental impacts based on Life-cycle Assessment; comparing bids to environmental costs. The program now covers 45 products.

7.2.2.3 Labeling and certification

Labeling and certification programs motivate and recognize the best performing plants in the industry, including cement plants.

For example, the U.S. EPA EnergyStar program focuses on cement plants' energy performance (measured by specific energy intensity, using an EnergyStar Energy Performance Indicator). The top 25th percentile of the cement plants receive certification recognition. The Energy Star has a Cement Focus Group and the EnergyStar Certification program. The U.S. EPA EnergyStar Program is completely voluntary.

7.2.2.4 Environmental Product Declaration

The Environmental Product Declaration (EPD) documents the product's lifecycle environmental impact to allow verifiable and transparent comparison. Currently mostly voluntary, unless mandated by certain programs.

In California, the Assembly Bill 966 requires every operating cement plant in CA to submit a facility-specific EPD by January 1, 2022. Portland Cement Association is currently updating industry-wide EPDs for four cement products and one low-carbon cement product. The Global Cement and Concrete Association developed a verified EPD tool for cement/concrete producers to provide EPDs.

7.2.3 Key zero-emission measures for the cement industry

In September 2020, President Xi announced China's goal to reach carbon peaking by 2030 and achieve carbon neutrality before 2060.[219] China Building Materials Federation announced an initiative on January 16, 2021 to pledge that the building materials industry needs to achieve

[219] Xinhua. (2020, September 20). *Speech of President Xi at the General Debate of the 75th Session of The United Nations General Assembly*. Xinhua. http://www.xinhuanet.com/politics/leaders/2020-09/22/c_1126527652.htm

carbon peaking before 2025, and the cement industry needs to achieve peaking earlier, before 2023.[220]

China's cement industry is facing significant pressure to meet all kinds of energy and environmental targets, such as the above-mentioned energy intensity reduction targets, phasing out outdated capacity, production curtailment, improving utilization rates, co-processing of wastes, reducing key air pollutant emissions, reaching carbon peaking by 2023, and achieving carbon neutrality before 2060.

A number of low or zero-emissions technologies and measures are identified in Table 8 to support the cement industry to reach carbon neutrality. These measures are grouped into key strategies, ranging from material efficiency, energy efficiency, electrification, fuel switching, and carbon capture, utilization and storage (CCUS). Sections below highlights several important examples under each of the key strategies, providing more details on the measure, saving potential, and potential implementation barriers.

Material efficiency/ Demand Reduction	Energy Efficiency	Electrification	Fuel Switching and CCUS
ï Clinker substitution with fly ash, blast furnace slags, natural pozzolans, calcined clays ï Material efficiency: higher quality, high performance, and longer life materials/ products ï Design optimization	ï Component (e.g., raw material grinding, kiln, finishing grinding) and system energy efficiency	ï Expand electricity end-use applications (e.g., electrify industrial heat processes)	ï Biomass/biofuel for feedstocks and low/high temp heat
ï Recycle and reuse demolition fine as clinker raw material ï Recycle and reuse concrete as clinker substitutes	ï Smart energy management	ï On-site or grid power generation using solar PV and wind turbines	ï Solar thermal Geothermal
ï Green cements based on new material/ chemistry ï Green cements based on concrete carbonation ï Material substitution: mass timber	ï Waste heat recovery and use	ï High-temperature electric heating (e.g., plasma heating; concentrated solar heating)	ï Carbon capture, use, and storage (CCUS): post-combustion, oxy-combustion, calcium-looping
ï Lightweight materials and construction ï Prefab construction ï 3D printing	ï Integrative design/ system optimization	ï Electrochemical calcination process	ï Hydrogen as fuel

Table 8. Low and zero-emissions measures for cement industry

220 China Building Materials Federation (CBMF). (2017, June 7). *Cement industry 13th Five-Year Development Plan*. China Building Materials Federation. http://www.cbmf.org/cbmf/yw/6675038/index.html

Note: Green: commercialized technologies. Orange: commercialized technologies with limited adoption. Red: emerging technologies.

7.2.4 Materials efficiency

A number of material efficiency measures and strategies exist to improve material efficiency in the cement and concrete industry and potentially reduce demand for cement. Here two examples are highlighted: extending building lifetimes and improving cement/concrete quality.

For example, product lifetimes can be extended and buildings can be constructed to be more resilient through improved material performance, integrated structural design with risk-based durability modeling, and optimized construction methods. Examples include the use of multiscale fiber reinforcement, steel with improved corrosion resistance, advanced chemical admixtures to improve the rheology of fresh concrete, creation of self-healing concrete (concrete containing limestone-producing bacteria of polymer microcapsules capable of healing microcracks) and development of ultra-lightweight cement composites with low thermal conductivity for energy-efficient buildings.[221] Studies estimated that a 50% increase of lifetime from the baseline (e.g., increase building lifetime from 30 years to 60 years) would result in a 14% decrease in cement demand.[222] The challenges of adopting this measure include requiring faster adoption of new technologies, improved design, cultural transition, and better planning.[223]

In another example, new technologies could be utilized to improve cement/concrete quality. This measure involves optimizing calcium silicate hydrate to achieve enhanced performance and more durable concrete. Advanced techniques, high-resolution synchrotron X-rayspectromicropscopy, high-pressure X-ray diffraction and total scattering methods are being employed to study calcium silicate hydrate. Coupled with advanced atomistic modeling, the results can provide the blueprint of how to optimize concrete from the ground up.[224] Studies alsofound that cementitious content could be reduced by 30% without significant loss of strength.[225] An estimated 15% cement demand could be reduced.[226] In practice, in order to implement and scale up this measure, it is important to change builders' and contractors' practices, requirements of code prescriptions, and perceived risks about safety, durability, and other performance requirements.

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221 Monteiro, P.J.M., Miller, S.A., and Horvath, A. (2017). Towards Sustainable Concrete. *Nature Materials 16* (7): 698–99. https://doi.org/10.1038/nmat4930.

222 Masanet, E. and Cao, Z. (2020). *Decarbonizing Concrete: Deep decarbonization pathways for the cement and concrete cycle in the United States, India, and China*. Northwestern University Technical Report. https://www.climateworks.org/wp-content/uploads/2021/03/Decarbonizing_Concrete.pdf

223 *Id.*

224 Monteiro, P.J.M., Miller, S.A., and Horvath, A. (2017). Towards Sustainable Concrete. *Nature Materials 16* (7): 698–99. https://doi.org/10.1038/nmat4930.

225 Obla, K.H., Hong, R., Lobo, C.L., and Kim, H. (2017). Should Minimum Cementitious Contents for Concrete Be Specified? *Transportation Research Record* 2629: 1–8. https://doi.org/10.3141/2629-01.

226 Dunant, C., Shanks, W., Drewniok, M., Lupton, R., Cabrera Serrenho, A., & Allwood, J. (2019). How much cement can we do without? Lessons from cement material flows in the UK. Resources, Conservation and Recycling, 141 441-454. https://doi.org/10.1016/j.resconrec.2018.11.002

7.2.3.4 Energy efficiency

The theoretical minimum thermal energy required for clinker production, including raw materials drying and calcination of raw materials at the temperature of 1,450°C, is 1.85 – 2.8 GJ/t clinker.[227] The current best available technology (BAT) for a six-stage preheater and precalciner kiln is in the range of 2.9 – 3.3 GJ/t clinker.[228] For electrical energy demand, the current BAT level is in the range of 90-100 kWh/tonne cement.[229]

Over the years, energy efficiency levels in the Chinese cement industry have significantly improved, from 5.27 GJ/t clinker in 1997 to 3.83 GJ/t clinker in 2005. From 2005 to 2020, energy intensity of clinker production continued to decline. China's 12th FYP set the goal for China's comprehensive clinker energy intensity to be decreased to 3.28 GJ/t clinker by 2015.[230] The 13th FYP set the goal of reducing clinker energy intensity to be 3.08 GJ/t clinker, approaching international BAT levels.[231]

7.2.3.5 Fuel switching

China's current use of municipal solid waste (MSW) is in the range of 2-5%.[232] In European countries, the share of MSW and other alternative fuels are significantly higher than China. There is large potential to use alternative fuels, such as paint residue, solvent, used tires, municipal solid waste, sewage sludge, and biomass (waste wood, sawdust) in cement kilns to replace coal. For non-biomass alternative fuels, the CO_2 savings are about 20-25% reduction in CO_2 emissions; for biomass, it is estimated that this could have a 30% CO_2 emission reduction potential. Studies have estimated the energy savings would be 0.6 GJ/t clinker.[233]

There are technical challenges related to using various alternative fuels such as the low calorific value and high moisture content of some alternative fuels as well as the potential for high concentrations of chlorine and other trace substances. Using alternative fuels may also require pretreatment to ensure uniform composition and optimum combustion and minimize the content of potentially problematic substances. Further waste collection, sorting, and management systems need to be established to ensure availability of and supply waste materials. Co-processing of wastes may face challenges in terms of social acceptance.

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[227] International Energy Agency, 2018.

[228] European Cement Research Academy (ECRA) and Cement Sustainability Initiative (CSI). (2017). *Development of State of the Art Techniques in Cement Manufacturing: trying to look ahead, Revision 2017*. https://ecra-online.org/fileadmin/redaktion/files/pdf/CSI_ECRA_Technology_Papers_2017.pdf

[229] *Id.*

[230] Ministry of Industry and Information Technology of China. (2011, November 8). *Cement Industry Development Plan during the Twelfth Five-Year (2011-2015).* Ministry of Industry and Information Technology of China. http://www.gov.cn/zwgk/2011-11/29/content_2005593.htm

[231] China Building Materials Federation (CBMF). (2017, June 7). *Cement industry 13th Five-Year Development Plan*. China Building Materials Federation. http://www.cbmf.org/cbmf/yw/6675038/index.html

[232] Sui, T. Personal communication. 2021.

[233] Price, L., Hasanbeigi, A., Lu, H., and Wang, L. (2009). *Analysis of Energy-Efficiency Opportunities for the Cement Industry in Shandong Province, China*. Lawrence Berkeley National Laboratory. https://www.osti.gov/servlets/purl/974444

7.2.3.6 Electrification

Even though electricity only accounts for about 20% of the cement industry's total energy use, it is important to decarbonize the electricity used onsite. Cement plants can increase the uptake of renewable power generation, through onsite renewable generation and power purchase agreements. Renewable electricity could come from wind power, solar PV, solar thermal, and hydro power. The barriers to adoption are lack of availability of renewable resources (depending on local resource conditions), and high electricity prices compared to low fuel prices.

Another emerging technology to electrifying cement production is through electrolysis of limestone. This is an electrochemical process that uses neutral water electrolysis to produce a pH gradient (acid) in which calcium carbonate ($CaCO_3$, limestone) is decarbonated at low pH and calcium hydroxide ($Ca(OH)_2$) is precipitated at high pH, concurrently producing a high-purity O_2/CO_2 gas mixture (1:2 molar ratio at stoichiometric operation) at the anode and H2 at the cathode. When heated with silicon dioxide (SiO_2), the calcium hydroxide decomposes to calcium oxide (CaO, or lime), and then combines with SiO_2 to form alite, the most abundant component in cement[234] (Figure 38). O_2 may be used as fuel in cement kiln to improve efficiency and lower CO_2 emissions.

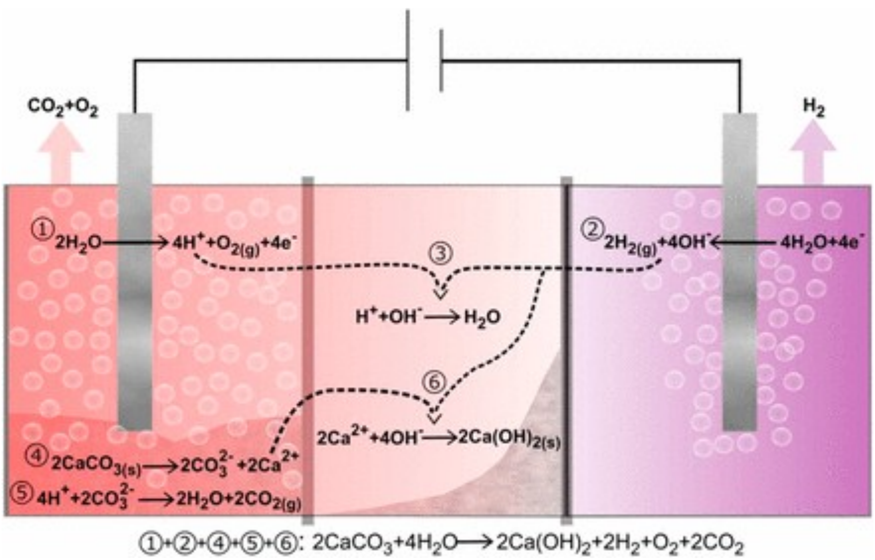

Figure 38. Schematic of electrolyzer-based decarbonation cell
Source: Ellis et al., 2020.

Potentially, this technology can reduce fuel-related CO_2 emissions if renewable electricity is used. It also produces highly concentrated gas streams that can be readily separated and sequestered. At present, this technology is yet to be piloted or demonstrated at the industrial scale, with potentially high costs and high water intensity processes. Electricity source needs to be non-fossil in order to achieve CO_2 mitigation goals.

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[234] Ellis, L.D., Badel, A.F., Chiang, M.L., Park, R.J.-Y., and Chiang, Y. (2020, June 9). Toward electrochemical synthesis of cement—An electrolyzer-based process for decarbonating $CaCO_3$ while producing useful gas streams. *Proceedings of the National Academy of Sciences of the United States of America* (PNAS). *117* (23), 12584-12591. https://doi.org/10.1073/pnas.1821673116

7.2.3.7 CO_2 utilization and abatement

Multiple technologies, such as post-combustion capturing, direct capturing, and oxy-combustion based capturing are being piloted and developed to capture CO_2 emissions from cement plants.

Currently, chemical absorption post-combustion capturing have the highest technological readiness level. This technology uses chemicals (amine-based) to absorb CO_2 emissions directly generated from both the fuel and the calcination process. The capture yields could reach up to 95%.[235] Thermal energy is required (1.0-3.5 GJ/t clinker and 50-90 kWh/t clinker) to heat and regenerate the sorbent. This is the end-of-pipe emissions control, involving only flue gas and does not affect manufacturing processes. The challenges to adopt and scale up the use of this technology involves increased energy costs, increased costs of CO_2 capturing, storage, and transportation. A schematic of an amine-based CO_2 capturing system is illustrated in Figure 39.[236]

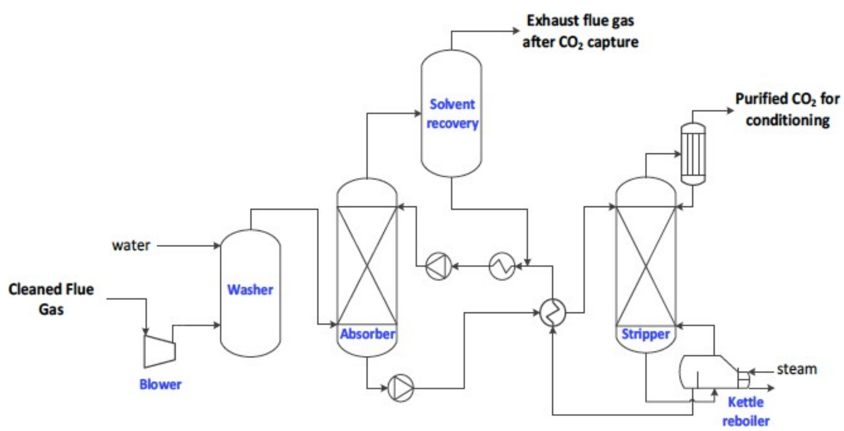

Figure 39. Schematic of amine-based CO_2 capturing process
Source: Jakobsen et al., 2017.

A full-scale CCS project in HeidelbergCement Norcem plant in Brevik, Norway plans to have the capacity to capture 400,000 tonnes per year and transporting for permanent storage. The project is approved in 2020 and expected to be completed by 2024, cutting down 50% of CO_2 emissions from the cement plant.[237]

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[235] European Cement Research Academy (ECRA) and Cement Sustainability Initiative (CSI). (2017). *Development of State of the Art Techniques in Cement Manufacturing: trying to look ahead, Revision 2017*. https://ecra-online.org/fileadmin/redaktion/files/pdf/CSI_ECRA_Technology_Papers_2017.pdf

[236] Jakobsen, J., Roussanaly, S., and Anantharaman, R. (2017). A techno-economic case study of CO2 capture, transport and storage chain from a cement plant in Norway. *Journal of Cleaner Production*, *144,* 523-539. https://doi.org/10.1016/j.jclepro.2016.12.120

[237] Jakobsen, J., Roussanaly, S., and Anantharaman, R. (2017). A techno-economic case study of CO2 capture, transport and storage chain from a cement plant in Norway. *Journal of Cleaner Production*, *144,* 523-539. https://doi.org/10.1016/j.jclepro.2016.12.120

7.2.4 Potential for energy efficiency savings and benefits for cement industry in China

To assess the potential of energy-saving measures in the cement industry, in terms of energy-savings, CO_2 emission reductions, and reductions of SO_2 and NOx emissions, the analytical methodology is shown in Figure 40.

This bottom-up method analyzed each of the identified, applicable energy efficiency (EE) measures, including each measure's energy-saving and emission reduction potential, as well as its penetration rate in China. The following section provides more information on the EE measures selected for each of the cement making process, including energy-saving potentials and adoption rates.

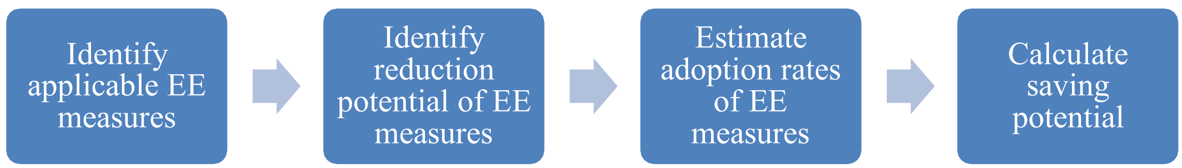

Figure 40. Method to quantify energy-saving and emission reductions potential

To test the range of energy-saving and emission reductions potential, the analysis establishes two scenarios:

- **Possible reduction scenario**: slower and gradual adoption of energy-efficiency measures in the cement industry
- **Maximum reduction scenario**: maximum adoption of energy-efficiency measures to theirtechnical feasibility by 2030

In addition, in order to single out the effects of EE measures on energy-saving and emission reductions, the analysis assumes China's clinker and cement production would stay frozen at the 2020 level for the next ten years through 2030.

Sections below provide analysis results on energy-savings, SO_2 emission reductions, NOx emission reductions, and CO_2 emission reductions.

7.2.4.1 Energy efficiency measures

A number of commercialized energy-efficiency measures can be applicable to the cement industry. Compared to the end-of-pipe control technologies to reduce SO_2 and NOx, energy-efficient technologies have the advantage of recovering investment through energy-savings and typically have a relatively short payback time. And because they can reduce energy use and energy cost, cement plants would have more incentives to implement energy-efficient technologies. The monitoring and enforcement efforts of implementing energy-efficient technologies are much reduced, compared to end-of-pipe control technologies.

While end-of-pipe controls are also needed and important for emission reductions, they do have the drawback of requiring new investment and the investment cannot be recouped through energy-savings. Facilities often lack motivation to adopt or use end-of-pipe control technologies due to their added costs (mostly from increased electricity consumption). The monitoring and enforcement costs are high. In addition, end-of-pipe control technologies do not reduce carbon dioxide emissions from the cement industry, while most energy-efficient technologies can reduce CO_2 emissions by reducing fuel and/or electricity consumption. Table 9 provides a quick comparison of end-of-pipe technologies and energy-efficient technologies.

Key Characteristics	**End-of-Pipe Controls**	**Energy-Efficient Technologies**
Require new investment?	✓	✓
Payback investment via energy savings?	x	✓
Increase energy use?	Increase electricity use	Decrease overall energy use
Reduce key air pollutant emissions?	✓	✓
Reduce CO_2 emissions?	x	✓
Efforts to monitor and enforce?	High	Low

Table 9. Comparison of end-of-pipe and energy-efficient technologies

The report analyzed the energy-saving, CO_2, SO_2, and NOx emission reduction potentials of a total of 39 measures. This includes three energy-efficiency measures in the fuel preparation stage, eight measures in the raw materials preparation stage, eighteen measures for clinker making, six measures for finish grinding and two general (cross-cutting) measures. In addition, the report also analyzed the potential of using alternative fuels and adopting blended cement in the cement industry.

Appendix 3 presents energy-efficient measures for fuel and raw material preparation and its electricity-saving potential. Appendix 4 shows energy-efficiency measures considered for the clinker making process and their associated fuel/electricity impacts, while Appendix 5 provides energy-efficiency measures for finish grinding, general measures, as well as using alternative fuels and changing product by blending cement. These measures and their energy-impacts are based on previous studies including Worrell and Galitsky (2004), Zhou et al. (2011), Hasanbeigi et al. (2012), and Zhang et al. (2015). Historical data of adoption rates of EE measures are based on studies of China's cement industry, including Hasanbeigi et al. (2012) and Zhang et al. (2015). Adoption rates from 2020 to 2030 are estimated based on scenario assumptions (Appendix 6 and Appendix 7).

7.2.4.2 Energy savings

As shown in Figure 41, under the Possible Reduction Scenario, a total of 22 million tonnes of coal equivalent (Mtce) of energy could be saved in the 14th FYP (2021-2025). The largest energy-saving measure is adopting and increasing the use of blended cement, accounting for 57% of the total saving by 2025. Under the Maximum Reduction Scenario, the energy-saving potential could be more than doubled, reaching 46 Mtce by 2025. The largest contributing measures are: blended cement (32% of total energy savings), conversion to grate coolers (21%), using wastes and biomass (19%), and kiln shell loss reduction (improved refectories) (7%). Energy management & process control systems and optimizing heat recovery systems also contribute 4%, and 3%, respectively.

In the 15th FYP, the Possible Reduction Scenario could deliver a total of 22 Mtce of energy savings during 2026-2030. The Maximum Reduction Scenario could save a total of 46 Mtce during this period.

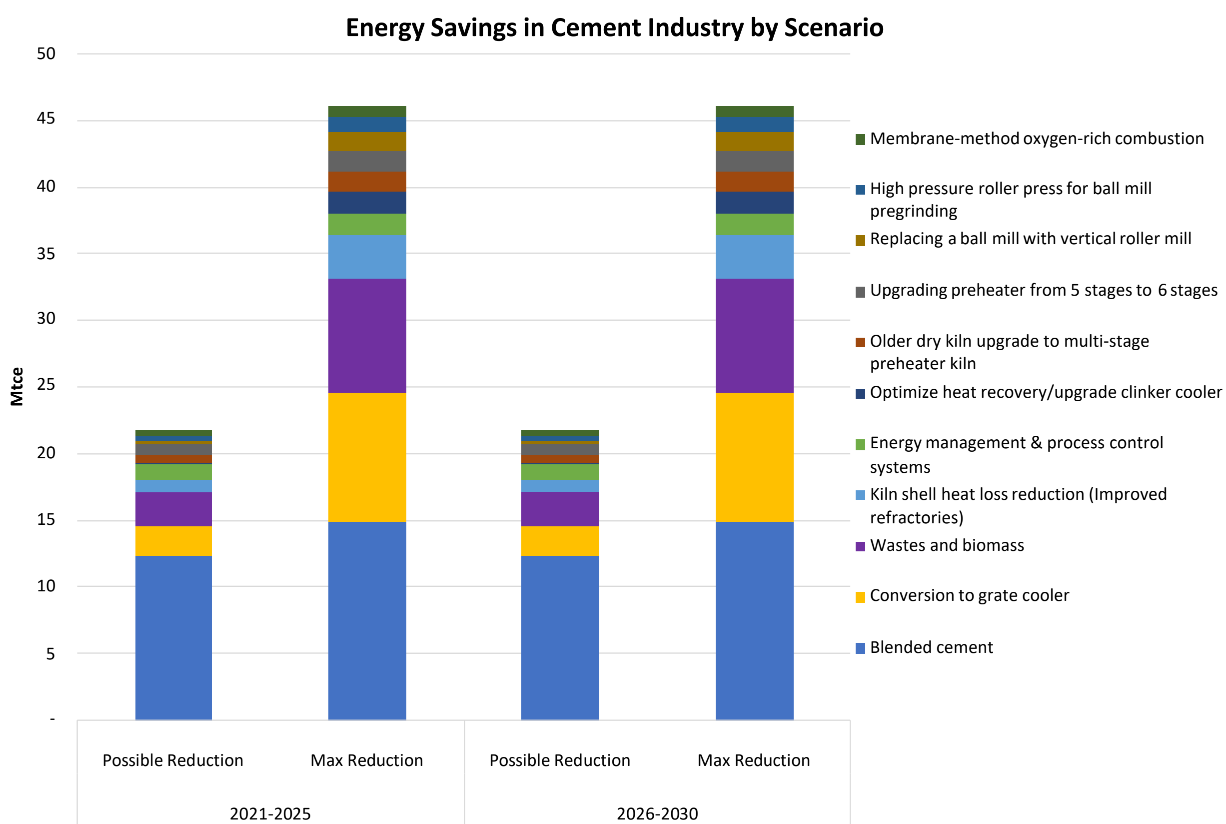

Figure 41. Energy saving potential by adopting energy-efficiency measures

7.2.4.3 SO_2 emission reductions

By adopting energy-efficiency measures, a total of 342,000 tonnes of SO_2 could be reduced under the Possible Reduction Scenario, from 2021 to 2025. The largest contributing measures are from blended cement (63%), wastes and biomass (12%), and conversion to grate cooler (6%), and upgrading to preheater/precalciner kiln (4%). Other measures, such as kiln shell loss reduction (improved refractories) and energy management & process control systems represent 3% and 3% of the total SO_2 reductions, respectively.

Under the Maximum Reduction Scenario, a total of 676,000 tonnes of SO_2 could be reduced from 2021 to 2025, doubling the SO_2 reduction potential under the Possible Reduction Scenario. The measures that have the largest SO_2-reduction impacts are blended cement (38% of total reduction), wastes and biomass (21%), conversion to grate cooler (14%), and upgrading to a preheater/precalciner kiln (9%).

As the adoption of energy efficiency (EE) measures continue to progress through 2030, another 342,000 tonnes of SO_2 reductions could be achieved during 2026-2030, under the Possible Reduction Scenario. If the EE measures are adopted to their maximum potential in all cement plants in China, the SO_2 reduction potential could be increased to 676,000 tonnes during this period, under the Maximum Reduction Scenario, as illustrated in Figure 42.

In comparison, it is reported the China's cement industry has reduced a total of 138,000 tonnes of SO_2 emission reductions during the 13^{th} FYP, by using a combination of EE measures and end-of-pipe technologies.[238] The results shown in Figure 42 demonstrated that energy-efficiency can deliver twice or greater SO_2 emission reductions in the 14^{th} FYP as achieved in the 13^{th} FYP.

[238] Fan, Y. (2016, November). *Achieving coal cap goals in the cement industry over the 13^{th} FYP*. China Cement Association. https://www.china5e.com/download/20161101-nrdc/1101-FanYongbin.pdf

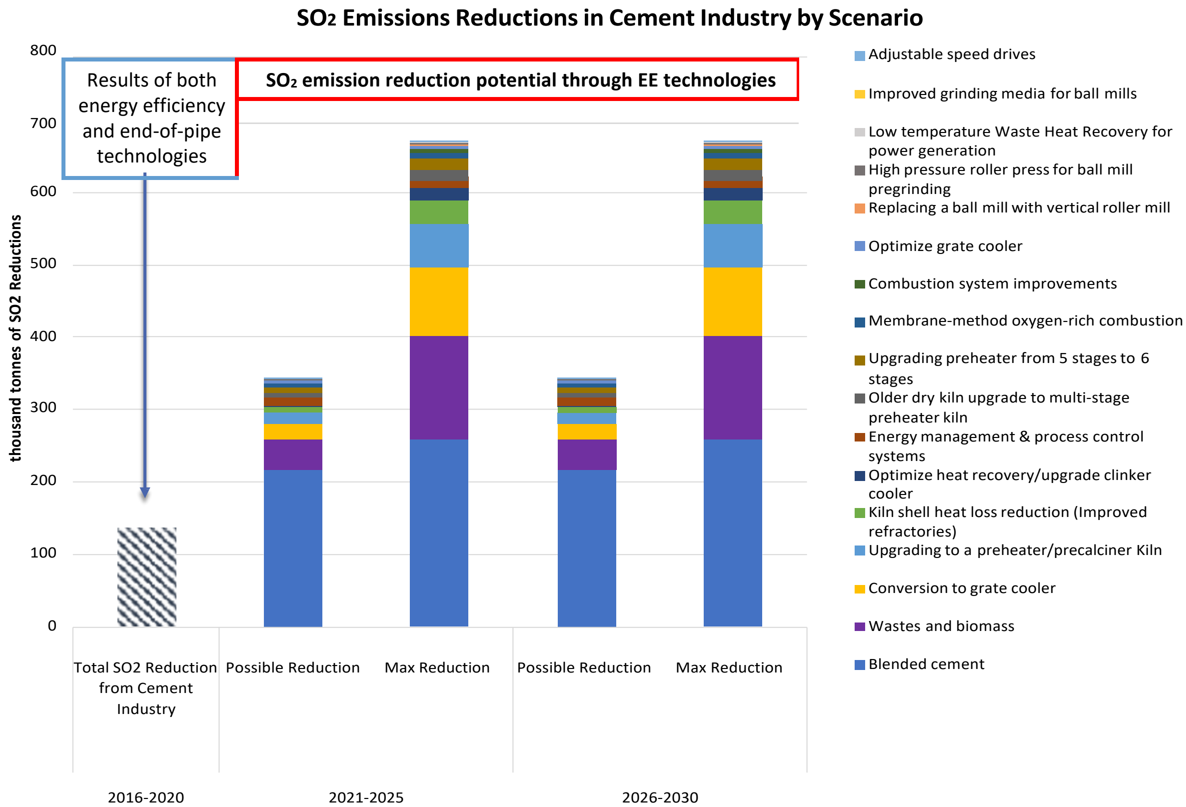

Figure 42. SO_2 emissions reduction potential from energy-efficiency measures

7.2.4.4 NOx emission reductions

Energy-efficiency measures have the potential to reduce NOx emissions by 531,000 tonnes under the Possible Reduction Scenario during the 14th FYP (2021-2025). Similar to the impacts on SO_2 emission reductions, the largest contributing measures are from blended cement (63% of total NOx emission reductions) and wastes and biomass utilization (13%). Other measures such as conversion to grate cooler and upgrading to a preheater/precalciner account for another 6% and 5% of the total NOx emission reductions, respectively. Under the Maximum Reduction Scenario, NOx emission reductions can be doubled, reducing a total of 1,058,000 tonnes of NOx emissions during 2021-2025. Blended cement wastes and biomass, and conversion to grate cooler represent 38%, 21%, and 14% of the total NOx emissions, respectively.

In the 15th FYP, the Possible Reduction Scenario can deliver another 531,000 tonnes of NOx emissions if the adoption of EE measures is continued at the assumed slower and gradual pace. If EE measures are adopted to their maximum feasible potential by 2030, under the Maximum Reduction Scenario, these measures can reduce 1 million tonnes of NOx by 2030.

During China's 13th FYP (2016-2020), the cement industry reduced 1,080,000 tonnes of NOx emissions by adopting both energy-efficiency and end-of-pipe technologies.[239] The results presented in Figure 43 shows that maximum adoption of energy-efficiency measures can continue to deliver the same amount of NOx emission reductions in the 14th FYP as in the 13th FYP.

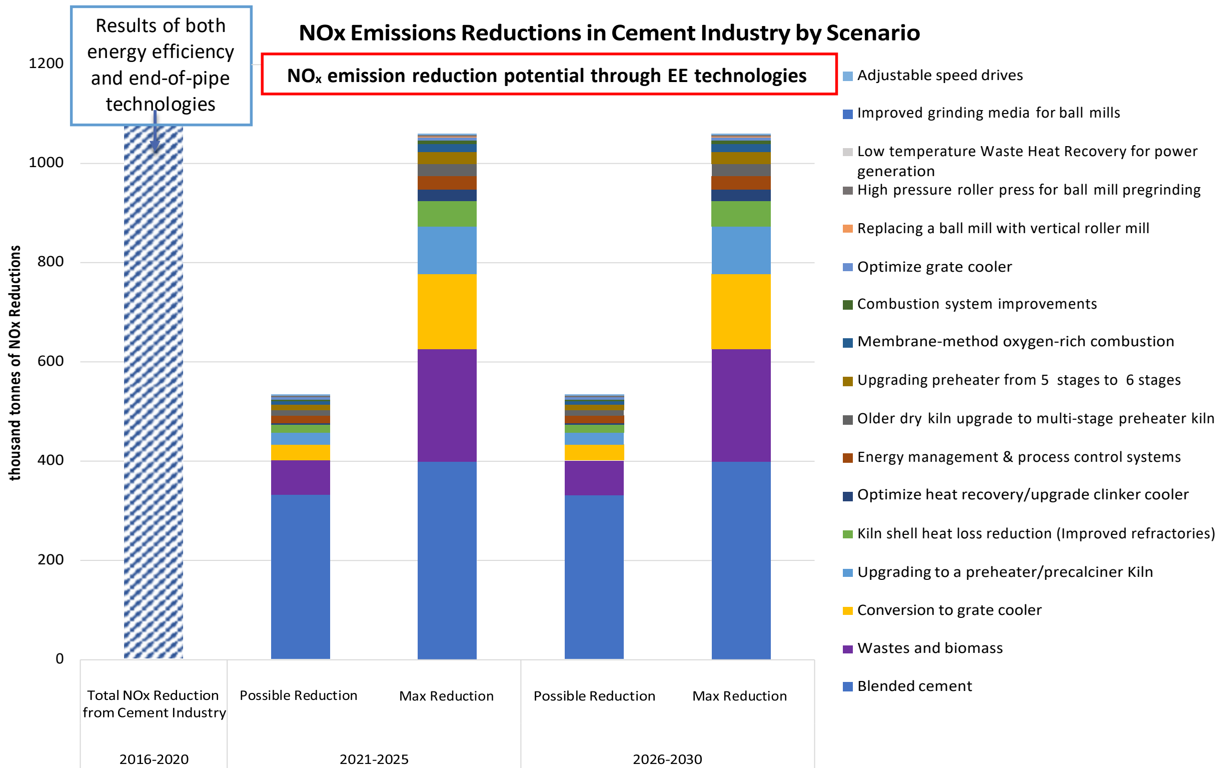

Figure 43. NOx emissions reduction potential from energy-efficiency measures

7.2.4.5 CO_2 emission reductions

Energy-efficiency measures not only can reduce energy use, SO_2 and NOx emissions, but can also reduce CO_2 emissions. Under the Possible Reduction Scenario, a total of 62 million tonnes (Mt) of CO_2 can be avoided during 2021-2025. The largest contributing measures are blended cement (56% of total CO_2 reductions), wastes and biomass (11%), and conversion to grate cooler (10%). In addition, energy management & process control systems and kill shell heat loss reduction (improved refractories) also represent another 4% and 5% of the total CO_2 reductions, respectively. Under the Maximum Reduction Scenario, CO_2 reductions can be more than doubled, avoiding 133 Mt of CO2 emissions during 2021-2025. Blended cement, conversion to grate cooler, and the use of wastes and biomass account for 31%, 20%, and 18% of the total CO_2 emissions during this period, respectively.

[239] Fan, Y. (2016, November). *Achieving coal cap goals in the cement industry over the 13th FYP*. China Cement Association. https://www.china5e.com/download/20161101-nrdc/1101-FanYongbin.pdf

In the next five-year period, from 2026 to 2030, a total of 62 Mt of CO_2 emissions can be avoided under the Possible Reduction Scenario, which assumes a slower and gradual pace of adopting EE measures. Under the Maximum Reduction Scenario, a total of 132 Mt of CO_2 emissions can be reduced. The saving potential of each scenario during 14th and 15th FYPs are shown in Figure 44.

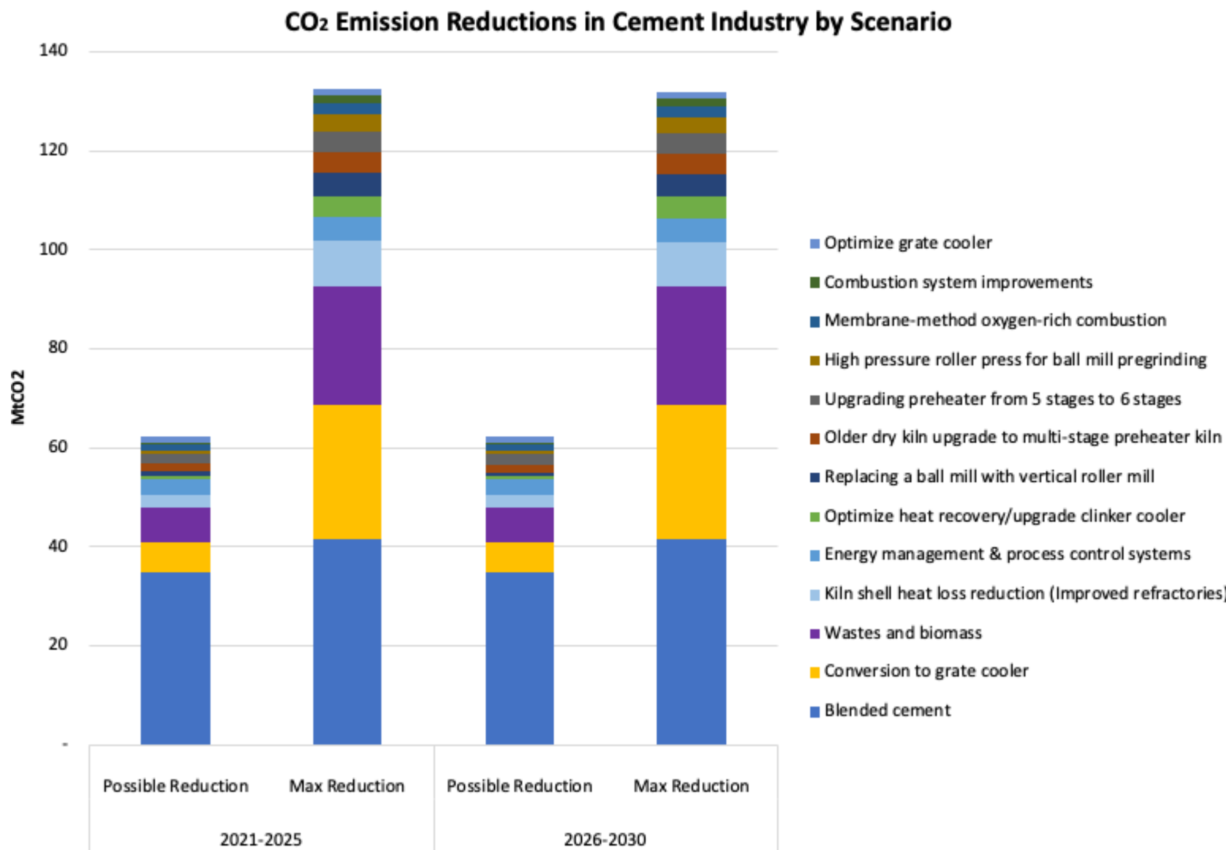

Figure 44. CO_2 *emissions reduction potential from energy-efficiency measure*

8 Conclusions

Energy Efficiency and Air Quality co-benefits in California

Planning Coordination

There are opportunities for coordination between the updating of California's Scoping Plan, which has just begun for adoption by 2022, and the subsequent updates every five years, and China's current Five-Year Plan and future updates. Both California and China must update their plans to address not only air pollution control goals but also their zero net carbon goals. CARB intends this update to adopt California's pathway to Net Zero Carbon by 2045 and to integrate health benefits from reduced toxic emissions into the design of its climate change programs.[240] Also CARB must examine the performance of the existing Scoping Plan and identify areas for improvement. With its carbon neutrality goal, China will need to incorporate GHG emissions reduction into every sectoral and regional policy development. China and its provinces might benefit from California's lessons learned on co-benefits and programs to achieve both air quality and climate pollutants reductions through dialogues with not only CARB but also with SCAQMD and BAAQMD. China has made amazing progress since 2013 in reducing PM2.5 which has had substantial public health benefits. As we discussed above, the actual details of the optimal co-benefit strategies depend upon pollutant inventories, the stock of equipment, atmospheric chemistry, etc. However, achieving synergies among air pollutants, climate and energy strategies should be able to reduce compliance costs. Thus, California's policies and programs may not be directly applicable to China and all of its provinces.

The Scoping Plan and some local SIPs build in a substantial role for energy efficiency. Even after decades of energy efficiency programs, doubling energy efficiency savings is planned to account for 10.3% of the cumulative emissions reductions (64 MMTCO2e out of 621 MMTCO2e) from 2021 by 2030 under the 2017 Scoping Plan scenario, although its air quality benefits are relatively small as transportation is the major source of air pollutant emissions in the state. CEC has observed that California is unlikely to reach its doubling goal, so the 2022 Scoping Plan update is a good time for further review and revision. Unfortunately, the doubling goal, while very visionary, had little analytical support. California's energy efficiency programs began in the 1970s and have been fairly aggressive. To lay the groundwork for the next Scoping Plan revisions of energy efficiency, CEC has begun the rethinking of the Energy Efficiency Action Plan to place highest priority on cost-effective actions that reduce GHG emissions (along with consideration of how to reduce the inequalities across Californians). Renewable development means that California has periods of surplus renewable generation, so energy efficiency in these periods would have limited value. CEC has developed more sophisticated energy efficiency program metrics that target GHG savings by starting with assessment of the actual variation in hourly GHG emissions throughout the year and over time. Regardless of the precise goal in this update, energy efficiency will continue to play a significant role in California's future.

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[240] *California's 2017 Climate Change Scoping Plan*. ARB, 2017. p. 50.

Implications of Substantial Additions of Intermittent Resources – Storage and Flexible Demand

California's pathway toward zero net carbon is grounded in transitioning to a 100% renewable grid and electrification of end uses in buildings, vehicles and industry. California will add very substantial amounts of solar and wind generation in both distributed and central station modes between now and 2045. While this report did not examine the renewable pathway in any detail, the reality of grid reliability will require integrating renewables over broad geographical areas, development of low-cost storage and flexible demand. This report did address both storage development and flexible demand measures.

In terms of storage, California has had an aggressive program of battery storage development since the beginning of the Brown administration. As Attorney General, Governor Brown had developed legislation for CPUC to adopt storage procurement goals and this legislation was adopted in his first year as Governor. Pursuant to this legislation, CPUC adopted specific procurement goals for its regulated utilities, which included both distributed and grid-level storage requirements. The utilities were allowed the flexibility to adjust the timing of the procurement based on the cost-effectiveness of the bids. This procurement program has been very successful at leading to increasingly competitive solicitations of battery electric storage systems (BESS). Lithium-based BESS costs have decreased very significantly in the past decade given the market pull of both the grid and transportation options (see Figure 21 above). CPUC storage procurement programs resulted in reforms to the interconnection requirements to facilitate more timely interconnections, revisions to the CAISO market rules, and development of policies to allow greater operational flexibility for storage facilities so they could participate in multiple ancillary service markets and thus enhance their overall revenues. Grid-level storage has been important to maintain grid reliability as numerous gas-fired power plants have retired due to the reduced operating levels. As discussed above, California has the largest BESS in the world at Moss Landing, and thousands of additional MWs are under construction to address summer reliability concerns. After last summer's outages, California wants to enhance reliability by accelerating the adoption of grid-level BESS instead of being required to maintain large quantities of gas-fired peaking plants over the longer term. California also has had to institute power shut-offs in areas and times of high fire risks, which has resulted in a flurry of interest in dispersed storage. California has among the highest retail rates in the U.S., so combinations of storage and solar installations can be economically attractive. This is particularly true since storage systems that are installed in combination with solar systems can be eligible for the federal solar tax credit. While California is the leading market for BESS both at the grid and behind-the-meter levels, it is also becoming clear that there are a variety of storage duration markets and that longer-term storage options beyond BESS are also very valuable.

Storage is a key technology that requires both scaling and innovation to further reduce costs for BESS and also the development of longer-term storage options, which should provide opportunities for collaboration between California and China. China could benefit from California's lessons learned in both grid and dispersed behind-the-meter applications. In addition, current battery electric applications can cover four to eight hours. Germany experienced 10-day periods of low wind and solar, so multiple-week storage technologies are needed. Common expectations are that going above 80 or 90% renewables on the grid will need very significant amounts of storage with a variety of time periods, including seasonal. There are many potential priority areas for coordinated research such as addressing long-duration storage. This research could consider alternative technologies such as flow batteries, alternative battery chemistry, advanced pumped storage facilities and “green” hydrogen. In general, recycling of storage technologies will become increasingly important as the market for storage applications increases. Working through the appropriate grid market rules to maximize the value of storage will also be important.

In terms of flexible demand, CEC has recently been granted the legislative authority to extend its appliance standards beyond energy efficiency to demand flexibility. Both California and China have benefited from coordination in appliance efficiency standards since the 1980’s. In response to both the ever-increasing levels of intermittent resources and last year’s grid outages, California is trying to expand its flexible demand programs. As China achieves increasing levels of renewables, it will also need not only the above discussed storage options but also flexible demand programs. China could benefit from the lessons learned from California’s efforts. California could benefit from greater Chinese flexible demand programs as it scales thesedemand flexibility technologies, particularly low-cost but reliable “command and control” technologies for both retrofit and new appliances, and also innovates these technologies.

Building Electrification

In terms of electrifying buildings, California is exploring the policy options for promoting heat pumps for space and water heating in a variety of sizes across buildings, and also reliance of inductive stoves for cooking. Electrification of heating end uses can significantly reduce CO_2 emissions through combustion and methane leakage as well as air pollutant emissions (CO, NOx, PM, and formaldehyde). CPUC and CEC have been directed by legislation to examine the feasibility of reducing GHG emissions of California’s buildings by 40% by 2030 and also for the development of pilot programs to facilitate heat pump adoption in California. A number of local governments in the state are adopting all-electric requirements for new construction. CEC has been examining the status of heat pumps for space and water heating in its Title 24 updating of the building standards for new construction for 2022 and trying to lay the framework for extensive inclusion in future updates. CEC’s draft regulations cover heat pumps in three ways:

- “Revise the prescriptive compliance path available for building projects to include only heat pump technology in specific circumstances;
- Revise the “standard design” used for the modeling-based performance compliance path available for building projects to establish the performance baseline based on heat pump technologies in specific circumstances; and

- Add new requirements that mixed fuel buildings be electric ready, meaning that electrical connections and other features needed to allow use of non-combustion equipment options are installed at the time of initial construction." [241]

California will need heat pumps that comply with the Montreal protocol/Kigali Amendment, so research in and development of alternative refrigerants will be critical before widespread adoption of heat pumps in California. Moreover, to incorporate heat pumps (and/or induction stoves) into the Title 24, they will have to be cost-effective on a life-cycle basis. California could benefit from working with China to reduce costs and improve performances in both heat pumps with alternative refrigerants and induction stoves again through scale and innovation. Moreover, there are likely to be a variety of appropriate heat pump and induction stove technologies necessary for single family, multifamily and commercial buildings and throughout a variety of weather conditions.

Both California and China face the challenge of achieving energy efficiency and reduced GHG emissions in their stock of existing buildings. For example, the Title 24 covers 150,000 new buildings a year at best. At the same time, there are over 10 million existing homes in California. There are similar statistics for the number of new constructions of commercial buildings in California relative to the stock of existing commercial buildings. California has been exploring policies to encourage retrofitting with energy efficient technologies its large stock of existing buildings for decades. These efforts are now being expanded to incorporate technologies to reduce GHG emissions as well as to provide load flexibility. There are currently two programs:

i. Establishing public databases of commercial building energy use. The information will help current and prospective owners and occupants make informed decisions.
ii. Design and implement financial incentives, behavioral programs, and education and outreach programs to encourage customers to switch to energy-efficient technologies.

This is another area where China and California can share the lessons learned from existing programs, and work together to develop potential solutions and technologies to achieve their common goals.

Electrifying the Transportation System

Finally, transportation is a major source of GHG emissions and criteria pollution in both California and China, with over 50% of the GHG emissions and over 80% of the criteria pollutants in California. It has been the main focus of CARB efforts for decades, and there have been frequent dialogues with appropriate Chinese officials. Indeed, both China and California are strongly promoting ZEV technology for automobiles, and at this time California has almost half of the ZEVs in the U.S., while China has about half of the ZEVs in the world. Increasing ZEV sales have resulted in the expansion of battery manufacturing capability, and the resulting scaling and innovation

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[241] California Energy Commission. (May 2021). *2022 Building Energy Efficiency Standards.* www.energy.ca.gov/programs-and-topics/programs/building-energy-efficiency-standards/2022-building-energy-efficiency, pages 4 and 5.

has helped drive down battery costs. (These transportation applications of batteries both complement and compete with the use of BESS in the grid and in dispersed applications, which was discussed above). Further expansion and innovation is expected to result in parity between internal combustion engine (ICE) and ZEV automobiles in the future. California relies upon its CAFE standards to require basic levels of efficiency in automobiles sold in the state and to encourage ZEV sales. Governor Newsom has even set 2035 as the end of ICE sales in California. The next priority for electrifying transportation is trucks, particularly heavy-duty vehicles, which would have substantial air quality benefits. CARB is requiring the production of zero emission trucks for California. As discussed earlier, zero-emission heavy-duty vehicles will require the development of cost-effective, reliable and safe ZEV technology for heavy duty vehicles. Once more, scaling and innovation will be important to reduce costs, so coordination between California and China will be critical. The expansion of ZEVs will require the associated development of the charging and fueling infrastructure, which will in turn rely upon its own supply chain. As discussed earlier, recycling batteries will become an increasing concern. Flexible ZEV charging loads could become a key demand resources to ensure grid reliability. Finally, California and China are tied together by the manufacture and transportation of goods from China which are then imported through the ports of Long Beach and Los Angeles for transportation throughout the U.S. This goods movement has great economic benefits but also substantial GHG emissions and air quality concerns. California has pursued a variety of tools to reduce the environment impacts, such as LCFS, AMP, zero-emission cargo-handling equipment, and land-use planning. Electrifying the goods movement sector could have substantial GHG emissions and air quality benefits in both China and California. Transportation is an area that offers opportunities for collaboration between California and China and its provinces. These opportunities were further discussed in CCCI's *Driving to Zero* and below for heavy-duty trucks.

Clean and Efficient Heavy-Duty Trucks in China

The analysis shows that there is significant potential for reducing energy (particularly diesel) demand, CO_2 emissions and air pollution in the form of NOx and PM2.5 emissions from heavy-duty trucking energy efficiency and logistics improvement, as well as NEV adoption, but technological, economic, market and institutional barriers to achieving these reductions exist. Based on international experiences and best practices and China's current market situation, some possible policy actions for overcoming these barriers during the 14^{th} and 15^{th} Five-Year Planperiods include:

1. Expanding and introducing phased ultra-low emission zones in large cities where air quality concerns are high;
2. Encouraging subnational leadership in announcing ambitious NEV adoption targets that include heavy-duty trucks and supporting subnational experience-sharing and coordination;
3. Continuing to support the implementation and enforcement of new and more stringent HDT fuel economy and vehicle emission standards, and recognizing the important values in energy and air quality co-benefits in future standard revisions;
4. Supporting the development of innovations in technologies and business models to

support logistics improvement and NEV charging, such as improved supply chain coordination and battery swapping.

Low-Carbon Cement

China's cement industry is facing significant pressures to meet all types of energy, environment, and climate targets. The analysis finds that energy-efficiency measures can still play an important role in achieving China's goals of energy conservation, reducing air pollutant emissions, and the recently announced carbon peaking and carbon neutrality by 2060. It finds that maximum adoption of energy-efficiency measures can deliver twice as much or more SO_2 emission reductions in the 14th FYP as achieved in the 13th FYP. Maximum adoption of energy-efficiency measures can deliver the same amount of NOx emission reductions in the 14th FYP as achieved in the 13th FYP. In addition, by adopting energy-efficiency measures to their maximum feasibility, the cement industry can also save 45 Mtce of energy savings and avoid a total of 132 Mt of CO_2 emissions in the 14th FYP as compared to a frozen (2020 activity) baseline.

For policymakers, it is important to continue recognizing energy efficiency as the first resource to meet multiple economic, energy, environmental, and climate goals. It is important for multiple governmental agencies to have a coordinated approach to achieve these multiple goals in a low-cost, efficient, and systematic approach.

9 Appendices

Appendix 1: ECC Measures for the 2016 South Coast AQMP

Number	Title	Description	Emission Reductions
ECC-01	Co-Benefit Emission Reductions from GHG Programs, Policies, and Incentives [All Pollutants]	- Criteria pollutant co-benefits from the federal, state, and local mandates and programs to reduce GHG emissions. - Programs include market programs, renewable energy targets, incentive and rebate programs, and promoting development and deployment of new technologies.	NOx – TBD
ECC-02	Co-Benefits from Existing Residential and Commercial Building Energy Efficiency Measures [NOx, VOC]	- Criteria pollutant benefits from the state's energy efficiency mandates such as Title 24 and SB 350.	NOx - 0.3 tpd by 2023, 1.1 tpd by 2031 VOC - 0.07 tpd by 2023, 0.29 tpd by 2031
ECC-03	Additional Enhancements in Reducing Existing Residential Building Energy Use [NOx, VOC]	- Criteria pollutant benefits from incentive programs that encourage to go beyond the goals of ECC-02. - Programs include supporting weatherization, solar thermal and PV, and upgrading older appliances.	NOx - 1.2 tpd by 2023, 2.1 tpd by 2031 VOC - 0.2 tpd by 2023, 0.3 tpd by 2031
ECC-04	Reduced Ozone Formation and Emission Reductions from Cool Roof Technology [All Pollutants]	- Adoption of cool roofs can lower daytime ambient temperatures, slowing the rate of ozone formation. - It also reduces electricity consumption required for cooling, leading to reduction in emissions from the power generation.	NOx – TBD

Source: SCAQMD[242]
Note: TBD are reductions to be determined once the measure is further evaluated, the technical assessment is complete, and inventories and cost-effective control approaches are identified, and are not relied upon for attainment demonstration purposes.

Appendix 2: Bay Area AQMD Control Measures for Transportation, Energy, and Buildings

Number	Name	Description	Estimated Annual Emission Reductions	
			Criteria Air Pollutants (lbs/day)	GHG (MTCO2e/yr)

[242] *Final 2016 Air Quality Management Plan*. South Coast AQMD. March, 2017. Chapter 4.

			ROG	NOx	PM2.5	SO2	
Transportation							
TR14	Cars and Light Trucks	Commit regional clean air funds toward qualifying vehicle purchases and infrastructure development. Partner with private, local, state and federal programs to promote the purchase and lease of battery-electric and plug-in hybrid electric vehicles.	64	64	14		3,963
TR19	Medium and Heavy Duty Trucks	Directly provide, and encourage other organizations to provide, incentives for the purchase of 1) new trucks with engines that exceed ARB's 2010 NOX emission standards for heavy-duty engines, 2) new hybrid trucks, and 3) new zero-emission trucks. The Air District will work with truck owners, industry, CARB, CEC, and others to demonstrate additional battery-electric and hydrogen fuel cell zero-emission trucks.	44	36 2	10		138,30 6
TR20	Ocean Going Vessels	Replicate the Green Ship Program that has been implemented at the ports of Los Angeles and Long Beach. Financial incentives for cleaner Tier 2 and Tier 3 oceangoing vessels to call at the ports serve as the basis of the Program. The Program was initiated as part of the San Pedro Bay Ports Clean Air Action Plan. This measure also recognizes the need to monitor progress under such programs and augment them as necessary to ensure sufficient results.		38			
Buildings							
BL1	Green Buildings	- Collaborate with partners such as KyotoUSA to identify energy-related improvements and opportunities for onsite renewable energy systems in school districts and investigate funding strategies. - Identify barriers to effective local implementation of Title 24 building codes and develop solutions to improve implementation and	30	36 7	53	9	141,767

		enforcement. - Work with BayREN program to make additional funding available for energy-related projects in the buildings sector. - Engage with additional partners to target reducing emissions from specific types of buildings.					
BL2	Decarbonize Buildings	- Explore potential Air District rulemaking options regarding the sale of fossil fuel-based space and water heating systems for both residential and commercial use. - Explore incentives for property owners to replace their furnace, water heater or natural-gas powered appliances with zero-carbon alternatives. - Update Air District guidance documents to recommend that commercial and multi-family developments install ground source heat pumps and solar hot water heaters.	54	635	98	34	313,586
BL3	Market-Based Solutions	- Implement a call for innovation to support market-based approaches that bring new, viable solutions to significantly reduce GHG emissions associated with existing buildings.	N/A				
BL4	Urban Heat Island Mitigation	- Develop and urge adoption of a model ordinance for "coolparking". - Develop and promote adoption of model building code requirements for new construction or re-roofing/roofing upgrades for commercial and residential multi-family housing. - Collaborate with expert partners to perform outreach to cities and counties to make them aware of cool roofing and cool paving techniques, and of new tools available.	3	31	6	3	14,512

Energy				
EN1	Decarbonize Electricity Production	- Engage with utilities to maximize the amount of renewable energy in electricity production and import. - Work with local governments to implement local renewable energy programs. - Engage with industry stakeholders and public works agencies to increase use of biomass in electricity production.	N/A (The level of uncertainty is too high to make assumptions.)	
EN2	Decrease Electricity Demand	- Support local government energy efficiency programs via best practices, model ordinances, and technical support. - Work with partners to develop messaging to decrease electricity demand during peak times.	N/A	
Super-GHGs				
SL1	Short-Lived Climate Pollutants	- Reduce methane from landfills and farming activities through various control measures listed under waste and agriculture sectors. - Develop a rule to reduce methane emissions from natural gas pipelines and processing operations, and amend regulations to reduce emissions of methane and other organic gases from equipment leaks at oil refineries. - Enforce applicable regulations on the servicing of existing air conditioning units in motor vehicles, support the adoption of more stringent regulations byCARB and/or U.S. EPA, and encourage better HFC disposal practices.	N/A	28,600

Source: Bay Area AQMD (2017)[243]

[243] *Final 2017 Clean Air Plan*. Bay Area AQMD, April, 2017. Chapter 5, Appendix H.

Appendix 3: Energy efficiency measures: fuel preparation and raw material preparation processes

#	Energy Efficiency Measure	Fuel Saving (GJ/t-clinker)	Electricity Impact (kWh/t-clinker)
	Fuel preparation		
1	Efficient coal separator		0.26
2	Efficient roller mills for coal grinding		1.47
3	Installation of Variable Frequency Drive (VFD) & replacement of coal mill bag dust collector's fan		0.16
	Raw materials preparation		
4	Raw meal process control for vertical mill		1.41
5	High efficiency classifiers/separators		5.08
6	High efficiency roller mill		10.2
7	Efficient transport system		3.13
8	Raw meal blending (homogenizing) systems		2.66
9	VFD in raw mill vent fan		0.33
10	Bucket elevator for raw meal transport		2.35
11	High efficiency raw mill vent fan w/inverter		0.36

Sources: Worrell and Galitsky (2004), Zhou et al. (2011), Hasanbeigi et al. (2012), and Zhang et al. (2015).

Appendix 4: Energy efficiency measures: clinker making process

#	Energy Efficiency Measure	Fuel Saving (GJ/t-clinker)	Electricity Impact (kWh/t-clinker)
	Clinker making		
12	Replacing Vertical Shaft Kilns with New Suspension	2	
13	Conversion to grate cooler	0.6	-0.01
14	Upgrading to a preheater/precalciner Kiln	0.43	
15	Kiln shell heat loss reduction (Improved refractories)	0.26	
16	Membrane-method oxygen-rich combustion	0.22	-5.5
17	Energy management & process control systems	0.15	2.35
18	Older dry kiln upgrade to multi-stage preheater kiln	0.11	-1.17
19	Upgrading preheater from 5 stages to 6 stages	0.11	-1.17
20	Optimize heat recovery/upgrade clinker cooler	0.11	-2
21	Optimize grate cooler	0.09	
22	Combustion system improvements	0.03	
23	Low temperature Waste Heat Recovery for power generation		30.8
24	Adjustable speed drive for kiln fan		6.1
25	Low pressure drop cyclones for suspension preheater		2.6
26	Bucket elevators for kiln feed		1.24
27	Use of high efficiency preheater fan		0.7
28	Efficient kiln drives		0.55
29	VFD in cooler fan of grate cooler		0.11

Sources: Worrell and Galitsky (2004), Zhou et al. (2011), Hasanbeigi et al. (2012), and Zhang et al. (2015).

Appendix 5: Energy efficiency measures: finish grinding process, general measures, alternative fuels, and product change

#	Energy Efficiency Measure	Fuel Saving (GJ/t-clinker)	Electricity Impact (kWh/t-clinker)
	Finish grinding		
30	Energy management & process control in grinding		4
31	Replacing a ball mill with vertical roller mill		25.9
32	High pressure roller press for ball mill pre-grinding		24.4
33	Improved grinding media for ball mills		6.1
34	High-Efficiency classifiers (for finish grinding)		6.1
35	High efficiency cement mill vent fan		0.13
	General measures		
36	High-efficiency motors		4.58
37	Adjustable speed drives		9.15
	Alternative fuels	**Fuel Saving (GJ/t-cement)**	**Electricity Impact (kWh/t-cement)**
38	Wastes and biomass	0.6	
	Product change	**Fuel Saving (GJ/t-cement)**	**Electricity Impact (kWh/t-cement)**
39	Blended cement	1.77	-7.21

Sources: Worrell and Galitsky (2004), Zhou et al. (2011), Hasanbeigi et al. (2012), and Zhang et al. (2015).

Appendix 6: Energy-efficiency adoption rates under the Possible Reduction Scenario

	Fuel preparation	**2020**	**2025**	**2030**
1	Efficient coal separator	39%	44%	50%
2	Efficient roller mills for coal grinding	67%	73%	80%
3	Installation of Variable Frequency Drive (VFD) & replacement of coal mill bag dust collector's fan	45%	53%	60%
	Raw materials preparation			
4	Raw meal process control for vertical mill	17%	23%	30%
5	High efficiency classifiers/separators	47%	53%	60%
6	High efficiency roller mill	66%	73%	80%
7	Efficient transport system	30%	37%	45%
8	Raw meal blending (homogenizing) systems	30%	38%	45%
9	VFD in raw mill vent fan	74%	80%	85%
10	Bucket elevator for raw meal transport	30%	37%	45%
11	High efficiency raw mill vent fan w/inverter	78%	81%	85%
	Clinker making	**2020**	**2025**	**2030**
12	Replacing Vertical Shaft Kilns with New Suspension	97%	98%	100%
13	Conversion to grate cooler	17%	23%	30%
14	Upgrading to a preheater/precalciner Kiln	27%	33%	40%
15	Kiln shell heat loss reduction (Improved refractories)	37%	43%	50%
16	Membrane-method oxygen-rich combustion	6%	11%	15%
17	Energy management & process control systems	53%	67%	80%
18	Older dry kiln upgrade to multi-stage preheater kiln	30%	40%	50%
19	Upgrading preheater from 5 stages to 6 stages	33%	47%	60%
20	Optimize heat recovery/upgrade clinker cooler	18%	22%	25%
21	Optimize grate cooler	78%	87%	95%
22	Combustion system improvements	17%	23%	30%
23	Low temperature Waste Heat Recovery for power generation	85%	87%	90%
24	Adjustable speed drive for kiln fan	33%	42%	50%
25	Low pressure drop cyclones for suspension preheater	65%	70%	75%
26	Bucket elevators for kiln feed	30%	37%	45%
27	Use of high efficiency preheater fan	38%	47%	55%
28	Efficient kiln drives	52%	58%	65%
29	VFD in cooler fan of grate cooler	70%	75%	80%
	Finish grinding	**2020**	**2025**	**2030**
30	Energy management & process control in grinding	60%	67%	75%
31	Replacing a ball mill with vertical roller mill	22%	28%	35%
32	High pressure roller press for ball mill pregrinding	37%	43%	50%
33	Improved grinding media for ball mills	22%	28%	35%
34	High-Efficiency classifiers (for finish grinding)	42%	46%	50%
35	High efficiency cement mill vent fan	52%	61%	70%

	General measures	**2020**	**2025**	**2030**
36	High-efficiency motors	62%	68%	75%
37	Adjustable speed drives	57%	68%	80%
	Alternative Fuel	**2020**	**2025**	**2030**
38	Wastes and biomass	15%	20%	25%
	Product change	**2020**	**2025**	**2030**
39	Blended cement	50%	60%	70%

Appendix 7: Energy-efficiency adoption rates under the Maximum Reduction Scenario

	Fuel preparation	2020	2025	2030
1	Efficient coal separator	59%	84%	100%
2	Efficient roller mills for coal grinding	70%	81%	100%
3	Installation of Variable Frequency Drive (VFD) & replacement of coal mill bag dust collector's fan	64%	90%	100%
	Raw materials preparation			
4	Raw meal process control for vertical mill	10%	10%	100%
5	High efficiency classifiers/separators	42%	43%	100%
6	High efficiency roller mill	89%	119%	100%
7	Efficient transport system	49%	75%	100%
8	Raw meal blending (homogenizing) systems	46%	70%	100%
9	VFD in raw mill vent fan	77%	84%	100%
10	Bucket elevator for raw meal transport	42%	62%	100%
11	High efficiency raw mill vent fan w/inverter	101%	127%	100%
	Clinker making	**2020**	**2025**	**2030**
12	Replacing Vertical Shaft Kilns with New Suspension	123%	152%	100%
13	Conversion to grate cooler	20%	30%	100%
14	Upgrading to a preheater/precalciner Kiln	50%	80%	100%
15	Kiln shell heat loss reduction (Improved refractories)	36%	42%	100%
16	Membrane-method oxygen-rich combustion	27%	52%	25%
17	Energy management & process control systems	53%	67%	100%
18	Older dry kiln upgrade to multi-stage preheater kiln	46%	72%	100%
19	Upgrading preheater from 5 stages to 6 stages	43%	67%	100%
20	Optimize heat recovery/upgrade clinker cooler	33%	52%	100%
21	Optimize grate cooler	82%	93%	100%
22	Combustion system improvements	10%	10%	100%
23	Low temperature Waste Heat Recovery for power generation	98%	114%	100%
24	Adjustable speed drive for kiln fan	53%	82%	100%
25	Low pressure drop cyclones for suspension preheater	83%	107%	100%
26	Bucket elevators for kiln feed	50%	79%	100%
27	Use of high efficiency preheater fan	51%	71%	100%
28	Efficient kiln drives	64%	83%	100%
29	VFD in cooler fan of grate cooler	65%	65%	100%
	Finish grinding	**2020**	**2025**	**2030**
30	Energy management & process control in grinding	70%	89%	100%
31	Replacing a ball mill with vertical roller mill	15%	15%	100%
32	High pressure roller press for ball mill pregrinding	47%	63%	100%
33	Improved grinding media for ball mills	15%	15%	100%
34	High-Efficiency classifiers (for finish grinding)	48%	58%	100%
35	High efficiency cement mill vent fan	43%	43%	100%
	General measures	**2020**	**2025**	**2030**
36	High-efficiency motors	55%	55%	100%
37	Adjustable speed drives	45%	45%	100%

	Alternative Fuel	**2020**	**2025**	**2030**
38	Wastes and biomass	10%	10%	60%
	Product change	**2020**	**2025**	**2030**
39	Blended cement	40%	40%	70%

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