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Energy and Environmental Innovation for Growth in California

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Research Papers on Energy, Resources, and Economic Sustainability

This report is part of a series of research studies into alternative energy and resource pathways for the global economy. In addition to disseminating original research findings, these studies are intended to contribute to policy dialogue and public awareness about environment-economy linkages and sustainable growth. All opinions expressed here are those of the authors and should not be attributed to their affiliated institutions.

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Executive Summary

With the passage of the Global Warming Solutions Act (Assembly Bill 32) in 2006, the state of California embarked on a new path toward more sustainable economic growth. California's response to rising levels of global warming pollution (GWP) has drawn the world's eighth largest economy into an unprecedented policy dialogue that will influence energy and environmental decisions around the world. Within the state, it is widely acknowledged that GHG policies already implemented and under consideration will have far reaching economic consequences, yet the basis for evidence on these effects remains weak. This report is part of a series of studies that will improve public and private awareness of climate policy options and their economic implications.

Two central perspectives emerge in the present analysis. Firstly, although climate change is in the first instance about environmental processes, for society it represents a momentous economic agenda. Both the risks of climate damage and the rewards of effective adaptation implicate the most fundamental determinants of our livelihoods, including employment, income, and consumption patterns. Secondly, the public interest in climate change is so great that national, state, and local government all have responsibility to address it, yet public intervention can never meet this challenge alone. To achieve the changes needed for a sustainable, low carbon future, the creative and economic resources of private agency must be committed to far-reaching innovation.

Our estimates indicate that California's current policy commitments, as expressed in the Air Resources Board's recent Draft Scoping Plan, can achieve the state's 2020 emission targets and promote economic growth by doing so. Moving beyond this to the longer term goals of 2050, however, will require nothing less than a New Green Revolution. While its predecessor focused on rural households, farming, and food in poor societies, this revolution will fundamentally alter behavior, technology, and resource use across modern society. To achieve such change will require combined hard (technological) and soft (institutional) innovation on a scale that is probably unprecedented.

To effectively support this transformation, governments need to enunciate clear objectives, sustained commitments, and flexible, incentive based solutions. In this report, we review a broad spectrum of innovation opportunities across the California economy, suggesting how each might contribute to a more energy efficient, low carbon future. If energy and environmental innovation take their rightful place among the state's knowledge intensive industries, California can become a vibrant incubator for the New Green Revolution, securing its energy future and extending its legacy of prosperity through innovation.

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1. Introduction

In September 2006, California became the first U.S. state to formally embark on a low carbon path to the future. The Global Warming Solutions Act (Assembly Bill 32, or AB 32), signed by the Governor and passed by the state legislature, commits California to reduce its Global Warming Pollution (GWP) to 1990 levels by 2020, and by 80 percent over 1990 levels by 2050. Neither of these goals will be met as a matter of course. Achieving the nearer-term target will require an estimated 170 million metric ton reduction in Global Warming Pollution against California's business as usual baseline, representing approximately a 30 percent reduction in projected 2020 emissions. Achieving the longer-term target will require fundamental changes in the way that Californians produce and use energy.

Innovation, from simple changes in energy use to advanced technologies, will be crucial to attainment of these goals. California has a long history of leadership in technology and policy innovation, and AB32 provides the state with an opportunity to solidify its leadership in U.S. and indeed global climate policy. Moreover, by creating conditions favorable to incubating energy efficient technologies, the state can also to extend its leadership in research and development for products, practices, and institutions that advance energy efficiency, low carbon energy production, recycling, GWP-neutral manufacturing and agriculture, and the policies that encourage innovation and adoption

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of these technologies. By revenue, energy is the world's largest industry. Because this product so pervades today's economy, efficiency can do for energy what ICT did for management and logistics, deliver innovation that revolutionizes traditional practices around the world. This will save money in the production of every single modern good and service. In this era of escalating energy prices, demand for energy innovation will grow robustly even without environmental regulation. Additional demand induced by climate action will trigger a tsunami of global demand for new energy use technologies, from hybrid vehicles to compact fluorescent light bulbs. By integrating energy and environmental innovation with its other knowledge intensive industries, California can become a vibrant incubator for the New Green Revolution, securing its energy future and extending its legacy of technology driven prosperity.

In this report, we review AB32's basic commitments, discuss its long term implications, and provide new estimates of nearer term economic impacts. Finally, the report presents and synthesizes a broad range of options for the kind of innovation and adoption strategies that can help the state achieve its ambitious climate and energy security goals.

In addition to many detailed estimates and discussion below, a few salient findings deserve emphasis:

- California can meet its nearer term objectives without compromising aggregate economic growth objectives. Indeed, the policies currently recommended by ARB for implementation of AB32 will achieve higher real GSP and employment by 2020.
- If the state can also increase its energy efficiency modestly above historical trends, these policies will be accompanied by employment growth of about half a million new jobs by 2020.
- California needs an explicit innovation agenda that has flexible targets, tracks progress in technologies, and reviews policies periodically to make sure that the state is on track.
- Timing is important – Early action to promote large-scale investment in R&D and cost reductions in existing technologies will confer multiplier gains from low hanging fruit, help avoid fossil fuel infrastructure trade-offs, and to capture one-time savings from longer-lived infrastructure, such as buildings, by 2020.
- In the nearer term, focus should be on efficiency improvements in vehicles and electricity and heating, but as population growth begins to overcome the benefits of efficiency investments, technologies must be ready to offset rises in net emitting fossil fuels (between 2020 and 2030).

- The negative net costs in energy efficiency drive the net positive economic effects of climate policies in the near term, but these are mostly from capturing gains at the very inefficient side of the spectrum; important for financing more expensive abatement options later
- Total direct employment generated directly by AB 32 is a relatively small fraction of the jobs the state needs to create over the next two decades. Broader employment considerations should be part of a review of the state's business environment and longer term innovation strategy.

2. An Overview of AB 32

AB 32 is a state-level initiative that seeks to establish precedence and leadership in U.S. and international climate policy. Although California is the world's eighth largest economy and twelfth largest emitter of greenhouse gases, the state accounted for less than ten percent of U.S. and less than two percent of global CO_2 emissions in 2005.[2] Unilateral efforts by California will not reduce either U.S. or global Global Warming Pollution to a meaningful extent. Alternatively, with a federal climate policy increasingly likely under the next U.S. presidential administration, California has an opportunity to influence the design and implementation of federal climate policy, to gain experience with managing the complex regulatory regime and innovation agenda that will accompany AB 32, and to take the lead in attracting investment in low and zero carbon technologies.

Table 2.1: AB 32's Implementation Timetable

Date	Activity
September 27, 2006	**AB 32 Signed into Law**
June 30, 2007	**Early Action Measures (plan)** California Air Resources Board (ARB) developed list of early action measures, to be adopted in 2010
January 1, 2008	**Mandatory Emissions Reporting** ARB established GWP reporting and monitoring system; largest emitters required to report emissions on an annual basis
January 1, 2008	**GWP Emissions Baseline Determination** ARB determined 1990 emissions levels and emissions cap for 2020
January 1, 2009	**Scoping Plan for Cost-Effective Implementation** ARB develops scoping plan for how the 2020 cap can be met in a cost-effective manner
January 1, 2010	**Early Action Measures (adoption)**
January 1, 2011	**Implementing Regulations** ARB develops specific regulations to achieve reductions
January 1, 2012	**AB 32 Takes Effect**

Source: Adapted from Union of Concerned Scientists (UCS) AB 32 fact sheet,
Online at: http://www.ucsusa.org/assets/documents/global_warming/AB-32-as-passed-fact-sheet.pdf.

AB 32 also comes at a strategic moment for energy planning in California. As we describe in greater detail below, since the late 1990s California has become an increasingly large importer of oil and natural gas — the state's two main primary energy

[2] Energy Information Administration (EIA) website, www.eia.dov.gov.

sources. Continued population and energy demand growth will increase this import dependence, straining California's existing energy infrastructure and making its economy more vulnerable to energy supply disruption and potentially to price volatility. Through facilitating improvements in end use energy efficiency and diversifying primary energy sources, AB 32 will be an important part of state agency efforts to plan for a reliable, cost-effective supply of energy for California over the medium- and long-term future.

Regardless of the extent to which AB 32 targets are met through regulatory measures or markets, public sector involvement in AB 32 will be ubiquitous. AB 32 requires an array of public sector support activities, including public science to set baselines and monitor emissions, planning to ensure well-sequenced policies, market design to ensure that solutions are cost-effective, and regulatory teeth to ensure compliance. The preparatory work required before AB 32 takes effect in 2012, shown in Table 1, gives a sense of the strong creative, coordinating, and regulatory role that state agencies will play in California's climate change mitigation efforts. All of the activities in Table 1 are the charge of the California Air Resources Board (ARB), which is the lead agency implementing AB 32. Three other state agencies — the California Environmental Protection Agency (CalEPA), California Energy Commission (CEC), California Public Utilities Commission (CPUC) — will also play important roles in AB 32 implementation, and we will refer to all four agencies frequently throughout this report.

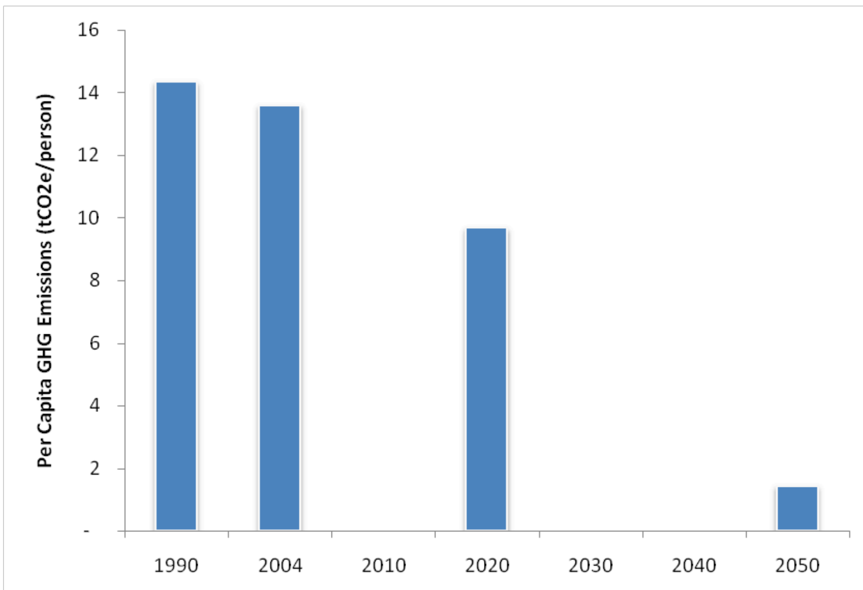
In the nearer term, AB 32 will require the state to reduce Global Warming Pollution to 1990 levels by 2020. Given the uncertainty associated with projecting state emissions for 2020, the absolute level of reduction required between 2012 and 2020 is a moving target. Population growth, economic growth, and other demographic variables can significantly affect California's baseline emissions growth. Current official projections estimate the state's 2020 Global Warming Pollution at 596 million metric tons CO_2 equivalent (mmtCO_2e), which would represent growth of 169 mmtCO_2e over 1990 emissions (427 mmtCO_2e).[3] This 169 mmtCO_2e, which we round to 170 mmtCO_2e in this report, is the estimated level of reductions required to bring baseline 2020 emissions down to 1990 levels.

In the longer term, AB 32 will require a fundamental transformation of California's economy, while requiring the removal of the bulk of atmospheric carbon emissions from state's energy systems. Reducing Global Warming Pollution by 80 percent over 1990 levels by 2050 would require at least a fixed reduction of 341.6 mmtCO_2e, but the actual reduction needed to meet this goal may be much larger depending on population growth

[3] California Air Resources Board (ARB), Draft Scoping Plan, Sacramento, California, 2008. This 2020 business as usual estimate is slightly lower than the 600 mmtCO_2e and 173 mmtCO_2e reductions that ARB had been previously using.

in California post 2020. Such a dramatic fall in emissions would leave 85 $mmtCO_2e$ to be shared by a projected state population of 59.5 million people in 2050, or per capita emissions of 1.44 tCO_2e, a nearly ten-fold reduction over 2004 per capita emissions of 13.59 tCO_2e (Figure 1). While this scale of reduction is not feasible with current technologies, technology and land use decisions made in the next decade will determine whether such a large-scale decarbonization of the state's economy can be achieved. In that sense, AB 32's 2020 goal should be seen as placing the state on a trajectory to meet its 2050 goal, rather than as an endpoint in itself. Still, meeting the 2020 target is important for maintaining the credibility of the 2050 end goal.

Figure 2.1: Per Capita GWP Emissions in California, 1990, 2004, and AB 32 Targets for 2020 and 2050



Sources: Emissions data are from California Energy Commission (CEC), Inventory of California Global Warming Pollution and Sinks: 1990-2004*, Sacramento, California, 2006; population data are from State of California, Department of Finance (DOF),* Population Projections for California and Its Counties 2000-2050, by Age, Gender and Race/Ethnicity, *Sacramento, California, 2007.*

To put these issues in perspective, we consider two time horizons, compatible with the target milestones of AB32. Looking to the near horizon of 2020, we have a well articulated set of climate strategies like those covered in the Air Resources Board's scoping plan. Because these policies are clearly specified and soon to be implemented, we analyze their economic consequences in detail in the next section. For the farther horizon (2050), it is more appropriate to inform public and private thinking heuristically, reviewing a wider range of adjustment options that can be adopted over the next generation. In the following caption, we give an example of the kind of conceptual exercises that will be needed as we move beyond short term implementation priorities to address more ambitious goals for climate change mitigation and adaptation.[4]

A Moment's Reflection on a Generation of Change:

The Prospect of Low Carbon California by 2050

Much of the world of 2050 lies beyond the realm of detailed analysis. Nonetheless, it is useful to consider more impressionistically what a California that has met AB 32 goals might look like. The following thought experiment, focusing on electricity and light duty vehicles, gives a sense of the magnitude of the dramatic transformation of energy systems and lifestyles that is needed before 2050, and the importance of timing in meeting longer-term climate goals.

From 2020 to 2050 California is committed to reducing Global Warming Pollution from at most 427 to 85.4 million metric tons carbon equivalent (mmtCO_2e). By 2050, California's population is expected to reach 59.5 million people, a 15.4 million (35 percent) increase over its projected 2020 population.

Now assume, for the sake of discussion, that the following two things are true of California in 2050:

- Through dramatic improvements in efficiency, per capita electricity consumption in the state falls by roughly 40 percent over 2006 levels (8,250 kWh/person) to 5,000 kWh/person, a decline of roughly 1 percent per year. Through these efficiency improvements electricity consumption in 2050 (298 GWh) remains largely unchanged from its 2006 levels (295 GWh).
- In 2050, with better planning and smart growth the average California household (2.93 persons, 2006 average) travels 35 vehicle miles per day (12,775/year), a 26 percent reduction against the California Air Resources Board's 2050 baseline. New high efficiency vehicles get 75 miles per gallon gasoline equivalent (a 3.4-fold increase over 2007 levels of 22.2 mpg), which would mean the average Californian requires 0.2 gallons of gasoline equivalent per day, or 58 gallons/year.

Assuming, hypothetically, that shares of California's Global Warming Pollution have been reduced in proportion to 2004 emissions, so that the electricity sector is allocated 22 percent of 2050 emissions (19.0 mmtCO_2e) and the transportation sector is allocated 41 percent of 2050 emissions (34.8 mmtCO_2e). Assume also

[4] The issue of adaptation per se will be addressed in a fourth study of this series, appearing in November, 2008

that passenger vehicle emissions are proportional to 2004 levels (62 percent of total emissions), which gives passenger vehicles an emissions allocation of 21.6 mmtCO_2e.

For the electricity sector, 19 mmtCO_2e/year is equivalent to 46.9 GWh/year from high-efficiency (50 percent thermal) combined cycle natural gas plants. Assuming that these plants are running for 7,446 hours/year (i.e., a capacity factor of 0.85), this would imply a natural gas installed capacity of 6.3 GW by 2050. California had 40.4 GW of natural gas-fired generation capacity in 2007, which implies that nearly 85 percent of California's 2007 natural gas generation capacity would have to be retired or retrofitted with carbon capture and storage (CCS) technology before 2050. Put another way, using the state's 2006 generation mix as a baseline, California would need 124 GWh of new generation, or 42 percent of the state's 2006 generation, from net zero carbon sources by 2050. Eighty-four percent of California's electricity in 2050 would be generated with sources that have net zero carbon emissions.

At 58 gallons of gasoline equivalent per capita, California would need 3.5 billion gallons/year in 2050 to meet demand for vehicle fuel. It is important to note what a tremendous reduction in transportation energy demand this would be; total gasoline sales, of which light duty vehicles represent the majority, in California were 15.7 billion gallons in 2007. If by 2050 light duty vehicles are running solely on gasoline their emissions would be 31.7 mmtCO_2e, or 10.1 mmtCO_2e more than their 21.6 mmtCO_2e allocation. Reducing emissions to meet that limit would imply that 32 percent, or 1.1 billion gallons gasoline equivalent, of the fuel used in passenger vehicles generates no net carbon emissions. To put that number in context, 1.1 billions gasoline equivalent equates to 1.6 billion gallons of zero net carbon ethanol, or 12 percent of world ethanol production in 2007.

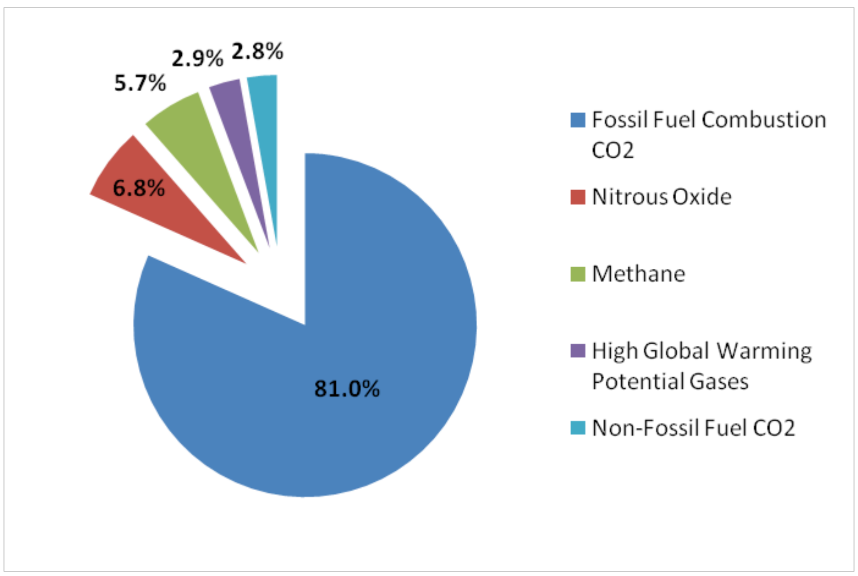
This example is only meant to be illustrative. There is no reason to think, for instance, that Global Warming Pollution reductions by sector will be proportional to 2004 emissions shares. It does, however, highlight the magnitude, the timing, and some of the trade-offs of emission reduction strategies. If 2050 Global Warming Pollution are concentrated in one sector (e.g., transportation), steeper cuts will be required in other sectors (e.g., electricity). In any instance, the reductions required in production from non-CCS equipped fossil fuel-based facilities will dramatically change the state's energy infrastructure. Given the longevity of fossil fuel infrastructure, sending signals that optimize long-term energy infrastructure investment will be one of the most important dimensions to managing the costs of California's energy transition.

Sources: Population estimates and projections are from the California Department of Finance; electricity data are from the California Energy Commission; emission factors are from IPCC guidelines; VMT of 35 miles/household-day is from James Goldstene, "Smart Growth Strategies for Addressing Greenhouse Gases: The California Story," Presentation at New Partners for Smart Growth, February 2008, Washington DC; California gasoline sales for 2007 are from the California State Board of Equalization; world ethanol production data are from the Renewable Fuels Association website; all other data are based on commonly used conversion factors.

3. Global Warming Pollution in California

Reducing emissions to levels needed to meet both the 2020 and 2050 goals will require strategies to change the way energy is produced and consumed in California. The majority of California's Global Warming Pollution — 81 percent in 2004 — result from the release of carbon dioxide (CO_2) into the atmosphere as a result of fossil fuel combustion. Nitrous oxide (N_2O) emissions from agricultural soils and methane (CH_4) produced from agricultural activities and landfills comprise the bulk of the remainder (Figure 2).

Figure 2. Global Warming Pollution in California, 2004



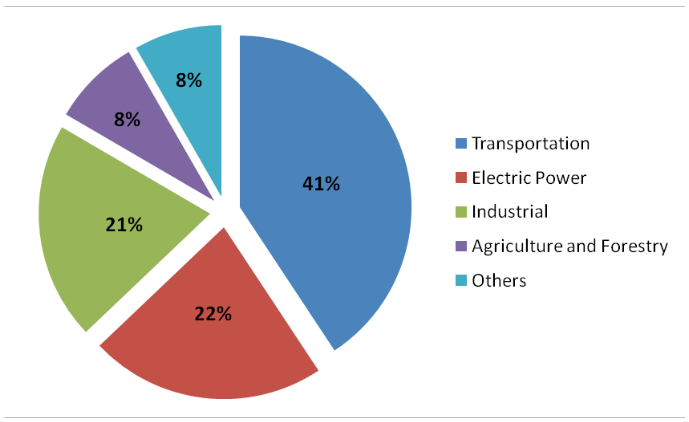
Source: CEC, 2006.

Unlike most other U.S. states, the transportation sector is California's predominant source of Global Warming Pollution (Figure 3).[5] Transportation's share of Global Warming Pollution in California is nearly double that of the electricity sector, which

[5] The shares reported here and in Figure 2 are from the CEC's GWP inventory for California. Because of different categories and methods, the CEC's shares are significantly different than those compiled by the Department of Energy's Energy Information Administration (EIA). For California, the EIA estimates that in 2004 transportation and the power sector accounted for 57 and 12 percent of GWP emissions, respectively. For the U.S. as a whole, EIA estimates for these shares are 33 and 39 percent, respectively. There are 8 other states that have an energy profile similar to California: Connecticut, Idaho, Maine, New Jersey, New York, Oregon, Rhode Island, and Washington.

dominates in most other states. This discrepancy is not the product of a disproportionately active or polluting transportation sector; California ranked 40th among U.S. states in per capita highway travel in 2005,[6] its per capita gasoline consumption is below the U.S. average,[7] and it has historically been a leader in driving higher emissions and, more recently, fuel economy standards. Instead, California's electricity sector is a lesser source of emissions vis-à-vis other states because of the low proportion of coal and high proportion of hydropower in California's electricity generation mix, and because of California state agencies' success in reducing per capita electricity consumption over the past 30 years.

Figure 3. Sources of Global Warming Pollution in California, 2004



Source: CEC, 2006.

Industry and agriculture are, perhaps surprisingly, larger shares of total Global Warming Pollution than the average for U.S. states (Figure 3). California has a vibrant, diverse manufacturing sector that produces everything from semi-conductors to furniture and employs nearly 10 percent of the state's population.[8] California is also the largest agricultural producer and exporter in the U.S.,[9] and, although agriculture is a small percentage of gross state product (GSP), the agricultural sector has extensive input and employment linkages with the rest of the California economy.[10] Managing the adjustment burden imposed on these two sectors will be important for controlling the

[6] Department of Transportation Bureau of Transportation Statistics (BTS) website, online at: http://www.bts.gov/publications/state_transportation_statistics/

[7] Energy Information Administration (EIA) website, www.eia.doe.gov.

[8] California Employment Development Department (EDD) website, online at www.labormarketinfo.edd.ca.gov/?pageid=145.

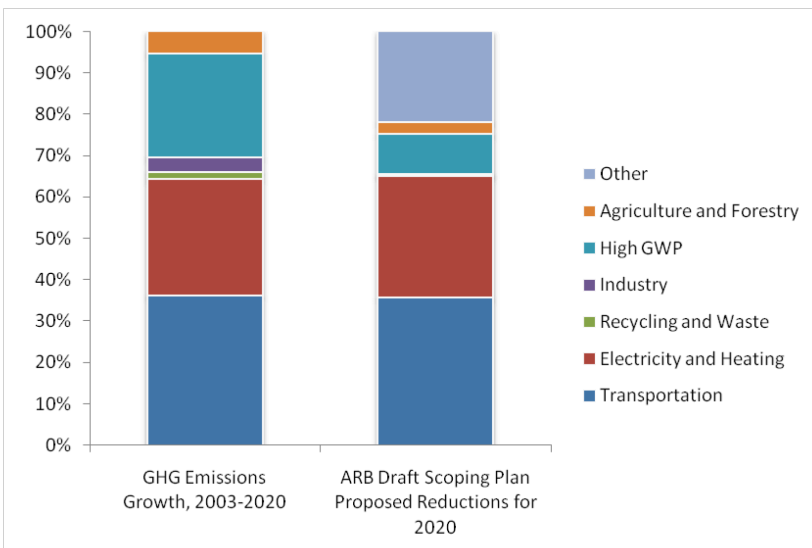
[9] U.S. Department of Agriculture Foreign Agricultural Service (USDA FAS), "Trade and Agriculture: What's at Stake for California?" November, 2007. Online at: http://www.fas.usda.gov/info/factsheets/WTO/states/ca.pdf.

[10] University of California Agricultural Issues Center (UCAIC), "The Measure of California Agriculture: Highlights," July 2006. Online at: http://aic.ucdavis.edu/research1/mocahighlights06.pdf.

costs associated with AB 32 implementation. Alternatively, neither sector is expected to be a major source of growth in Global Warming Pollution over the next two decades, and efforts to meet nearer-term targets will focus principally on reducing emissions growth.

More than 60 percent of the AB 32 target for 2020, or 104 mmtCO_2e by current estimates, must be met by reducing growth in emissions since 2004. Nearly 85 percent of the growth in California's Global Warming Pollution from during this period is expected to come from 3 sources: electricity, transportation, and high global warming potential (GWP) gases.[11] Electricity and transportation emissions will be driven primarily by population growth; the substantial growth in emissions from high GWP gases is largely the result of refrigerant leakage and disposal. Mirroring anticipated growth, ARB's Draft Scoping Plan envisages that 74 percent of reductions will come from reductions in emissions from electricity, transportation, and high GWP gases, with the bulk of the remainder coming additional emissions reductions from capped sectors (Figure 4).

Figure 4. Shares of Growth in GWP Emissions and Proposed 2020 Reductions



Source: ARB, 2008.

ARB's Draft Scoping Plan proposes that roughly 40 percent of greenhouse gas emission reductions by 2020 will come from improvements in transportation and electricity and heating end use efficiency. These improvements will build on California's impressive strides in reducing per capita energy use over the past 30 years. A carbon neutral California is, however, not a per capita goal. Population growth will continue to

[11] ARB, 2008.

push the state's Global Warming Pollution higher, even as reductions in emissions per capita allow California to meet its nearer-term goals. To begin the transition toward a low carbon economy by 2050, California will need a revolution in energy technologies that make absolute reductions in California's current consumption of oil and natural gas.

4. AB 32 and California's Energy Challenges

Fossil fuels represent over three-quarters of California's energy supply, dominated by Oil (46 percent) and natural gas (27 percent).[12] Crude oil is the primary feedstock for a broad spectrum of petroleum products, particularly gasoline and diesel fuel, that power the state's transportation systems. Natural gas is California's primary fuel for generating electricity, for water and space heating, cooking, and as an energy carrier for industrial processes. Over the past two decades, California has become increasingly dependent on imported fossil fuel energy supplies, and its energy import dependence will continue to increase as overall and source-specific energy demand grows and state oil and natural gas production fall.

Over the next two decades California's growing dependence on energy imports will increase the state's exposure to energy supply disruptions and price volatility, and will require a significant expansion of its energy import infrastructure. Through mandates and incentives for higher end use energy efficiency and a preliminary diversification of the state's primary energy sources, AB 32 provides a means for California to improve the reliability of the state's energy supplies, to reduce its vulnerability to higher fossil fuel prices and price fluctuations, and to minimize the capital investments in energy transport infrastructure needed to sustain fossil fuel supplies. These positive externalities to AB 32 are important, both because global fossil fuel energy prices and the security of global energy supplies are unlikely to return to levels seen during the 1980s and 1990s,[13] and because the longevity of fossil fuel energy infrastructure has the potential to create expensive cost recovery issues for underutilized infrastructure over the next four decades.

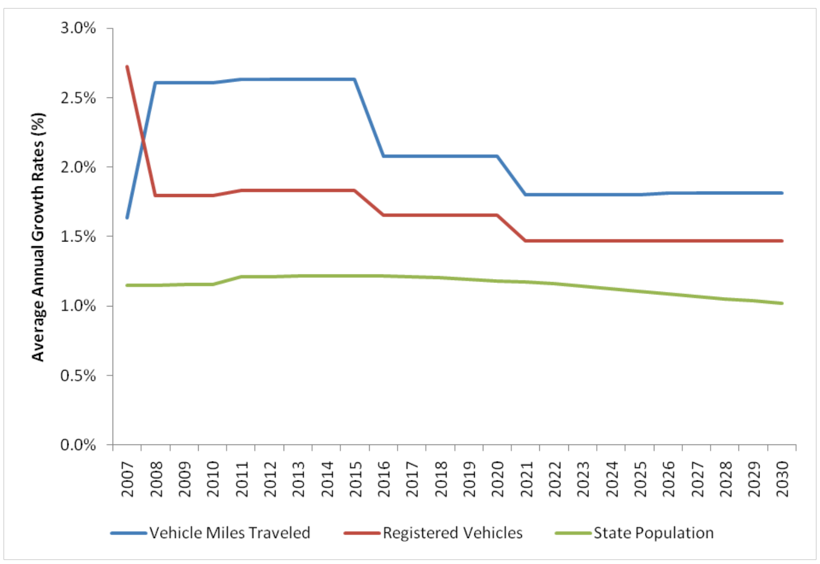
Crude Oil

California's petroleum dependence is the result of both historical land use decisions and the state's position as a trade link between the U.S. and Asia. At 24 million in 2000, California has the largest number of registered vehicles in the U.S.,[14] and southern

[12] California Energy Commission (CEC) website, online at: www.energy.ca.gov.
[13] International Energy Agency (IEA), *World Energy Outlook 2007*, Paris, IEA/OECD, 2007.
[14] Registered vehicles from California Energy Commission and California Air Resources Board, 2003, "Reducing California's Petroleum Dependence.", largest in U.S. from EIA website.

California in particular has a high automobile dependency. California also has three of the five largest ports in the U.S.,[15] and California's shipping industry has experienced a boom as U.S. trade with Asia, and particularly China, has increased over the past two decades. The California Department of Transportation forecasts the number of registered vehicles will reach 33.58 million by 2020 and 38.87 by 2030, with the growth in both registered vehicles (1.7 annual) and vehicle miles traveled (2.1 percent annual) exceeding population growth estimates (1.2 percent annual) from 2006-2030 (Figure 5). The CEC projects that gasoline, diesel, and jet fuel demand will grow by between 13.5 to 42.8 percent from 2005-2030.[16] In the absence of countermeasures to manage demand, meeting this scale of consumption growth would require a significant expansion of the state's petroleum refining and distribution infrastructure.

Figure 5.1: Forecasted Growth in California Vehicle Miles Traveled, Registered Vehicles, Population, 2007-2030



Sources: VMT and registered vehicle data are from California Department of Transportation, 2007 California Motor Vehicle Stock, Travel and Fuel Forecast*, Sacramento, California, 2008; population projections are from DOF, 2007.*

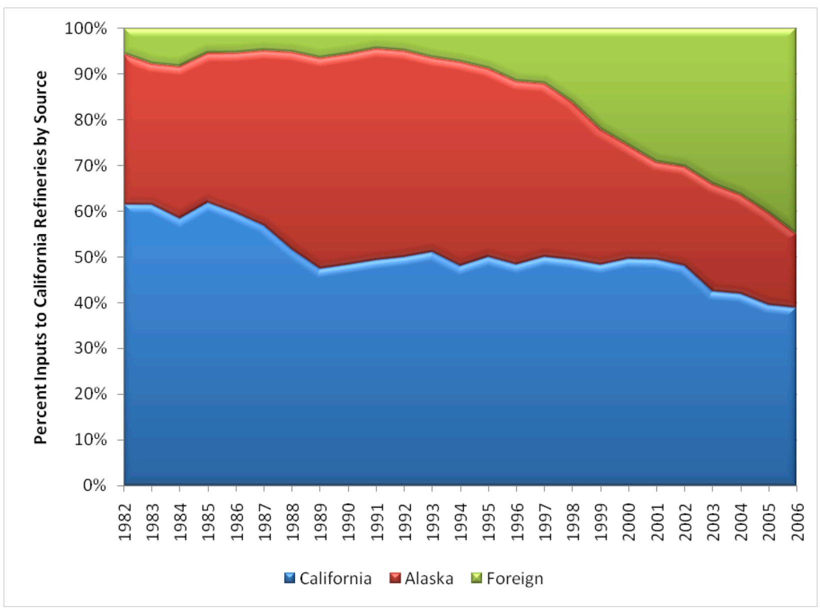
The nation's fourth largest oil producer, California has historically been a major supplier of refined petroleum products for both itself and the western U.S. California produced

[15] BTS website, "California Transportation Profile 2002," online at: http://www.bts.gov/publications/state_transportation_statistics/california/index.html.

[16] California Energy Commission (CEC), "Transportation Energy Forecasts for the 2007 Integrated Energy Policy Report," Sacramento, California, September 2007.

most of its own oil throughout its history and until the late 1990s. As late as 1997, California refineries still sourced more than half of their inputs in-state.[17] This continued apparent self-sufficiency occurred against the backdrop of declining in-state production. California's annual oil production peaked at 424 million barrels (bbl) in 1985 and had declined at an annual average of 2.5 percent to 249 bbl, or less than 60 percent of peak levels, by 2006.[18] As state oil production began to decline, California refineries' oil supplies were initially buffered by crude imports from Alaska; these, however, peaked in 1989, and since the mid-1990s California has become increasingly reliant on foreign oil imports to meet demand at refineries. As late as 1995, less than 10 percent of California's refinery inputs were from foreign sources. By 2006, more than 45 percent of California's refinery inputs (656 million bbl/year) were from abroad (Figure 6).[19]

Figure 5.2: California Refinery Inputs by Source



Source: CEC website.

In the face of growing in-state and west coast demand for petroleum products, California refineries' domestically sourced oil supplies are expected to continue to decline over the next two decades. California's own demand is expected to grow markedly in the absence of policy intervention; the CEC projects that pipeline exports to

[17] CEC website.
[18] Division of Oil, Gas & Geothermal Resources (DOGGR), "Annual Report of the State Oil & Gas Supervisor 2006," Sacramento, California, 2007.
[19] The above data are from the CEC website.

Arizona and Nevada will increase by 50-65 percent by 2025.[20] In-state crude oil production in California is expected to decline by an annual average of 2.2-3.5 percent through 2019,[21] while Alaska North Slope oil production is declining at 5 percent per year.[22] Based on these trends, California's crude oil imports would need to grow by 37-65 percent by 2025, with the large range in this CEC estimate stemming from uncertainty in rates of decline in in-state production, policy measures to reduce demand, and demographics.[23]

Even without increases in demand, declining in-state production will strain California's oil import infrastructure. Current petroleum marine terminal, storage tank, and gathering pipeline capacity in California could be inadequate by as early as the middle of the next decade, and with higher certainty by 2025.[24] Investments in petroleum infrastructure are capital-intensive and the infrastructure itself is long-lived. If these investments are made to meet "peak" demand for petroleum products over the next two decades, the precipitous decline in petroleum use in the California economy required between 2030 and 2050 could potentially strand these assets, requiring expensive interventions. California's transition to a predominantly oil importing economy will require further investments in petroleum infrastructure, but these should be considered within an "avoided cost" framework similar to the one that has guided investments in the state's electricity sector.

Sourcing petroleum imports will entail a trade-off between supply vulnerability and the California's climate policy goals. A growing share of conventional crude imports will mean greater dependency on historically less stable regions; more than 12 percent of California's foreign oil imports in 2005 came from Iraq, for instance.[25] As some proposals have suggested,[26] shifting to unconventional oil sources, such as tar sands from Canada or oil shale from the Rockies, might ensure greater reliability of supply. However, a shift toward unconventional oil sources would contravene the spirit of AB 32; both tar sands and oil shale have a significantly higher carbon footprint than conventional crude.[27] California's low carbon fuel standard (LCFS) will, in all likelihood, prevent unconventional crude from entering the state's oil supplies, but will also increase the state's reliance on imports from OPEC countries. While efficiency and

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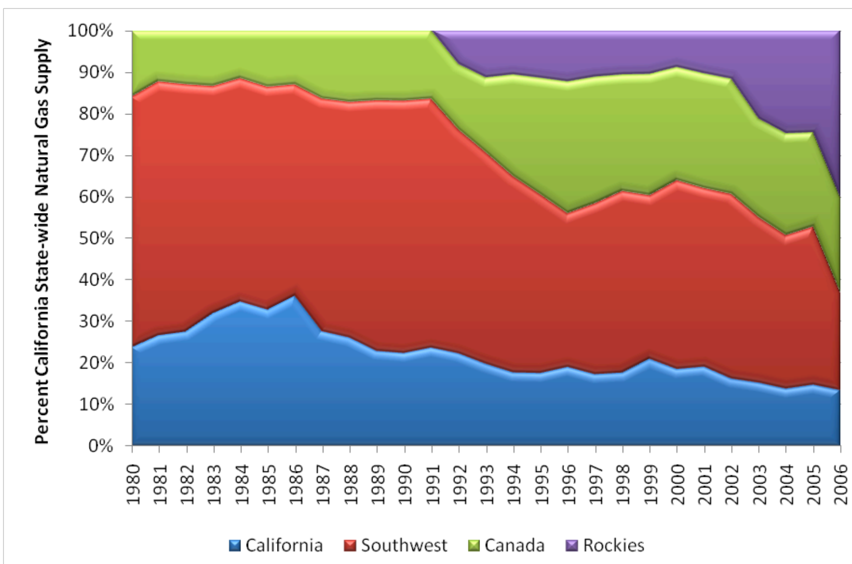
[20] CEC, 2007.
[21] Schremp, Gordon, "Outlook for Crude Oil Imports into California," CEC Presentation, 2007. The actual rate of decrease in California oil production will depend on whether the decline in production more closely resembles its long-run average of 2.2 percent, or its short-run average of 3.5 percent.
[22] Sheridan, Margaret, "California Crude Oil Production and Imports," CEC Staff Paper, April 2006.
[23] CEC, 2007.
[24] CEC, 2007.
[25] CEC website.
[26] See, for instance, California Energy Commission (CEC), "Long Term Crude Oil Supply and Prices," ICF Consultant Report, Sacramento, California, September 2005.
[27] Brandt, Adam and Alex Farrell, "Risks of the Oil Transition," *Environmental Research Letters* (1), 2006.

higher hybrid penetration will reduce oil demand at the margin, presently there are no obvious substitutes for oil.

Natural Gas

Since the early-1980s, natural gas has become the dominant feedstock used in electricity generation and heating in California. At the time, natural gas was seen as a cleaner-burning alternative to heavier hydrocarbons, or in California's case, fuel oil. This reputation as the "clean" fossil fuel has solidified over time, and, more recently, has driven demand for natural gas in the western U.S. as a substitute for coal in power generation. California's own increased dependence on natural gas has been paralleled by an increase in demand in other states and other countries, and a decline in production both in California and North America. Although the physical scarcity of natural gas is not usually discussed in the same vein as crude oil, as global demand for natural gas increases economic scarcity (i.e., due to supply constraints) will drive up prices.

Figure 5.3: California Natural Gas Supplies



Source: CEC website.

Over the past three decades California has never supplied more than 36 percent (in 1986) of its natural gas demand. Annual natural gas production in California peaked at 714.9 bcf in 1968, falling to 327.2 bcf by 2006.[28] Nevertheless, the portion of own demand that California does produce has shrunk considerably since 1986, to less than

[28] DOGGR, 2007.

14 percent in 2005 (Figure 7). Natural gas imports from the U.S. Southwest and Canada have peaked and fallen over time, and with a surge since 2003 the Rocky Mountain Basin became the largest source of natural gas imports for California in 2006. California is the last stop along five major natural gas pipelines that extend from these three regions, and with growing demand for natural gas in western states California faces greater competition for supplies. California's demand for natural gas is expected to grow significantly slower than the U.S. as a whole, mostly due to rapidly expanding demand for natural gas in the electricity sector.[29] A national climate policy will only exacerbate this competition by encouraging fuel switching from coal to natural gas; on an energy basis natural gas (56.1 tCO_2/TJ) emits just over half as much CO_2 as coal (96.1 tCO_2/TJ).[30]

Foreign imports of liquefied natural gas (LNG) are expected to help expand California's natural gas supply options and stabilize prices.[31] However, the expansion of LNG terminals along the western coast of North America and potentially in California will bring the state more directly into the emerging global market for natural gas. Historically, although natural gas prices have generally moved in step with world oil prices because of inter-fuel substitutability, natural gas markets have been regionalized because of the difficulty of transporting natural gas by sea. LNG allows for arbitrage in regional markets, which will lead to greater convergence in regional natural gas prices and the emergence of a global price for natural gas, similar to what exists for crude oil. Particularly as a result of rising demand from the EU, the International Energy Agency (IEA) projects that natural gas prices will increase significantly by 2030.[32] Again, a global climate agreement will put even greater pressure on natural gas prices as coal-natural gas substitution becomes more economically attractive.

Natural gas prices are an important consideration for economic planning in California because the state's economy has become and is expected to become increasingly dependent on natural gas. In 2006, natural gas powered 41.5 percent of California's electricity supply, an increase from a 33 percent share in 1991.[33] Even with growth in alternative sources, the share of natural gas in California's generation portfolio is likely to remain stable or grow as contracts for imported coal-fired electricity, no longer renewable under SB 1368, expire and these contracts are replaced by natural gas-fired generation. In addition, new potential uses of natural gas as a feedstock for transportation fuels — either to generate electricity for plug-in hybrid of fully electric

[29] California Energy Commission (CEC), "2007 Final Natural Gas Market Assessment," Sacramento, California, December 2007.
[30] Intergovernmental Panel on Climate Change (IPCC), *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Hayama, Japan: IGES, 2006.
[31] California Energy Commission (CEC), *Integrated Energy Policy Report 2007*, Sacramento, California, 2007.
[32] IEA, 2007.
[33] CEC website.

vehicles or as a feedstock for synthetic fuels and hydrogen — could significantly increase the share of natural gas in California's primary energy mix, as it displaces crude oil. In this context, the state's renewable portfolio standard (RPS) looks less like a climate policy and more like an energy security policy.

Implications of Declining In-State Fossil Fuel Production

Declining in-state oil and natural gas production pose somewhat different challenges to the California economy. Falling oil production in California means lower state revenues from and employment in the oil sector, which lessens any potential state benefits of higher oil prices. Declining state natural gas production comes as in-state, regional, and global natural gas demand is on the rise and potential uses for natural gas are expanding, putting sustained upward pressure on prices and potentially increasing price volatility. For both oil and natural gas, decreasing consumption per GSP — either through improved end use efficiency or fuel substitution — is an important strategy to reduce the impact of both higher prices and greater fluctuations in prices on the state economy.

This strategy should not be confused with energy import substitution for its own sake. Import substitution will not necessarily decrease California's vulnerability to energy price volatility if in-state producers are linked to external, arbitraged markets. Similarly, as a strategy purely to boost in-state output and employment, energy import substitution might come at the expense of more cost-effective energy resources elsewhere. For instance, many of the renewable resources California will use to meet longer-term AB 32 goals are likely to be outside the state, with no clear output or employment benefits that accrue directly to California. Instead, declining in-state fossil fuel production gives an impetus to the need to diversify primary energy sources to increase the share of those that are not linked through inter-fuel substitution.

AB 32 thus comes at a critical time for energy planning in California, both in terms of augmenting access to supplies and diversifying away some of the risk associated with an over-reliance on increasingly scarce — either physically or economically — fossil fuel resources. The innovations in energy efficiency and alternative technologies that will allow California to achieve its nearer- and longer-term climate policy goals will also be part of a broader strategy to diversify the state's energy profile.

5. Climate Innovation Options

There is a broad array of technologies and lifestyle choices that can achieve net reductions in Global Warming Pollution. At least in the near term, no single technology, or core collection of technologies, will likely be sufficient for meeting AB 32 goals. For California, as for U.S. as a whole,[34] abatement opportunities are spread out across technological options and economic sectors. PIEE estimates that the largest single reduction for California would be those associated with AB 1493, at 18.6 mmtCO_2e or only 11 percent of California's 2020 reduction target.[35] In part for this reason, AB 32 covers the entire California economy, and ARB has been tasked with achieving the maximum technically feasible and cost-effective emission reductions across a range of potential technologies and economic sectors.

Almost by definition, all abatement options will require innovation and creativity. ARB's baseline assumes that none of the actions described in this report — including the RPS — take place. Meeting the 2020 AB 32 goal will thus require continued adoption of efficient and alternative energy technologies, requiring innovations in adoption and learning to bring down costs. In meeting the 2050 goal, innovations in the next generation of climate technologies must proceed on a parallel track.

Abatement Technologies

Despite the diversity of abatement options, because CO_2 emissions from fossil fuel combustion are the dominant source of Global Warming Pollution, technologies that replace fossil fuels and increase the efficiency of their use will play the predominant role in meeting both nearer- and longer-term AB 32 goals. For these energy technologies, the four primary options for reducing net Global Warming Pollution are captured by the simple relationship

$$Net\ Carbon\ Emissions = Emission\ Factor \times \frac{1}{Conversion\ Efficiency} \times Energy\ Use - Sequestration$$

or similarly

$$Net\ Carbon\ Emissions = f(Fuel, Technology, Behavior, Sinks)$$

In words, net carbon emissions are a function of fuel, technology, behavior, and the capacity and use of carbon sinks. CO_2 emissions can be reduced by switching from higher carbon fuels to fuels with a lower or zero ***emission factor*** (e.g., tCO_2e/TJ); by using technologies with a higher ***conversion efficiency*** (e.g., a more efficient power plant or more efficient light bulbs) that reduce the amount of energy, and thus the

[34] McKinsey & Company, Reducing U.S. Global Warming Pollution: How Much at What Cost? 2008, Online at: http://www.mckinsey.com/clientservice/ccsi/pdf/US_GWP_final_report.pdf
[35] Sweeney et al. (2008) separates the effects of federal fuel economy standards and AB 1493, which explains the difference between this estimate and the ARB 1493 estimate reported earlier.

amount of CO_2 emissions, required for producing useful work; by reducing ***energy use*** itself (i.e., conservation); and/or by increasing the stock of carbon stored through ***sequestration*** (e.g., terrestrial or underground sinks).

Solar photovoltaic (PV) cells, for instance, do not have any CO_2 emissions associated with the electricity that they generate and so reduce the average emissions factor for electricity. Green building options, such as lighting retrofits, HVAC system upgrades, building envelope improvements, and more advanced building control systems, decrease net CO_2 emissions by reducing the amount of electricity and heating required to operate a building. Real-time metering can trim peak electricity demand and CO_2 emissions from inefficient "peaker" plants. Carbon capture and storage (CCS) will perhaps one day be a commercial-scale option for sequestering carbon-based fuels underground.

In this report we identify six main sources of, and focal areas for reducing, Global Warming Pollution. These areas, and the key abatement technologies in each area, are listed in Table 6.1.

Table 6.1: Focal Areas and Key Technologies for Abatement

Focal Area	Key Abatement Technologies
Electricity and Heating Sources	Utility-scale renewable energy Distributed renewable energy Nuclear power Carbon capture and storage
Electricity and Heating Demand	Efficient lighting, appliances, HVAC systems, and motors Building shell improvements Energy management
Transportation Fuels	Second generation biofuels Low carbon electricity Hydrogen
Transportation Energy Demand	Conventional ICE improvements Hybrid and plug-in hybrid electric vehicles (PHEVs) Intelligent transportation systems Smart growth
Manufacturing and Waste Management	Cement manufacturing Increased recycling
Agriculture and Forestry	Improved efficiency in agricultural water use Agricultural soil management Manure management Forest conservation Improved forest management

Electricity and Heating Sources and ***Transportation Fuels*** include the technologies that will allow alternative energy sources to substitute for fossil fuels and to capture and store carbon from fossil fuels. Presently these two categories are distinct because oil is no longer a significant source of electricity generation or heating in California, and because natural gas and the majority of renewable energy sources are not used in providing automotive power. If electricity becomes more widespread as a feedstock for vehicles, this distinction could eventually break down. Nuclear power and carbon capture and storage (CCS) may eventually be important abatement options. Both still face important technical, regulatory, and financial hurdles[36] and the CEC does not expect that either will play a role in nearer-term abatement.[37]

Electricity and Heating Demand and ***Transportation Energy Demand*** include the technologies and lifestyle choices that reduce Global Warming Pollution by increasing the efficiency of energy use. LEDs and hybrid vehicles fall into this category, but so do demand response and smart growth. The latter play a large role in determining the scale of long-lived infrastructure, and are thus an important consideration both because they are often low cost abatement options and because they have longer-term financial implications. Information technologies will eventually play a role in this category to improve the efficiency of our activities, in addition to the energy that powers them.

Technologies that will reduce energy- and process-based emissions from industry and waste are included in ***Manufacturing and Waste Management***. Emissions from these two sectors include the full suite of greenhouse gases, and their assessment and abatement is often complex. In manufacturing, cost-effective emission reductions are available from improving efficiency and capturing and in some cases replacing high GWP gases, such as those used in refrigerants and insulators. Emissions reduction options in the waste management sector include both the direct reduction of emissions, such as methane from landfills, the indirect reduction of emissions, such as the decrease in emissions in other sectors that results from higher recycling rates.

Agriculture and Forestry includes the range of options that are available for reducing emissions and expanding sinks in these two sectors. Agricultural soils and particularly forests are potentially an important source of net carbon emission reductions because they store carbon. Changes in livestock management practices and technologies are likely the agricultural sector's largest source of emission reductions, though these are relatively small. We include water pumping for the distribution of agricultural water in

[36] See for instance, Hiranya Fernando, John Venezia, Clay Rigdon, Preeti Verma, Capturing King Coal: Deploying Carbon Capture and Storage Systems in the U.S. at Scale, 2008, WRI: Washington, DC; Steven C. McClary, Robert B. Weisenmiller, Heather L. Mehta, and Laura B. Norin, "Nuclear Power in California: 2007 Status Report," Final Consultant Report to the California Energy Commission, October 2007.

[37] CEC, IEPR.

this category, which is a significant source of emissions through its consumption of electricity.

Because the technologies that will allow California to achieve a large-scale decarbonization of its economy are unknown, in this report we focus on the combination of R&D in new technologies and deployment of existing technologies over the next two decades that will place the state on a trajectory to meet its 2050 goal. We provide a more detailed review of nearer-term technologies, their reduction potentials, costs, and barriers to adoption in *Review of Climate Technologies*.

Abatement Technology Costs

Abatement options differ in both their potential and cost, ranging from high potential – low, and in some cases even negative, cost (AB 1493) to low potential – high cost (California Solar Initiative). Both potential and cost are important considerations for policymakers in prioritizing regulatory measures to reduce emissions. Policy prioritization is particularly important given ARB's definition of cost-effectiveness as a "cost of a bundle of strategies" approach,[38] which allows flexibility in interventions but does not provide guidance for focusing ARB's regulatory efforts. A flexible but rigorously updated and maintained assessment of reduction potential and costs, as we describe in this section, is an important foundation for such an approach.

Annualized lifecycle costs typically consist of an annualized fixed capital and operational cost that include any salvage value, annual variable costs that include energy costs, and any annual energy cost savings. Mathematically, annualized lifecycle costs can be represented as

$$Annualized\ Lifecycle\ Cost = FC \times \frac{r}{(1-(1+r)^{-t})} + AVC - AES$$

where FC is a fixed, upfront cost, the second term (a capital recovery factor) converts the fixed cost into an annual payment ($/year) at an interest rate r over time t, AVC is the annual variable cost ($/year), and AES is the annual energy savings ($/year). The above equation illustrates two important points. First, because the majority of energy efficient products are more expensive but offer savings over time, and because alternative energy sources are often capital intensive and need to be financed, there is a temporal dimension to valuing technology costs that is reflected (often approximately) in the discount rate, r. As we discuss later, the selection of values for r can significantly change, and even change the sign of, abatement costs. Second, if the annual energy

[38] California Air Resources Board (ARB), "Cost-Effectiveness," AB 32 Technical Stakeholder Working Group Meeting, June 2008.

savings are larger than the annualized fixed and annual variable costs, the entire term will be negative, indicating a net savings.

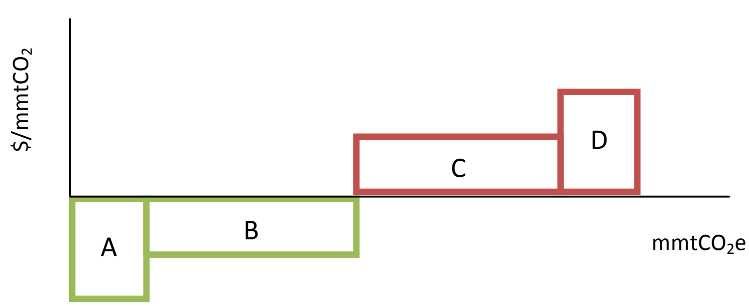
An average abatement cost for a given technology can be calculated by dividing the net cost by the total annual emission reductions that the technology produces.

$$Average\ Abatement\ Cost = \frac{Annualized\ Lifecycle\ Cost}{Reduction\ Potential}$$

For instance, if a technology is able to reduce 10 mmtCO_2e annually by a given year at a net cost of $100 million/year, its average abatement cost will be $10/t$CO_2$e. Adding up different costs of technologies creates an MAC curve, which shows the marginal cost-effectiveness of different abatement options.

In an MAC curve, the y-axis indicates the average abatement cost of a suite of options, while the x-axis indicates the annual abatement potential of those options. In Figure 6.1, for instance, technologies A and B are both available at a negative cost. A has higher savings per ton CO_2 but B provides nearly three times the reductions. Similarly, C is a large reduction, low cost option, whereas D is a low reduction, high cost option. Assuming that the area of A and D and B and C are equivalent, the net cost of the above four strategies is zero. This does not imply that the total cost to the economy of implementing these four options would be zero, as we explain below.

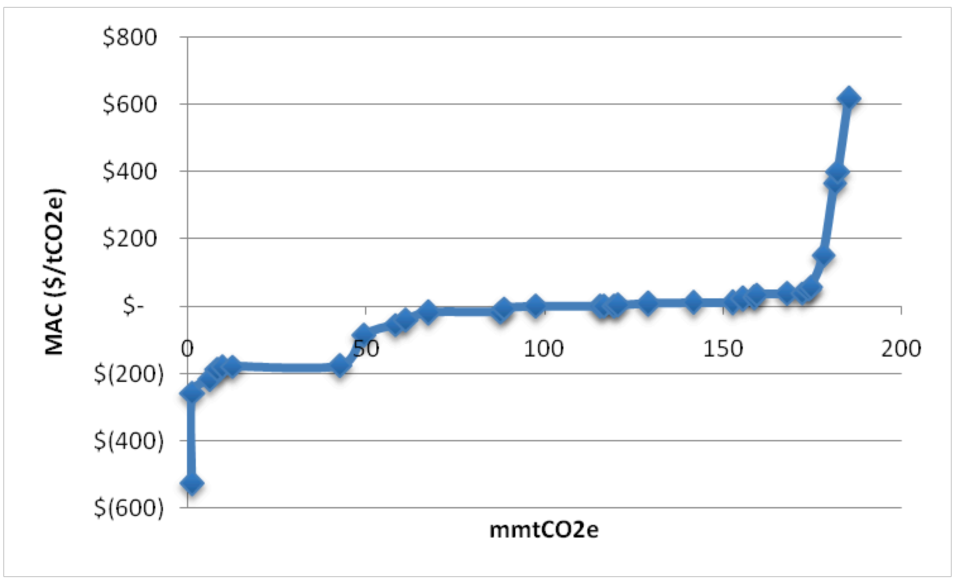
Figure 6.1. An Example Marginal Abatement Curve



For California, and for the U.S. as a whole, a significant portion of the nearer-term MAC comes at a negative net cost. For California, PIEE estimates that more than 50 mmtCO_2e is available at a negative or zero net cost, and roughly 150 mmtCO_2e is available at an average abatement cost of less than $50/t$CO_2$. Their most expensive options, including industry fuel-switching and CCS, have an estimated abatement cost of more than $100/t$CO_2$ and, for CCS, nearly $250/t$CO_2$. It is useful to put these numbers in context. A $100/t$CO_2$ charge on a combined cycle natural gas (NGCC) plant would increase its costs by \$0.05/kWh; if applied to the California electricity grid as a whole, \$100/tCO_2 would amount to a charge of \$0.028/kWh. For gasoline-powered cars \$100/tCO_2 would increase the cost of gasoline by \$0.91/gallon.[39]

ARB does not have recent annualized cost estimates that complement projections of reduction potential in different sectors published in its Draft Scoping Plan. For illustration, we use dated estimates from the 2006 final Climate Action Team (CAT) report and somewhat dated, but recently published, cost estimates from ARB in Figure 6.2. These, though now more conservative, show roughly 115 mmtCO_2e available at a negative net or zero cost. Based on ARB's recent Draft Scoping Plan, annual reductions available at negative or zero cost would likely fall to around 75 mmtCO_2e. At \$617/tCO_2e, ARB's highest cost option is the California Solar Initiative (CSI).

Figure 6.2: Example Marginal Abatement Cost Curve for California



Sources: Reduction potential data are from Climate Action Team (CAT), 2007; cost data are from Air Resources Board, "Review of Studies that Estimated the Costs of CO2 Emission Reductions," 2008.

Table 3. Reduction Potential and Cost of Different Nearer-term Abatement Options

Reduction Potential	Negative Cost (≤\$0/tCO_2e)	Low Cost (\$1-50/tCO_2e)	Moderate Cost (\$50-100/tCO_2e)	High Cost (> \$100/tCO_2e)
High	← AB 1493 →			

[39] For NGCC power plants, this assumes the SB1368 limit emissions factor of 1,100 lbsCO_2/MWh, or 0.0005tCO_2/kWh. For the California grid, this example uses an emission factor of 275 kgCO_2/kWh. For gasoline we use the IPCC emission factor of 69.3 tCO_2/TJ and a LHV for gasoline of 132 MJ/gallon.

(> 20 mmtCO$_2$e)	Smart Growth			
				RPS (33%)
Medium-High (10-20 mmtCO$_2$e)	IOU EE Programs		RPS (20%)	
Medium (3-10 mmtCO$_2$e)	Cellulosic Ethanol			
		HFC Reduction		
		Petro Refining		
		Petro Production		
			PHEVs	
		Sustainable Forests		
				CHP
	Building and Appliance Standards			
	MUD EE Programs			
		Agricultural Measures		
Low (< 3 mmtCO$_2$e)		PFC Reduction		CSI Conventional Ethanol
Negligible (< 1 mmtCO$_2$e)	Biodiesel			

Sources for this typology are contained in the Review of Abatement Technologies *section*.

Table 3 provides a heuristic typology of the reduction potential and costs of different abatement options. In number abatement options are dominated by medium potential, low cost options, while in total abatement potential three major options dominate — AB 1493, the RPS, and IOU efficiency programs. Both the reduction and cost of these options depend on the level of aggregation; there is a range of costs associated with options in the RPS and in forestry, for instance. The RPS serves as an important reminder that abatement costs are generally calculated as average costs, and that the costs of many of these options, including energy efficiency programs, increases as they are scaled up.

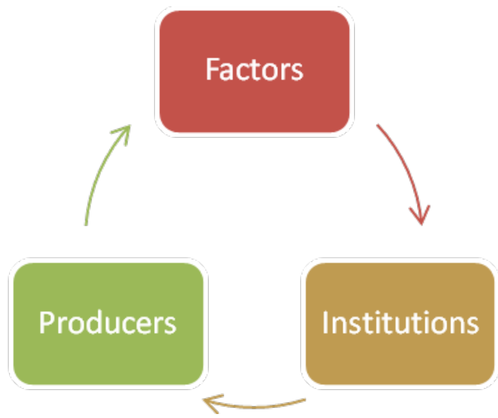
While Table 3 demonstrates that there are many low cost abatement options for California, adding up the options laid out in ARB's Draft Scoping Plan leaves 35.2 mmtCO$_2$e (20 percent of total reductions) as "Additional Emissions Reduction from Capped Sectors," which indicates the considerable uncertainty in reduction potential, and with it cost, beyond more obvious strategies. Curiously, the Draft Scoping Plan only includes 2 mmtCO$_2$e from better land use planning, which represents a significant decrease from the nearly 20 mmtCO$_2$e identified in the first CAT report and potentially a missed opportunity to avoid more costly abatement options.

Economy-wide Costs, or Why Abatement Costs are not the Whole Picture

Negative average abatement costs drive the results of macroeconomic models that show a positive stimulus from climate policies. Understanding why this is the case also highlights the limitations of the cost-effectiveness approach for analyzing the broader economic impacts of abatement options. Average abatement cost calculations, which are essentially technology-specific, do not place technologies in an economy-wide context, and thus do not account for such factors as inter-sectoral production linkages, savings-investment shifting, or the behavior of the institutions (e.g., households, firms, government) that comprise an economy. For instance, the abatement cost approach says nothing about the erosion of purchasing power and multiplier contraction caused by higher relative energy prices, or the expansion of purchasing power and positive multipliers through energy savings.

Situating technology-specific cost estimates in a broader economic context requires both a database that maps inter-sectoral linkages throughout an economy and an approximation of the behavior of institutions. Computable general equilibrium (CGE) models provide a framework for capturing both economic linkages, through a social accounting matrix (SAM), and economic behavior, through specifying, for instance, price, income, and substitution elasticities. These foundations allow CGE models to reflect an important dimension of the macroeconomic impacts of climate policy that we describe here: expenditure shifting.

Figure 6.3. The Circular Flow of Income



To understand why negative abatement costs are so important in the financial calculus of climate policies, it is first instructive to review how income flows in an economy. CGE models, and economies more generally, are driven by a circular flow of income from production activities, to factors of production, such as labor, land, and capital, to institutions, such as households, firms, and governments, and back to production activities through demand for goods and services (Figure 6.3). Factors of production are essentially a holding account; more intuitively, companies pay their employees, these employees are consumers who spend and save their income, companies produce goods and services to meet this consumer and investor demand, and a portion of the revenues companies make from meeting this demand are, of course, paid out as incomes.

Sectors where firms pay a larger share of their inputs as compensation for (income to) labor, capital, and land (e.g., the services sector) have higher value added than sectors where intermediate goods and service comprise the bulk of inputs (e.g., heavy industry). By extension, when households spend a greater share of their income on goods and services from high value added sectors, they increase the share of the total production in an economy that is allocated to institutions as income. If this income is spent on high value added domestic (or in-state) goods and services, more domestic production is needed to meet this new demand, more income is generated for domestic institutions, and so on, creating multiplier effects that amplify the impact of the initial shift in expenditure. If this income is spent on imports, these multiplier effects take place outside of a country's (or state's) borders and the local benefits occur less directly through exports.

The economic benefits of net savings from energy efficiency work much in this fashion. For households, for instance, the purchase of a more energy efficient appliance usually requires a higher upfront cost but leads to an energy savings. If savings exceed costs on an annualized basis, the household has more income to spend on goods and services. On average, households are usually assumed to spend this savings as they spent their original income. For instance, if 70 percent of income was spent on services, an assumed 70 percent of the savings will be spent on services. In other words, energy efficiency causes an expenditure shift from a lower value added good (energy) to a higher value added service. Because services are less likely to be imported, there are strong local multiplier effects. This simplified picture neglects a number of intervening factors, but nevertheless provides a general sense of how net savings from energy efficiency investments are amplified throughout an economy.

Innovation Policies

Neither the invention nor adoption of options for reducing Global Warming Pollution will materialize without the strong, coordinating role of state agencies. To meet AB 32 goals, California policymakers need an explicit, well-defined, forward looking agenda to manage a state-wide innovation process that will likely extend for more than a generation. A climate innovation agenda would not provide grounds for state agencies to micromanage either end of the invention-adoption spectrum. Instead, it would institutionalize a process to identify strategic opportunities, track progress in innovation, and provide principles and a framework for making trade-offs.

Balancing the need for an open, creative innovation process and a relatively tight timeline for innovation will require the careful design of policy instruments. Both in the academic and policy communities there is an emerging but still loosely defined consensus on what these instruments should look like. This section provides a brief overview of the scope and strengths of different approaches, emphasizing the complementarities between market-based and regulatory policies.

At its most broadly defined, innovation is a complex chain spanning production and consumption that includes invention, commercialization, learning, adoption, and use (Figure 6.4). Many of the measures required to meet the 2020 AB 32 target will involve a scaling up of existing energy supply technologies, such as wind turbines, and energy end use technologies, such as CFLs. Meeting the 2050 goal will require the emergence of technologies that are on the cusp of commercialization, such as LEDs, technologies that still require significant research and development, such as cellulosic biofuels, and technologies that have yet to be imagined.

Figure 6.4. The Innovation Chain

During the next two decades climate innovation to meet the 2020 goal will be more concentrated along the right hand side of Figure 11 (i.e., learning to bring down costs, adoption of new technologies, and more appropriate use); innovation to meet the 2050 goal will be more concentrated on the left hand side (i.e., invention and commercialization of new technologies). From a policy perspective, a climate innovation agenda will require five kinds of measures that stimulate and provide a balance among these five segments:

Transparent price signals to encourage longer-term public and private R&D investments;

- An enabling environment for the commercialization of new technologies;
- A level playing field to foster competition and cost-reduction;
- Incentives to encourage adoption; and
- Standards and pricing to rationalize use.

The most challenging aspect of any climate innovation agenda is how to sustain and accelerate long run innovation. The role of government in this process is particularly complex, reflecting, as noted above, the dual and at times contradictory need for flexibility (i.e., market-based policies) and strong guidance (i.e., regulation). More generally, there are two main kinds of policies that can induce innovation: direct emissions policies and technology-push policies.

Direct emissions policies increase the price of carbon-based fuels through taxing them or restricting their supply. This increase in prices leads to technological change by increasing the incentives to discover substitutes or ways to reduce consumption. Most of the technological change induced by direct emissions policies will come from the business sector, which is simply a product of economic incentives. Several market failures might occur in the early stages of innovation under these policies. Lack of sufficient incentives to invest in basic research leaves businesses unable to take full advantage of new knowledge and the commercial payoffs may be too uncertain and long-term to incentivize firms to make the desired investments.

In the climate context direct emissions policies include:

- Carbon taxes;
- Carbon quotas;
- Tradable CO_2 emission permits (cap-and-trade); and
- Subsidies to CO_2 emissions abatement.

Technology-push policies decrease the cost of investing in knowledge to firms and raise private incentives to engage in RD&D. Proponents of these policies have typically argued that, given that climate risks are a function of long-term accumulation of greenhouse gases in the atmosphere, it would be preferable to concentrate in the near term on investments in technological innovation, and adopt emissions limitations later when innovation has lowered the costs of limiting Global Warming Pollution, rather than mandating costly reductions now.[40]

Technology-push policies include:

- Subsidies to RD&D in low-carbon technologies;
- Public-sector RD&D in low-carbon technologies;
- Government-financed technology competitions; and
- Strengthened patent rules.

Direct emissions and technology-push policies are not exclusive. Goulder's (2004) examination of the role of induced technological change in the effective design of climate policy provides three insights relevant to California's climate policies:

1) In the presence of induced technological change, announcing climate policies in advance can lower policy costs.
2) Economic analysis offers a justification for public policies to induce technological change, even when the returns are highly uncertain.
3) Both direct emissions and technology-push policies are required in order to most cost-effectively induce technological change and reduce Global Warming Pollution.[41]

[40] Wigley, T., Richels, R., and Edmonds, J. (1996), "Economic and Environmental Choices in the Stabilization of Atmospheric CO2 Concentrations", Nature 379, 240-243.
[41] L.H. Goulder, "Induced technological Change and Climate Policy," prepared for the Pew Center on Global Climate Change, 2004.

Taylor et al. (2006) reached similar conclusions in their empirical analysis of the implications of policy design and implementation on innovation in abatement technologies. Five of their observations are particularly relevant for the design of a long run innovation agenda.

- Technologies require time to become competitive;
- Patenting activity appears to respond to demand-pull (direct emission) policies;
- Technology-push instruments can further innovation, but in cases where demand-pull instruments also exist the combination is stronger than RD&D support alone;
- Cap-and-trade programs alone will not solve the innovation problem; and
- Subsidies and subsidized industries are generally not stable.[42]

Both Goulder's and Taylor et al.'s conclusions reflects a growing consensus that neither market-based nor regulatory policies alone will be sufficient to adequately encourage the technological innovation required for a significant decarbonization of the California economy over the next 40 years. As we describe throughout this report, the period between 2010 and 2020 will be key for the invention of technologies that can be brought to market between 2020 and 2030. Existing technologies may be sufficient to reach the 2020 AB 32 goal, but will not be sufficient to make cost-effective emissions reductions beyond then.

[42] M. Taylor, Rubin E.S., Nemet G.F., "Chapter 3: The Role of Technological Innovation in Meeting California's Greenhouse Gas emission Targets," The California Climate Change Center at UC Berkeley, 2006.

6. Insights for Developing a Climate Innovation Agenda

Population Growth, Efficiency Improvements, and the Need for Complementary Measures

Energy efficiency will undoubtedly play a major role in nearer-term efforts to meet AB 32 goals. Nearly half (62.9 out of 133.8 mmtCO_2e) of the specified reduction measures in the ARB's Draft Scoping Plan are related to improvements in electricity and heating and transportation energy end use efficiency. Population growth and growth in energy consuming activities, however, provide a practical limit to the potential for energy efficiency to achieve absolute reductions in Global Warming Pollution. The two also signal the need for policies that reduce the energy required to maintain current energy using activities. Transportation provides an illustration of this tension between reductions in per capita use and absolute growth.

The tension between efficiency gains and population growth is captured by the steady state relationship between the rate of decline in per capita energy use and the population growth rate

$$r_e = \frac{1}{(1+r_p)} - 1$$

where r_e is the rate of decline in per capita energy use and r_p is the population growth rate.[43] When the two sides of this equation are equal, absolute energy use is in a steady state, neither increasing nor decreasing. When the right side of the equation is smaller than the left, the effects of population growth exceed gains in energy efficiency. For instance, if population growth is increasing at an average of 1.2 percent per year (California forecast for 2004-2020), per capita energy use would have to decrease at an average 1.19 percent per year — roughly the same rate as population growth — to keep total energy use constant.

For transportation, vehicle miles traveled (VMT) provide an added layer of complexity. If demand for travel grows faster than population growth, maintaining constant levels of gasoline and CO_2 emissions means that per capita use must fall even faster than population growth. An additional term (r_v, the rate of growth in VMT) is required in the steady state equation, which now becomes

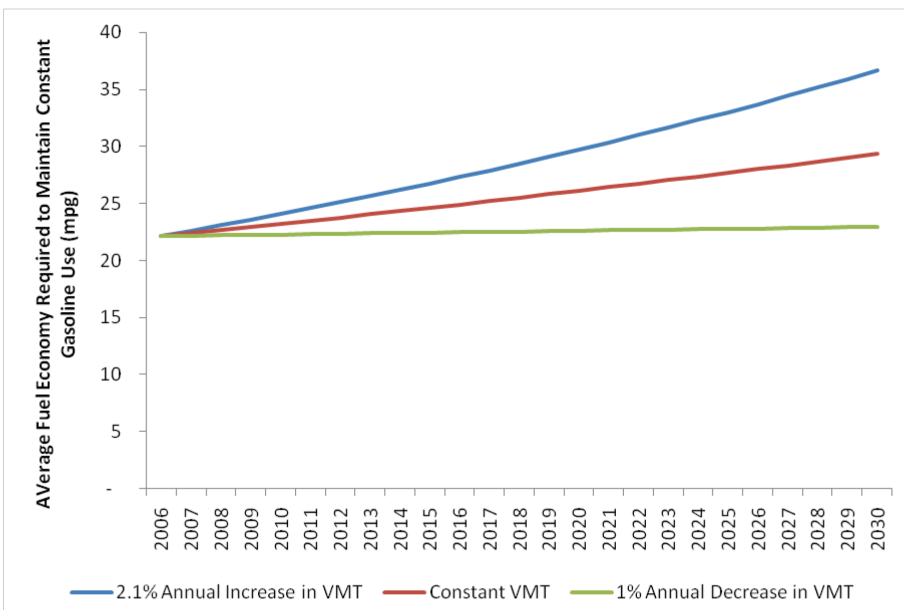
[43] To follow the derivation for this formula set population times per capita energy use at a given time t equal to an initial population times an initial per capita energy use, or $P_tE_t = P_oE_o$, where $P_t = P_o(1+r_p)^t$ and $E_t = E_o(1+r_e)^t$, and solve for r_e.

$$r_g = \frac{1}{(1+r_p)(1+r_v)} - 1$$

As we have noted previously, the DOT predicts that VMT growth (2.1 percent annual) will indeed outpace population growth (1.2 percent annual) to 2030, largely due to higher and more suburban population growth in the Central Valley over the next two decades.

Growth in population and travel demand are major drivers behind increases in demand for transportation fuels. Using the DOT's forecasts for VMT and the DOF's population growth estimates, maintaining constant statewide gasoline consumption to 2030 would require raising average fuel economy to 36.7 mpg,[44] more than either proposed federal fuel economy standards or AB 1493 measures. This assessment is consistent with ARB's analysis of AB 1493, where it projected that, despite declines in per capita emissions, absolute emissions begin to increase after 2030 as population and transportation demand growth exceed efficiency gains.[45]

Figure 7.1



If, instead, VMT remains constant until 2030, the required VMT to maintain constant gasoline consumption and CO_2 emissions falls to 29.3 mpg, which would imply that federal fuel economy standards (35 mpg) would lead to a 22.8 mmtCO_2e reduction in

[44] Average fuel economy is calculated as a harmonic average because fuel economy is a rate, which implies a *decrease* in gallons per mile (gpm).
[45] ARB, Pavley analysis

absolute emissions by 2030 over a 2.1 percent VMT growth base case. A one percent annual decrease in VMT (from 24 miles per day per person to 19 miles per day per person) from 2006-2030 would not require an appreciable increase in fuel economy to maintain constant levels of gasoline consumption, and reaching a 35 mpg standard would reduce CO_2 emissions over the 2.1 percent VMT growth base case by 47.1 $mmtCO_2e$.

This example illustrates two points. First, adoption of more efficient technologies will help California to reduce growth in emissions to meet its AB 32 goals and set the state on a "softer" energy pathway, but as population continues to climb achieving absolute reductions in emissions will almost certainly require new, low or zero carbon primary energy sources, which in turn require higher levels of investment in R&D. For both transportation energy and electricity and heating end use, most of the nearer- and likely longer-term emission reductions associated with energy efficiency will be reductions in growth, rather than absolute emissions.

Second, the benefits of energy efficiency can be greatly enhanced by complementary measures that reduce growth in use. Smart Growth provides an example. Although the California DOT estimates significant VMT growth due to more suburban population growth, there is an increasing awareness in the ability of Smart Growth measures to mitigate growth in VMT, or to reduce it significantly in California. Smart Growth interventions involve the reductions of trips generated, as well as the length of those trips due to trip chaining behavior.

Smart Growth is a set of policies and programs that incorporates land use and transportation objectives that encourage compact, mixed use development, aiming for the following general principles:

- Maximizing accessibility through land use design (compact building, cluster development)
- Maximizing accessibility through transportation options (walkable neighborhoods, transit-oriented development, street design)
- Creating self-contained mixed use communities (mix of land uses, ranges of housing opportunities, distinctive sense of place)
- Management of automobile travel (transportation demand measures, parking management)

Smart Growth contributes to meeting goals of AB 32 through management of automobile travel through reduction in VMT. The literature provides some insights on the relationship between Smart Growth features and VMT, but the field of study is still nascent, and the ranges of reduction are wide.

A study[46] reviewing how different land use design mixes can achieve trip reductions nationally shows that a mix-use development along a transit corridor can lead to a reduction in 20 percent. More specific to California, a survey of California Municipal Planning Organizations (MPs) by the California Energy Commission sought to assess potential statewide reductions in transportation energy consumptions from Smart Growth Developments.[47] In the survey MPOs were asked to evaluate Smart Growth planning scenarios, regional growth characteristics and travel demand for non-Smart Growth developments.

Table 7.1

Study Region	Scenario	VMT Savings
Riverside	City Centered	0.23%
	Transit Centered & Transit Supply	1.7%
San Francisco	City/Transit Centered	1.7%
	City/Transit Centered & Transit Supply	2.4%
San Diego	Transit Centered	13%
	Transit/City Centered	14%
	Transit/City Centered with caps	13%
Sacramento	City/Transit Centered	11%
Monterey	City Centered	9%
	Transit Centered	8%

The survey shows that trip reduction or VMT savings gained from Smart Growth developments ranged from 0.2 to 14 percent. The wide range reflects regional differences, and how suburban or urban the regions are.

Project-Based Smart Growth Measures

Project based VMT reductions have shown greater reductions than compared to regional reductions because of the specific site case studies which can target key Smart Growth elements. A study conducted by the Environmental Protection Agency (EPA) shows that several mixed use/TOD infill projects had significant VMT reduction

[46] Dagang, D. "Transportation Impact Factors: Quanifiable Relationships Found in the Literature." JHK & Associates for Oregon DOT. 1995.
[47] California Energy Commission. "California Smart Growth Energy Savings MPO Survey Findings." September 2001.

compared to conventional or Greenfield developments.[48] The results revealed significant reductions in VMT for specific developments.

Table 7.2

Project Location	VMT Savings
Atlanta, GA	15-52%
Baltimore, MD	55%
Dallas, TX	28%
Montgomery County, MD	42%
San Diego, CA	52%
West Palm Beach, FL	39%

These examples, while not precise, do provide insight into the need for Smart Growth measures as key components in meeting the goals of AB 32. Thus far, the debate has set aside planning and policy around urban development and land use which do contribute largely to the meeting of California's climate change reduction goals. California can take stronger leadership in encourage growth around transit corridors, supporting infill development and planning in a strategic regional fashion. These coordination efforts in land use can contribute to an environment where energy use and transportation demand can be tempered. This will result in lower impact living environments not only create livable spaces, but also lower global warming impact in California.

Well Timed Policies can Capture Important Savings and Avoid Trade-offs

Abatement technologies have different technical and economic characteristics, including their reduction potential, costs, lead times, adoption rates, and lifecycles. Technology lead times, adoption rates, and lifecycles have important, and often overlooked, implications for the design and timing of innovation policies.

A clear distinction exists between energy producing (e.g., a power plant), using (e.g., a refrigerator), and insulating (e.g., a building) technologies. Appliances, electronics, and

[48] EPA. "Our Built and Natural Environments: A Technical Review of the Interactions between Land Use Built Environment, Transportation and Environmental Quality." January 2001.

vehicles — energy end use technologies — are essentially “off the shelf” technologies; there is no appreciable lag between the time an appliance is purchased and the time it can be deployed. The longest-lived consumer appliances, for instance, are refrigerators and washing machines, which have a lifespan slightly less than one generation. A building or a power plant, in contrast, requires several years to site, permit, and build, but lasts for more than one and usually several generations (Table 4).

Table 7.3. Typical Lifetimes for Different Technologies

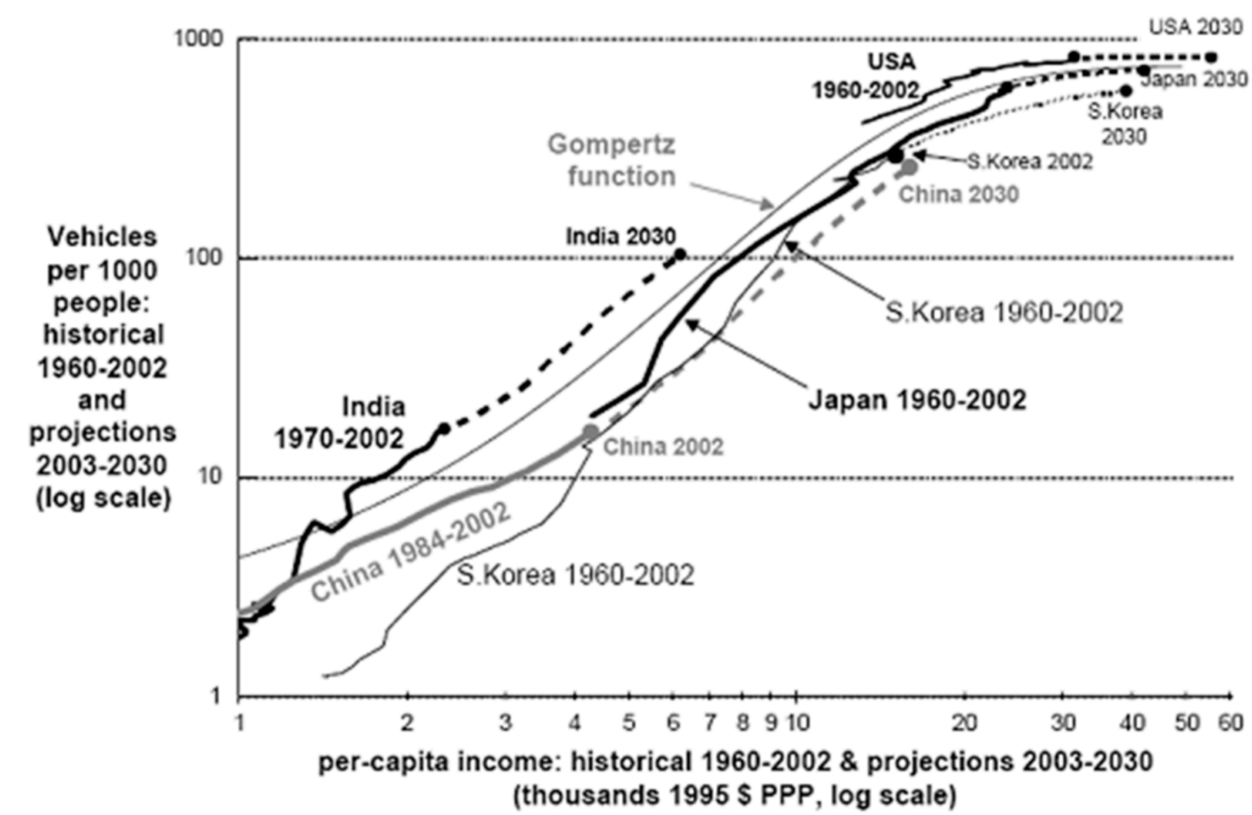
Technology	Typical Lifetime (years)
Conventional Incandescent Light Bulb	1-2
Personal Computers	3-8
Passenger Vehicles	10-15
Refrigerator	15-20
Washer and Dryer	15-20
Refineries	20-40
Power Plants	30-50
Buildings	50-100

Sources: Edward Rubin, Engineering Environment (2005); Flex Your Power website, www.fypower.org.

Another way to interpret Table 4 is that the entire stock of conventional incandescent light bulbs is replaced on average every one to two years. Precisely because the stock of appliances, electronics, and vehicles is relatively short lived, continued improvements in these technologies can have a visible, near-term impact on average stock efficiency. For instance, if all households were to buy CFLs to replace existing incandescent light bulbs at the end of the latter’s lifetime, energy use from residential lighting might be reduced three to four fold in two years.[49] Adoption rates are almost never linear — market penetration is usually modeled as a logistic curve — but this example is nonetheless indicative of the rapid reductions in energy use that can come from the turnover of relatively short-lived energy end use technologies.

[49] This would assume that, for instance, an average wattage for incandescent bulbs of 75 W and a replacement wattage of 18 W for CFLs, with a likely rebound effect still included in this range of savings.

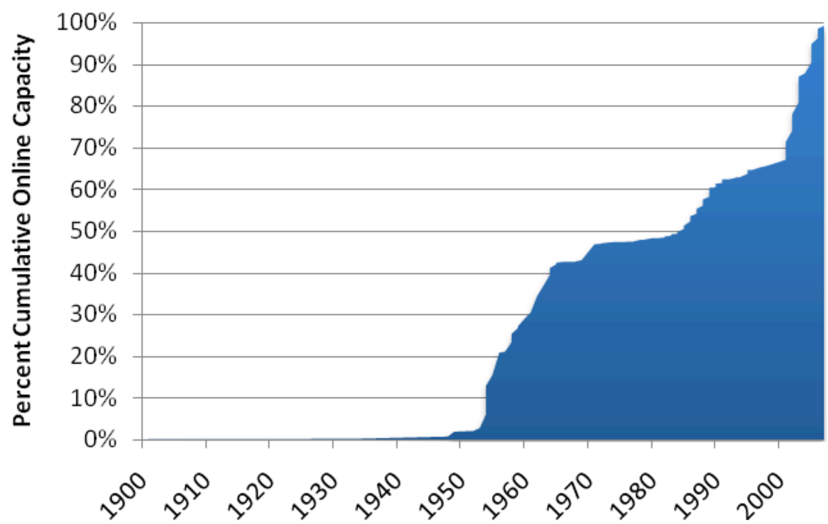
Figure 7.2: Patterns of Vehicle Adoption



Fossil fuel energy infrastructure is among the most complex issues in climate policy because of its long lead times and lifetimes. As touched on briefly in Box 1, natural gas-fired power plants provide an example of the trade-offs between the need to meet nearer-term energy demand and the longer-term financial implications of investments in fossil fuel infrastructure that is not equipped with, or able to cost-effectively add, CCS technology. By virtue of its chemical structure (natural gas is mostly CH_4, which gives it among the lowest carbon-energy ratios of any fuel), natural gas will be a preferred fossil fuel worldwide over the coming decades. Ultimately, though, even natural gas will have to either be dramatically phased down or equipped with technology to reduce its net carbon emissions.

As Figure 12 shows, 48 percent (19.4 GW) of California's 2007 natural gas-fired generation capacity (40.4 GW) was built before 1980. Assuming that natural gas-fired power plants have a technical life expectancy of 50 years and a financial lifetime of 20-30 years, much of the natural gas generation capacity that would need to be replaced over the next two decades would still be operational, with some of it still being financed, after 2050. Using the same approach and inputs as in Box 1, the largest allowable scale (i.e., emitting 85.4 mmtCO_2e) of non-CCS equipped natural gas-fired generation after 2050 would be 28.4 GW, and the optimal scale, allocating emissions to other sectors like transportation and industry where emission reductions are currently more expensive, is more likely near or below 5 GW (emitting roughly 15 mmtCO_2e). While an aggressive deployment of energy efficiency and renewable energy would limit the scale of legacy natural gas generation that needs to be replaced over the next decade, a dramatic scale up of alternatives is needed in California post 2020 to avoid over-building conventional, large-scale natural gas power infrastructure.

Figure 7.3: California Natural Gas Capacity by Date Online



Source: CEC website.

At the completely opposite end of the longevity spectrum, buildings turn over every 50 to 100 years. Because making buildings more energy efficient during their design and construction is often significantly cheaper than retrofitting them, capturing cost-effective energy efficiency savings in all new buildings is an important strategy for managing AB 32 costs. In that sense, building energy efficiency is what McKinsey calls a "time perishable option":[50] typically infrastructure whose net abatement cost (in \$/tCO_2e reduced) increases substantially once that infrastructure is already built, with retrofits then the only way emissions reductions can be achieved.

The examples in this section suggest three justifications for a rapid and determined scale up of innovation in technologies that reduce Global Warming Pollution.

[50] McKinsey & Company, 2007.

1) For shorter-lived appliances, electronics, and vehicles, their quick turnover means that new technologies can relatively quickly reduce average stock efficiencies and, in some cases, produce savings that can in turn be used to offset the higher social costs of more expensive abatement options.
2) From a financial perspective there is an optimal scale down pathway for longer-lived fossil fuel infrastructure, such as refineries and power plants, and alternative options must be available to avoid over-building that infrastructure.
3) The longest-lived technologies, such as buildings, are replaced on a time scale of several generations and integrating new technologies during construction is nearly always cheaper than retrofitting them. In all three cases, waiting on an innovation agenda can significantly raise final costs of abatement.

In all three cases, delaying the innovation agenda can significantly raise the costs of abatement.

The Highest Savings from Energy Efficiency come from Replacing the Most Inefficient Vehicles, Appliances, and Buildings

In the analyses thus far on the cost-effectiveness of AB 32 options, the largest potential negative cost option is that associated with AB 1493. There is now broad consensus that fuel economy in the U.S. could improved at a negative social cost. In its 2002 review of CAFE standards, the National Research Council argued that, for many of the technology options for improving fuel economy, discounted savings outweigh the additional capital costs.[51] ARB's initial estimate of the reduction potential of AB 1493 was 31.7 mmtCO_2e,[52] at an average abatement cost of -\$177/tCO_2e, or a total direct savings of \$5.6 billion. While some have argued that ARB's discount rate used in its analysis was too low,[53] the gasoline price used in ARB's analysis was also \$1.74/gallon.[54] Using updated gasoline prices and 3 and 14-year payback periods, PIEE estimates a reduction potential of 15 mmtCO_2e at -\$323/tCO_2 to -\$3.39/tCO_2 for federal fuel economy standards, and 18.6 mmtCO_2e at -\$298/tCO_2 to \$30/tCO_2 for the remaining components of AB 1493 (Pavley emission standards).

It is important to put fuel economy measures in context. Fuel economy standards in the U.S. are set at a federal level, and the U.S. has not increased standards measurably since 1985. New federal fuel economy standards would increase vehicle efficiency to 35 mpg by 2020, which would raise average fuel economy for new vehicles in the U.S. to the same level as in China. The savings associated with AB 1493 are, in fact, so high

[51] NRC
[52] The Draft Scoping Plan increased this reduction potential estimate to 31.7 mmtCO_2e.
[53] Stavins
[54] ARB.

because fuel economy in California is so low. Fuel economy is linear in gallons per mile and not miles per gallon, and for this reason the savings associated with improved fuel economy in mpg are curvilinear, as shown in Figure 13. In other words, savings are highest where mpg fuel economy is lowest, and the savings from improved fuel economy diminish at higher mpg levels. In Figure 13, by the time fuel economy improvements reach the 74-75 mpg increment, for instance, marginal savings (in $/1,000 miles) from fuel economy improvements (in increments of 1 mpg) have dropped to $0.017, starting from $0.88 at 19-20 mpg. Toggling gasoline prices changes values on the y-axis and creates slightly higher savings at lower efficiencies, but does not change the fundamental shape of the curve.

Figure 7.4: Gasoline Price-Cost Profiles

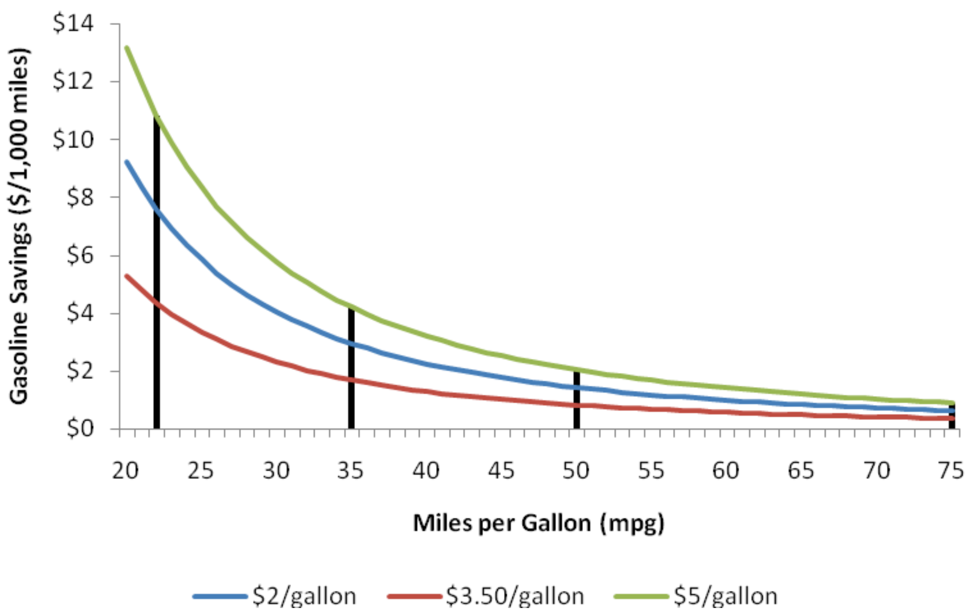


Table 7.4: Average Annual Savings per Vehicle from Different Levels of Fuel Economy Improvements at Different Gasoline Prices

	$2.00/gallon	$3.50/gallon	$5.00/gallon
Increase from 22-35 mpg (Area A in Figure 13)	$427	$748	$1,068
Increase from 35-50 mpg (Area B in Figure 13)	$217	$380	$542
Increase from 50-75 mpg (Area C in Figure 13)	$169	$295	$422

Notes: This example uses 2006 VMT and registered vehicle data from DOT, 2008.

Figure 7.4 and Table 7.4 reinforce two main points. First, the savings from bringing vehicles that are at or near the current fuel economy average for California (22.2 mpg) up to proposed fuel economy standards (35 mpg) exceeds what is commonly thought to be the next "level" of efficiency (e.g., a 45-50 mpg hybrid) by nearly a factor of two. Second, savings scale linearly; savings at $5.00/gallon are 2.5 times higher than those at $2.00/gallon. In other words, regardless of how savings are weighted, implementing energy efficiency programs at higher energy prices is inherently cheaper than implementing them at lower energy prices. This fact also implies that efficiency abatement options that are not cost-effective at lower energy prices will become cost-effective at higher energy prices.

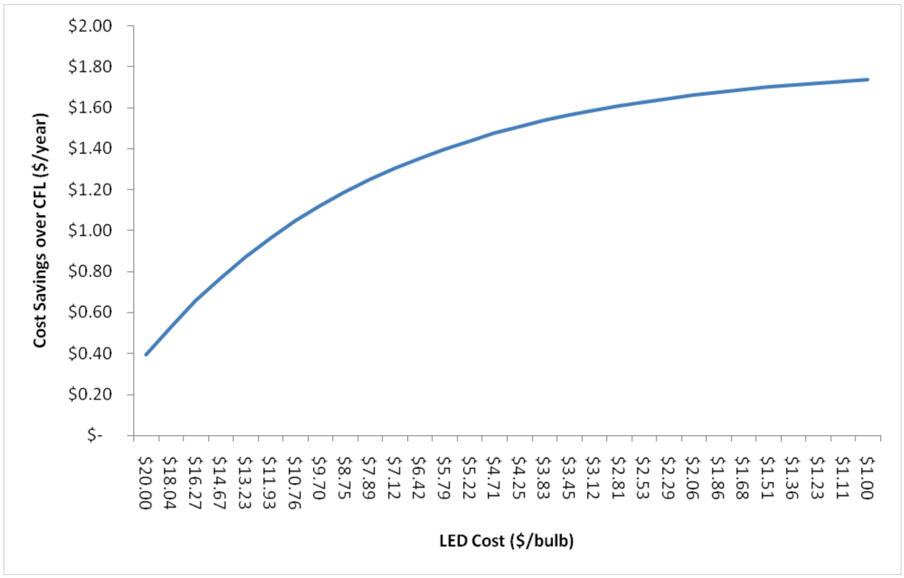
For different reasons, there is a similar phenomenon for efficiency gains in many electrical appliances, such as light bulbs. Contrary to the fuel economy case, savings from decreased wattage in electricity appliances are linear. Each incremental decrease in wattage saves the same amount. For instance, switching light bulbs from a 60 W incandescent to an equivalent 18 W CFL would reduce annual electricity use from 44 kWh/year to 13 kWh/year, a savings of 31 kWh/year, or 0.73 kWh per watt reduction.[55] Switching that CFL to a 1.3 W LED would produce a further 12 kWh/year in savings, again a 0.73 kWh savings per watt reduced. Relative gains in electricity use efficiency can thus be deceiving. The improvement from 60 W to 18 W is roughly a 3-fold reduction, whereas the improvement from 18 W to 1.3 W is nearly a 14-fold reduction. But because the savings are linear, the benefits from replacing incandescent bulbs with CFLs outweigh the benefits of replacing CFLs with LEDs by a factor of roughly 2.5.

Similarly, even as the cost of more efficient light bulbs comes down, the largest cost savings will occur in the jump from conventional incandescent bulbs to more efficient light bulbs. Though there are additional savings to be earned by replacing the 18 W CFL with a 1.3 W LED, particularly as the cost of LEDs falls, these never exceed the savings of replacing the 60 W incandescent with a 18 W CFL ($3.34 per year assuming an electricity price of $0.12/kWh), regardless of the price of the LED bulb. As the price of LEDs falls (starting at a high of $20 in Figure 7.5), savings increase but flatten out with further reductions in bulb costs.

[55] Assuming daily use of 2 hours/day.

Figure 7.5. Additional Electricity Cost Savings by

Replacing a CFL with an LED, with Falling LED Prices



In short, for both vehicles and appliances there are likely diminishing returns to investments in energy efficiency. For vehicles, most of the fuel cost savings arise via improvements from extremely inefficient to somewhat more efficient vehicles. Replacing a 15 mpg clunker with a 35 mpg compact would produce greater savings than replacing the 35 mpg compact with a 50 mpg advanced hybrid. For appliances, most of the electricity cost savings arise via switching high wattage for low wattage models. Replacing a 1,800 kWh/year refrigerator with an 800 kWh/year refrigerator would produce greater savings than replacing that 800 kWh/year refrigerator with a 400 kWh/year refrigerator, for instance.

These examples are not meant to suggest that investments in energy efficiency are not cost-effective from a climate policy perspective. Indeed, depending on capital costs, replacing high efficiency products with even higher efficiency products may still have a net negative abatement cost. Rather, the examples are meant to show that much of the economy-wide gains from investments in energy efficiency accrue from replacing the most inefficient products with more efficient — and often existing — products, and that the total CO_2 and cost savings from these investments diminish as the most inefficient products are replaced with more efficient ones.

The Direct Employment Effects of Abatement Options Should not be a Major Consideration for AB 32 Implementation

California has become a magnet for clean technology investments; of the roughly $3.67 billion in clean technology venture capital invested in the U.S. in 2007, California garnered a 48.5 percent share, or $1.78 billion.[56] Planning for AB 32 has, in turn, included an extensive discussion on the employment benefits of climate policies, emphasizing its potential to create in-state jobs in clean technology sectors and to shore up the state's declining manufacturing sector. This is particularly true for renewable energy, which has become a proxy for green tech. ARB's Draft Scoping Plan stresses this message, with its affirmation that "investments in green technologies produce jobs at a higher rate than investments in comparable conventional technologies," in which it is referring to the distinction between employment in the renewable energy and fossil fuel industries. While in principle not disagreeing with this message, we argue that the employment benefits of AB 32 need to be kept in context, and that, when placed in context, do not warrant a major emphasis on employment creation as part of AB 32 implementation.

The need for fossil fuel alternatives generates employment opportunities in the manufacturing and operation of alternative, and particularly renewable, energy technologies. A number of studies have now shown that renewable energy creates more employment per MW installed than fossil fuel, and there is a growing literature on the job benefits of renewable energy development vis-à-vis conventional fossil fuel options.[57] These benefits will be reinforced by policy. Meeting either the 20 percent or 33 percent RPS goals would require a scaling up of renewable energy in excess of new fossil fuel generation (Table 6).

[56] ETAAC, 2008.

[57] See, for instance, Dan Kammen, Matthias Fripp, and Kamal Kapadia, *Putting Renewables to Work: How Many Jobs can the Clean Energy Industry Generation?* Berkeley: RAEL, 2006; L. Stoddard, J. Abiecunas, and R. O'Connell, *Economic, Energy, and Environmental Benefits of Concentrating Solar Power in California*, NREL Subcontract Report, April 2006.

Table 7.5. Current and Newly Installed Capacity by 2020 under Different RPS Scenarios, California

	Current (2007) (MW)	20 percent RPS Scenario (MW)	33 percent RPS Scenario (MW)
Utility-scale Solar	357	–	3,370
Wind	2,655	4,154	6,032
Geothermal	1,791	1,263	2,096
Biomass	697	–	593
Biogas	54	1,314	297
Small Hydro	n/a	–	3
Rooftop Solar PV		847	3,000
Total Renewable	5,891	7,578	12,391
Total Natural Gas	40,369	n/a	5,721

Sources: California 2007 installed capacity data are from the CEC's list of online capacity in California, CEC website. Both RPS scenarios are taken from the "NewGen" sheet of E3's GWP Calculator.

Kammen et al.[58] have carried out the most systematic attempt to compare the employment benefits of different technology options, and we use their jobs per MW installed power (jobs/MW_p) coefficients as inputs here. A few adjustments to these coefficients are necessary. First, because renewable energy sources are often intermittent, they generate electricity for fewer hours in a year than fossil fuel (i.e., they have a lower capacity factor). For instance, more than twice as much wind capacity (with an average capacity factor of 0.35) is required to produce the same amount of electricity as natural gas (capacity factor of 0.85). In making consistent comparisons across technologies it is necessary to correct for these differences in capacity factors.

The employment benefits of technology diffusion are more accurately thought of as a net rather than a gross value, because of the displacement effects of new technologies. For instance, generation from a new wind turbine might displace generation from a natural gas power plant, in which case we are interested in the net employment effect of installing that wind turbine. As a convenient simplification we assume that the California baseline would be entirely natural gas-fired generation in the absence of RPS policies. For each technology, the net total employment benefits will be the new installed capacity (NIC) multiplied by a net employment coefficient (α)

$$Net\ Total\ Employment\ Benefits = \alpha NIC$$

[58] Kammen et al., 2006.

where α includes an employment intensity coefficient for renewable energy source (E_{RE}, in jobs/MW$_p$), and subtracts out a natural gas employment baseline (E_{NG}, in jobs/MW$_p$) corrected for differences in capacity factors ($\frac{CF_{RE}}{CF_{NG}}$)

$$\alpha = E_{RE} - E_{NG}\frac{CF_{RE}}{CF_{NG}}$$

Kammen et al. include only solar PV, wind, and biomass in their assessment. We add solar thermal to this list by including a coefficient from Stoddard et al. for utility-scale solar and by assuming that geothermal's employment profile is similar to wind and utility-scale solar, and that biogas' profile is similar to biomass. Using the range of relevant coefficients, the total net employment intensity coefficients (α) are listed in Table 7.6.

Table 7.6: Total and Net Employment Intensity Coefficients for Renewable Energy and Natural Gas

	Construction, Manufacturing, Installation (Jobs/MW$_p$)		Operations, Maintenance, Fuel (Jobs/MW$_p$)		Total (Jobs/MW$_p$)		Net Employment (Jobs/MW$_p$)	
	Low	High	Low	High	Low	High	Low	High
Utility-scale Solar	–	–	–	–	–	0.94	–	0.70
Wind	0.15	0.88	0.1	0.1	0.25	0.98	-0.08	0.65
Geothermal	–	–	–	–	0.25	0.98	-0.61	0.12
Biomass	0.34	0.34	0.32	2.08	0.66	2.42	0.45	2.21
Biogas	–	–	–	–	0.66	2.42	0.45	2.21
Small Hydro	–	–	–	–	0.25	0.98	-0.23	0.50
Solar PV	1.29	1.20	0.25	1	1.54	2.20	1.34	2.00
Natural Gas	–	0.21	–	0.60	–	0.81	–	–

Notes and Sources: All data except for utility-scale solar are from Kammen et al., 2006. Utility-scale solar is taken from Stoddard et al., which is CSP-specific but does not differ significantly from other large, utility-scale renewables and we thus extrapolate to all large-scale solar.

Using the two RPS scenarios listed in Table 6 and the high coefficients from Table 7, Table 8 presents implied total net job increases under both scenarios, total gross job increases under the 33 scenario RPS, and annual gross job increases under the 33 percent RPS scenario. Net and gross jobs are the total number of jobs created out to 2020 through meeting RPS goals; the gross jobs per year column is an annual average calculated through dividing total gross jobs by 12. For the sake of illustration, these estimates assume that all employment generated through meeting RPS targets occurs in California. They are also estimates of *average direct* employment, and do not include the indirect employment induced in other industries by an increase in output in these industries — because renewable energy is a capital-intensive industries the backward linkages in California are likely to be comparatively small. In addition to these qualifications, it is important to note that the estimates in Table 7.7 are highly uncertain, and are intended only as order of magnitude approximations.

Table 7.7: Gross and Net Employment for Different RPS Scenarios

	20 percent RPS Scenario (net jobs)	33 percent RPS Scenario (net jobs)	33 percent RPS Scenario (gross jobs)	33 percent RPS Scenario (gross jobs/year)
Utility-scale Solar	600	1,600	3,200	300
Wind	2,700	3,900	5,900	500
Geothermal	150	300	2,000	200
Biomass	–	1,000	1,400	100
Biogas	–	500	700	60
Small hydro	–	–	–	–
Rooftop Solar PV	1,700	6,000	6,600	600
Total Renewable	5,000	13,000	20,000	1,700
Percent 2004 Employment in CA	0.03 percent	0.08 percent	0.12 percent	–
Percent of Annual Job Additions in CA, 2004-2014	–	–	–	0.6 percent

Note: Individual and total estimates do not add up due to rounding.

We use the high net and total coefficients from Table 7 in Table 8 calculations simply to make a point. Total statewide employment in California in 2004 was roughly 16 million people. To this stock of labor, total, direct employment from the renewable energy industry to 2020 will add about one-tenth of one percent, even assuming that the construction, manufacturing, and installation all occur in California. The number of jobs added annually, in the highest possible scenario, would account for less than one percent of the total annual number of average jobs (~264,000) that the California economy is expected to create from 2004-2014.[59] The market for renewable energy technologies is obviously not limited to California, and there may be opportunities for California firms to capture a greater market share for these technologies, both nationally and globally. However, it remains the case that the energy industry is generally capital and not labor intensive, and that the direct employment benefits of AB 32 are likely to be

[59] http://www.labormarketinfo.edd.ca.gov/?pageid=145

much smaller than the employment effects of changing relative energy prices because of the pervasiveness of energy as an input to production and consumption.

Neither is employment in fossil fuel production, distribution, or sales a salient issue for the California economy. As described previously, the employment effects of climate policies in California will occur against the backdrop of a decline in the state's fossil fuel production. Over time, this decline implies that the oil and gas production sectors will lose jobs, though the oil and gas import business will gain jobs as a result. It is unclear what the net effects of this process would be, but the overall impact on California employment would be small in any case. The oil and gas (O&G) sector, from extraction to retail, accounts for just over one percent of California's employment in NAICS sectors, with most of that concentrated in wholesale and retail (Table 7.8).

Table 7.8: California Oil and Gas Sector Employment

	Employment (persons)	percent California NAICS Employment	Average Wage ($/year)	Employment Intensity (jobs/$\$10^6$ output)
O&G Extraction	3,910	0.04 percent	$60,489	1.0
Natural Gas Distribution	9,172	0.10 percent	$61,038	n/a
Support for O&G Operations	6,750	0.07 percent	$35,644	8.0
O&G Pipeline Construction	7,350	0.08 percent	$39,243	10.3
Petroleum Refineries	8,561	0.09 percent	$73,071	0.4
Subtotal	35,743	0.39 percent	$54,583	1.0
Petroleum Wholesalers	8,769	0.10 percent	$48,924	0.3
Gasoline Stations	64,696	0.71 percent	$16,225	2.8
Total	109,208	1.21 percent	$31,405	1.2
California NAICS Total	9,059,840	100 percent	$39,748	5.8

Source: Bureau of Economic Analysis (BEA), Economic Census 2002.

Over the next two decades, the expanding share of alternative energy in California's energy profile will likely have a minimal impact on existing output and employment in the O&G sector, because this expanding share will substitute predominantly for growth in demand and not existing demand. As Table 7.8 suggests, natural gas capacity will continue to expand in the electricity sector, and, as we have discussed previously, demand for petroleum-based fuels is unlikely to fall significantly if at all.

The employment effects associated with energy efficiency provide an illustrative example of the distinction between direct employment benefits and broader economy-wide gains in employment. Most state-level studies of the job creation benefits of energy efficiency use input-output tables to examine both the direct and the indirect impacts of energy efficiency programs,[60] in part because the direct impacts (e.g., building contractors hired to do energy audits) are much smaller than the indirect impacts (e.g., lower spending on energy by firms causing them to expand output and hire more workers). Adding the induced impacts (e.g., lower spending on energy by households causing them to buy more services), increases this gap between direct and indirect/induced effects even further.

Our point is not to suggest that AB 32 will not generate employment benefits. Rather, our argument is that the direct employment benefits associated with AB 32 are negligible compared with the number of jobs the state will need to create over the next two decades as its population grows, and with the potential positive and negative impacts on employment in the state from changes in energy prices. This finding suggests that employment in abatement technology sectors should not be a major focus of California's AB 32 implementation efforts. With limited resources, the state should instead work to ensure a level playing field to encourage competition, review its tax and investment policies to encourage employment and ensure California businesses are competitive across the board.

7. Review of Abatement Technologies

This section provides a review of the technologies whose more widespread commercialization and adoption will be important for meeting the AB 32 2020 goal, as well as a selected overview of longer-term technologies. We separate abatement technologies into six focal areas, following our classification in the *Climate Innovation Options* section:

- Electricity and Heating Sources
- Electricity and Heating Demand
- Transportation Fuels
- Transportation Energy Demand
- Manufacturing and Waste Management
- Agriculture and Forestry

For each focal area, we review major technology options, estimates of the costs and abatement potential of those options, and key barriers to adoption.

[60] Skip Laitner and Vanessa McKinney, *Positive Returns: State Energy-Efficiency Analyses Can Inform U.S. Energy Policy Assessments*, Washington DC: ACEEE, 2008.

Electricity and Heating Sources

Alternative energy sources — for electricity, heating, and transportation — will be the most important target of California's nearer- and longer-term innovation efforts. Renewable energy sources, such as wind, geothermal, solar, biomass, and small-scale hydro, can ultimately play a critical role as primary inputs to all three of these energy uses, but they will be initially scaled up for use in electricity generation. Other abatement options for centralized electricity generation, including nuclear power and CCS, currently face legal and financial obstacles, and the CEC does not anticipate that these will play a major role in meeting the 2020 AB 32 goal.[61]

Renewable energy is expected to be a significant share of AB 32 abatement, contributing about 13 percent (21.2 mmtCO_2e) to the 2020 target (169 mmtCO_2e).[62] These reductions will come as part of California's renewable portfolio standard (RPS), which currently requires investor owned utilities (IOUs), energy service providers (ESPs), and community choice aggregators (CCAs) to meet 20 percent of their retail electricity load with renewable energy by 2020. ARB's Draft Scoping Plan assumes that calls for an increase in the state RPS to 33 percent by 2020 will be approved, which is reflected in 21.2 mmtCO_2 estimate. More ambitious plans for scaling up the RPS are reflected in Proposition 7, the Solar and Clean Energy Act of 2008, which would require that utilities meet at least half of their retail load from renewable sources by 2025.

California is endowed with abundant renewable energy resources, particularly geothermal, solar, and wind. However, using these resources requires both developing the resource itself and integrating it into the electricity grid. The latter needs an advanced transmission, storage, and management infrastructure, which ETAAC concludes California does not yet adequately possess.[63] In part as a result, the cost of scaling up the RPS from 20 percent to 33 percent is substantial; E3's GWP Calculator projects that abatement costs of renewable energy associated with a 33 percent RPS scenario would increase by \$54/tCO_2. Others argue that the benefits of energy portfolio diversification through meeting a 33 percent RPS would outweigh the added costs.[64] In any case, both the economic and technical issues associated with increases in the RPS suggest the need for tripartite focus on technology, learning, and management in a dramatic scale up of renewable energy in California.

[61] CEC, IEPR, 2007.
[62] ARB, Draft Scoping Plan, 2008.
[63] ETAAC, 2008.
[64] KEMA, Inc., "Achieving California's 33 Percent Renewable Portfolio Standard Goal: Policy and Analysis Options," Final Consultant Report, January 2008.

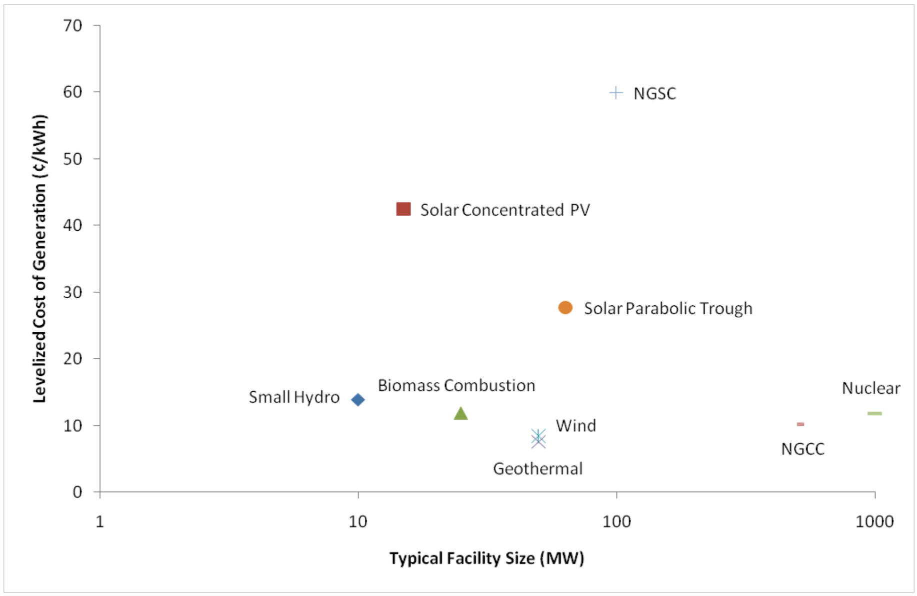
Table 8.1: Abatement Potential

Source	Main GWP	Abatement Technology	Abatement Potential ($mmtCO_2e$)	Abatement Cost ($\$/tCO_2e$)
Natural gas and coal combustion	CO_2	Wind	8.4	$88
		Geothermal	7.8	$100
		Utility-scale Solar	5.6	$116
		Rooftop Solar PV	2.2	$902
		Biomass	2.2	$205
		Biogas	1.1	$49
		Small Hydro	0.01	$112
		CHP	4.9	$228
		CCS	n/a	n/a

Sources: Abatement potential and cost are from E3's GWP Calculator; ARB's baseline does not include the 20% RPS goal, and we thus combine E3's Reference Case and High EE/33% RPS Case here.

There is a range of facility scales and levelized and abatement costs associated with different renewable energy technologies (Figure 8.1). Utility-scale renewable energy tends to be less than 100 MW in capacity, with a wide variation of costs that extend from cheaper wind and geothermal to more expensive solar. It is important to note that the renewable energy paradigm, even when centralized for utility-scale generation, is markedly different than either the natural gas or nuclear model. Both natural gas and nuclear power achieve low costs through economies of scale in large-scale power plants (typically greater than 500 MW); moving toward a higher share of renewable energy on the grid will entail a large increase in the number of generating facilities and an increase in complexity for grid managers.

Figure 8.1: Levelized Cost of Different Electricity Generating Sources in California, 2007



Source and Notes: California Energy Commission (CEC), "Comparative Costs of Central Station Electricity Generation Technologies," Final Staff Report, December, 2007. The above costs are from the "Merchant" category and reflect only a sample of the technologies in the report. NGSC is natural gas simple cycle; NGCC is natural gas combined cycle.

Transmission constraints are potentially the largest medium-term barrier to bringing more renewable energy online in California, as California's existing transmission system was not designed to support renewable energy.[65] Renewable energy resources are often clustered far from load centers, and thus require long transmission lines to connect to load centers. To address this problem, the CEC established the Renewable Energy Transmission Initiative (RETI), which is tasked with identifying and assessing competitive renewable energy zones in California and potentially neighboring states, and designing transmission strategies for integrating these resources. With some of its members recommending that no further renewable energy mandates be put in place without adequately addressing transmission and storage issues, the ETAAC report hints at the importance of overcoming transmission hurdles.[66]

[65] Center for Resource Solutions, "Achieving a 33% Renewable Energy Target," Report Prepared for the California Public Utilities Commission, November 2005.
[66] ETAAC, 2008.

Utility-scale Renewable Energy Options

Over the 2008-2012 period, California's three most important utility-scale renewable energy resources will be wind, geothermal, and solar, in that order. Biomass and biogas will play small but key roles in meeting a 33 percent RPS. Small hydro is not expected to be a major contributor to RPS goals.

The CEC estimates that California's technical wind potential is roughly 100 GW of capacity, including both high and low speed sites,[67] but nevertheless substantial when compared with the state's current 2.7 GW of capacity. A large portion of this 100 GW potential comes from repowering existing wind sites rather than developing new sites. California's neighbors have significant wind potential that could be imported, but this would require major investments in long-distance transmission capacity that are unlikely in a 2008-2020 timeframe. Wind itself is an inexpensive but intermittent renewable resource, with wind power typically generated at night. This intermittency raises reliability concerns once the share of wind power increases above a certain threshold of total generation. Innovations in grid storage capacity would assuage these concerns.

California currently has the largest geothermal installed capacity in the U.S. at 1.9 GW, a technical potential for an additional 2.9 GW at known sites, and a total estimated technical potential of 15.1 GW.[68] Geothermal energy is relatively inexpensive, having a levelized cost structure similar to wind, but has the added advantage of not being intermittent. Geothermal can thus be used as a reliable baseload resource, and is notably the only major renewable energy source among the "big three" for California that can. A key drawback to geothermal energy is the high cost of resource characterization and discovery, which can account for about one-half of the cost of a project and injects a substantial amount of risk into geothermal projects.[69] Public-private cost-sharing has been and will continue to be an important strategy to reduce risk barriers for geothermal projects.

Solar remains California's largest untapped renewable resource, and, of all California's renewable energy resources, solar has the largest potential for meeting the state's longer-term energy needs. NREL estimates the technical potential for utility-scale solar in California at 877 GW, with less than 1 GW currently developed.[70] Both solar photovoltaic and solar thermal are expensive relative to other renewable energy technologies (Figure 15), and more broadly solar shares wind's intermittency and transmission requirement problems. Bringing down the cost of solar conversion technologies will be important for mainstreaming utility-scale solar power.

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[67] ETAAC, 2008.
[68] ETAAC, 2008.
[69] ETAAC, 2008.
[70] ETAAC, 2008.

From a strictly engineering perspective, biomass resources continue to be underutilized for energy production in California, with only 15 percent of useable forest, agricultural, and municipal solid waste being used for energy. However, biomass is also one of the most expensive generating options among renewable energy sources, and will likely continue to play a more minor role until innovations bring feedstock costs down. The collection and distribution of feedstocks typically accounts for 60-70 percent of total costs for biomass power producers. In addition, biomass requires greater coordination than other renewable energy sources because biomass collection and distribution extends across several sectors, including agriculture, forestry, and electricity. New technologies for biomass gasification could help to bring down capital costs, but ultimately innovations in biomass collection and distribution will be the key to making biomass power generation more cost competitive.

Distributed Energy Options

Utility-scale renewable energy will represent one of two complementary pathways for California's renewable energy industry. Distributed generation (DG), which in the nearer term will most likely be represented by rooftop solar PV and combined heat and power (CHP), will in the short term play a small but meaningful role in reducing Global Warming Pollution, and in the long term will likely become a core part of California's energy supply. DG remains expensive vis-à-vis utility-scale resources, but DG has a number of technology-specific co-benefits that could help to accelerate adoption.

California has an estimated 74 GW of rooftop solar PV potential at peak output,[71] which dwarfs the less than 200 MW currently on roofs in the state. In accordance with the Million Solar Roofs Initiative (MSRI), the state will seek to expand rooftop solar PV capacity to 3 GW by 2016. Distributed solar PV would fail most standards of cost-effectiveness because of its high costs; in most analyses of the cost-effectiveness of different abatement options for California the California Solar Initiative (CSI)[72] is the most expensive option. However, the MRSI was designed in part to drive down costs, and costs for rooftop solar PV are expected to fall with improvements in module efficiency, innovations in balance of systems (BoS) components and system topologies, and learning in manufacturing and installation. Module costs were an estimated $4.82/watt in July 2008, but the solar industry is optimistic that module prices can fall by another $2 over the next decade to make solar cost competitive with grid electricity.[73]

[71] ETAAC, 2008.

[72] The CSI is the CPUC's portion of the MSRI, and accounts for the bulk of the 3 GW target. We use the two interchangeably here, although the MSRI officially includes a 400 MW component as part of its IOU New Solar Homes Partnership (NSHP) and a 660 MW component run by publicly owned utilities.

[73] Solarbuzz website, www.solarbuzz.com/Moduleprices.htm.

The economics of rooftop solar PV are significantly different than utility-scale renewable because of the former's distributed character. Because rooftop solar PV is already at the point of use, it competes with retail and not wholesale electricity prices and its ultimate "cost competitive" target would thus be around $0.12/kWh (i.e., the current retail base rate in California). To the extent that rooftop solar PV can reduce peak load and generation from "peaker" plants, that target can vary, as peak prices in California are more than $0.30/kWh. "Net metering" programs, in which utilities buy back surplus electricity produced by households, can improve the economics of rooftop PV by reducing costs for homeowners and, in some cases, total resource costs for utilities by reducing peak load, alleviating transmission congestion, and reducing line losses.

Despite these potential benefits, rooftop solar PV is currently not cost competitive in most cases. ARB uses a levelized cost of $6.46/W by 2020 in its Draft Scoping Plan to calculate MSRI costs, which translates to $0.41/kWh at a discount rate of 7 percent, a 20-year lifetime, and ARB's capacity factor of 0.17. With a slightly more optimistic capacity factor of 0.25 and a slightly lower discount rate of 5 percent, costs could fall to $0.24/kWh by 2020, but still much higher than the level required to be independently competitive without government support. A dramatic reduction in module and BoS costs — to a level likely in the range of $4-5/W — is the only way to make rooftop solar viable without large-scale subsidies.

CHP involves the capture of waste heat from the production of electricity ("topping cycle"), or using high quality waste heat to produce electricity ("bottoming cycle"). In both cases, a useable energy resource that would otherwise be wasted is allowed to do useful work, which increases the efficiency of energy conversion and thereby reduces Global Warming Pollution. California currently has 9.2 GW of CHP, including both topping and bottoming cycle plants and small and larger facilities. Smaller CHP units (less than 1 MW) are typically installed in service facilities, such as hospitals and schools. Slightly larger CHP units (5-10 MW) are used in manufacturing facilities that have relatively constant thermal loads, such as food processors and data centers. CHP units larger than 10 MW run continuously, are often grid tied, and in some cases export electricity.[74]

There are a range of estimates for both the potential and costs for CHP. ARB's current estimates for CHP are drawn from an EPRI report done for the CEC in 2005, which estimated California's CHP potential at 4.4-7.3 GW between 2002 and 2020. ARB uses a capacity equivalent of 4.3 GW to calculate a 6.8 mmtCO_2e abatement potential from CHP by 2020, at a negative net cost of -$193/t$CO_2$. E3's GWP Calculator computes a much higher cost of $228/t$CO_2$. PIEE estimate a moderate scenario for industrial CHP of 1.26 mmtCO_2e at $30/t$CO_2$ and 2.3 mmtCO_2e at $30/t$CO_2$ for residential and

[74] ARB, Draft Scoping Plan Appendices, 2008.

commercial CHP. PIEE's more aggressive includes 12.8 mmtCO_2e at \$6/tCO_2 for industrial CHP and 7.13 mmtCO_2e at \$6/tCO_2 for residential and commercial.

A number of barriers to CHP exist, which must be overcome before CHP can become a larger-scale energy resource in California. ETAAC indentifies three main barriers that include difficulties in securing power purchase agreements, long-standing debates over rates, and fees on "departing loads."[75] In most instances, the principal barrier lies between the CHP facility and the utility. Resolving this impasse will require strong government intervention. AB 1613 (The Waste Heat and Carbon Reductions Act), promotes the adoption of CHP under 20 MW in size but does not go to the extreme of requiring utilities to purchase surplus power from CHP systems. Without an incentive structure to overcome some of these barriers, it is unclear whether the potential for CHP in California will materialize.

Solar water heating is likely the most viable option for reducing Global Warming Pollution associated with natural gas used in heating. AB 1470 directs the state to target 200,000 solar water heating systems by 2017, which ARB estimates would lead to a 0.1 mmtCO_2e reduction in emissions at an exorbitant average abatement cost of \$2,920/tCO_2. A more aggressive measure, currently under consideration, would expand this goal to 750,000 homes and require that 75 percent of all new homes have solar water heating systems by 2020. A study by Kema and Xenergy in 2003 estimated that, if adopted statewide, solar water heaters could reduce emissions by 6.2 mmtCO_2e and reduce residential natural gas use by 22 percent.[76] A significant amount of uncertainty in prices, demand, and cost-effectiveness for solar water heating systems exists, and the CPUC is currently evaluating these dimensions as part of a pilot program. California policymakers would also be wise to look to China for insights in solar water heaters, as China has become the world's largest market for solar water heaters over the last decade.

Longer-term Options

Nuclear and CCS remain potential abatement options for the power sector over the longer term, but both will require extensive public discussion, an ability to reduce cost overruns and manage costs, and, at least in the case of CCS, greater technical feasibility.

Nuclear power is currently a major part of California's energy portfolio, accounting for 5 percent of total primary energy consumption and 11 percent of in-state electricity generation in 2007.[77] California has two large nuclear plants in operation, Diablo

[75] ETAAC, 2008.
[76] ARB,
[77] CEC website.

Canyon and San Onofre, both of which were built in the mid-1980s and both of which will have their licenses expire between 2022 and 2027.[78] California law currently prohibits the further construction of any nuclear power plants until the "federal government has approved and there exists a demonstrated technology for the permanent disposal of spent fuel from these facilities,"[79] a decision that dates back to a 1978 CEC study entitled *Status of Nuclear Fuel Reprocessing, Spent Fuel Storage and High-level Waste Disposal*. For 25 years, nuclear power was not on the state's energy planning agenda.

The federal Energy Policy Act of 2005 sparked a resurgence of interest in nuclear power across the U.S. As part of its 2005 Integrated Energy Policy Report, the CEC reopened the discussion on nuclear and California, with a review of existing plants, current federal laws, and the potential for nuclear as a longer-term energy source. A review for the CEC as part of its 2007 IEPR process concluded that federal plans for permanent disposal site are more than a decade away, and potentially longer.[80] Without breakthroughs in disposal, nuclear power will not be a major option for emissions abatement under AB 32.

CCS has potential as a longer-term AB 32 strategy by geologically sequestering both carbon emitted from natural gas combustion in California and carbon embedded in electricity generated outside of the state. CCS is a longer-term technology; neither the capture nor the storage aspects of CCS have been adequately demonstrated. The CEC has been active in CCS research as part of the West Coast Regional Carbon Sequestration Partnership (WESTCARB), and is currently participating in a large-scale, federally funded carbon storage demonstration project. The potential for geologic sequestration in California is vast, at an estimated 5.2 $GtCO_2$.[81] However, unless the costs of CCS come down markedly it will be an expensive backstop technology. For California, a joint CEC/CDOC report benchmarks CCS average abatement costs at \$50-100/tCO_2,[82] while PIEE sets the nearer-term costs for coal with CCS at roughly \$250/tCO_2;[83] for the U.S. power sector as a whole McKinsey more optimistically compute an abatement cost of \$44/tCO_2.[84] CCS research efforts have also fallen short of expectations. The federal government's FutureGen project has struggled with cost

[78] ETAAC, 2008.
[79] CEC website.
[80] Steven C. McClary, Robert B. Weisenmiller, Heather L. Mehta, and Laura B. Norin, "Nuclear Power in California: 2007 Status Report," Final Consultant Report to the California Energy Commission, October 2007.
[81] California Energy Commission (CEC) and California Department of Conservation (CDOC), "Geologic Sequestration Strategies for California: Report to the Legislature," Joint Report, February 2008.
[82] CEC and CDOC, 2008.
[83] Sweeney et al., 2008.
[84] McKinsey & Co., 2007.

overruns and it is increasingly unlikely that the Electric Power Research Institute's (EPRI's) goal of demonstrating the feasibility of CCS by 2020 will materialize.[85]

Electricity and Heating Demand

The CEC estimates that combined residential, commercial, and industrial annual statewide electricity demand will reach 300,000 GWh by 2020, growing at a rate of 1.1 percent annually between 2007 and 2020. Statewide demand for natural gas is projected to grow by 0.9 percent annually from 2007-2020.[86] With California's population expected to add nearly six million people by 2020, population growth will be a major driver of upward pressures on statewide demand for electricity and heating. At roughly 6,900 kWh/year,[87] California's electricity use per capita is already more than 40 percent lower than the U.S. average.[88] Further reductions in absolute electricity and heating demand will require even lower average levels of per capita use, which will entail a combination of innovative approaches to encourage adoption of existing technologies and innovation in new technologies.

Table 8.2

Emission Source	Main GWP	Abatement Measure	Abatement Potential ($mmtCO_2e$)	Abatement Cost ($\$/tCO_2e$)
Electricity consumption	CO_2	Building Standards	2.14	-$188
		Appliance Standards	4.48	-$219
		IOU EE Programs (economic potential)	14.5	-$2
		Municipal Utility EE Programs	6	$-17

Sources: Building and appliance standards are from ARB; IOU EE programs are from Sweeney et al., 2008; municipal utility EE programs are from ARB.

In the near term, efficiency and emissions targets for electricity and heating are likely to be met through more widespread adoption of existing technologies, and by all accounts there is still significant potential to do so. ARB's Draft Scoping Plan budgets 26.4 $mmtCO_2e$ of emissions reductions from energy efficiency by 2020, and ARB has argued that at least that amount is available at a negative average cost. Other analyses

[85] Matthew Wald, "Mounting Costs Slow the Push for Clean Coal," *New York Times*, May 30, 2008.

[86] California Energy Commission (CEC), "California Energy Demand 2008 - 2018: Staff Revised Forecast," FINAL Staff Forecast, 2nd Edition, Sacramento, California, 2007.

[87] Gorin, Tom, and Kurt Pisor. California's Residential Electricity Consumption, Prices, and Bills. California Energy Commission. Sacramento: CEC, 2007.

[88] Art Rosenfeld, "Achieving the 2050 Greenhouse Gas Reduction Goal: How Far Can We Reach with Energy Efficiency?" CEC Presentation, 2007.

suggest that the average costs of energy efficiency are likely to rise and become positive before 25 mmtCO_2e can be reached.[89] Nevertheless, in both the near and longer term, energy efficiency will play an important role in meeting AB 32 targets, and in reducing the impact of higher energy prices on California households and businesses.

As practical, technical limits to efficiency begin to be reached, the next generation of energy efficient technologies will reduce the activities required to maintain current standards of living, rather than simply reducing the energy required to perform these activities. Some of these high precision technologies are already commercial; sensors, for instance, reduce lighting load by automatically turning off lights when not in use. These “smart,” point of use technologies can play an important role in reducing electricity and heating load, but their technical and economic potential is not well understood.

For existing technologies, there are a number of barriers to the more widespread diffusion of energy efficient products, including risk or uncertainty, high initial costs, and differing attitudes towards efficiency.[90] To overcome these barriers, California’s policymakers have historically employed a mix of open-ended regulatory policies to decouple electricity sales and revenues and nurture technological growth, and minimum efficiency standards for appliances to set a floor on end use. Of the latter, the two most prominent are Title 20, which regulates and creates new energy efficiency standards for appliances sold within California, and Title 24, which provides standards and regulations for improving energy efficiency in California’s buildings and structures. In addition, approximately 1 percent of each IOU customer’s electric bill and 0.7 percent of their gas bill support an energy efficiency public benefits program that provides funding and incentives for upgrading structures and appliances to higher standards of efficiency.

In addition to reducing energy use, California’s energy efficiency policies also provide employment opportunities specialized firms and general contractors. Energy service companies (ESCOs), which are often specialized service providers, offer technical expertise and finance for efficiency upgrades. Presently, the energy services industry in California is relatively small, with only 17 firms in operation in 2004.[91] Job growth in this sector will increase as businesses begin to make efficiency upgrades and look for guidance in doing so. Potentially more so than ESCOs, California’s contractors will benefit as the demand for efficiency retrofits increases with new standards and incentives. There are hundreds and potentially thousands of contractors that conduct

[89] E3 GWP Calculator.

[90] Alan H. Sanstad, Michael W. Haneman, and Maximillian Auffhammer, *Managing Global Warming Pollution in California*, Berkeley: UC Berkeley, 2008.

[91] California Energy Commission (CEC), “Summary of Energy Services Companies,” Sacramento, California, 2005.

energy efficiency upgrades in California, but no systematic assessment of their numbers has been undertaken.[92]

Over the next two decade, improvements in efficiency will come via adoption of more energy efficient technologies and processes, as well more energy efficient behavior. More efficient products often come with higher upfront costs. However, the extra cost incurred by upgrading to more efficient products can be offset by long run savings in energy costs, depending on the magnitude of the additional cost and energy savings. The remainder of this section identifies the existing and emerging technologies that will allow California to reach the near-term and some long-term objectives identified in AB 32, and provides an overview of the costs and benefits of, and barriers to, the large-scale adoption of these technologies.

Residential: Lighting

Residential electricity use accounts for 33 percent of California's total statewide electricity consumption,[93] which, at an implied 36 mmtCO_2, represents about 7 percent of California's total Global Warming Pollution. Of the 5.5 mmtCO_2 market potential that PIEE estimates for emission reductions from energy efficiency, more than 45 percent (2.48 mmtCO_2) comes from the residential sector.[94] While there are a number of ways households can reduce their energy demand, the largest opportunity comes from the adoption and proper use of high efficiency products. Lighting represents the single household appliance with the greatest potential for major emissions reductions through simple implementation of existing high efficiency technologies, and we focus on lighting upgrades here.

Lighting is responsible for nearly 20 percent of total electricity use by California residents,[95] or approximately 7 mmtCO_2 in 2004. Though a smaller share of California's total Global Warming Pollution (about 1.5 percent), lighting has a disproportionate potential for emission reduction in the near term because of the considerable efficiency gains associated with switching from conventional incandescent lights to more efficient lighting technologies. Increasingly, lighting upgrades offer savings at nearly any discount rate and are nearly all available at negative abatement cost. Of the possible 5.5 mmtCO_2 market potential mentioned previously, 2.14 mmtCO_2 of these reductions are expected to come from more widespread use of high efficient lighting products and

[92] For instance, the Association of California Energy Contractors (ACE) included over 600 contractors directly involved in home energy improvements at the time of its creation in 2001. Steve Joyce, "New 'Energy Contractors' Association Starts in California," online at: http://www.buildingonline.com/news/viewnews.pl?id=977.

[93] California Energy Efficiency Strategic Plan. California Public Utilities Commission. 2008.

[94] Sweeney et al., 2008.

[95] California Energy Efficiency Strategic Plan. California Public Utilities Commission. 2008.

practices in the residential and commercial sectors.[96] If Californians were to implement all currently available high efficiency lighting technologies, Flex Your Power estimates that households could cut lighting costs by 30-60 percent.[97]

With lighting, the most important and effective efficiency upgrade that can be made is the replacement of current incandescent bulbs with high efficiency compact fluorescent lights (CFLs) or light emitting diodes (LEDs). A CFL uses about 75 percent less energy than an incandescent bulb of comparable brightness, and has an expected lifetime nearly 10 times longer. CFLs have not yet become mainstream; their share of the market for medium screw-based lamps increased roughly seven fold from 1999 to 2005, but represented only 7 percent of all new sales in 2005.[98] Higher upfront costs remain a major obstacle; for instance, an 18-watt CFL lamp might cost $7.00, while an incandescent lamp of similar lighting quality might cost only $0.50. However, because of its lower wattage and because the life of a CFL (10,000 hrs) is so much longer than that of an incandescent (750 hrs), the annualized savings from the CFL outweigh the higher upfront cost of purchasing the bulb, even at extremely high discount rates (Table 10).

Table 8.3: Cost Comparison between Incandescent, CFL, and LED

	Incandescent	Compact Fluorescent (CFL)	Light Emitting Diode (LED)
Bulb Cost	$0.50	$7.00	$48.00
Bulb Watts	60	18	1.3
Life (hrs)	750	10,000	50,000
Life (yrs)	1	14	68
CRF	1.04	0.12	0.07
Annual Use (kWh/year)	44	13	0.9
Annual Electricity Cost ($/yr)	$5.26	$1.58	$0.11
Annualized Bulb Cost ($/yr)	$0.52	$0.81	$3.39
Total Annualized Cost ($/yr)	$5.78	$2.39	$3.51
Annual Electricity Savings (kWh/yr)	-	31	43
Annual Cost Savings ($/yr)	-	$3.39	$2.27
Annual CO2 Reductions (kgCO2)	-	8.43	11.78
Marginal Abatement Cost ($/tCO2)	-	-$402	-$193

Sources and Notes: Bulb prices are from www.1000bulbs.com; this example uses an electricity cost of $0.12/kWh, a daily use of 2 hrs/day, a discount rate of 7 percent, and a grid emissions factor for California of 0.275 kgCO_2/kWh.

CFLs and LEDs demonstrate the efficiency potential of current commercial technologies and current technologies that are on the cusp of commercialization. LEDs are an existing, but not yet fully commercialized, technology that offers efficiency gains over

[96] PIEE, 2008.
[97] Flex Your Power website, http://www.fypower.com/res/tools/products_results.html?id=100195.
[98] Next 10, *The Green Innovation Index*, Palo Alto: Next 10, 2007.

both incandescent and CFLs. Currently LEDs are most widely used as indicator lights on electronic devices but are becoming increasingly more popular for higher power applications. In 2006, Japan-based company Nichia Corp. unveiled the first LED with a luminous efficiency of 150 lm/W.[99] This LED is 1.7 times more efficient than a standard fluorescent lamp, which has a luminous efficiency of only 90 lm/W, and is nearly 11.5 times more efficient than a standard incandescent bulb (13 lm/W). The estimated lifetime of an LED is nearly 50,000 hours, 5 times greater than that of a CFL. The major upside of LEDs, though, is the minimal electricity required to operate the bulb. An LED lamp that has lighting power comparable to an 18-watt CFL requires only 5 watts to operate. LEDs are expected to become more mainstream over the next decade as their costs come down.

Commercial: HVAC

With more than 5 billion plus square feet of utilized space inhabited by a wide range of businesses and corporations,[100] California's commercial sector accounts for nearly 38 percent of the state's electricity consumption and about 25 percent of its natural gas consumption. Lighting, refrigeration, and HVAC systems account for 75 percent of its electricity consumption, while space heating, water heating, and cooking account for almost 90 percent of the gas used.[101] California's commercial sector provides significant opportunities for emissions reductions through implementation of new efficiency standards and adoption of more efficient technology. PIEE estimates a nearer-term potential of 1.75 mmtCO_2 available in commercial sector efficiency gains at a negative cost of abatement.[102]

The CEC outlined three main goals for the commercial sector in its strategic plan for achieving AB 32 targets:

1) An increased percentage of high efficiency commercial construction space, ultimately reaching 100 percent of new commercial buildings using zero net energy by 2030.
2) Existing buildings will achieve high levels of energy efficiency with a substantial and increasing amount reaching zero net energy by 2030.
3) Heating, ventilation, and air conditioning (HVAC) systems will be transformed to yield optimal performance for packaged heating and AC systems used by small commercial consumers.[103]

[99] Luminous efficiency is the amount of light, in lumens, a bulb emits per watt of electricity used. Ookubo, Satoshi. "Nichia Unveils White LED with 150 Lm/W Luminous Efficiency." Tech News, Straight From Asia 21 Dec. 2006.
[100] California Energy Efficiency Strategic Plan. California Public Utilities Commission. 2008.
[101] California Energy Efficiency Strategic Plan. California Public Utilities Commission. 2008.
[102] PIEE, 2008.
[103] California Energy Efficiency Strategic Plan. California Public Utilities Commission. 2008.

This plan reveals the important role that HVAC systems will play in reducing California's energy demand.

It may seem odd that the CEC explicitly emphasizes HVAC systems rather than lighting, as lighting uses 35 percent of commercial electricity and HVAC uses only 27 percent.[104] The use of efficient lighting products and practices are as important in the commercial sector as they are in the residential, and the efficiency gains in commercial lighting are likely larger than those in the residential sector. However, upgrading a lighting system is technically easier and can be done at a lower cost than an HVAC upgrade. It is for this reason that the CEC is seeking to enhance the "quality of installation and maintenance so that by 2020, 90 percent of systems are installed to quality standards and optimally maintained for systems' useful lifetimes."[105]

HVAC systems account for 40-60 percent of total energy used by California's commercial sector.[106] By utilizing and implementing available efficient HVAC technologies and practices in the residential and commercial sectors combined, PIEE estimates that 0.76 mmtCO_2 could be reduced at a negative cost.[107] This simply means that there are many small things that can be done to existing HVAC systems to increase efficiency without replacing the entire system. The CEC's plan of action to integrate high efficiency HVAC practices has two main objectives: 1) increase the quality of installation and maintenance on central AC systems to achieve additional energy and peak savings and 2) accelerate market penetration of new technologies that are more energy and peak efficient than existing equipment. The CEC's strategy is multifaceted in that it seeks to educate end users on energy saving maintenance practices, ensure that contractors are installing equipment properly and up to code, increase Title 24 compliance, and encourage R&D on whole house design and system advances. The CEC estimates that by 2012 annual energy savings from improvements in HVAC systems will reach 400 MW statewide, with the commercial sector alone seeing a 45 percent reduction in energy costs by 2011.[108]

The efficiency of most heating and AC systems is described by the energy efficiency ratio (EER), which measures how much heat per hour is removed per watt of power it draws. Currently the federal minimum EER is 9.7, which is typical of the largest systems using greater than or equal to 760,000 Btu/hr. The most efficient technology available has an EER of around 14 and has a capacity of less than 65,000 Btu/hr.[109] By using a high efficiency packaged system, energy use can be reduced by about 40 percent

[104] CEC, Energy Efficiency Strategic Plan, 2008.
[105] CEC, Energy Efficiency Strategic Plan, 2008.
[106] Flex Your Power website, http://www.fypower.com/com/tools/products_results.html?id=100124.
[107] PIEE, 2008.
[108] Messenger, Mike, and Anne Premo. California HVAC Strategic Plan. CEC, CPUC. 2007.
[109] 2007 Appliance Efficiency Regulations. California Energy Commission. Sacramento: CEC, 2007.

compared to using a system that performs at minimum standards. However, since entirely replacing an HVAC system comes at a high cost most businesses will seek to upgrade the system that is currently being used in their home or business. Since many components in an HVAC system have relatively long lives of 10-20 years, these upgrades will account for the most substantial reductions in the near and medium term.

One upgrade that can be made at a relatively low cost is the installation of an Energy Star thermostat. These thermostats save energy by regulating the temperature of a system so as to be maintained at or near the desired level, and can be programmed for different temperatures at different times of day. Integration of these thermostats to existing systems can help to save up to 30 percent on energy costs annually if programmed properly. And since these thermostats cost around $150, payback times are fairly short and lifecycle energy savings generally outweigh costs.[110]

Another modification that can be made to an already operating system is properly attaching and sealing the ducts incorporated with the HVAC unit. Duct losses can account for nearly 30 percent of energy consumed by an HVAC system. By using aerosol sealants to fix small leakages the average system could see savings of $150 annually on electricity costs, depending on the output of the system.[111] Adjustable speed drives can be added to fans within the system to help control the speed at which air is moved throughout the building to match demand. These drives can help reduce energy costs by 30-40 percent and can cost anywhere from $200 to $1000 depending on the output of the HVAC system.[112] These drives look to play an important role in HVAC efficiency in the future as they can be added to multiple parts of the system, helping to cut energy use even further. For those using older systems that do not possess the capital to upgrade, replacing old fan and pump motors can be a relatively cost effective way to reduce energy use by 35-45 percent annually.[113]

While upgrading a system that is currently in use, it may prove to be more cost-effective to replace a large component of the system, such as the air conditioner. Replacing a mid-size air conditioner performing at the federal minimum standard with the highest efficiency model can reduce electricity consumption by nearly 1,600 kWh/year.[114] This would result in a 1.3 ton/year reduction in CO2 emissions and save nearly $930 in energy costs over the lifetime of the unit. However, the highest efficiency air conditioners come with high upfront costs, which may deter more aggressive replacements.

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[110] Energy Star website, http://www.energystar.gov/index.cfm?c=thermostats.pr_thermostats.

[111] Flex Your Power website, http://www.fypower.com/com/tools/products_results.html?id=100124.

[112]http://www.driveswarehouse.com/showcategory.aspx?CategoryID=22&ppc=1&gclid=CNPH7OXKkJQCFSEbagodyGyWtw

[113] Flex Your Power website, http://www.fypower.com/com/tools/products_results.html?id=100124.

[114] Flex Your Power website, http://www.fypower.com/com/tools/products_results.html?id=100124.

Industrial: Motors

California's industrial sector represents 16 percent of the state's total electricity end use and 33 percent of its end use gas consumption. At 21 percent of the state's CO_2 emissions in 2004, industry is also a focal point for policymakers as they identify areas with high potential for cost-effective emissions reductions. PIEE estimates that increasing efficiency in the industrial sector could result in reductions of 1.32 mmtCO_2,[115] and a study by Lawrence Berkeley National Laboratory (LBNL) contends that these reductions could come at significant negative cost.[116]

The CEC's Energy Efficiency Strategic Plan identified four strategies that will work together to promote energy efficiency by industrial consumers, including:

1) Branding, certification, and continuous improvement of certification to ensure industrial commitment to efficiency;
2) Integrated utility programs and incentives;
3) A central knowledge base for industrial efficiency; and
4) A coordinated regulatory committee to oversee efficiency within the industrial sector.[117]

Unlike the commercial and residential sectors, the CEC put no particular emphasis on the integration and development of new high efficiency products, though there are many available and emerging technologies with high energy reducing potential. LBNL found that California's industrial sector could reduce electricity consumption by 2,748 GWh, or 8 percent, and reduce gas consumption by 192 Mth, or 5 percent, annually by 2016 if all cost effective and achievable opportunities are pursued.[118] LBNL identified pump systems, compressed air systems, fans, and lighting as having the largest potential for electricity savings. For natural gas, boilers and process heating equipment show the largest potential for savings. Embedded within the end uses identified above are motors and drives that consume a large portion of the energy used by the systems as a whole. Motor-driven equipment consumes upwards of 55 percent of the total energy consumed by California industry, and Flex Your Power estimates that, by adopting new motor technology and efficient methods of use, industry could reduce total energy use by 18 percent.[119]

Many changes can be made to existing motors or motor systems to increase efficiency. For instance, optimizing a system's performance reduces load requirements for that system, creating opportunities to use less or smaller motors to power the same process.

[115] PIEE, 2008.
[116] Lawrence Berkeley National Laboratory (LBNL), *California Industrial Energy Efficiency Potential*, Berkeley: Ernesto Orlando Lawrence Berkeley National Laboratory, 2005.
[117] California Energy Efficiency Strategic Plan. California Public Utilities Commission. 2008.
[118] LBNL, 2005.
[119] Flex Your Power website, http://www.fypower.com/ind/

Optimizing an existing system could mean widening pipe diameter to reduce resistance, leveling process flows over time to reduce peak loads, or eliminating unnecessary by-passes. Studies have shown that by making these types of changes energy used by an existing system could be reduced by 5-60 percent, depending on the status of the system being upgraded. Reducing speed to match load size or using an adjustable speed drive (ASD) to do so can reduce a system's energy use by 30-80 percent depending on system size and current efficiency.[120] Purchasing an ASD can be a costly upgrade as they range in price from $3,000 to nearly $30,000.[121] As a result, many within the industrial sector may look to manually configure their system to match motor speed to fluctuating load size, which may cost as little as hiring a technician to audit the system and make changes where possible.

A more ambitious way to reduce energy used in the industrial sector would be to replace all or a significant portion of outdated motors with new, high efficiency models. By replacing a single outdated 100 hp motor with a General Electric X$D Ultra model savings could reach 2,812 kWh annually,[122] saving about $250, and reducing CO_2 by 2.2 tons/year. The high preliminary cost associated with purchasing and installing new motors may deter retrofits, but through government intervention and incentives motor replacement could be a relatively easy way to reduce industrial electricity use by a substantial amount and ultimately reduce spending.

In the future the development of variable speed drives has significant potential for increasing motor efficiency. As technology progresses variable speed drives will become small enough so as to be integrated with the body of the motor and sold as a unitary variable speed motor. This would mean that motors could internally manage speed according to load size, helping to reduce the amount of energy wasted on inefficient load management. Currently, variable speed motors are used in a variety of applications. However, full commercialization has been prevented because current technology has problems with motor cooling in high torque applications and can cause problems if they are not selected and installed properly.[123]

More so than the commercial or residential sectors, the industrial sector possesses internal barriers that would make the implementation of technology and efficiency policies increasingly difficult. First, California industry is highly diverse in type, size and operation, and therefore a one size fits all policy will not suffice. Capital investment and process changes are limited by internal financial constraints and access to the necessary technical information. Also, conflicting resource management objectives and regulations inhibit efficiency improvements. Most importantly, the industrial sector

[120] Flex Your Power website, http://www.fypower.com/ind/
[121] EMotorstore website, http://www.emotorstore.com.
[122] General Electric website, ge.ecomagination.com/site/products/ulmo.html#linksdownloads.
[123] Donald Wulfinghoff, "Variable Speed Motors and Drives," Energy Institute, 2003.

operates under the banner of profit maximization. Therefore, if the cost of becoming energy efficient begins to outweigh relocation, industries will start to leave the state. To avoid this, policymakers must work closely with industry leaders to develop a strategy that not only promotes energy efficiency, but also strengthens the competitiveness of California industry.

Demand Response

The CEC has identified the adoption of demand response systems using advanced monitoring infrastructure (AMI) as a likely addition to California's buildings and structures to promote efficient energy use.[124] Demand response allows consumers to shed loads in response to utility or market price conditions. AMI provides the user with a real time view of how much energy is being consumed and at what price level. Many are unaware that utility companies charge different prices for electricity at different times of the day, sometimes charging up to three times more for electricity used during peak hours. Demand response would allow consumers to regulate their own electricity use according to price and necessity. The Federal government has recognized the energy saving potential of demand response and created initiatives such as GridWise and EnergyWeb to nurture development of this technology. A 2006 case study done by the Bonneville Power Administration found that the cost of adopting technology similar to demand response is justified by the amount of avoided transmission.[125] This type of technology is still being developed for marketable integration into California's homes and businesses, and is being looked at as a medium- to long-term reduction strategy.

Transportation Fuels

Transportation fuels account for roughly 40 percent of California's Global Warming Pollution, making transportation arguably the most critical sector for meeting long run AB 32 targets. Although improvements in vehicle efficiency will likely account for most of the nearer-term emission reductions in the sector, in the medium- to longer-term California will eventually be required to reduce the share of petroleum-based fuels — and particularly gasoline, diesel, and jet fuel — in its transportation energy portfolio, even with huge gains in vehicle efficiency and reductions in VMT. Petroleum-based fuels are extremely well-suited to transportation because of their high volumetric energy densities (e.g., in MJ/m^3), which makes them lighter to carry in a constrained volume and thus difficult to replace (Table 8.4).

Table 8.4: Energy Densities of Selected Fuels on a Mass and Volume Basis

[124] California Energy Efficiency Strategic Plan. California Public Utilities Commission. 2008.

[125] Du Bois, Denis. "Demand Side Technology Avoids Grid Construction for Bonneville Power." Energy Priorities 28 Apr. 2006. 22 June 2008

	Mass (MJ/kg)	Volume (MJ/m^3)
Biodiesel	42.2	33.0
Butanol	36.6	29.2
Diesel	45.8	38.7
Ethanol	30	24
Gasoline	46.9	34.6
Liquid Hydrogen	143	10.2
Jet Fuel	42.8	33
Methanol	19.7	15.6
Natural Gas		38.3

Of the 186.9 mmtCO_2e in emissions from transportation in 2004, gasoline accounted for 77 percent, diesel represented 19 percent, jet fuel 2 percent, and other fuels the remaining 2 percent.[126] Gasoline and diesel thus comprise the bulk of emissions from petroleum-based fuels, and we focus on these two energy sources here. Because the majority of fuels in the transportation sector are energy carriers (i.e., refined or converted from primary fuels), Global Warming Pollution from different energy sources are usually measured on a lifecycle basis, which includes the greenhouse gases emitted during the production and combustion of the fuel. On the fuels side of the transportation sector, there are only three options for reducing lifecycle Global Warming Pollution:

1) Reducing the carbon intensity of upstream activities (e.g., extraction and refining in the case of petroleum derivatives, growing and refining in the case of biofuels);
2) Reducing petroleum-based fuels used per mile through either blends (e.g., biofuels) or other partial substitutions (e.g., electric batteries);
3) Completely switching to a non-fossil fuel, low or no carbon source, such as biofuels, hydrogen, or electricity.

Currently, it is far more cost-effective and technologically feasible to reduce upstream emissions (option 1) and gasoline use per mile (option 2) than to replace petroleum-based fuels wholesale (option 3). Both because of the opaqueness of the oil refining sector and the still emergent nature of the alternative fuels sector, it is also not clear what kinds of technologies will be most cost-effective for options 1 and 2. California's 2007 Low Carbon Fuel Standard (LCFS), which calls for a 10 percent reduction in California's carbon intensity for transportation fuels by 2020, is a flexible performance-based standard that clearly recognizes this uncertainty, but does not send explicit signals for R&D investment in larger-scale replacements for petroleum-based fuels.

[126] ETAAC, 2008.

Table 8.5:

Emission Source	Main GWP	Abatement Technologies	Abatement Potential ($mmtCO_2e$)	Abatement Cost ($\$/tCO_2e$)
Gasoline and Diesel Combustion	CO_2	Improvements in Petroleum Production/Refining Efficiency	7.4	n/a
		Ethanol	7.4	-$15
		Biodiesel	0.8	$0
		Renewable Electricity (PHEVs)	6.68	$89
		Hydrogen from renewable feedstock	n/a	n/a

Source: See below.

The remainder of this section discusses four primary focal areas for reducing Global Warming Pollution from transportation fuels: petroleum production and refining, sustainable biofuels, electricity powered with low carbon energy, and hydrogen generated from a low carbon feedstock.

Petroleum Production and Refining

Oil refining is necessary to convert crude oil into useable petroleum products. California is a major oil producer and has the third largest petroleum refining industry in the U.S., behind Texas and Louisiana.[127] California refineries supply the bulk of the state's substantial demand for petroleum products. Refineries are also the most energy-intensive industry in the state. In 2004, emissions from petroleum production and refining were 12 $mmtCO_2$ and 35 $mmtCO_2$, respectively, or collectively 10 percent of California's total Global Warming Pollution. ARB estimates that petroleum production and refining could reduce emissions by 3 $mmtCO_2$ and 4.4 $mmtCO_2$, respectively, by 2020, but these estimates are highly uncertain.[128] Little information exists on abatement potential or costs in the petroleum sector.[129]

In principle, there are a number of strategies for reducing emissions in petroleum refining in California, including: requiring energy efficiency audits and best available control technology (BACT), curtailing refinery expansions, and limiting the push to use heavier crude. Energy efficiency audits should use current available methods in order to identify the largest energy users within each refinery, as well as uneven practices among refineries, and set stringent emission standards. BACT will be particularly effective if applied toward refinery boilers and heaters, many of which are old and have "grandfathered" permit requirements allowing exemption from modernized NO_x

[127] Ernst Worrell and Christina Galitsky, *Profile of the Petroleum Refining Industry in California*, Berkeley: The Lawrence Berkeley National Laboratory, 2004.
[128] ARB estimates are cited from Sweeney et al., 2008.
[129] Sweeney et al., 2008.

emissions standards. If refineries were required to meet strong NO_x emissions standards across the board this would decrease Global Warming Pollution because newer boilers and heaters are so much more efficient than older boilers. Lastly, improving efficiency at refineries would allow them to reduce their grid electricity requirements; refineries are already a major source of cogeneration in California, but there is still potential to increase this capacity.[130]

Ethanol

Biofuels are a promising technology that may play a key role in achieving nearer-term LCFS targets, and in replacing a greater share of petroleum-based fuels in the longer term. California's ethanol production capacity was 71 million gallons per year in 2004, meaning that the bulk of the 900 million gallons consumed in California are imports, mostly from the Midwest.[131] At nearly 6 percent, ethanol, which is also used as an oxidant in gasoline to improve combustion, is already a significant share of California's gasoline blend, and California is the largest consumer of ethanol in the United States.[132] With mounting concerns over the food and net emissions impacts of first generation biofuels,[133] California has a strategic opportunity and responsibility to lead RD&D efforts for second generation biofuels. Executive Order S-06-06 (April 2006) commits the California to produce a minimum of 20 percent of its biofuels in-state by 2010, 40 percent by 2020, and 75 percent by 2050.

Corn ethanol does not currently provide a substantial reduction in Global Warming Pollution over gasoline. Ethanol from refining facilities powered by natural gas yields a small reduction in Global Warming Pollution; conversely, net Global Warming Pollution from coal-fired ethanol facilities exceed those from gasoline.[134] While these "first generation" ethanol is less energy intensive in the refinery processing stage than "second generation" cellulosic ethanol, first generation ethanol requires more energy for growing the crop. As a result, the global warming intensity of first generation feedstocks is significant higher than that of second generation feedstocks.

Global warming intensity (GWI) is an indicator of how much CO_2 is emitted per unit energy content (e.g., MJ) of the fuel. The lower the GWI value the smaller the amount of pollution and potential environmental impact. Because of changes in technologies, GWI values are not fixed, but values at a given time are nonetheless indicative. For corn

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[130] The above discussion is drawn from California Air Resources Board (CARB), "Attachment C: Comments on CARB AB 32 Scoping Plan, Oil Refineries," May 2008.
[131] CEC, *Integrated Energy Policy Report*, 2005.
[132] ETAAC, 2008.
[133] See, for instance, Renewable Fuels Agency, *The Gallagher Review of the Indirect Effects of Biofuels Production*, East Sussex: RFA, 2008.
[134] Farrell and Sperling, 2007.

ethanol, an equal mix of four production arrangements generates a GWI value of 58 gCO_2e/MJ. Based on a mix of cellulosic production pathways, cellulosic ethanol has a GWI of 4 gCO_2e/MJ.[135] This significant difference highlights the importance of finding alternative feedstocks to corn as an ethanol source.

Other ethanol feedstocks have varying degrees of potential. Sugarcane is already produced in large quantities in Brazil, and is the most productive, commercially viable ethanol feedstock, with yields of 1200-1400 gallons per acre and additional growth possible from bagasse, a cellulosic residue of sugarcane, of 400-700 gallons per acre.[136] However, in California only the Imperial Valley is suitable for sugarcane growing. If an ambitious 20 percent crop shift to sugarcane is implemented yields could reach 140-200 million gallons of ethanol, while using only 100,000 acres of agricultural land.[137] Sweet sorghum is another potential feedstock, which requires less water than corn and has annual yields of 400-700 gallons per acre (corn yields are 550 gallons/acre), with possible additional growth from bagasse of about 400-700 gallons per acre.[138]

Though cellulosic ethanol shows promise it remains fundamentally land constrained. Dramatically scaling up cellulosic ethanol production might potentially displace, for instance, land used agriculture. While this displacement might negatively impact global food supplies it might also increase the lifecycle emissions associated with the ethanol feedstock. As the recent Gallagher Report notes, the indirect land use change (iLUC) impacts — farmers, for instance, converting natural forest into agricultural land to make up for reduced soy bean production in the U.S. — of biofuel production are potentially large. When corn ethanol includes iLUC effects, for instance, its GWI rises to an estimated 100-200 gCO_2e/MJ.[139]

Residual biomass — biomass from agricultural and forest "wastes" — is expected to be a small but relevant source of ethanol. The total annual ethanol potential for residue biomass in California is considered to be about 6 billion gallons gasoline equivalent, although all of this amount may not be available for industrial use.[140] Residual biomass, coupled with a modest growth in energy crop production, is expected to produce between 1-2 billion gallons of ethanol per year within 15 years, in addition to contributing to electricity generation.[141]

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[135] Farrell and Sperling, 2007.
[136] Farrell and Sperling, 2007.
[137] Farrell and Sperling, 2007.
[138] Farrell and Sperling, 2007.
[139] (LUC Biofuels)
[140] Farrell and Sperling, 2007.
[141] (A roadmap for the development of biomass in California 2006)

Because of concerns and uncertainties about the social, economic, and technical feasibility of larger-scale commercialization of cellulosic ethanol in the near future — questions that remain open ended — there is a wide range in abatement potentials and costs for ethanol. PIEE estimates that, as part of LCFS goals, cellulosic ethanol will contribute to a 7.4 mmtCO_2e reduction in emissions by 2020 at -$15.40/t$CO_2$.[142] For conventional corn ethanol, ARB estimates an abatement potential of 2.4 mmtCO_2e by 2020 and costs of $365.13/t$CO_2$.[143]

Biodiesel

Biodiesel has an ability to provide a small but relevant impact in achieving AB32 goals. ARB estimates that biodiesel can provide a reduction of about 0.4 mmtCO_2 by 2010 and 0.8 mmtCO_2 by 2020. This is based on an estimated 2 percent displacement of diesel fuel by 2010 and a 4 percent displacement by 2020.[144] Currently there are 7 biodiesel refining facilities in California, with an annual production of 32.85 million gallons.

These facilities are mostly used by the federal government (Marine Corps), utility companies (PG&E), municipalities (City of Berkeley), and private companies (Fetzer Wine).[145] In 2004 California's diesel consumption was 1.036 billion gallons. With current biodiesel production, biodiesel can only cover about 3 percent of the state's diesel needs. In California a smaller-scale approach has been taken for biodiesel production facilities. More large-scale biodiesel production facilities will need to be created if an increase in biodiesel is wanted. There is no shortage on the number of biodiesel capable vehicles, as virtually all of the 1 billion barrels of petrol diesel are potentially replaceable with biodiesel should more firms and productions facilities decide to enter the market place.

The difficulty of biodiesel as a viable replacement for diesel is supply driven. The area requirements for biodiesel crops are larger than conventional ethanol. Biodiesel yields of about 100 gallons per acre are expected with an oil extraction efficiency of 94 percent, assuming a yield of 2,000 pounds of oil crop/acre with 40 percent oil content of seed. Under LCFS scenarios, necessary agricultural acreage will be 0.3-3.4 million acres, depending on the blend rates of biodiesel.[146] California has 27.6 million acres of farmland; meaning anywhere from about 1-12 percent of California farmland would

[142] Sweeney et al., 2008.
[143] ARB abatement potential is from CAT, 2007; costs are from "ARB, Review of Studies that Estimated the Costs of CO2 Emission Reductions," 2008.
[144] (CA EPA)
[145] Roland-Holst, 2007.
[146] Farrell and Sperling, 2007.

need to be dedicated to biodiesel crops (Table 8.6). The expected biodiesel adoption rate is 2 percent for 2010 and 4 percent for 2020.[147]

Table 8.6: Land area requirements to meet different blend ratios for conventional biodiesel in (1,000 acres, percent of current California farmland in parenthesis)

	B2	B5	B10	B20
2010	130 (0.5%)	324 (1%)	648 (2%)	1,295 (5%)
2020	343 (1%)	857 (3%)	1,713 (6%)	3,427 (12%)
2050	1,488 (5%)	3,719 (13%)	7,438 (27%)	14,875 (54%)

Sources and Notes: Farrell and Sperling, 2007; California farmland data is from the Farmland Information Center; B2 is a 2 percent biodiesel blend, B5 is a 5 percent blend, and so on.

Alternatives to oil-seed crops for biodiesel include algae, with potential yields up to 30 times greater than oil-seed crops.[148] Also possible are thermochemical conversion technologies such as biomass-to-liquids (BTL), which would allow for the production of renewable diesel production from lignocellulosic biomass, which is widely available in California.[149] Finally, there are uncertainties regarding biodiesel relating to its impact on climate change. The nitrous oxide emissions both from growing soybeans and black carbon from diesel emissions are of particular concern.[150] More research must be conducted to better understand the possible implications for larger adoption of biodiesel.

Electricity

Electricity generated with a fossil fuel alternative, such as nuclear, solar, wind, or biomass, would allow net zero carbon emissions from plug-in hybrid electric vehicles (PHEVs) running in all-electric mode or from all-electric battery electric vehicles (BEV). In the case of California, which mostly depends on low carbon sources for electricity, current use of PHEVs and BEVs would allow for reduced Global Warming Pollution.[151] To increase the share of electricity among transportation fuels and ensure that electrically powered vehicles contribute to LCFS goals, significant expansion of renewable and low-carbon power sources must occur.

A key question for more widespread use of electricity in the transportation sector is the implications for the required scale of electricity generating capacity. If all light duty

[147] Farrell and Sperling, 2007.
[148] J. Sheehan, T. Dunahay, H. Benemann, and P. Roessler, *A look back at the U.S. Department of Energy's aquatic species program--biodiesel from algae*, NREL/TP-580-24190, 1998.
[149] M. Tijmensen, A. Faaij, C. Hamelinck, and M. van Hardeveld. "Exploration of the possibilities for production of Fischer Tropsch liquids and power via biomass gasification," *Biomass and Bioenergy* 23:129-152, 2002.
[150] Farrell and Sperling, 2007.
[151] Farrell and Sperling, 2007.

vehicles in California were fueled by electric vehicles, for instance, more than 100,000 GWh of electricity, or one-third of current electricity generation, would be necessary to meet this demand.[152] A rise in demand at this scale would represent a substantial increase in electricity generation. For determining capacity requirements, however, the timing of electricity demand is more important than the total amount. Power generation capacity is designed to meet "peak" requirements; most businesses do not run their air conditioning systems all day, for instance, but generating capacity must be expanded to provide sufficient electricity so that all potential demand is met. As a result, many power plants are underutilized because they are only needed during peak demand periods.

In other words, a portion of electric vehicles' electricity requirements could be met without building more generating capacity. For instance, utilities and independent system operators can provide incentives to time electrical vehicle charging to be during off-peak hours.[153] In California, the current electricity grid could economically support over 1 million PHEVs, even during peak hours, with real-time pricing.[154] The main barrier to expanding the use of electricity as a feedstock for transportation fuels lies more on the vehicle than on the generation side. In order to achieve production and sales of 1 million or more PHEVs battery pack costs would need to be around the $650/kWh mark, a substantial reduction from the current $1,000/kWh mark.[155]

Hydrogen

In 2005 California created the Hydrogen Highway Network, whose goal is to promote the use of hydrogen and to put in place an infrastructure that would support hydrogen fuel cell vehicles, utilize at least 20 percent renewable sources in the production of hydrogen, and reduce climate change emissions by 30 percent.[156] Hydrogen is one of the few energy carriers that offer a long-term replacement for petroleum-based fuels,[157] but there continue to be considerable technical and economic challenges to the more widespread commercialization of hydrogen fuel cell vehicles.

Despite the multitude of feedstocks, hydrogen does not occur naturally and instead must be "mined." Steam methane reforming, gasification of coal or other fossil fuels, nuclear-thermal conversion of water, biomass gasification, and the electrolysis of water are the main options for producing hydrogen.[158] Of these methods, gasification from

[152] Farrell and Sperling, 2007.
[153] Farrell and Sperling, 2007.
[154] Derek Lemoine, Dan Kammen, and Alex Farrell, "An Innovation and Policy Agenda for Commercially Competitive Plug-in Hybrid Electric Vehicles," *Environmental Research Letters*, 2008.
[155] Lemoine et al., 2008.
[156] (CA EPA)
[157] (NRC 2004, IEA 2005)
[158] (UC DAVIS)

biomass and electrolysis from renewable energy offer the most substantial savings in Global Warming Pollution.

Hydrogen's true obstacle lies not in production or supply, but in storage and transportation. Since hydrogen is not dense (about one-tenth the density of gasoline), it must be compressed to high pressure (1000-10,000 psi) or liquefied to a low temperature (-253°C). Both of these processes are energy intensive, especially liquification. A more important measurement for hydrogen is thus its delivered cost. There is a range of costs associated for large-scale systems, varying between $2-4/kg depending on how the hydrogen is delivered.[159] In a central storage system, the delivered cost is about $2/kg, with some potential to go even lower over the future. Distributed hydrogen necessary for a network useable by the public has delivered costs of $7-10/kg depending on the method of production.[160] As a reference, because hydrogen fuel cells are 2-2.5 times more efficient than an internal combustion engine and 30-60 percent more efficient than a hybrid engine, a $3/kg of hydrogen has a cost per mile basis equivalent to $2/gallon of gasoline.[161] Because of its higher costs, hydrogen faces a chicken and egg problem with refueling and vehicle infrastructure, in that businesses are not willing to provide a decentralized refueling infrastructure if there are no drivers, and drivers are not willing to buy hydrogen fuel cell vehicles if there is no refueling infrastructure.

While the technical and economic issues for decentralized hydrogen distribution are still being addressed, the nearer-term potential for hydrogen is in the public sector. For vehicles that require centralized stations, such as public buses, hydrogen fuel cells are an economically viable option. Refueling stations may be placed in areas near hydrogen refineries, helping to curtail hydrogen storage and transportation issues. Currently there are 15 hydrogen refueling station demonstration projects operating in California, and there are plans for an additional 24. The California Hydrogen Highway Network Blueprint calls for a total of 50 stations by 2010, 11 more than are currently planned.[162] More extensive use in the public sector would be one approach to scaling up the hydrogen infrastructure, but even this requires resources and the state must, at some level, make a decision on how much of its resources it should commit to hydrogen to the exclusion of other competing technologies.

Transportation Energy Demand

Transportation is the largest source of greenhouse gas (GWP) emissions in California, contributing 40.7 percent of California's total Global Warming Pollution, or 188

[159] Farrell and Sperling, 2007.
[160] California Hydrogen Highway Network Blueprint Plan 2005
[161] Farrell and Sperling, 2007.
[162] Farrell and Sperling, 2007.

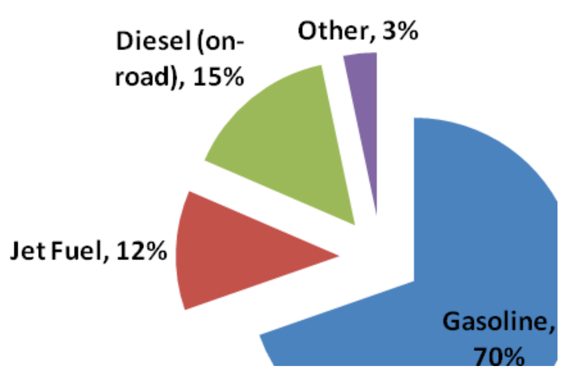
$mmtCO_2e$, in 2004.[163] Given the difficulty of finding nearer-term replacements for petroleum-based transportation fuels, trimming demand for these fuels will be a more feasible, cost-effective option for reducing Global Warming Pollution in the transportation sector to achieve nearer-term emission reductions. Emission reductions associated with compulsory fuel economy improvements (AB 1493) are the largest single measure in ARB's Draft Scoping Plan, and will be one of the most important measures for meeting the 2020 AB 32 goal.

Table 8.7:

Emission Source	Main GWP	Abatement Technologies / Measures	Abatement Potential ($mmtCO_2e$)	Abatement Cost ($\$/tCO_2e$)
Gasoline and Diesel Consumption	CO_2	AB 1493	31.7	-$350
		Vehicle Efficiency Measures	4.8	-$368
		PHEVs	6.7	$89
		Medium/Heavy Duty Vehicles	2.5	$297
		Goods Movement	3.7	-$1,173
		High Speed Rail	1	$0

Source and Notes: Other vehicle efficiency measures include low friction engine oils, ARB's tire pressure program, and cool paints; PHEV estimates are from Sweeney et al., 2008; all other estimates are from ARB's Draft Scoping Plan and its appendices.

Table 8.2:



Source: CEC, Inventory of California Global Warming Pollution and Sinks: 1990 to 2004, 2006

2 CEC, GWP Inventory, 2006.

Motor gasoline, consumed mostly by light duty vehicles (LDVs), accounted for 70 percent of total emissions from California's transportation sector in 2004. Diesel for medium- and heavy-duty on-road vehicles (15 percent) and jet fuel used by aircraft (12 percent) accounted for the bulk of the remainder. LDVs include passenger cars, light duty trucks (SUVs, minivans, pickup trucks), and motorcycles; passenger cars and light duty trucks account for a majority of transportation sector emissions, and are the focus of AB 1493.

This section highlights the transportation end use technologies that will make a major contribution to meeting the 2020 AB 32 goal, such as improved engine and transmission technologies in conventional internal combustion engine (ICE) vehicles and, to a lesser extent, efficiency improvements in multi-modal technologies. In addition, we provide a brief overview of the technologies and strategies that will begin to displace ICE vehicles, and will lay the foundation for meeting longer-term goals, such as hybrid and plug-in hybrid, fuel cell, and hybrid diesel electric vehicles.

Regulation will play a preponderant role in nearer-term improvements to vehicle fuel efficiency. AB 1493, passed in September 2004, requires vehicle manufacturers to reduce emissions from 2009 and later model year light duty vehicles and passenger trucks sold in California by about 30 percent by 2016.[164] A proposed second phase (Pavley II) would require further emission reductions post-2016 through hybrid engine technologies, use of lightweight materials in vehicle frames, and low-GWP refrigerants. In tandem, ARB's most recent estimate suggests that AB 1493 measures to 2020 would reduce baseline emissions by 31.7 mmtCO_2, at a cost (net savings) of roughly -\$350/tCO_2.[165] At its previous cost-effectiveness estimate of -\$177/tCO_2, ARB's estimate of the macroeconomic effects of AB 1493 found that, because of the multiplier effects of household savings noted previously, AB 1493 would increase gross state product by about \$50 billion and create about 22,000 jobs.[166]

Implementing AB 1493 requires a waiver from the EPA, which was initially denied but is likely to be granted under a new administration. If an AB 1493 waiver is not granted, ARB will either require original equipment manufacturers to verify greenhouse gas emission reductions or will use a fee-bate scheme in which fees on the purchase of high greenhouse gas emitting vehicles would be returned as rebates to buyers of low greenhouse gas emitting vehicles. Higher federal fuel economy standards, agreed upon in November 2007, would raise mpg for light duty vehicles to a 35 mpg average by 2020 and would lead to a significant reduction in Global Warming Pollution regardless of the

[164] ARB, "Climate Change for Mobile Sources," 2008, www.arb.ca.gov/cc/ccms/ccms.htm.
[165] ARB, Draft Scoping Plan Appendices, 2008.
[166] ETAAC, 2008.

AB 1493 waiver status. However, ARB argues that AB 1493 would achieve a 41 percent greater greenhouse gas reduction vis-à-vis federal fuel economy standards by 2020.[167]

A number of other measures will contribute to AB 32 goals in the transportation sector, additional vehicle efficiency improvements, heavy/medium duty vehicle measures, efficiency enhancements in goods management, and high speed rail. Combined ARB expects these measures to contribute to 12 mmtCO_2e of reductions by 2020,[168] which is significant but much less than reductions associated with light duty vehicles. For this reason, our focus here will be on the latter.

California drivers used an estimated 18.1 billion gallons of motor fuel to travel 330 billion miles in 2005, a 15 percent increase since 1990. Provided this demand for vehicle miles traveled continues to grow, gasoline use and related GWP emissions in the transportation sector will grow by an estimated 30 percent over the next 20 years.[169] While improvements to conventional ICE vehicles have the potential to reduce the emissions associated with much of this growth, such improvements do not lead to a significant decrease in absolute emissions from the transportation sector. Achieving absolute reductions in emissions through fuel economy improvements will require technologies that displace ICE vehicles. The remainder of this section describes major technologies for ICE fuel economy improvements, hybrid and plug-in hybrid electric vehicles, fuel cell vehicles, hybrid diesel electric trucks, hybrid and fuel cell buses, and finally more efficient rail, aircraft, and ships.

ICE Fuel Economy Improvements

The largest efficiency gains to conventional ICE vehicles will come through reductions in vehicle weight, engine modifications, and new transmission technologies. Weight is the key parameter in vehicle acceleration and climbing, and reductions in average vehicle weight will be an important strategy for automakers to meet AB 1493 standards. Weight can either be reduced through decreasing average vehicle size or by using lighter weight materials in vehicle frames and parts. Although engine efficiency is the largest determinant in overall fuel economy, because of thermodynamic constraints there are limits to the potential of efficiency improvements in conventional ICEs. Nearer-term engine and transmission efficiency improvements will rely on higher precision technologies that are already present on some vehicles, but will be scaled up to cover a large share of vehicle fleets.

[167] "Comparision of Greenhouse Gas Reductions" California Air Resources Board May, 08, 2008. <http://www.arb.ca.gov/cc/ccms/reports/final_pavleyaddendum.pdf>
[168] ARB, Draft Scoping Plan, 2008.
[169] "Climate Action Program at Caltrans" California Department of Transportation Business, Transportation, and Housing Agency Dec. 2006. < http://www.dot.ca.gov/docs/ClimateReport.pdf>

Engine modification technologies can improve fuel economy by reducing pumping losses and engine friction, and by improving combustion.[170] Variable valve timing (VVT) and cylinder deactivation are two key technologies for improving engine efficiency. VVT is a high precision technology that allows vehicles to optimize both the timing and extent of intake and exhaust valve opening and closing, thereby improving combustion. Cylinder deactivation similarly improves the engine's operational precision by shutting down cylinders when they are not in use. Cylinder deactivation systems shut down half of the engine's cylinders when running in deactivation mode. For example, a six-cylinder engine operates with three cylinders in deactivation mode.[171] However, a four-cylinder engine would have too few cylinders active in deactivation mode. Thus, the technology has been found to be better suited for vehicles with relatively high engine displacement to weight ratios and engines with at least six cylinders.

New transmission technologies improve overall vehicle efficiency by increasing the amount of time that the engine operates near its optimal speed.[172] Three existing transmission technologies have high potential for raising fuel economy: five- and six-speed automatic transmissions, continuously variable transmission (CVT), and dual clutch transmission. All three technologies reduce losses associated with delivering engine power to the wheels. Five- and six-speed automatic transmission technology increases the number of gears available on automatic transmissions from four to five or six, allowing for more optimal operating ranges and resulting in a two percent reduction in Global Warming Pollution for each increase in the number of speeds.[173] CVT is an automatic transmission technology that enables the driving shaft to maintain constant angular velocity as the vehicle changes speed, allowing a constant RPM. Dual clutch transmission is a semi-automatic transmission that reduces power interruptions associated with shifting gears through separate clutches for odd and even gears. Higher speed transmissions are currently the preferred choice for manufacturers because of their lower cost.[174]

These existing technologies can improve fuel economy on a range of vehicles. For smaller and larger increases in fuel economy that are accompanied by higher upfront costs, fuel economy savings over the lifetime of the vehicle can outweigh the additional

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[170] UCS website, www.ucsusa.org/clean_vehicles/cars_pickups_suvs/technologies-to-reduce-vehicle-greenhouse-gases.html.

[171] "Engine Cylinder Deactivation" Sep. 07, 2004. <http://www.patentstorm.us/patents/6786191/description.html>

[172] UCS website, www.ucsusa.org/clean_vehicles/cars_pickups_suvs/technologies-to-reduce-vehicle-greenhouse-gases.html.

[173] ARB, Staff Proposal Regarding the Maximum Feasible and Cost-effective Reduction of Global Warming Pollution from Motor Vehicles, 2004.

[174] ARB, Staff Proposal Regarding the Maximum Feasible and Cost-effective Reduction of Global Warming Pollution from Motor Vehicles, 2004.

cost. The “net” cost or savings depends on a number of behavioral considerations, including consumer discount rates, which significantly affect the economics.[175] Even accounting for discount rates, the savings from fuel economy improvements — and with them, decreases in Global Warming Pollution — are likely to be substantial. ARB estimates that the additional cost of reducing CO_2 emissions by 20 percent for small cars at near or less than $500, and for large cars, minivans, and small trucks at $500-$1500. At $3.50/gallon gasoline, the 20 percent decrease in gasoline consumption that would accompany a 20 reduction in CO_2 emissions would amount to an annual savings of $700. Longer-term technologies that lead to higher emission reductions currently have much higher upfront costs, but this example does give a sense of the cost savings available from nearer-term, existing technologies.

Hybrid-electric Vehicles and Plug-in hybrid Electric Vehicles

Hybrid vehicles combine the use of an internal combustion engine and an electric motor powered by a battery. The degree of hybridization in these vehicles extends from “mild” hybrids, which tend to bear greater resemblance to conventional ICE vehicles, to “full” hybrids, which make greater use of the vehicles’ electrical power. Moderate to aggressive hybrids can achieve improvements in fuel economy of over 30 percent, and with it reduced CO2 emissions on the same scale. A hybrid engine also operates more efficiently and produces less pollution than an ICE vehicle, while maintaining a similar or greater driving range.

The chief barrier to greater hybrid penetration has historically been cost. As the sticker price for hybrid vehicles continues to fall they will be become increasingly competitive as perceived fuel savings over the life of hybrids offset the upfront cost barrier. Currently, hybrid vehicles are eligible for a federal income tax credit of up to $3,400, depending on the vehicle make and model. These credits begin to phase out once a manufacturer has sold over 60,000 eligible vehicles.[176] While supply-side incentives for hybrid-electric vehicles are important in accelerating the adoption of hybrid electric vehicles, demand-side incentives, such as higher gasoline prices, are likely to be just as important. Changes in the price of gasoline significantly change the economics for hybrid adoption, although, as Heffner et al. note, economics are not the only driver of hybrid adoption.[177]

Plug-in hybrid electric vehicles (PHEVs) combine the benefits of pure electric vehicles and hybrid electric vehicles. Like electric vehicles, they plug into the electric grid and

[175] Maximilian Auffhammer, W. Michael Hanemann, and Sarah Szambelan, “Transportation,” *Managing Global Warming Pollution in California*, 2006.
[176] “New Energy Tax Credits for Hybrids” < http://www.fueleconomy.gov/feg/tax_hybrid.shtml>
[177] Reid R. Heffner, Kenneth S. Kurani, Thomas S. Turrentine (2008) Symbolism in California’s Early Market for Hybrid Electric Vehicles. *Transportation Research Part D* 12 (6), 396 – 413.

can be powered solely be electricity. Like hybrid electric vehicles, they have internal combustion engines that allow for a greater driving range and battery recharging. PHEVs maintain the efficiency advantages of a conventional hybrid even when they drive beyond their battery range and are in gasoline mode.[178] PHEVs could potentially be cost saving at a lower price point than conventional hybrids because they require comparatively little gasoline and electricity is typically a lower cost feedstock than gasoline. PIEE estimates that PHEVs could reduce 6.68 mmtCO_2 at an abatement cost of \$88.61/tCO_2 by 2020.[179]

However, there are several barriers preventing widespread commercialization of PHEVs, most of which are related to their greater battery reliance. PHEVs cannot be used for long trips because they must be charged. Additionally, because PHEVs require far more battery capacity than regular hybrid electric vehicles, battery costs are pivotal. Batteries must become cheaper, lighter, and longer-lasting before PHEVs become cost competitive. A PHEV will be 10-20 percent more expensive than a regular hybrid, for instance.[180] A United States Advanced Battery Consortium's (USABC) study predicts that battery prices must fall to around \$200 to \$300/kWh, or \$1,700 and \$3,400 for the PHEV-10 and PHEV-40 battery packs, respectively, for PHEVs to be competitive.[181]

Fuel cell vehicles

Fuel cell vehicles use hydrogen as a feedstock, and operate without combustion or pollution. If hydrogen is produced from renewable sources, fuel cell vehicles would be truly CO2 neutral and would bring substantial co-benefits from reducing criteria pollutant emissions, which UCS estimates at \$4,300 to \$8,300 over the vehicle's lifetime.[182] A number of major auto manufacturers are currently developing fuel cell vehicles, many of which can already perform near ICE vehicle standards. Honda's first fuel cell vehicle, the FCX Clarity, has a range of about 270 miles per tank of hydrogen and can reach speeds of up to 100 mph. Vehicle cost is a barrier; mass-produced fuel cell vehicles may ultimately add about \$1,000-\$3,000 to the cost of conventional cars.[183] However, as discussed previously, the main factors slowing the adoption of fuel cell vehicles are the cost of building hydrogen stations and continuing technical difficulties with storing hydrogen.

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[178] "Plug-in Hybrid Electric Vehicles" Energy Efficiency and Renewable Energy May. 13, 2008. http://www.eere.energy.gov/afdc/vehicles/plugin_hybrids.html.

[179] Sweeney et al., 2008.

[180] "All About Plug-in Hybrids" CalCars < http://www.calcars.org/vehicles.html#3>

[181] Axsen, Jonn; Burke, Andre; and Kurani, Ken "Batteries for PHEVs: Goals and the State of Technology Circa 2008" May. 2008. < pubs.its.ucdavis.edu/download_pdf.php?id=1169>

[182] UCS website, http://www.ucsusa.org/clean_vehicles/cars_pickups_suvs/the-promise-of-fuel-cell-vehicles.html

[183] Tomoko A. Hosaka "Honda rolls out new zero-emission car" Associated Press Jun. 17, 2008. http://www.statesman.com/news/content/business/stories/other/06/17/0617honda.html?cxtype=rss&cxsvc=7&cxcat=3

The timing for scaling up penetration for zero emission vehicles like fuel cell vehicles is an important consideration for state policymakers. UCS argues that to meet the 2050 AB 32 goal, California would need to have 379,000 fuel cells or other zero emission vehicles in its fleet within the next 12 years.[184] However, California's low carbon transportation model is still far from set, and it may be more cost-effective to rely on low emission vehicles that blend gasoline and petroleum substitutes and rely heavily on batteries. How fuel cell vehicle technology develops over the next ten years will be an important determinant in this question.

Hybrid Diesel Electric Trucks

Like hybrid cars, hybrid diesel electric trucks can run on both petroleum-based fuels (diesel) and electric power from a battery. Hybridization is particularly useful in diesel trucks that are used in waste collection and parcel delivery because of their frequent stops, which plays to the strengths of regenerative braking. ARB expects that hybrid trucks will make a small contribution to the AB 32 2020 goal, at 0.5 mmtCO_2. In 2009, Volvo aims to begin mass production of a hybrid truck engine that would cut fuel consumption per vehicle by up to 35 percent.[185]

Hybrid and Fuel Cell Buses

Hybrid and fuel cell buses also offer opportunities for emission reductions, though both are limited by cost considerations. Hybrid buses can cost up to $500,000, nearly twice as much as a standard diesel buses that costs around $300,000. Hybrid buses can reduce fuel consumption by 15-30 percent and NO_x emissions by 25 percent.[186] Fuel cell buses are currently being used in California, and offer the advantage of centralized refueling to reduce hydrogen costs. Alameda-Contra Costa Transit District (AC Transit) is undertaking a multi-year demonstration program to examine the commercial viability of fuel cell buses vis-à-vis the company's diesel buses. ARB does not calculate emission reductions from either of these options as part of its Scoping Plan.

High Speed Rail, Aircraft, and Marine

California is presently debating construction of a high speed rail (HSR) system that would connect major cities in northern and southern California. The HSR system, which would extend 700 miles from north to south and connect major cities in California, would reduce total greenhouse emissions by displacing trips in automobiles and airplanes,

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[184] UCS, "A New Vision for California's Zero Emission Vehicles Program: An analysis of the impact of the Zero Emission Vehicle Program on California's long term global warming pollution goals," 2008.

[185] "Volvo Says to Launch Hybrid Truck Engine in 2009" Mar. 13, 2006. <http://www.planetark.com/dailynewsstory.cfm/newsid/35601/story.htm>

[186] "Hybrid Transit Buses Are They Really Green?" Hybrid Center < http://www.hybridcenter.org/hybrid-transit-buses.html>

which are more individualized or more carbon-intensive modes. If the current bond measure is passed, phase I of the HSR (between Anaheim and San Francisco) is scheduled for completion in 2019. ARB's estimate of 1 mmtCO_2 is for the HSR's first year of service. Construction of the full HSR system would not be complete until 2030.

Jet fuel is a major contributor to California's greenhouse gas inventory, although the state currently lacks the authority to regulate CO_2 emissions from the aviation industry. Much like gasoline and diesel, jet fuel is difficult to replace because of its high energy density, and there are few options for reducing Global Warming Pollution from aviation aside from improvements in aircraft fuel efficiency and decreased air travel. For the U.S. as a whole, air travel rose much more rapidly than the level of Global Warming Pollution from 1990-2003, due to a higher number of occupied seats per plane and improved aircraft fuel efficiency. Consequently, Global Warming Pollution per passenger-mile decreased 24 percent from 1990 to 2003, the largest improvement of any transportation mode.[187] Boats and other marine vessels account for a much smaller share of California's Global Warming Pollution. As with aircraft, California is limited in the regulatory instruments with which it can reduce GWP emissions from marine transportation.

Manufacturing and Waste Management

Manufacturing and waste management are a significant source of primary energy and non-CO_2 Global Warming Pollution. A number of abatement options exist, ranging in size from negligible to medium and in abatement costs from zero to expensive. The majority of abatement measures are relatively inexpensive (< \$50/tCO_2e) and capital intensive (with the notable exception of MVAC servicing), which means the employment effects will be minimal in either direction.

[187] "Global Warming Pollution from the U.S. Transportation Sector, 1990-2003" U.S. Environmental Protection Agency Office of Transportation and Air Quality Mar. 2006 <http://www.epa.gov/oms/climate/420r06003.pdf>

Table 8.8:

Emission Source	Main GWP	Abatement Technologies/Measures	Abatement Potential ($mmtCO_2e$)	Abatement Cost ($\$/tCO_2e$)
Cement Manufacturing	CO_2	Energy Efficiency	0.8	$33
		Fly Ash	2.4	0
		Fuel switching	2.2	$119
Semiconductor Manufacturing	PFCs	Plasma etching	1.7	$23
Refrigerants	HFCs	MVAC servicing, refrigerant capture	8.5	$28
Waste Management	CH_4	Landfill gas capture	2.3	$42
		Zero waste	3	$33

Sources: See below.

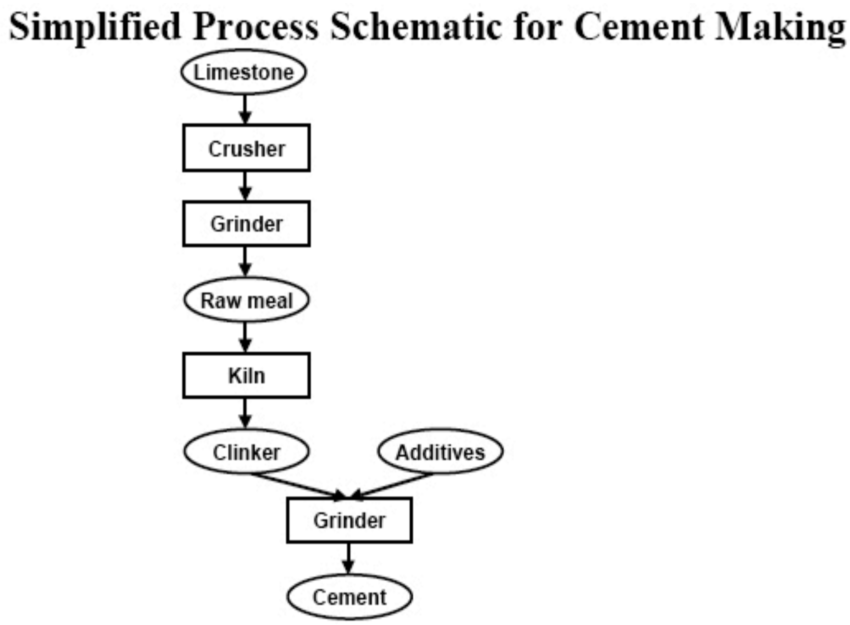
Cement Product Manufacturing

Cement is one of the most carbon-intensive industries in California. The cement and concrete sectors account for an annual 12 $mmtCO_2e$ in California,[188] or nearly 2.5 percent of total state Global Warming Pollution in 2004, but less than 1 percent of the state's NAICS revenue (0.4 percent) or employment (0.2 percent). However, cement and concrete are a vital input into commercial building and highway construction sectors and, as such, an important part of the California economy. Additionally, 40 percent of cement is imported into CA from around the world,[189] and the impacts of AB 32 policies are a concern both to the industry itself and for leakage considerations.

[188] California Energy Commission (CEC), "Emission Reduction Opportunities for Non-CO2 Greenhouse Gases in California," (2005): CEC-500-2005-121.

[189] Tom Pyle, "Overview: AB 32 Implementation Status," California Air Resources Board, 2008.

Figure 8.3:



Cement is an "inorganic, non-metallic substance with hydraulic binding properties and is used as a bonding agent in building materials."[190] The cement production process begins when limestone is harvested from a quarry near the processing plant. Shipping costs for the raw material necessitates building the refinery near the limestone source, unless the material is shipped overseas in which case the plant must be near a port. The raw material is then transported to the plant where it is processed through a crusher and grinder and blended with a mix of siliceous, aluminous, and ferrous materials into raw meal. The raw meal is heated to over 3000°F in a kiln then rapidly cooled to yield clinker, which contains the hardening agent alite (tricalcium silicate). Clinker is then ground into a fine powder and mixed with 3-5 percent gypsum, an additive that aids in cement setting.[191]

This process is energy intensive, and uses a number of different energy inputs. In California, the cement manufacturing process consumed 1,600 GWh of electricity, 22 million therms of natural gas, 2.3 million tons of coal, 0.25 tons of coke, and numerous waste materials (e.g., tires).[192] Correspondingly, there are a variety of strategies to

[190] California Energy Commission (CEC), "Optimization of Product Life Cycles to Reduce Global Warming Pollution in California," (2005) CEC-500-2005-110-F.

[191] LBNL Environmental Energy Technologies Division. "Case Study of the California Cement Industry." U.S. Environmental Protection Agency (2005): LBNL 59938.

[192] LBNL, 59938, 2005.

reduce Global Warming Pollution from cement manufacturing, and a wide range of costs for these different strategies, depending on the technologies adopted and production tax credits. The remainder of this section describes four of these options: energy efficiency improvements, fuel switching, greater use of fly ash, and burning of waste tires. Adopting these strategies could lead to reductions that total 5.4 mmtCO2e/yr by 2020, with a cost-effectiveness ranging between 0 and \$119/tCO_2e.[193]

There are a number of potential options for improving energy efficiency in cement production. The main energy efficiency opportunities in kiln operation for clinker production include pre-heating, "optimization of the clinker cooler, improved burners, and process control and management systems."[194] Other potential improvements in energy efficiency come from reductions in electricity consumption through the use of more efficient grinding and motor systems for processing limestone. Significant energy efficiency gains for cement manufacturing in CA have already been made through the use of dry processing technology that consumes less water and energy than wet processing. Sweeney et al. (2008) estimate that energy efficiency gains in the cement industry can generate a 0.8 mmtCO_2e reduction at \$33/tCO_2e. Barriers to adopting more energy efficient kilns, crushers and grinders include limited capital, concerns involving interruption of the production process, facility managers' lack of information, and the durability and reliability of the new equipment.[195]

Natural gas consumption in the cement industry is the most energy intensive in the kiln. A kiln uses about 10 percent electricity, with the remaining fuel primarily from coal, pet coke, and some natural gas. As of 2005, one California plant out of 11 utilizes 100 percent natural gas to heat the kiln as opposed to coal and pet coke.[196] Two reports show the cost of mitigation by using 100 percent natural gas to be expensive. ARB estimates the cost for replacing coal and pet coke with natural gas as \$137.76/tCO_2e, with an annual reduction of 2.2 mmtCO_2e.[197] Sweeney et al. (2008) find the same potential for emission reductions, but at a slightly lower cost of \$119/tCO_2e.[198] The largest barrier to fuel switching for cement manufacturers is clearly the cost, and as a policy measure would likely fail a cost-effectiveness test.

Clinker can be blended with various forms of aggregate (limestone, fly-ash, steel slag, and Cemstar®) that require less energy in the manufacturing and use processes. Of these forms of aggregate, limestone seems the most promising for adoption in California, as it is more abundant than fly-ash or blast furnace slag, which must be

[193] Sweeney et al., 2008.
[194] CEC, 2005, 110-F.
[195] LBNL, 59938, 2005.
[196] LBNL, 59938, 2005.
[197] CARB California Air and Resources Board. "NRDC Cement GWP Reduction Calcs Final," 2008.
[198] Sweeney et al., 2008.

imported. Fly-ash can be used as pozzolan and is an abundant by-product of power plants. Adding limestone would lead to CO_2 emission reductions of 436 ktCO_2 per year, or 5 percent of the total emissions of the CA cement industry, at a cost of \$0.7/t CO_2, reflecting the cost of delivery, storage, and electricity consumption.[199] Fly-ash has a net zero cost (\$0/tCO_2e) and an estimated reduction potential of 2.4 mmtCO_2e.[200] The primary barrier to adoption is the continued difficulty in obtaining approval for use through government and industry standards for product composition.[201]

Waste tires can be used as an alternative to coal for heating the kiln. LBNL estimates that a 20 percent replacement of fossil fuels by waste fuels would result in a reduction of 616 ktCO_2 per year, even though CO_2 emissions from kilns will increase. The reduction in pollution comes from reducing the quantity of tires being incinerated without energy recovery.[202] In 2004, permits for burning tires were issued by the EPA to seven CA plants. Four of the participating plants incinerated over 71,000 tons of scrap tires.[203] Continued barriers to adoption include the need to maintain clinker and fuel composition, which physically limits the adoption threshold. Also, there is public resistance to incinerating tires and the EPA permit is not a rubber stamp.[204]

Semiconductor Manufacturing

A semiconductor is a solid piece of silicon that has electrical conductivity and is used in almost any electrical device that needs to do a calculation. The semiconductor industry is a “technology enabler” in that its level of production has direct effects on multiple industries. Innovation and R&D can constitute up to 20 percent of annual revenues, and capital production on semiconductor fabrication plants, or “fabs,” can consume up to 25 percent of annual revenue. The semiconductor is a major source of revenues (\$20 billion in 2002) and jobs (99,714 in 2002) for the California economy.[205]

[199] CEC, 2005, 110-F.
[200] Sweeney et al., 2008.
[201] CEC, 2005, 110-F.
[202] CEC, 2005, 110-F.
[203] CEC, 200, 110-F 5.
[204] CEC, 2005, 110-F.
[205] BEA, 2002 Census.

Table 8.9: Global Warming Potential of Non-CO2 Gases

Global Warming Potentials of Gases Analyzed in this Report

Greenhouse Gas	Global Warming Potential (GWP)
Methane (CH_4)	21
Sulfur Hexafluoride (SF_6)	23,900
Tetrafluoromethane (CF_4)	6,500
Hexafluoroethane (C_2F_6)	9,200
Octafluoropropane (C_3F_8)	7,000
Octafluorocyclobutane (C_4F_8)	8,700
Trifluoromethane (HFC-23)	11,700
Nitrogen Trifluoride (NF_3)	8,000

The semiconductor industry emitted 2 mmtCO_2e in 2005, and following baseline trends emissions will increase to 7.74 mmtCO_2e annually by 2020.[206] The process-related Global Warming Pollution in semiconductor manufacturing are collectively referred to as perfluorocompounds (PFCs). PFCs have a significantly greater impact on atmospheric warming per mass unit compared to CO_2 (Figure @@).[207] In this section, we outline six technologies to reduce PFC emissions in the semi-conductor industry: plasma etching, remote cleaning, catalytic abatement, capture/recovery, thermal destruction, and clean room efficiency. The cost-effectiveness of these technologies is variable due to different tax rates and discount rates.

Plasma etching involves using high GWP gases to create an architecture of circuitry features on a silicon wafer's surface. The new process technology would isolate the etching tool from the fab's waste stream, oxidizing the GWP gases before the exhaust reaches the stack.[208] The costs of reductions in PFCs for adopting the new process technology range from \$12.86/tCO_2e for 0.72 mmtCO_2e of mitigation by 2010, to \$22.99/tCO_2e for 1.65 mmtCO_2e by 2020.[209] Barriers to adopting this technology include the low technical applicability, which is the degree to which the adoption of the process technology reduces baseline emissions. Another adoption barrier is market penetration,

[206] CEC, 2005, 121.
[207] CEC, 2005, 121.
[208] U.S. Climate Change Technology Program, Emissions of High Global-Warming Potential Gases- Semiconductor Industry: Abatement Technologies. "Technology Options for the Near and the Long Term." (2005).
[209] CEC, 2005, 121.

the percent of emissions from a given source that are expected to be addressed by a given option. The market penetration for plasma etching is only 55 percent.[210]

The remote clean process uses fluorine gas (F_2) as a cleaning agent for removing residue from the dielectric chamber.[211] Fluorine gas is not a global warming gas, unlike the conventional compounds used for cleaning, such as NF_3, C_2F_6, and SF_6.[212] Plasma abatement has an incremental reduction ranging between 1.64 mmtCO2e at a break-even price of \$20.39/tCO_2e in 2010 to 3.76 mmtCO_2e in 2020 with a cost effectiveness of \$38.48/tCO_2e. Adopting the technology has a one-time capital cost of \$90.76/tCO_2e, which covers the cost of purchasing and installing the equipment.[213] Besides the high capital cost, there have been no other reports on barriers to adoption.

Catalytic abatement is a four-step process that essentially breaks PFCs into CO_2 and HF through diluting and heating processes prior to feeding it though the scrubber.[214] Catalytic abatement is highly effective, with destruction removal emission of over 95 percent for different PFCs.[215] Potential reductions from catalytic abatement total 0.26 mmtCO_2e with a cost-effectiveness of \$20.45/tCO_2 in 2010, and 0.61 mmtCO_2e with a cost-effectiveness of \$33.87/tCO_2e in 2020. Catalytic abatement has a market penetration of 20 percent, likely due to the high capital cost of \$67.35/tCO_2e.[216]

Capture/recovery with a membrane is another process technology which separates unreacted and/or process-generated fluorinated compounds from other gases using a membrane as a filter. The capture/recovery process has the potential to abate 0.24 mmtCO_2e at a cost of \$22.30/tCO_2e in 2010 and 0.56 mmtCO_2e at a cost of \$30.38/tCO_2e in 2020. Capture/recovery has a market penetration of 8 percent, again likely due to high capital costs.[217]

Thermal destruction reduces emissions from the etching and CVD chamber cleaning process.[218] Thermal destruction can reduce emissions by 0.24 mmtCO_2e by 2010 and 0.56 mmtCO_2e by 2020, at average abatement costs of \$29.96/tCO_2e and \$48.57/tCO_2e for 2010 and 2020, respectively. Based on the high capital costs

[210] CEC, 2005, 121.
[211] CEC, 2005, 121.
[212] Brown, Roy S. and Joseph A. Rossin Guild Associates Inc. "Catalytic Process for Control of PFC Emissions." Semiconductor International (2001).
[213] CEC, 2005, 121.
[214] CEC, 2005, 121.
[215] Brown et al., 2001.
[216] Brown et al., 2001.
[217] CEC, 2005, 121.
[218] CEC, 2005, 121.

($93.39/t$CO_2$e) and high annual costs ($8.98/t$CO_2$e), more incentives may be necessary to encourage market penetration.[219]

The clean room is a dust free area where semiconductors are processed. Increased ventilation, efficiency improvements to process controls, cooling systems, and air handling are all potential process technologies for improving clean room energy efficiency.[220] Increasing clean room energy efficiency by 30 percent could lead to annual reductions of 0.72 mmtCO_2e.[221] However, compressed production cycles leave little time for efficiency improvements, and energy costs might only represent a small percentage of total production costs, both representing barriers to adoption.[222]

HFC Manufacturing and Disposal

Hydrofluorocarbons (HFCs) are a major source of Global Warming Pollution in California, and HFC reductions represent a significant share of planned emission reductions. ARB's strategy for HFC abatement focuses specifically on refrigerant HFC-134a, which, with an extremely high GWP of 1,300, is the most commonly used refrigerant. HFCs can be used in motor vehicle air conditioning (MVAC) and retail cans as well as commercial refrigeration. Baseline HFC emissions are expected to grow from 14.32 mmtCO_2e in 2010 to 24.38 mmtCO_2e by 2020. ARB estimates that 8.5 mmtCO_2e can be reduced from this baseline by 2020,[223] at a cost that Sweeney et al. (2008) estimate at $28/mmt$CO_2$e. More specifically, ARB estimates reductions of high-GWP refrigerants at 3.5 mmtCO2e for vehicles and cans and 5 mmtCO2e for commercial refrigeration.[224] Two major reduction areas for reductions, which we examine here, are HFC-134a reductions in MVAC servicing, and refrigerant recovery from decommissioned shipping containers.

There are a variety of ways to reduce HFC-134a in MVAC servicing, and many of these are interrelated. One strategy is to ban the retail sale of HFCs in 12-oz cans. The estimated cost of a can is approximately $10 and 2-4 million are sold in CA each year. Dividing this cost by the estimated emission reductions gives a preliminary cost effectiveness range, from $12-40/t$CO_2$e.[225] Banning cans would lead to a reduction of 0 mmt in 2010 and 2.4 mmt by 2020.[226] Banning cans would only eliminate the supply on

[219] CEC, 2005, 121.
[220] CEC, 2005, 121.
[221] CEC, 2005, 121.
[222] CEC, 2005, 121.
[223] CEC, 2005, 121.
[224] California Air and Resources Board. "Work Plans for Potential GWP Reduction Measures." Air and Resources Board (2005).
[225] Potts, Winston. "Reduction of HFC-134a Emissions From Nonprofessional Servicing of Motor Vehicle Air Conditioning Systems (MVACs)." Climate Action Team 2008.
[226] ARB, 2005.

one end while leakage would continue to occur throughout the life-cycle of the MVAC, eventually tapering off and reducing Global Warming Pollution as the cars with the leaky MVACs are serviced and HFC-134a is properly disposed of. The costs of eliminating the cans could be offset by the jobs increased in professional installation.

Focusing more on the MVAC manufacturer, another option is to use low-GWP (under AB 1493 legislation) gases like HFC-152a. Substituting HFC-152a has a high capital cost of \$192.33/tCO_2e with benefits of \$54.15/tCO_2e.[227] Emissions would be reduced by 0.1 to 0.9 mmtCO_2e by 2020.[228] Barriers to adoption include the technical difficulties with enforcing this regulation.

Another option for the mechanic focuses on including a leak-tightness check on vehicular inspections that can be implemented at the same time as a smog check. Estimates are that this would reduce leakage by 50 percent.[229] Industry determined a windfall profit to the professional mechanic, who in 2006 on average charges \$147 for recharge service, on the order of more than \$166 million.[230] CEC estimates a \$10.89/tCO_2e cost with \$6.23/tCO_2e in benefits.[231] By 2010, reductions can be between 0.4 mmt and 1.4 mmtCO_2e, and by 2020, between 0.3 mmtCO_2e and 0.9 mmtCO_2e.[232] Barriers to adoption include the cooperation from the Bureau of Automotive Repair and may necessitate legislation. Professionals already have the equipment and training to service MVAC systems in a more efficient manner. However, reductions vary based on what other measures are implemented. For example, these costs would be borne by the consumer, who obtains partial savings by being legally not able to buy the can.

Refrigerant recovery entails properly disposing of HFC-134a, of which decommissioned shipping containers are a major source. ARB estimates that the reduction will be less than 0.1 mmtCO2e in 2020.[233] The equipment to cover the cost of recovering the refrigerant may cost up to \$5,000. The CEC estimates a one-time capital cost of \$26.19/tCO_2e, with annual payments of \$3.40/tCO_2e, and \$1.69/tCO_2e in benefits.[234] Issues that need to be addressed for the population of commercial systems include their emission rates and the rate of turnover of these systems. Barriers include the need to identify an enforcement mechanism to regulate proper disposal.

[227] CEC, 2005, 121.
[228] ARB, 2005.
[229] ARB, 2005.
[230] Potts, 2008.
[231] CEC, 2005, 121.
[232] ARB, 2005.
[233] Potts, Winston and Leeman, Whitney. "Refrigerant Tracking, Reporting and Recovery Program." Air and Resources Board (2007)
[234] CEC, 2005, 121.

Waste Management

There are 159 waste management sites in California with current GWP emissions of 8.4 mmtCO_2e. A large portion of these emissions comes from methane, which has a GWP 21 times higher than CO_2.[235] The California Integrated Waste Management Board (CIWMB) is the regulatory authority in charge of waste management and, recognizing the links between waste and Global Warming Pollution, is also a member of the CAT.[236] The CIWMB breaks landfills down into categories based on the content of the landfill, ranging from concrete to e-waste, compost to hazardous medical waste.[237] Landfill size ranges from less than 100,000 tons of waste to over 1,000,000 tons. Assuming baseline growth, methane emissions will increase from 10.64 mmtCO_2e in 2010 to 11.43 mmtCO_2e by 2020.[238]

Table 8.10:

Table 15: Landfill Size Category Characteristics

Landfill Category (short tons WIP)	Number of Landfills 2000[a]	Average Landfill Age (yrs)[b]	Average Landfill Acreage (acres)[b]	Total WIP Contained in All Landfills in Size Category (short tons)[a]
< 100,001	87	33	2.1	8,700,000
100,001–200,000	13	24	3.8	2,390,000
200,001–300,000	10	22	5.6	2,795,000
300,001–400,000	7	26	7.6	2,545,000
400,001–500,000	10	28	10.3	5,000,000
500,001–1,000,000	20	28	17.8	14,960,000
> 1,000,000	12	38	38.6	27,400,000

[a] BFRS (2005).

[b] Calculated using CEC (2004a).

The potential for reducing emissions of non-CO_2 gases in landfills is significant and low cost. In 2020, California could achieve 2.44 mmtCO_2e reductions at a break-even cost equal to or less than zero, depending on the discount rate, the tax rate, and the landfill's size and age.[239] Currently, all large, major landfills in California use methane capture or destruction process technology.[240] For landfills with the mitigation technology already

[235] ARB, 2005.

[236] CIWMB California Air and Resources Board. "Climate Action Team Proposed Early Actions to Mitigate Climate Change in California." California EPA (2008).

[237] CIWMB, 2008.

[238] CEC, 2005, 121.

[239] CEC, 2005, 121.

[240] Sweeney et al., 2008.

installed, the goal is to increase the efficiency of methane capture and energy recovery above 85 percent.[241]

One innovative sub-technology within the Landfill Methane Capture Strategy scenario is a bioreactor landfill, where liquid or air is dripped through the waste in order to accelerate biostabilization.[242] Estimated total GWP emissions reductions of 1.0 mmtCO2E for 2010 and 4.0 mmtCO2E for 2020.[243] The IWMB, working with the ARB, is jointly developing regulation and a guidance document for landfill operators that will recommend technologies and best management practices for improving landfill design, construction, operation, and closure for the purpose of reducing GWP emissions. Separately, the EPA is in the process of developing the New Source Performance Standards/Emission Guidelines (NSPS/EG) for landfills.

Projected costs vary based on the scenario. Parameters include the size of the landfill, the year (2010 or 2020), discount rate, and tax rate.[244] With a 4 percent discount rate, implementing the process technology has a cost-effectiveness ranging from a high of \$4.68/tCO_2e for a landfill with a WIP (Waste in Place) greater than 1 million tons and continuously decreases to \$1.39/tCO_2e for a landfill with a WIP between than 200,000 and 300,000 tons. With a 20 percent discount rate and a 40 percent tax rate, break-even pricing has substantially different costs, ranging from \$1.35/tCO_2e for 1 million short tons to \$7.17/tCO_2e for 300,000 to 400,000 short tons.[245]

These ranges provide evidence for the dramatic impact that financial incentives have on greenhouse gas mitigation. With a 4 percent tax rate, the costs of abatement are positively related to the WIP; as the size of the landfill grows, break-even pricing grows. However, with a 20 percent discount rate and a 40 percent tax rate, the costs and WIP are inversely related.[246] Break-even costs can be substantially higher but are always under \$10/tCO_2e, regardless of landfill size of discount rate. Other estimates have similar greenhouse gas abatement amounts (2.3 mmtCO2e) but significantly higher costs, in this case between \$34/tCO_2e and \$42/tCO_2e.[247]

Baseline emissions from landfills are uncertain, which may be the variable that leads to confusion on the cost-effectiveness of adopting new processes.[248] There is a low technical applicability and no market penetration for the installation of direct gas use as

[241] CEC, 2005, 121.
[242] CIWMB, 2008.
[243] CEC, 2005, 121.
[244] CEC, 2005, 121.
[245] CEC, 2005, 121.
[246] CEC, 2005, 121.
[247] Sweeney et al., 2008.
[248] Sweeney et al., 2008.

landfills.[249] At the lowest WIP (<100,001), direct gas projects have capital costs of $429,026 and O&M costs of $13,942 and are correlated positively with WIP increase.[250] Such high-perceived capital costs likely affect adoption.

Materials/Waste Types

Appliances	**Food Waste**	**Packaging**
Asphalt	**Glass**	**Paint**
Batteries	**Hazardous Waste**	**Paper**
Biomass	**Health Care Waste**	**Pesticides**
Biosolids	**Herbicides**	**Plastics**
Cellular Phones	**Holiday Waste**	**Recycled-Content Products**
Christmas trees	**Household Hazardous Waste**	**Rerefined Oil**
Compost	**Hypodermic Needles**	**Rigid Plastic Packaging Containers**
Computer Monitors	**Ink and Toner Cartridges**	**RPPC**
Computers	**Litter**	**Rubber**
Construction/Demolition Debris	**Lumber**	**Sharps**
CRTs	**Medical Waste**	**Solvents**
Diapers	**Metals**	**Trash Bags**
E-Waste	**Mulch**	**Universal Waste**
Electronic Products	**Newsprint**	**Used Oil**
Electronic Waste	**Oil**	**Waste Tires**
Fluorescent Tubes	**Oil Filters**	**White Goods**
Food Scrap	**Organics**	**Wood**

Recycling is another important option for decreasing waste emissions. In 2006, California achieved a 52 percent waste reduction, equivalent to 3 mmtCO_2e, meeting the mandate for AB 939. Seventy-seven percent of all the waste generated in California was diverted from landfills. The goal is to "achieve high recycling levels and move towards zero waste."[251] The IWMB approved a Scope of Work for a Lifecycle Assessment and Economic Analysis goal to provide an additional 3-5 mmtCO_2e by 2020. The cost of these measures is estimated at $23/t$CO_2$e.[252]

[249] CEC, 2005, 121.
[250] CEC, 2005, 121.
[251] CIWMB, 2008.
[252] Sweeney et al., 2008.

Agriculture and Forestry

Agriculture and forestry play a comparatively small but important role in efforts to reduce Global Warming Pollution in California. Agriculture accounted for 4.9 percent of California's GWP inventory in 2002, and is the main source of methane (CH_4) and nitrous oxide (N_2O), both of which have higher global warming potential than CO_2. The main sources of emissions in agriculture are enteric fermentation, manure management, soil management, and agriculture water use. Enteric fermentation and manure management are the main source of methane, and soil management is the main source of nitrous oxide. Global Warming Pollution from agricultural water use derive from emissions in electricity generation, which powers the pumps that distribute water.

Table 8.11:

Emission Source/ Sink	Main GWP	Abatement Technologies/Measures	Abatement Potential ($mmtCO_2e$)	Abatement Cost ($/$tCO_2e$)
Enteric Fermentation	CH_4	Improving livestock diets	< 1	$3
Manure Management	CH_4	Biogas digesters	3.1	$34
Soil Management	N_2O	Conservation tillage, changes in fertilizer use	3.1	$6
Agricultural Water Use	CO_2	Improving water use efficiency	n/a	n/a

Sources: See below.

Additional potential greenhouse gas reduction strategies in agriculture aside from these main four include riparian restoration and farmscape sequestration and the adoption of organic farming.

Table 8.12:

Sink	Main GWP	Abatement Measures	Abatement Potential ($mmtCO_2e$)	Abatement Cost ($/$tCO_2e$)
Forests	CO_2	Afforestation	1.98	$11
		Forest management	2.35	$2
		Forest conservation	0.4	$38
		Forest fuels management	3	-$86
		Urban forestry	0.88	$150

Sources: See below.

Forestry is an important abatement option because of its ability to store carbon in trees and the soil. Greenhouse gases are sequestered in forests, but wildfire and deforestation lead to Global Warming Pollution from the forestry sector. Forest carbon sinks can be increased through improved forest management and/or preventing deforestation and converting rangelands to forests. More specifically, key abatement measures in forestry, as identified in various CAT and ARB reports, include forest management, forestry conservation, urban forestry, fuel management and biomass, and afforestation. Calculating forest sinks is complex because of the variable growth rates and permanence issues surrounding forests. As a result there is a range of different estimates for the sequestration potential of forests in California, ranging from 5 mmtCO_2e to 35.68 mmtCO_2e.

As an individual sector, the role of agriculture and forestry in California's economy is relatively small, but agriculture plays an important role in the California economy because a number of industries, such as the food and beverage business, closely depend on agriculture and because agriculture is a major source of indirect employment. In 2003, agriculture, crop and animal production, forestry, fishing, hunting and soil preparation, planting, and harvesting services only accounted for $21 billion of output in California, or 1.5 percent of GSP.[253] However, once production linkages are accounted for the agricultural sector is a much more substantial component of the California economy. The UC Agricultural Issues Center estimates that in 2002 agricultural production, including direct, indirect, and induced effects, employed 822,879 workers and paid $23 billion in payroll.[254]

Agriculture and forestry is also a greenhouse gas-intensive sector because its share of state Global Warming Pollution is more than three times as large as its role in GSP. In 2004, 4.9 percent of California's Global Warming Pollution, or 23.28 mmtCO_2e, came from agriculture, forestry and rangelands.[255] Accounting for Global Warming Pollution from fuel combustion in agriculture, forestry, fishing, and fish farming and electric generation for agriculture water use (3 percent of California electricity demand) would increase this total by 4.86 mmtCO_2e and 2.8 mmtCO_2e, respectively. Once these two sources are included, agriculture and forestry accounted for 6.5 percent of California greenhouse gas inventory in 2004.[256]

By 2020, Global Warming Pollution from agriculture will increase and greenhouse gas sinks from forestry will decrease without the adoption of new technologies or improvement of current technologies. According to ARB's Draft Scoping Plan, by 2020 baseline Global Warming Pollution from agriculture are projected to increase by 2.1 mmtCO_2e from a 2002-2004 average to 29.8 mmtCO_2e, and baseline sinks in forestry are zero, decreasing by 4.7 mmtCO_2e from the 2002-2004 average. Global Warming

[253] BEA, U.S. Economic Census, 2002.
[254] University of California Agricultural Issues Center, 2006
[255] ARB website, "California Greenhouse Gas Inventory Data," ARB 2007.
[256] ARB, 2007.

Pollution from agriculture were 19.1 mmtCO_2e in 1990 and carbon sinks from forests and rangelands were 6.69 mmtCO_2e in 1990. If greenhouse gases were to be reduced proportionally, 10.7 mmtCO_2e would be reduced in agriculture and 6.7 mmtCO_2e would be sequestered in forests by 2020.

According to the ETAAC assessment, there is a technical potential to reduce 17 mmtCO_2e of greenhouse gases in California agriculture, which is about 10 percent of the AB 32 goal for 2020, or about 3.5 percent of California's total 2004 emissions. From forests, ETAAC estimates that 18.8 mmtCO_2e can be stored by 2020, which is about 11 percent of the AB 32 goal for 2020. In total 36 mmtCO_2e, or 21 percent of the AB 32 2020 goal, can be sequestered by agriculture and forestry. The remainder of this section describes options for achieving these reductions.

Enteric Fermentation

Enteric fermentation from livestock is the major source of methane in California. The amount of methane is affected by the digestive system of livestock and food intake. Ruminant livestock emits by far the most methane from enteric fermentation due to their unique digestive system. Ruminant animals, such as cattle, buffalos, or sheep, have a special stomach called a rumen, where hundreds of microorganisms break down foods and produce methane. Enteric fermentation accounts for 1.6 percent of California's 2002 greenhouse gas inventory. Beef cattle and dairy cows are main sources of emissions, contributing 94 percent of total emissions from enteric fermentation.[257] One dairy cow produces 118 kg methane/year, or 2.5 tons CO_2e/year.[258]

Increasing the efficiency by which animals convert feed to product is the main means of reducing methane from enteric fermentation. Production efficiency can be improved by implementing proper cattle management, the practice of artificial insemination, and the adoption of new market system. ETAAC calculates that 50 percent of these practices can be implemented by 2020, and the estimated average abatement cost is to be \$3/tCO_2e.[259]

Proper management techniques are practices that will improve animal nutrition and reproductive health. Animal nutrition can be improved by: first, feeding cattle more grain and food high in protein and easily digestible; second, having cattle checked by veterinarians on a regular basis; and third, implementing proper grazing management. Artificial insemination increases production efficiency by improving the genes of cattle by impregnating the animals with semen from healthy and productive ones. Production enhancing agents can increase production efficiency by enhancing the effect of animal

[257] ARB, 2007.
[258] W Smink et al., "Calculation of Methane Production from Enteric Fermentation in Dairy Cows," October 2005.
[259] David Roland-Holst, *Economic Assessment for Climate Action in California*, 2007.

nutrition, health, and management practices. However, the health risks are not fully identified, and further research on the effect of production enhancing agents on human health is needed.

The main barrier for providing better animal diets is cost. Since feed is one of the costliest inputs, Californian farmers have already optimized animal diets to maximize production efficiency. New techniques are needed that are cost-effective and can be implemented within the current economically optimized system. Therefore, more research tailored to California conditions and diets is needed to improve both the knowledge base and the potential emissions reductions for enteric fermentation.[260]

Manure Management

Animal manure is another large source of Global Warming Pollution from agriculture. In California, methane-emitting manure accounts for 1.4 percent of total greenhouse gases.[261] With adoption of anaerobic digesters in dairy and beef cattle ranch, 3.1 mmtCO_2e of methane could be reduced by 2020.[262] Typically, storage or treatment of manure in anaerobic conditions produces methane. Liquid-based manure management systems, such as manure ponds, anaerobic lagoons, and holding tanks, cause more than 80 percent of total methane emissions from animal wastes.[263] Other treatment systems, like solid manure management, which spreads manure on fields, also causes water pollution from nutrient runoff. Currently, liquid manure is used for year-round irrigation (62.2 percent), spread as a slurry (9.5 percent), or sold or transported off the farm (12.2 percent). With solid manure, farmers spread it on farm land (78.4 percent), use it for bedding (27.0 percent), sell it off the farm (58.1 percent), remove it from the farm (6.8 percent), or compost it (5.4 percent).[264]

With adoption of anaerobic digesters, farmers can reduce Global Warming Pollution, as well as generate additional income, by selling electricity and biogas and using the byproduct as fertilizer and animal bedding. Anaerobic digestion is a naturally occurring process that produces methane and carbon dioxide when microorganisms break down manure in the absence of oxygen. This process can be facilitated under a controlled atmosphere by installing special tanks known as anaerobic digesters. As a result, biogas, which contains 50-75 percent of methane and 25-45 percent of carbon dioxide, and digestate, which can be applied over fields due to its nutrient value, are produced.

[260] ETAAC, 2008.
[261] ARB, 2007.
[262] Economic and Technology Advancement Advisory Committee (ETAAC), "Final Report: Technologies and Policies to Consider for Reducing Global Warming Pollution in California," Sacramento, California, 2008.
[263] State & Local Climate Change Program (SLCCP), "Manure Management," January 2000.
[264] D. Morse, Guthrie, G. C., and Mutters, R., "Anaerobic Digester Survey of California Dairy Producers," *Journal of Dairy Science*, v. 79, no. 1, 1996.

Methane can be reduced by 79 percent, which is equivalent to a reduction of 137 kgCO_2e/cow per year.[265]

Currently, only 1 percent of California ranchers have installed anaerobic digesters, and size has played a role in this limited penetrated.[266] According to EPA's AGSTAR, there are 16 livestock farms with anaerobic digesters in California, 13 of which are dairy farms, and 16 anaerobic digester providers.[267] In 2003, there were 1.7 million dairy cattle and 2,109 dairy farms in California,[268] with the average number of cows per dairy in California county ranging from 142 to 1,354. In Europe, a dairy with a herd as small as 125 cows will install an anaerobic digester.[269] Based on the European experience, this would imply that size should not be an obstacle to adoption in California. According to ETAAC, anaerobic digesters can reach 100 percent penetration in California by 2020 and reduce emissions by 3.1 mmtCO_2e. PIEE estimates the average abatement cost of anaerobic digesters at \$34/tCO_2e.

There are several adoption barriers for anaerobic digestion. First, it requires high capital costs. The payback period with anaerobic digesters ranges from 5 to 16 years, when operated under optimum and worst conditions, respectively.[270] Second, the electricity market is not in favor of dairy farmers. With California's current electricity market structure, only a dairy that can dispatch 1 MW, which is unlikely, can sell electricity. Even if the dairy is large enough to dispatch 1 MW, the price at which the farmer can sell the generated electricity matters. Utilities like PG&E are required to purchase renewable energy only if the price is equal to or below the price referent determined by the CPUC (\$0.0605/kWh), which is less than the cost of generating electricity at dairy farms.[271] Third, management of anaerobic digesters is not easy. Collection of manure in wet form is also challenging.[272] Systems may not perform well enough without adequate control so there should be education and the availability of engineers and expertise for farmers. Fourth, anaerobic digester can produce environmental pollution. The combustion of biogas in an engine to generate electricity can emit NO_x. The San Joaquin Air Pollution Control District requires farmers with anaerobic digesters to install additional air pollution control technology, which requires high capital costs. Farmers

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265 IEA Bioenergy, "Greenhouse Gas Benefits of an Anaerobic Digester in the USA," February 2005.
266 ETAAC, 2008.
267 ATTRA-National Sustainable Agriculture Information Service website, http://attra.ncat.org/farm_energy/farm_energy_results.php?Class=CA.
268 Ken Krich et al., "Biomethane from Dairy Wast: A Sourcebook for the Production and Use of Renewable Natural Gas in California," July 2005.
269 Dennis, A. and Burke, P.E., "Dairy Waste Anaerobic Digestion Handbook," Environmental Energy Company, 2001.
270 Alberta Agriculture and Rural Development, "Anaerobic Digesters," February 2008.
271 Krich et al., 2005.
272 D. Morse, Guthrie, G. C., and Mutters, R., "Anaerobic Digester Survey of California Dairy Producers," *Journal of Dairy Science*, v. 79, no. 1, 1996.

still use anaerobic digesters for biogas production without the installation, but farmers have low incentives to use digesters without being paid for electricity generation.

Soil Management

In 2004, 1.7 percent of California's greenhouse gases were emitted from soils.[273] Soil management includes activities such as fertilizer application, which is a large source of nitrous oxide, and cropping practices, which are a source of carbon dioxide. Greenhouse gas can be sequestrated by more efficient fertilizer application, use of low N_2O-emitting fertilizer, use of slow-release fertilizers and nitrification inhibitors, use of a cover crop, and conservation tillage.

ETAAC reports that if farmers apply 25 percent less fertilizer, 1.8 mmtCO_2e of nitrous oxide could be reduced. The challenge is to reduce fertilizer use without hurting yield. Research is needed on the wide variety of crops and soils in California, the effect of different cultivation practices on N_2O emissions, and ways to increase fertilizer application efficiency. Costs for constructing this database and developing a biogeochemical model validated in California crops and soils are estimated to be $2-$3 million, or roughly $1/t$CO_2$e of reduction potential. Both increasing fertilizer application efficiency and higher sales of digestate from anaerobic digesters imply a decrease in demand for synthetic fertilizer, which would likely have an impact on California's agricultural chemical business. According to the U.S. Bureau of Census, in 2002 California's agricultural chemical manufacturing was a 2,000 employee industry with $668 million revenue.

Conservation tillage is expected to be adopted on 50 percent of California farmland by 2020, reducing greenhouse gases by 3.1 mmtCO_2e at a cost of $6/t$CO_2$e.[274] Conservation tillage technologies include reduced tillage, manure application, and winter cover cropping. Currently less than 2 percent of California cropland is cultivated using conservation tillage,[275] compared with 30-50 percent in some other regions.[276] The primary reasons for this low level of adoption are the lack of information on using conservation tillage with furrow irrigated agriculture[277] and farmers' risk aversion related to the production of high value agricultural crops. Farmers need financial support and incentives to change their cropping practices. Carbon credits provide a solution for overcoming these obstacles. Monitoring and verifying the amount of greenhouse gas reductions for soil management is likely to be difficult, so the USDA, universities, and

[273] ARB, 2007.
[274] ETAAC, 2008.
[275] ETAAC, 2008.
[276] Winrock International, "Carbon Supply From Changes in Management of Forest, Range, and Agricultural Land of California," PIER Final Project Report, 2004.
[277] ETAAC, 2008

scientists should establish minimum protocol standards. USDA should actively support a minimum of $15 million for research on GWP emissions and carbon sequestration in agriculture so proper soil management suitable for regional characteristics, such as soil types, can be practiced in California. Conservation tillage, including no tillage, requires special equipment that performs precise seeding in order to minimize plowing, and is thus not expected to have a significant impact on the farm machinery and equipment manufacturing industry. Farmers would be expected to switch from old equipment to new ones.

Water Management

Agriculture uses a substantial amount of energy, especially through electricity to pump water for irrigation. California's water system consumes 20 percent of generated electricity and 80 percent of developed water supply is used by irrigation for agriculture.[278] Global Warming Pollution can be reduced by reducing energy consumption from agricultural water use. There are two ways to save energy: increasing water pumping efficiency and increasing water use efficiency. Although agriculture accounts for 80 percent of California water demand and California's water system consumes 20 percent of generated electricity, agriculture does not consume the electricity proportionally. Electricity demand for water for agriculture end use in 2001 was 7,372 GWh, or 3 percent of total California electricity demand and 15 percent of electricity demand from California water system. Natural gas demand for agricultural end use of water is 18 therms, or 0.1 percent of California's natural gas demand.[279] Thus, the electricity used in pumping agricultural water is less than might be expected proportional to the sector's total water use, mainly because agricultural water requires less treatment. Improving agricultural water use efficiency is not likely to impact employment in the water sector because increasing pumping efficiency and water use efficiency requires precise management, which is likely to be capital intensive.

Agriculture mainly uses electricity to pump water for irrigation. Currently, there are efforts to reduce energy consumption by agriculture water use, such as the Agriculture Pumping Efficiency Program (APEP) run by PG&E. APEP is designed to increase the penetration of more efficient equipment, including pumping plants, irrigation systems, and water distribution systems, and ensure that this equipment is managed correctly. APEP provides 2,050 subsidized pump efficiency tests per year, cash incentives for 295 pump retrofit projects per year, and 14 educational seminars per year. Since this is an ongoing project its costs and benefits have yet to be assessed. The Center for Irrigation Technology, funded by the CPUC, ran a similar program from 2001 to 2003. The

[278] Next 10, "California Green Innovation Index," 2007.
[279] Martha Kreb, "California Water-Energy Issues," PIER Report, 2006.

program saved 19.4 GWh and 355,000 therms annually and over 3 years, CIT spent $2.9 million, which included pump test subsidies and incentive rebates.

Organic Farming and Global Warming Pollution

Organic farming can reduce Global Warming Pollution by increasing carbon stored in soil and using less synthetic fertilizers. One study estimated that levels of carbon in the soils of organic farms in California were as much as 28 percent higher than conventional farms.[280] Based on farm trials covering conventional, legume-based organic and manure based organic farming, the Rodale Institute estimates that organic farms sequester as much as 1.7 tCO_2 per acre-foot each year.[281] In addition to carbon saving in soil, organic farming uses less energy. Dr. David Pimentel of Cornell University found that organic farming systems use just 63 percent of the energy required by conventional farming systems due to not applying synthetic fertilizer.[282] More research on this topic is needed.

Riparian Restoration and Farmscape Sequestration

Riparian restoration and farmscape sequestration refers to re-establishing natural woody vegetation on rangeland, field edges and marginal farmland and riparian areas that have been cleared. Assuming 500,000 acres on the edges of cropland and rangeland might be available for re-vegetation or farmscaping with woody shrubs and trees, there is a technical potential of 2.9 $mmtCO_2e$. The main barrier to adoption is the cost to facilitate the process of restoration. Based on estimates for woody hedgerow plantings, farmscape sequestration would cost $12,000 per acre for initial planting and $500 for annual maintenance in the first five years. The solution to overcome these cost hurdles is to quantify the carbon storage from these practices and develop protocols that give landowners the ability to generate greenhouse gas reduction credits. Another possible solution is to grow revenue generating trees, crops, and biofuel crops in combination with revenues from federal programs, such as the Conservation Reserve Program, which gives farmers greater economic incentives.

Forestry

Forests offer significant opportunities for greenhouse gas reductions because they absorb carbon, which is accounted in four basic pools: soil, ecosystem, standing trees, and products after harvest.[283] Forestry will play an important role in meeting AB 32 targets because carbon sequestration from forestry is relatively inexpensive and forests

[280] Laura Sayre, "Organic Farming Combats Global Warming," Rodale Institute, 2003.
[281] Sayre, 2003
[282] Sayres 2003
[283] Winrock, 2004.

increase their ability to store carbon as they grow to maturity. ARB's Draft Scoping Plan estimates that California forests could store 5 $mmtCO_2e$ by 2020, which is the equal to the amount of carbon reduction from current California forests. The latest CAT report, released in 2007, estimated 8.61 $MMTCO_2e$ to be sequestered by 2020 in five areas of forestry: conservation forest management, forest conservation, fuels management and biomass, urban forestry, and afforestation and reforestation.

Forest management enhances the ability of forests to store carbon by applying appropriate management techniques. Forest conservation includes action to prevent forestlands from conversion to other use. Fuel management and biomass is a fire risk reduction strategy by removing biomass from the forest. Urban forestry includes planting trees in urban areas. In California afforestation chiefly means converting rangelands to forest. Except for urban forestry, the remaining four area of forestry cost less than $50/$tCO_2e$. The cheapest strategy is the fuel management and biomass, which is estimated to cost $86.38/$tCO_2e$. Forest fuel management linked with biomass feedstock development could generate power and help to prevent catastrophic wildfires.[284]

Afforestation

Afforestation of rangelands in California has the largest greenhouse gas reduction potential in forestry. An estimated 1.98 $mmtCO_2e$ Global Warming Pollution might be stored by afforestation at a cost of $10.61/$tCO_2e$.[285] Among 56.3 million acres of rangeland in California, 13.34 million acres can be potentially converted into forest. With the conversion of 12.03 million acres of rangeland into forest, 887 $mmtCO_2e$ could be sequestered over 20 years at $13.6/$tCO_2e$. With an 80-year project, afforestation could store 5,639 $mmtCO_2e$ on the same plot. Moreover, carbon could be sequestered at an even lower price; at a price of $2.7/$tCO_2e$, 33 $mmtCO_2e$ could be stored in 200,000 acres over 20 years, and 4,569 $mmtCO_2e$ over 80 years.[286]

The cost of afforestation includes an opportunity cost, planting and conversion costs, measuring and monitoring costs, and a maintenance cost. Opportunity cost is the forgone profit per hectare of cattle ranching in California. Planting and conversion costs are the cost to plant trees on rangeland, and measuring and monitoring costs are the cost of measuring carbon production over its lifetime. Maintenance cost is the expenditure during the first five years in order to make sure tree seedlings survive. Although the longer the duration of afforestation is the lower the carbon costs, landowners may be hesitant to start afforestation due to the long duration of the project, which can last up to 80 years. The largest risk of carbon sequestration from

[284] ETAAC, 2008.
[285] Roland-Holst, 2007.
[286] Winrock, 2004.

afforestation is the possibility of wildfire. However, 78 percent of potential land for afforestation has low risk of fire rotation interval, based on the fire rotation interval map which tells the expected number of years it would take for an area to get burned.[287]

There has not been any research done on the employment effects in California due to afforestation projects. However, the National Forest Strategy and National Development Plan in Hungary concluded in 2004 that forestry is not likely to increase employment in farming significantly because of the high technical level of forest machinery.[288]

Conservation Forest Management and Forest Conservation

Proper application of forest management can improve forest carbon storage. Forest management improvements include increasing the growth of individual trees, the overall age of trees prior to harvest, or dedicating land to older aged trees. With those strategies, an estimated 2.35 mmtCO_2e could be reduced at a cost of \$1.70/tCO_2e.[289] In other words forest management reduces more at a lower cost than afforestation in this estimation. However, Winrock suggests the opposite. There are two methods of forest management in the Winrock report: lengthening harvesting rotation by 5 years and increasing the riparian buffer zone by an additional 200 feet. The cost of carbon sequestration from changing forest management regimes is higher than that from afforestation because, from forest management, no carbon can be stored at the price less than \$13.60/tCO_2e. Storing carbon by increasing rotation ages is likely to be feasible only on industrial forestlands that are managed in even-age rotation. Over 20 years, lengthening rotation by five years can store 2.61-3.91 mmtCO_2e on a land area of 310,000 acres, and increasing the riparian buffer zone by 200 feet can sequester 3.91 mmtCO_2 permanently (assuming no catastrophic fire risk) on the land area of 44,000 acres at a cost of \$13.60/tCO_2e.

Forest conservation is the effort to prevent or minimize the conversion of forestlands into lands of non-forest use by giving incentives to maintain forests. According to the 2006 CAT report, 35,000-40,000 acres of forest in California are annually converted to lands for non forest use, causing emissions of 12 mmtCO_2e annually[290]. One possible way to conserve forest in California is to establish a state forest conservation program in addition to the federal program. In this manner, 14,000 acres could be saved with an annual \$11 million investment from the Forest Legacy Program Funding.[291] The

[287] Winrock, 2004.

[288] Zoltan Andrasevits, Buzas Gyula, and Endre Schiberna, "Current Afforestation practice and expected trends on family farms in west Hungary," *Journal of Central European Agriculture*, 2004, 297-302.

[289] Roland-Holst, 2007.

[290] Climate Action Team, *Climate Action Team Report to Governor Schwarzenegger and the Legislature*, Sacramento, California, March 2006.

[291] CAT, 2006.

estimated reduction from forest conservation is 0.4 mmtCO_2e at a cost of \$37.50/tCO_2e.[292]

Forest Fuel Reduction

Connecting forest fuel management with biomass utilization will help sequester Global Warming Pollution by reducing the risk of catastrophic wildfire. Forest fuel management would remove excess stems or fuel loading from forests and direct them to biomass energy production plants. Greenhouse gas reduction potential from forest fuel management is highly variable depending on assumptions of acres treated; wildfires avoided or reduced; and the expansion of facilities to produce electricity and biofuels.[293] Assuming that the average treatment cost is \$400/acre, and \$37 million from existing sources and an increase to \$5 million for the California Forest Improvement Program (CFIP) support are expected, 3 mmtCO_2e can be sequestered by year 2020.[294] ARB estimates the expected greenhouse gas emission reduction to be 3 mmtCO_2e at a cost of -\$86.38/MTCO_2e. Barriers to this project are uncertainty in fuel supply as a result of litigation, or the threat of litigation, and expensive and labor intensive fuel treatment cost, especially hauling cost of wood waste to the plant.[295]

Urban Forest

Planting trees in urban area sequesters carbon and can provide biomass for power generation. If 5 million trees were planted in urban areas by 2010, 4 mmtCO_2e could be reduced by 2030. By 2020, 0.88 mmtCO_2e could potentially be reduced, with 0.14 mmtCO2e coming from carbon storage in trees, 0.05 mmtCO_2e from energy saving from tree shading, and 0.69 from the power generation from biomass.[296] The estimated average abatement cost for urban forestry is \$150/tCO_2e.[297] Compared with forest management and afforestation, which cost \$2.7-\$13.6/tCO_2e, urban forest is expensive and may not meet ARB's final measure of cost-effectiveness. However, the ETAAC report considers urban forestry to be a highly feasible project and the supply of biomass to the power plant quite stable. Barriers are to establish additional funding for tree planting at state and local levels, to provide ongoing maintenance services to planted site, and to site of biopower facilities. These barriers can be overcome by funding the projects through bonds, grants, and utility support, and supporting and expended tree-nursery programs.

[292] Roland-Holst, 2007.
[293] ETAAC, 2008.
[294] ETAAC, 2008.
[295] ETAAC, 2008.
[296] ETAAC, 2008.
[297] CAT, 2006.

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