Energy Research and Development Division
FINAL PROJECT REPORT

SCENARIOS FOR MEETING CALIFORNIA'S 2050 CLIMATE GOALS

California's Carbon Challenge Phase II Volume I: Non-Electricity Sectors and Overall Scenario Results

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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ABSTRACT

This study provides an updated analysis of long-term energy system scenarios for California consistent with the State meeting its 2050 climate goal, including detailed analysis and assessment of electricity system build-out, operation, and costs across the Western Electricity Coordinating Council (WECC) region. Four key elements are found to be critical for the State to achieve its 2050 goal of 80 percent greenhouse (GHG) reductions from the 1990 level: aggressive energy efficiency; clean electricity; widespread electrification of passenger vehicles, building heating, and industry heating; and large-scale production of low-carbon footprint biofuels to largely replace petroleum-based liquid fuels. The approach taken here is that technically achievable energy efficiency measures are assumed to be achieved by 2050 and aggregated with the other key elements mentioned above to estimate resultant emissions in 2050. The energy and non-energy sectors are each assumed to have the objective of meeting an 80 percent reduction from their respective 1990 GHG levels for the purposes of analysis. A different partitioning of energy and non-energy sector GHG greenhouse reductions is allowed if emission reductions in one sector are more economic or technically achievable than in the other. Similarly, within the energy or non-energy sectors, greater or less than 80 percent reduction from 1990 is allowed for sub-sectors within the energy or non-energy sectors as long as the overall target is achieved. Overall emissions for the key economy-wide scenarios are considered in this report. All scenarios are compliant or nearly compliant with the 2050 goal. This finding suggests that multiple technical pathways exist to achieve the target with aggressive policy support and continued technology development of largely existing technologies.

Keywords: GHG emissions 2050, GHG saving pathways, California Carbon Challenge, electrification, 2050 electricity system, energy efficiency, low-carbon biofuels, low-carbon electricity

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Introduction

California is a leading international test bed for innovative climate policies. Assembly Bill 32 (AB 32) requires the State to reduce its greenhouse gas (GHG) emissions in 2020 to the level of 1990 and Executive Order S-3-05 calls for GHG emissions in 2050 to be reduced by 80 percent from the 1990 level. Much policy focus and attention has been on achieving the 2020 target but planning and coordination is required to address the long-term 2050 goal.

Project Purpose

The goal of this study is to provide an updated analysis of long-term energy system scenarios for California consistent with the State meeting its 2050 climate goal, including detailed analysis and assessment of electricity system build-out, operation, and costs across the Western Electricity Coordinating Council (WECC) region.

Project Results

Four key elements are critical for the State to achieve its 2050 goal of 80 percent GHG reduction from the 1990 level: aggressive energy efficiency; clean electricity; widespread electrification of passenger vehicles, building heating, and industry heating; and large-scale production of low-carbon footprint biofuels to replace most petroleum-based liquid fuel. Recent downward revisions in the State's long-term population will abet the State's efforts as will continued strong federal and state policy support for improved light duty vehicle efficiency standards.

The approach taken here is that technically achievable energy efficiency measures are assumed to be achieved by 2050 and aggregated with the other key elements to estimate resultant emissions in 2050. The energy and non-energy sector are each assumed to have the objective of meeting an 80 percent reduction from their respective 1990 GHG levels. A different partitioning of energy and non-energy sector GHG reductions is allowed if emission reductions in one sector are more economical or technically achievable than in another. Greater or less than 80 percent reduction from 1990 is allowed for sub-sectors within the energy or non-energy sector as long as the overall target is achieved.

Figure ES.1 shows overall emissions for the key economy-wide scenarios considered in this report and a basic table of scenarios is shown in Table ES.1. All scenarios are compliant or nearly compliant with the 2050 goal. This finding suggests that multiple technical pathways exist to achieve the target with aggressive policy support and continued technology development of largely existing technologies.

The Base Scenario meets the 2050 California target with aggressive energy efficiency, sharply reduced electricity sector emissions, electrification of building heating, partial electrification of transportation and industry heating, and low carbon biofuels. This compliant 2050 Base Scenario assumes an 86 percent carbon reduction from 1990 levels, and there was a wide range of electricity supply scenarios that meet the 2050 cap on electricity emissions, including ten electricity system variants (Scenarios 2-11 in Table ES.1).

Additional scenarios that could meet the target are the minus 20 percent and minus 40 percent electricity carbon cap/bio-carbon capture and storage (CCS) scenarios and aggressive electrification scenario, but these may be even more challenging to achieve from a techno-economic standpoint than the Base Scenario and electricity sector variants.

Figure ES.1: Overall GHG Emissions for All Scenarios

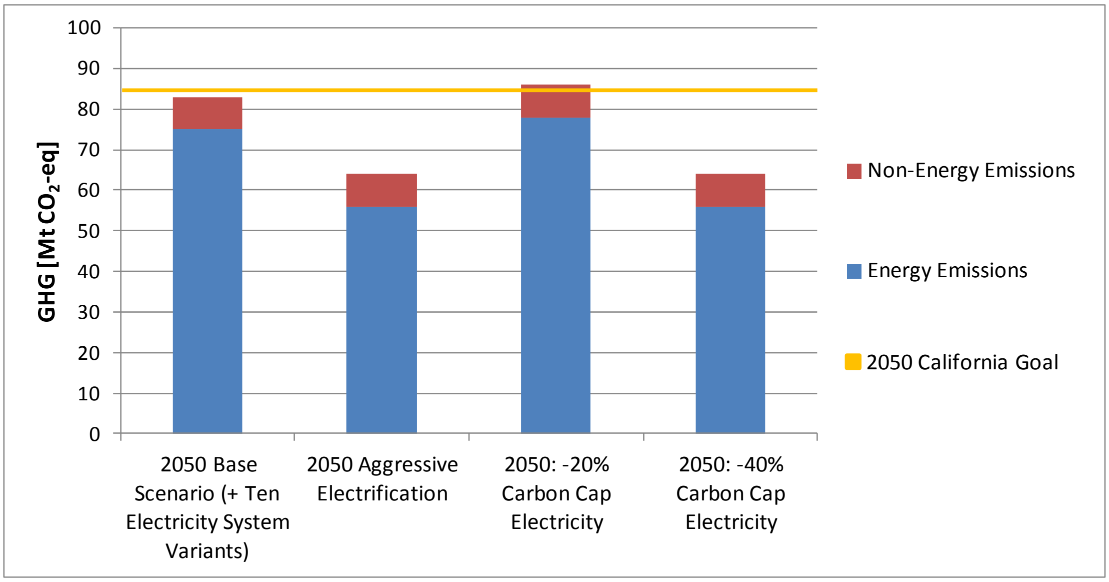


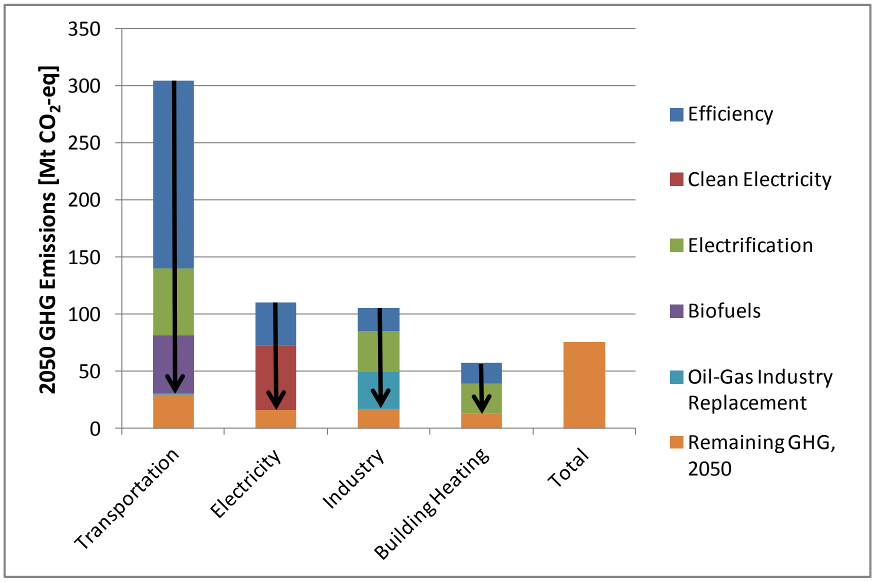
Figure ES.2 shows the progression of energy-sector GHG reductions by key element starting from a "Frozen Efficiency/Business as Usual Electricity" scenario to the Base Scenario. "Frozen Efficiency" assumed that efficiency levels are frozen at current levels, and "business as usual (BAU) electricity" assumes that electricity GHG emissions for California are capped ("frozen") at the 1990 level after 2020. Figure ES.3 shows the percentage contribution to GHG savings by sector and key element. Transportation efficiency, clean electricity, and electrification are the largest levers with 55 percent of energy-sector GHG reduction coming from the transportation sector.

Table ES.1: Basic Table of Scenarios

#	Scenario	Electricity Sector Carbon Cap in 2050 [Relative to 1990 Level]	Electricity Demand	Electrification	Biomass	Total GHG Emissions in 2050 [Mt CO_2eq]; California Target = 85Mt
1	Base Scenario	14%	Base	Base	Base	83
2	No CCS	14%	Base	Base	Base	83
3	Small Balancing Areas	14%	Base	Base	Base	83
4	Limited Hydro	14%	Base	Base	Base	83
5	Expensive Transmission	14%	Base	Base	Base	83
6	Demand Response	14%	Base	Base	Base	83
7	12 GW Distributed PV	14%	Base	Base	Base	83
8	California 50% RPS	14%	Base	Base	Base	83
9	SunShot Solar	14%	Base	Base	Base	83
10	Low Gas Price	14%	Base	Base	Base	83
11	New Nuclear	14%	Base	Base	Base	83
12	-20% Carbon Cap/ Bio-CCS	**-20%**	Base	Base	**More Biomass to Electricity Sector than Base**	85
13	-40% Carbon Cap/ Bio-CCS	**-40%**	Base	Base	**More Biomass to Electricity Sector than Base**	64
14	Reduced Efficiency in Buildings, Industry	14%	**50% Efficiency**	Base	Base	86
15	Aggressive Electrification	14%	**Higher than Base**	**Greater PEV adoption and heating electrification**	Base	64
16	Frozen Efficiency/BAU Electricity	**100%**	**Frozen Efficiency**	**Minimal Electrification**	**Less Biomass available than Base**	686

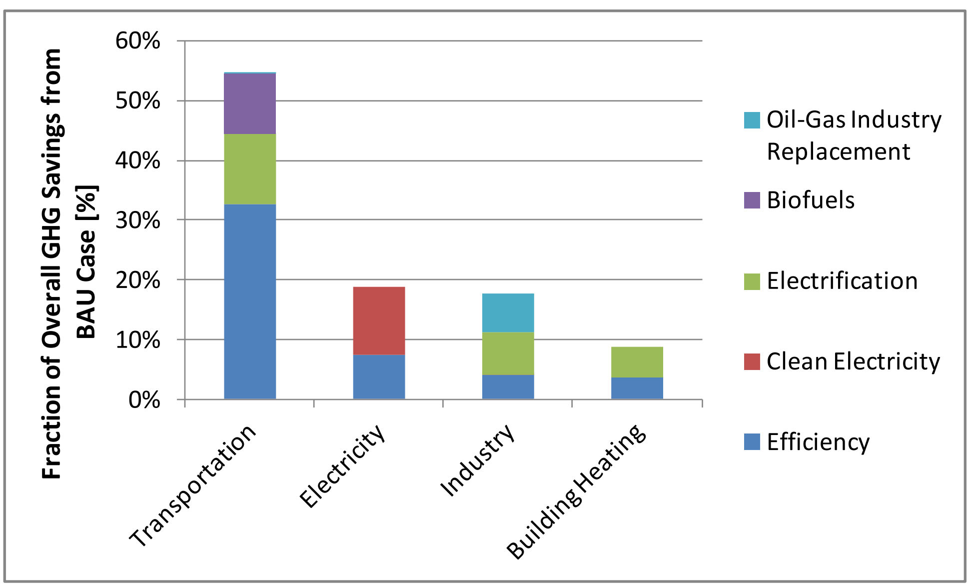
Base Electricity Demand = Technical potential energy efficiency savings in buildings and industry; Base Electrification = Full electrification of building space and water heating; partial electrification of transportation and industry heating; Base Biomass = 10.3 billion gallons gasoline-equivalent low carbon biofuel available to transportation sector in 2050 and none to electricity sector. CCS = Carbon capture and storage; PEV = plug-in electric vehicles.

Figure ES.2: Progression of Energy-Sector GHG Savings in 2050 from the Frozen Efficiency/BAU Electricity Case to the Base Scenario



Total energy-sector emissions in 2050 for the resultant Base Scenario is 75Mt CO_2eq.

Figure ES.3: Fraction of Overall Energy-Sector GHG Savings by Sector for the Base Scenario in 2050



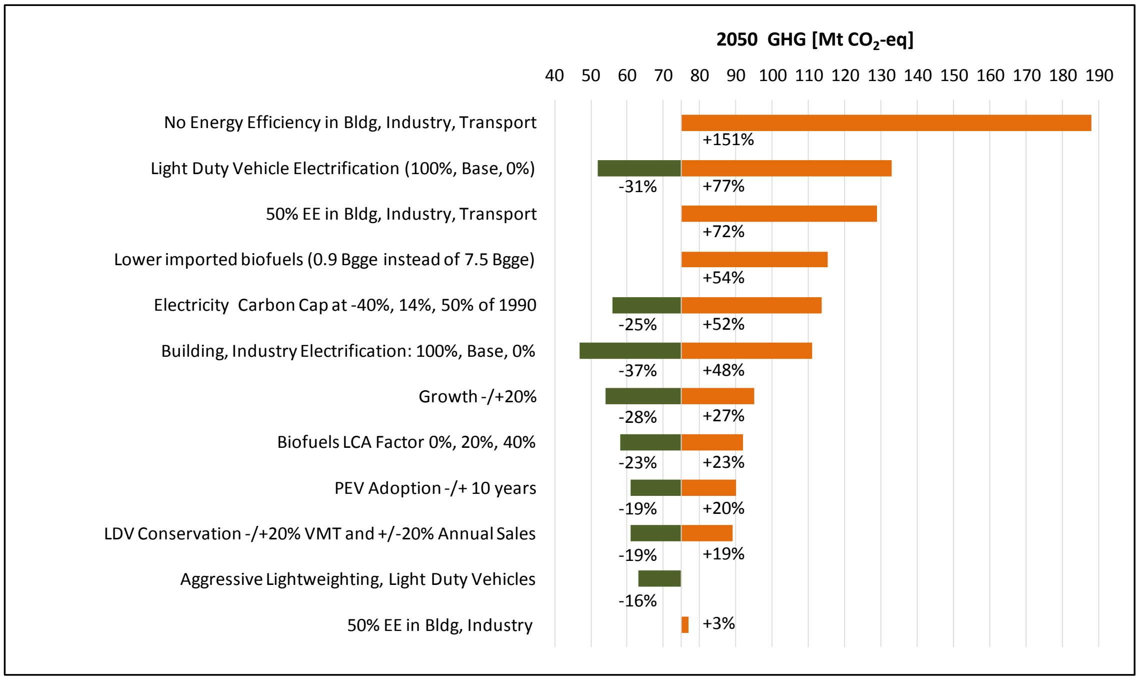
Electrification savings are predicated on the availability of clean electricity. In this compliant scenario, the transportation sector contributes 55 percent of overall savings from the frozen efficiency/BAU electricity scenario.

This work also considers detailed sensitivity analyses for the compliant Base Scenario (Figure ES.4). The sensitivity analysis quantifies the impact of partial or more aggressive implementation of efficiency, light duty electrification, building and industry electrification and other key factors. Key hinge factors for the State include the large role for transportation efficiency, the amount of available imported low carbon biofuels, the degree to which the electricity system is decarbonized and the amount of building and industry electrification. Emissions could increase by more than 40 percent over the target level if any one of these elements does not achieve the GHG reduction amount assumed in the Base Scenario.

The critical role of developing a robust and cost-effective clean electricity supply system is also highlighted. Clean electricity enables a decarbonization path in the building sector through electrified heating and electrification of building heating, and enables near GHG-compliance even with a reduced level of building shell and insulation measures (the reduced or 50 percent energy efficiency scenario in Figure ES.1). This reduced efficiency scenario assumes that clean electricity and electrified building heating are achieved and if either of these measures are not in place, emissions would increase by about 50 percent (Figure ES.4).

Each sensitivity case had Base Scenario conditions except for the noted measure or measures, and sensitivity bars are relative to Base Scenario energy emissions of 75Mt CO_2eq. The labels indicate the midpoint and endpoints for each sensitivity case.

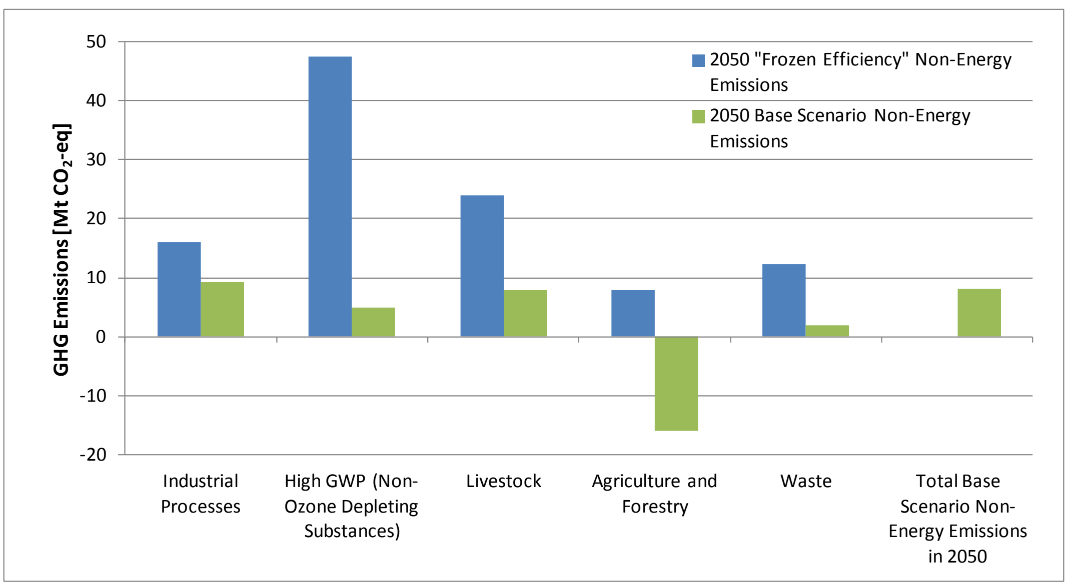
Figure ES.4: Sensitivity Plot for Base Scenario Energy Sector Emissions



Earlier studies indicated the importance of the non-energy sector in future GHG emissions (Velders 2009). A more detailed treatment of this sector's components, anticipated growth, and mitigation options is provided in this project. Non-energy emissions are projected to reach 108 Mt CO_2eq in 2050 without new and tighter regulations, and non-energy emissions alone exceed the total economy-wide GHG goal for 2050 in this "Frozen Efficiency" scenario.

A Base Scenario for non-energy sector emissions achieving 80 percent GHG reduction from 1990 includes aggressive livestock manure management and soil nitrous oxide (N_2O) management, methane capture and combustion for waste, and net zero GHG hydrogen production in industry, (Figure ES.5). High global warming potential gases (high GWP) are the key contributor while afforestation could be a potential path to sequester carbon. Figure ES.6 shows the increase or decrease in emissions from the compliant Base Scenario as a function of key non-energy sectors. A scenario whereby the State does not replace high GWP gases with low GWP substitutes would increase the amount of GHGs in 2050 by 40 Mt CO_2eq. If afforestation is not pursued GHGs would increase by 17 Mt. Conversely, GHG emissions could be further reduced by 17 Mt from the Base Scenario if double the amount of carbon sequestration from afforestation can be achieved.

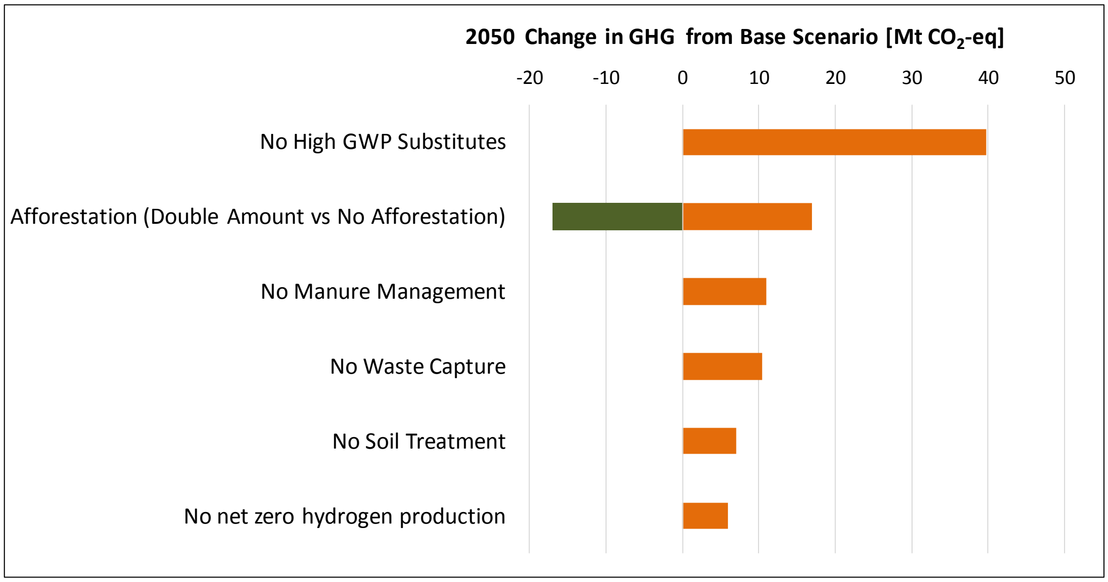
Figure ES.5: 2050 Non-Energy Sector Emissions for the "Frozen Efficiency/BAU Electricity" Scenario and the Base Scenario



Total non-energy sector emissions for the Base Scenario are 8.1 Mt CO_2eq.

Figure ES.4 and Figure ES.6 assume total GHG emissions are a capped quantity in 2050 and represent overall economy-wide sensitivities to the overall target in the context of active carbon trading across energy and non-energy sectors. These sensitivity plots underscore the difficulty of meeting the target with currently known technology since it may be difficult to achieve every measure shown to the full extent assumed in the Base Scenario. Many required supporting policies and infrastructure elements must largely be in place by the 2030-2040 timeframe to intercept retiring stocks of vehicles and/or appliances or to provide adequate lead-time for 2050 reductions to reach fruition. Each of the measures shown as "carbon negative" relative to the Base Scenario is quite challenging to achieve technically and at the scale required in this timeframe.

Figure ES.6: Sensitivity Plot for Non-Energy GHG Emissions



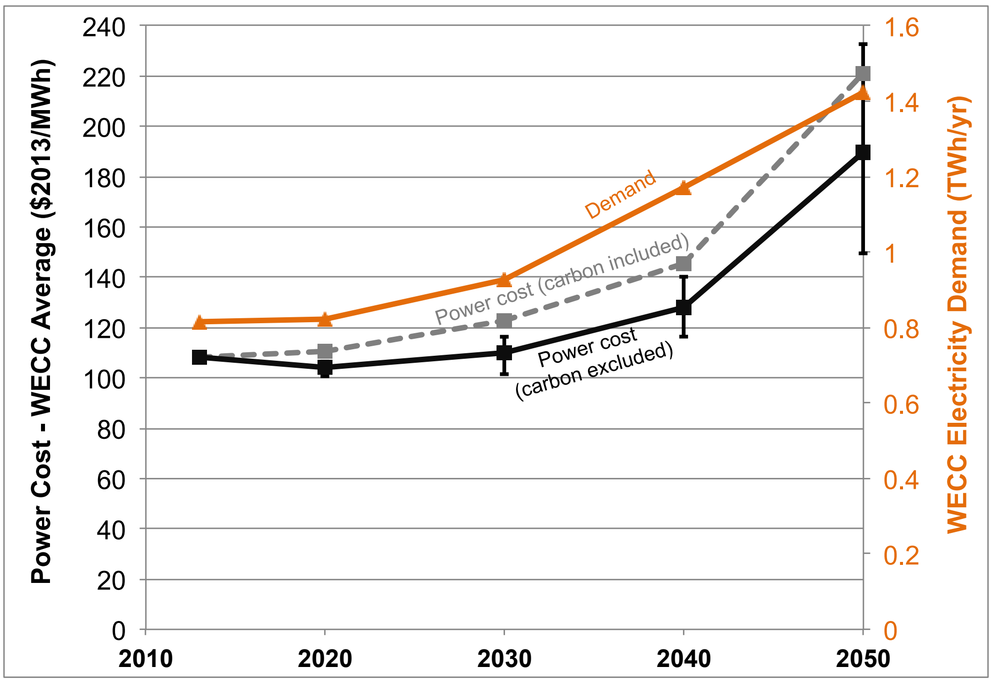
This study uses a state-of-the-art planning model for the electric power system – the SWITCH model – to investigate the evolution of the power systems of California and western North America, specifically the Western Electricity Coordinating Council (WECC), in the context of deep decarbonization of the economy. The analysis spans present-day to 2050. Economy-wide results can be found in Volume 1 of this report.

A cost-minimization framework is employed because the cost of electricity is an important factor for the economic welfare of society. Researchers simulate how projected electricity demand, reliability requirements, and policy goals might be met at the lowest possible cost. The power system is constrained to reach 14 percent of 1990 carbon dioxide (CO_2) emission levels by 2050 under a range of scenarios. These scenarios make specific assumptions about future demand profiles, costs, policy mandates, technological availability, and electric system flexibility.

The electricity system is fundamentally important to the decarbonization of the entire energy system, as switching away from oil and natural gas and towards electricity is a key decarbonization strategy. The scenarios presented here incorporate hourly electricity demand profiles resulting from the electrification of heating and vehicles, as well as from substantial energy efficiency. Even with aggressive efficiency measures, WECC-wide electricity demand is found likely to increase by at least 75 percent between present-day and 2050 (Figure ES.7) due to population growth and additional demand from electric vehicles and electric heating.

The results presented here should be interpreted in the context of the economic optimization from which they are generated. They do not represent prescriptions or projections, but rather depict minimum-cost strategies for a range of possible scenarios that meet policy targets while also supplying reliable electricity.

Figure ES.7: WECC Average Power Cost and Electricity Demand by Investment Period in the Base Scenario



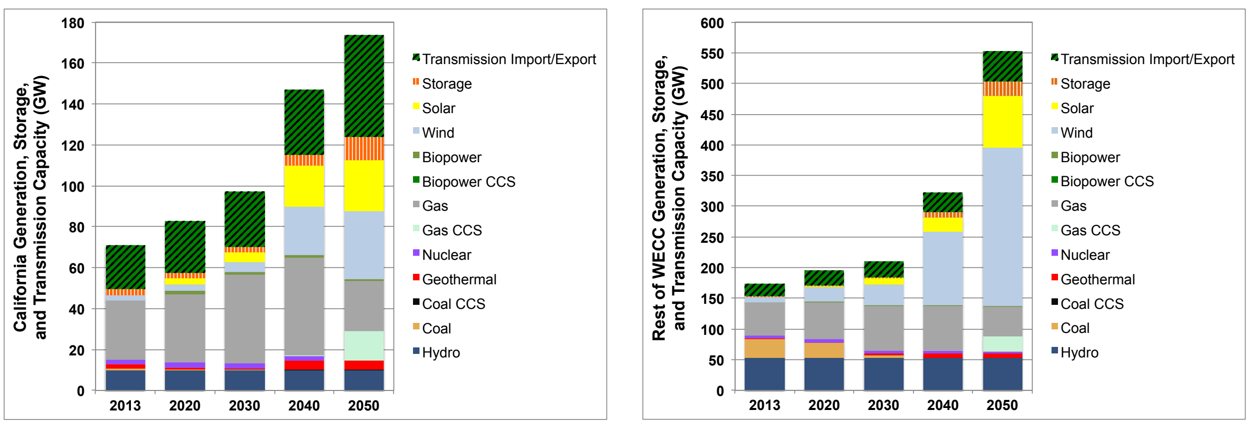
The power cost with 'carbon included' differs from that with 'carbon excluded' by the cost of carbon permits. The error bars represent the range of power costs (with carbon excluded) found in scenarios other than the Base Scenario.

Researchers conclude that drastic carbon emission reductions in the power sector are feasible by 2050 under a wide range of possible scenarios. The WECC-wide average cost of power in 2050 ranges between $149 per megawatt hour (MWh) and $232 per MWh across scenarios assuming that carbon permit revenues are reinvested into the power system. This power cost level represents a 21 to 88 percent increase in real terms relative to a business-as-usual scenario in which emissions stay flat after 2020, and a 38 to 115 percent increase relative to the present-day cost of power. These cost estimates may represent an upper bound since this study assumes little technological progress in many parts of the electricity system. The study demonstrates that breakthroughs in the cost of solar energy or the deployment of demand response could contribute greatly to containing the cost of electricity decarbonization.

The power system would need to undergo sweeping change in order to decarbonize rapidly. Between present-day and 2030, the evolution of the WECC power system is dominated by the implementation of aggressive energy efficiency measures, the installation of renewable energy and gas-fired generation facilities, and the retirement of coal-fired generation (Figure ES.8). In the 2030 timeframe, the flexibility provided by the existing transmission network, existing hydroelectric facilities, geographic consolidation of balancing areas, and a large fleet of gas-fired generation units is largely sufficient to integrate 45 - 86 gigawatts (GW) of wind and solar power capacity in the WECC, representing 12 - 21 percent of total electricity produced. Deployment of new storage or long-distance, high-voltage transmission capacity is shown not to be a dominant strategy through 2030. Transmission capacity into California, made available in part by the retirement of out-of-state coal generation, is dominated by renewable power in the form of bundled Renewable Energy Certificates (RECs) in the 2030 timeframe. Despite demand growth and reduction in emissions, the cost of power stays almost constant until 2030 due to moderate gas prices, the expiration of existing generator sunk costs and the development of high quality renewable resources.

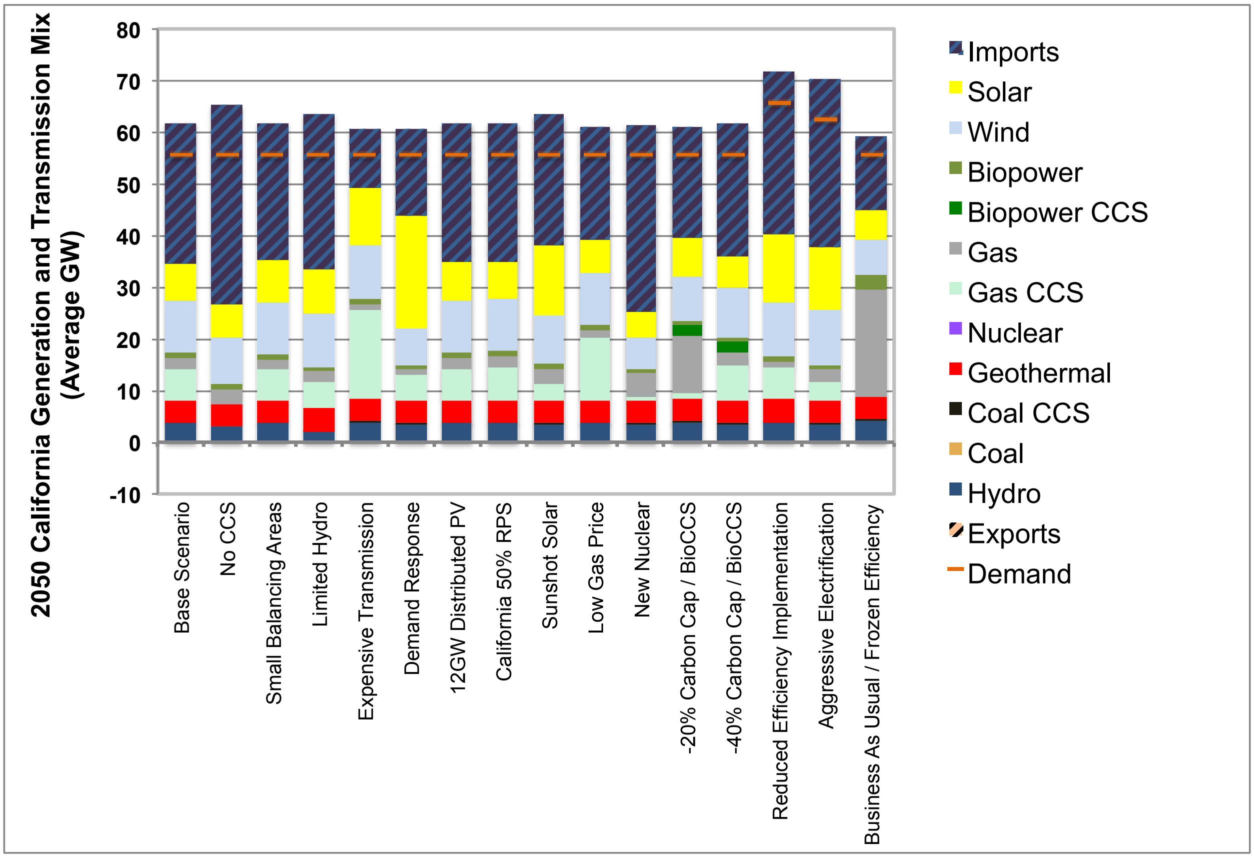
Near- to mid-term renewable energy policy targets could help to deploy renewable generation in California on an accelerated schedule. These targets could include either a 12 GW distributed generation mandate in California by 2020 or a California 50 percent Renewables Portfolio Standard (RPS) by 2030. These policy targets have less effect on the generation mix in the 2040 to 2050 timeframe, as the cap on carbon emissions is the dominant driver of renewable energy deployment post-2030.

Figure ES.8: Base Scenario Generation Capacity, Storage Capacity, and Transmission Import/Export Capacity across the California Border as a Function of Investment Period in California and the Rest of WECC



Transmission import/export capacity is the same magnitude on both plots.

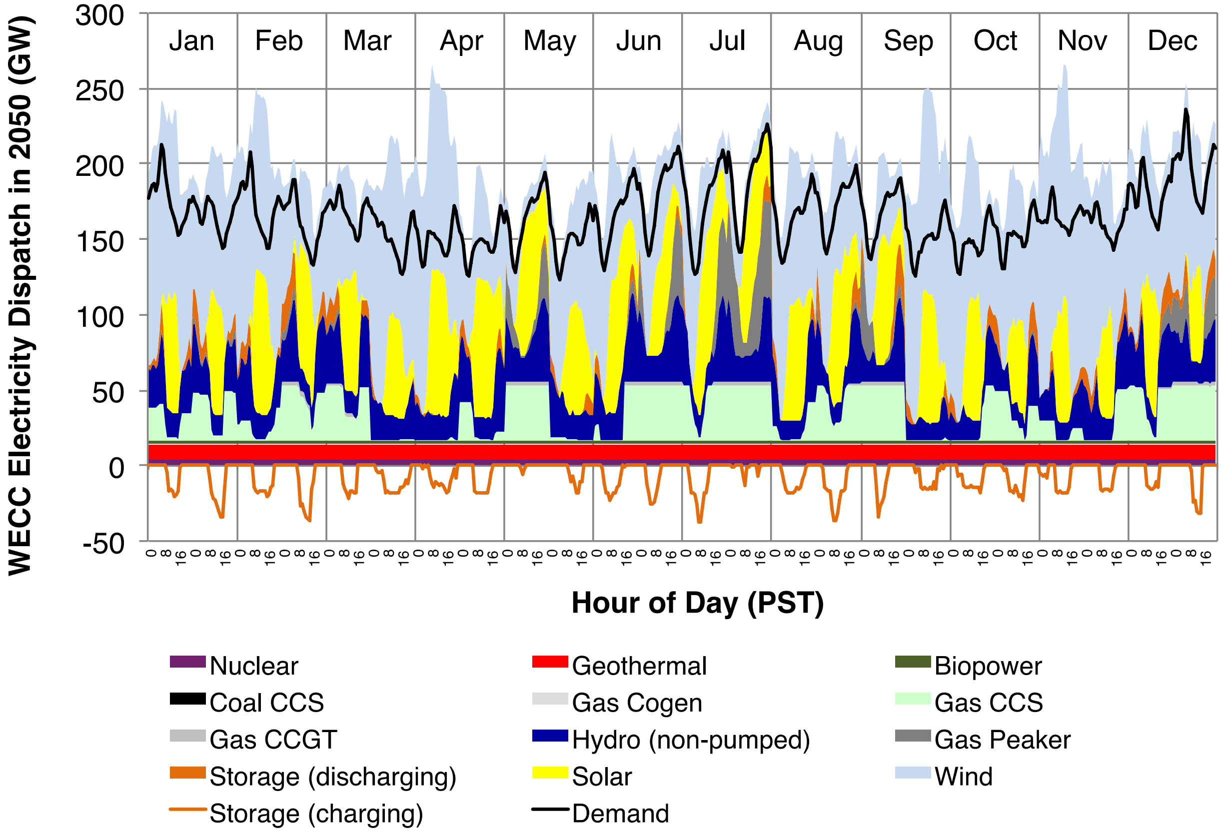
Figure ES.9: California Average Hourly Generation Mix by Fuel, Imports and Exports, and Demand in 2050 for All Scenarios



A similar figure for the rest of WECC can be found in the main text (Figure 3-4 in Volume 2). California remains a net importer in all scenarios.

Post 2030, the electricity system undergoes a radical transformation to eliminate almost all carbon emissions from the generation mix. Deployment of wind, solar and geothermal power reduces power system emissions by displacing gas-fired generation in the 2040 timeframe. In the 2050 timeframe this deployment trend continues for wind and solar, but is accompanied by large amounts of new storage and long-distance high-voltage transmission capacity. In stark contrast to present-day operation, electricity storage is used primarily to move solar energy from the daytime into the night in order to charge electric vehicles and to meet demand from electrified heating (Figure ES.10). Low-cost solar power is found to increase the need for electricity storage. If demand response is deployed in large scale in this timeframe, it would substitute for the functionality of storage, thereby strongly incentivizing the deployment of solar generation, especially in California.

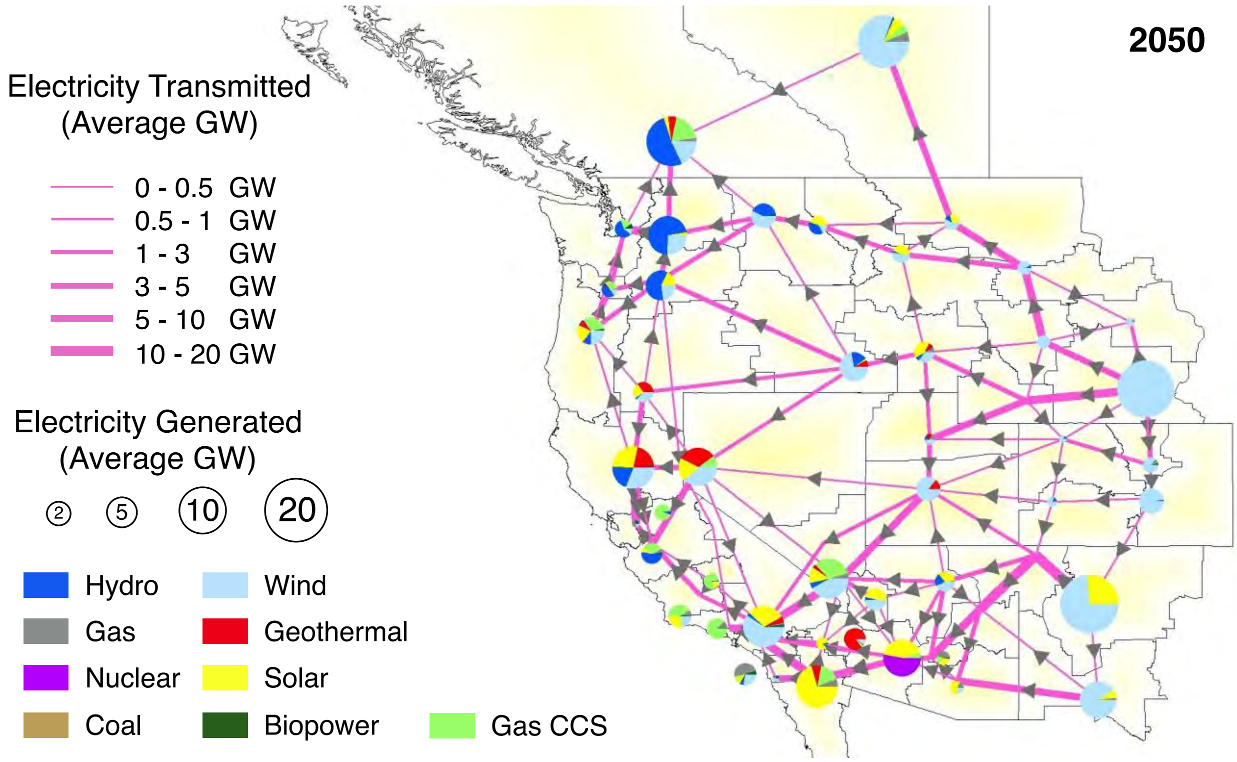
Figure ES.10: Base Scenario Hourly Power System Dispatch across WECC in 2050



Two days per month are represented – the median demand day and the day on which the hour of peak demand occurs. Total generation exceeds demand due to distribution, transmission, and storage losses, as well as variable renewable energy curtailment. Plots of specific days can be found in the main text in Figure 3-13, Volume 2.

Through 2050, transmission lines that exist today are found to be mostly sufficient to move power between Pacific Coast states. New transmission capacity is built primarily to move power over hundreds of miles from the inside of the continent towards demand centers on the coast. High-voltage DC transmission may be well suited to provide much of this new transmission capacity. Transmission capacity over the California border increases by 40 - 220 percent, implying that transmission siting, permitting, and regional cooperation will become increasingly important over time. California remains a net electricity importer in all scenarios investigated. The percent of electricity imported into California ranges from 22 percent to 60 percent, with most scenarios resulting in imports of about 40 percent. The implementation of demand response programs could reduce the necessary import/export capacity. The deployment of out-of-state nuclear power or a lack of availability of carbon capture and sequestration (CCS) technology could prompt deployment of high levels of California transmission import/export capacity.

Figure ES.11: Base Scenario Average Hourly Generation Mix by Fuel within Each SWITCH Load Area, and Average Hourly Transmission Flow between Load Areas in 2050



Wind and solar power are key elements in power system decarbonization, providing 37 – 56 percent and 17 – 32 percent of energy generated across WECC in 2050, respectively, if no new nuclear capacity is built. The least cost strategy for meeting policy, reliability, and demand targets includes curtailment of wind, and to a lesser extent solar facilities, at hours of high renewable output and/or low electricity demand (Figure ES.9). Transmission and storage are installed to capture energy from variable renewable facilities. There is an economic trade-off between building additional storage and transmission facilities or slightly over-sizing renewable power facilities so that there is ample energy from these facilities in hours of great need. Curtailment of some variable renewable power is the lowest-cost strategy under the aggressive carbon targets investigated in this study. Demand response could help to reduce curtailment, but would not entirely eliminate it. Determining how the cost of variable renewable curtailment is compensated will become increasingly important over time.

In order to integrate wind and solar resources into the power system, the amount of installed gas capacity remains relatively constant between present-day and 2050 (Figure ES ES.8), although CCS is installed on some gas plants by 2050. The fleet-wide average capacity factor of non-CCS gas generation drops steeply between 2030 and 2050, reaching only five to 16 percent in 2050 for scenarios that met the 86 percent emission reduction target. Gas plants are only operated for a handful of hours each year but are of extremely high value during those few hours. This result indicates the difficulty of supporting gas generation through market revenues from energy and ancillary services and implies the need for other revenue streams such as a capacity market. Sub-hourly spinning reserves are almost exclusively provided by hydroelectric and storage facilities since there is little space in the carbon cap for fossil fuel emissions by 2050.

Both gas-fired CCS and nuclear power are found to be economical in the context of deep emission reductions, but neither is found to be essential to meeting 2050 emission targets. Both technologies are subject to large political and/or technical uncertainty and therefore economics may not be the driving force for installation. The deployment of moderate amounts of flexible gas CCS to balance variable renewable generation is found to be one of the most effective ways to contain the costs of reducing carbon emissions, especially in California. Gas CCS is not found to be economical to run in baseload mode due to the prevalence of inexpensive wind and solar power, as well as incomplete emissions capture by the CCS system. Coal-fired CCS is not deployed at scale in any scenario due to unfavorable economics and incomplete emissions capture. The finding that baseload fossil fueled CCS is not economical at deep carbon reduction levels is counter to the prevailing thinking about CCS and follows directly from using a detailed modeling platform such as SWITCH.

Biomass CCS could be effective at reducing power sector emissions far below zero by 2050 and can therefore be thought of as a hedge against incomplete decarbonization of other sectors (notably the transportation sector). The cost to make the power system net carbon negative is moderate if biomass is made available to the electric power system instead of to the production of biofuels.

Project Benefits

This study provided an updated analysis of long-term energy system scenarios for California consistent with the State meeting its 2050 climate goal, including detailed analysis and assessment of electricity system build-out, operation, and costs across the Western Electricity Coordinating Council (WECC) region. The research team identified four key elements that are critical for the State to achieve its 2050 goal of 80 percent GHG reductions from the 1990 level: aggressive energy efficiency; clean electricity; widespread electrification of passenger vehicles, building heating, and industry heating; and large-scale production of low-carbon footprint biofuels to largely replace petroleum-based liquid fuels. Meeting these goals could help reduce global warming that contributes to climate change.

CHAPTER 1: Introduction

California is a leading international test bed for innovative climate policies. The groundbreaking AB32 legislation requires the State to reduce its greenhouse gas (GHG) emissions in 2020 to the level of 1990 and Governor Arnold Schwarzenegger's Executive Order S-3-05 calls for GHG emissions in 2050 to be reduced by 80% from the 1990 level. While much policy focus and attention has been on achieving the 2020 target, planning and coordination is required to address the long-term 2050 goal. For example, since the statewide fleet vehicles or refrigeration equipment can take 15 to 20 years to be fully replaced, market adoption of cleaner technologies such as zero emissions vehicles or deployment of low global warming refrigerants must achieve a large penetration by the 2030-2035 timeframe in order to meet 2050 climate goal. Similarly, if the State determines that fossil fuel consumption must be curtailed in the building and/or industry sectors to meet the 2050 climate goal, then fuel switching strategies and supporting policies must be developed in order to intercept the turnover of building heating equipment and industrial process heating systems.

1.1 Other 2050 Studies

Several studies have been done over the last few years to assess the State's potential prospects and pathways to meet the 2050 goal. Three recent studies all highlight four key pathways for the State to meet its goal: aggressive energy efficiency across sectors, deep decarbonization of the electricity supply, widespread electrification in the transportation, building heating and industrial heating areas, and much larger supply of low carbon-footprint biofuels. The studies also highlight the importance of aggressive policy support consistent with meeting the long range goal and continued investment in technological development in energy efficient technologies and clean energy supply sources.

The CCST (2011) study estimates that California can achieve emissions roughly 60% below 1990 levels with largely existing technology if such technology is rapidly deployed at rates that are aggressive but feasible. Key technology hinges in this study include the supply of low carbon biofuels, the emissions associated with electricity load balancing in the case of high renewable power, and the role of carbon capture and sequestration. Similarly, Williams et al. (2012) emphasizes that energy efficiency and lower carbon energy supplies are not sufficient and that widespread electrification of transportation and other sectors is required. The authors highlight the need for technology development demonstration and deployment for technologies that are not yet fully commercialized and the critical need for coordination of investment, technology development, and infrastructure deployment.

The CEC California Carbon Challenge study (Wei at al., 2012) includes a detailed cost optimization modeling of the electricity sector over the entire WECC region, a detailed energy efficiency analysis in the building sector, and a treatment for the carbon savings potential from energy conservation. This study finds the State can achieve emissions about 70% below 1990 levels with largely known technologies, and again highlights the importance of policies and the greater integration of sectors to support the transition.

This work is a follow-up study to Wei et al. (2012). The purpose of this report is to provide an updated assessment of key GHG-saving pathways that can allow the State to achieve the 2050 goal, to identify key opportunities and risk areas for GHG reductions, and to highlight the sensitivities of various approaches toward meeting the goal.

On the demand side, two key updates since 2012 are incorporated into the report:

- In 2012, Gov. Jerry Brown announced a Zero-Emission Vehicle (ZEV) Plan for the State, calling for 1.5 million ZEV (e.g., battery-electric vehicles, low emissions plug-in hybrid vehicles, or fuel cell vehicles) on the road by 2025 and 15% of new vehicle sales are ZEV by 2025. This work incorporates the Governor's ZEV plan and extrapolates vehicle adoption trends to 2050. Note that fuel cell vehicles were not included in this work.
- In early 2013, the California Department of Finance (CADOF) released updated population projections for the state to 2060. The State's Population estimate for 2050 is now 50.4 million people or 15% lower than the earlier 2007 CADOF estimate of 59.5 million assumed in Wei et al. (2012).
- The electricity sector modeling in this study contains numerous improvements including revised generator and storage cost estimates, a more detailed treatment of transmission and the inclusion of a simplified unit commitment algorithm.

The three earlier studies highlight that the non-energy sector (e.g. high GWP gases) alone will surpass overall 2050 goal at current growth rates but none of the studies provide a detailed discussion of mitigation options or potentials. This report also provides a more detailed analysis of the non-energy sector sources of emissions and mitigation options.

1.2 GHG Emission Goals

Overall emissions are targeted to reach 427 Mt CO2eq in 2020 per AB-321 or equivalent to 1990 levels and to be at 20% of 1990 levels in 2050 (per Governor's Executive Order S-3-05 as shown in Figure 1.1). A strategy of commensurate 80% emissions reduction in energy and non-energy sectors would yield emission targets of 77Mt and 8Mt, respectively in 2050.

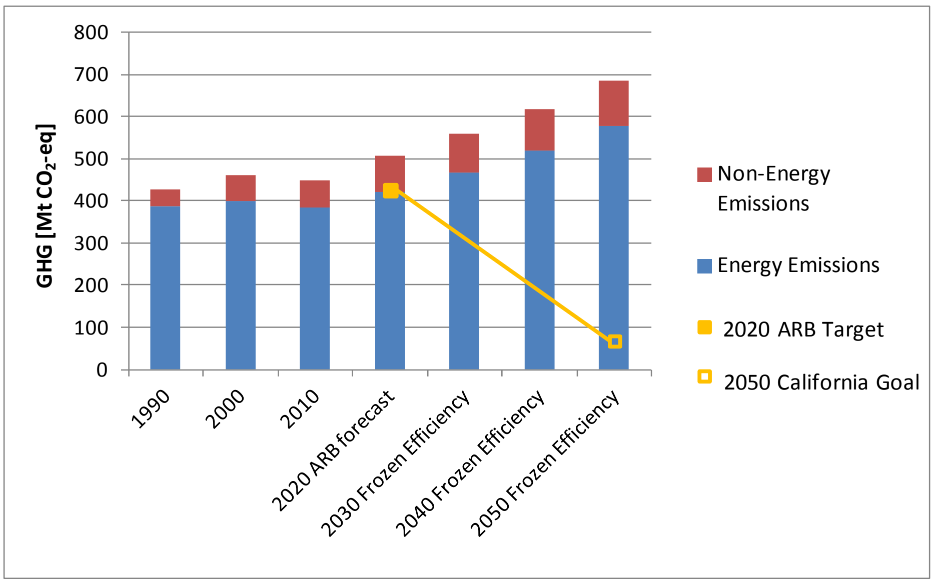
Figure 1.1 also shows projected "frozen efficiency case/BAU electricity" emissions by decade to 2050. This assumes efficiency levels are frozen at current levels, and that electricity GHG

[1] A recent update, "Climate Change Scoping Plan First Update, Discussion Draft for Public Review and Comment," was released in October 2013 and updated the 1990 carbon emissions level to 431 from 427 based on more current IPCC estimates for GWP, and "ARB is beginning to transition to the use of the AR4 GWPs in its climate change programs." Since this proposed change is a late-breaking development and only a 1% increase, we keep the 427 target for this report.
http://www.arb.ca.gov/cc/scopingplan/2013_update/discussion_draft.pdf, Accessed 5 December 2013.

emissions are held at 1990 levels in 2030, 2040, and 2050. ARB targets are to meet 1990 level of emissions by 2020 (AB-32) and in 2050 to reduce emissions by 80% from 1990 level (Gov. Executive Order S-3-05). Non-energy emissions alone are projected to exceed the total GHG goal in the 2050 frozen efficiency/BAU electricity case.

Figure 1.2 and Figure 1.3 show the energy sector and non-energy sector emissions historical values and projections to 2050. Transportation is the largest and fastest growing component in the energy sector while high global warming potential (high GWP) gases are the largest segment and fastest growing segment in the non-energy sector.

Figure 1.1: Decadal Data Since 1990, 2020 ARB BAU Forecast[2], and 2030-2050 Decadal Frozen Efficiency GHG Estimates



[2] ARB 2020 BAU forecast is "an estimate of the emissions expected to occur in the year 2020 if none of the foreseeable measures included in the Scoping Plan were implemented." http://www.arb.ca.gov/cc/inventory/data/forecast.htm, Accessed September 30, 2013.

Figure 1.2: Overall Energy Emissions by Decade with ARB BAU Forecast for 2020

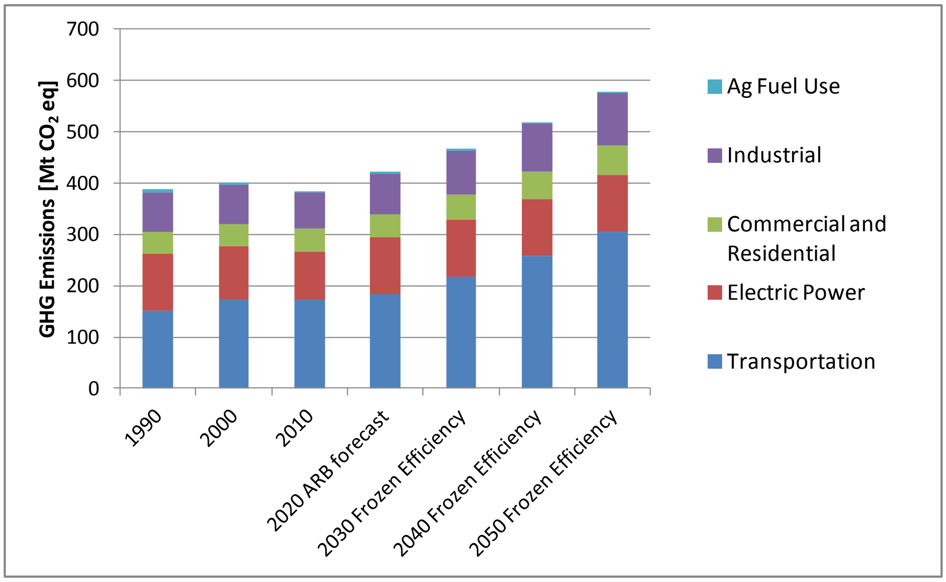
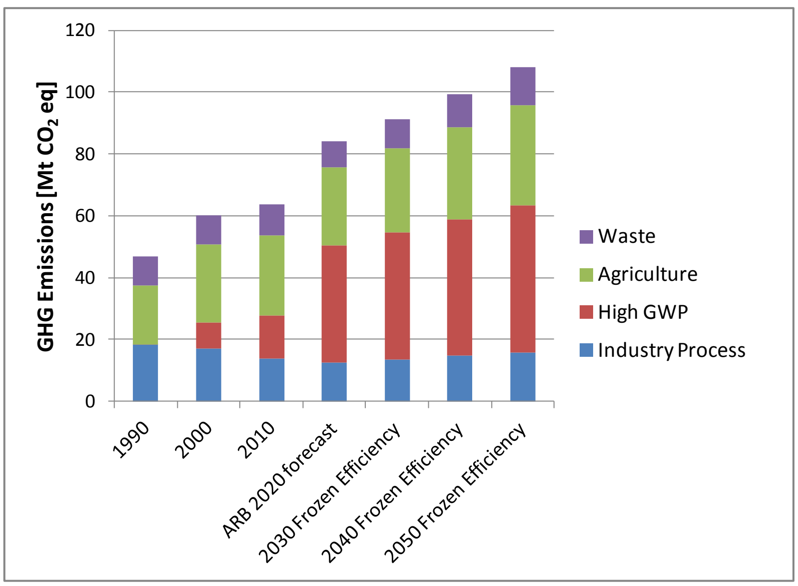


Figure 1.3: Non-Energy Emissions Are Increasing at a Faster Rate than Energy Emissions and High GWP Gases in Particular Are Expected to Grow Rapidly from 2010 to 2020[3]



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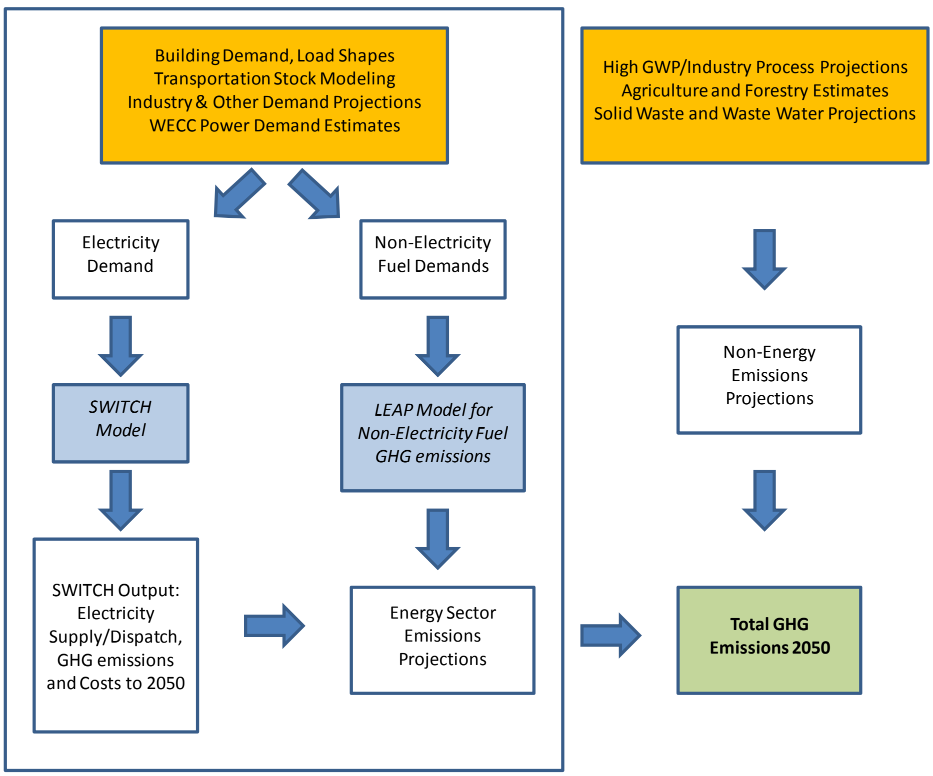
[3] This increase in high GWP in 2020 is taken directly from CARB estimates for High GWP sources (http://www.arb.ca.gov/cc/inventory/data/forecast.htm, accessed September 30, 2013) and it is arguable whether such a large spike in High GWP emissions will be seen. However, a separate recent study of high GWP sources by CARB has found a similar estimate for High GWP by 2050 for the BAU case as our estimates shown in Figure 1.3. Note also that high-GWP CFC and HCFC refrigerants are not counted in the CARB GHG inventory since they are being phased out by the Montreal Protocol.

CHAPTER 2:
Modeling Approach and Scenarios

The structure of the California Carbon Challenge 2 (CCC2) model is shown in Figure 2.1 below. The energy system model structure is similar to Wei et al. (2012) (also referred to as CCC1) but updated with the most recent demand estimates including new population projections and the Governor's ZEV Plan. As in CCC1, two separate modeling tools are used for the energy sector: the SWITCH model for the electricity supply system and LEAP model for the State's non-electricity fuel demands. In this work, we augment the energy sector modeling with more detailed estimates of non-energy sector emissions and mitigation options. Total GHG emissions in 2050 are found by combining energy and non-energy emissions.

Figure 2.1: Structure of the CCC2 Model



Electricity demand is synthesized from existing and recently updated sources and new vehicle demand scenarios and then input into the SWITCH supply model. Non-electricity sector fuel demands are tracked in the LEAP model, which is essentially a graphical bookkeeping tool linking bottom-up demands with overall fuel requirements and greenhouse gas emissions. A more detailed description of the energy model structure can be found in Wei et al. (2012). We provide a briefer description of model components below as well as key updates to the modeling output.

A scenario approach is adopted in the energy sector to estimate total GHG emissions in 2050. We start by projecting a frozen efficiency scenario or those demands that would follow from a trajectory with no additional energy efficiency measures. We then add successive elements to the frozen efficiency case and calculate their respective impacts on electricity demand, fuel demands and resultant emissions with the objective to achieve 80% emissions reductions in the energy sector relative to the 1990 level in this sector.

As in CCST (2011) and Wei et al. (2012), a "Base Scenario" is defined comprising the following key elements: increased efficiency to technical potential levels, clean (understood here to mean much lower carbon-intensity than present day) electricity, partial electrification of building and industrial heating, and partial electrification of the transportation sector. In this updated report, we also include detailed sensitivity analysis for both the energy and non-energy sector emissions relative to the Base Scenario.

Technical potential energy efficiency savings and technologies for inclusion in this study follow the approach of CCC1. We utilize existing studies for the most part for "technical potential" energy efficiency in the buildings, industry and transportation sectors. Technical potential energy savings assumes technically achievable energy savings with existing technology with less focus on costs.

For the most part our technology envelope includes "within paradigm" items which exist in the marketplace today or are beyond the demonstration and prototyping stage. For example, known technologies such as solar PV and wind are modeled and included in the electricity supply but enhanced (deep) geothermal is not demonstrated nor proven at reasonable cost or scale and is not included. Heat pump technologies are assumed to be available in buildings but promising "out of paradigm" HVAC technologies such as novel thermodynamic cycle cooling systems are excluded.

2.1 Key Model Updates to Non-Electricity Sector

The structure of the non-electricity LEAP model is essentially the same as in CCC1. The main changes to the model are inputs to both the electricity and non-electricity fuel demands which will be described in the next chapter. Electricity demands are revised to take into account recent electricity demand projections from the CEC (Kavalec 2011, 2012). Reduction in fuel demand is driven largely by lower population growth, reducing overall fuel demand in transportation and building heating. We also adopt the zero-emissions vehicle (ZEV) market adoption targets in 2025 in accordance with the Governor's ZEV plan, a change which represents a slight increase in ZEV market adoption rates relative to CCC1.

2.1.1 Non-Energy Sector

A detailed accounting is provided in the non-energy sector for current emissions, projected growth by sub-sector, and both short term and longer term mitigation options. The main sub-sectors contributing to non-energy emissions include industry process-related emissions, agriculture, land, and forestry, waste, and high global warming potential (high GWP) gases such as hydrofluorocarbon-based refrigerants (HFC). Three main scenarios are considered in this sector: a business as usual approach, a case where theoretically achievable reduction measures are taken and a third case where one-half of the theoretically achievable reduction measures are achieved by 2050. As with the energy sector, the target in this study is to achieve an 80% emissions reduction in the non-energy sector relative to the 1990 level in this sector.

2.1.2 Scenario Descriptions

Table 2.1 describes the Base Scenario assumptions for this work. This case assumes aggressive levels of energy efficiency (at or close to technical potential levels) are achieved in all sectors by 2050, vehicle electrification follows a trajectory consistent with Governor's ZEV Plan, all space and water heating is electrified, and industry heating is partially electrified. The Governor's ZEV Plan is extrapolated from 2025 to 2050 and the fuel demand sensitivity to this evolution of market adoption post 2025 will be examined in greater detail in Chapter 4. Note that fuel cell vehicles were not considered in this report due to time constraints but should be included for future State energy system modeling. FCV are planned for mass market release as early as 2017[4] and fueling infrastructure is expected to grow in the next few years.

A moderate supply of instate solid biomass and biofuels is assumed for the Base Scenario (35 million dry tons Biomass or 2.8 billion gallons gasoline-equivalent of instate biofuels) with all available biomass directed to the transportation sector. Biofuel imports are assumed to be 7.5 billion gallons gasoline-eq. and capped at that level, consistent California receiving a population-weighted share of national biomass resources in 2050 (CCST 2011). This requirement of approximately 10 Bgge of low carbon biofuels could also be met with a different mix of instate and out-of-state biomass but we take 35 million dry tons of instate biomass supply for the Base Scenario based on earlier estimates for instate biomass from the CEC.[5]

The Base Scenario includes a 20% life-cycle assessment (LCA) factor for biofuels versus petroleum-based liquid fuels, or that the average life-cycle GHG emissions of biofuels in 2050 is 80% lower than the average life-cycle GHG emissions of petroleum-based liquid fuels. The impact of a higher or lower LCA factor will be explored in the Scenario Results section below. Beyond this sensitivity analysis, we do not explicitly consider land-use impacts of much greater biofuel production, and most of the increased biomass supply can be from energy crops, forest and crop residues, and municipal solid waste (Youngs 2013).

Electricity sector emissions are capped at 14% of 1990 levels in 2050. This number was deliberately set to be more aggressive than a 20% cap (or 80% reduction) since CCC1 and other studies (e.g., CCST, 2011) find it extremely challenging to achieve 80% reductions in

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[4] Jim Motavalli, "Three Automakers Combine Forces on Fuel-Cell Cars," *New York Times*, January 28, 2013, accessed October 1, 2013, http://wheels.blogs.nytimes.com/2013/01/28/three-automakers-combine-forces-on-fuel-cell-cars/?_r=0.

[5] For example, the Governor's Executive Order S-06-06 of 2006 calls for no greater than 25% of instate biofuel supply be imported by 2050, but this target may not be achievable depending on many factors, including the overall amount of low carbon biofuels that are required and the relative supply and economics of instate and out-of-state biomass supply and biofuel production. For the purposes of meeting the 80% GHG reduction target in 2050 however, this study adopts the approach that Executive Order S-06-06 is not necessarily binding since is not a requirement to meet the GHG reduction target.

transportation fuels. The optimal mix of electricity supply options are then determined by SWITCH.

Several electricity system variants are described in Table 2.2. The "Frozen Efficiency/BAU Electricity" scenario for 2050 refers to a scenario where energy efficiency is frozen at current levels and where electricity sector emissions are capped at 1990 levels for each year after 2020. Scenarios 5 through 14 start with the same set of assumptions as the Base Scenario but then assume a key modification to policy, technology, or cost assumptions. All instate biomass is directed to the production of biofuels for transportation with the exception of the two Biomass CCS cases (Scenarios 15 and 16). Here, 23 million dry tons (Mdt) of instate biomass is made available to the power sector with the remainder for transportation biofuels, with the amount of biomass available for the power sector set by the biomass supply curve as described in CCC1.

Key scenarios for the non-electricity sectors are Scenario 1 (Base Scenario), 12, 13, 14, 15, and 16. This set of scenarios will be the primary focus of the GHG scenario analysis section of this report. The Base Scenario is compliant with 2050 energy emissions targets and thus will be the reference point for sensitivity analysis. For the purposes of overall GHG emissions, scenarios number 2 through 11 all have the same emissions since the non-electricity fuel demands are assumed to be the same, and electricity sector emissions are all capped at the same 14% level of 1990 emission.

Table 2.1: Base Scenario Assumptions for 2050

Scenario name	Demand profile	Electricity supply options	GHG Mitigation Policies	Electricity Sector System Flexibility	2050 WECC electricity carbon cap (vs. 1990)	Total Biomass/Biofuel Supply
Base Scenario	Technical potential efficiency achieved in all sectors by 2050, vehicle electrification consistent with Governor's ZEV Plan, partial building heating electrification (all space and water heating electrified) and industry heating partially electrified.	Optimal mix of electricity supply options determined by SWITCH. Several variants described in the Table below.	Electricity sector emissions are capped at 14% of 1990 levels in 2050 Governor's ZEV Plan is extended from 2025 to 2050	Baseline conditions in Load area, Hydro supply, Transmission price, with no Demand shifting	Baseline = 14% carbon cap in Electricity sector vs.1990.	129 million dry tons total Biomass (10.3 billion gallons gasoline-equivalent biofuels) for Transportation Sector (35Mdt instate); None for Electricity Sector in Base Scenario

Table 2.2: Scenarios for Electricity Sector Considered in This Report

	Scenario name	Demand profile	Electricity supply options	Policy options	System flexibility	2050 WECC electricity carbon cap (vs. 1990)	Biomass/ Biofuel Supply (Instate)	Biomass/Biofuel Supply (Imported)
1	**Base Scenario**	Base	Base	Base	Base	14%	35 Mdt instate biomass or 2.8 Bgge biofuels; All for transportation Sector	94 Mdt biomass or 7.5 Bgge imported biofuels; All for transportation sector
2	**No CCS**	Base	**CCS unavailable**	Base	Base	14%		
3	**Small Balancing Areas**	Base	Base	Base	**Load-area level operating reserves**	14%		
4	**Limited Hydro**	Base	Base	Base	**Linear decrease to 50% hydro energy by 2050**	14%		
5	**Expensive Transmission**	Base	Base	Base	**Expensive New Transmission**	14%		
6	**Demand Response**	Base	Base	Base	**Aggressive demand-shifting**	14%		
7	**12 GW Distributed PV**	Base	Base	**12 GW distributed PV in California by**	Base	14%		

				2020				
8	**California 50% RPS**	Base	Base	**50% RPS in California by 2030**	Base	14%		
9	**SunShot Solar**	Base	**SunShot solar costs**	Base	Base	14%		
10	**Low Gas Price**	Base	**Low natural gas price**	Base	Base	14%		
11	**New Nuclear**	Base	**New nuclear allowed outside California**	Base	Base	14%		
12	**-20% Carbon Cap / BioCCS**	Base	**BioCCS included**	Base	Base	**-20%**	23 Mdt biomass for Electricity; 12Mdt biomass or 0.96 Bgge for biofuels	32.2 Mdt biomass or 2.6 Bgge imported biofuels
13	**-40% Carbon Cap / BioCCS**	Base	**BioCCS included**	Base	Base	**-40%**		
14	**Reduced Efficiency Implementation**	**Reduced efficiency implementation**	Base	Base	Base	14%	35 Mdt instate biomass or 2.8 Bgge biofuels; All for transportation sector	94 Mdt biomass or 7.5 Bgge imported biofuels; All for transportation sector
15	**Aggressive Electrification**	**Aggressive heating and vehicle electrifi-cation**	Base	Base	Base	14%		
16	**Frozen Efficiency/Business-As-Usual Electricity**	**Frozen efficiency & minimal electrify-cation**	**New nuclear allowed outside California & new biomass allowed**	Base	Base	**100%**	23 Mdt biomass available for Electricity sector; No Biofuels	None

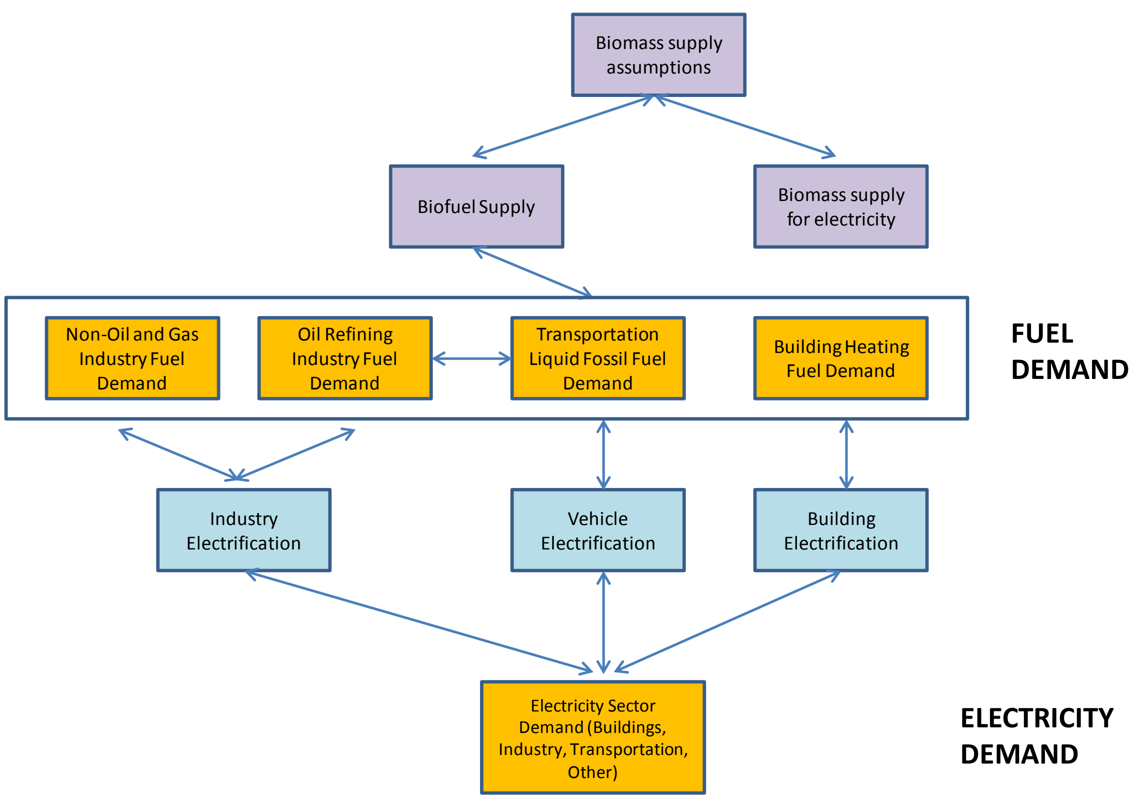
Scenarios 2 through 11 are electricity sector variants modeled by the SWITCH model and are assumed to not have interaction with other sectors, while scenarios 1 and 12-16 interact with the non-electricity sectors. These latter scenarios and sensitivities around them will be the primary focus of the non-electricity system analysis sections of the report. (CCS = carbon capture and storage, RPS = renewable portfolio standards, Mdt = million dry tons, Bgge = billion gallon gas-eq).

CHAPTER 3:
Demand Projections – Buildings and Industry

3.1 Demand Interactions

We begin by exploring the tradeoffs in allocating biomass to the liquid biofuel sector versus the power sector. The interaction of biomass supply and electrification with fuel demands are shown in Figure 3.1. Increasing the allocation of biomass for biofuels and/or increasing the amount of vehicle electrification reduce the demand for liquid fossil fuels. This is assumed to result in a smaller instate oil industry in the 2050 timeframe. Conversely, increasing the supply of biomass for the power sector decreases the amount available for biofuels and in our model would result is less downsizing of the liquid fossil fuel industry. As we will see in the Scenario Analysis section, making more biomass available for electricity also enables the option to achieve negative carbon emissions through bio power with carbon capture and sequestration (biomass CCS).

Figure 3.1: Interactions of Biomass Supply and Electrification with Fuel Demands



Demand side dependencies: Interaction of biomass, biofuels, electricity. Biomass can be allocated for biofuels or electricity. Increasing biofuels reduces demand for liq. fossil fuels in x-port and size of oil industry, decreasing biofuels increases demand for liq fossil fuels in x-port and inc size of oil industry.

Table 3.1 is a table of dependencies of key pathways and energy sector demands. For example energy efficiency and conservation[6] reduce demands across the board. While biofuel production can increase electricity demand depending on the type of production pathway it can also be a net producer of electricity from combusting by-products of the production process. In this work, biofuel production is assumed to have negligible impact on net electricity demand.

Table 3.1: Table of Dependencies of Key Pathways and Energy Sector Demand

Pathway	Transportation Fossil Fuel Demand	Industry: Oil and Gas Fossil Fuel Demand	Industry: Non Oil and Gas Sector Fossil Fuel Demand	Building Heating Fossil Fuel Demand	Electricity Demand	Comment
Energy Efficiency	↓	↓	↓	↓	↓	Global demand reduction
Conservation	↓	↓	↓	↓	↓	Global demand reduction
More Biomass for biofuels	↓	↓				
More Biomass for Electricity	↑	↑				Enables negative electricity sector emissions with Biomass CCS.
Industry Electrification		↓	↓		↑	
Vehicle Electrification	↓	↓			↑	
Building Electrification				↓	↑	

3.2 Population Projection Update

California population growth has moderated and is projected to slow over next few decades (Figure 3.2). The new 2050 forecast is 50.4 million residents in 2050 (CADOF, 2013) down from 59.5 million (CADOF, 2007) that was assumed in CCC1 and in other reports. Building heating and transportation demands are adjusted from CCC1 levels in 2050 due to this lower population growth. The industry sector is taken to have same frozen growth as CCC1 since industry is not necessarily correlated to population growth but rather to other macro factors such as structural changes in the sector and other macro-economic factors.

[6] Here, energy efficiency is defined as a lower amount of energy required to deliver the same degree of energy service, while energy conservation denotes a reduction in energy service demand e.g., less vehicle miles travelled or reducing household hot water usage. In practice, the two terms are often used interchangeably.

Figure 3.2: CADOF/CEC State Population Forecasts

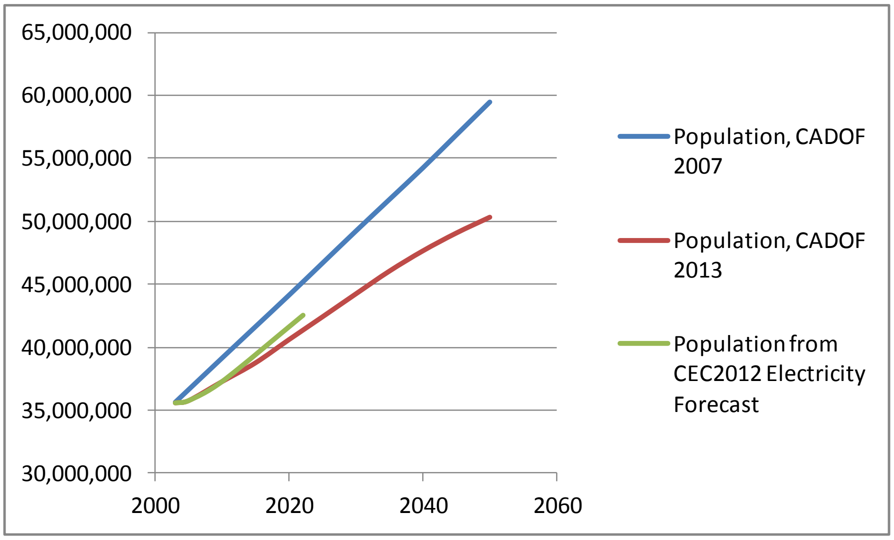


Table 3.2: State Population Forecast and Growth Rates

Year	Population, CCC1 CADOF 2007	Approx. Pop. Electricity Forecast CEC 2012	Population, CADOF Jan. 2013
2003	35,614,509		35,614,509
2005	36,620,557		35,795,255
2010	39,135,676	37,500,000	37,309,382
2015	41,635,800		38,801,063
2020	44,135,923		40,643,643
2022	45,156,917	42,500,000	41,367,000
2025	46,688,407	-	42,451,760
2030	49,240,891	-	44,279,354
2035	51,753,503	-	46,083,482
2040	54,266,115	-	47,690,186
2045	56,886,996	-	49,108,689
2050	59,507,876	-	50,365,074
Annual Growth Rates			
2010-2022	1.2%	1.05%	0.86%
2010-2050	1.05%		0.75%

Electricity sector demand was based on CEC (2012) and estimates from the U.S. Energy Information Annual Energy Outlook (AEO, 2013). The 2012 CEC report has population estimates to 2022 which are slightly higher than CADOF (2013) (1.05% annual growth rate to 2022 vs. 0.86%[7]). Note that the electricity demand estimates for this work are informed by these reports as described below and were not adjusted for slightly lower population growth in the

[7] http://www.eia.gov/forecasts/aeo/assumptions/pdf/macroeconomic.pdf. Annual pop growth in U.S. at 0.9% per year from 2011 – 2040 in AEO 2013, but forecasts for CA electricity demand are lower than CEC.

updated CADOF (2013) projections because the growth rate difference is not markedly different in this time frame, and this provides a slightly more conservative electricity demand projection.

Frozen efficiency scenario electricity demands are based on CEC and AEO estimates are shown in Table 3.3. We moderate the CEC (2012) residential growth rate from 1.9% to 1.5% since (1) the historical growth rate is 0.4% per capita and the expected population growth rate is expected to be 1% or less over the next several decades; (2) AEO sector-based estimates are lower than CEC estimates; and (3) we are extending the population to 2050 and thus moderate the growth rate for the longer estimation period as seen in the population growth curve.

Table 3.3: Frozen Efficiency Annual Growth Rate Assumptions in the Electricity Sector

Sector	CEC 2010-2022 Reference Forecast [CEC 2012]	AEO 2011-2040 [AEO2013]	CCC1 2010-2050	CCC-2 2010-2050
Residential	1.9%	0.5%	0.7%	**1.5%**
Commercial	1.5%	1.2%	1.4%	**1.4%**
Industrial	0.19%	0.9%	1.4%	**1.4%**

Industry frozen growth is taken from Masanet et al. (2013) and all efficiency savings are taken relative to that baseline, so the 1.4% growth is kept for this study. For reference, the CEC (2012) “high estimate” for industry growth is 1.73% annual growth to 2022 and de la Rue du Can, et al. (2011) report that both the oil and gas refining and extraction sector grew at about 1% per year from 1997-2008.

Both the CCC1 report and this work take 2011 as the starting year and technical potential savings in 2050 from the frozen efficiency case in the electricity sector are adopted from CCC1: 44% in the residential buildings, 30% for commercial buildings, and 28% for Industry and Other.

The rest of WECC electricity (WECC excluding California) demand estimates were not updated in this work from the CCC1 report and are based on AEO 2011 projections.

3.3 Base Scenario Electricity Demands

Base Scenario electricity demand through 2050 (Base Scenario = technical potential efficiency savings + electrification) is shown in Figure 3.3 for California and in Figure 3.4 for the rest of WECC. In California, electricity demand in the frozen efficiency case increases by about 1.4% a year or by almost 80% in the frozen efficiency case in 2050 relative to the 2010 level. This is reduced by about one-third in the technical potential efficiency case in 2050, but then increases again back to the frozen efficiency level after including vehicle, building and industry electrification. Consistent with the idea of California as a policy leader, the rest of WECC is assumed to adopt electrification 10 years after California. A similar set of plots is shown for the

Aggressive Electrification case in Figure 3.5 and Figure 3.6. In this case, overall electricity demand approximately doubles from the 2010 level.

Figure 3.3: Base Scenario (Tech. Potential + Electrification) Electricity Demand in California through 2050

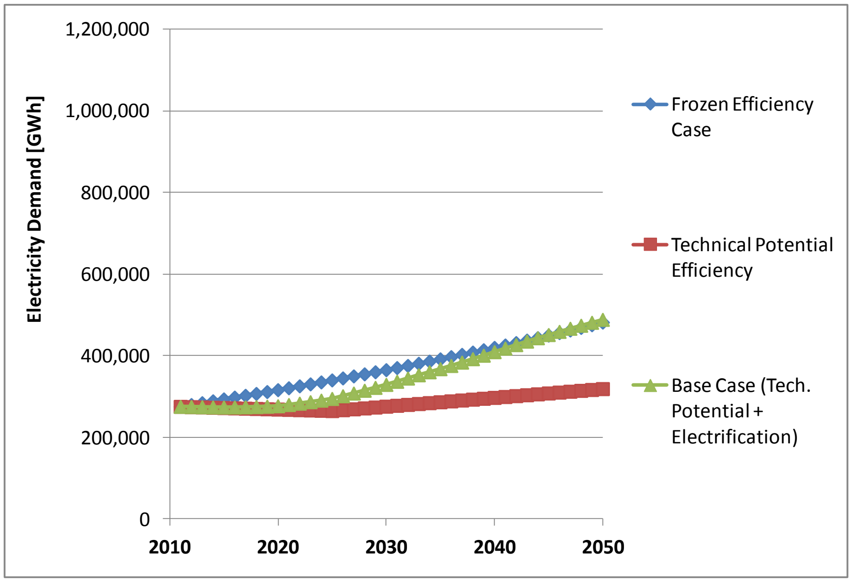


Figure 3.4: Base Scenario Electricity Demand in the Rest of WECC through 2050

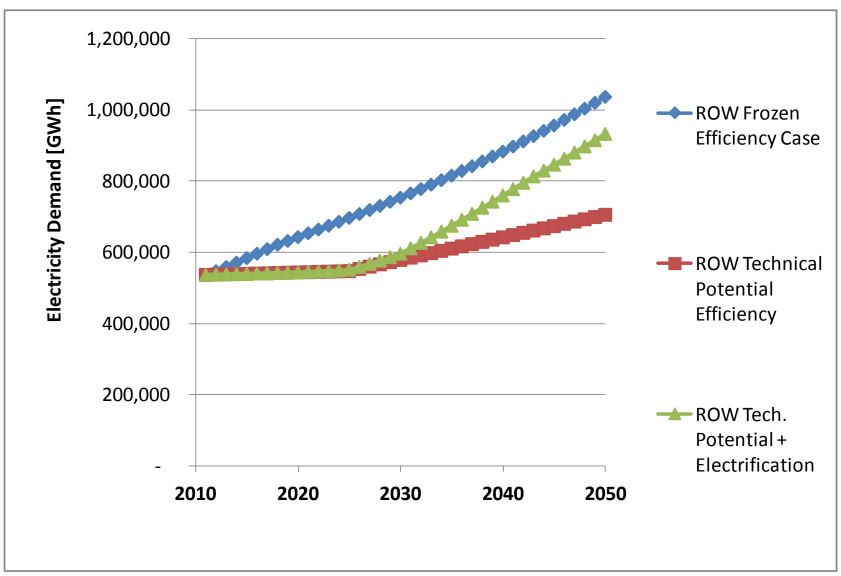


Figure 3.5: Aggressive Electrification Scenario Electricity Demand in California through 2050

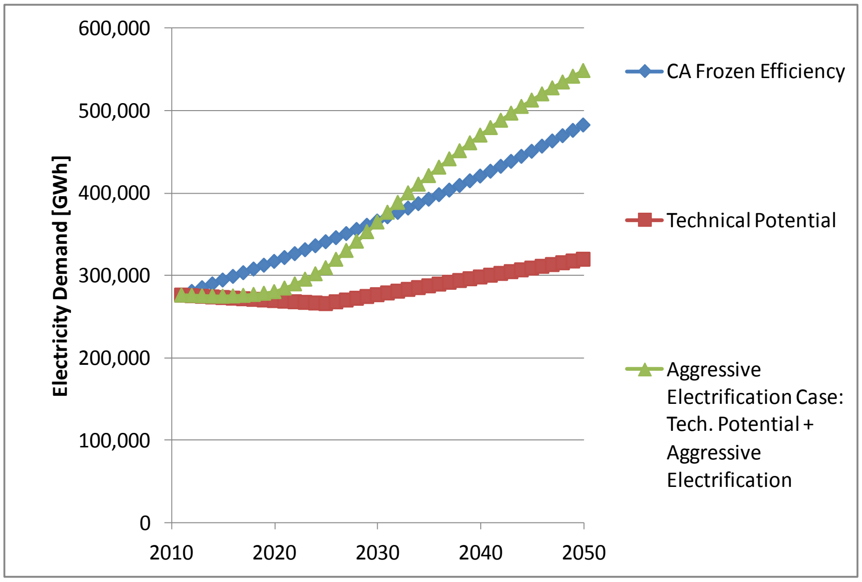
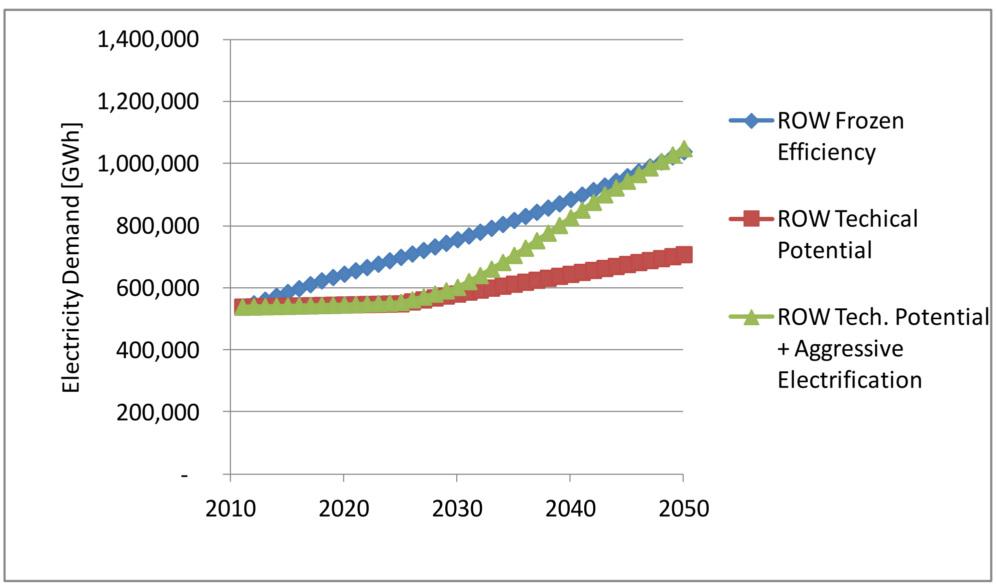


Figure 3.6: Aggressive Electrification Scenario Electricity Demand in the Rest of WECC through 2050



3.4 Building Energy Efficiency and Fuel Switching

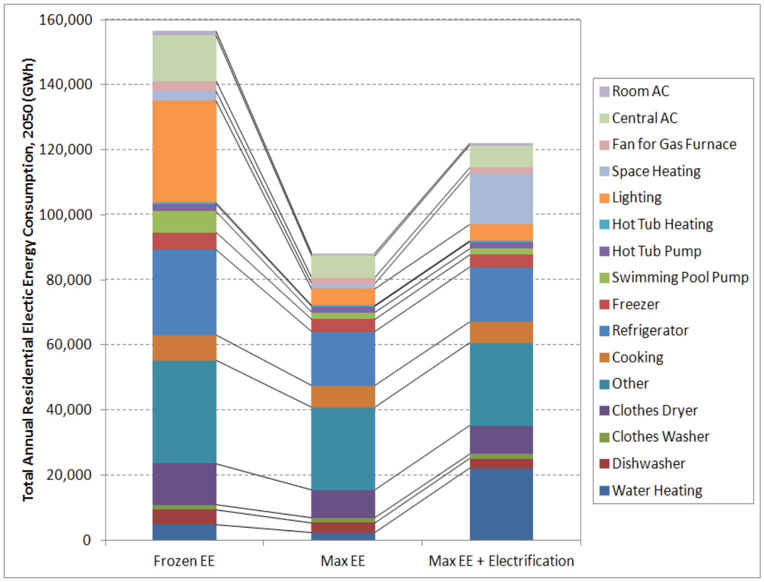
Energy efficiency and fuel switching follow the same treatment as Wei et al. (2012). All end uses are assumed to achieve their full technical potential savings by 2050 (with varying rates of adoption depending on cost projections and replace on burnout rates), and water heating and space heating are assumed to be fully electrified in both residential and commercial buildings. Although full electrification of building heating is assumed in this study, it is possible to utilize solar water heating for low carbon water heating as well. The relative economics and efficiency of solar versus electrified water heating as a function of building type and micro-climate is an important area for further investigation.

For illustration, residential electricity maximum or technical potential energy efficiency savings are shown in Table 3.4 and Base Scenario residential electricity demand in Figure 3.7. Lighting, cooling, and refrigeration dominate efficiency savings. Water heating and space heating are fully electrified in the Base Scenario leading to an increase in electricity demand. Fuller discussion of the technical energy efficiency, adoption rate and electrification methodology are described in Wei et al. (2012).

Table 3.4: Residential Electricity Energy Efficiency Savings Assumed in This Work in 2050 Compared to the Frozen Efficiency Case

Residential End Use	Max EE savings	Pct. of overall savings	Cum. savings
Lighting	**84%**	**38%**	**38%**
Refrigerator	**37%**	**14%**	**53%**
Central AC	**52%**	**11%**	**63%**
Other	**20%**	**9%**	**72%**
Swim. Pool Pump	**70%**	**7%**	**79%**
Clothes Dryer	32%	6%	85%
Water Heating	53%	4%	89%
Space Heating	50%	2%	91%
Dishwasher	33%	2%	93%
Freezer	25%	2%	95%

Figure 3.7: Building Efficiency Savings



3.5 Building Heating Demand and the Reduced Efficiency Case

Heating demand in residential and commercial buildings was adjusted downward with revised CADOF (2013) population estimates. As in CCC1, electrification of building space and water heating is projected to start in 2015 and achieve 100% penetration at the margin (or equivalently, replace on burnout) by 2025. This implies fully electrified space and water heating by 2050.

In the reduced efficiency case (50% technical potential efficiency is achieved by 2050), less building insulation and shell efficiency will lead to greater space heating demand, but to first order no increase in water heating demand or other end use heating demands (e.g., cooking, swimming pool heating, dryers). We thus estimate that space heating demand will increase by 20% in this case and overall building electrification demand by 10%.

3.6 Industry Baseline and Demand Assumptions

We begin with a general discussion of the industry sector in California to understand the fuel makeup, related emissions by sub-sector and to help identify fuel-switching opportunities. Much of this discussion is drawn from LBNL's California Energy Balances study (de la Rue du Can, et al. 2011) which provides a rich set of data and analyses for industry energy and GHG emissions.

CO_2 represents nearly 90% of industry emissions in the State with non-energy emissions such as process related emissions constituting the remainder. Gaseous fuels constitute almost 80% of fuel demands and there is a fuel switching opportunity from coal and petroleum coke, which constitute only 11% of energy demand but 17% of industry CO_2 emissions, to gaseous fuel. In the area of non-energy emissions, there is opportunity to reduce emissions from industry processes such as cement manufacturing and hydrogen production. These will be discussed in the non-energy section of this report.

More than half of industry emissions are from petroleum refining (40%) and oil and gas extraction (17%). Thus opportunity exists to displace this sector if cleaner, lower carbon sources of liquid fuel can be developed and if demand for natural gas can be reduced, for example through a program of greater end-use electrification. This could materially change however, if the oil industry experiences a boom in the state due to productive and commercially viable extraction of oil from the Monterey Shale formation through alternative extraction technologies such as hydraulic fracking, steam extraction, and/or horizontal drilling. Shale development to date has been limited by technology but the regulatory environment remains to be seen, with preliminary regulations requiring environmental disclosures for fracking and other “well stimulation” treatments taking effect in January 2014.

Manufacturing emissions are about 30% of overall industry emissions and are dominated by the minerals sector (cement, glass, clay) and food products sector. Cement industry fuel usage dominates manufacturing energy and again, opportunity exists for both energy efficiency and fuel switching from coal and petroleum coke-based fuels to natural gas. An earlier report on fuel saving opportunities reports about 20% fuel savings potential from energy efficiency measures in cement manufacturing (Price et al., 2005).

Base Scenario industry fuel demand is assumed to grow consistent with Wei et al. (2012), or 0.5% in the oil and gas sector and 0.68% for non-oil and gas sectors. No adjustment has been made for industry growth due to population projection changes since in many developed economies such as California’s, the size of the industrial sector is set more by structural changes and macro-economic factors than population. For 2050 we assume that there is fuel switching from coal and petroleum coke to natural gas and from natural gas to electricity for low-to-medium temperature process heating. This aggressive transition has equipment design constraints and implementation issues not detailed in this report, but some discussion of these issues can be found in a recent report on building and industry energy efficiency by the California Council on Science and Technology (Greenblatt et al., 2012).

3.7 Oil and Gas Industry

About 90% of California refining for gasoline and distillate fuel (primarily diesel) is for in-state use. The 2050 Base Scenario assumes that with continued aggressive fuel economy improvement, vehicle electrification, and low-carbon biofuel supply, demand for petroleum-based liquid fuel will be sharply reduced. With current refining capabilities in place, this drop in demand will provide excess capacity for production. Either this capacity will result in a greater fraction of exported petroleum products or, if the rest of WECC and the world act to reduced petroleum demand by 2050, the size of the refining industry in California will be reduced. The size of the remaining oil refining industry in 2050 is taken as the ratio of remaining liquid fuel demand for transport in the Base Scenario to a projected frozen efficiency case production of 30 Bgge gallons of liquid fuel per year. We also assume that the oil and gas extraction industry energy use is reduced by the same fraction as that for the refining industry. Oil extraction in the state has been dropping for the last 30 years and instate natural gas extraction (currently 12% of overall supply) has been falling as well.

Overall industry demand in the frozen scenario is projected to grow 29% from 1308 Tbtu in 2010 to 1688 Tbtu in 2050. Efficiency savings and electrification potential adopt the same assumptions as CEC (2012) with a combined 51% reduction in fuel usage in 2050 to 824 Tbtu.

Final 2050 industry energy demand for the Base Scenario after including low carbon biofuels and oil and gas industry replacement is reduced by 70% to 247 Tbtu.

CHAPTER 4:
Demand Projections – Transportation

4.1 Light Duty Vehicles

Light Duty vehicles have accounted for a steady 73% of transportation emissions from 2000-2010 and are the key focus for this study. Other efficiency and electrification gains in non-LDV transportation sectors (heavy duty trucks, aviation, buses, shipping and rail) are adopted from the CCC1 report and adjusted for lower population in 2050. Two key events have occurred since the publication of the CCC1 report:

- Release of Gov. Brown's ZEV Plan in 2012
- Ratification of more aggressive federal CAFÉ standards for 2017-2025.

Efforts have been made to be consistent with these two changes for the light duty vehicle sector and LDV transportation demand is also adjusted to lower expected population in 2050.

4.2 Vehicle Stock Modeling

Vehicle efficiency as a function of time through 2050 is assumed to be the same as CCC1 for all vehicle types (where ICE = internal combustion engines, HEV = hybrid electric vehicles, PHEV = plug-in hybrid vehicles, and BEV = battery electric vehicles). Fuel cell vehicles are not considered in this report. Adoption curves are based on CCC1 but PHEV/BEV (or PEV for plug-in electric vehicles) adoption is slightly increased to be in accord with the Governor's ZEV Plan for the state, namely to have 1.5 million fuel cell, plug-in electric, or battery electric vehicles on the road by 2025, and with ZEVs to constitute 15% of new vehicle sales by 2025. Henceforth FCV/PHEV/BEV are referred to as "ZEV", although plug-in electric vehicles are not strictly zero emission vehicles.

The Governor's ZEV Plan market adoption is then extrapolated to 2050 but shares of HEV, PHEV, BEV are assumed to be similar roughly 1/3 each of the overall market in 2050 as in the CCC1 market adoption projection. Other vehicle assumptions for the Base Scenario are shown in Table 4.1 as well as additional conditions considered for sensitivity analysis. These assumptions were coded into a LEAP stock turnover model for LDVs and the resultant output is described below. Note that a +/- 40% change in annual population growth rate only corresponds to a +12%/-11% change in overall population in 2050.

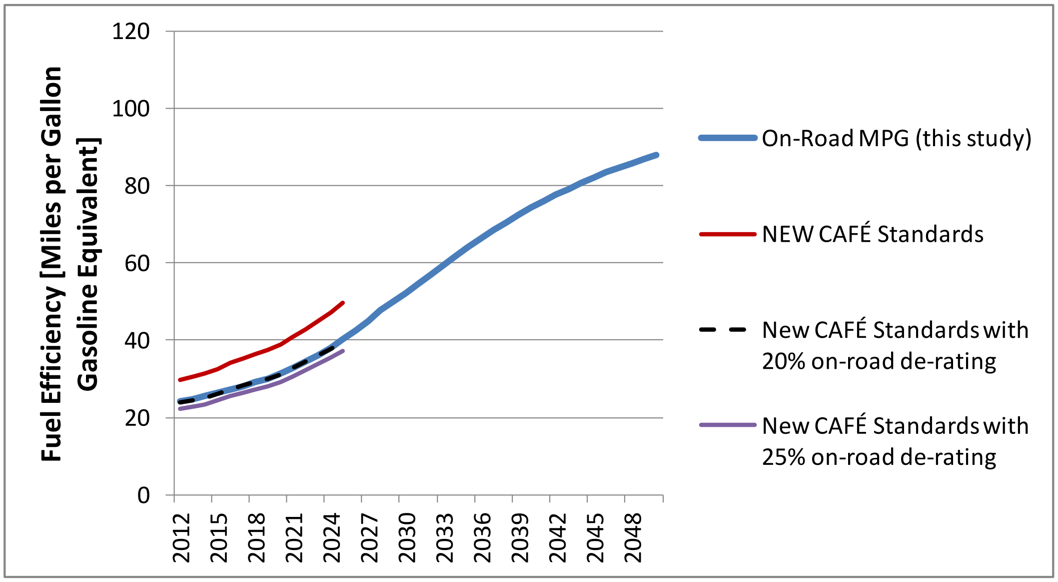
Table 4.1: Base Scenario LDV Assumptions and Conditions for Single Factor Sensitivity Analysis

Factor	Base Case	Sensitivity from Base Case Center Point	Optimistic	Pessimistic
PEV Adoption	Gov. ZEV Plan	Aggressive Electrification Case/ 10 yr.	Aggressiv Electrification Case	10 year Delay
Annual Vehicles Sales (% of Pop.)	5.7% of pop.	+-20%	4.6%	6.8%
Annual VMT for New Vehicles [miles]	15400	+-20%	12320	18480
Fuel Efficiency (MPG)	Base	+-20%	20% higher in 2050	20% lower in 2050
Population (Annual growth rate)	0.75%	+/-40% Annual Growth Rate	0.45%	1.05%

(VMT = vehicle miles travelled).

New car fuel efficiency in MPG is shown in Figure 4.1 below. Note that the CAFÉ standards are laboratory- tested mileage numbers and actual on-road mileage is expected to be 20-30% lower. Thus the on-road MPG in this work is as aggressive as or more aggressive than federal standards which are in effect to 2025. On-road MPG is further seen to reach 88 MPG by 2050 in the Base Scenario. This is consistent with the National Academies Report which estimates 90-116 on-road MPG for new hybrid cars in 2050 and 62-80 MPG for light trucks (NAS, 2013).

Figure 4.1: New Car Fuel Efficiency in Miles per Gallon Gasoline Equivalent[8] for This Work versus New Federal CAFÉ Fuel Standards to 2025



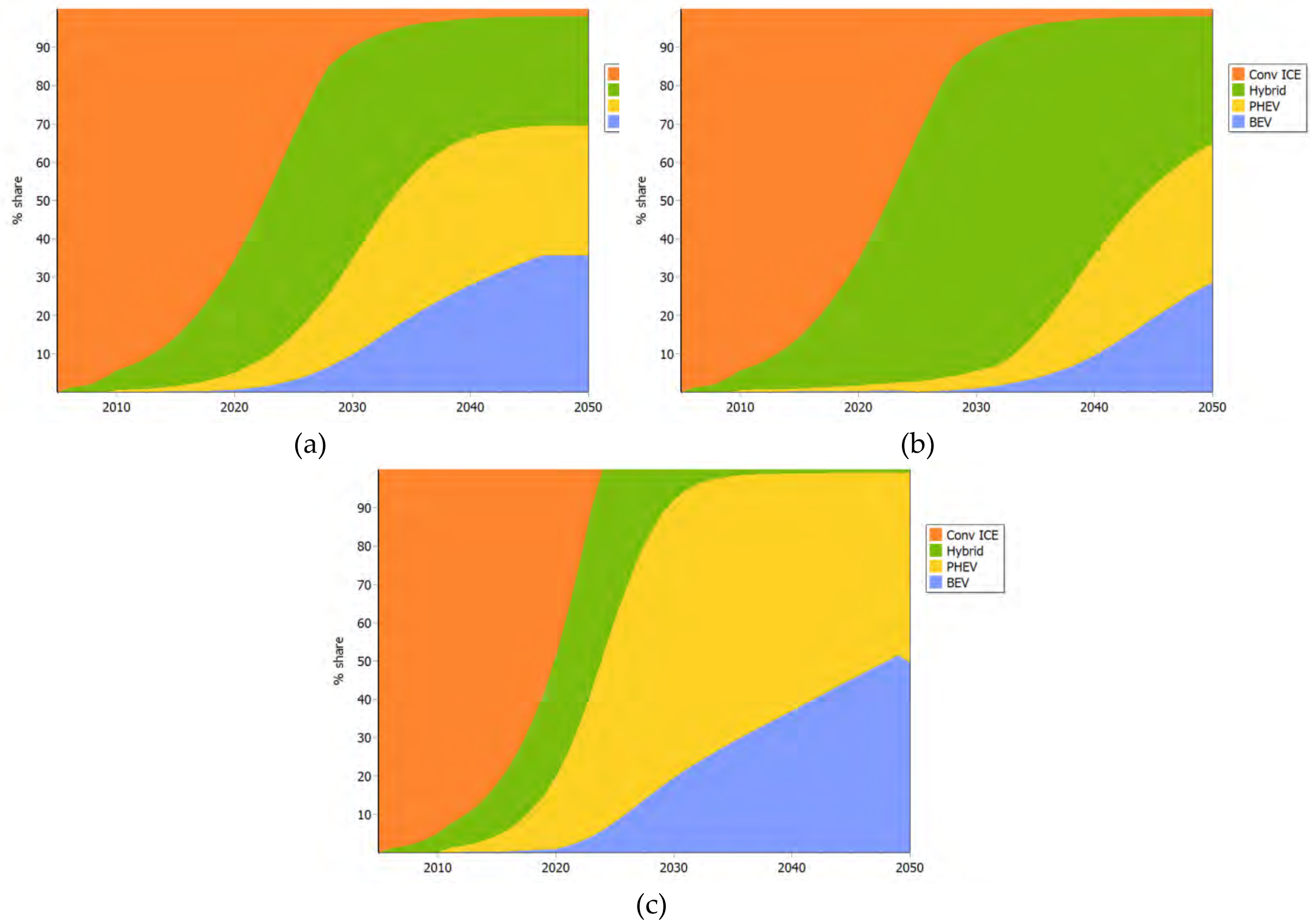
4.3 Vehicle Adoption

We consider three cases for vehicle adoption: (a) the Base Scenario, (b) slower PEV adoption (10 year delay of the Governor's ZEV plan), and (c) the Aggressive Electrification case which achieves nearly 100% PEV new car market adoption by 2030. Two of the four cases are modeled in SWITCH: the Base Scenario and the aggressive electrification case to provide the greatest range in demand to the electricity system.

Note that for 2050 vehicle emissions, market adoption and sales after 2035 are critical since vehicles from sales before 2035 are largely replaced. The Aggressive Electrification case provides a bounding case for the amount of vehicle electrification that the state could see in 2050 and represents a scenario where the percentage market share of PEV in the state is close to 100% of market share in 2030-2050.

[8] Miles per gallon gasoline equivalent is a measure of the average distance traveled per unit of energy consumed, where 33.7 kilowatt hours of electricity is equivalent to one gallon of gasoline, and is a metric used to compare energy consumption of alternative vehicles with ICE vehicles.

Figure 4.2: Light Duty Vehicle Market Adoption Curves (Percentage of New Vehicle Sales by Year)

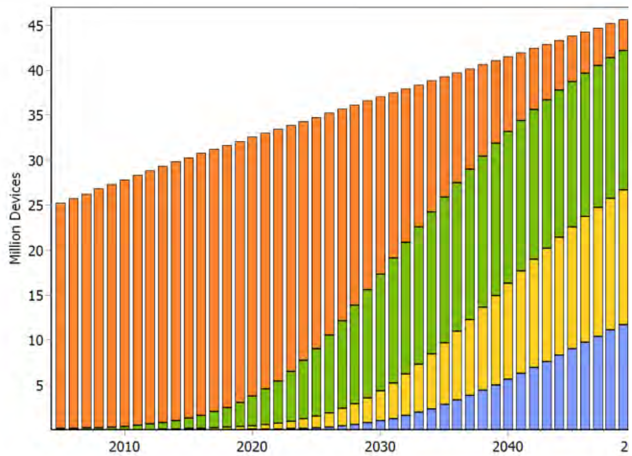


(a) Base Scenario (Governor's ZEV plan for passenger vehicles extrapolated to 2050); (b) Delay of ZEV adoption by 10 years; (c) Aggressive Electrification scenario. [Orange = Conventional ICE, Green = Hybrid, Yellow = PHEV, Blue = BEV].

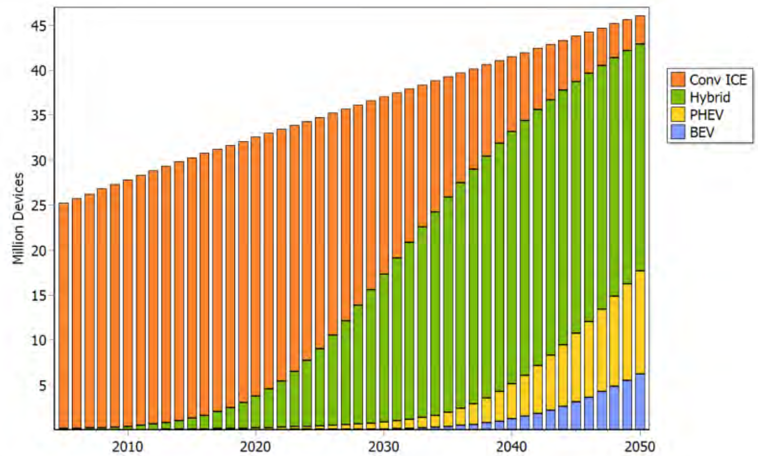
4.4 Results

Three sets of output are shown in this section based on the vehicle market adoption curves in Figure 4.2 and the assumptions in Table 4.1. The results are summarized in Table 4.2.

Figure 4.3: Light Duty Vehicle Stocks



(a)

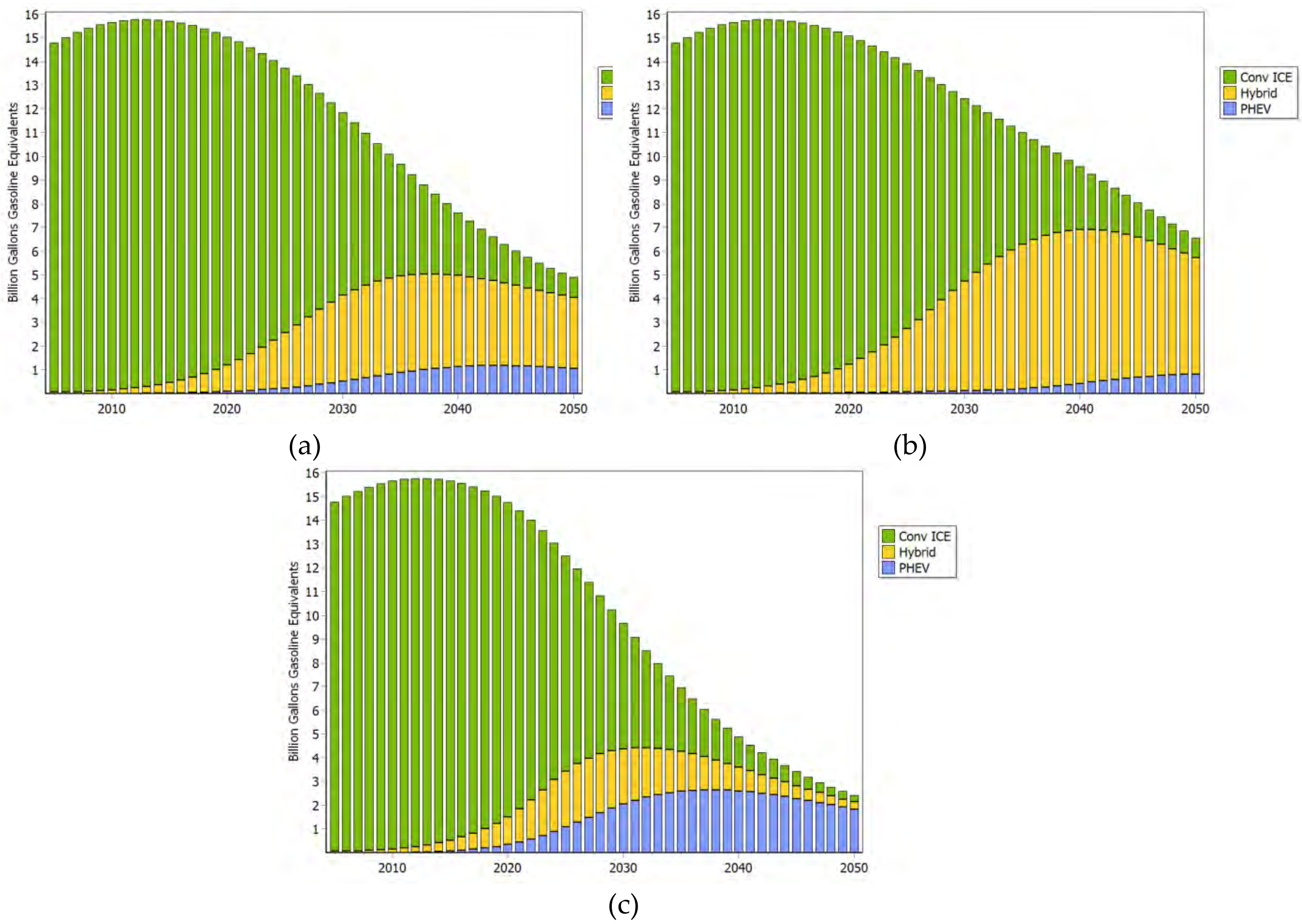


(b)

(c)

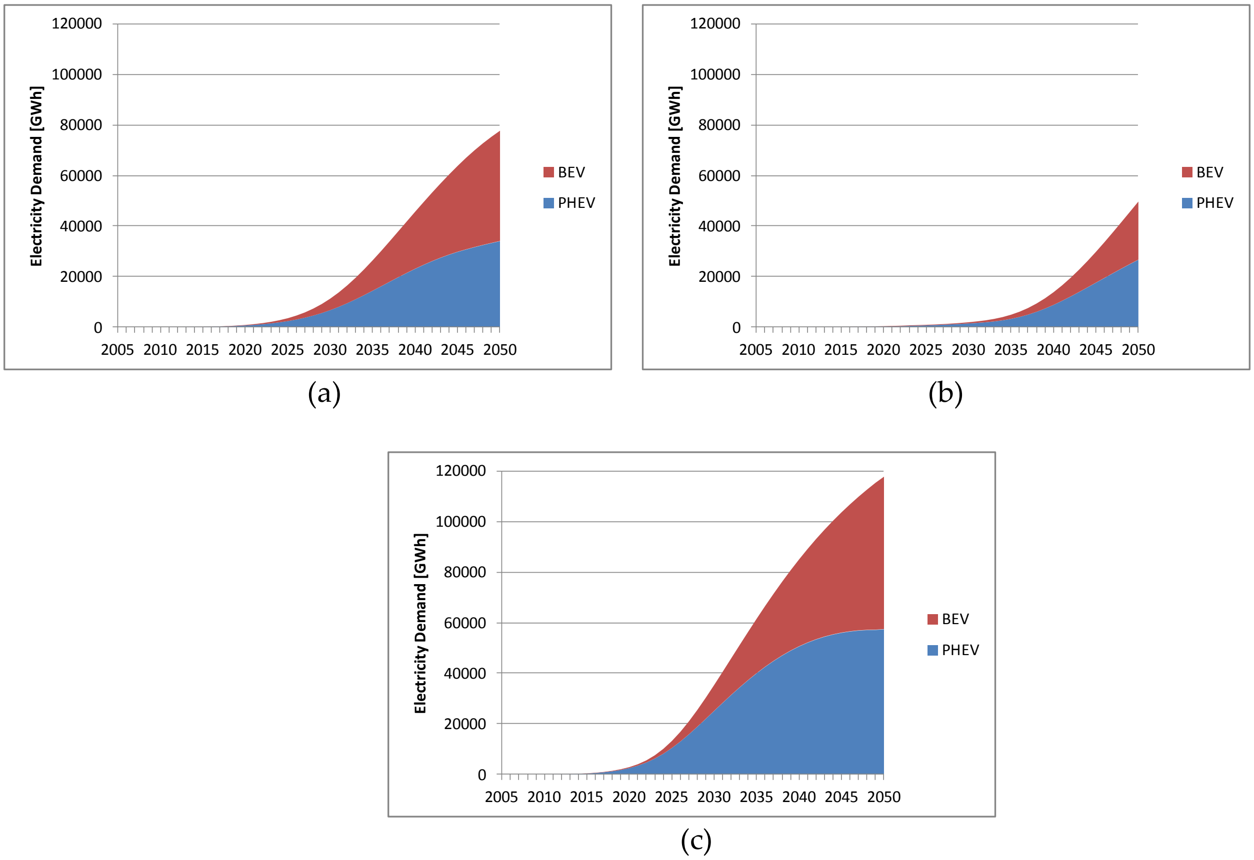
Base Scenario (Governor's ZEV plan extrapolated to 2050) with 1.5 million on-road ZEV (PHEV and BEV) vehicles in 2025 per the Governor's target. (b) Delay of ZEV adoption by 10 years; (c) Aggressive Electrification scenario. [Orange = Conventional ICE, Green = Hybrid, Yellow = PHEV, Blue = BEV].

Figure 4.4: Remaining Liquid Fossil Fuel Demand in Light Duty Vehicles



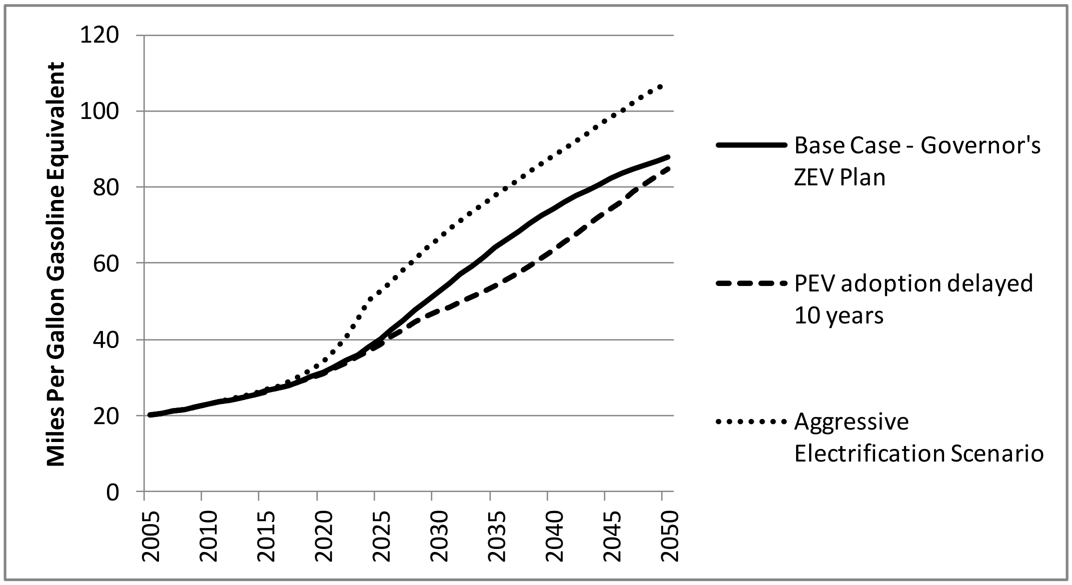
(a) Base Scenario (Governor's ZEV plan extrapolated to 2050); (b) Delay of ZEV adoption by 10 years; (c) Aggressive Electrification scenario [Green = Conventional ICE, Yellow = Hybrid, Blue = PHEV].

Figure 4.5: Electricity Demand for Light Duty Vehicles



(a) Base Scenario (Governor's ZEV plan extrapolated to 2050); (b) Delay of ZEV adoption by 10 years; (c) Aggressive Electrification scenario.

Figure 4.6: New Car MPG-Equivalent for the Base Scenario



(Governor's ZEV plan extrapolated to 2050), delay of ZEV adoption by 10 years, and Aggressive Electrification scenario.

Table 4.2: Summary of Results in 2050 for Three Market Adoption Scenarios

Output Factor	Units	Base Case (Gov. ZEV)	Slower PEV	Aggressive Electrification Scenario
Liquid Fossil Fuel Demand 2050	Bgge	4.9	6.57	2.42
Electricity Demand 2050	GWh	77.7	49.6	118
PEV 2025 Stock	Million Vehicles	1.5	0.5	6.0
PEV 2050 Stock	Million Vehicles	27.6	17.7	43.3
Total 2050 Stock	Million Vehicles	46.1	46.1	46.1
PEV% of 2050 Stock		60%	38%	94%
Avg New MPG 2050	MPG	88.1	84.9	107
PEV% of 2050 New sales		70%	65%	99%

Table 4.3: Single Factor Sensitivity Analysis Results for the Base Scenario

Factor	Sensitivity from Base Case Center Point	Demand [Bgge]			Pct. Change from Base	
		Base Case - Gov ZEV Plan	Optimistic	Pessimistic	Optimistic	Pessimistic
PEV Adoption	Aggressive Electrification vs ZEV 10 year delay	4.9	2.4	6.6	-50%	35%
Annual Vehicles Sales (% of Pop.)	+/-20%		4.1	5.7	-16%	17%
Annual VMT for New Vehicles	+/-20%		4.1	5.6	-16%	15%
Fuel Efficiency (MPG)	+/-20%		4.5	5.8	-8%	18%
Population	+/-40% Annual Growth Rate		4.4	5.4	-9%	10%

Remaining liquid fuel demand for LDV in 2050.

4.5 Sensitivity Analysis

Single factor sensitivity analysis for the Base Scenario is shown in Table 4.3 showing remaining liquid fuel demand in 2050 for LDV. Sensitivity conditions are also described on Table 4.1. Liquid fuel demand is most sensitive to PEV adoption, followed by annual vehicle sales and VMT per vehicle. Annual vehicle sales and annual VMT for new vehicles can also be viewed as conservation measures. For example, a 20% reduction in VMT for new vehicles would lower demand for liquid fuels by 16% and a reduction in annual vehicle sales by 20% from the Base Scenario center point would also reduced fuel demand by 16%.

4.5.1 Vehicle Light Weighting Case

Base Scenario MPG gains for various vehicle types do not take into account large-scale vehicle light weighting via new composite material such as carbon fibers and magnesium-alloys. For example, reducing weight with carbon fiber materials is not included in a recent National Academies analysis because “the committee was uncertain if costs would be low enough by 2050 for mass market acceptance” (NAS, 2013). Here we examine the technical potential fuel savings from an aggressive vehicle light weighting for light-duty vehicles.

Wider scale adoption of these materials in vehicle design and manufacturing can lead to much lighter vehicle bodies and engines and to further improvements in vehicle mileage across drive trains while still maintaining vehicle safety standards and manageable production costs. Note that about 75% of vehicle weight is in non-power train systems for ICE vehicles (Heywood, 2008).

As one example of the design potential for vehicle weight reduction, Rocky Mountain Institute (RMI) projects about a six-fold increase in on-road mpg (125 mpg car mileage) with its lightweight “hyper car” concept with over 50% curb-mass reduction, and potential for streamlined manufacturing with large-scale consolidation of parts in the vehicle frame.

Other studies suggest sizable weight reductions across vehicle subsystems are possible. A Lotus study (Zoia 2011) finds 44% reduction in BIW (body-in-white or body frame before moving parts attached), 20% from interior components and 33% from suspension/chassis components. NRC (2011) reports that carbon fiber can reduce steel structure mass by 40-50%. Furthermore, up to a factor of 10 in chassis-parts consolidation is possible (Ulrich, 2012). The 2013 NAS study assumes 28-37% new car mass reduction in 2050 without carbon fiber.

Based on the NAS (2013) and Bandivadekar (2008) reports, we assume that every 10% of weight reduction translates to 7% fuel consumption savings and that 75% of vehicle mass is non-power train. Further Technical potential fuel consumption savings is assumed from more aggressive vehicle light weighting with 2050 MPG for aggressive vehicle light weighting based upon three data points:

- Extension of Bandivadekar (2008) 35% weight reduction from vehicle light weighting in 2035 to 49% technical potential weight reduction in 2050.
- RMI hyper-car concept paper and analysis (RMI, 2011)
- Extrapolation of current EPA MPG standards from 2017-2025 to 2050 at or slightly below the annual rate of improvement from 2017-2025.

Resultant vehicle mileage increases the new car MPG (actual on-road) for ICE, PHEV, BEV in 2050 from the Base Scenario's 42, 64, 126 MPG-equivalent to 60, 90, 180 MPG-eq. respectively. Liquid fuel demand is reduced by 25.2% from the Base Scenario with these assumptions.

CHAPTER 5: Non-Energy Emissions

5.1 Overview

The California Air Resources Board (ARB) has estimated California's greenhouse gas emissions from non-energy related sources to be 68 Mt CO_2eq in 2009 and 63 Mt CO_2eq in 2010. This report describes the method for projecting the 2050 emissions from non-energy related greenhouse gas (GHG) sources. The report is divided into three sections: industry, agriculture and waste. Table 5.1 shows the projected emissions from each sector in 2050. Each section contains a detailed description of the various sources from that sector, along with the method for determining the 2050 projection. Subsequent to this work, the authors learned of internal ARB efforts in 2013 to model some classes of non-energy GHGs, specifically fluorinated gases known collectively as "F-gases" (Gallagher, 2013). We include estimated emissions in 2050 from this study for comparison.

The approach here is to treat the non-energy sector as autonomous from the energy sector. The target for non-energy GHGs in 2050 is an overall 80% reduction from 1990 levels in concert with an 80% reduction in the energy sector. This corresponds to a target of 8.1 Mt CO_2eq for the non-energy sector. As noted in the Executive Summary, this approach is taken as a first pass assessment of GHG reduction potentials, but of course, a different partitioning of energy and non-energy sector GHG reductions is allowed if emission reductions in one sector are more economic or technically achievable than another.

Non-energy sector emissions are typically in the form of CH_4, N_2O and various F-gases, and also include some industrial processes that emit CO_2 as a by-product, as in the production of cement.

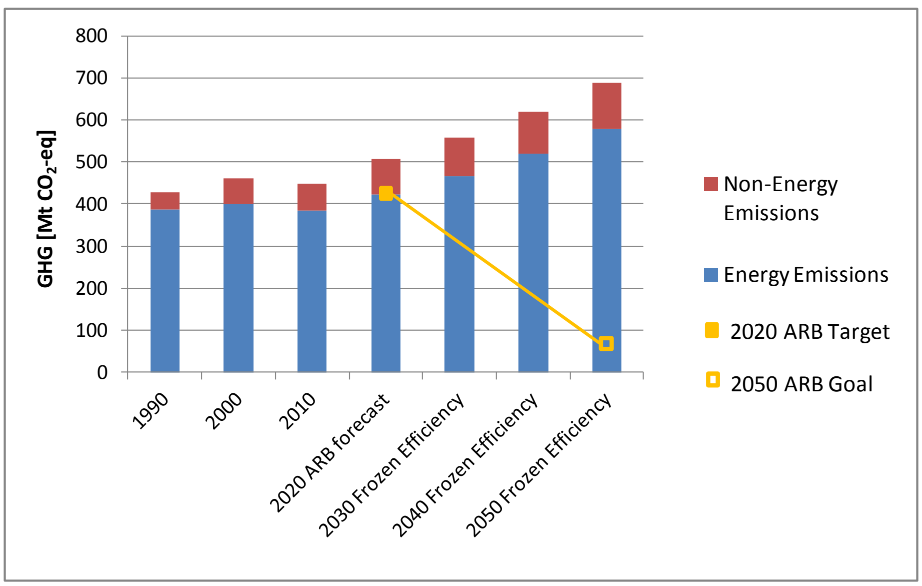
Table 5.1: Overview of Non-Energy Related GHG Emission Projections by Sector

Sector	Source	ARB 2000 estimate (Mt CO_2eq)	ARB 2010 estimate[i] (Mt CO_2eq)	ARB 2020 emission projection (Mt CO_2eq)	LBNL 2050 "Frozen Efficiency"[9] emission projection (Mt CO_2eq)
Industry		**25.52**	**27.62**	**50.5**	**63.4**
	Mineral industry	5.51	3.49	5.6	5.5
	Chemical industry	0.12	0.08		0.12

[9] The "Frozen Efficiency" scenario in the non-energy sector is essentially a "BAU" estimate for 2050 emissions based on historical trends and in the absence of new and tighter regulations. Although non-energy emissions are not typicially linked to efficiency measures. the "Frozen Efficiency" name is retained for consistency with the energy sector "Frozen Efficiency/BAU electricity "nomenclature.

	Non-energy fossil fuel products and solvents	2.46	1.87		1.7
	Electronics industry	0.97	0.96		0.8
	Ozone depleting substance substitutes	8.55	13.84	37.9	47.5
	Electrical equipment	1.25	1.55		1
	CO_2, soda ash and limestone consumption	0.62			0.62
	Hydrogen production	6.04	5.83		6.15
	Other Process emissions			7	
Agriculture		**25.31**	**26.09**	**25.1**	**32.33**
	Livestock	16.43	19.60	16.4	24.14
	Crop and land management	8.89	6.49	8.7	8.19
Waste		**9.20**	**9.17**	**8.5**	**13.61**
	Solid waste	6.55	6.98	8.5	9.2
	Waste water treatment	2.65	2.19	N/A	2.71
Total		**60.03**	**62.88**	**84.1**	**107.6**

Figure 5.1: Energy and Non-Energy Emissions for the Frozen Efficiency Case to 2050 Plotted Relative to Historical Emissions and the 2020 ARB Forecast



The near term ARB target is to meet the 1990 level of total emissions by 2020 (AB 32) and the 2050 goal is to reduce emissions by 80% from the 1990 level (Gov. Executive Order S-3-05).

5.1.1 Industry

Non-energy related GHG emissions from industry are currently estimated to be 27.6 Mt CO_2eq. Over half of these are from substitutes for ozone depleting substances; therefore mitigation of these has the greatest potential for reducing emissions. The rest of the emissions are produced by several small sources which are described in Table 5.1. A description of the methods used to project the emissions from each of these industries is presented. The final part of this section is a discussion on mitigation options and an estimate of how much they could reduce emissions by 2050.

5.1.2 Use of Ozone Depleting Substances and Their Substitutes

Ozone depleting substances (ODS), such as chlorofluorocarbons (CFCs) and other fluorine-containing gases (collectively known as F-gases) have been useful in many industries (see Table 5.2) due to their low reactivity, low toxicity and low flammability. Emissions to the atmosphere of these substances can be released directly, such as from aerosols or fire extinguishers, or as leaks from refrigerators and air conditioners. Due to the high ozone layer depletion potential of these substances, their use has been phased out. The first phase substituted them with hydrochlorofluorocarbons (HCFCs), which have a significantly lower ozone depleting potential. These are also being phased out and replaced with substances that have zero ozone depleting potential. Many substances have been identified by the U.S. Environmental Protection Agency's (USEPA) Significant New Alternatives Policy Program (SNAP) as alternatives for nearly all applications (USEPA, 2012). Unfortunately some of these substitute substances, especially hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) have a significant global warming potential and are referred to as high global warming potential (GWP) gases. For instance, HCFCs have a mean GWP of 700, while HFCs have a mean GWP of 950 but can be as high as 1300;[10] by definition, CO_2 has a GWP of 1.

GHG emissions from ODS substitutes were estimated by ARB (ARB, 2012) to have risen from 8.55 to 13.84 Mt CO2eq over the period 2000-2010. They project that this value will continue to rise sharply, to 37.9 Mt CO2eq in 2020. In this projection study, emissions were determined by sector, as shown in Table 5.2. The method for these emissions estimates will be described in the following section. The total emissions from all ODS substitutes are projected to be 47.5 Mt CO2eq in 2050. By comparison, a 2013 ARB projection estimates total emissions of ODS substitutes to rise to 37.8 Mt CO2eq in 2050 (Gallagher, 2013). Note that this estimate included some mitigation efforts that were not captured in our baseline projection.

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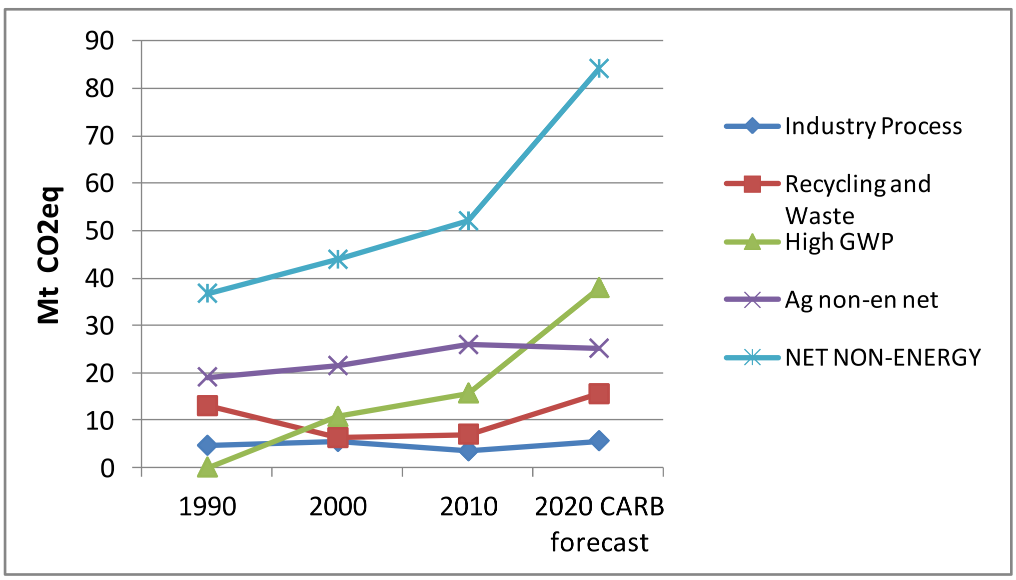
[10] Although CFCs and HCFCs also have high GWPs, they are not required as part of inventories, as they are being phased out under the Montreal Protocol. Therefore there contribution to greenhouse gas emission in 2050 is projected to be zero.

Table 5.2: California Emissions from Industries That Use HFCs and PFCs as ODS Substitutes (ARB 2012 and USEPA, 2012)[11]

Industry	Historical GHG emissions (Mt CO_2eq)							ARB BAU projection (Mt CO_2eq)	LBNL BAU projection (Mt CO_2eq)
	2000	2005	2006	2007	2008	2009	2010	2020	2050
Refrigeration and Air Conditioning		10.72	11.01	11.06	11.09	11.23	11.8	35.11	39.9
Aerosols[12]		0.89	0.94	1.00	1.06	1.12	1.1	1.46	3.2
Foam Blowing Agents		0.23	0.26	0.28	0.31	0.48	0.7	1.01	3.8
Cleaning Solvents		0.16	0.16	0.16	0.16	0.16	0.2	0.16	0.16
Fire Suppression and Explosion Protection		0.06	0.073	0.086	0.086	0.098	0.1	0.16	0.48
Total	8.6	12.1	12.4	12.6	12.7	13.1	13.8	37.9	47.5

Figure 5.2: Non-Energy Emissions by Decade and by Sector



Non-energy emissions are increasing at a faster rate than energy emissions, especially for the high GWP segment. ("Ag non-en net" are non-energy net agriculture-related emissions).

[11] Scaled from USEPA's national contribution emissions, based on U.S. Census Bureau population data.

[12] Aerosols are defined here as "substances that are stored under pressure than released as a suspension of particles in air" per USEPA.

5.2 Method for Projecting 2050 Emissions

Total U.S. emissions estimates for each of the five end uses of ODS substitutes, were available from the USEPA for the years 2005-2010 (USEPA, 2012a). These values were scaled to California using population data, and projections to 2050 were determined based on trends in the data.

Refrigerants are used in refrigerators, air conditioners, central air conditioning systems, freezers and dehumidifiers and are the dominant component of high GWP gases. As shown in Figure 5.2, emissions from high GWP sources have been increasing steadily over the period 1990-2010 and are projected to grow rapidly from 2010 to 2020 by ARB.

To project 2050 emissions of HFCs, growth estimates are adopted from a study by Velders (2009) of HFC consumption and climate forcing impact. This reference projects 7.4% annual increase in HFCs from 2008-2020 in the U.S. and then consumption grows in proportion to population from 2020 to 2050 due in part to a diminishing rate of conversion from older ODS refrigerants to HFCs. This projection for a rapid increase to 2020 is roughly consistent with the ARB's projection of high GWP emissions growing by 9.2% a year from 2010 to 2020 from 15.7 MMt to 37.9 MMt. HFCs are projected to grow to 47.5 MMt in 2050 with the bulk of the growth in two market areas: refrigerants for commercial refrigeration/transport and mobile air-conditioning.

Emissions of aerosols increased linearly over the period 2005-2010. Emissions from this sector are projected to increase at the same rate to 2050, as there appears to be no technically feasible substitute for some aerosol applications.

Emissions of HFCs from foams used in insulation applications such as buildings, appliances, transport refrigeration units (TRUs), and marine products, have been increasing steadily since their introduction in the late 1990s (Vetter and Ashford, 2011). Table 5.3 shows the stock of foam in various applications, and Table 5.4 shows the corresponding emissions estimates. As can be seen the emissions are relatively low, compared to the stock. This is because the emissions mainly occur during end-of-life management.

Table 5.3: Summary of HFC Foam Blowing Agent Banks

	Total stock of HFCs in foam application (Mt CO_2eq)					
Year	Buildings	Appliances	Other Refrigeration	TRUs	Marine & Other	Totals
1996	0	0.04	0	0	0	0.04
2005	2.93	5.79	0.25	0.69	0.69	10.35
2010	9.99	17.27	0.89	1.72	1.72	31.59
2020	53.98	37.88	2	2.47	2.47	98.8

Table 5.4: Summary of HFC Foam Blowing Agent Emissions

	Emissions from foam applications (Mt CO_2eq)					
Year	Buildings	Appliances	Other Refrigerants	TRUs	Marine & Others	Totals
1996	0	0	0	0	0	0
2005	0.08	0.1	0.01	0.02	0.02	0.23
2010	0.5	0.17	0.01	0.01	0.01	0.70
2020	1.41	0.84	0.04	0.07	0.07	2.43

Reproduced from Vetter and Ashford, 2011

Projecting to 2050 it was expected that this high rate of increase would continue for some years, but then eventually slow down, as the current stock of products reaching their end-of-life becomes saturated. A logarithmic projection was used to give a conservative estimate of 3.8 Mt CO_2eq in 2050.

USEPA emissions estimates for solvents used in precision electronics and metal cleaning have stayed constant over the period 2005 to 2010. No information was found that indicated this is likely to change in the future, therefore in our 2050 projection this was also assumed.

Gases from fire suppression and explosion protection equipment are released when equipment is used or tested. The USEPA estimated emissions increased at a steady rate over the period 2005-2010. For the 2050 projection, a logarithmic regression analysis was used and the value was projected to be 0.48 Mt CO_2eq.

5.3 Other Industrial Emissions

Projected emissions in 2050 for each of the other industrial processes described in Table 5.1 were determined by analysis of previous emissions estimates from the ARB for 2000 through 2009, and their projected emissions in 2020.

Trend data analysis as well as a review of relevant literature was undertaken, for any indication that trends in the data may vary in the future, for example, if an industry was likely to decrease production in the U.S. due to increased imports from overseas.

For the chemical industry, CO_2, soda ash, and limestone and dolomite production, the ARB estimated values were the same in 2000 and 2009 (Table 5.5) and no 2020 emissions were projected. No information was found to indicate that the rate of production for these substances would change in the future; therefore it was assumed the values would remain the same in 2050.

Cement and lime production also showed a relatively constant value from 2000 to 2008, then decreased suddenly in 2009. ARB projected a 2020 emission value for this process that was similar to the 2000 to 2008 values, and no other information was found indicating the rate of production is likely to change in the future. Therefore a static value was also assumed, based on the 2020 projection.

ARB emissions estimates for non-energy uses of fossil fuels and semiconductor manufacture decreased from 2000 to 2009. No information was found that indicated production from each of these industries were likely to change in the future. Emissions estimates of sulfur hexafluoride (SF_6) also decreased; the 2020 projection value showed a minor decrease due to the potential for preventing leaks through improved detection and upgrading of older equipment to new, better quality equipment that requires less gas, and is less likely to leak. Improvements in leakage detection were assumed to be the maximum achievable without intervention in 2020, therefore each of these values was also assumed to remain the same in the 2050 projection. By comparison, in the ARB analysis by Gallagher (2013), SF_6 emissions were assumed to decline slightly through 2050 (from 1.1 Mt CO_2eq in 2010 to 0.7 Mt CO_2eq in 2050).

Table 5.5: Other Industrial Sources of Greenhouse Gas Emissions

Source	Description	2050 Projection Method
Mineral Industry	CO_2 is released during the production of cement and lime, in a process known as clinker. To produce clinker, limestone (mainly made up of $CaCO_3$) is heated in a kiln to produce lime (CaO), and CO_2 (calcinations). CaO then reacts with SiO_2, Al_2O_3 and Fe_2O_3 in the raw materials to make the clinker minerals. During the making of clinker some cement kiln dust (CKD) may leave the kiln system. Since that CKD is made up of partially calcined carbonates, cement manufacture emission estimates also account for the CO_2 emissions associated with the CKD.	ARB emission estimate static from 2000 to 2008, and 2020 projection
Chemical Industry	Two chemical processes contribute to GHG emissions, inorganic chemical manufacturing and nitric acid production. This is mostly for the manufacture of nitrogen fertilizer, but also adipic acid and explosives, metal etching and in the processing of ferrous metals. The high temperature catalytic oxidation of ammonia (NH_3), leads to N_2O emissions. The amount emitted depends on the process conditions, catalyst composition and age.	ARB emission estimate static from 2000 to 2009
Non-energy uses of fossil fuels	Fossil fuels are used as feedstock in the manufacture of plastics, rubber synthetic fibers, lubricants, waxes, and asphalt, which leads to CO_2 emissions.	Static from the ARB 2020 projected value
Semiconductor manufacturing	Fluorinated gases are used in plasma etching and plasma enhanced chemical vapor deposition processes. These are converted to fluorine atoms in plasma, which etches away dielectric material or cleans the chamber walls and hardware. Undissociated fluorinated gases and other products end up in the waste stream and unless captured by abatement systems, into the atmosphere. Some fluorinated compounds can also be transformed into other compounds during the plasma process. If they are not captured by emission control systems the process-generated gases will also be released into the atmosphere.	Static from the ARB 2020 projected value
Sulfur hexafluoride from use of electrical equipment	Used in gas-insulated substations, circuit breakers, and other switchgear because of its dielectric strength and arc-quenching characteristics. Emissions of the gas occur during equipment installation and servicing, and from leaks.	Static from the ARB 2020 projected value
Carbon dioxide	Direct emissions can occur as a result of its use in food processing, carbonated beverages, and refrigeration. CO_2	ARB emission estimates static from 2000 to 2009

	is also used in enhanced oil recovery (EOR) in petroleum production. In this case the CO_2 is produced either as a by-product from energy production and industrial processes, as a by-product from the extraction of crude oil and natural gas, or from naturally occurring CO_2 reservoirs.	
Soda Ash	Mainly used in glass production, but also in soap and detergents, paper, textiles and processed food. For every mole of soda ash used, it is believed one mole of C is emitted as CO_2.	ARB emission estimates static from 2000 to 2009
Limestone and Dolomite Consumption	CO_2 emissions occur during the high temperature stages of processing limestone and dolomite. These are used in flux stone (metallurgical furnaces), glass manufacturing, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.	ARB emission estimates static from 2000 to 2009
Hydrogen Production	Hydrogen is used in the petroleum refinery process to upgrade heavier products into lighter products, which are more valuable. Hydrogen production often uses carbon based feedstocks, such as methane, the byproduct of this process is CO_2 which is released to the atmosphere.	Mean of ARB estimated values for 2000 to 2009

For hydrogen production the ARB emissions estimates varied from year to year, with no consistent trend. No other information was found that indicated any likely significant change in the future, therefore a mean value from the available data was used for the 2050 projection. As more reported values are collected over the next few years, a trend may become obvious in the data, but currently it appears to be remaining close to this value.

5.4 Mitigation Options

Table 5.6 shows the mitigation options for each of the non-energy industrial greenhouse gas emission sources, along with an estimate of the remaining emissions after the maximum potential reduction from the 2050 projection. Many of the emission sources do not currently have technically feasible mitigation options, especially where emissions occur during the use of the product. In these cases the only option would be to find an alternative gas and therefore no reduction is shown. While in some cases there are no suitable substitutes available, research into alternatives is on-going and there is potential for these to be found in the future.

Where emissions are a byproduct of an industrial process it is often also difficult to find mitigation options, although these are sometimes possible through capturing and destroying emissions, prior to their release to atmosphere. It is common for gas abatement to be enforced through regulation; however, in the U.S. voluntary methods are having a significant effect on emissions reduction from some industries. The semiconductor manufacture industry for example has a voluntary partnership with the USEPA which has developed methods they believe can reduce emissions by 10%. Our mitigation estimate assumes that participation will cover the total industry by 2050.

For sources where emissions mainly occur during installation, maintenance, or as a result of leaks, especially in the case of refrigerants and SF_6, increased product quality control, the use of leak detection equipment, and regular maintenance by qualified personnel could all lead to emissions reductions.

For SF_6 there is a voluntary emission reduction partnership between the USEPA and 79 electricity generation companies, nearly half of the total industry (USEPA, 2012b). Participants in the program have reduced their emissions from 17% to 6% of total gas consumed over the period 1999 to 2006, while saving $2.5 million dollars. The technically feasible emissions rate is 4%. In the mitigation table we have assumed the partnership expands to include 100% of the industry, reducing leaks to the current technically feasible minimum by 2050. A doubling of SF_6 usage instate with the high amount of electrification described in this report would increase overall emissions by 0.4 Mt CO_2eq in 2050 and thus this high GWP source is not a large overall contributor assuming technical potential emission rates are achieved.

In California the improvement of leaks from refrigerants is already enforced through regulation, leaving only minimal room for further emissions reductions.

The use of low GWP substitutes is now being proposed by the USEPA (Environment News Service, 2010). Internationally, HFC-134a for mobile AC in new cars is being phased out 2011-2017 in Europe. Four alternative substances are being proposed including the naturally occurring hydrocarbons (HCs) such as propane, cyclopentane and isobutane. HC refrigerants have been used in other countries such as Germany, the UK, Australia and Japan for up to 10 years, reducing fears over the safety of using these highly flammable gases. The Coca-Cola company has already committed to stop using HFCs in all of their coolers and vending machines by the end of 2015, which could lead the way for many other companies (The Coca-Cola Company, 2009). HCs have much lower GWPs than HFCs. For example, cyclopentane and isobutane each have a GWP of 3 (CECED, 2001). The mitigation emissions projection shown in Table 5.6 is based on the assumption that all refrigerants are HC gases or low GWP substitutes by the year 2050.

End of life management is another important area for emissions control. Refrigerants are already required to be reclaimed and reused where possible, or else destroyed. Therefore there is not much potential for further emissions reduction.[13]

Mitigation potential of emissions from foams was investigated for ARB by Caleb Management Services Ltd. (Vetter and Ashford, 2011). The two approaches considered were using low GWP substitutes and better end of life management. The three main options for end of life management are reprocessing, incineration, or landfilling. Currently reprocessing is very rare, as there is very little opportunity for reuse, and reclamation of the material would be expensive and difficult.

Waste to energy through incineration, with destruction of the harmful gases, is currently the best environmental option. However, it is only practiced at a few locations in California.

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[13] The quality of the reclaimed material must be very high, as contamination could lead to leakages of the substances to atmosphere, as well as damaging products. Current reprocessing claims of emissions of harmful substances are 5%.

Incineration has minimal transport costs, which is important for foam with its high volume and low mass. Also insulating foam has a high calorific value and thus high potential from an energy generation perspective. The cost is also minimal with gate fees of approximately $65 per metric ton (Vetter and Ashford, 2011).

Landfilling is the worst option as it has the highest potential for releasing HFCs to atmosphere. However, it is currently the most common option, as it is the cheapest, with minimal transport cost and gate fees of only $60 per ton (Vetter and Ashford, 2011), and more widely available than waste-to-energy. For most products containing foam insulation, the foam is shredded and disposed of to landfill as part of mixed construction and demolition waste.

The potential for natural mitigation of CFCs, HCFCs and HFCs in a landfill has been investigated (Scheutz, 2007). The study investigated breakdown of the gases by bacteria that are commonly found in landfills. CFCs were effectively broken down within two weeks, while HCFCs were much slower and HFCs did not degrade significantly. These experiments were performed in idealized conditions, and the bacteria were produced from biodegradable waste, which is increasingly being diverted from landfills. Construction and demolition waste also tends to be relatively low in biodegradable content. If further research found bacteria that effectively degraded HFCs into a less harmful substance, there could be more potential for mitigation but it is not currently feasible.

The use of low GWP substances for foam blowing agents is also under consideration by the USEPA. Coca-Cola has also committed to stop using foams containing HFCs in their chillers and vending machines by 2015 (The Coca-Cola Company, 2009). However, as shown in Table 5.3 the majority of the HFC foam bank is contained in buildings, which have lifetimes on a scale of decades. Thus, even if HFC use were phased out by 2020, there would still be significant emissions if end-of-life disposal is not carefully managed for HFC containing foams. Better end of life management is therefore still an important consideration for this sector.

In the maximum potential reduction estimate in Table 5.6, it was assumed that all appliances would contain HC foam blowing agents, while buildings would have incineration, with careful destruction of gases as their end-of-life treatment. The reduction in emissions due to incineration, compared to landfilling was 39% as reported by Vetter and Ashford (2011).

Table 5.6: Mitigation Options for Non-Energy Industrial Sources of Greenhouse Gases

Source	**Mitigation options**	**2050 projection (Mt CO_2eq)**	**Remaining after maximum potential reduction (Mt CO_2eq)**
Refrigerant	HCs, CO_2, or other alternative, low GWP refrigerants could be used instead of HFCs	39.86	0.04
Foam blowing agents	Better end-of-life management HC alternatives could be used	3.8	0.80
Aerosols	Unavoidable emissions release during use. Alternatives technologies are used, such as finger	3.2	3.2

	pump sprays for personal care products, roll on deodorants. These developed as a replacement for CFCs, rather than HFCs, therefore there is no contribution to account for. However, no alternatives yet available for certain medical equipment and these are not likely to be able to change in the near future. Therefore no mitigation was assumed for this emissions source.		
Solvents	Unavoidable emissions release during product use. Alternative substances are used for metal surface cleaning, but fluorocarbons are still widely used in precision and electronics cleaning. Only using alternative substances would really mitigate emissions. As this does not appear to be the trend, assumed no reduction	0.16	0.16
Fire Suppression and Explosion Protection	Unavoidable release during use or testing of equipment. Only mitigation option is using alternative substances, but doesn't seem to be feasible at the moment. Therefore no mitigation assumed	0.48	0.48
Mineral Industry	Cement production emissions are unavoidable, and changes in emissions are directly relatable to product rates. Therefore no mitigation was assumed	5.5	5.5
Chemical Industry	Nitric Acid Production: Plants fitted with selective catalytic reduction systems emit 9.5 kgN_2O per kg HNO_3. Changing to non-selective catalytic reduction systems reduces emissions to 2kgN_2O per kg HNO_3. However in California all plants are already NSCR, therefore there are no further mitigation opportunities with current technology.	0.12	0.12
Non-energy uses of fossil fuels	Gases are treated thermally prior to release to atmosphere, destroying some of the more potent chemicals. However, significant quantities of CO_2 are still released, with no current options for prevention. Therefore no further mitigation assumed.	1.7	1.7
Semiconductor manufacturing	Plants can be fitted with equipment to capture and destroy emissions preventing their release to atmosphere	0.8	0.72
Sulfur hexafluoride from use of electrical equipment	Improve equipment quality, better leak management At end-of-life can be captured and reused Ideal emission rates are 4%, realistic emission rates are 17%. In the inventories 10% were used. Assuming the ideal 4% could be achieved by 2050 through mitigation measures	1	0.4
Carbon dioxide, Limestone and Dolomite, and Soda Ash consumption	No mitigation options for $CO_{2,}$ and limestone and dolomite consumption were found. For soda ash production in California, CO_2 is captured and recycled back into the manufacturing process, preventing its release to atmosphere.	0.62	0.62
Hydrogen Production	Net zero GHG production (fossil/CCS, renewable electrolysis)	6.15	0
Total		**63.4**	**13.8**

Table 5.7: Rough Reduction Potential by Category of ODS and Industry Sector

Category	Subcategory	Mitigation options	Estimated reduction
Non Ozone-depleting substances	Refrigeration and air conditioning coolants	Low GWP substitutes End of life recovery	~100%
	Foams	Low GWP substitutes End of life recovery Waste to energy incineration Biological degradation (research)	~80%
	Aerosols, solvents, fire protection	Low GWP substitutes (research) End of life recovery (unlikely)	0%
	Semiconductor manufacturing	Gas recovery & destruction	~90%
	Electrical equipment (SF6)	Leak detection & maintenance End of life recovery & re-use	~60%
Hydrogen production	All	Net zero GHG production (fossil/CCS, renewable electrolysis)	~100%

5.4.1 International Legislation

EU legislation to regulate emissions of F-gases, including HFCs was passed in 2006 (European Parliament, Council, 2006). The main requirements are: all persons responsible for emissions are required to take all measures that are technically and economically feasible to prevent and minimize leakages; refrigeration, air-conditioning and heat-pump equipment and fire protection systems must undergo at least one leakage inspection a year (the frequency of inspections varies depending on the quantity of F-gases contained in the equipment); the owners of the above types of equipment containing 300 kg or more of F-gases are required to install leak detection systems, while equipment containing 3 kg or more of F-gases are required to maintain records indicating the quantity and type of gas. Additionally, certain products must be labeled to indicate the quantity and GWP of F-gases they contain.

As noted above, HFC-134a for mobile AC in new cars is being phased out 2011-2017 in Europe.

5.4.2 Agriculture, Forestry and Other Land Use

As shown Table 5.1 around two-thirds of emissions from the agricultural sector are due to livestock management, with the remainder related to crop growing and harvesting. Therefore opportunities for emissions reductions discussed in this section focus on the livestock sector. Furthermore many of the emissions from crop management have remained stable over time, according to the ARB emissions inventory (ARB, 2009).

5.4.3 Livestock Management

Emissions from livestock management fall into two categories, enteric fermentation and manure management. Enteric fermentation is the microbial fermentation in the digestive system of some animals. In this process microbes breakdown indigestible carbohydrates, and reprocess them into nutrients that can be absorbed by the animal. Methane is released as a by-product of this process. The quantity depends on the type of animal, and the amount and type of feed it consumes, which in turn depends on the animal's size, growth rate and production, and what it is used for. The greater the amount of food ingested the greater amount of methane emitted. Coarser, more fibrous feed, such as straw and hay, generally also leads to higher CH_4 emissions than more concentrated feed such as grains.

During manure management, methane is produced by the anaerobic decomposition of manure, and nitrous oxide (N_2O) is produced through nitrification and denitrification of nitrogen in manure and urine.

Both of these are dependent on the population of livestock, therefore the first step in projecting a 2050 emission rate, was to project the livestock population in 2050.

Table 5.8: California's Historical Livestock Populations (CFDA)

Year	Dairy Cattle[a]	Beef Cattle[a]	Sheep[a]	Hogs/Pigs[a]	Goats[a]	Horses[a]	Chickens[b]	Turkeys[b]
	1000 Head							
2000	N/A	N/A	810	150	N/A	N/A	47,525	6,000
2001	1560	780	805	110	N/A	N/A	46,726	6,233
2002	1620	760	755	150	N/A	132	46,634	5,900
2003	1670	740	730	135	N/A	N/A	43,654	5,767
2004	1700	720	675	140	N/A	N/A	40,429	5,233
2005	1740	720	690	145	116	N/A	39,322	4,833
2006	1770	680	650	145	128	N/A	40,251	5,267
2007	1790	700	610	155	135.5	181	40,708	5,400
2008	1835	655	620	80	129	N/A	38,478	5,333
2009	1840	620	660	100	136	N/A	36,907	5,000
2010	1760	610	610	105	134.5	N/A	N/A	N/A
2011	1750	600	610	N/A	141.5	N/A	N/A	N/A

N/A indicates data not available
[a] Taken from the California Department of Agriculture website
[b] Taken from ARB emissions inventory Annex 3B (ARB, 2012)

The U.S. per capita consumption of animal products was also taken into consideration. Data for this is shown in Table 5.9. As can be seen, the annual consumption of dairy products has increased since the 1970s from 546 pounds per capita to 597 for the period 2001-2009. The increase has not been gradual; the annual per capita consumption in the 1980s and 1990s was very similar at 575 and 573 pounds per capita, respectively with a more rapid increase in more recent years. This recent increase is reflected in the livestock population statistics which have shown an increase from 1.56 million to 1.76 million over the period 2001 to 2009. While this implies that livestock populations will need to steadily increase to continue to meet demands, it is also important to note that the amount of milk produced per cow has shown an increase. From 2009 to 2010 the increase in milk produced per cow was 4.7%[ii]. The U.S. also exports significant quantities of dried milk product to South East Asia. In 2010 this market expanded, due to poor production in New Zealand and Australia. In the projection it was assumed that the population would continue to increase at a steady rate and a linear regression analysis was applied to the data in order to project forward. Although the per capita consumption is not expected to continue to increase, the increase in population and increase in overseas exports are likely to mean a steady increase in the dairy population.

Table 5.9: Annual Per Capita Consumption of Meat Products (USDA ERS, 2011)

	U.S. Consumption in pounds per capita					
Years	**Dairy**	**Beef**	**Lamb**	**Pork**	**Chicken**	**Eggs**
1971-1980	546	85	1.9	50.8	29.0	36.1
1981-1990	575	75	1.4	50.7	37.2	32.5
1991-2000	573	66	1.2	50.8	49.3	30.6
2001-2009	597	65	1.1	50.1	58.2	32.6

Per capita consumption of red meat, especially beef, in the U.S. peaked in the 1970s, where the mean annual per capita intake for the decade was 140 pounds. In the 1980s and 1990s the annual intake was 129 and 119 pounds respectively. From 2001 to 2009 the annual mean was 110 pounds. This decrease in annual per capita consumption is partly related to increased awareness of the health impacts of excessive meat consumption and in more recent times can be attributed in part to increased awareness of the environmental impacts of meat production. Industry changes, consolidation, and changes in livestock production patterns among states are among other factors that were not explored in detail here. While the general increase in population will offset some of the decrease in livestock requirements, the beef livestock population in California appears to reflect this trend with a decrease from 780,000 in 2001 to 600,000 in 2011 (Table 5.8).

The projection therefore assumed that the population would continue to decrease, but that the rate of decrease would slow down. Therefore a logarithmic regression analysis was applied to the data set in order to project forward to 2050. The U.S. census bureau has presented per capita consumption projections to 2020[iii], which also show a steady decrease in consumption of beef, further supporting this approach.

The next biggest livestock population in California is sheep and lambs, which have decreased from 810,000 to 610,000 from 2001 to 2011. However the population has remained steady over the past two years. Consumption of lamb has always made up a much smaller portion of the average U.S. diet appealing to particular minority groups. The consumption in 1970s was 1.9 pounds per capita annually, which has decreased to 1.1 in the period from 2001 to 2009. It is expected that per capita consumption will remain relatively stable. Lamb was not included in the 2020 per capita consumption projections from the U.S. Census Bureau.

Hogs and pigs are the next biggest livestock population. These have decreased from 150,000 to 105,000 over the period 2001-2009. The per capita consumption has remained stable since the 1970s with the decade mean being 50 lbs per year. Therefore it was assumed that the population would remain relatively stable projecting forward, only increasing in line with human population projections, taken from the U.S. Census Bureau. The 2020 projection of per capita consumption from the U. S. Census Bureau also finds consumption to remain stable.

The goat population on the other hand has been increasing. Statistics for this population have only been collected since 2005, but it has increased from 116,000 to 141,500 over that time. Goats are farmed for their wool, milk and meat. The wool and milk populations have remained relatively stable, while the meat population is the one that has increased. Per capita consumption has not been collected on goat meat, so there is not data to support the increase in production and whether this trend is likely to continue. It was therefore decided to keep the population constant projecting forward to 2050.

Data on horses were only available for 2002 and 2007 from the Agricultural Census (USDA, 2009). Horses were the only other animal considered to make a significant contribution to enteric fermentation emissions. Their populations were 131,951 in 2002 and 180,723 in 2007. Projecting ahead to 2050 is more difficult than other livestock, as most horses are not raised for consumption, and therefore would not necessarily increase in line with the population. Due to the lack of data it was assumed that the horse population would remain stable to 2050.

Table 5.8 shows that chicken and turkey populations both decreased over the period 2000 to 2009. As can be seen in Table 5.9 the per capita consumption of chicken has increased significantly from 29 to 58 lbs, while consumption of eggs decreased from the 1970s to the 1980s, but has stayed relatively stable since then and is currently at 32 lbs. Due to these consumption trends, the chicken population was projected to increase in line with the human population. No data were available for the consumption of turkey therefore it was assumed to remain stable.

Table 5.10 shows 2050 population projection for each livestock type, along with the emission factor, as taken from the IPCC.

Table 5.10: 2050 Projections of Livestock Populations and Emissions

Livestock type	2050 Population Projection	Enteric Fermentation emission factor ($kgCH_4$/animal/year)[a]	Enteric Fermentation projected 2050 Emissions (Mt CO_2eq)	Manure Related projected 2050 emissions (Mt CO_2eq)
Dairy Cattle	2,690,000	N/A	9.864	9.281
Beef Cattle	205,000	N/A	2.007	0.045
Horses	610,000	18	0.231	0.074
Sheep	200,000	8	0.034	0.011
Swine	76,000	1.5	0.002	0.028
Goats	270,000	5	0.028	0.005
Chickens	149,000,000	N/A	N/A	2.412
Turkey	5,000,000	N/A	N/A	0.127
Total	152,502,000		12.2	12.0

[a] taken from ARB emission inventory reports (ARB, 2012)

Emissions for enteric fermentation for all animals except cattle were calculated from the emission factors described in the ARB inventory (ARB, 2012). Poultry do not contribute to enteric fermentation, as they have a different digestive system. For enteric fermentation of cattle, ARB used the IPCC Tier II method, which involved breaking the population into categories based on age, and determining emission factors based on diet. This level of information was not available for this project. Instead it was assumed the population proportions would remain the same, thus a ratio of emissions to population was determined from the ARB data.

Similarly for manure management, the ARB method divided the populations into further categories, therefore, the same approach of assuming the proportions would remain the same was used.

5.4.4 Enteric Fermentation Mitigation Options

While reducing livestock populations would be the most effective method of mitigating emissions from this sector, it would not be politically acceptable to impose dietary restrictions on the human population of any country. While encouraging people to reduce their consumption of animal products by raising awareness of the impacts of meat production, and emphasizing the health benefits of a diet high in plant protein could result in lower meat consumption and lower livestock populations, we limit reductions in emissions to technical approaches. The most practical approach would be optimizing feedstocks. Feed optimization can act on three levels to reduce methane from enteric fermentation: 1) the rate of fermentation; 2) the type of volatile fatty acids produced; and 3) the efficiency of microbial biosynthesis (Monteny et al., 2006). About 40% reduction potential is taken in enteric fermentation (roughly 5 Mt reduction from 12 Mt CO_2eq released in 2050) based on a recent USDA study (Denef, 2011) which has up to 44% enteric fermentation reduction also through forage quality and early grazing.

5.4.5 Manure Management Mitigation Options

Manure stored as a soil or applied to land decomposes aerobically producing CO_2 and H_2O, therefore treating manure in an aerated process can prevent the production of the more potent CH_4. However, a carefully managed anaerobic process will allow the methane to be captured and used for energy generation. Temperature, moisture, and residency time all affect the amount of methane produced during anaerobic digestion. The animal's feed also affects the decomposition rate of the manure: animals that eat higher energy content feed have greater potential for methane emissions.

Nitrous oxide emissions from manure and urine depend on the composition, type of bacteria, oxygen availability and moisture. Generally only a small portion of N is converted to N_2O during manure management. For manure that is applied to land, N_2O is accounted for under land management therefore is not considered in this section.

Denef (2011) estimates up to 88% CH_4 reduction from manure management, and up to 99% N_2O from covering manure solids. A 92% reduction potential is taken for 2050, or 11 out of 12 $MtCO_2$ eq. in 2050.

5.4.6 Agricultural Residue Burning

The majority of the CO_2 released from this process is not accounted for in GHG inventories, as it is biogenically sourced, and therefore considered part of the natural carbon cycle. However, inefficient burning practices can lead to the formation of methane or nitrous oxide. Careful burning practices should be able to prevent the formation of these gases, restricting emissions to biogenic CO_2. Over the period 2000 to 2009 the ARB estimated emissions decreased from 0.8 to 0.7 Mt CO_2eq with no trend in the data. The 2020 projected emission is 0.1 Mt CO_2eq. The decrease is most likely due to the fact that rice straw burning is currently being phased out. The 2050 projection was predicted to remain static in line with the 2020 projection.

5.4.7 Carbon Dioxide from Liming

Liming is added to soils to reduce acidity and improve plant growth in agricultural fields and managed forests. Lime is made of either limestone ($CaCO_3$) or dolomite $CaMg(CO_3)_2$ which emits CO_2 as the carbonate lime dissolves[14]. The estimated emissions from liming over 2000-2009 showed no trend with a mean over the period of 0.25 Mt CO_2eq, and this was assumed to be the value in 2050.

5.4.8 Nitrous Oxide from Agricultural Soil Management

Nitrous oxide emissions from soils occur as a result of the addition of nitrogen fertilizers. The nitrogen goes through microbial processes known as nitrification and denitrification. In denitrification nitrous oxide is an intermediate gas product, while in nitrification it is a byproduct that leaks from microbial cells into the soil, and potentially the atmosphere. Applying nitrogen in the most readily available form for uptake by plants, as in the case of synthetic fertilizers, can reduce losses of nitrous oxide to the atmosphere. Aside from synthetically manufactured nitrogen fertilizers, other sources include organic fertilizers, manure and sewage sludge, production of N-fixing crops, decomposition of crop residues and mineralization of N in soil organic matter following drainage of organic soils. These are considered 'direct' nitrous oxide emissions from soils.

Two indirect pathways to N_2O emissions from managed soils also occur. Firstly some of the nitrogen in its applied form will become airborne and deposit on land or water surfaces further away, leading to potential N_2O production. The second source is leaching and runoff into ground water, ditches, streams, rivers, and estuaries, and their sediments, where land water eventually drains. Nitrification and denitrification can then occur at these locations resulting in nitrous oxide emissions. The emissions are clearly related to the area of land being fertilized and the amount of fertilizer applied per unit area. However, there is a lack of understanding relating to the precise mechanisms that produce and consume nitrous oxide in soils. Therefore current values are only an estimate, using IPCC guidelines.

ARB estimates for the period 2000-2009 show no trend, but ranged between 7.5 and 9.4 Mt CO_2eq. The 2020 projected value is 7.1, indicating emissions are predicted to decrease. Therefore this projected value was assumed to remain static looking ahead to 2050.

5.4.9 Rice Cultivations

California is the second largest rice growing state in the U.S., covering 500,000 acres of farmland and producing more than 2 million metric tons per year (California Rice, 2012). According to the

[14] Biocarbonate ($2HCO_3$) is released initially and is converted to CO_2 and water in the atmosphere

CDFA's latest report there have been a stable 500,000 of acres of rice growing land in California from 2000 to 2010. It is therefore expected that California will continue to produce the same amount of rice going into the future. Methane is produced by the anaerobic decomposition of organic material in flooded rice fields. It escapes to the atmosphere mostly through the rice plants aerenchyma system. The amount of methane emitted annually per unit area is a function of the number and duration of crops grown, the flooding regime before and during the cultivation period, the amount of organic and inorganic soil amendments, the soil type and temperature, and the rice cultivar. ARB estimated emission over the period 2000 to 2009 did not change very significantly, going from 0.57 to 0.58 Mt CO_2eq. They did not project for 2020. Here it was assumed rice production would remain static going into the future, therefore emissions were taken as the mean from the period 2000 to 2009, or 0.55 Mt CO_2eq.

5.4.10 Forests and Rangelands

Trees and other green plants can remove CO_2 from the atmosphere via photosynthesis. After they die, the carbon stored in plants will be released back into the atmosphere during decomposition. These emissions are not accounted for when they occur naturally, but when anthropogenic influences affect the balance they need to be considered. For example harvesting trees for manufacturing paper or wood products alters the carbon balance in the forest. In the estimates from ARB the emissions were 0.19 Mt CO_2eq. for all years, and the 2020 projection was rounded to 0.2Mt CO_2eq. It was therefore projected to continue to remain static looking ahead to 2050.

Estimates of N_2O reduction potential are taken from Denef (2011) at 7 MtCO_2 eq. primarily based on improved nitrogen-based fertilizer formulation and application practices, reduced tillage, irrigation improvements and cover crops. Approximately 25 million acres of in-state farmland and a reduction potential of 0.3 tCO_2 eq./ acres-yr (0.74 tCO_2 eq./ hectare-yr) are assumed.

5.4.11 Afforestation

Afforestation is an option for negative emissions due to carbon sequestration in biomaterial. Cost-effective afforestation of rangelands in California has been characterized in geo-spatial and economic detail by the CEC (Brown 2004). Potentials vary by cost of carbon price points and duration in years of the overall calculation. The study finds that for a 20-year duration, overall carbon accumulation can range from 33 to 887 Mt CO_2eq for a price of \$2.70 to \$13.50 per Mt of CO_2. This corresponds to an average annual accumulation rate of 1.7 to 44 Mt CO_2eq per year over an area of 0.2 to 12 million acres or 0.5%-29% of California total rangeland. In comparison, energy crops for the high-instate biofuel supply scenario require up to 9 million acres of land and the low-instate supply scenario about 1 million acres. Since rangeland that is suitable for afforestation may also be suitable for energy crops, there may be constraints on the amount of land available for afforestation, especially in the case of high in-state biofuel supply. For this study, we assume that an average of 17 Mt CO_2eq is accumulated per year by 2050 due to afforestation on 2.7 million acres of land corresponding to the intermediate carbon price of \$5.50 per ton of CO_2. It is further assumed that this does not impinge upon the amount of land available for biomass for biofuels.

Table 5.11: Mitigation Options for Livestock, Agriculture/Land and Waste

Category	Mitigation options	Reduction potential in 2050 (Mt CO2eq)	50% Reduction Potential in 2050 Scenario
Livestock	Optimization of animal's diet	5	2.5
	Manure management via anaerobic digestion	11	5.5
Agriculture/Land	Soil N_2O management	7	3.5
	Afforestation	17	8.5
Solid waste (landfills)	CH_4 capture & combustion	7.8	3.9
	Biological remediation ("biocovers"), anaerobic digestion		

5.4.12 Waste

Total emissions from the waste sector were 9.2 Mt CO_2eq in 2010. Around two thirds of this is the methane generated from landfills that accept biodegradable waste. Landfill management also has many opportunities for emissions mitigation therefore it forms the majority of the discussion in relation to the waste sector.

5.4.13 Landfills

A landfill is a solid waste disposal site in which refuse is buried between layers of dirt to fill in or reclaim low lying ground or excavated pits. There are 372 landfills containing biodegradable waste in California which produce methane as it degrades in the absence of oxygen. Landfills are California's second largest source of anthropogenic methane emissions. 94% of California's landfills have some form of emissions control in place. (CalRecycle, 2011a)

The most practical emissions control system, for landfills with a high enough rate of methane generation, is a combustion system that converts the methane into energy. A rough guideline is a minimum flow of $100m^3$ per hour, although in practice this can be much higher depending on the landfill conditions (Donovan et al., 2010a). If the flow rate is too low for combustion, the gas can be flared to convert the methane to CO_2 before it is released to the atmosphere. Flaring technology can capture a minimum flow rate of around $10m^3$ per hour, although improving the technology to capture lower flow rates is an active area of research.

To model long-term methane generation from a landfill it is useful to know the composition of the incoming waste, the width and composition of any liners or top covers, the annual rain fall, and any other water infiltration into the site. ARB found that this kind of data were available for less than half of California's landfills. In the absence of site-specific data state averages were used (ARB, 2009).

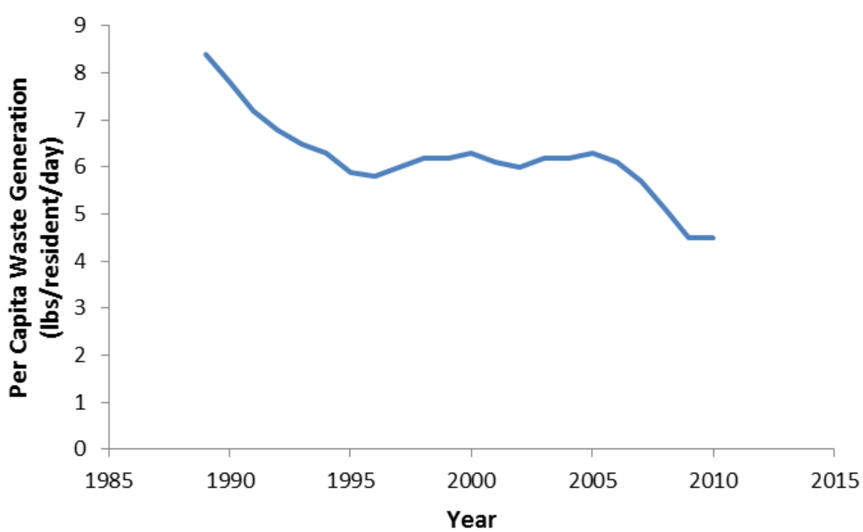
CalRecycle, formerly the California Integrated Waste Management Board, has adopted a Climate Action Team (CAT) strategy for increasing landfill methane capture to reduce methane emissions by 2020. The Landfill Methane Capture Strategy includes three core components (CalRecycle, 2011a):

- Install new methane control systems at landfills currently without control systems.
- Maximize landfill methane capture efficiencies by optimizing landfill design, operation, and closure/post-closure practices.
- Increase recovery of landfill gas for use as a biomass renewable energy source to replace energy from nonrenewable fossil fuel sources.

CARB approved a regulation to reduce methane emissions from landfills (CalRecycle, 2011). The regulation, which became effective June 17, 2010, is a discrete early action greenhouse gas emission reduction measure, as described in the California Global Warming Solutions Act ("AB 32"). The regulation addresses the first two points identified above by requiring around 14 landfills lacking gas collection systems to install them (Kay, 2009), while certain landfills with gas collection systems are required to be optimized. The regulation allows local air districts to voluntarily enter into a memorandum of understanding with ARB to implement and enforce the regulation and to assess fees to cover costs. It is expected to impact around 218 of California's 367 landfills (Kay, 2009).

The current regulation is projected to decrease landfill emissions by 1.5 Mt CO2eq. However, once all gas collection systems are optimized it would be difficult to achieve any further reductions without developing a new waste treatment structure. Therefore the 2050 projection is based on the projections of per capita waste generation shown in Figure 5.3 (CalRecycle, 2011b). The per capita waste generation has been decreasing slightly year on year; however, the trend has started to level off in recent years, at 4.5 lbs per person per day. Therefore this value was used along with the 2050 population from the California Department of Finance (CADOF, 2013). The 2050 projected value is 9.2 Mt CO_2eq.

Figure 5.3: California per Capita Waste Generation 1989 -2010 (CalRecycle, 2011b)



There is currently much research into different ways of preventing and mitigating landfill methane emissions which are discussed below.

CalRecycle is trying to expand the recovery of landfill gas as a fuel and has provided funding to two sites to demonstrate the conversion of landfill gas to liquefied natural gas for use as a fuel in vehicles (CalRecycle, 2011). To support their research CalRecycle have commissioned SCS Engineers to develop a guidance document for landfill operators (CalRecycle, 2011). The document aims to inform landfill operators of practical and cost-effective technologies for reducing landfill emissions focusing on site-specific measures that can be used on a voluntary basis.

CalRecycle also set up a demonstration project in Yolo County to investigate the use of biologically active landfill covers (biocovers) (Yazdani, 2010a). Biocovers act as a medium for microbial methane oxidation, preventing its release to the atmosphere. It could be a good alternative to installing a gas collection system at small landfills, or landfills with low gas flow rates, that are difficult to capture for flaring. The demonstration project concluded that yard waste could provide a suitable cover if pretreated for at least one year. This stabilized waste will not consume significant amounts of oxygen, allowing this to react with the methane generated from the landfill. Similarly, Leikam (1999) found that green waste, composted for at least six months provided a suitable landfill biocover. The optimal thickness of the cover was also considered, however no conclusion was made in regard to this, it was flagged as an area for further research.

A longer term European study (Einola et al., 2008) documented the methane mitigation of a biocover made from composted yard waste over a year in Northern Europe. Reductions in methane emissions were observed in all four seasons, indicating good potential for use of biocovers.

Yolo County has also been funded by CalRecycle to demonstrate an in-situ anaerobic digestion process, followed by a composting process, at a landfill to increase recovery of biogas for energy and recover a residual compost product from yard wastes otherwise used as landfill alternative daily cover (Yazdani, 2010b). The goal of this project was to assess the capabilities of a new landfill-based, in-situ, anaerobic digester technology designed to generate electricity, achieve emissions less than those of current aerobic composting technology, and be cost effective with California's tip fee structure. The project successfully managed to build and operate the system. However, problems arose when trying to add food waste to the system. This is common in anaerobic treatment facilities that attempt to take in food wastes, as they can upset the acid balance causing system failures. The report also expresses concern in relation to emissions from the composting part of the process, in particular that nitrous oxide emissions could be offsetting any benefit from reducing the methane emissions. Therefore further research to prove the benefit of such a system would be necessary before it could be implemented on a wider scale. A potential issue not discussed was whether the final material would be suitable for application to land as a soil improver. This is important as experience in other countries have shown that there is a high risk of contamination from other components of the waste stream, making it unsuitable for use on edible crops, or land that is publically accessible (Donovan et al. 2010b).

Landfill waste reduction potential is assumed to be 85% based on the technical considerations above as well as the potential reduction described in Choate 2005 (CEC).

5.4.14 International Legislation

In many European countries, landfills have been required to install gas collection systems, with energy recovery where possible, for many years. The initial reason was to prevent explosions caused by the methane emissions, rather than the prevention of greenhouse gas emissions. More recently the EU has decided to take a more preventative approach to the landfill gas problem, by requiring the diversion of biodegradable municipal solid waste from landfills, to other treatment processes. In California, Alameda County already has similarly implemented a ban on landfill of yard waste. The ban currently applies only to those properties that produce 4 cubic yards or more yard waste per week (Balsley, 2009). It will be interesting to track the progress of the ban to see whether it is successful and whether it has the potential for expansion.

For older landfills the use of aeration techniques, which flush the waste with oxygen increasing the biodegradation rate and reducing the formation of methane, have been shown to reduce the long-term emissions from landfills by decades. There is some concern that this method could lead to significant emissions of nitrous oxide (Vor et al., 2008), or that the energy required to aerate the landfill would offset any potential reduction in greenhouse gas emissions (Ritzkowski and Stegmann, 2007). Therefore this method needs further investigation before consideration for implementation.

Therefore while there are many possible methods for further reducing methane emissions from landfills, these need more research to determine whether they are viable for widespread implementation in California.

5.4.15 Wastewater Treatment and Discharge

Wastewater from households, commercial activities, and industrial production contains soluble organic matter, suspended particles, pathogenic organisms, and chemical contaminants. Methane is emitted during anaerobic treatment. In California, a large percentage of wastewater is collected and processed in centralized wastewater treatment plants.

The magnitude of CH_4 emissions is determined by the degradable organic component of the wastewater, the temperature, and the type of treatment system. The more organic material and the higher the temperature, the more methane will be generated. The degradable organic material content in wastewater is quantified by its biochemical oxygen demand and chemical oxygen demand (BOD and COD). The BOD measures the amount of biodegradable organic material present in wastewater, while the COD measures all organic materials both biodegradable and non-biodegradable.

Nitrous oxide is emitted as the results of the nitrification and denitrification processes at wastewater treatment plants; however these emissions are relatively insignificant. Nitrous oxide can also be emitted in the water bodies where effluent is discharged, which is the more significant source of this gas from wastewater treatment.

ARB estimate for 2010 is 2.2 Mt CO2eq, which has shown little variation since 2000, when it was estimated to be 2.65 Mt CO_2eq. It is therefore not expected to change in the future and ARB did not project a value for 2020. Therefore it is also assumed that it will not change in this report, but will increase in line with the population. The 2050 projection is 2.71 MtCO_2eq.

The main methods for reducing emissions are collecting the gas from the anaerobic digestion process and converting to a fuel source. The remaining solids can be applied to land as a soil conditioner, providing moisture and some nutritional value. However, the high potential for contamination to be present often makes this very restrictive. For example in the United Kingdom, there are strict guidelines known as the 'Safe Sludge Matrix' (ADAS, 2001). These specify the type of treatment the sludge must go through prior to application to land; limit the amount that can be applied; specify the type of crop that it is applied to; and restrict the period of time prior to harvesting that it is safe to use. Note that municipal waste water is not used for energy production currently in the U.S.

We take the same technical potential capture rate of 85% for waste water as for solid waste (Bogner, 2008).

5.4.16 Summary of the Non-Energy Sector

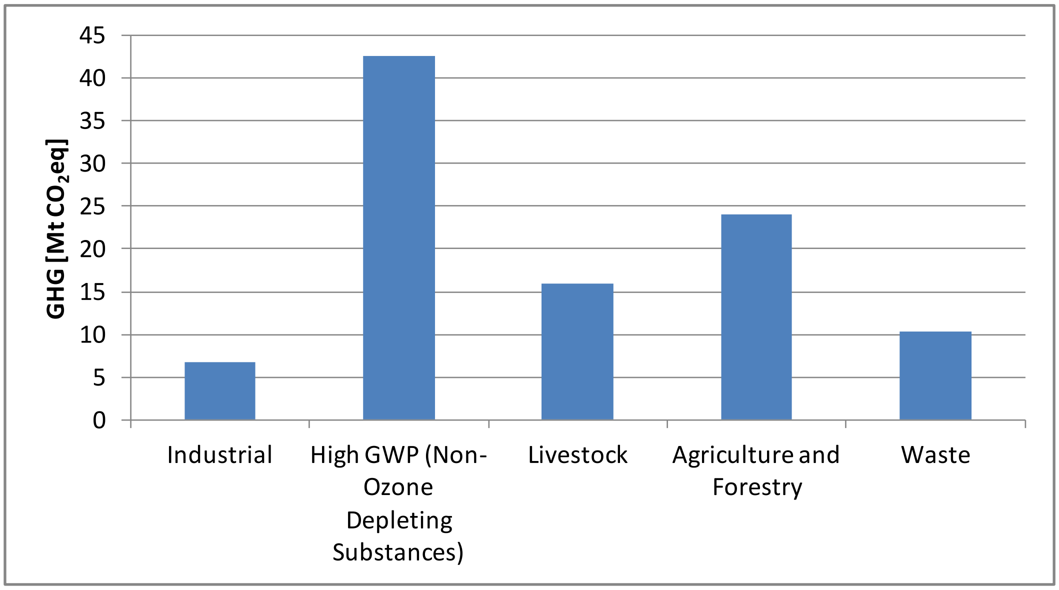
Table 5.12 shows non-energy emissions in 2010, projected emissions in 2050 and 2050 reduction potential. Final non-energy emissions for the base compliant case in 2050 are 8.1 Mt CO_2eq. (80% lower than the 1990 level), or 57.9 Mt CO_2eq if 50% of the reduction potential is achieved.

The GHG reduction potential and percentage of total reduction by category of non-energy emissions is plotted in Figure 5.4. Emissions reduction is for the base compliant case (8.1 Mt CO2 eq) relative to the frozen case (107.7 Mt CO2 eq). Two thirds of the total reduction is in High GWP and Agriculture and Forestry. Figure 5.5 shows a sensitivity plot of further subcomponents for non-energy emissions in 2050.

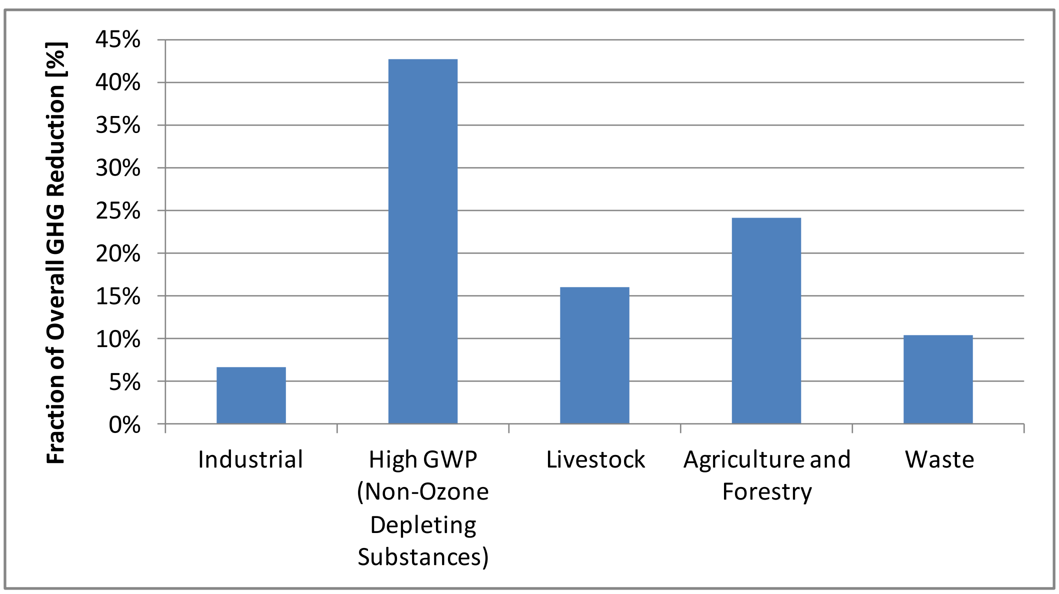
Table 5.12: Non-Energy Emissions in 2010, Projected Emissions in 2050 and 2050 Reduction Potential

Source	**2010 Estimated Emissions (Mt CO2eq)**	**2050 Projected Emissions (Mt CO2eq)**	**2050 Base Scenario Emissions, Full Reduction Potential Achieved (Mt CO2eq)**	**2050 Emissions with 50% Reduction Potential Achieved (Mt CO2eq)**
Mining & chemicals	3.5	6	6	6
Non-energy fossil products	1.9	2	2	2
High GWP (Non-Ozone depleting substances)	13.8	47.5	5	26.2
Hydrogen production	5.8	6	0	3
Other industrial	2.6	2	1.3	1.65
Livestock	19.6	24	8	16
Agriculture & forestry	6.5	8	-16	-4
Solid waste	7.0	9.2	1.4	5.3
Wastewater treatment	2.2	3	0.4	1.7
Total Emissions	**62.9**	**107.7**	**8.1**	**57.9**

Figure 5.4: (a) Emissions Reduction Potential and (b) Percentage of Total GHG Reduction by Category for Non-Energy Emissions in 2050



(a)



(b)

Emissions reduction refers to the compliant Base Scenario (8.1 Mt CO_2eq) relative to the frozen case (107.7 MtCO_2eq).

Figure 5.5: Sensitivity Plot for Non-Energy GHG Emissions

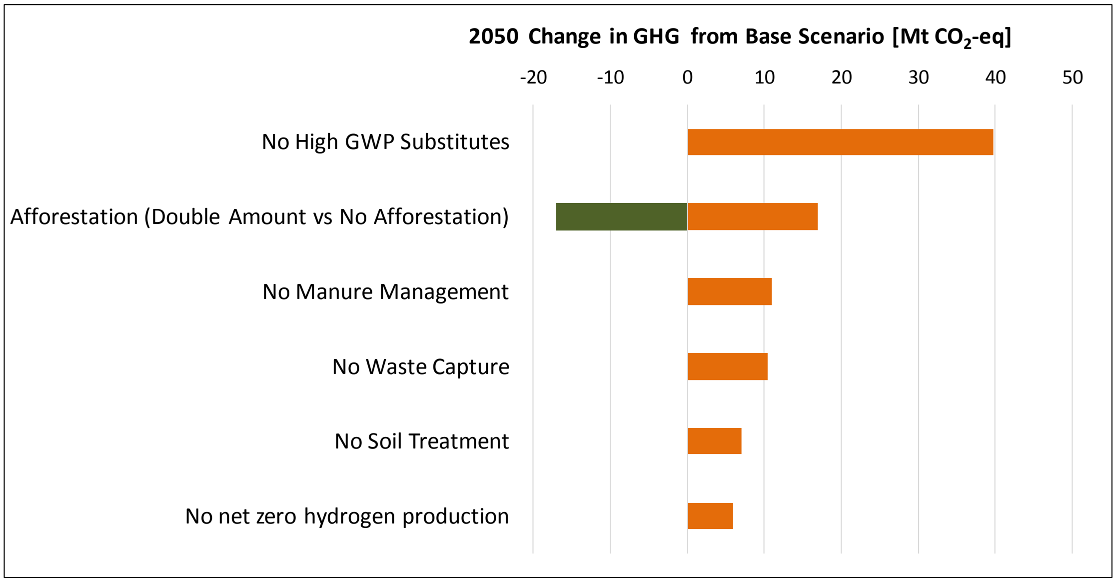
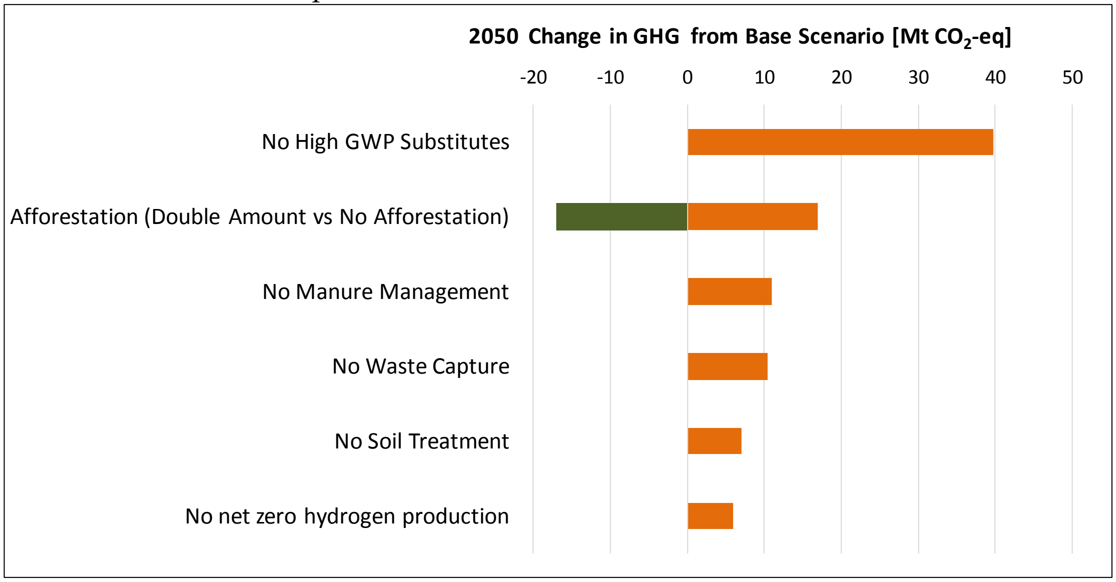


Figure shows the increase or decrease in emissions from the compliant Base Scenario. For example, not replacing high GWP gases with low GWP substitutes would increase emissions by 40 Mt CO_2eq in 2050. A larger amount of afforestation can reduce the constraints on achieving other items such as soil treatment and/or manure management.

The single largest contributor to GHG emissions reduction is the substitution of high GWP gases by low GWP gases. Not achieving this element while all other elements are achieved would increase emissions by 40 Mt to 48 Mt CO_2eq or six times the 8Mt target. Afforestation, manure management, waste emissions capture are the next most sensitive factors. If no afforestation is done, non-energy emissions would increase by 17Mt to 25Mt or three times the target, while doubling the annual rate of sequestration from afforestation versus the Base Scenario would lower emissions by 17Mt CO_2eq (Figure 5.7). An even larger amount of afforestation may be possible but this would require a larger fraction of range land in California to be converted and the possible competition of rangeland for energy crops for biomass and afforestation was not explored in this work.



also shows the potential flexibility in achieving the 80% target in 2050, namely that a larger amount of afforestation can reduce the constraints on achieving other items such as soil treatment and/or manure management.

Note that there may be other low-cost options to reduce net GHG emissions in rangelands beyond afforestation. For example, a recent work has explored the potential for carbon sequestration from diversion of composted manure and plant waste from conventional high-emission waste management to compost amendments in managed grasslands(DeLonge et al. 2013). The authors find that compost amendments could result in significant GHG offsets when scaled up to 5% of California rangelands as well providing enhanced soil fertility and reducing solid waste loads. Most likely there are other options in other sectors but the general area of terrestrial carbon sequestration has to the authors' knowledge not been extensively studied or characterized.

CHAPTER 6: Scenario Results

6.1 Scenario Results

Results for the energy sector and system-wide GHG results are presented in this section. The non-energy sector was described in the preceding chapter. A detailed analysis of the Base Scenario, which is compliant with the 2050 GHG target, is provided followed by a sensitivity analysis, which addresses the question of how much GHG emissions would increase if certain mitigation elements presented here are not achieved, relative to the compliant Base Scenario.

6.1.1 Energy Sector

A scenario chart and estimated 2050 GHG emissions is shown in Table 6.1. Primary cases considered here are the Frozen Efficiency/BAU Electricity case, the Base Scenario, Reduced Energy Efficiency, Aggressive Electrification case, and the -20% and -40% carbon cap cases with biomass CCS electricity. Also shown are ten electricity-sector supply variants (Scenarios #2-11) that meet the 14% electricity carbon cap for 2050. These scenarios have the same non-electricity sector emissions as the Base Scenario and thus meet the overall 2050 GHG goal. The electricity-supply Base scenario and variants are described in more detail in Volume II of this report.

The Base Scenario includes the following: 48% of light duty miles are electrified in 2050, technical potential energy efficiency savings, 14% electricity carbon cap relative to the 1990 level, full electrification of building space and water heating, and 2.8 and 7.5 Bgge of instate and imported biofuels, respectively. As discussed previously the base in-state biomass supply is 35Mdt and is directed to biofuels for all cases except for the two Biomass CCS cases. For both Biomass CCS cases, 23Mdt are made available to the electricity system in California, with the remainder for biofuels (12 Mdt of biomass).

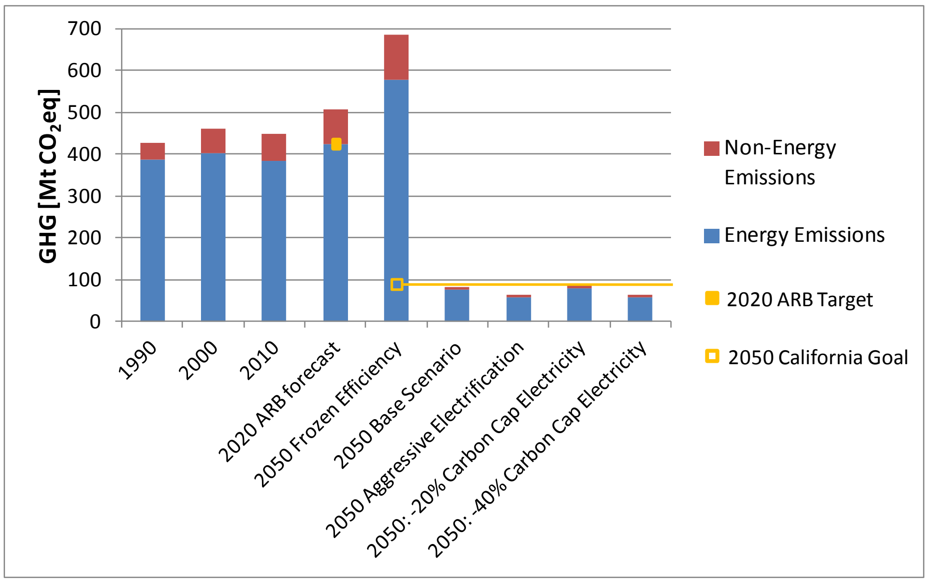
The Base Scenario, Reduced Energy Efficiency, and -20% Biomass CCS case are either very close or meeting the 85Mt 2050 target, while Aggressive Electrification and the -40% Biomass CCS case are both 21Mt below the 2050 target. These cases will be described in further detail below.

Table 6.1: Scenario Chart and Final System Emissions

<table>
<tr><th>Scenario name</th><th>Demand profile</th><th>Electricity supply options</th><th>2050 WECC electricity carbon cap (vs. 1990)</th><th>Biomass/ Biofuel Supply (Instate)</th><th>Biomass/ Biofuel Supply (Imported)</th><th>2050 Energy Emissions [Mt CO_2eq]</th><th>2050 Non-Energy Emissions [Mt CO_2eq]</th><th>2050 Total GHG Emissions [Mt CO_2eq]</th></tr>
<tr><td>1. Base</td><td rowspan="11">Base</td><td>Base</td><td rowspan="11">14%</td><td rowspan="11">35 Mdt instate biomass or 2.8 Bgge biofuels; All for transport-tation sector</td><td rowspan="11">94 Mdt biomass or 7.5 Bgge imported biofuels; All for transporta-tion sector</td><td rowspan="11">75</td><td rowspan="11">8</td><td rowspan="11">83</td></tr>
<tr><td>2. No CCS</td><td>No CCS</td></tr>
<tr><td>3. Small Balancing Areas</td><td>Small Balancing Areas</td></tr>
<tr><td>4. Limited Hydro</td><td>Limited Hydro</td></tr>
<tr><td>5. Expensive Transmission</td><td>Expensive Transmissio n</td></tr>
<tr><td>6. Demand Response</td><td>Demand Response</td></tr>
<tr><td>7. 12 GW Distributed PV</td><td>12 GW Distributed PV</td></tr>
<tr><td>8. California 50% RPS</td><td>California 50% RPS</td></tr>
<tr><td>9. SunShot Solar</td><td>SunShot Solar</td></tr>
<tr><td>10. Low Gas Price</td><td>Low Gas Price</td></tr>
<tr><td>11. New Nuclear</td><td>New Nuclear</td></tr>
<tr><td>12. -20% Carbon Cap / BioCCS</td><td>Base</td><td>BioCCS included</td><td>-20%</td><td rowspan="2">23 Mdt Biomass for Electricity; 12Mdt biomass or 0.96 Bgge for Biofuels</td><td rowspan="2">32.2 Mdt Biomass or 2.6 Bgge imported biofuels</td><td>78</td><td>8</td><td>86</td></tr>
<tr><td>13. -40% Carbon Cap / BioCCS</td><td>Base</td><td>BioCCS included</td><td>-40%</td><td>56</td><td>8</td><td>64</td></tr>
<tr><td>14. Reduced Efficiency</td><td>50% energy efficiency impleme ntation in Buildings and Industry</td><td>Base</td><td>14%</td><td rowspan="2">35 Mdt instate biomass or 2.8 Bgge biofuels; All for transport-tation sector</td><td rowspan="2">94 Mdt biomass or 7.5 Bgge imported biofuels; All for transporta-tion sector</td><td>77</td><td>8</td><td>85</td></tr>
<tr><td>15. Aggressive Electrification</td><td>Greater PEV adoption and heating</td><td>Base</td><td>14%</td><td>77</td><td>8</td><td>85</td></tr>
</table>

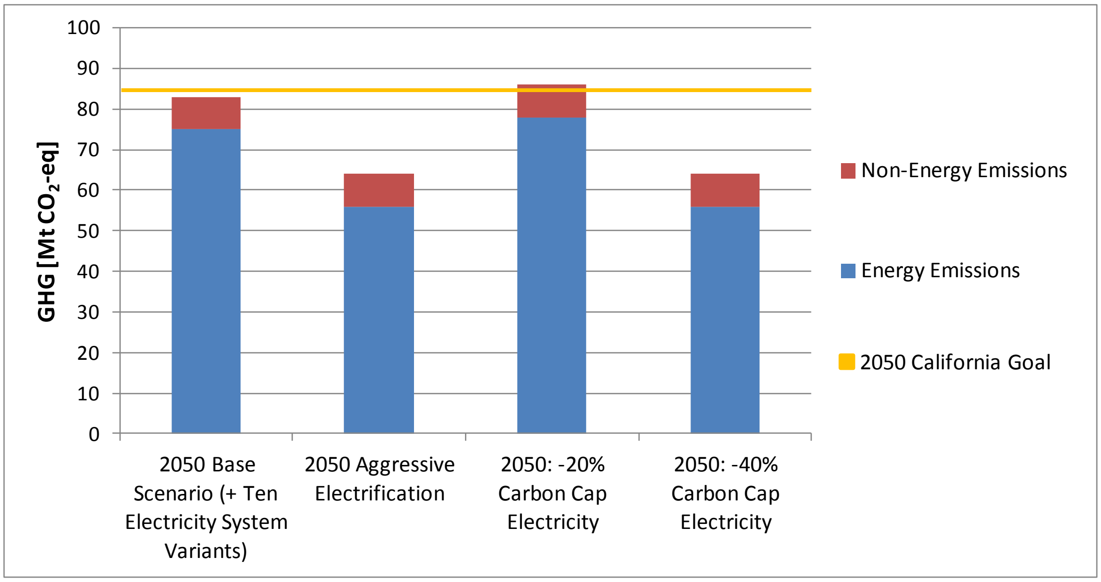
	electrification							
16. Business As Usual / Frozen Efficiency	Frozen efficiency & Minimal electrification	New nuclear allowed outside California & New biomass allowed	100%	23 Mdt Biomass available for Electricity	None	578	108	686

Figure 6.1: Overall Emissions in 2050 for Scenarios in Table 6.1, Plotted Relative to Historical Emissions and 2020 ARB BAU Forecast



The ARB target is to meet the 1990 level of emissions by 2020 (AB-32) and the 2050 California goal is to reduce emissions by 80% from the 1990 level (Gov. Executive Order S-3-05).

Figure 6.2: Overall Emissions Scenario for 4 Scenarios of Table 6.1



All cases are compliant or nearly compliant (-20% carbon cap electricity case is within 1Mt of 85Mt goal and others are at or below the goal)

6.1.2 Frozen Efficiency/BAU Electricity to the Base Scenario

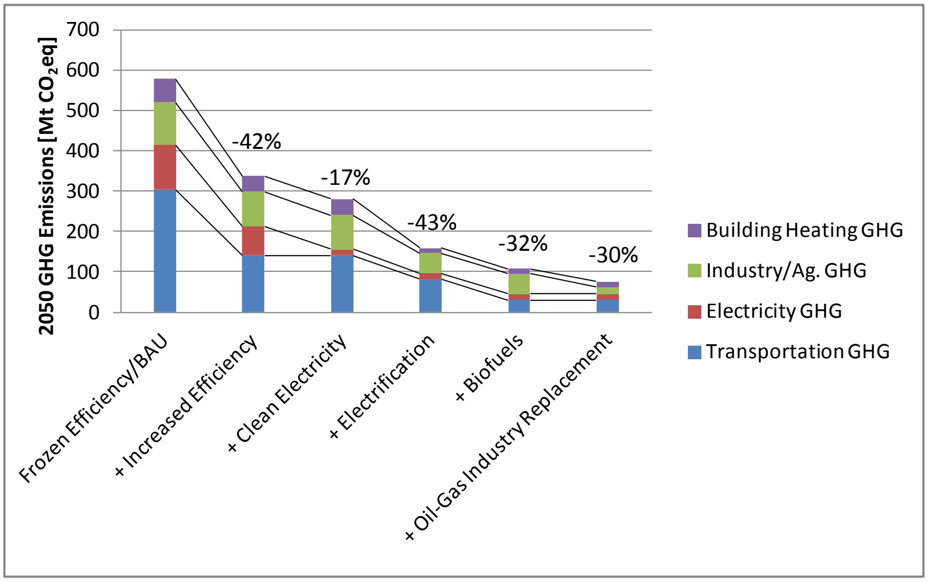
Table 6.2 shows the progression of emissions from the Frozen Efficiency/BAU Electricity case to the Base Scenario. Each row represents the new level of emissions after an element has been added. For example implementing "Increased Efficiency" across the board reduces overall energy emissions from 578 Mt to 337 Mt CO_2eq. The final row represents the Base Scenario, which contains all of the preceding five elements. The 2050 target for energy emissions is 77Mt, so this scenario meets the 2050 target with 75 Mt.

Table 6.2: Base Scenario Overall Energy Emissions Progression as Individual Elements Are Added

Element	Transportation GHG (Mt CO2eq)	Electricity GHG (Mt CO2eq)	Industry/ Ag. Energy GHG (Mt CO2eq)	Building Heating GHG (Mt CO2eq)	Total (Mt CO_2eq)	Pct. Reduction
Frozen Efficiency/BAU Electricity	305	110	106	58	578	
+ Increased Efficiency	140	73	85	39	337	-42%
+ Clean Electricity	140	16	85	39	280	-17%
+ Electrification	81	16	50	13	159	-43%
+ Biofuels	30	16	50	13	108	-32%
+ Oil-Gas Industry Replacement	30	16	17	13	75	-30%

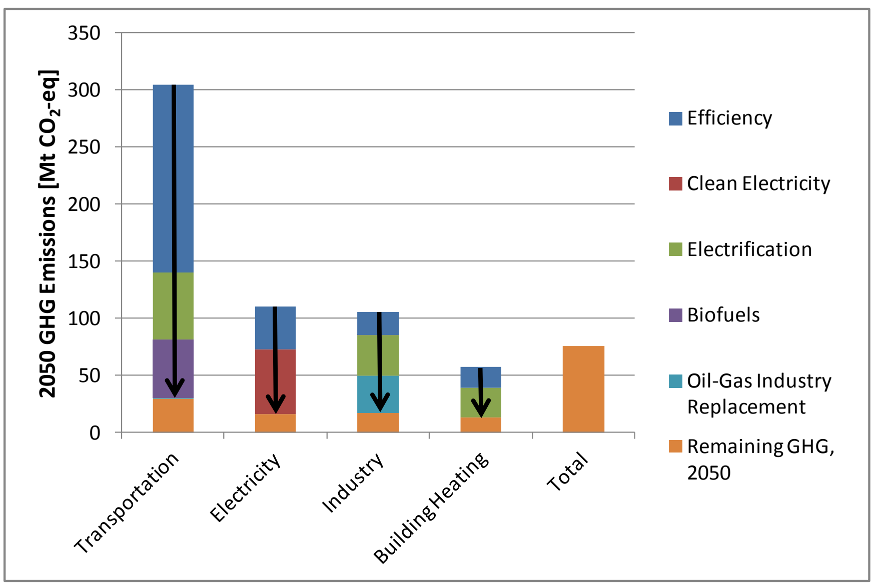
Note that the order in which individual elements are added will change the magnitude of emission reduction shown.

Figure 6.3: Sequential Progression of GHG Emissions Reduction from Frozen Efficiency/BAU Electricity Case to the Base Scenario



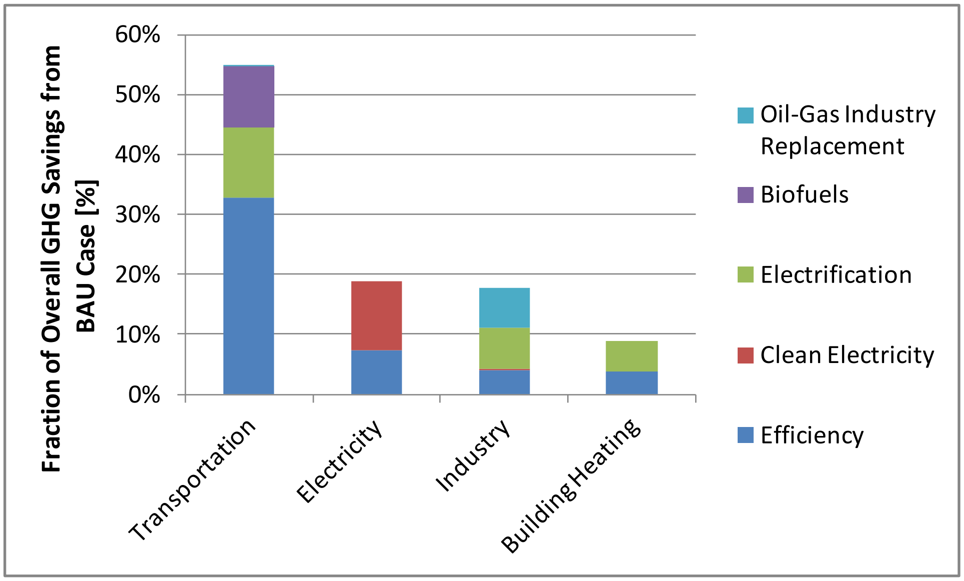
The percentage reductions represent the savings relative to the preceding bars. For example, efficiency saves 42% of frozen efficiency/BAU electricity energy emissions and clean electricity provides 17% savings relative to the Increased Efficiency case. The resultant Base Scenario has 75Mt GHG emissions which meets the 77Mt goal for energy emissions in 2050.

Figure 6.4: Progression of GHG Savings in 2050 for the Base Scenario Plotted by Sector



GHG savings in 2050 by pathway for the Base Scenario relative to the Frozen Efficiency/BAU Electricity Scenario. Note that electrification savings are predicated by availability of clean electricity.

Figure 6.5: Percentage of Overall GHG Savings by Sector for the Base Scenario



Note that electrification savings are predicated by availability of clean electricity. Transportation sector has 55% of overall savings.

Figure 6.3 shows the percentage reduction in GHG from each of the four key pathways relative to the preceding bar and the savings from oil and gas industry replacement. Efficiency is seen to give the largest percentage reduction followed by electrification and low carbon biofuels. Figure 6.4 shows the reduction by pathway in the Transportation, electricity, industry and building heating sectors relative to the Frozen Efficiency/BAU Electricity Scenario. The remaining emissions are the sum of the remaining 2050 energy emissions in each subsector.

The amount of oil and gas industry replacement is assumed inversely proportional to the amount of remaining liquid fossil fuel demand in 2050. Although instate oil extraction is dropping over time as it becomes more difficult to extract (energy intensive thermally extracted oil recovery is common today), instate refinery activity in petroleum product output and energy consumption has been slowly growing. Instate natural gas production has also been dropping, to 12% of overall state supply in 2010. Continued downward trends in instate oil and natural gas extraction is assumed so that by 2050 oil refining is assumed to be the dominant component in the fossil fuel industry. The analysis presented here does not include the potential for greatly increased production of "tight" oil from the Monterey Shale formation but it is unclear at this time how much of oil from this reserve is economically recoverable.

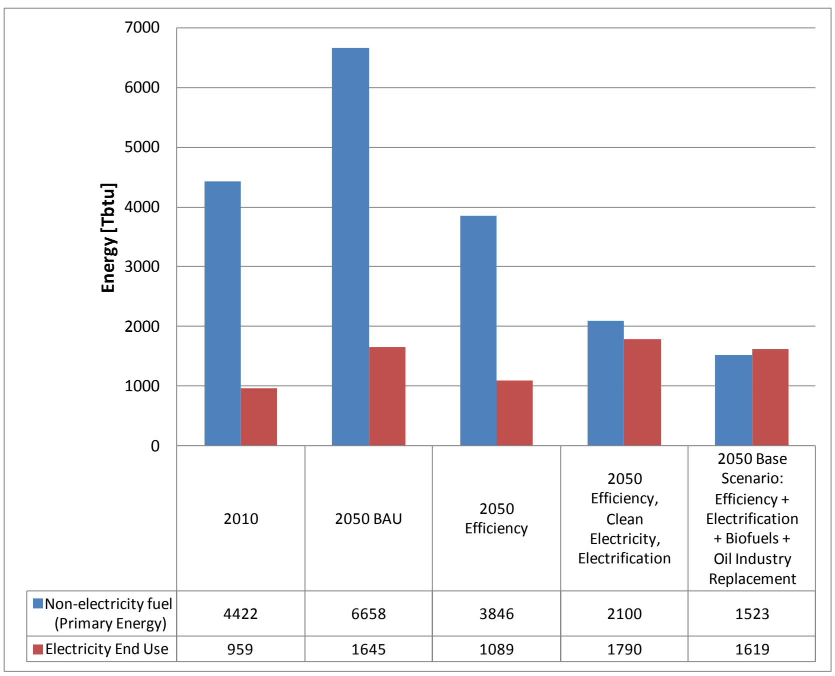
Using an annual growth rate of 0.5% per year (Wei 2013), instate production of liquid petroleum-based fuel in the frozen efficiency case is projected to be about 30 Bgge. In the Base Scenario, there is 1.9 Bgge remaining liquid fuel demand in 2050 and 94% of the instate oil industry is assumed to be replaced. No accounting is made for chemical industry feedstock since a smaller proportion of oil industry production output is for chemical products, and bio-based replacements may become more widespread in the future. A reduction in out-of-state demand for petroleum products by 2050 is also implicitly assumed so that domestic production is not simply exported. The amount of GHG reduction from oil-industry replacement in the Base Scenario is seen to be 33Mt CO_2 in Table 6.2.

6.1.3 Energy System Demand for the Base Scenario

Energy system demand evolution for the Base Scenario is shown in Figure 6.6 and Table 6.3. 2050 Frozen Efficiency case non-electricity primary energy increases by 50% over 2010 and electricity demand by 70%. Energy efficiency reduces building fuel and electricity demands by 30% and 37%, respectively, while transportation fuel demand is reduced 54%. Electrification sharply reduces fuel demand by almost 50% but increases electricity demand by 64%. Base Scenario assumptions for low-carbon biofuel production and oil industry replacement further reduce fuel and electricity demands. The net remaining electricity demand is very close to the 2050 BAU (Frozen Efficiency/BAU Electricity) demand. Overall fuel demand is reduced nearly 80% through the combination of energy efficiency and fuel switching.

Industry treatment is similar to the CCC1 report, where about 40% of industry fuel demand is assumed to be electrified by 2050 and the oil and industry is assumed by be largely replaced by low carbon biofuels and electrified transport in the Base Scenario.

Figure 6.6: Energy System Demand[15] Evolution for 2050



	2010	2050 BAU	2050 Efficiency	2050 Efficiency, Clean Electricity, Electrification	2050 Base Scenario: Efficiency + Electrification + Biofuels + Oil Industry Replacement
Non-electricity fuel (Primary Energy)	4422	6658	3846	2100	1523
Electricity End Use	959	1645	1089	1790	1619

BAU(Frozen Efficiency/BAU Electricity), 2050 efficiency, 2050 with EE, clean electricity and electrification, and the 2050 Base Scenario.

[15] End use electricity is shown since primary energy demand for electricity in 2050 will be highly dependent on the actual mix of generation technologies. For reference, the approximate ratio of source to site energy is 3:1 for current grid-based electricity, and if the current mix of generation technologies does not change, primary energy would be three times the end use electricity demand shown here.

Table 6.3: Non-Electricity Fuel Primary Energy and End-Use Electricity for 2010 and 2050 Base Scenario

Sector	Energy Supply	Units	Energy					Relative emissions intensity relative to current (2010=1)			
			2010	2050 Frozen Efficiency/BAU Electricity	2050 Increased Efficiency	2050 Increased Efficiency, Clean Electricity, Electrification	2050 Base Scenario: Increased Efficiency + Electrification + Biofuels + Oil Industry Replacement	2050 Frozen Efficiency/BAU Electricity	2050 Increased Efficiency	2050 Increased Efficiency, Clean Electricity, Electrification	2050 Base Scenario: Increased Efficiency + Electrification + Biofuels + Oil Industry Replacement
Buildings	Liquid, Solid Fuels	Tbtu	52	52	26	26	26	1	1	1	1
	Gaseous Fuel	Tbtu	710	946	658	194	194	1	1	1	1
	sum	Tbtu	762	998	684	220	220				
	change			31%	-30%	-67%	0%				
	Electricity	GWh	190,828	324,800	205,900	244,600	244,600	0.68	0.68	0.10	0.10
	change			70%	-37%	19%	0%				
Industry	Liquid, Solid Fuels	Tbtu	205	265	212	0	0	1	1	1	1
	Gaseous Fuel	Tbtu	1103	1423	1139	824	247	1	1	1	1
	sum	Tbtu	1308	1688	1350	824	247				
	change			29%	-20%	-39%	-70%				
	Electricity	GWh	35,266	81,100	58,400	127,840	78,000	0.68	0.68	0.10	0.10
	change			130%	-28%	119%	-39%				
Transportation	Liquid, Solid Fuels	Bgge	19.6	33.1	15.1	8.8	8.8	1	1	1	0.38
	change			69%	-54%	-42%	0%				
	Electricity	GWh	0	0	0	97,000	97,000	0.68	0.68	0.10	0.10
	change						0%				

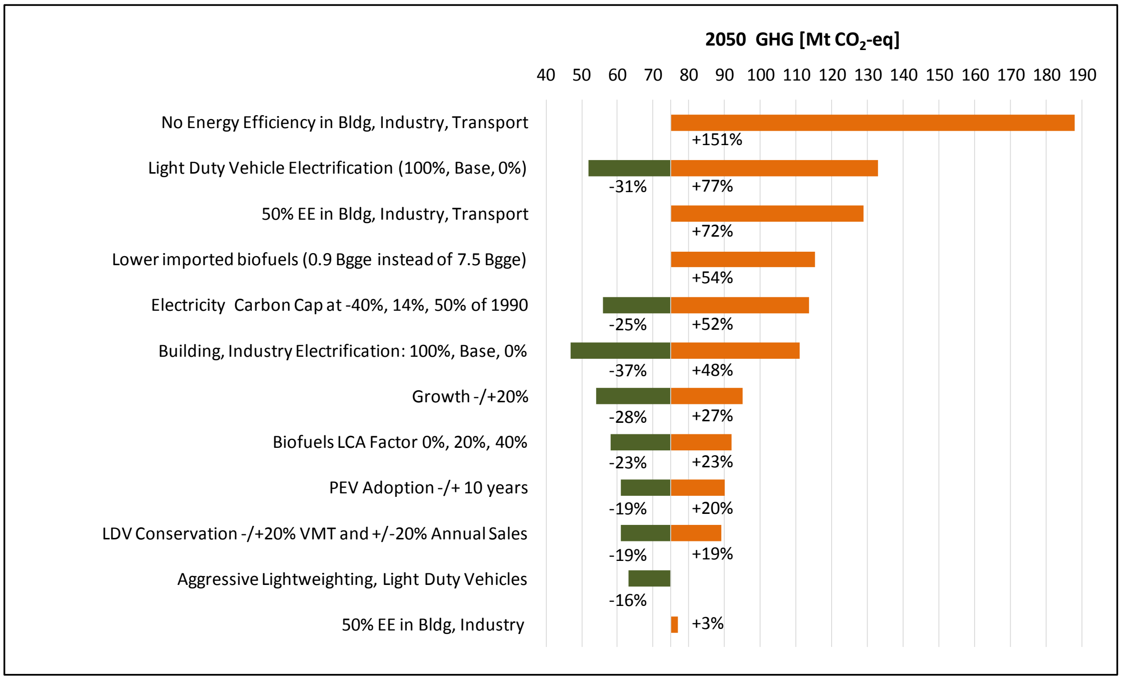
6.1.4 Base Scenario Sensitivity Analysis for Energy Emissions

Single factor sensitivity relative to the Base Scenario in 2050 is considered in this section. Each of the elements in Table 6.4 can be thought of as spanning a continuous range of values from the "optimistic" value to the "pessimistic" value and thus show the sensitivity of key elements for the State to reach its 2050 climate targets. For example, "No Energy Efficiency" means that there is a frozen energy efficiency assumption across sectors, but that the other key elements of the Base Scenario (clean electricity, electrification, and low carbon biofuels) are still included. Note that since the 80% target for energy emissions is 77MMt GHG in 2050 and the Base Scenario is at 75Mt , the percentages in Figure 6.8 are roughly the amount by which the energy emissions target is exceeded or reduced in 2050.

Table 6.4: Energy Emissions for Base Scenario Sensitivity Analysis

	ENERGY EMISSIONS ONLY [Mt CO_2-eq]			
Element	**Optimistic**	**Compliant Emissions**	**Pessimistic**	**Range**
No Energy Efficiency in Bldgs, Industry, Transport	75	75	188	113
Light Duty Vehicle Electrification (100%, Base, 0%)	52	75	133	81
50% EE in Bldg, Industry, Transport	75	75	129	54
Lower imported biofuels (0.9 Bgge instead of 7.5 Bgge)	75	75	115	
Electricity Carbon Cap at -40%, 14%, 50% of 1990	56	75	114	58
Building, Industry Electrification: 100%, Base, 0%	47	75	111	64
Growth (-/+20% change in 2050 population)	54	75	95	41
Biofuels LCA Factor 0%, 20%, 40%	58	75	92	34
PEV Adoption -/+ 10 years	61	75	90	29
LDV Conservation -/+20% VMT and +/-20% Annual Sales	61	75	89	28
Aggressive Lightweighting, Light Duty Vehicles	63	75	75	12
50% EE in Bldg, Industry	75	75	77	2

Figure 6.7: Sensitivity Plot for Base Scenario Energy Sector Emissions



Each of these sensitivities represents a scenario with Base Scenario conditions except for the measure or measures as noted, and sensitivity bars are depicted relative to Base Scenario energy emissions of 75 CO_2eq. For example, "50% EE in Bldg, Industry, and Transport" has the same percentage of decarbonized electricity and electrification adoption as the Base Scenario but 50% of overall energy efficiency savings in Building, Industry and Transportation. The labels indicate the midpoint and endpoints for each sensitivity case. For example, electricity with a carbon cap set at -40% and 50% of 1990 emissions levels in 2050 results in energy sector emissions that are -25% and +52% relative to the Base Scenario, respectively.

6.2 Discussion of Sensitivities

The first two bars have the highest impacts to the energy system: no energy efficiency and no LDV electrification. The state has embarked on a well-established path for efficiency and starting (or restarting) a major campaign for vehicle electrification so these two outcomes are extremely unlikely, but they underscore the importance of economy-wide energy efficiency and vehicle electrification.

The Base Scenario assumes 2.8 billion gallons of gas-equivalent biofuels and 7.5 Bgge imported biofuels (further details in Chapter 2). As noted there, this mix of instate and out-of-state biofuels would contribute the Base Scenario's compliance with the 80% GHG reduction target in 2050 but not meet the 2006 Governors Executive Order S-06-06 that calls for no greater than 25% of instate biofuel supply be imported. Lowering imported biofuels to 0.9 Bgge or 25% of overall biofuel supply in compliance with this order would increase energy emissions by an additional 40 Mt or +54%.

The Base Scenario includes a 20% life-cycle assessment (LCA) factor for biofuels versus petroleum-based liquid fuels, or that the average life-cycle GHG emissions of biofuels in 2050 is 80% lower than the average life-cycle GHG emissions of petroleum-based liquid fuels. A 0% or

40% LCA factor for the Base Scenario biofuel supply would decrease or increase emissions by 23% respectively.

The "Electricity" sensitivity refers to the amount of capped emissions relative to the 1990 amount: -40% emissions, 14% or 50% of 1990 electricity sector emissions (or -44Mt, 15.5Mt, or 55.3 Mt CO_2eq in 2050). The Base Scenario cap is set at 14% of 1990 levels in 2050. We do not explicitly simulate the 50% case using the SWITCH model, but rather presume a level of emissions here for the purposes of sensitivity. This sensitivity shows that achieving only a 50% reduction from 1990 electricity emissions would increase the overall level of emissions by 52%.

PEV adoption sensitivity depends largely on the shape of adoption curves after 2035, since the bulk of cars sold before 2035 are replaced through new vehicle purchases. The PEV adoption of -/+ 10 years thus is an attempt to either pull in PEV sales by 10 years versus the Governor's ZEV Mandate or to delay it by 10 years. Perhaps surprisingly, PEV adoption is not as sensitive an overall factor compared to some of the others. This is in part because LDV emissions become a smaller relative fraction of overall transport emissions (55% from current 73%) by 2050.

"LDV Conservation" refers to the case where new vehicle VMT is 20% lower than current (12,320 vs. 15,400 miles) and the number of vehicles per capita is reduced by 20% from Base Scenario values by 2050. We make no allowance for increases in public transit because of this conservation (e.g., any increase elsewhere is assumed to have no impact on GHG emissions).

"Growth -/+ 20%" corresponds to a State population that is 20% lower or higher in 2050 (40.3 million or 60.5 million, respectively). Demands for the building and transportation sectors are adjusted accordingly. Industry is not increased due to the assumption that industry growth or reduction is not primarily driven by in-state population trends. One could also think of the growth sensitivity as a proxy for either a "High consumption" or "High conservation" wedge where energy demands are either increased or reduced above the baseline assumptions for the same state population. This can be seen for example by comparing the size of reduction of the -20% Growth bar with the LDV conservation bar.

There are no easy options to go below the GHG target at least from a current day perspective (negative bars in Figure 6.8). Full LDV electrification, net carbon negative electricity, full building/industry heating electrification, low growth, net zero carbon biofuels, and high passenger vehicle conservation each offer savings beyond the compliant Base Scenario, but each of these is difficult to achieve by 2050 and each option has its own set of implementation challenges.

6.2.1 Reduced Efficiency: 50% EE Sensitivity and 50% EE Scenario

Next is the "50% EE in buildings, industry, and transport" scenario. The 50% EE cases refer to the case where half of the baseline technical potential savings are achieved by 2050. Note also the last bar in the sensitivity, "50% EE in Buildings and Industry Only" has a very small impact on overall emissions and thus most all the impact of reduced EE is from the transport sector. This is because the transport sector still has a large amount of remaining fossil fuel after 50% efficiency savings and this directly increases GHG emissions. For the industry and building sectors, however, the 50% efficiency case has a much-muted effect due to the other conditions assumed in the Base Scenario, namely electrification and the binding cap for electricity emissions. Industry GHG emission reductions in 2050 are dominated by oil and gas industry replacement and electrification, and efficiency measures have a smaller net impact. For the building heating sector, space heating and water heating are dominant (over 80% of building heating energy demand) and assumed to be completely electrified by 2050. Reducing the efficiency in buildings increases the space heating electricity demand but emissions in the electricity sector are capped. Heating demands from remaining end uses that use natural gas (cooking, dryers, swimming pool and hot tub heaters) are not increased appreciably with the 50% efficiency assumption since overall technical potential energy efficiency savings for these end uses are generally small.

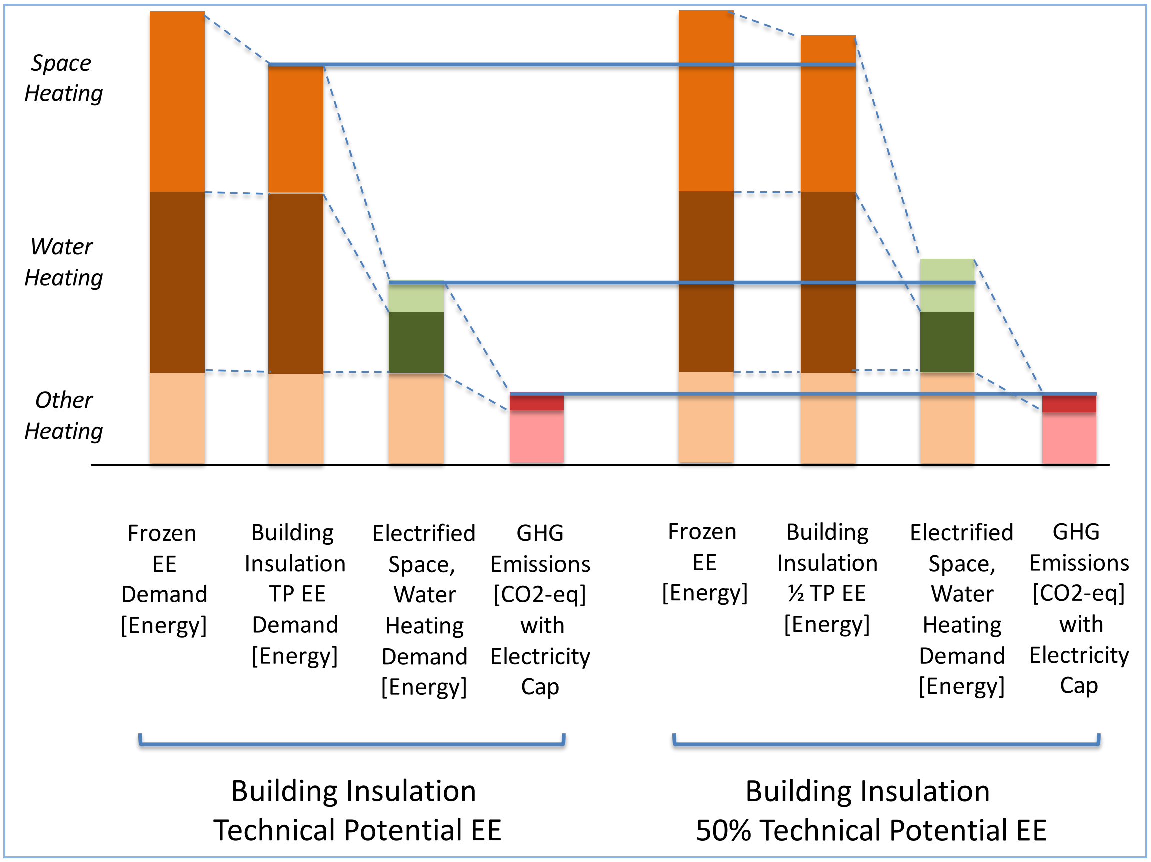
Thus, for building heating in the Base Scenario, a reduction in building efficiency measures (e.g. building insulation and shell measures) does not appreciably shift the building-related carbon emissions since space heating and water heating are electrified and electricity emissions are constrained by a carbon cap in 2050 in this scenario. This is shown schematically in Figure 6.9. Similarly, lower levels of efficiency in the electricity sector (e.g. plug load efficiency) will increase electricity demand but carbon emissions are capped, so the electricity system build-out will need to be larger but still meet the cap.

This result for reduced efficiency in the building heating sector presents an alternative pathway to reducing building-related GHG in contrast to the existing paradigm of achieving comprehensive energy efficiency for all residential and commercial buildings (e.g., AB 758). While there is room for further increased efficiency in appliance standards and further tightening of building codes, the economics and viability of achieving technical potential saving in all existing California building is still an open question. Costs remain high for deep energy efficiency retrofits and several well-documented barriers to achieving high market adoption exist. The challenges of full electrification are perhaps no less daunting, but could provide a pathway to achieving deep carbon reductions even with incomplete building efficiency measures.

6.2.3 Aggressive Electrification Scenario

This scenario achieves nearly full vehicle electrification by 2050 with 94% of light duty vehicle stock ZEV and 99% of new vehicle sales ZEV in 2050 as described in Table 4.2 of the Transport Chapter. The case achieves 56 Mt energy GHG emissions and total GHG emissions of 64 Mt in 2050. Another way of viewing this scenario is that this scenario is near but not quite at the emissions level of the 100% light duty vehicle electrification case in the Sensitivity analysis above.

Figure 6.8: Schematic of 50% EE Case for Building Insulation Showing No Change to Emissions with Base Scenario Conditions Assumed for Electricity Sector and Building Heating



All heating demand is electrified and carbon emissions capped in the electricity sector, and less building insulation does not lead to higher emissions in the Base Scenario.

6.2.4 Biomass CCS Scenarios

For the two biomass CCS scenarios about 2/3 of the instate biomass supply is available for the electricity sector and proportionally less biomass is available for liquid biofuels in the transportation sector (23 Mdt for the electricity sector and the remaining 12 Mdt are available for biofuel production). This supply fraction for the power sector is set by the biomass supply curve whose assumptions are described in the Electricity Chapter and Wei et al. (2012). Both the -20% and -40% Carbon cap scenarios utilize about 95% of this available biomass and thus the biofuel supply is taken to be the same in both scenarios. A proportionally lower amount of imported biofuels is assumed in this scenario as well, or 32 Mdt (2.6Bgge) versus 94Mdt (7.5 Bgge) in the Base Scenario.

With these assumptions and the rest of the non-electricity energy system the same for the two scenarios, the -20% biomass CCS scenario has a slight increase in energy emissions to 78 Mt and total emissions or 86Mt. The -40% biomass CCS scenario has 22Mt lower emissions in the electricity sector than the -20% scenario and total emissions of 64 Mt CO_2eq. (As described in the Electricity results volume of this report, the -20% scenario allows more low cost gas into the system and even some coal CCS. To achieve the -40% cap with biomass CCS, wind generation increases, gas CCS takes the place of gas, and there is no coal CCS).

Similar to the imported biofuel sensitivity in Figure 6.8 above, if the amount of imported biofuel is increased back to the Base Scenario level of 7.5 Bgge, both the -20% and -40% BioCCS scenarios 2050 energy GHG emissions are reduced by 30 Mt CO_2eq, and overall emissions reduced to 56 Mt and 34 Mt, respectively.

6.3 Total GHG Emission Estimates for 2010-2050

Total GHG emission estimates for 2010-2050 for the Base Scenario, Frozen Efficiency/BAU Electricity, and the two BioCCS Scenarios are shown in Figures 6.9-6.11. In the Base Scenario (Figure 6.9), GHG emissions from the industry, transport, electricity, and non-energy sectors are all reduced by over 80% relative to 2010 levels, and the building sector is reduced by 69%. Overall emissions are reduced from 454Mt CO_2eq. in 2010 to 83Mt in 2050, meeting the 2050 target of 85.4Mt. Note also that the "mid-term" emissions in 2030 are 319Mt versus a target of 270Mt if the 2030 target was based on a straight linear reduction in emissions from 2010 to 2050.

In the Frozen Efficiency/BAU scenario (Figure 6.10), transportation and non-energy GHG sectors each increase by 72%, and industry, buildings, and electricity increase by between 24% and 33% relative to 2010 levels. Overall emissions increase by just over 50% from 454Mt CO_2eq. to 686Mt.

In the -20% Carbon Cap/BioCCS Scenario (Figure 6.11), overall emissions are within 1Mt of the 2050 target. Electricity sector emissions are -21.3 Mt due to carbon sequestration or about 37Mt lower than the Base Scenario. The transportation and industry sector are estimated to increase, however, by 38Mt since less biomass is available to for transportation biofuels. In the -40% Carbon Cap/BioCCS Scenario (Figure 6.11), overall emissions are reduced to 64Mt driven primarily by -43.8 Mt emissions in the electricity sector.

Figure 6.9: Total GHG emissions in the Base Scenario, 2010-2050.

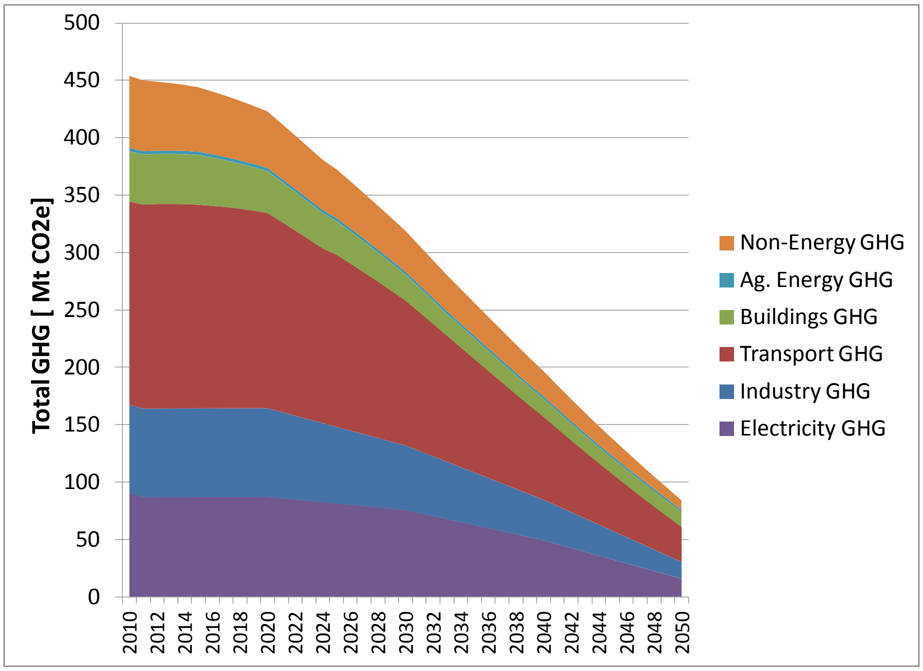


Figure 6.10: Total GHG emissions in the Frozen Efficiency/BAU Electricity Scenario, 2010-2050.

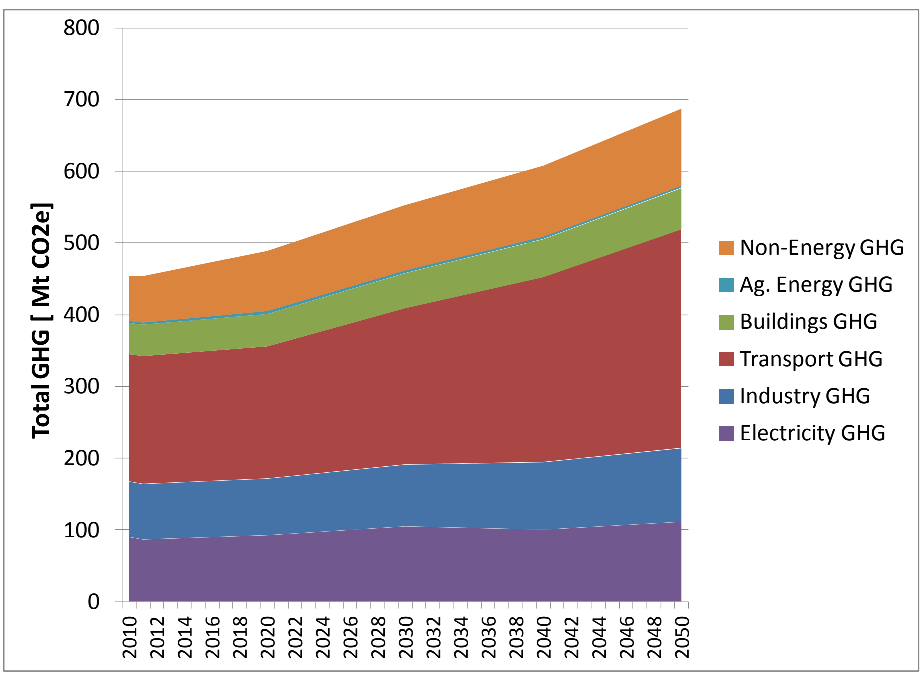


Figure 6.11: Total GHG emissions in -20% Carbon Cap/BioCCS Scenario, 2010-2050.

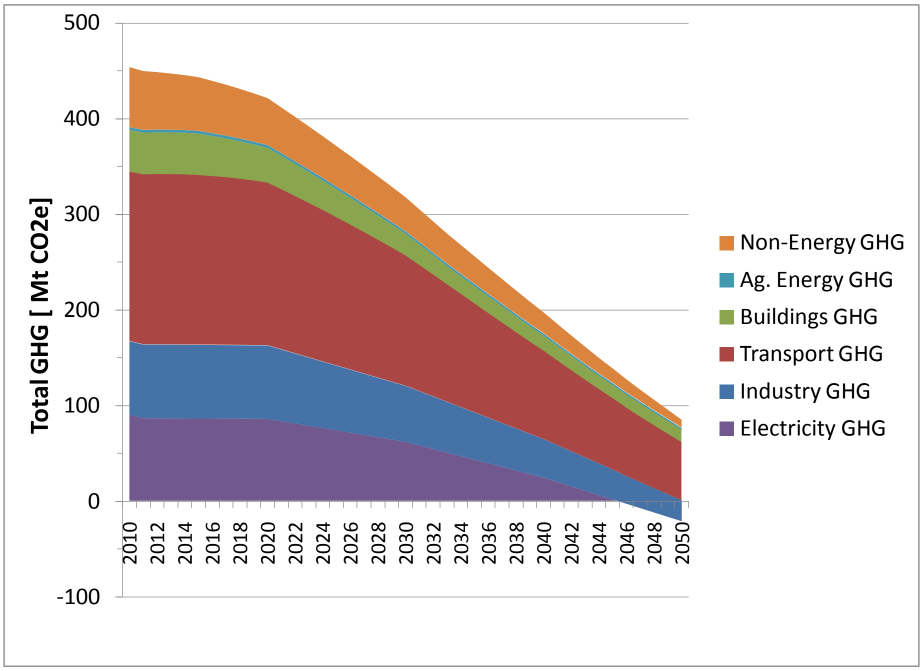


Figure 6.11: Total GHG emissions in -40% Carbon Cap/BioCCS Scenario, 2010-2050.

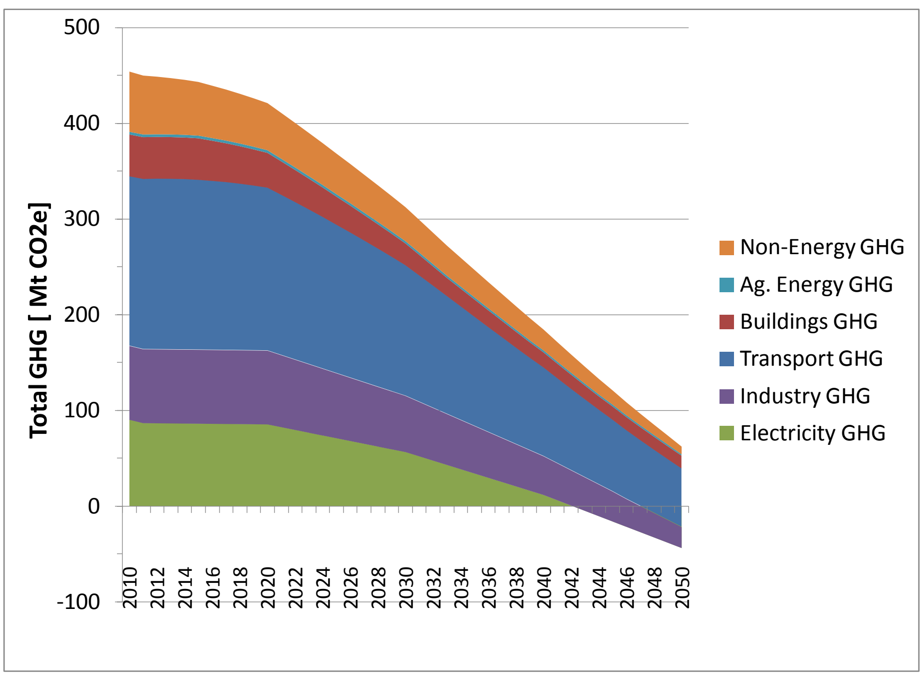


Table 6.5: Total GHG emissions (in Mt CO_2e) by decade for Base Scenario, Frozen Efficiency/BAU Electricity, and two BioCCS Scenarios.

Year	Base Scenario	Frozen Efficiency/BAU Electricity	Neg. 20% Electricity Cap/BioCCS	Neg. 40% Electricity Cap/BioCCS
2010	454	454	454	454
2020	423	489	421	421
2030	319	553	318	312
2040	196	608	197	185
2050	83	686	86	64

6.2.1 Summary of Energy Scenarios

The Base Scenario in this work is meeting the 2050 energy sector GHG target with about 10 Bgge total biofuel supply. Compared to the CCC1 with the same biofuel supply, energy emissions are about 20Mt lower in 2050 due to lower population growth, lower petroleum fuel demand, slightly higher ZEV adoption, and less resultant instate oil and gas industry activity.

Efficiency contributes about 48% of the overall GHG savings reduction with clean electricity and electrification combining for an additional 35% savings. The biggest single factors are transportation efficiency, electricity sector decarbonization, and transportation electrification. Reduced efficiency at half the technical potential savings level in buildings and industry has a small impact on overall emissions assuming the other Base Scenario conditions of clean electricity (14% cap relative to 1990 in 2050) and building and industry electrification held at Base Scenario levels are achieved.

Biomass CCS scenarios can achieve low overall GHG but the technology is not well established and is viewed as a higher technological and financial risk than other more established renewable energy technologies.

Many single factors can reduce energy GHG emissions well below target but none are easy to implement: e.g., 100% building and industry electrification, LDV conservation measures, a -40% carbon cap in the electricity sector, and carbon neutral biofuels (0% LCA).

If these "GHG favorable" measures could be deployed, they might enable a relaxation of other elements. For example, a low growth (or high conservation) scenario with no building and industry electrification could still meet the 2050 target; or a scenario of biofuel with 0% LCA factor and no industry electrification could meet the 2050 target.

CHAPTER 7: Conclusions

Consistent with the key conclusions of other 2050 studies, this study finds that achieving the 2050 GHG target requires a portfolio of key pathways, including aggressive energy efficiency, clean electricity, low carbon biofuels, and large-scale electrification of light duty vehicles, and building and industrial heating. Key hinge factors include vehicle efficiency (MPG standards and ZEV adoption); the development of a clean electricity supply; overall biomass supply availability and the life-cycle impact associated with resultant biofuels; and the decarbonization of building heating. Not achieving any one or more of these elements will require offsetting with deeper carbon reduction in other elements, and this study develops quantitative estimates for these tradeoffs. Key elements such as much greater deployment of energy conservation (reduction in energy service demand) or a carbon-negative electricity sector may be needed.

This study also highlights that deep reduction in high global warming potential gases are critical for the state to meet the 2050 GHG target. Afforestation is assumed to provide some GHG mitigation by 2050, and again, if this option is not pursued, then other elements must be tightened or others added. As other studies have highlighted, the combination of clean electricity and electrification is a critically important combination that can enable deep reductions in transportation emissions but also provides the technical possibility of largely replacing heating fuels in buildings. Sensitivity analysis also indicates that the combination of clean electricity and electrification of building heating can mitigate the requirements for maximum energy efficiency retrofits in buildings, and a comparative cost-benefit analysis should be done to further explore this scenario.

Important to emphasize, or re-emphasize is that to reach the 2050 target, high adoption of alternate technology or measures must largely be in place by 2035-2040, e.g., ZEV adoption, equipment with low GWP refrigerants, afforestation. For example, if the infrastructure and measures to support the adoption of low GWP equipment are not in place by 2035, it will be very difficult and/or costly to transform the equipment base by 2050. Similarly, afforestation can take two decades to reach maturity, so not embarking on large scale efforts by 2035 will not be able to intercept the 2050 target date.

Critically important to enable the transition to a low-carbon economy are supporting policies such as tightening existing policies in the buildings and electricity sector and developing effective policies to decarbonize building and industry heating and address the non-energy sector. Sustained technology development is required to scale up and reduce costs of existing technologies (e.g., batteries for ZEV, low carbon biofuels). Finally, greater integration of sectors is needed to achieve the long-term climate target (e.g., coordinated planning, regulation, and research across transportation, electricity sector, buildings, and industry sectors).

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