California's Energy Future - The View to 2050

Summary Report

California Council on Science and Technology
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Jane C. S. Long (co-chair)

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Message From CCST

CCST is pleased to present the results of the California's Energy Future (CEF) project, a study designed to help inform the decisions California state and local governments must make in order to achieve our state's ambitious goals of significantly reducing total greenhouse gas emissions over the next four decades.

This report is a summary of the CEF project and as such presents an overview of the project, the high-level findings, conclusions and recommendations. Subsequently, the CEF committee plans to produce a series of reports which give the details of the analysis.

California's Global Warming Solutions Act of 2006 (AB32) and Executive Order S-3-05 set strict standards for the state to meet. In order to comply, California needs to reduce its greenhouse gas emissions to 80% below 1990 levels by 2050 while accommodating projected growth in its economy and population.

The goal of the CEF project is to help California develop sound and realistic strategies for meeting these standards, by providing an authoritative, non-partisan analysis of the potential of energy efficiency, electrification of transportation and heat, low-carbon electricity generation and fuel. Our analysis is designed to identify potential energy systems that would meet both our requirements for energy and the emission target specified by executive order.

This study includes a set of energy system "portraits" which are descriptions of the set of energy demands, the portfolio of energy supply to meet these demands, and the associated emissions for each supply. Each portrait focuses on a different combination of energy strategies California might choose to provide the energy needed for future growth while aiming to reduce greenhouse gas emissions to the target amount. Each portrait incorporates strict accounting standards to ensure that trade-offs are made explicitly, energy measures are only counted once and all first-order emissions associated with various choices are counted.

The CEF study indicates that California can likely achieve significant reductions in greenhouse gas emissions by implementing technology we largely know about now. However, a combination of energy strategies and significant innovation will almost certainly be needed to achieve the 80% target, and the state will need aggressive policies, both near term and sustained over time, in order to make this possible.

We believe that the CEF project represents a valuable insight into the possibilities and realities of meeting California's electricity needs and emissions standards over the decades to come, and hope that you will find it useful.

Jane C.S. Long
California's Energy Future Committee
Co-chair

Miriam John
California's Energy Future Committee
Co-chair

Introduction

This summary report synthesizes the results of a two-year study of California's energy future sponsored by the California Council on Science and Technology. The study was funded by the California Energy Commission and the S.D. Bechtel Foundation, and was completed by a committee of volunteers from major energy research institutions in California.

This report assesses technology requirements for reducing greenhouse gas (GHG) emissions in California to 80% below 1990 levels by 2050 as required by Executive Order S-3-05 (2005). Details of this analysis, assumptions and data are to be found in forthcoming reports, including a detailed analyses for specific energy technologies. The present document serves to synthesize the results and present the major findings.

The challenge of meeting these GHG emission targets is large:

- By 2050, California's population is expected to grow from the 2005 level of 37 million to 55 million. Even with moderate economic growth and business-as-usual (BAU) efficiency gains, we will need roughly twice as much energy in 2050 as we use today.

- To achieve the 80% reduction goal, California's greenhouse gas emissions will need to fall from 470 $MtCO_2e$/yr (million metric tons of CO_2 equivalent per year) in 2005 to 85 $MtCO_2e$/yr in 2050, with most of those emissions (77 $MtCO_2e$/yr) coming from the energy sector. Accomplishing this will require a reduction from about 13 tons CO_2e per capita in 2005 to about 1.6 tons CO_2e per capita in 2050 (Figure 1).

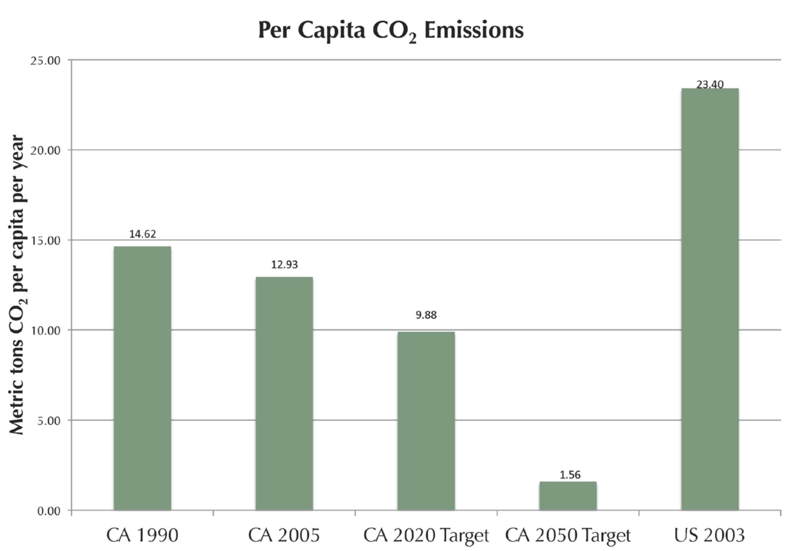


Figure 1. Per capita emissions.

This study has developed a set of energy system "portraits", each of which meets the challenge of providing the energy needed for future growth while striving to achieve the required greenhouse gas emissions reductions. We use the term energy system portrait to mean a set of energy sources, carriers and end-use technologies that meet all the energy needs of Californians projected for 2050. An energy system portrait describes an end-state or target energy system that could be a goal for California. This study connects related sectors of the energy system in order to account for trade-offs and inter-relationships. For example, if vehicle electrification is chosen as a strategy to reduce emissions, we also have to account for the emissions produced by the generation of the additional electricity needed for the vehicles.

Key Findings and Messages

California can achieve emissions roughly 60% below 1990 levels with technology we largely know about today if such technology is rapidly deployed at rates that are aggressive but feasible.

The following four key actions can feasibly reduce California greenhouse gas emissions to roughly 150 $MtCO_2e$/yr by 2050:

1. Aggressive efficiency measures for buildings, industry and transportation to dramatically reduce per capita energy demand.
2. Aggressive electrification to avoid fossil fuel use where technically feasible.
3. Decarbonizing electricity supply while doubling electricity production, and developing zero-emissions load balancing approaches to manage load variability and minimize the impact of variable supply for renewables like wind and solar.
4. Decarbonizing the remaining required fuel supply where electrification is not feasible.

Leaving any of these off the table will significantly increase the 2050 emissions.

- **The state will need aggressive policies, both near term and sustained over time, to catalyze and accelerate energy efficiency and electrification.** While innovation can improve the outlook for energy efficiency and electrification by reducing costs, we know how to improve efficiency or electrify for the majority of end uses.

- **The most robust, and thus most desirable, electricity system will not rely exclusively on a single generation technology.** We cannot predict with certainty the rate of technology or cost evolution of various approaches to generate low-carbon electricity. Moreover, each approach offsets the drawbacks of the others, and increases resiliency. It is imperative to pursue a suite of generation technologies, to keep options open as well as obtain the desired reliability in the full energy generation system:

    - Nuclear power provides reliable baseload power with very low emissions and can offset variability issues incurred by renewables, but faces obstacles with current public policy and public opinion. By law, new nuclear power in California is currently predicated on a solution for nuclear waste. Present electricity costs are expected to be higher than those from coal- or gas-fired plants if there are no emission charges. In addition, the recent 9.0 earthquake and tsunami in Japan, which led to a number of reactor explosions and radioactivity releases, will force a re-evaluation of nuclear power safety.
    - California has ample in-state renewable resources that can provide emission-free power and protect us from international energy politics that might affect fossil or nuclear power, but a high proportion of intermittent resources would result in significant emissions (if the power is firmed with natural gas) or a loss of reliability (if the power is not firmed), unless zero-emission load balancing technology

becomes available.

- Fossil fuel with carbon capture and sequestration (CCS) would modify an existing electricity pathway to provide a transition to the future, but relies on the large-scale development of a system of underground CO_2 storage.

- All forms of electricity require load balancing services to meet peak demand, accommodate ramping, ensure grid reliability, and address resource intermittency. Currently, this is mostly accomplished through the dispatch of natural gas turbines to respond to rapid changes in supply or demand for electricity. Load balancing with natural gas produces significant emissions. **If electric generation is predominantly intermittent renewable power, using natural gas to firm the power would likely result in greenhouse gas emissions that would alone exceed the 2050 target for the entire economy.** Thus, development of a high percentage of intermittent resources would require concomitant development of zero-emissions load balancing (ZELB) to avoid these emissions and maintain system reliability.[1] ZELB might be achieved with with a combination of energy storage devices and smart-grid technology.

- High-density hydrocarbon fuels (both gaseous and liquid) are imperative for some uses which cannot be electrified and where CCS cannot be deployed. These include transportation sectors (especially heavy-duty trucks and airplanes), high-quality heat, some stationary uses and some load balancing.[2] In 2050, even after aggressive electrification and efficiency gains, we will likely require 70% as much liquid and gaseous fuel as we use today.[3] Current mean supply estimates of available, sustainable biofuels in 2050 are about 13 bgge/yr, or about half of the projected 2050 residual fuel demand including heavy duty transport, high quality heat, and gas needed to produce electricity for load balancing.[4] **Even after aggressive efficiency and electrification measures have reduced fuel use as much as feasible, if just half of the estimated residual fuel demand in 2050 is still supplied by fossil fuel, the resulting emissions alone will exceed the 2050 target.**

We could further reduce 2050 greenhouse gas emissions to 80% below 1990 levels with significant innovation and advancements in multiple technologies that eliminate emissions from fuels. All of these solutions would require intensive and sustained investment in new technologies plus innovation to bridge from the laboratory to reliable operating systems in relatively short timeframes.

1 We define zero-emissions for ZELB as adding no new emissions through the use of load balancing technology. The energy used to charge storage devices may incur emissions, but the storage device itself should have none if it qualifies as ZELB.
2 Hydrogen may be a viable substitute for some of these end uses; see discussions later in this report.
3 Exclusive of gas used for load balancing
4 Assuming renewable are limited to 33% of the electricity portfolio

- **The supply of renewable biomass, decisions regarding its use, and possibilities to import biofuels into the state will have a large impact on additional GHG reductions from fuels.** Large quantities of bio-energy could reduce emissions significantly primarily by displacing the use of fossil fuels, but quantities are uncertain. If biomass or biofuel becomes an energy commodity, ancillary impacts on food, water and fertilizer could become a serious problem.

- **There are many additional technologies that reduce emissions from fuels. In combination these could achieve the required additional emission cuts from 60% to 80% below 1990. Many require multiple simultaneous strategies, some are industrially complex and costly and some are actually offsets, but all of them require research and innovation.**

- CCS is likely to be an important part of several possible schemes to provide hydrogen, low-carbon fuels or offsets that allow continued fossil fuel use. **For California, the utility of CCS in achieving a low carbon fuel portfolio could be as important as the the utility of CCS for electricity production per se.**

- Possible breakthrough technologies such as carbon neutral fuel from sunlight or advances in nuclear power could be game changers. These would allow us to produce abundant electricity or fuel with nearly zero emissions.

Methodology

To arrive at these conclusions, the committee took a two step approach. First, we conducted a "stress test" to see if any one technology option (e.g. efficiency, nuclear power, renewable energy, biofuels etc.) could meet the 2050 energy requirements and not exceed the emissions target. The net result of these "stress tests," following considerable analysis, is "no single approach can solve the problem."

Secondly, the committee systematically examined various combinations of energy processes and technologies to find systems that could best reach the requirement with technology that is largely available today, i.e., either deployed or at least demonstrated at scale. These system combinations are referred to as "energy system portraits."

Assuming that California's population and economy grow as expected, we addressed four key questions with each scenario:

1. How much can we control demand through efficiency measures in buildings, transportation and industry by 2050?	This measure will decrease the need for electricity and fuel. We evaluate efficiency measures in buildings, transportation and industry.
2. How much can we electrify (or convert to hydrogen fuel) for transportation and heat by 2050?	This measure will increase the demand for electricity (or hydrogen fuel produced with little or no emissions), but decrease the need for fuels that cause emissions.
3. How do we de-carbonize enough electricity to meet the resulting electricity demand and satisfy the need for load balancing with what remaining emissions?	We examine nuclear power, fossil fuel (both coal and natural gas) with carbon capture and storage (CCS) and renewable energy. We look at two ways to avoid the use of natural gas for load balancing: electricity storage and flexible load management.
4. How do we de-carbonize enough fuel (hydrocarbons or hydrogen) to meet the remaining demand and with what remaining emissions?	We examine the future of biomass to either make biofuels, or to produce electricity with CCS and therefore create offsets that allow continued use of fossil fuels, and examine the use of hydrogen produced with methane and CCS or other emerging technologies.

Table 1. Four key questions.

Our approach is a logical analysis, not a projection or a prediction. We have performed an "existence proof" – to see if we could identify energy systems that will meet our needs, including economic and population growth –while attempting not to violate very aggressive emission standards or demanding very large, obvious increases in cost.

The process of eliminating emissions from the energy system while still meeting our requirements for energy can be illustrated in Figure 2a-e. The width of the box represents the demand for energy we expect to need in 2050, divided into electricity and fuel, and the height of the box is the GHG intensity of that energy. Thus, the area of the box is the GHG emissions or "footprint" of the resulting energy system (a). We are reducing the 2050 BAU (business-as-usual) footprint into a smaller 2050 target footprint. We decrease the width of the box from both sides (b) by using less energy to do the same work (efficiency), and we shift the box to the right (c) by switching from fuel to electricity where it makes sense energetically[5] (electrification) because electricity is more easily decarbonized than fuel, and then we decrease the height of the box (d) by using de-carbonized electricity and fuel sources ("low-carb" energy).

5 For example, boiling water with fuel to make steam, which is then used to make electricity, which is then used to make steam again, doesn't make sense energetically. Using an efficient electric heat pump in lieu of gas heating in homes, however, does make sense.

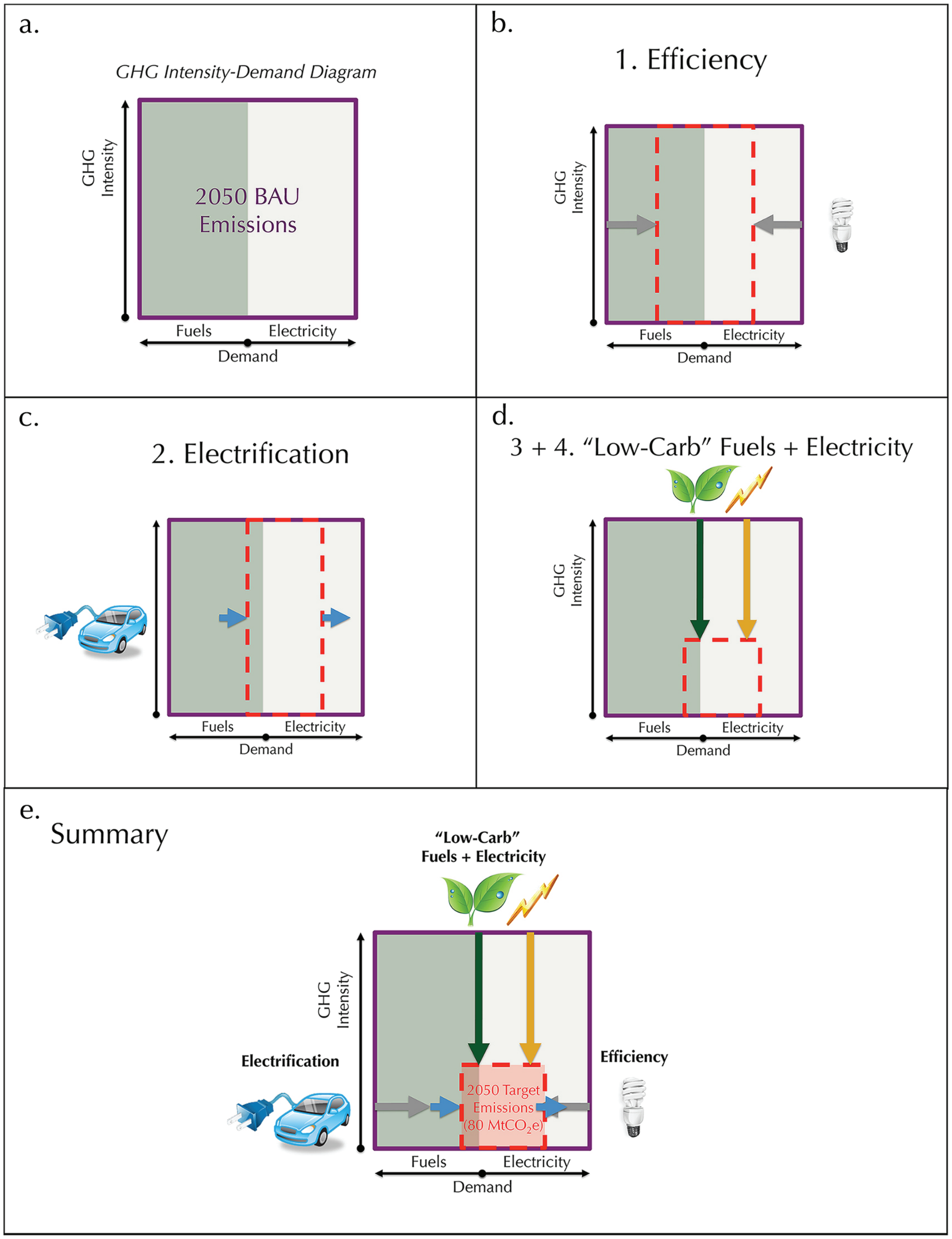


Figure 2. Schematic illustrating strategies for meeting our energy needs while eliminating emissions.

The calculations required for this process are embedded in a large, multi-tiered spreadsheet developed specifically for this study described in the sidebar, the California's Energy Future Spreadsheet. The quantification of the spreadsheet is based on a combination of state data, national data, prior analyses and the expert judgment of the committee. Some choices are expedient simplifications, such as choosing a single median value for population and economic growth. There are other choices where data is limited so we selected a median estimate from a very wide range of possibilities. The value of the observations and conclusions below are as good as the estimates we have made, but the tools and methodology we have produced are robust and can be used to examine different assumptions or incorporate new data as this becomes available. These tools and study methodology should be considered a major contribution of the CEF project.

The California's Energy Future Spreadsheet

The CEF spreadsheet insures that our portraits of the 2050 energy system have:

1. Accounted for all major demands for energy in the future as modified by efficiency gains.
2. Matched each of these demands with a source of energy (e.g., sunlight, coal, etc.) and the carrier for that energy (e.g., electricity, or various fuels).
3. Kept track of all the emissions that will result from utilizing these sources.
4. Estimated the required build-out rates for the technologies invoked in the portrait.

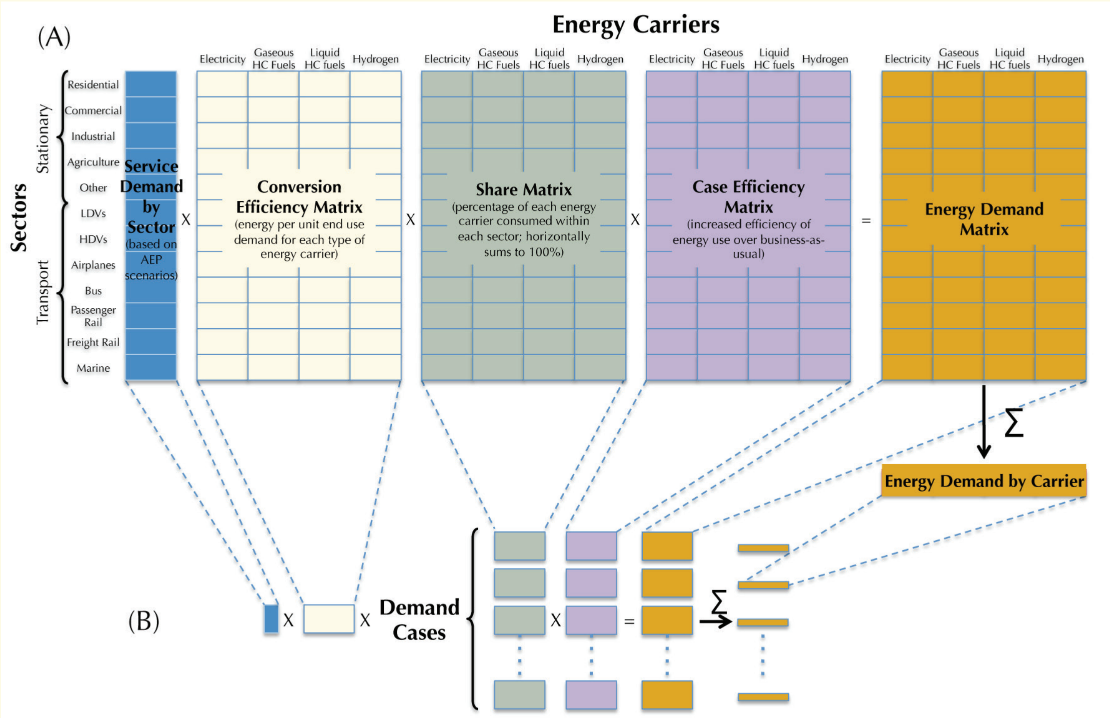
Efficiency, electrification and hydrogen fuel switching measures can be specified by the user. Because the end use efficiency also depends on the energy carrier, this factor is built into the spreadsheet. The user can also modify the technology used for load balancing and the spreadsheet will modify energy demands associated with this choice. In some cases, the choice of energy supply technology changes the total demand (e.g., use of fossil fuel increases the total demand for fuel because refining consumes some energy) and this calculation is also included. Resource limitations, such as the total amount of available biofuel, are also specified by the user.

Figure 1 illustrates the way the spreadsheet calculates the set of energy end-use demands separated into energy carriers: electricity, gaseous hydrocarbon fuels, liquid hydrocarbon fuels and hydrogen. Figure 2 illustrates how the choices of energy source for each carrier, as specified by the user, is used to calculate the total emissions.

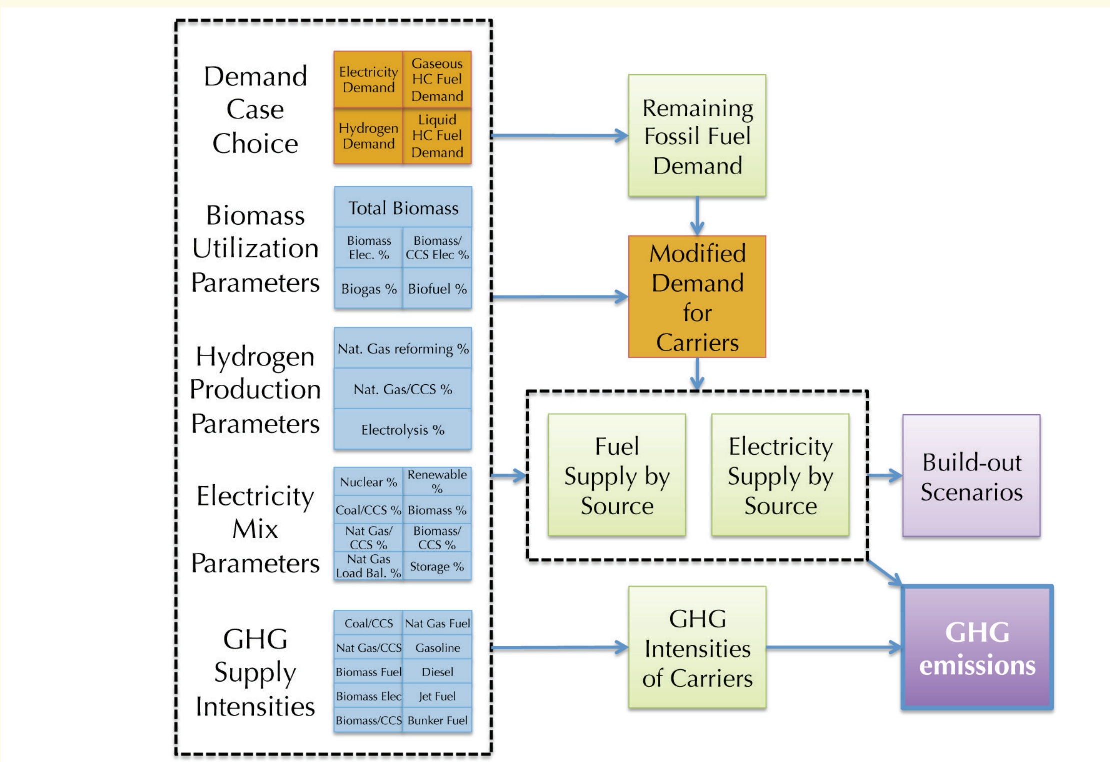
The spreadsheet is set up to calculate the GHG emissions of many dozens of portraits simultaneously, and group them for plotting in various ways. The adjustable input parameters that determine each portrait, including GHG intensities, are summarized in a single column.

While portraits describe the energy system for a single year (2050), the spreadsheet also makes some simple calculations concerning the build-out of various technologies from 2005 to 2050, using input parameters from selected portraits.

The spreadsheet tool offers the opportunity to explore the effects of different assumptions and policies on the outcomes for 2050. For example, the CEF study only used one value of population growth and economic growth. It would be useful to know how given choices would be affected by a range in these values. As well, we have made assumptions about the amount of available biomass and the carbon intensity of various technologies. These will surely be updated over time and the effect of new information can be calculated. Most importantly, various advocates present one idea or another as important for our energy future. The CEF spreadsheet is a tool that can be used to see just how important each of these ideas actually is.



Calculation of energy system end-use demands categorized by energy carrier.



Calculation of emissions associated with the energy supply technologies needed to meet the end-use demands.

Our focus was to evaluate the capacity of technology to provide the solution. We discuss four kinds of technology (Table 2). We first invoked technology currently available at scale or currently demonstrated (almost entirely bins 1 and 2). Deployment of this technology was able to reduce emissions significantly. For the most part, we did not invoke technology in bin 3 except in a few cases where committee members thought implementation of this technology would in fact happen by 2050.

Bin 1 and 2 technology was not enough to reduce emissions by 80%. To meet this target, we had to draw on technology that was not currently available at scale (bins 3 and 4). Thus our assessments indicate where energy innovation will be needed to create energy systems that meet our needs without exceeding 2050 emission limitations.

Technology Bin	Description
Bin 1	Deployed and available at scale now
Bin 2	Demonstrated, but not available at scale or not economical now
Bin 3	In development, not yet available
Bin 4	Research concepts

Table 2. Technology readiness bins.

We assumed that scaling up energy technology in California would be performed in the context of scaling up the same technologies throughout the world. Thus California can only command its share of resources. Our analysis allows these "fair-share" imports, but requires that the emissions associated with these sources of energy are counted in our inventory. We do not allow "leakage" of emissions.

We did not perform our own economic projection analysis, as such an analysis was beyond the scope of this project. Instead, we qualitatively relied on several recent studies of energy systems for 2050, some of which show that prices estimated for 2050 (A study by E3 on California,[6] a European 2050 study,[7] and The National Academy of Sciences' America's Energy Future study.[8]) are not a significant differentiator of the major supply technologies. As well, escalating world-wide demand for fossil fuels might make low carbon energy relatively less expensive. We attempted to rule out choices that were clearly too expensive to consider based on economic information in other studies, and we asked our investigators to provide information on why prices might go down from where they are today (e.g., economies of scale) or why they might go up (e.g., resource limitations). We remain concerned about the level of capital investment required to create the energy systems we have described. These economic issues deserve further study. The technology analysis presented in this study provides strong guidance for subsequent economic analysis.

Our base study does not initially include any factors for behavioral change, in order to evaluate whether technology alone could solve the problem. At the end, we evaluated behavioral change as an added factor in reducing energy demand and making the problem easier to solve.

Finally, we evaluated how California's research institutions are contributing to the development of energy technology in Bins 3 and 4 and thus could contribute to new energy systems -- for California and for the world as well.

6 Energy and Environmental Economics, Inc., Meeting California's Long-Term Greenhouse Gas Reduction Goals, Novembver 2009: http://www.ethree.com/documents/2050revised.pdf,

7 Roadmap 2050, A Practical Guide to a Prosperous, Low Carbon Europe: http://www.roadmap2050.eu/.

8 National Academies Press, America's Energy Future: Technology and Transformation: Summary Edition 2009: http://www.nap.edu/catalog.php?record_id=12710.

Stress Tests

An initial analysis addressed the question: could any single, isolated approach solve this problem? To answer this question we proposed a series of "stress tests" for each set of technologies. Could we solve the whole problem if we just became more efficient? Could we solve the entire problem with just nuclear power, or CCS or renewable energy, without worrying about efficiency? Could we have enough emissions-free biomass to fuel our entire economy?

The answers to these questions are either categorically "no, it is not physically possible", or "yes, but the impacts and obstacles are so large, the concept does not appear rational":

- Energy efficiencies sufficiently great are possible in some building sectors, but ubiquitous implementation is likely prohibitively expensive; in other sectors they are thermodynamically impossible.
- Solving the whole electricity problem with renewable energy creates extremely large problems in load balancing due to intermittency, significant land-use issues.
- Fossil fuel with CCS alone would stress the emission target – as it is difficult to capture more than 90% of the CO_2 economically – and would push us quickly into using largely uncharacterized saline aquifers for storage.
- Nuclear power has perhaps the best technical chance to meet all our electricity needs, but the build out rate would be several large nuclear power plants per year and raises questions about nuclear waste and safety.
- If in addition we were to try to make liquid and gaseous fuels from electricity, we would create a nearly insurmountable demand for decarbonized electricity.
- The most optimistic possibilities with biomass indicate that, with significant innovation, and the highest estimates of biomass supply including imports, we could meet our needs for liquid and gaseous fuels, but there is significant uncertainty about supply and ancillary impacts on food, water and fertilizer.

The stress test indicates that even highly optimistic single solutions are most likely untenable and this leads to the conclusion that a portfolio of approaches will be required.

Energy System Component Analysis

Having determined that there are no simple solutions, the CEF committee searched for solutions that involved many components.

We assessed feasible progress in four major actions to modify the energy system: efficiency, electrification, decarbonizing electricity (including load balancing), and decarbonizing fuel.

1. Efficiency and Electrification

Efficiency and electrification measures are discussed together because many electrification measures are also often efficiency measures. Electrification refers to the process of switching from using a fuel to provide the desired end use service to using electricity-powered systems. For instance, replacing natural gas for water or space heating to high efficiency electric heat pumps, or switching from gasoline-powered cars to plug-in hybrid or all-electric vehicles.

Projected advances in 2050 are largely limited by turnover rates. We assumed aggressive turnover rates that are nonetheless within the range of historical precedents. These measures include:

- All new buildings built to new energy standards starting in 2015. These standards result in progressively more efficient buildings which, by 2040, use 80% less energy than business-as-usual. All remaining buildings are either aggressively retrofitted or replaced as part of their natural lifecycle, yielding 40% overall efficiency improvements in buildings.
- Seventy percent of building space and water heating shifts from natural gas to using electricity.
- A reduction of 30% in petroleum use and 50% in natural gas use from business-as-usual will be achieved in industry primarily through BAU efficiency gains and some electrification. Downsizing of the refining industry as the economy transitions to using biofuels could further reduce industrial fossil fuel use from BAU by about 15%.
- By 2050, approximately 70% of new light-duty vehicles (LDV), and about 60% of the fleet, are either plug-in hybrid or all-electric. The liquid fuel portion of vehicles is quite efficient relative to today: 64 mpg for new vehicles, and 58 mpg for the fleet average. Including electric vehicle miles in the average gives 87 mpgge[9] for new vehicles and 72 mpgge for the fleet. Bus and rail are 100% electrified.
- For the hydrogen scenario, approximately 60% of the 2050 LDV fleet are hydrogen-powered and 20% are either plug-in hybrid or all-electric, resulting in a lower conventional fuel usage than in the non-hydrogen scenario. The efficiency of hydrogen-powered vehicles is about 80 mpgge.
- Overall fuel use in aviation and trucks drops by about half due to significant efficiency and operational improvements and, for trucks, electrification of short-range vehicles.

In total, we find that aggressive efficiency measures could reduce the projected demand for electricity by 36% relative to BAU. The majority of technologies needed for these efficiency measures are either currently commercial or in demonstration. Technologies in demonstration or development will require innovation and widespread consumer adoption.

9 Miles per gallon gasoline equivalent.

The resulting demands, compared to 2005 and BAU estimates, are given in Table 3. These demands must be met under an energy sector emissions budget of 77 MtCO_2e/yr to comply with the 2050 target.

Energy Carrier *	**2005**	**BAU 2050**	**2050 Efficiency only**	**2050 Efficiency and Electrification**	**2050 Efficiency, Electrification and Hydrogen**
Electricity (TWh/yr)	270	470	330	510	460
Gaseous fuel** (bgge/yr)	12	24	13	9	6
Liquid fuel (bgge/yr)	24	44	22	16	12
Hydrogen (bgge/yr = TgH_2/yr)					8

Table 3. Projected energy demands in 2050. (Note that 1 gge of gaseous fuel is 1.15 Therms)
* See Appendix A for explanation of energy units.
** Some portfolios include additional gas for electricity generation (load balancing and/or CCS).

Enhanced electrification would simultaneously increase the demand for electricity by about 70%. The net effect is that electricity demand nearly doubles from 270 TWh/yr today to 510 TWh/yr in 2050 at the same time emissions from electricity must be largely eliminated.

The demand for gaseous and liquids fuels could be reduced by over 60% each relative to 2050 BAU demand by a combination of efficiency plus electrification. So, in 2050, we would use about 70% of the fuel we use today.

If hydrogen were readily available, its use as a fuel would decrease the need for gaseous fuels by about 40% and liquid fuels by 24%, and decrease the end-use demand for electricity by about 10% relative to the efficiency plus electrification case.

Today, a new building can be constructed to be 40-50% more efficient with no difference in up-front cost.[10] Estimates for the cost of "deep" efficiency retrofits (~70-80% energy use reductions) to existing buildings range from $40,000 to $100,000 per building.

For industry, the ACEEE[11] estimates a cost of $200-300 billion through 2025 for the U.S. for a 25-30% reduction in energy intensity. These figures are roughly 6-10% above what industry (manufacturing) historically spends on energy and capital expenditures on an annualized basis. In California, this would translate to $1.5-2.2 billion per year, assuming the state maintains a constant share of U.S. industry. Costs beyond 2025 are difficult to project since there is considerable uncertainty in electrification capital, re-tooling and design costs and actual state industry composition in 2050.

10 Walker I (2009), Personal communication, Lawrence Berkeley National Laboratory.
11 Elliott N (2009), Personal communication, American Council for an Energy-Efficient Economy.

Estimates are that advanced light-duty vehicles such as PHEVs and FCVs could become cost-competitive with conventional gasoline vehicles on a life-cycle basis as the price for conventional liquid fuels rises. However, reaching this point of cost-competitiveness will require several decades and require large subsidies (on the order of tens of billions of dollars in the U.S. as a whole) to buy down the vehicle costs.[12] Transitions to Alternative Transportation Technologies – Plug-in Hybrid Electric Vehicles.[13] An important challenge for adoption of these vehicles is that consumers are sensitive to initial cost and tend to discount future savings on fuel expenditures when considering vehicle purchases.

Efficiency and Electrification Research

UC Santa Barbara, UC Davis, and Lawrence Berkeley National Laboratory (LBNL) conduct valuable research on energy efficient LED lighting, and LBNL is also a world-class center for work on energy-efficient buildings (including appliances, equipment and electronics) and industry. In addition, both Stanford University and UC Davis have energy efficiency centers. These capabilities can help California companies become leaders in these areas.

Fuels cells can be used in both vehicles and buildings, and California has major hydrogen capabilities at UC Davis, UC Irvine, Sandia National Laboratory - California, Lawrence Livermore National Laboratory, and elsewhere. The “father” of the plug-in hybrid electric vehicle is at UC Davis.

2. Electricity

In general, three are three ways to produce de-carbonized electricity: nuclear power, fossil fuel with carbon capture and storage (CCS), and renewable energy. The stress test analysis indicated that, although we could not expect to solve the whole energy problem with any given electricity generation technology, we could theoretically meet the 2050 electricity demand given in the above table with any of the three sources of electricity (nuclear, fossil with CCS, or renewables). Further, we assumed that the California law requiring 33% renewables would remain in place, as would our existing hydropower resources. Therefore nuclear power or fossil with CCS would be asked to provide at most 67% of the electricity (340 TWh/yr), whereas renewable energy could be asked to provide 100% (510 TWh/yr).[14]

12 Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council, National Academy of Engineering. The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs. National Academies Press, 2004. (http://www.nap.edu/catalog.php?record_id=10922#toc)

13 Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, National Research Council. Transitions to Alternative Transportation Technologies – Plug-in Hybrid Electric Vehicles. National Academies Press, 2010. (http://www.nap.edu/catalog.php?record_id=12826#toc)

14 Depending on how load balancing is accomplished, additional electricity generation might be required to make up for electrical storage losses—up to an additional 7% or 34 TWh/yr for renewables-only generation. Moreover, depending on the demand for fossil fuels, refining might add up to 15 TWh/yr in additional demand. Finally, if hydrogen is produced from electricity, demand could increase by 350 TWh/yr—a 70% increase above the median 2050 demand.

Our analysis focused on three key issues:

1. What are the emissions associated with meeting the increased demand for electricity in 2050 with either nuclear power, fossil with CCS, or renewables?
2. What are the requirements for scaling up?
3. What are the ancillary impacts?

For nuclear and renewable energy, the emissions associated with generation are nearly zero. For fossil fuel with CCS, CO_2 capture technology with a 90% removal rate would result in residual emissions of 28 $MtCO_2$/yr for coal - and 13 $MtCO_2$/yr for gas - fired electricity in 2050. Technologies with greater than 90% capture will likely suffer from severe energy penalties or are considered bin 3 or 4 technology which may not be available by 2050.[15] Thus providing 67% of electricity in 2050 through coal with CCS would produce about one third of the allowed 2050 emissions, leaving significantly less left for remaining distributed fuel use requirements. Natural gas with CCS has a lower GHG footprint and would produce about a fifth of the allowed emissions.

<u>*Nuclear Power*</u>

The requirements for scaling up nuclear power include:

1. Either licensing a national nuclear waste repository or changing the California law which requires a licensed repository before new reactors can be built;
2. Building about one new plant per year starting in about 2020;
3. Licensing Gen III[16] reactors;
4. Reducing costs, which are currently high (if the nuclear industry were reinvigorated, costs might be reduced to about $60-80/MWh.);
5. Renewing the Price Anderson Act, which indemnifies operators against catastrophic accidents with costs exceeding $10 billion; and
6. Reassessing the safety of nuclear power, especially given the recent events in Japan.

We would have to build approximately one new power plant a year from 2020 to 2050 in order to provide 67% of California's expected 2050 baseload electricity demands, which is deemed possible with standardized designs. The technology to build advanced (Gen III) nuclear power plants is commercially available now. Costs, although high now, are expected to decline significantly if construction cost reductions observed in Japan, Korea, and China also occur in the U.S.

The potential ancillary impacts of expanding the use of nuclear power in California include public opinion and nuclear waste. The waste issue is currently being examined by a Presidential Blue Ribbon Commission that is likely to recommend changes to the Nuclear Waste Policy Act. The issue of nuclear waste disposal remains unresolved, but is deemed technically solvable, as it has been solved in Sweden and Finland.[17] New nuclear power is currently banned in California until a geologic disposal facility for nuclear wastes is licensed by the federal government. Proliferation

15 This assumption is consistent with estimates used in the Intergovernmental Panel on Climate Change Special Report on Carbon Dioxide Capture and Storage (2005), http://www.ipcc.ch/pdf/special-reports/srccs/srccs_summaryforpolicymakers.pdf, and the National Academies Summit on America's Energy Future (2008), http://www.nap.edu/openbook.php?record_id=12450&page=143.

16 Gen III refers to third generation or advanced nuclear technology.

17 "Nuclear Power in Sweden." Feb. 2011. World Nuclear Association. 3 May 2011. (http://www.world-nuclear.org/info/inf42.html)

concerns are not an issue for expanding nuclear power in California, but would be an issue for the federal government if the whole world expands nuclear power.

Water for cooling nuclear reactors can be a sustainability concern. However, progress in the use of waste water, sea water, and air-cooled systems can reduce freshwater impacts. Air cooling is an alternative but would reduce efficiency and increase costs.[18] Siting in an earthquake-prone state is feasible, as demonstrated with the State's two existing sites. However, additional concerns about having a source of water for emergencies and siting in seismic zones may arise on review of recent events in Japan (see below). Uranium fuel assessments indicate that adequate amounts will be available through 2050 and beyond, and fuel reprocessing technologies exist in the event uranium fuel supplies were to run short.[19]

In March of 2011, Japan experienced a record breaking earthquake of magnitude 9.0 followed by a 30-50 ft high tsunami. The consequent damage to reactors at the coastal Fukushima Daiichi Nuclear Power Station has resulted in the worst nuclear accident since the Chernobyl reactor disaster a quarter century ago. This episode included multiple, simultaneous damaged re-actors and breached containment, and has resulted in radiation leakage and loss of life. It is too early to completely understand the full impact and importance of this accident, as events are still unfolding. We will need to evaluate exactly what happened and why, and interpret these events in a variety of relevant contexts to determine what it is we should learn from them. However, what is clear even now is that this event will have a major impact on the way we think about nuclear power and will be a factor in considering the future of nuclear power in California.

Fossil with Carbon Capture and Storage (CCS)

Given the stringency of the 2050 greenhouse gas emissions target, any use of fossil fuel for electricity generation would need to be paired with capture and geologic storage of the resulting CO_2 emissions. There are a number of approaches to pairing CCS with combustion or gasification of fossil fuels, each of which has its advantages and drawbacks. Much of the technology required for CCS is in the demonstration phase (bin 2).

Natural gas with CCS is a better choice than coal with CCS from an emissions standpoint (e.g. fewer CO_2 molecules overall to capture and store), but natural gas availability and costs are volatile. It is unlikely that California would begin to develop coal-fired electricity in-state, but we might import electricity produced this way and thus have to count the emissions. As a result, any imported electricity from coal would have to be produced with CCS. Environmental issues with gas and coal production are mainly outside of California, but remain significant, including degradation from coal mining and issues with water used for hydrofracking[20] tight gas reservoirs in the production process.

Based on assessments from the U.S. Department of Energy and others, it is estimated that California has only a few decades' worth of CO_2 storage capacity in well-characterized, abandoned oil and gas

18 Planning for cooling without using water is likely to be the norm. Recently, the State Water Resources Control Board has mandated the retrofit of 19 of the State's largest fossil and nuclear power plants to prohibit the use of once-through cooling with ocean or estuarine waters. Estimated costs for retrofit for Diablo Canyon and San Onofre nuclear plants are in excess of $2 billion each, casting doubt on those plants' continued operations.

19 Supply estimate per Uranium 2007: Resources, Production and Demand, jointly prepared by the OECD Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA)

20 Hydraulic fracturing (hydrofracking) is a process of fracturing rock in reservoir rock formations in order to increase the rate and recovery of oil and natural gas.

reservoirs in California, perhaps enough to last through the 21st century[21]. Saline aquifers could provide many decades of storage capacity beyond this, but more research is required to establish their safety and suitability for CCS.

The capacity factor[22] for fossil with CCS is 80%, somewhat lower than that for nuclear power. But in addition, the capture and sequestration of the CO_2 requires energy that is then not available for distribution. This energy is known as "parasitic load." The aspirational goal of CO_2 capture research is to reduce parasitic load down to 10%. This has been demonstrated in the laboratory but not at commercial scale; therefore this is a "bin 2" technology need. If there is a 10% parasitic load for CO_2 capture, the gross amount of fossil with CCS capacity needed is 54 GW (for the case where fossil with CCS serves 62% of 510 TWh/yr). However, if we limit ourselves to "bin 1" (e.g. current amine scrubbing), parasitic loads are in the neighborhood of 30% - which would result in a need for 64 GW of capacity in that case and increasing the cost of electricity from this source accordingly.

The build rate would be similar to nuclear power, about one plant per year (China builds one conventional coal-fired plant about every two weeks). The cost of capture remains quite high at $20 – 40/ MWh. The cost of sequestration in oil and gas reservoirs is a small fraction of the capture costs. Should pipelines be required, these are estimated at $500,000 per mile, as compared to $1+ million per mile for electricity transmission.

Renewable Electricity

California has a wide variety of renewable resources – wind, solar, biomass, geothermal, hydro, and marine energy offshore. As estimated in several California Energy Commission studies, the total available resources are more than sufficient to meet the expected demand for electricity required in 2050 and beyond.

Because renewable resources (particularly wind and solar) tend to have a lower capacity factor than other generation resources, much more renewable generation capacity would need to be built than in the other cases. If an average capacity factor of 37% is assumed, annual installed renewable energy generation would need to increase by an order of magnitude, from 16 GW in 2009 to 165 GW in 2050. To put this in perspective, this implies a growth rate for wind power of about 7.5% per year, and for solar power of about 12% per year, even with assumed increases in biomass and geothermal power and the assumption that California's large hydro resources remain in operation.

Most of the renewable generation technology is commercially available and much innovation is underway to improve performance or decrease generation cost. Most renewables will become competitive with a price for CO_2 of about $30/t. In some recent power purchase agreements, larger solar photovoltaic (PV) facilities were priced at or below the price of new natural gas facilities (thanks to Federal and State tax incentives), enabling them to compete with grid power. Wind energy in areas of good wind resource can be cost-competitive given this same favorable tax treatment, and conventional geothermal and hydropower resources are already among some of the lowest-cost resources in California.

21 Herzog, Howard, Weifeng Li, Hongliang (Henry) Zhang, Mi Diao, Greg Singleton, and Mark Bohm. 2007. West Coast Regional Carbon Sequestration Partnership: Source-Sink Characterization and Geographic Information System-Based Matching. California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2007-053.

22 The net capacity factor of a power plant is ratio of the actual output of a power plant over a period of time and its output if it had operated at full nameplate capacity the entire time.

However, most renewable energy resources must be located near the resource rather than near the load they serve. Thus in most cases, projects must also factor in the costs of increased requirements for transmission. Another key issue for renewable electricity is that only hydropower and biomass are "dispatchable" (e.g. they can be adjusted to meet available load). The other types of renewable generation are either baseload (marine and geothermal) or intermittent and variable (wind and solar). Neither of these types of generation is able to follow load and therefore require some other "load balancing" resource to satisfy changing electricity demand at all times (which is a requirement for reliable grid operations).

Harvesting of energy from the natural environment at such a scale will have obvious land use impacts. We estimate the land area required to produce 100% of California's electricity needs in 2050 will be about 5% of the land area in California. Wind farms only directly displace about 2% of the required land areas, with the rest available for other activities (e.g., ranching); distributed (rooftop) PV does not displace new land; and virtually all California biomass is assumed to come from municipal, agricultural and forest waste streams, and marginal lands not currently in agricultural production. So, the amount of land that would be directly displaced by renewable energy will be about 1.3% of California.

Other environmental impacts of concern associated with a large build out of wind energy may include adverse impacts on birds and other avian species, turbine noise effects on nearby communities, and downstream impacts on local weather and climate. For solar thermal systems (concentrating solar power (CSP)) and biomass systems, there are water impacts for cooling unless dry cooling is utilized, and a small amount of water is required for cleaning of solar PV installations. Geothermal energy may require water to keep the reservoirs from depletion, but, as with nuclear power, this can be waste water as is used at The Geysers. Hydro and marine resources significantly impact fish and other aquatic species if fish protection technologies or operations such as fine-mesh screens, spill, or diversions are not employed.

Load Balancing

To maintain a reliable electricity grid, grid operators (such as the California ISO) must ensure that supply of electricity is equal to demand for electricity at all times. In a conventional electricity generation mix, certain assets are operated in "baseload" mode, i.e. at a constant power output over all times. Other assets are operated in "intermediate" mode with a defined output curve, i.e., meeting the expected, predictable daytime increase in electricity demand associated with air conditioning use. Finally, additional resources are operated in "peaking" mode to close the residual gap between what baseload and intermediate assets are scheduled to provide, and the actual demand for electricity at any given time. If such "peaking" resources are not available or too expensive, imports of excess power from nearby regions can be used. Emerging technology approaches, such as energy storage or controllable loads (e.g., interruptible air conditioning) offer still further flexibility in grid system operations and planning. Finally, if no other resources are available to meet demand, electric loads are curtailed either voluntarily as part of a utility-offered rate program, or, as an absolute last resort, involuntarily through rotating "blackouts" (loss of service).

In each portrait considered here, we must make the assumption that "the lights stay on", i.e. the supply and demand are balanced at every point. We use the term "load balancing" to include all aspects of this matching of supply and demand as a function of time, including firming intermittent renewables, energy required to meet peak load over baseload, and energy for ramping. The additional energy requirements for load balancing and their corresponding GHG emissions signatures prove difficult to estimate. To do so, we would need to match the output shapes of the various resources (nuclear, fossil with CCS, renewables) with the expected demand curves of consumers in 2050 after all of the efficiency and electrification actions described above have been taken, and derive from that an estimate of additional generation resources needed for load balancing. This is a very large chain of poorly understood factors.

Rather than make a specific point estimate about how the 2050 electricity system is likely to evolve (and incorporate all of the uncertainty that would entail), we chose instead here to look at two extremes: (1) all load balancing met with natural gas turbines (with a 30% average efficiency and no CCS); or (2) all load balancing met with zero-emissions load balancing (ZELB) resources such as energy storage, or smart grid-connected controllable loads. For renewables, this would include ramping and storage to counter the variability in wind and solar resource availability due to wind gusts, clouds, storms, etc. For nuclear or fossil with CCS, this would include load-following dispatch of additional resources to meet peak demand that the baseload nuclear or fossil units could not or would not meet alone.

There is very little experience with electricity portfolios that have 33% or more variable renewable energy and a wide range of estimates in the literature. However, we are beginning to see the relationship between large percentages of renewable energy and reliability. The German electricity grid now faces instability because of very rapid growth of intermittent solar power as a result of laws that incentivize solar power through feed-in tariffs.[23]

The California renewable portfolio could be about 75% variable resources from solar and wind power based on the direction it is headed today. Without any hard estimate of the progress in ZELB technology and adoption, we made a median estimate that we will need natural gas to firm about half this power in 2050 to maintain system reliability. This estimate does not have a strong basis however and the topic is worthy of further study.

There is a significant difference between the load following services required for systems that are dominated by intermittent generation, versus those that have significant baseload. Not only do these resources require more storage to allow the peak of resource availability to be shifted to the time of peak demand, intermittent resources may also require storage that can provide gigawatt-days of energy if, for example, the wind does not blow for many days. Consequently, the difference in emissions from the three possible sources of electricity have mostly to do with assumptions about load balancing. Figure 3 shows the total energy system emissions for the major ways of generating electricity using either 100% natural gas for load balancing, or 100% ZELB. The use of natural gas (without CCS) to balance variability in electric generation units will eat up a significant fraction of the 77 $MtCO_2e$/yr GHG target allotted to the energy sector if the 2050 goals are to be met.[24]

If we use natural gas to firm the power, nuclear is estimated to have the lowest emission profile of any generation choice. Without ZELB, a 100% renewable portfolio will have more emissions than

23 http://www.solardaily.com/reports/German_grid_aching_under_solar_power_999.html#.

24 The use of biomass to provide some of this gas lowers emissions for load balancing and provides GW-days of low emission storage. Consequently, we add the required amount of gas to our total residual fuel demand estimates below. However, median estimates of biomass supply are inadequate for all the total of proposed uses and therefore emission reductions for electricity by using biomass for load balancing simply result in higher emissions for transportation.

any other electricity portfolio, about 30% more than a nuclear power portfolio. Without ZELB, natural gas or even coal plus CCS has fewer emissions than renewables.

With ZELB, emissions for fossil with CCS are the highest of the three choices, and a 100% renewable portfolio would have about the same emissions as nuclear power. No electricity portfolio does better than nuclear power from an emissions standpoint, but renewable energy can have as few emissions as nuclear power if ZELB is 100% available. Clearly, it will be easier to insure reliability and there will be a lower need for load balancing without emissions if there is a significant fraction of base-load power available through either nuclear or fossil with CCS.

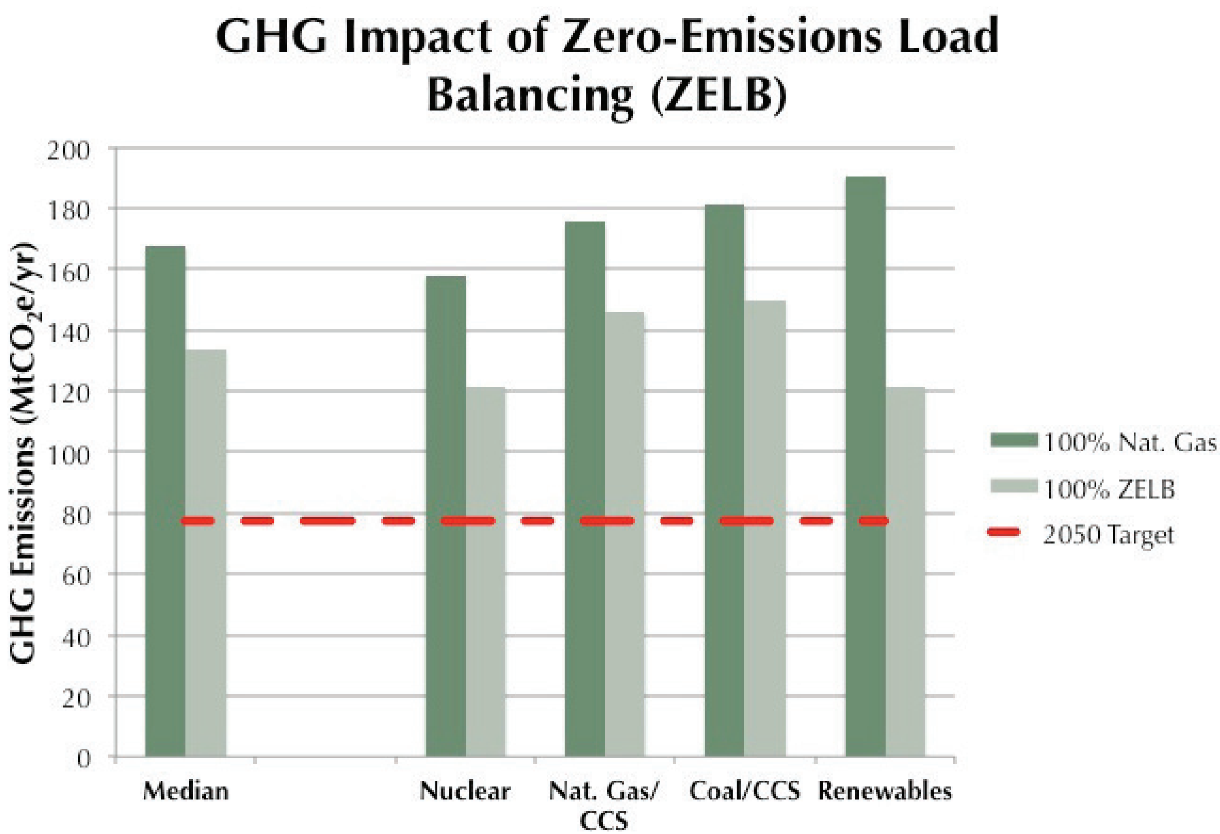


Figure 3. Impact of ZELB on total energy system emissions for two scenarios, one using natural gas for load balancing and the other employing zero-emissions load balancing technology (ZELB) as a function of the type of electricity generation. Note that all cases have at least 33% renewable energy in the mix. The renewables case is 100% renewable energy. The additional emissions from using natural gas to firm renewable energy (i.e. the difference between the light and dark bars for the renewable case) alone almost exceed the target emissions.

The technologies for ZELB include a wide variety of ideas for energy storage, including pumped hydro, compressed air energy storage (CAES),[25] flywheels and various battery designs. The cost barrier is quite high, with natural gas turbines currently providing load following services for about $0.10/ kWh and commercial batteries being from 4 to 10 times that value. Pumped hydro and CAES are more competitive, but are more limited to specialized geography. There are a number of battery designs in demonstration (Na/S, advanced Pb/Acid, Ni/Cd, Li ion as found in electric vehicles) and more advanced batteries (Pb/Acid, Vanadium redox, Vanadium flow, Zn/Br redox, Zn/Br flow, and Fe/Cr) are under development. It remains a concern that few or none of these energy storage technologies would be able to manage multiple GW-days of storage which might be required in the case where wind and solar are used for a substantial (>50%) fraction of the State's energy mix. The use of fossil fuel fired plants with CCS to manage variable loads could do this and is in development.[26] Off-peak hydrogen production could do this as well, although there are economic penalties associated with part-load operation of these plants.

Although some demand-side management is currently in place for commercial scale critical peak demand response, the technology for widespread residential time-of-use demand side management is only in development. System management technology is not yet available that would allow us to shift the business model from one in which the consumer buys and the utility supplies, to one in which the consumer is more in control of how much electricity is used, where it comes from and when. Beyond technology, such a system also requires the market to include as many consumers as possible, so that the load can be balanced over a larger group. Smart-grid pilot studies and projects currently ongoing in California and nationally will improve our understanding of the potential for -- and barriers to -- use of smart grid-connected demand response as a load balancing approach.

100% ZELB requires either major technology advances to decrease the cost of storage or a major shift in the electricity delivery system to having the load adjust to the supply, rather than vice versa. If the cost of energy storage can be reduced and the duration increased significantly, this would transform the energy business by allowing large quantities of reliable energy from intermittent resources. Alternatively, if the smart grid allows successful emission–free load balancing this would transform the industry in an entirely different way, most likely shifting control away from the utility by requiring the consumer to make more decisions about when to use power and from whom to buy the power. If neither ZELB strategy is successful, we will be choosing between emissions from natural gas load balancing or a loss of energy reliability.

25 Technically, CAES is not a zero-emission storage technology because it requires some natural gas combustion to regenerate the stored electricity. However, CAES technology that does not require fuel combustion has been proposed (bin 3), and it is possible to use biomass-based natural gas or even hydrogen to provide the fuel.

26 "Workshop on Operating Flexibility of Power Plants with CCS." Nov. 11-12, 2009. International Energy Agency Greenhouse Gas R&D Programme. 3 May 2011. (http://www.ieaghg.org/index.php?/20100113168/workshop-on-operating-flexibility-of-power-plants-with-ccs.html)

3. Fuel Supply

After all possible transportation and heat has been electrified, there remains a need for about 25 bgge/yr of liquid and gaseous hydrocarbon fuels for mobile and stationary uses (see table 3), plus approximately 2 bgge/yr of gaseous fuel to provide for half the required load balancing.[27] Therefore we are likely to require roughly 27 bgge of fuel in 2050. This fuel use will not be amenable to CCS and thus the only possible way to eliminate emissions from this fuel use is to use low-carbon fuels. We can meet this demand partly from biofuels made from biomass, with some associated emissions. Alternatively, we evaluated the option to burn biomass to make electricity and to sequester the associated emissions. This creates negative emissions which could then be used to offset some continued use of fossil fuels.

State resources alone could provide between 3 and 10 bgge/yr of biofuels from waste products, crop residues, and marginal lands not usable for agriculture. These sources are chosen because they would have minimal impact. It is possible that our "fair share" of likely world-wide production could make up the difference between the state's needs and in-state supplies. As this is uncertain, we chose a median estimate of 7.5 bgge/yr in-state production, of which 2.0 bgge/yr would be burned directly as biomass for electricity, and 5.5 bgge/yr would be available for fuel production. A similar amount of 7.5 bgge/yr as California's "fair share" of imported biofuel was included, for a total of 13 bgge/yr available biofuel. It is important to recognize that the amount of biomass or biofuel that might be available to California could be much smaller or much larger.

Currently, biofuel is produced from food crops such as corn, sugarcane and soybean with about 40% - 50% of the emissions of fossil fuel. Future technologies are expected to reduce this to 20% (80% reduction over current fossil) by 2050 for both liquid and gaseous biofuels. The renewable fuel standard (RFS2) has set caps on the production of corn ethanol and conventional biodiesel, thus bin 2 and bin 3 technologies such as cellulosic ethanol, renewable diesel and production of drop-in hydrocarbons were analyzed. The E85/biodiesel scenario (bin 1 and 2 technology) does not contribute to meeting the GHG reduction targets; whereas, the drop-in fuel scenario (bin 2 and 3 technology) does. These renewable gasoline and diesel replacement fuels can be made by several routes from biomass.

In addition, some biomass and wastewater will likely be used to produce methane through anaerobic fermentation followed by clean-up to prevent the release of nitrous oxide or sulfur compounds during combustion.

Various kinds of biomass can be routed into various forms of fuel (gas or liquid) or even burned for electricity. Conversion efficiencies and end-use requirements for gaseous and/or liquid fuel production should be weighed to determine the best use of the biomass.

Total emissions from fuel use are mostly dependent on the amount of fossil fuel still required, and this depends on how much low-carbon biofuel is sustainably available to displace fossil fuel use. Thus the amount of biomass supply, either in-state or in the form of sustainable imported fuel, is more important to meeting the target than is reducing biofuel-derived emissions from 80 to 100% below fossil fuel (see Figure 4). Thus the ability of biofuels to solve the problem of emissions from fuel use will depend first on the amount of biomass available and secondly on technology developed to improve the carbon signature of the fuel. The majority of the required technology is in the development stage.

27 The total demand for gas would be larger by about 10 bgge/yr if we use natural gas plus CCS to generate 31% of electricity. This amount is not counted here because the emissions can be sequestered. The amount of fuel required for load balancing assumes that the electricity portfolio is 33% renewable energy, i.e. the "median case."

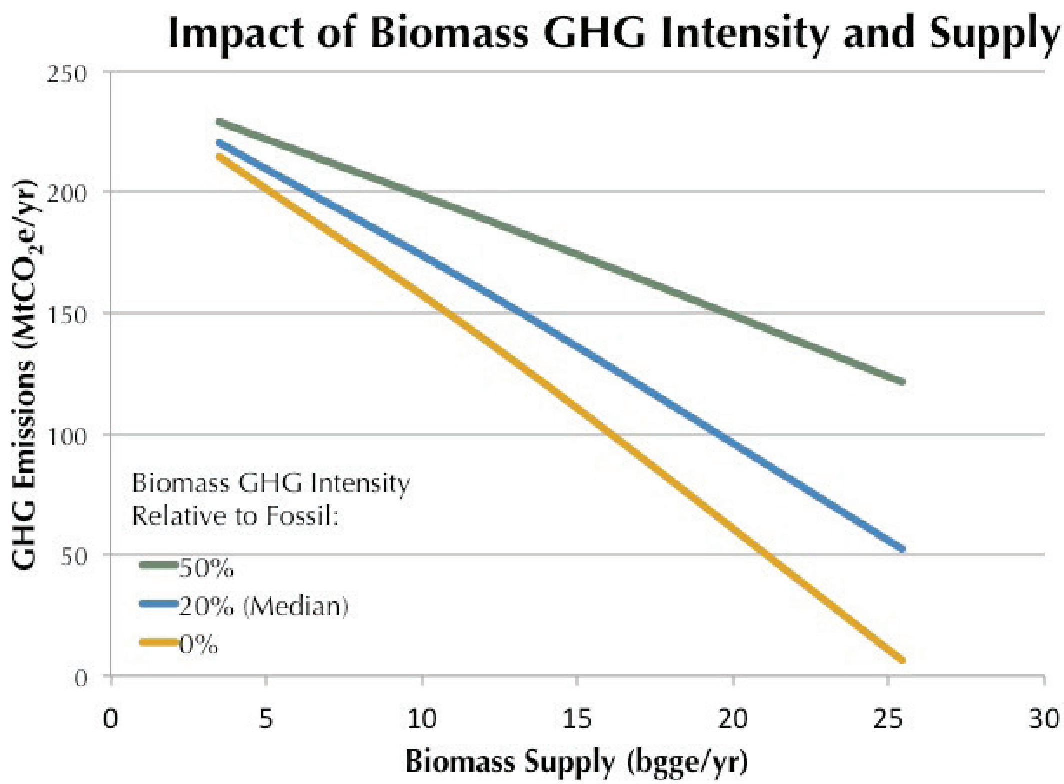


Figure 4. Total greenhouse gas emissions vs. increasing biomass supply curves for constant levels of carbon intensity in fuel.

The investments required for, and ancillary impacts of, biofuels could be significant. We estimate that producing 5.5 bgge/yr of biofuels in California would require building 110 plants, each with 50 Mgge/yr capacity at a cost of $300-$500 million for a total investment of about $33 to $55 billion over 40 years.

Although water, land, and fertilizer requirements could be significant, we have limited our analysis to low-impact biomass sources. Seventy percent of the biomass in our estimates is from waste, with no additional water, land or fertilizer requirements. The remaining 30% is derived from specialized energy crops grown with low inputs (no added fertilizer or irrigation) on marginal lands.

Currently evolving definitions of renewable biomass include considerations regarding prior land use, precluding the use of land in current agricultural production. We look to newly-emerging energy crops that could tolerate arid conditions and poor soils, such as agaves and salt-tolerant grasses and trees, to avoid possible impacts on current agricultural or silvicultural land use.

Worldwide, we will not only need about twice as much energy by 2050, but in this same time period we are expected to need twice as much food we produce now. Thus, care will have to be taken to insure that we account for unwanted impacts resulting from importing biofuel and international scale-up of this technology. Efforts to increase the biomass supply to meet the emissions targets must be approached carefully with attention to all life-cycle issues and in accordance with emerging certification programs for sustainable biomass production.

Fuel Supply Research

The Energy Biosciences Institute (lead by UC Berkeley and LBNL in partnership with BP and the University of Illinois), the Joint BioEnergy Institute, and UC Davis' partnership with Chevron on fuels from biomass all illustrate how deep California's strengths are in biofuels technology and the development of new energy crops to increase sustainable biomass supplies. They play a vital role in ensuring that the state can meet its future GHG reduction goals in the critical liquid fuel supply sector. While this center conducts fundamental scientific research, it will also build operational prototype processes with direct applications to industry. UC Merced works to produce county-level maps of lands availability for biofuels production and algae biofuels.

Alternatively, continued fossil fuel use could be offset with verifiable and validated sequestration. One choice is burning carbon–neutral biomass to make electricity with carbon capture and storage to create negative emissions. This solution requires the same advances in CCS that are required for fossil fuel plus CCS and could involve the same concerns for impacts in food, water and fertilizer as biofuel production. On paper, this solution is somewhat more advantageous from an emissions standpoint than using biomass for biofuels. However, siting could be a challenge. Biomass has a relatively low energy density and high moisture content, making it expensive to transport. Thus, the utility of this approach may be limited by the proximity of the biomass to potential electric generation sites or the ability to pipe CO_2 to the sequestration site.

Hydrogen

Starting with the high efficiency case, we estimated how much hydrogen might be used if hydrogen were freely available.[28] To meet this demand we examined various sources for hydrogen. Hydrogen burns without emitting CO_2, but the hydrogen must be produced without emitting CO_2 as well. Hydrogen can be made by reforming natural gas or gasifying coal and using CCS to take care of the emissions produced in the process, or by electrolysis using low-carbon electricity. The latter option, however, would significantly increase California's 2050 electricity demand (by 350 TWh/yr, or 70%) to more than triple the 2005 levels of electricity production in order to make the required hydrogen.

28 Electrification was then applied to end uses not entirely satisfied by hydrogen, up to the levels obtained in the efficiency plus electrification base case.

4. Technology Readiness

Tables 4A, 4B, 4C and 4D summarize the technology readiness of supply technologies. The highlighted cells of the table indicate the technology invoked in our 2050 energy system portraits (mostly bins 1 and 2 technology). Table 5 summarizes required build rates. Of the electricity supply cases, nuclear power appears to be the most technically certain way of providing reliable baseload electricity if issues with cost, safety and waste can be dealt with. Fossil with CCS remains the most technically challenging way of producing baseload. A renewable energy portfolio made of mostly intermittent resources will have much larger requirements for load balancing which is not in an advanced state of deployment. A very large percentage of the technology we need for decarbonized fuel supply is in the developmental stage. Our fuel problems cannot be solved without significant new technology. Innovation will be required to make the technology available that we require for emission reductions while meeting our energy needs.

Bin	Nuclear Technology	Coal or Natural Gas CO_2 Capture	CO_2 Storage
1	Generation III+ reactors	High-efficiency coal gasification, high-efficiency natural gas combined cycle, ultra-supercritical pulverized coal combustion, solid-oxide fuel cell (SOFC), solvent separation	Injection into oil/ gas reservoirs
2	Small modular reactors (LWR)	Post-combustion CO_2 capture technologies with 80% capture efficiency, integrated gasification systems with CCS, amine solvent separation	Saline aquifer injection
3	Generation IV (including small modular Na-cooled reactors)	New capture methods with >90% effectiveness, lower cost CO_2 capture technologies of all kinds, metal-organic framework separations, membrane separation	Coal bed injection
4	None	None	Shale injection

Table 4A. Summary of technology readiness for nuclear and CCS. The technologies in the highlighted rows were invoked to develop a feasible energy system portrait for 2050.

Bin	Wind	Concentrated Solar Power (CSP)	Solar Photovoltaic (PV)	Geothermal	Hydro and Ocean	Biomass
1	Onshore, shallow offshore turbines	Parabolic trough, central receiver	Silicon PV, Thin-film PV, Concentrating PV	Conventional geothermal	Conventional hydro	Coal/biomass co-firing, direct fired biomass
2		Dish Stirling				Biomass gasification
3	Floating (deepwater) offshore turbines		"Third generation" PV		Wave, tidal and river turbines	
4	High-altitude wind			Enhanced geothermal systems (EGS)		

Table 4B. Summary of technology readiness for renewable energy supply. The technologies in the highlighted rows were invoked to develop a feasible energy system portrait for 2050.

Bin	Natural Gas	Storage	Demand Side Management
1	Combustion turbine	Pumped hydro	Commercial-scale critical peak demand response
2		"First generation" compressed air energy storage (CAES), battery technologies (Na/S, advanced Pb/Acid, Ni/Cd, Li ion as found in electric vehicles)	Commercial time-of-use demand-side management
3	Combustion with CCS in load following mode	Battery technologies (some advanced Pb/Acid, Vanadium redox, Vanadium flow, Zn/Br redox, Zn/Br flow, Fe/Cr redox, some Li ion), flywheel, "second generation" CAES	Residential time-of-use demand-side management

Table 4C. Summary of technology readiness for supply-demand balancing technologies. The technologies in the highlighted rows were invoked to develop a feasible energy system portrait for 2050.

Bin	Biofuel Technology	Hydrogen
1	Ethanol from sugar and starch (e.g., corn, sugar cane, sugar beet, wheat) Biodiesel from oil crops (e.g., FAME=Fatty Acid Methyl Ester)	Natural gas reforming, H_2 electrolysis, H_2 pipeline network
2	Cellulosic ethanol Fischer-Tropsch diesel Hydrogen-treated biomass Improved lignocellulosic and oil-crop feedstocks (Miscanthus, Jatropha, etc.)	Gasification of coal or biomass with CO_2 capture for H_2 production, CO_2 storage in saline aquifers
3	Advanced biofuels (sugar to hydrocarbons) Algal biodiesel	
4	Improved enzymes, catalysts, microbes, feedstocks	Fuel from sunlight

Table 4D. Fuel technology readiness. The technologies in the highlighted rows were invoked to develop a feasible energy system portrait for 2050.

Strategy	Assumed Plant Size	Total Plant Capacity Needed in 2050	Build Rate 2011-2050 (Plants/Year)
Nuclear	1.5 GW	44 GW	0.73
Fossil/CCS	1.5 GW	54 GW*	0.90
Renewables Mix total		165 GW**	
- Wind	500 MW	59 GW	3.0
- Central Solar (CSP and PV)	500 MW	65 GW	3.3
- Distributed Solar PV	5 kW	22 GW	110,000
Biomass/CCS	500 MW	1.5 GW	0.77
CA Biofuels	50 Mgge/yr	5.5 bgge/yr	2.8
Hydrogen		8.0 bgge/yr	
- Natural Gas Reforming	0.5 Mgge/yr	0.8 bgge/yr	40
- Central Plant	440 Mgge/yr	7.2 bgge/yr	0.41

Table 5. Summary of supply build rates required.
*Gross capacity, assuming 10% parasitic loss from CCS (net capacity = 49 GW)
**Includes geothermal and hydropower not included in this table

The 2050 Energy System Portraits

We assembled the energy system components into a series of energy system portraits that met our demand for energy and lowered emissions by a feasible amount[29]. In each case we tracked the total GHG emissions. If we take no measures, emissions are likely to double by 2050 relative to 1990 levels. If we only employ efficiency measures, we could hold emissions to about 20% over 1990 levels. We define a median energy system portrait that uses roughly equal amounts of nuclear power, CCS and renewable energy, assumes that we have solved about half the load balancing problem without emissions and the other half is done with natural gas, and assumes we can meet about half of our remaining fuel requirements with biofuel that has 20% of the carbon signature of fossil fuel. For this median system, only by employing all four strategies (efficiency, electrification, decarbonized fuel and decarbonized electricity) did we find an energy portrait that reduces 2050 GHG emissions to 150 $MtCO_2e$/yr, still about twice the emission limit specified by the target value and only 60% below 1990 levels.

Figure 5 shows emission reductions associated with the four major strategies. The left side of the chart shows 1990 emissions (targeted by AB32 in 2020), 2005 emissions, and the projected BAU emissions in 2050 of over 800 $MtCO_2e$/yr. The vast majority of these emissions come from residual use of liquid and gaseous fuel, used primarily for transportation, with some used for heat. Next are a series of energy portraits that each use only one of the four key approaches to reducing future GHG emissions. Of these four, efficiency is the largest single contributor to reducing emissions. However, no single measure can reach the emission limits. Neither can any two measures, any three measures, or even all four. The lowest 2050 emissions would be obtained by using all four measures, and even this portrait only reduces emissions to 60% below 1990 levels.

29 The determination of what is "feasible" was based on a combination of historical precedent and judgments about the technical maturity, economic prospects, ancillary impacts and required policies.

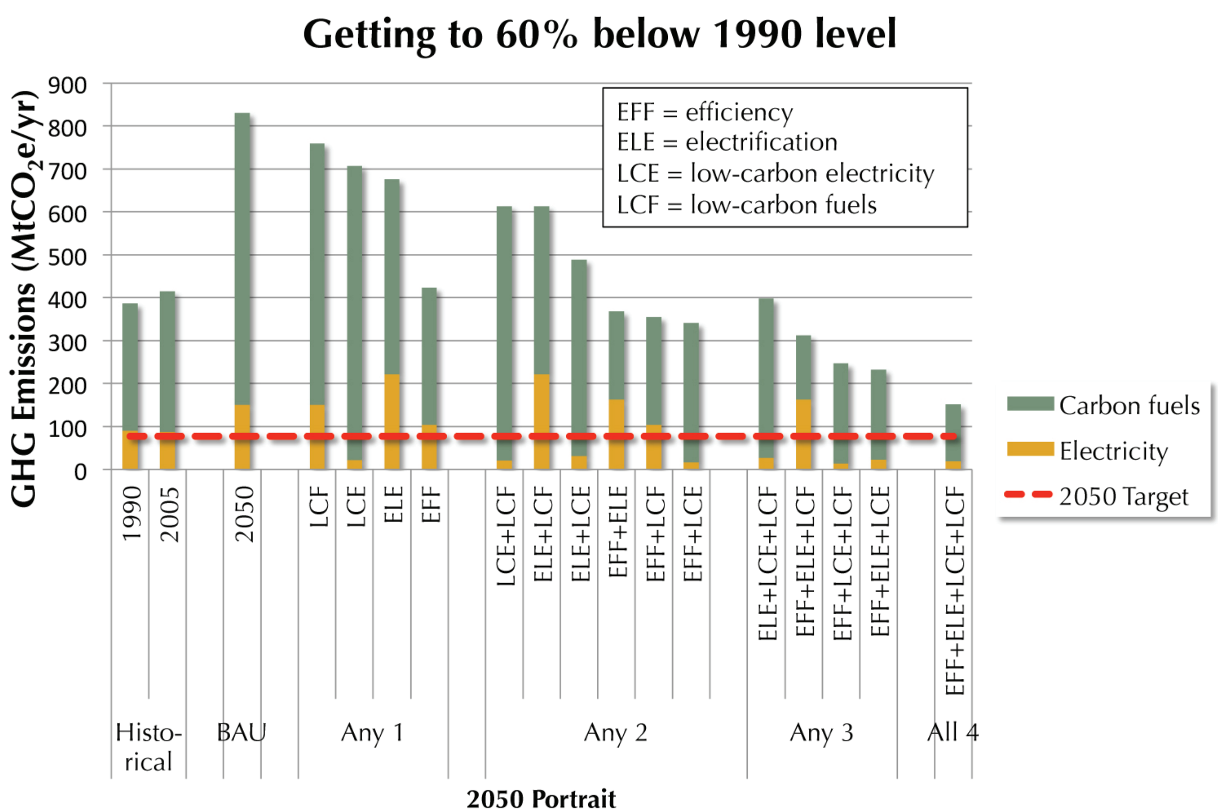


Figure 5. Using feasible technology scale-up to reach 60% reductions in emission below 1990. The red dashed line is the emission target. The figure shows the effects of using the four key strategies for reducing emisisons: efficiency, electrification, decarbonizing electricity and decarbonizing fuel. Historical and business-as-usual (BAU) emissions are shown on the left, the next group of bars shows emissions from deploying only one key strategy, then any two, any three and all four. Emissions from carbon fuels and electricity are depicted with different colored bars. Note that fuel use (green) accounts for the vast majority of emissions in almost every case.

Another way to think about this four-strategy portrait is illustrated in the diagram shown in Figure 6. Efficiency reduces both the need for electricity and fuel (grey arrow). Electrification further increases efficiency and reduces the need for fuel (blue arrow) but expands the use of electricity. Then we reduce the carbon content of the energy we use (yellow and green arrows). The carbon emitted per unit energy can be reduced much further for electricity than for fuels, mainly because biomass supplies are limited and significant usage of fossil fuels continues.

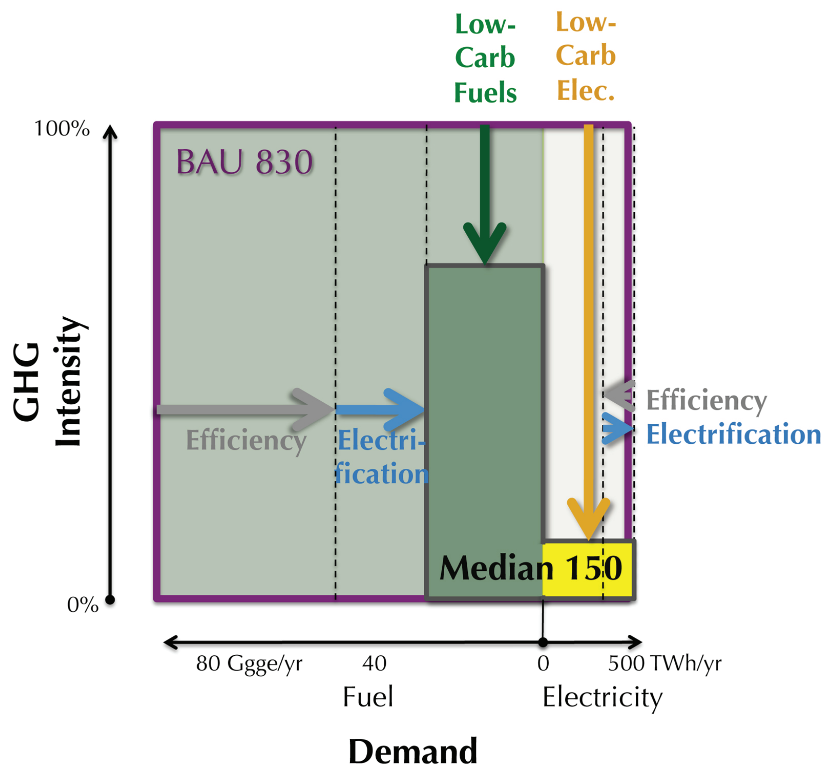


Figure 6. Strategy for reducing emissions from business-as-usual (BAU) to 60% below 1990 levels. The area of the box outlined in purple represents BAU emissions, while the smaller area of the darker colored boxes inside represent emissions in the "median" case (60% reduction below 1990). The horizontal axis indicates the relative demand for fuels and electricity, and the vertical axis indicates GHG intensity of each.

The build rates required for the median portrait are approximately 1 nuclear plant every 3 years (including retirements of older units) and 1 fossil plant with CCS every 2.5 years. These are likely to be co-located with prior nuclear or fossil power plants. Significantly more renewable power plants will be required: about 1 wind farm, 1 central solar plant, and about 40,000 distributed PV systems each year. Clearly any solution will require aggressive and expedited permitting processes to enable these build rates.

What does getting to 60% below 1990 levels look like?

- A "median" portrait that emits 150 $MtCO_2$/yr
- Efficiency + Electrification
  - Building stock 40% more efficient than today
  - 70% of heat is electrified
  - 60% of light-duty vehicles are plug-in hybrids or all-electric vehicles
  - 50% reduction in truck and aviation fuel use per mile compared to BAU
  - 30% reduction in liquid fuel, 50% reduction in gaseous fuel compared to BAU
  - Approximately double today's electricity use
- Low-carbon electricity: 522 TWh/yr
  - 95% of electricity capacity [from nuclear (31%, 22 GW), natural gas/CCS (31%, 27 GW), renewables (33%, 61 GW)
  - 5% of electricity for load balancing (from natural gas without CCS for half of the requirement)
  - Other half of load balancing provided with zero-emissions technologies such as hydropower, batteries, grid–connected controllable loads, etc. (ZELB)
- Low-carbon fuels for transportation, heat and electricity load balancing
  - Hydrocarbon fuel demand: 27.2 billion gallons gasoline equivalent (bgge/yr):
    - 11.7 bgge/yr gaseous fuel (not including 10.0 bgge/yr for natural gas with CCS)
    - 15.5 bgge/yr for liquid fuels
  - Biomass supply that can be burned directly or made into fuel: 94 mdt/yr, producing 5.5 bgge/yr biofuels plus 25 TWh/yr biomass electricity (equivalent to 2.0 bgge/yr), and an additional 7.5 bgge/yr imported biofuel. Total biofuels: 13.0 bgge/yr, with 20% GHG intensity of fossil fuels

Getting to the 80% Target (and Beyond)

We next examined further measures that would get California's emissions in 2050 to 80% below the 1990 level. In order to concentrate on the remaining problem of emissions from fuels, we assumed one electricity portfolio, the "median case" which has roughly equal amounts of nuclear power, fossil with CCS and renewables and we assumed that half the load balancing was accomplished with ZELB without emissions. We have already seen that an entirely renewable electricity portfolio is likely to exceed the emission target if load balancing is accomplished with natural gas. So, the ZELB variable has been set to "half way" as a means of roughly leveling the playing field for various methods of producing electricity, and to allow us to explore the fuel problem. As shown in Figure 7, we need to cut about 50% of the emissions in the median portrait in order to attain the carbon footprint of the 2050 goal. Nearly all these emissions are coming from remaining fossil fuel use for transportation and heat.

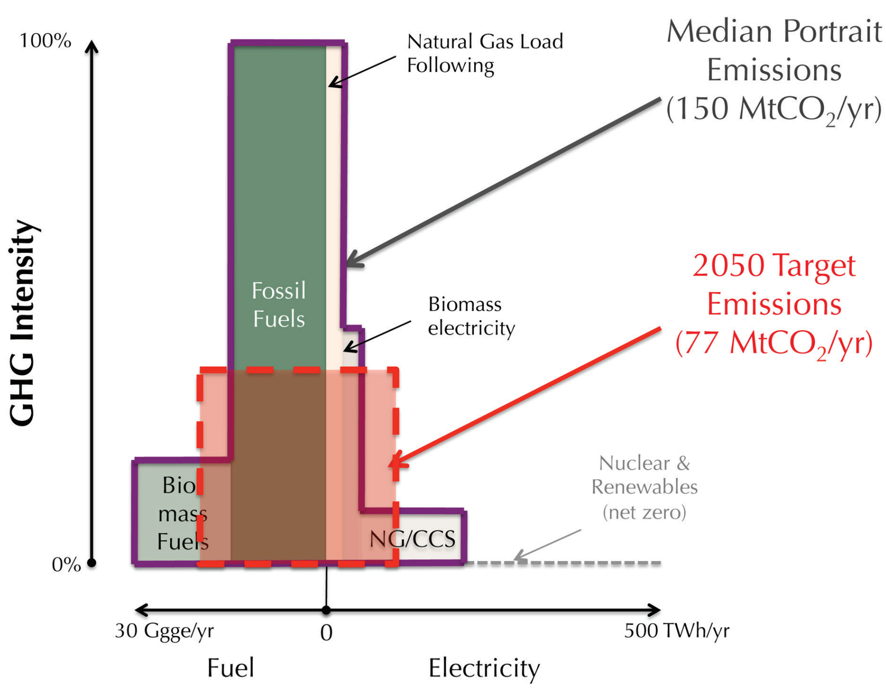


Figure 7. The difference between the carbon footprint of the median portrait and the required carbon footprint of the 2050 target. Note that remaining fossil fuel use is primarily for heavy duty transportation and heat. The horizontal axis has been rescaled from Figure 6, and areas of each component indicate their GHG emission contributions. The area surrounded by purple indicates median portrait emissions, while the area of the red box represents 2050 target emissions.

To illustrate how we might go beyond the median case, we looked at a few possible strategies. These strategies are not comprehensive and we have not evaluated their relative efficiencies or costs, but they illustrate some possible pathways with combinations of technologies that are more or less available:

1. Develop the technology to make CCS 100% effective and economical.
2. Eliminate fossil fuels with CCS from the electricity mix.
3. Increase the amount of load balancing that is achieved without emissions from 50% to 100%.
4. Produce biomass with net zero carbon emissions.
5. Reduce energy demand through ubiquitous behavior change.
6. Burn all domestic biomass supplies with natural gas and use CCS to make electricity with net negative GHG emissions, creating an offset for the required fossil fuel use. The same amount of biomass would be used as in the other portraits, and would supply about 20% of electricity demand. Imported biofuels would still be used.
7. The hydrogen case: reform hydrogen fuel from natural gas with CCS and use it to reduce fuel and electricity use.[30]
8. Increase the supply of sustainable biomass twofold, and use it to make low-carbon biofuels, using feedstocks that best fit efficient conversion to the needed energy mix.

Figure 8 shows the impact of the eight strategies on GHG emissions. Observations about specific strategies follow.

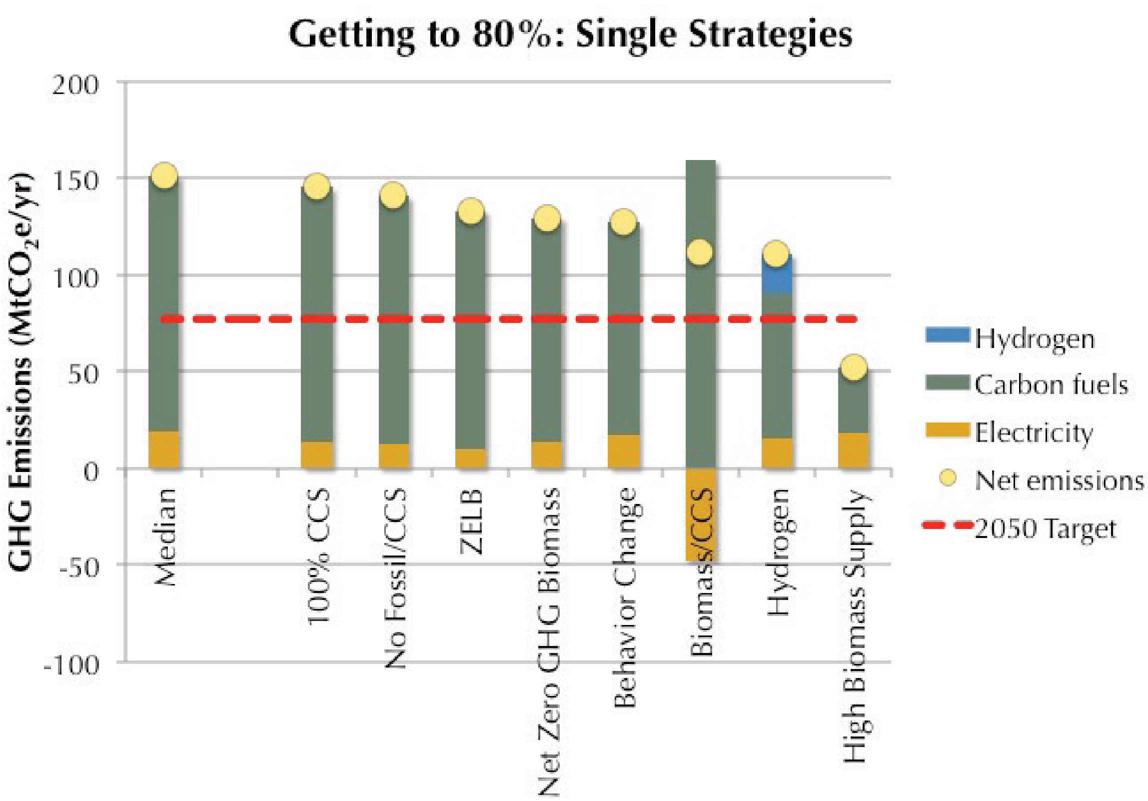


Figure 8. The effects of single strategies on reducing GHG emissions.

30 Making the required hydrogen from electricity results in a portrait with similar net GHG emissions, but is deemed more difficult due to the challenge of almost doubling electricity supply. However, if CCS is unavailable, this may be the only way to make low-carbon hydrogen.

1. Achieving CCS with 100% CO_2 removal would likely be through the use of fuel cells for generating electricity instead of thermal plants, or oxyfiring which separates out oxygen from air to burn the fuel and produces relatively pure CO_2 flue gas. While helpful, the median case only includes about 30% of fossil fuel with CCS, so it only saves roughly an additional 6 $MtCO_2$/yr and likely involves a substantial cost or power penalty and additional fundamental CO_2 capture research.
2. Eliminating fossil/CCS from the electricity portfolio would reduce emissions by 10 $MtCO_2$/yr, slightly more from than making CCS 100% effective, because it also reduces refining emissions from the production of natural gas. However, the use of fossil fuels with CCS for electricity would likely be very useful, provided CCS were successfully developed on a large scale, so would be difficult to justify eliminating it for a small reduction in emissions.
3. Achieving 100% zero-emission load balancing (ZELB) would save 18 $MtCO_2e$/yr compared with the median scenario. It might be accomplished with advanced batteries or smart grid solutions, load-following fossil generation with CCS, hydrogen generation with off-peak or renewable electricity, or carbon-neutral fuels from sunlight. However, all of these strategies are difficult with today's technologies.
4. Producing biofuels with net zero GHG emissions would save 22 $MtCO_2e$/yr, but as already discussed above in Figure 4, the amount of biomass supply has a larger effect on statewide emissions than reducing biofuel-derived emissions from 80% to 100%. Moreover, achieving this total life-cycle decrease may be technically very difficult.
5. Behavioral change including smaller houses and cars, less miles traveled, more use of public transportation, smaller industry footprints, etc., might reduce demand and lower emissions by 24 $MtCO_2e$/yr based on a 10% reduction across most sectors of the economy; studies by Dietz et al. and others indicate that even larger reductions in use (up to 20%) are possible in the household sector.[31]
6. Using biomass with CCS to produce electricity rather than fuels would save about 40 $MtCO_2e$/yr compared with the median scenario. Our calculations suggest that this option may result in lower net GHG emissions than the biofuel route, because more CO_2 can be captured during biomass combustion for electricity than is saved by using biomass-derived fuels in place of fossil fuels. It is an interesting option that deserves further examination.
7. Producing 8 bgge/yr of hydrogen and using it to run parts of the California economy would save more than 40 $MtCO_2e$/yr. However, it is challenging both from an infrastructure as well as a technology perspective, particularly for mobile uses that will consume the majority of the hydrogen in the portrait, because low-cost, high-density on-board hydrogen storage is not yet technically feasible, and fuel cell technology, while progressing, is still very expensive.
8. Doubling biofuel supply (by 188 mdt/yr or 15 bgge/yr, presumably through imports), achieves the greatest reduction in GHG emissions on its own: 99 $MtCO_2$/yr. This solution seems technically possible, but the impacts on food, water and mineral nutrients must be considered.

A combination of strategies would meet or exceed the 80% GHG reduction goal in 2050 as shown below in Figure 9. Here the impact on GHG emissions of sequentially applied strategies is illustrated. These are: burn domestic biomass (with CCS) for electricity rather than making biofuels; reform hydrogen fuel from natural gas with CCS; develop 100% zero-emission load balancing or ZELB; encourage widespread behavior change to reduce demand; increase biomass supply (as discussed above); and produce biomass with net zero GHG emissions. The application of the first two strategies could bring emissions down to the 2050 target, while the application of five or more strategies, though unlikely, could result in net emissions below zero.

31 Dietz, Thomas et al. "Household actions can provide a behavioral wedge to rapidly reduce U.S. carbon emissions." Sept. 2009. Proceedings of the National Academy of Sciences. 11 May 2011. (http://www.pnas.org/content/106/44/18452)

As well, combining the same amount of domestic biomass as in the other portraits (94 mdt/yr) with coal and CCS in an apparently highly efficient process that produces both fuel and electricity, and provides a very low emission profile while producing almost double the fuel from biomass alone, appears worthy of further examination.[32] This is done by efficiently converting the biomass and coal to "syngas" (a mixture of hydrogen and carbon monoxide) in a gasifier, making as much hydrocarbon fuel as required, burning the extra hydrogen in a turbine to make electricity, and converting the remaining carbon monoxide to CO_2 that is captured and sequestered. The technical challenges are similar to those encountered for biomass or fossil fuel electricity with CCS; the process for making fuels from syngas, known as Fischer-Tropsch, is well understood. It was not possible to estimate the GHG reduction impact precisely, but it is expected to be fairly sizable.

It is clear that the availability of sustainable biomass is an important factor in reaching the State's 2050 GHG goal. The most efficient use for different biomass types, availability of certified imported bioenergy, and proximity to meet end-use needs should be carefully considered to make the best use of available biomass. Reducing the carbon footprint of using biomass for energy is also important. Care must be taken to ensure that implementation and expansion of biomass for energy does not result in unwanted social, economic, or environmental impacts. It is possible to conceive of biomass derived energy without disastrous impacts on food supply if the biomass for energy production is limited to marginal lands, wastes and off-season cover crops, but this is not something to take for granted. Additional study of the sustainable biomass potential for energy use in California, in the context of bioenergy potential in the U.S. and globally, will be needed to thoroughly assess our options. Having alternatives to biomass for low-carbon fuel is an important hedge against the probability that there will not be enough biomass to provide all the fuel we would like. Carbon capture and storage (CCS) is likely to play a role in at least some of these alternative strategies for low-carbon fuel.

32 Guangjian Liu, Eric D. Larson, Robert H. Williams, Thomas G. Kreutz and Xiangbo Guo (2010) Making Fischer-Tropsch Fuels and Electricity from Coal and Biomass: Performance and Cost Analysis. Energy Fuels, Article ASAP doi: 10.1021/ef101184e.

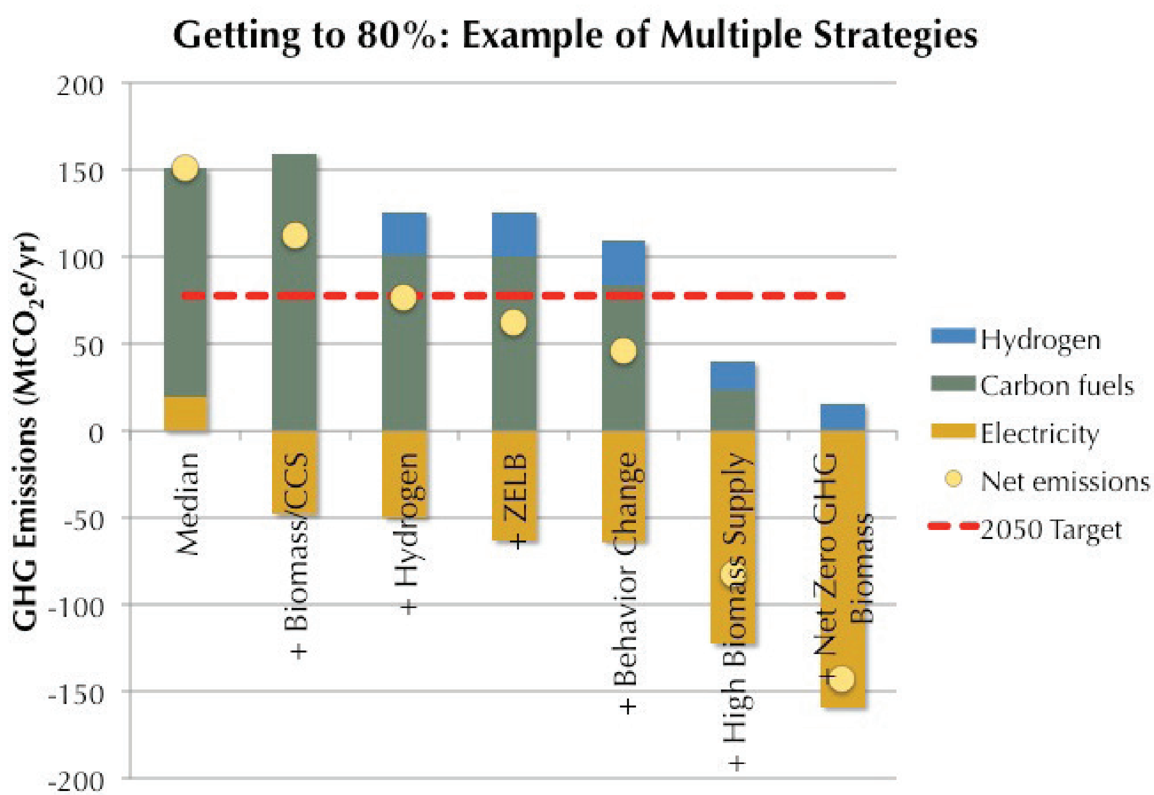


Figure 9. Example of multiple strategies that reduce emissions to 80% below 1990 levels and beyond.

Breakthrough Technology?

Breakthrough technologies -- game changers -- will undoubtedly surprise us in the next decades. These could allow us to produce fuel without emissions or provide very inexpensive carbon-free baseload electricity, making electrification adoption more successful and perhaps even allow fuel production from electricity. These technologies are unlikely to be fully deployed by 2050, although they may well start their deployment by then. Given the finite limits to other resources, these new technologies will be critical to ensuring that our 2050 GHG emissions goals are sustained well into the next century.

Energy technology for 2050 will come from around the world, but just within California institutions there is ongoing research on important breakthrough energy technologies with the potential for offering game-changing solutions to the energy problem. Most funding for this research comes from the Federal government and deserves support from the California delegation. The California Energy Commission funds critical research through the Public Interest Energy Research program for work specific to, and critical for, our state. About 25% of all U.S. patents are filed from California. We should expect our State to lead in energy technology as well.

The Joint Center for Artificial Photosynthesis (JCAP)

Fuel from sunlight could allow us to meet our needs for liquid and gaseous fuels without resorting to any fossil fuel. California Institute of Technology and LBNL share a DOE research hub on this topic. The goal of JCAP is to develop an integrated solar energy-to-chemical fuel conversion system and move this system from the bench-top discovery phase to a scale where it can be commercialized. Research will be directed at the discovery of the functional components necessary to assemble a complete artificial photosynthetic system: light absorbers, catalysts, molecular linkers, and separation membranes. JCAP will then integrate those components into an operational solar fuel system and develop scale-up strategies to move from the laboratory toward commercial viability. The objective is to drive the field of solar fuels from fundamental research, where it has resided for decades, into applied research and technology development, thereby setting the stage for the creation of a direct solar fuels industry.

Laser Fusion Energy a Potential Game Changer

California is the world leader in laser fusion energy—a potential game changer for supplying zero-carbon electricity and producing zero-carbon fuel sources such as hydrogen. To date, $5 billion has been invested in the National Ignition Facility (NIF) and its associated research and development programs, which are poised to demonstrate ignition and energy gain (producing more energy than the amount of energy used) in the laboratory by the end of 2012. When harnessed for electricity production, a Laser Inertial Fusion Energy (LIFE) power plant would be capable of supplying between 500 and 1500 MW net electricity to the grid, at very high energy density (> 1000 MWe/km^2). LIFE power production would meet baseload demand and be compatible with the existing power grid. Additional benefits of LIFE include the absence of any long-lived radioactive waste (obviating the need for geological repositories) and the inherently safe mode of operation (since there is no stored energy in the fusion system). It is also important to note that the high-temperature operation of a LIFE power plant will allow for co-generation of synthetic fuels, the production of hydrogen, and the potential for using the low grade waste heat for other industrial uses, given the ability to site these plants near load centers.

Conclusions

Overview

Our study shows that emission reductions of 80% can be achieved by 2050 with feasible technology implementation plus research, development and innovation. However, no single technological approach can accomplish this. We will require a portfolio of solutions.

As a first step, we can feasibly cut emissions to about 60% below 1990 levels with technology that is largely in use today or in a demonstration phase. From a technical perspective, we know how to do this much, but the existing policy framework of AB32 related laws and rules would need to be strengthened and supplemented with some new policies. We thus first need the societal will to implement technology that we know how to construct and deploy today.

The magnitude of the changes required and the pace of implementation will not occur without sustained and substantial capital investment and policy interventions. However, neither economic analysis of such interventions nor examination of alternative policies were within the scope of this study and should be the focus of follow-up work.

The remainder of the emission cuts to obtain the full 80% reduction below 1990 levels can also be accomplished, but this will require development and deployment of new or currently undeployed technology. Achieving this second cut will thus require a substantial commitment to technology development and innovation. To get this job done, we would have to bring technologies that are currently in the development and research stages into widespread implementation.

California can continue to be a leader in cutting GHG emissions

***California could achieve roughly 60% emission reductions of below 1990 levels with technology that we largely know about today, provided that four key strategies are implemented in a fashion that yields deployment at rates that are aggressive but feasible*:**

1. Aggressive efficiency measures for buildings, industry and transportation, to dramatically reduce per capita energy demand.
2. Aggressive electrification, to avoid fossil fuel use wherever technically feasible.
3. Complete decarbonization of the electricity supply while at the same time roughly doubling electricity production, and developing zero-emissions load balancing approaches to manage variability in loads as well as in supply.
4. Decarbonizing the remaining required fuel supply wherever electrification is not feasible.

We have to electrify the majority of end-uses that currently use fossil fuel in transportation and heat, in order to avoid emissions from that part of the energy system. If we do not at the same time institute aggressive efficiency measures, the demand for electricity would grow dramatically, to about two-and-a-half times the current level. Efficiency measures can help keep electricity demand to less than double current levels, while still supplanting fossil fuel use for transportation and heat.

We can decarbonize the electricity system using three fundamental methods of generation. Each of these methods involves very different benefits and penalties. Moreover, all generation schemes have the need for services to address load balancing, including peak loads, ramping, and firming intermittent power. Today, we largely provide load balancing service with natural gas, which produces emissions. But solutions that would reduce emissions are in development, including energy storage and smart grid solutions which include demand response, as well as the possibility of load-following fossil generation with CCS.

If we try to generate 100% of electricity with largely intermittent renewables, such as wind and/or solar, we will need a lot of innovation and systems management changes to deal with intermittent and distributed resources and to enable firming the power. We would need zero emission load balancing (ZELB) technology to work otherwise emissions from firming the power with natural gas (the primary current method) alone will nearly equal the 2050 emissions target. In order to maintain reliability and concomitantly eliminate emissions, we would need some combination of energy storage systems, the ability to capture sequester CO_2 from gas plants used to firm power, and smart grid technology to modify the demand to match load. Also, because of intermittency, we would have to build about 3 times the capacity we would need with non-intermittent power.

If we use 67% nuclear plus 33% renewables, the requirements for ZELB would be significantly less. We would have to build and permit a few tens of nuclear generation facilities, but we will have to deal with nuclear waste issues including California law which prohibits new nuclear power until a waste repository is licensed, as well as public opinion and new considerations of nuclear safety as a result of recent events in Japan.

Using 67% fossil with CCS and 33% renewable is similar in many ways to nuclear power, but we would only be able to sequester 90% of the emissions cost-effectively, and we would have to plan on using largely uncharacterized saline aquifers for CO_2 storage. Moreover, we would need to provide the pipeline infrastructure required for CCS. (As well, it may be best to reserve CCS as part of a process to make decarbonized fuel for transportation and heat.) Required generation capacity could be 10% to 25% higher than for the equivalent service from nuclear power.

To oversimplify for the purpose of illustration, the state will, at a minimum, need to overcome the legal problems with nuclear power related to the requirement for nuclear waste storage, or solve the load balancing problem without emissions for renewable energy.

If we electrify as much as we can and make all end uses as efficient as we can, we will still need about 70% of the fuel we use today, mainly for heavy duty transport and high quality heat. The use of biomass to make carbon-neutral fuel is promising and is a critical component for eliminating the use of fossil fuels. But the quantity of available biofuels is highly uncertain. The amount of biomass from low impact sources (wastes, residues, and crops grown on marginal lands without irrigation or fertilizer) that could be used for energy in California ranges from 3 to 10 billion gallons of gasoline equivalent per year (bgge/yr). However, the demand for fuel in California in 2050, even with aggressive electrification wherever technically feasible, is nevertheless likely to be three times the high end estimate of the availability of biofuels.

As well, the carbon signature of current commercial-scale biofuels is on average about 50% that of fossil fuel. With technologies in the pipeline for drop-in advanced fuels, we could lower this to 20%.

If we use a median estimate for the amount of biomass that could be used for energy – including some imports—we can thus displace about half of the remaining the fossil fuel demand.

With aggressive electrification and efficiency and:

- ***An electricity portfolio that is roughly equal parts nuclear, natural gas with CCS, and renewables;***
- ***half of the ZELB problem solved and the rest managed with natural gas; and***
- ***a median estimate for the amount of available sustainable biomass,***

we can achieve 60% cuts in emissions below 1990 levels.

California can cut emissions to 80% below 1990 levels, but this will require significant new research and development as well as deployment of the resulting technologies.

It is the remaining fossil fuel use that provides almost all of the remaining emissions. ***Thus, getting the rest of the way to an 80% reduction essentially means dealing with the problem of decarbonizing fuels.*** If we had all of the biomass that we wanted for energy, we could address all of our fuel needs in this way, including load balancing. This scenario is not completely outside the range of the possible, as there are several novel bioenergy feedstocks that could increase the potential for in-state biomass production that is economically, socially, and environmentally sustainable over the long term. However, we will want to plan for a limited use of biomass because of uncertainties around land-use and interactions with current and future agricultural and silvicultural practice. So, robust solutions to the problem will require invention, innovation, development and alternatives to using biomass for low-carbon fuel.

There are a large number of possible technologies, including some possible breakthrough technologies, which can help to solve our problem with decarbonizing fuel. If we convert as much of the 2050 fuel use as possible to hydrogen, generate hydrogen from methane and sequester the resulting CO_2, this gets us very close to the 80% cut. Adding zero emission load balancing (ZELB) or having zero emission bio-energy would then finish the job of achieving the 2050 target. Another technology which could theoretically reduce most of the remaining emissions involves burning some of the biomass to make electricity with CCS, thereby creating negative emissions. Again, with zero-emission load balancing or bio-energy with zero emissions, this gets to the target. Each strategy will reduce more emissions, and if applied in combination, could bring us below the target 2050 level. In the long run, we may learn to make fuels directly from sunlight and solve many of the emission problems this way. ***All of the approaches that will reduce emissions from 60% below 1990 levels to the target value of 80% below 1990 levels are going to require significant levels of research, technology development, invention and innovation. This part of the problem is therefore as much a technology problem as it is a policy problem.***

California needs a set of analytical tools to support strategic planning and inform strategic decision and investments. This report developed one such approach and analytical tool, which is capable of interrogating a wide range of outcomes from a variety of assumptions about our energy future. Other approaches may be available. Any tool or tool set must keep track of sources, carriers and end uses of energy and all associated emissions. Such tools could then be used to examine the impact of various energy choices, and most importantly, the tool should be capable of informing policy choices.

Although this report has shown that a number of low emission energy systems are technically feasible, the study team's analysis did not explicitly examine which of these portraits is likely to be the most advantageous and least costly for California, nor did it draw time-based roadmaps to reach the desired end state. A more detailed analysis which includes economic, strategic, and policy analyses would be the next step.

In pursuit of the 2050 target, California is capable of leading the world in energy innovation with concurrent economic benefits to the state. The 80% reduction scenario assumes innovation that can, and should, be done in California. The state needs to be aggressive in competing for Federal funds. It should also be attentive to the California investment community to insure that existing leadership is not lost by California companies, and to insure that we attract private capital to support this endeavor.

Recommendations

California is an international leader in the reinvention of energy systems and is poised to expand that leadership. AB32 and a suite of other legislation, regulations, and executive orders have provided a framework for decreasing GHG emissions from the energy system using elements of all four strategies (efficiency, electrification, low-carbon electricity, and low-carbon fuels). The AB32 family of regulations and complementary laws forms a policy framework for accelerating the development and commercialization of low-carbon technologies, and was the inspiration for this report.

The AB32 set of policies is largely premised on placing a price on carbon and utilizing performance standards. The policies include carbon cap and trade; performance standards on vehicles and fuels; renewable requirements for electricity, efficiency standards for appliances and buildings; and performance targets for metropolitan areas to reduce GHGs from passenger travel and sprawl. Other rules, such as the zero emission vehicle program, are intended to jumpstart advanced technologies and set the stage for their large scale commercialization.

Recommendation #1: Achieving more than a 20% GHG emissions reduction fron the current level

Strengthen existing AB32-related laws and rules to accelerate innovation and advance commercialization of cost-effective, advanced low-carbon technologies. Few entirely new rules or policies would be needed. What will be needed is a continual tightening of carbon caps and performance and efficiency standards, and reconciling these rules and policies to make sure that they are well aligned. For example, it will be necessary to:

1. Ensure that aggressive performance standards are aligned with price signals to customers (for instance, with pricing of vehicle use, feebates for purchased vehicles and appliances, higher prices for high-carbon electricity and fossil fuels, etc);
2. Ensure that the electricity infrastructure (e.g. vehicle recharging facilities and distribution transformers) is sufficient to accommodate the rapid adoption of electrification, including uses for vehicles as well as for heat; and
3. Continually examine the low carbon fuel standard to ensure that it adequately addresses potential impacts on water, land, food, biodiversity, and perhaps social impacts (especially for biofuels imports).

Recommendation #2: Getting to a 60% GHG emissions reduction from the 1990 level

The following 7 items represent potential policy gaps that need to be considered in order to achieve the technically feasible 60% reduction outlined in the report:

1. Ensure that all existing buildings are either aggressively retrofitted, or replaced as part of their natural lifecycle. Require rapid implementation of high efficiency standards for buildings, appliances, equipment and vehicles, to reduce energy consumption in new buildings by 80% relative to 2010. The overall energy reduction in buildings must increase to 40% or greater by 2050. Vehicle efficiency improvements and electric vehicle adoption rates need to result in a light duty fleet average of at least 72 mpgge by 2050.
2. Effect rapid and ubiquitous electrification of all technically feasible transportation and heat.

Electrify all bus and rail transportation, and 70% of building heating and cooking.

3. Ensure that new clean electricity is being developed at a rate of about 1.3 GW/yr (baseload) or 4.0 GW/yr (intermittent), so that by 2050 we have the capacity to meet twice the demand we have today from sources that all have extremely low life-cycle emissions.
4. Decide how to provide de-carbonized baseload electricity and especially whether to develop this de-carbonized electric generation system with, or without, nuclear power. To provide 67% (about 44 GW) of our electric power in 2050 with nuclear facilities would require about 30 new nuclear power plants and would require the need to manage waste (a federal responsibility). To replace this amount of nuclear power with renewable energy, the state will need to build about 110 GW of capacity (in addition to the 55 GW that would be required under the state's renewable portfolio standard) to allow for intermittency and will have to clearly commit to a plan for firming variable supply without associated emissions.
5. Fill the low-carbon fuel gap with multiple strategies, including, but not exclusively, those based on biomass. Work with agriculture to assess, increase and delineate sustainable amounts of biomass for energy. Support the development of biofuel technology to reduce the life-cycle emissions from these fuels and to reduce the land and water use associated with them. Develop import standards to prevent leakage of emissions and ancillary impacts of using biomass. Develop carbon-neutral alternatives to biofuel.
6. Advance carbon capture and storage, especially as a technology that supports low-carbon fuel production. A number of possible methods for solving the low-carbon fuel problem involve CCS, including producing hydrogen from methane with CCS, and combing CCS with biomass combustion for electricity, to achieve emission credits.
7. Develop a plan for emission-free reliable electric load balancing, including some combination of energy storage, smart grid, bio-electricity, load-following fossil generation with CCS, use of renewable hydrogen in load-following turbines for ramp-up generation, etc.

Recommendation #3: Monitor the implementation rate: actual versus what is needed

Monitor the rate of actual implementation for efficiency, electrification, clean electricity generation and de-carbonized fuel production, and provide an annual report of progress against plan, with a listing of the specific actions that are required to keep progress on target.

For example, based on the assumptions regarding population growth, economic growth, electrification and efficiency in this report, the state needs to almost double the production of electricity by 2050, and at the same time decarbonize this sector. So, we need an average of 1.3 GW (baseload) or 4.0 GW (intermittent) near-zero carbon electricity generation every year from now until 2050. In 2050, the state will also need about 70% as much fuel as we use today. We should be reducing fuel use while we substitute low carbon fuel for fossil fuel. A standard part of the Integrated Energy Policy Report (IEPR) should look at the rate of new construction and implementation compared to the needed rate and remove barriers that can be eliminated without risk to public health and safety.

Recommendation #4: Support the innovation needed to achieve an 80% GHG emissions reduction from the 1990 level

The State of California, working where appropriate with the U.S. Federal Government and industry, should foster, support and promote an innovation ecosystem in energy including universities, national laboratories, small business, innovation hubs, regional clusters, etc. The California delegation should support federal funding for this activity and the CEC should work with California institutions to develop successful proposals to harness and nucleate efforts around the energy R&D capability of the state.

Recommendation #5: Put in place the structure needed to inform future portraits

Consider the potential utility of the energy system-wide analytical tools in strategic planning and evaluate how to manage the future use of such tools to inform strategic decisions and investments. Analytic tools and methodologies such as those developed for this report should keep track of all end-use requirements, sources of energy, energy delivery mechanisms and associated emissions. The assumptions used in this report are very likely to change over time as conditions evolve and some new technologies become more realistic, and the tool can be used to examine the impact of these changes. Most importantly, the tool can help to show the system-wide effects of policy choices. For example, does a policy simply raid one part of the energy system to optimize another, or does it in fact set us on a path to reduce emissions and provide for our energy needs overall?

Recommendation #6: Maintain a long-term plan

The Governor should direct the key agencies (CEC, CARB, CPUC etc.) to jointly examine a range of pathways to determine the most desirable 2050 energy system configurations from a combination of economic, policy and technology perspectives. Interagency efforts will benefit from using system-wide analyses, such as the approach used in this study, as the basis for creating the long-term plans and near-term priorities for securing California's energy future as well as viable infrastructure pathways to get to the 2050 GHG target. A key element of the long term plan should be to maintain several future pathways, in order to maximize options under uncertainty and increase the probability that innovation may make significant contributions in the future.

Appendix A: Units and Conversion Factors and Acronyms

The following table shows the conversion between the most commonly used units in this report. Conversion was performed in order to compare different types of energy use, and in particular for estimating the total demand for fuels (both liquid and gaseous) that could be supplied by biomass:

	To Units					
From Units	**Electricity (kWh)**	**Gaseous fuel (therms)**	**Liquid fuel (gge)**	**Hydrogen (kg H_2)**	**Thermal (million Btu)**	**Biomass (dry tons)**
Electricity (kWh)	1.	0.03412	0.029567	0.030016	0.0034120	0.00036958
Gaseous fuel (therms)	29.308	1.	0.86655	0.87973	0.1	0.010832
Liquid fuel (gge)	33.822	1.1540	1.0	1.0152	0.1154	0.012500
Hydrogen (kg H_2)	33.315	1.1367	0.98502	1.	0.11367	0.012313
Thermal (million Btu)	293.08	10.	8.6655	8.7973	1.	0.10832
Biomass (dry tons)	2,705.7	92.320	80	81.21	9.2320	1.

Electricity (W, MW, GW): One hundred watts (W) is the typical power consumption of an incandescent light bulb, equal to about a 25 W compact fluorescent bulb. A household space heater can consume 1,000 W or more. Power plants are typically measured in millions of watts (megawatts or MW) or billions of watts (gigawatts or GW).

Electricity (kWh, TWh): Electrical energy consumption is measured in kilowatt-hours (kWh). One kWh is the energy consumed by 1,000 W in an hour. California's current demand is roughly 300 billion kWh (terawatt-hours or TWh) per year. This is the output of roughly 40 one-gigawatt nuclear plants operating 85% of the time.

Gaseous fuels (therms, Mtherms): One therm is equal to approximately 30 kWh of electricity. In 2005, California consumed approximately 15,000 million therms (Mtherms) of natural gas.

Liquid fuels (gge, bgge): One gallon of gasoline equivalent (gge) is, by definition, equal to one gallon of gasoline, or approximately 0.9 gallons of diesel, 1.4 gallons of ethanol, or 1.15 therms of natural gas. California's current demand for liquid fuels is approximately 25 billion gge (bgge) per year.

Hydrogen (kg H_2, MtH_2): One kg of hydrogen (H_2) is almost exactly equal to one gge. One billion kg H_2 is equal to 1 million metric tons H_2 (MtH_2).

Thermal (million Btu, TBtu): One million British thermal units (million Btu) is equal to approximately 300 kWh of electricity, 10 therms of natural gas, or 9 gge of liquid fuel. California's total energy demand in 2005 from all sources was approximately 5,000 trillion Btu (TBtu).

Biomass (dry tons, dt, mdt): One dry ton (dt) of biomass can produce approximately 80 gge of biofuels or biogas. California's biomass supply is estimated at approximately 40-120 million dry tons (mdt) per year.

Acronyms

AB	Assembly bill
ACEEE	American Council for an Energy-Efficient Economy
BAU	Business-as-usual
CAES	Compressed air energy storage
CARB	California Air Resources Board
CCS	Carbon capture and sequestration
CCST	California Council on Science and Technology
CEC	California Energy Commission
CEF	California's Energy Future
CPUC	California Public Utilities Commission
CSP	Concentrating solar power
FCV	Fuel cell vehicle
GHG	Greenhouse gas
GW	Gigawatts
IEPR	Integrated Energy Policy Report
ISO	Independent System Operator
JCAP	Joint Center for Artificial Photosynthesis
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
LDV	Light-duty vehicles
LED	light emitting diode
LWR	Light water reactor
NIF	National Ignition Facility
PHEV	Plug-in hybrid electric vehicles
PV	Photovoltaic
UC	University of California
ZELB	Zero-emissions load balancing

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