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The 80% Solution
Radical Carbon Emission Cuts for California

The technology and knowledge exist to take the state most of the way to its ambitious 2050 goal, but more research will be needed in a few key areas to achieve full success.

There is a lot of buzz about innovation being needed to radically reduce emissions of carbon dioxide (CO_2) and other greenhouse gases while meeting energy needs. But what innovation is required? And are the gaps all technical? A study in California offers some insight. Although it does not provide all the answers, it may help to clarify the state of energy technology and identify areas where more R&D are needed.

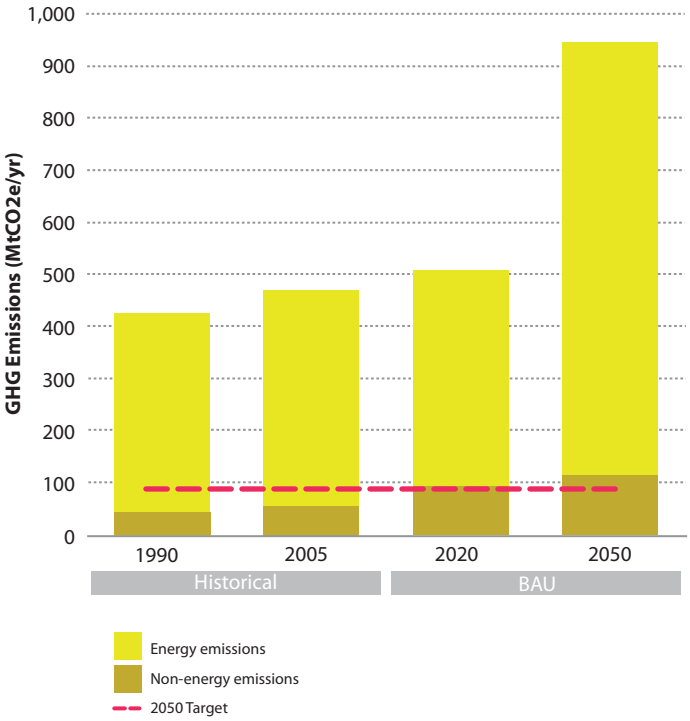
In 2005, the governor of California issued an executive order requiring the state to reduce its CO_2 emissions to 80% below the 1990 level by 2050. In response to this decision, the California Council on Science and Technology launched the California's Energy Future project to explore whether the technology and resources were available, or likely to become available, to meet this goal.

As part of the project, we and our colleagues developed a simple model for identifying energy systems that would meet the state's energy requirements for buildings, transportation, and industry in the future, while at the same time addressing the emission-reduction goal. Using this model, the team identified four steps that the state would need to take:

1. Decrease the demand for electricity and fuel as much as possible through efficiency measures.
2. Decrease the demand for distributed use of hydrocarbon fuels as much as possible by focusing on electrification of transportation (including light-duty vehicles, trains, buses, and some trucks), water and space heating in buildings, and industrial process heating.
3. Produce electricity with very low emissions through a combination of nuclear power, fossil fuel generation with carbon capture and storage (CCS), and renewable sources; and provide load-balancing services without emissions as much as possible, using energy storage or smart-grid solutions.
4. Use low-carbon–intensity biofuels to meet as much of the remaining hydrocarbon fuel demand (both liquid and gaseous) as possible.

FIGURE 1

Historical and business as usual emissions



The first step will have the effect of decreasing the demand for fuel and electricity relative to what is called the "business as usual" scenario (Figure 1). The second step will decrease the demand for fuel and increase the demand for electricity. In the third step, the state will have to double the amount of electricity generated to meet increased demand, while also decarbonizing the generation process. Even after the first three steps are taken, the state will still need to use fuel, because some uses, such as heavy-duty trucks, airplanes, and high-quality industrial heat, cannot be electrified. Low-carbon biofuels could help meet this demand.

In examining these four steps, the team ranked technologies in their order of availability. First, there are technologies that are currently available on the market. Second, there are technologies that have been demonstrated but are not currently for sale at scale. Third, there is a limited number of technologies that are still in development but may become available commercially by 2050. Analysts did not include technologies deemed to be only research concepts or technologies that although available, were excessively expensive and likely to remain so. This bottom-up analysis provided a clear picture of what kind of innovation would be required to do the job.

Here is what we thought might be possible by 2050 (Figure 2):

First, energy efficiency measures could cut the demand for energy roughly in half by 2050. In the built environment, current buildings would either be demolished or retrofitted to much higher efficiency standards, and all new buildings would be built to much higher efficiency standards. The majority of the energy savings would come from demolishing old buildings and building new ones. The majority of the costs are likely to be incurred by retrofits. The innovation required to accomplish this has to do entirely with implementation: bringing down the costs, changing the building codes, educating the workforce, and paying for the changes. What needs to be done is clear, but the state does not have the institutional structures in place to do it.

In transportation, the automobile fleet, given historic turnover rates, would evolve to average over 70 miles per gallon as it becomes more efficient (and largely electrified). There is room for technical innovation, but the technologies needed are largely known. Innovation will be required to introduce them and expand their use.

The same is not true for efficiency measures in the industrial sector. Here, we found a large number of technologies that were only in development and had not yet been demonstrated that would provide significant energy savings in industrial processes. For example, integrated and predic-

tive operations and sensors, advanced materials and processing, electrified process heating (for example, by using microwave or ultraviolet energy), and process intensification are all under development and would produce economic improvements. Thus, the necessary innovation is motivated and likely.

Second, all buildings could be heated with electricity, and many forms of transportation—light-duty vehicles (cars), short-range trucks, buses, and trains—could be electrified. The electrification of transportation and of space and water heating can be accomplished with technologies available today. There are policies and innovation to support the electrification of light-duty vehicles, but generally, other sectors that could be electrified are ignored. The policy and economic framework to do this will require innovation.

Third, electricity generation capacity could be doubled at the same time as it is decarbonized, using almost any combination of nuclear power, fossil fuel generation with CCS, and renewable energy sources. In this scenario, electricity generation would increase from the 270 terawatt hours (TWh) per year used statewide today, to a projected demand for about 510 TWh in 2050. Although we may decarbonize electricity generation capacity, the electricity system can still produce emissions. Supply and demand both fluctuate during the day, and some forms of renewable energy (wind and solar in particular) can experience long periods when they cannot produce electricity at all (intermittency). If peaking, ramping, and covering for intermittent renewable energy are accomplished with natural gas, this will produce emissions that must be eliminated.

The team determined that nuclear power has no technical obstacles. With a modest efficiency penalty, power plants can be air-cooled—that is, run without cooling water—or cooled with wastewater, there is a sufficient supply of nuclear fuel, nuclear waste can be safely stored, siting reactors safely is possible, and new passive reactor concepts have many improved safety advantages. However, the March 2011 nuclear accidents at the Fukushima Daiichi nuclear power facility in Japan, triggered by an earthquake and tsunami, have significantly affected public opinion and confidence that it is possible to manage nuclear power safely, and California law prohibits the building of new nuclear power plants until there is a licensed federal nuclear waste repository. Innovation in the managing of nuclear power so that public opinion favors this solution will be required.

Technologists know how to build electricity generation plants that use natural gas or coal, as well as how to separate CO_2 from the flue gas, and the oil and gas industries have a great deal of experience in putting CO_2 underground (al-

FIGURE 2

GHG reductions with a single strategy

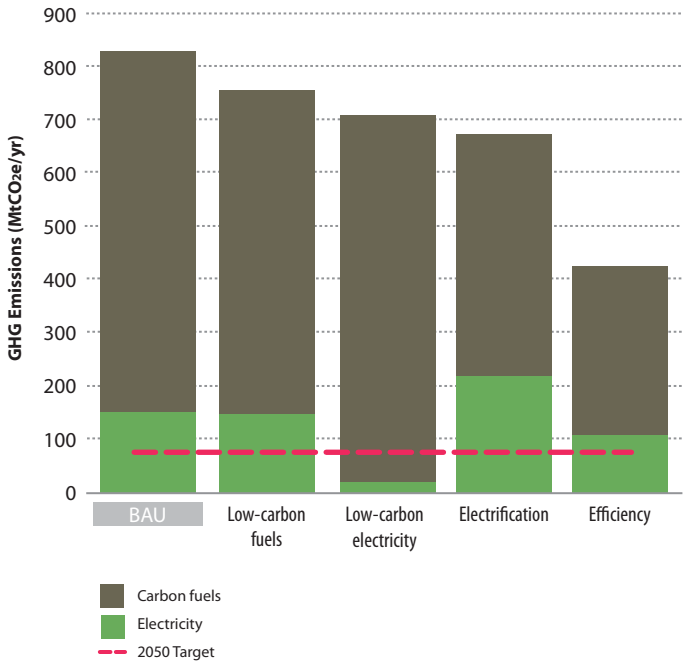
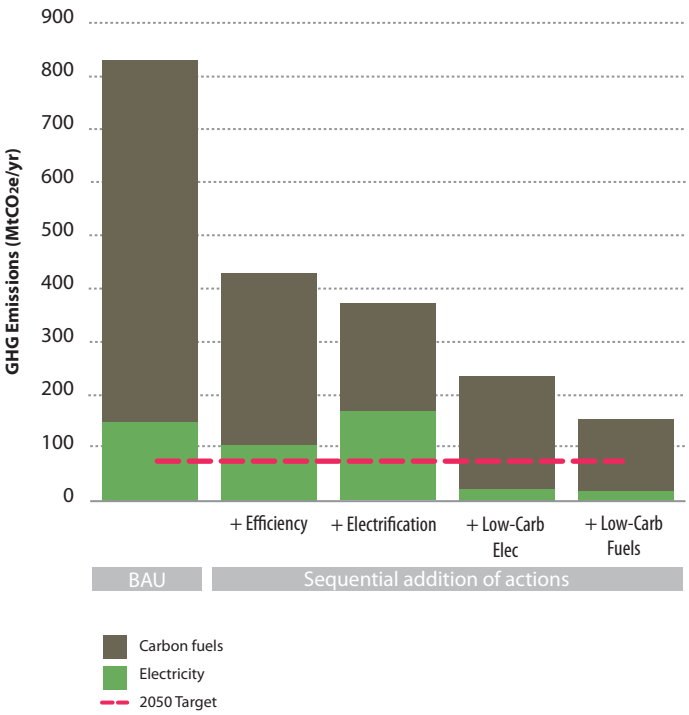


FIGURE 3

Getting to 60% below 1990 level



beit for enhanced resource recovery, not permanent CO_2 storage). Although these processes are currently available, the integration of power generation with CCS at scale is yet to be demonstrated. The energy required to drive the CCS process is currently very high, as much as 30% of generation. Innovation could reduce this, and engineers expect that it could be as low as 10% by 2050. If California chooses to use natural gas for electricity generation, there will be decades of storage available within the state in abandoned oil and gas reservoirs. These sites have been of economic interest and are well characterized and known historically to effectively trap hydrocarbons. The use of saline aquifers to store CO_2 is also possible but will require more effort.

California has a wealth of renewable resources, including hydropower, geothermal, wind, solar, and biomass, that are sufficient to provide all the capacity it needs. The technology is available now. Innovation could make it less expensive, but engineers already know how to build renewable energy–generation facilities. However, if much of this generation is intermittent wind and solar, significant innovation will be needed to integrate these resources in order to maintain reliability when the wind does not blow or the Sun does not shine.

All forms of electricity generation will require load balancing for meeting peak requirements; for providing rapid ramping up of power to meet sudden changes in demand; and, in the case of renewables, for covering periods of intermittent supply. The electricity sector knows how to accomplish load balancing with natural gas turbines, but these produce carbon emissions. In our analysis, we found that, in the case of a completely renewable-energy electricity portfolio, if all load balancing is accomplished with natural gas, the emissions from this source alone will nearly equal the allowed emissions for the entire energy system. The load balancing for electricity is much easier to achieve if part of the carbon-free electricity generation comes from base-load plants. We found little information to quantify how much a smart grid could contribute to solving the load-balancing problem without emissions. We see innovation required to implement smart-grid concepts, particularly in the business models and controls required to achieve these gains. We found that the technology to support "load following" through energy storage was insufficient and very expensive at scale. Importantly, the technology for providing large amounts of electricity to cover for intermittent renewable energy is currently lacking. Technical innovation is clearly required here.

Fourth, innovation in biofuels can be expected to lower their carbon footprint by about 80% as compared to fossil fu-

els by 2050. Likely feedstocks for biofuels would include all of the waste biomass from agriculture, forestry, and municipal waste, plus crops that could be grown on marginal land without irrigation or fertilizer. Other sources such as algae may contribute, but we deemed them extremely difficult to scale up.

Even though this would be of significant help, there is also a problem: The state is expected to be able to produce or import enough biofuels to meet only about half of its requirement for fuel. The remaining demand would still have to be met with fossil fuel, which would generate emissions that would total about twice the state target and represent the primary source of carbon emissions in 2050. Given this shortage, the state would need policy innovation to reserve biofuels primarily for uses that cannot be electrified, such as heavy-duty transport or load balancing that cannot be handled with energy-storage devices or smart-grid solutions. Technological innovation will be needed to lower the carbon footprint of biofuels and to supply biomass that does not compete with food supplies. Such innovations will help enormously, because every gallon of biofuel displaces a gallon of fossil fuel, and thus the effect of each gallon is leveraged significantly. However, even with imports of biofuel, the state is almost certainly not going to have enough biomass to meet its fuel demand, and there is a major technology innovation gap in solving the remaining fuel problem.

As our bottom line, we determined that the four necessary steps identified, even taken collectively and aggressively, would not be sufficient to reach California's stated goal (Figure 3). At best, taking all four steps has the potential to reduce emissions to about 60% below 1990 levels, leaving them at about twice the target rate.

Getting from 60% to 80% reduction

At a more detailed level, the emissions remaining in the energy system all arise from the continued use of fossil fuel in transportation and of natural gas to provide load balancing. Thus, the single largest technology gap in achieving radical emission cuts is the fuel problem.

There are a number of ideas for filling this gap. They are generally complex from an industrial perspective, require substantial infrastructure, and are likely to be expensive. They also will require technological, economic, industrial, and perhaps societal innovation. These ideas include, among others, solving the load-balancing problem without emissions, through storage technology or the smart grid; developing a biofuel with no net emissions; using biomass combined with CCS to make electricity and/or fuel to offset fossil emissions elsewhere; using hydrogen, produced from coal or methane with CCS, to replace fossil fuel use that electricity cannot displace; and developing the industrial process to use biomass, coal, and CCS to simultaneously make electricity and fuel with very low net CO_2 emissions.

Although none of these innovations could solve the remaining fuel problem on its own, in combination they hold the potential of reducing the remaining emissions to the target of 80% reduction below the 1990 level, or perhaps even lower. In addition, societal innovations could reduce demand through behavior change. Although there is little solid data to support the potential of behavior change, there is considerable speculation that this could be a major component of a larger energy strategy. In the long term, research ideas including getting fuel from sunlight may solve this problem, but this is unlikely before 2050.

It is notable that many of the potential solutions for fuel-use reduction involve CCS. Even load balancing could involve CCS if technologists can find a way to make the process economical for gas turbines in load-following mode. It seems that even if the state does not choose to use CCS for electricity, it will remain an important technology for solving the fuel problem.

Based on our analysis, then, we concluded that the major technology gaps in making radical emissions reductions are in energy storage, smart-grid solutions, and low-carbon fuels that go beyond the simple conversion of biomass to biofuels. If current problems in these areas are solved, then the prospects for radical emission reductions are dramatically improved.

The radical reduction of emissions also will require substantial policy and institutional innovation. A short list of questions inspired by our analysis includes:

- What policies could result in halving the energy required for the same services? How would these policies prevent rebound effects, in which lowering the energy cost of an activity stimulates an increase in its use? Are certain efficiency measures more effective in the long term than the short term? What are the comparative costs versus benefits for critical policy choices? What are the relative effects and costs of new procurements that are energy-efficient, as compared with those of retrofitting for energy efficiency?
- What policies could help achieve electrification at the least expense? What alternative policy designs could achieve the required levels of electrification beyond light-duty vehicles (cars)?
- What policies would eliminate emissions from the electricity sector and allow for doubling the capacity as well? What are good policies for controlling emissions that come from filling in the gaps created by intermittent power? What

kind of policy designs would encourage investment in energy storage and result in eliminating emissions from this underappreciated sector?

- Given that biomass supply is limited, what policies would ensure that supplies are used to greatest advantage and least harm and that every end use that can be electrified is? What policies would be appropriate to improve low-carbon, non–biomass-based fuel technology options?

In addition to addressing such technology-inspired questions, there is a need to gather more and better data on how best to change behaviors in ways that would help reduce the size of the energy problem and to better delineate what the potential for saving energy through behavior change actually is.

In summary, achieving radical emission cuts will take deployment and new technology. California needs to take the four key deployment steps identified, and the longer it waits to take them, the steeper the climb will be.

The state cannot achieve its goal with efficiency improvements alone, but doing so without efficiency gains will make the lift enormous and virtually unachievable. The state cannot do it with electrification alone, but without increased electrification, the demand for emission-free fuels cannot be met. The state needs to replace fossil fuels with nonemitting energy sources for the generation of electricity. The problem would be a lot easier to solve if the state were to develop additional base-load generating capacity that does not emit carbon; this would include geothermal or nuclear capacity or facilities that incorporate CCS. Also, sustainable sources of biofuels need to be developed, and these fuels should be used primarily for heavy-duty transport and airplanes. And as there almost certainly will not be enough biomass for all our fuel needs, major new innovations will be needed for decarbonizing the remaining fuel use.

Innovation will be the hallmark of a new energy system with radically reduced emissions. But waiting on innovation to solve the problem will make the target much harder to reach. California already knows much about what must be done and has many effective tools for the job. The challenge today is to both apply known technologies, aided by policies designed to foster their implementation, and at the same time continue the search for better technologies that can be phased in over time to better balance energy needs with minimal carbon emissions.

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