CALIFORNIA
ENERGY
COMMISSION

Public Interest Energy Research Program
Research Development and Demonstration Plan

Attachment V - Developing Greenhouse Gas Mitigation Supply Curves for In-State Sources

Contractor/Consultant Report

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The key objective of this greenhouse gas (GHG) emission reduction supply curves roadmap is to contribute to advancements in the science of supply curve development, particularly as applied to understanding GHG emissions reductions opportunities in California. To achieve this goal, it will also likely be necessary to develop GHG reduction supply curves for California in cases where such curves are otherwise unavailable.

Part of the long-term vision of this roadmap is to develop the technical information necessary to ensure that California's policy makers can effectively respond to any GHG-reduction commitments made on its behalf by the United States. Even absent a national commitment to international agreements such as the Kyoto Protocol, California might decide to adopt its own GHG mitigation goals for the state. Already, the State has created a California Climate Action Registry to help companies and organizations doing business in California establish GHG emissions baselines against which future GHG emission reduction requirements could be applied. State policymakers will need robust and credible estimates of GHG mitigation costs and impacts in order to develop GHG mitigation strategies, policies, programs, and, possibly, regulations.

This roadmap seeks to advance the state-of-the-art of supply curve development, as well as improve the applicability and functionality of such curves for policy making and macroeconomic modeling. The strengths and limitations of supply curves vary significantly by greenhouse gas type and by sector; however, virtually all supply curves developed to date can be improved with respect to their methods, data limitations, and models.

Background

"Supply curves" have been utilized in a number of disciplines for many years as a way to graphically display, in simple terms, the cost and availability of a resource or other market good. The supply curve paradigm was adopted to characterize the potential costs and benefits of energy conservation in the early 1980s. These early conservation supply curves were intended to graphically illustrate the amount of energy *savings* that could be achieved through widespread implementation of energy conservation measures, as well as the costs of achieving those savings. In this way, conservation supply curves were designed to allow direct comparison of the costs of saving a unit of energy with the costs of producing it. Generally, the vertical axis of the curve represented the cost of each conservation measure, usually in dollars per unit of energy saved, while the horizontal axis represented the total amount of energy savings available. Measures are ordered on a marginal, least-cost basis.

Over the last ten years, the energy conservation supply curve framework was adapted and applied to the problem of characterizing the costs and benefits of various GHG mitigation strategies. In these GHG mitigation supply curves, costs are generally expressed in dollars per ton of carbon-equivalent reduction and plotted against the total amount of carbon-equivalent reduction that can be achieved by implementing the mitigation measures.

Despite some inherent weaknesses and limitations in the supply curve approach, it has been adopted in many GHG mitigation studies for several reasons. First, supply curves are an effective way of presenting the combined results of individual measure analyses into a simple graphical format that is intuitively easy to understand. This is important because many GHG mitigation supply curve studies often include cost and impact data on hundreds or thousands of individual technologies and practices. A second reason supply curves have proved useful to GHG researchers is that their results can be directly incorporated into a number of existing energy and economic forecasting models. These models use GHG mitigation supply curves as inputs to estimates of the total macroeconomic costs associated with achieving specific levels of reductions in greenhouse gas emissions.

Roadmap Scope

This roadmap addresses research needs associated with the development of California-specific GHG emission reduction supply curves for a variety of GHG types and sectors. Carbon dioxide mitigation through sequestration and direct removal approaches is not addressed.

General Supply Curve Methodological and Data Limitation Issues

Despite their usefulness, research for this roadmap indicates that there are a number of methodological problems and data limitations associated with GHG mitigation supply curve studies, including the following: inadequate incorporation of measure costs and benefits; a lack of access to proprietary industry data; a lack of measure adoption analysis and modeling; inadequate forecasting of technological innovation; use of average case measure analyses (resulting in aggregation bias); use of static versus dynamic stock modeling; and a lack of uncertainty analysis.

Goals

This roadmap's primary goal is to contribute to advancements in the science of GHG mitigation supply curve development, particularly as applied to understanding emissions reductions opportunities in California. To achieve this goal, it likely will be necessary to develop mitigation supply curves for the State of California in cases where such curves are otherwise unavailable. Improved GHG reduction supply curves will help both private and public sector decision makers to formulate the most effective and economical GHG mitigation policies.

The achievement of these goals depends on a variety of factors that vary by sector and greenhouse gas. Generally, it will be necessary to improve baseline inventory data in a variety of areas, including fuel consumption, landfills, and livestock farms. In addition, a number of methodological and macroeconomic integration issues will need to be improved. Finally, it will be critical that PIEREA efforts in this area are leveraged with the resources and talent available from other organizations with convergent research needs and interests.

The research activities in this roadmap begin with sector/gas-specific recommendations and conclude with recommendations that integrate or cut across sectors and greenhouse gases. The short-term sector/gas-specific recommendations focus on the development or synthesis of *initial* supply curve information. That is, the development, analysis, and organization of technology costs and benefits into supply curves similar to those developed in past GHG and conservation supply curve studies and described in Section 3 of this roadmap. Such basic supply curves have important limitations, particularly when they are incorporated into macroeconomic and mid- to long-term forecasting models. In addition, supply curves that focus only on technology costs and benefits do not provide policy guidance per se, though they are an important input to policy analyses.

The short-term Crosscutting/Integration recommendations address the broader needs associated with advancing the state-of-art of supply curve development and their integration with larger economic modeling efforts. One of the reasons for this organization is practicality. First-order benefits for California's climate change policy makers can be achieved fairly quickly by developing supply curves that capture incremental measure costs, measure applicability, and the potential impacts of measures on reducing GHGs in California. Further value will be obtained by expanding such analyses to explicitly include technology innovation over time, the diffusion-of-innovation framework to technology adoption, incorporation of market barriers and market failures, and integration into macroeconomic models. Although these advances are addressed primarily under the Crosscutting/Integration area, the initial supply curve work should also incorporate at least qualitative identification of market barriers and failures, as well as other co-benefits and collateral costs.

The mid-term recommendations focus on the development of *advanced* supply curves, which would build off of the initial studies to more definitively resolve current analytical and data-related weaknesses.

The PIEREA program recognizes that much work is currently under way in these areas and seeks to draw from, build upon, and broaden the focus of those efforts. Whenever possible, PIEREA will identify existing efforts and form partnerships to leverage resources.

PIER GHG Mitigation Supply Curve Research Objectives

In the short-term (1–3 years) this roadmap recommends addressing the objectives summarized in the table below:

Objective	Projected Cost ($000)
Contribute to the development of an initial California-specific CO_2 reduction supply curves for residential buildings**.**	50–100*
Contribute to the development of an initial California-specific CO_2 reduction supply curves for commercial buildings.	100–200*
Establish the feasibility of adapting LBNL industry-specific studies to California	50–100
Contribute to development of initial California-specific CO_2 reduction supply curves for remaining major industries	100–300**
Develop basic California-specific CO_2 reduction supply curves for the transportation sector	200–500
Address weaknesses and gaps in current transportation supply curve studies	100–300
Develop basic California-specific CO_2 reduction supply curves for the electricity generating sector	100–400*
Forecast the future generation mix in California and incorporate the ability to model changes in response to GHG mitigation policies	100–300
Develop CH_4 reduction supply curve for the landfill population in California	25–100
Develop California-specific CH_4 reduction supply curves from manure management	25–100
Develop N_2O reduction supply curve for California, reduce uncertainty in N_20 emission estimates	25–100
Develop supply curve for mitigating high global warming potential gases in California, reduce uncertainty in high GWP emission estimates	25–50
Develop/Implement a Dynamic Technology Adoption Model	100–500***
Advance the state-of-the-art associated with bottom-up analyses of GHG reduction options	50–100
Total Short-term Cost	**1,050–3,150**

Note: An asterisk (*) indicates a high probability that the work will be leveraged with other ongoing efforts. The figure given is the California Energy Commission's projected expenditure to complete each short-term objective.
**Range depends on number of industry-specific studies conducted ($35,000–$75,000 per industry).
***Higher range includes funding for one or more studies to empirically estimate model parameters.

The Public Interest Energy Research (PIER) Climate Change Research Plan also identifies mid-term (3–10 year) and long-term (10–20 year) goals, all of which build on the short-term work listed above. This roadmap outlines a comprehensive research agenda that would be necessary to fully address the research gaps identified in this document. PIER, however, due to the limited funding, will be able to support only some of the identified areas of research. PIER is currently examining all of the roadmaps to determine which projects should be supported with PIER funding.

Roadmap Organization

This roadmap is intended to communicate to an audience that is technically acquainted with the issue. The sections build upon each other to provide a framework and justification for the proposed research and development.

Section 1 states the issue to be addressed. *Section 2: Public Interest Vision* provides an overview of research needs in this area and how PIER plans to address those needs. *Section 3: Background* establishes the context of PIER's climate change work, as it pertains to the issue of developing GHG mitigation supply curves. *Section 4: Current Research and Research Needs* surveys current projects and identifies specific research needs that are not already being addressed by those projects. *Section 5: Goals* outlines proposed PIEREA activities that will meet those needs. *Section 6: Leveraging R&D Investments* identifies methods and opportunities to help ensure that the investment of research funds will achieve the greatest public benefits. *Section 7: Areas Not Addressed by this Roadmap* identifies areas related to the development of GHG supply curves that the proposed activities do not address. *Appendix A: Current Status of Programs* offers an overview of work being done to address climate change issues in this area.

Acronyms

ARB	California Air Resources Board
Cal/EPA	California Environmental Protection Agency
BAU	business-as-usual
CAFE	Corporate Average Fuel Economy
CALMAC	California Measurement Advisory Council
CAST	Council for Agricultural Science and Technology
CCIG	California Conservation Inventory Group
CCNG	combined-cycle natural gas
CEF	Clean Energy Futures study
CH_4	methane
CHP	combined heat and power
CIWMB	California Integrated Waste Management Board
CO_2	carbon dioxide
CPUC	California Public Utilities Commission
CEUS	Commercial End Use Surveys
DEER	Database for Energy Efficiency Resources
DG	distributed generation
DOE	U.S. Department of Energy
DWR	California Department of Water Resources
EPA	U.S. Environmental Protection Agency
ER	Electricity Report
GHG	greenhouse gas
GWh	gigawatthour
GWP	global warming potential
HFC	hydrofluorocarbon
IWG	Interlaboratory Working Group (DOE)
kWh	kilowatthour
LBNL	Lawrence Berkeley National Laboratory
MAC	marginal abatement curve
MMTCE	million metric tons of carbon equivalent
MMBtu	million British Thermal Units
MPO	municipal planning organization
MT	metric tons
Mth	megatherm
NAS	National Academy of Sciences
NEMS	National Energy Modeling System
NREL	National Renewable Energy Laboratory
PFC	perfluorocarbon
PG&E	Pacific Gas & Electric
PIEREA	Public Interest Energy Research, Environmental Area (California Energy Commission)

RASS	Residential Appliance Saturation Surveys
RD&D	Research, development, and demonstration
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
SF_6	sulfur hexafluoride
SIC	standard industrial classification
TCE	metric ton of carbon equivalent
TWh	terrawatt-hour (a thousand million kilowatt hours)
USDA	U.S. Department of Agriculture
WIP	waste-in-place

1. Issue Statement

California lacks a full complement of supply curves that would enable State agencies and decision makers to develop informed decisions about the cost-effectiveness of potential greenhouse gas (GHG) mitigation measures. This lack of capability leaves the State unprepared to address potential state or national mandates for GHG reduction, or to benefit from the nascent GHG emissions trading markets.

2. Public Interest Vision

The potential magnitude of adverse ecological, agricultural, and economic impacts warrants development and implementation of technologies and policies to mitigate GHG emissions.[1] The key objective of this roadmap is to help advance the state-of-the-art of supply curve development, particularly as applied to the understanding of GHG emissions reductions opportunities in California. It also seeks to improve the applicability and functionality of such curves for policy making and macroeconomic modeling. To achieve this goal, it will also likely be necessary to develop GHG reduction supply curves for the State of California in cases where such curves are otherwise unavailable. The strengths and limitations of supply curves vary significantly by greenhouse gas type and by sector; however, virtually all supply curves developed to date can be improved with respect to their methods, data limitations, and models.

Part of the long-term vision of this roadmap is to develop the technical information necessary to ensure that California's policy makers can effectively respond to any GHG-reduction commitments made on its behalf by the United States. Even absent a national commitment to international agreements such as the Kyoto Protocol, California might decide to adopt its own GHG mitigation goals for the state. Already, the State has created a California Climate Action Registry to help companies and organizations doing business in California establish GHG emissions baselines against which future GHG emission reduction requirements could be applied. State policy makers will need robust and credible estimates of GHG mitigation costs and impacts in order to develop GHG mitigation strategies, policies, programs, and, possibly, regulations.

There are a number of target audiences for whom the information developed throughout implementation of this roadmap would likely be applicable, including the following:

- Executive and Legislative branches of State government
- State agencies, such as members of the Interagency Team on Climate Change
- Local governments that decide to develop and pursue their own GHG-reduction plans (e.g., as has occurred in Portland and Seattle)
- The California Climate Action Registry (created through SB 1771)
- Private-sector firms participating in the Climate Action Registry

[1] The potential impacts and costs of global warming on California are addressed through companion PIEREA RD&D roadmaps.

- Investor-owned and municipal utilities throughout the State
- Other national and international government and research organizations (e.g., U.S. Department of Energy (DOE) and U.S. Environmental Protection Agency (EPA)).

3. Background

3.1 Supply Curves Basics[2]

Supply curves have been utilized in a number of disciplines for many years as a way to graphically display, in simple terms, the cost and availability of a resource or other market good. The supply curve paradigm was adopted to characterize the potential costs and benefits of energy conservation in the early 1980s. Technologies or practices that conserve energy were characterized as "liberating 'supply' for other energy demands" and could therefore be thought of as a resource and plotted on a supply curve.[3] In the early 1980s, Arthur Rosenfeld,[4] Roger Sant,[5] Amory Lovins (Lovins et al. 1986), and Alan Meier (Meier 1982) conducted much of the initial work developing and applying this framework to energy conservation. Over the last ten years, the energy conservation supply curve framework was applied in a number of studies that focused on characterizing the costs and benefits of various GHG mitigation strategies. For example, two recent EPA studies (EPA 2000 and EPA 2001) developed supply curves for mitigation of high global warming potential gases and methane, respectively.[6]

Despite some inherent weaknesses and limitations in the supply curve approach (discussed further in Section 3.4), it is likely that supply curves have been adopted in many GHG mitigation studies for at least two key reasons. First, supply curves are an effective way of presenting the combined results of individual measure analyses into a simple graphical format that is intuitively easy to understand. This is important because many of the so-called "bottom up" supply curve studies often include cost and impact data on hundreds or thousands of technologies and practices. A second reason supply curves have proved useful to GHG researchers is that the format of their results can sometimes be directly incorporated into existing energy or economic models (though more so in the former than in the latter, and rarely as effectively as researchers would like). Another appealing aspect of supply curves is that their potential savings or mitigation impacts are adjusted for the effects of overlapping options that are targeted at

[2] This section describes conservation supply curves as they have been defined and implemented in numerous studies. Readers should note that Stoft 1995 describes several technical errors in the definition and implementation of conservation supply curves in the original and subsequent conservation supply curve studies. Stoft concludes that "conservation supply curves" are not "true" supply curves in the standard economic sense but can still be useful (albeit with his recommended improvements) for their intended purpose (demonstration of cost-effective conservation opportunities).

[3] National Academy of Sciences (NAS 1991, Appendix C).

[4] Rosenfeld provides an excellent and interesting historical summary of the "early days" of developing estimates of energy-efficiency potential, beginning in the 1970s, in Rosenfeld 1999.

[5] Sant is often credited with coining the terms "least cost energy services" and "cost of conserved energy."

[6] Supply curves have also been used by government agencies, including the California Air Resources Board, to make decisions about the relative costs and benefits of reducing criteria pollutants.

the same base case technologies and segments. These points can be appreciated more easily through some generic examples.

Figure 1 presents a generic example of a supply curve. As shown in the figure, a supply curve typically consists of two axes—one that captures the cost per unit of saving a resource or mitigating an impact (e.g., $/kilowatthour (kWh) saved or $/ton of carbon avoided)[7] and the other that shows the amount of savings or mitigation that could be achieved at each level of cost. The curve is typically built up across individual measures that are applied to specific base case practices or technologies by market segment. Savings or mitigation measures are sorted on a least-cost basis and the total savings or impacts mitigated are calculated incrementally with respect to the measures that precede them. Supply curves typically (but not always) end up reflecting diminishing returns as costs increase rapidly and savings decrease significantly at the end of the curve.

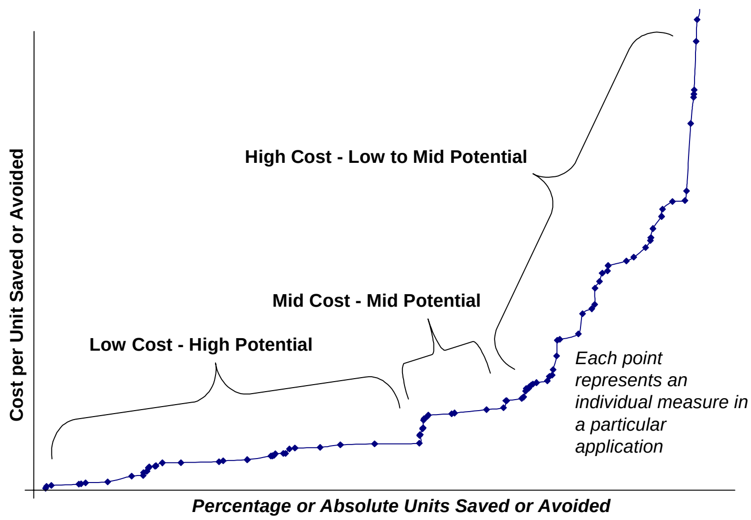

Figure 1. Generic Supply Curve

[7] Note that costs are usually annualized (sometimes referred to as "levelized") in supply curves. For example, energy conservation supply curves usually present "costs of conserved energy," which relate energy savings achieved by implementing a given efficiency measure, to that measure's "cost of conserved energy" (CCE).

$$CCE = \frac{\text{Annualized investment } (\$ / yr)}{\text{Annual energy saved } (kWh / yr)}$$

The initial investment in an efficient technology or program is annualized by multiplying it by the "capital recovery rate" (CRR).

$$CRR = \frac{d}{1-(1+d)^{-n}},$$

where *d* is the real discount rate and *n* is the number of years over which the investment is written off (i.e., amortized).

Table 1 presents a simplified numeric example of a supply curve calculation for several energy-efficiency measures applied to commercial lighting, for a hypothetical population of buildings. What is important to note in this example is that measures are stacked incrementally, based on least cost. When multiple measures are applicable to the same base case technology, supply curves avoid the double counting of savings. This is accomplished by applying measures sequentially and logically to the base case in question. These adjustments are typically made in energy supply curve studies by taking into account the increasing efficiency that occurs as the most cost-effective, energy-efficiency options are adopted. As the energy efficiency goes up as each measure is applied, the savings attributable to the next measure decrease, if the measures are interactive. For example, the occupancy sensor measure shown in Table 1 would save more at less cost per unit saved if it were applied to the base case consumption before the T8 lamp and electronic ballast combination. Because the T8/electronic ballast combination is more cost-effective, however, it is applied first, leaving less energy savings potential for the occupancy sensor. Thus, in a typical energy-efficiency supply curve, the sector usage of the base case end use is reduced with each unit of energy-efficiency that is acquired. Notice in Table 1 that the total end-use GWh consumption is recalculated after each measure is implemented, thus reducing the base energy available to be saved by the next measure.[8]

Table 1. Sample Technical Potential Supply Curve Calculation for Commercial Lighting (*Note: Data are illustrative only*)

Measure	Total End Use Consumption (GWh)	Applicable Square Footage (000s)	Average kWh/ft^2	Savings Percentage (%)	GWh Savings	Levelized Cost ($/kWh saved)
1. Federal Standards	500	100,000	5.0	15	75	0.01
2. T8 with Elec. Ballast	425	100,000	4.3	21	89	0.04
3. Occupancy Sensors	336	40,000	3.4	10	13	0.11
4. Perimeter Dimming	322	20,000	3.2	45	29	0.25
With all measures	293		2.9	41	207	

In the early 1990s, researchers began to apply the conservation supply curve framework to the problem of global warming. The CO_2 reduction associated with reduced power plant generation caused by implementation of energy conservation measures was added as a dimension to the conservation supply curve. Figure 2 shows an example of such work. This curve focuses on the costs of reduced CO_2 associated with implementation of conservation at different energy price points.

8 The process of ordering measures becomes somewhat more complex when dealing with bundles or packages of multiple measures that are combined (see Stoft 1995).

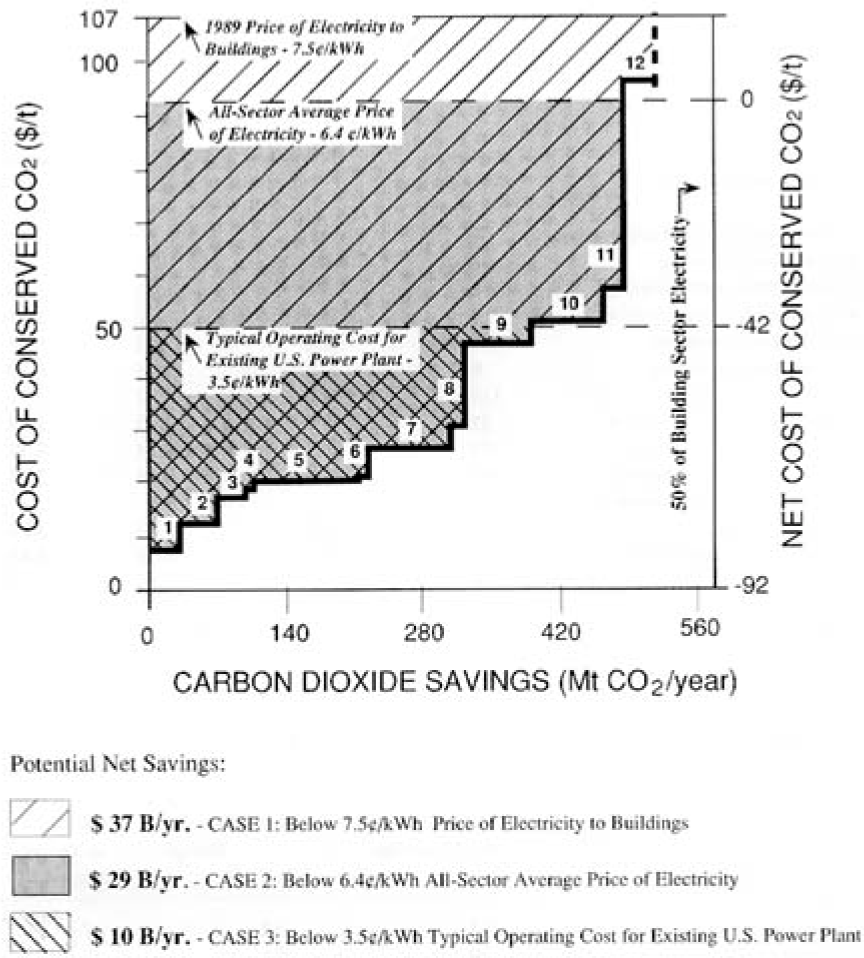

Figure 2. Net Cost of Conserved Carbon Dioxide (CC CO_2) for Electric Efficiency in the Buildings Sector

Source: NAS 1991, Appendix C.

3.2 The Many "Potentials"

Like any resource, there are a number of ways in which an energy efficiency resource can be estimated and characterized. Definitions of energy efficiency potential are in some ways analogous to definitions of potential developed for finite fossil fuel resources like coal, oil, and natural gas. For example, fossil fuel resources are typically characterized along two primary dimensions: the degree of geologic certainty with which resources may be found, and the likelihood that extraction of the resource will be economic. This relationship is shown conceptually in Figure 3. As illustrated by the lower left block in the figure, some fossil resources are known with respect to their location and size (usually from drilling samples) and are economically feasible to extract. These are usually referred to as *Proven Reserves*. Other resources are known but not economic to extract. Outside of the known resources are resources that are possible but not well known. Thus, all other quadrants of the figure are *Possible Resources*. However, both the certainty of knowledge about existing resources and their economic viability of extraction can change quickly, for example in response to wide swings in global oil prices. Thus, the conceptual boundaries in the figure have proven to be very amorphous and dynamic over time.

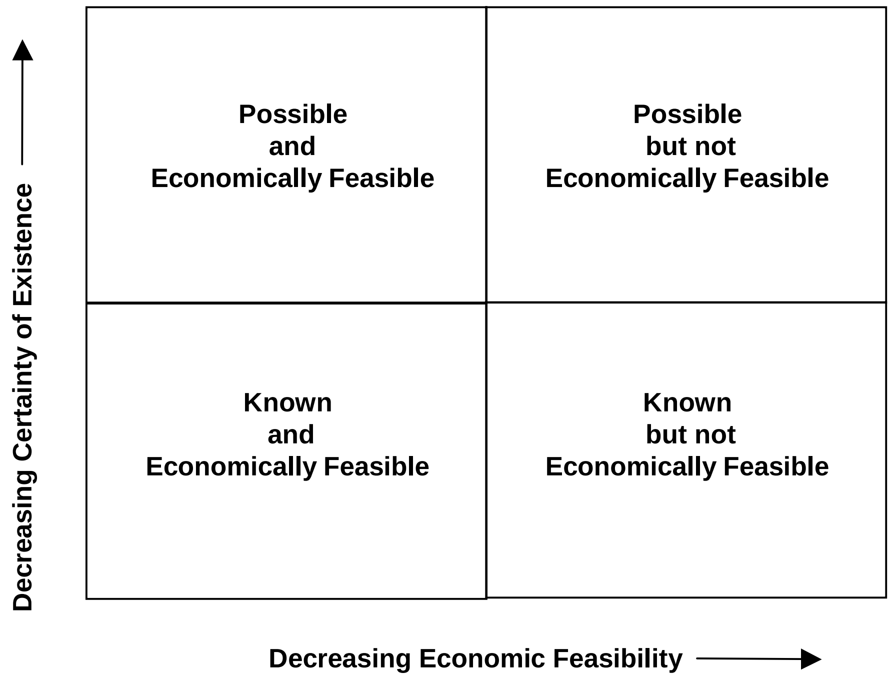

Figure 3. Conceptual Framework for Estimates of Fossil Fuel Resources

Source: Healy et al. 1983.

Somewhat analogously, previous energy-efficiency-potential studies have defined several different types of energy efficiency potential. Among the most common of these terms are *technical, economic, achievable, program,* and *naturally-occurring* potential. These potentials are shown conceptually in Figure 4 and described below.

In previous studies, a number of definitions of energy conservation and GHG mitigation *potential* have been used. The first set of energy conservation supply curve studies focused on identifying *technical potential.* **Technical Potential** was usually defined as the *complete* penetration of all measures analyzed in applications where they were deemed *technically* feasible from an *engineering* perspective. As the bottom-up methodologies began to be employed in utility integrated resource planning (IRP) processes in the late 1980s and early 1990s, many studies formally added the concept of *economic* potential (XENERGY 1992, EPRI 1990). **Economic Potential** was typically used to refer to the *technical potential* of those energy conservation measures that were cost-effective when compared to supply-side alternatives.[9]

[9] *Economic potential* has been defined differently in different studies. For example, in the traditional IRP framework, economic potential was often defined based on the marginal cost of building and running new power plants. In California, the Total Resource Cost (TRC) test was often used as part of this determination. The TRC test is a form of societal benefit cost test commonly used to compare a utility's resource alternatives. In general terms

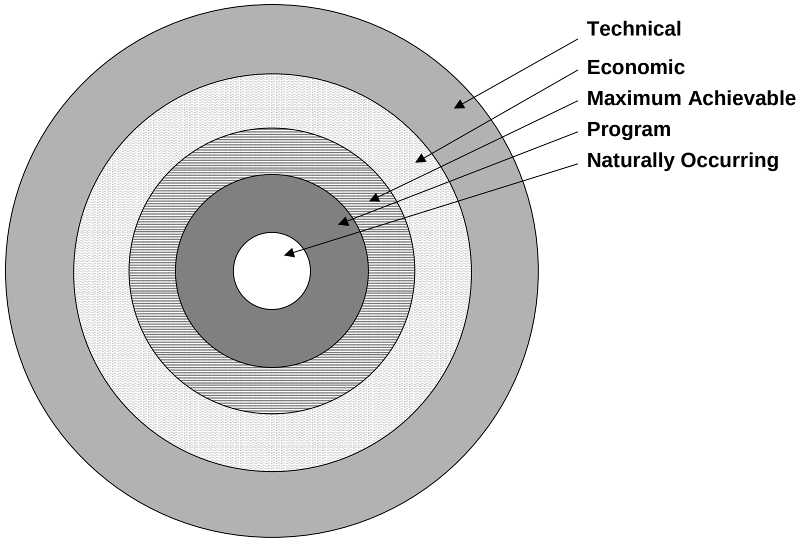

Figure 4. Relative Relationship among Common Energy Efficiency Potential Definitions

Although the concepts of technical and economic potential were important and helpful in establishing the amount of potential theoretically available in energy conservation or GHG mitigation measures, utility resource planners and government policymakers were most interested in knowing the amount of savings or resource mitigation that were likely to occur in response to a particular program or policy, rather than the maximums possible in theory. As a result, many energy studies began in the 1990s to formally estimate what is often called *achievable potential.* **Achievable Potential** usually refers to the amount of savings or resource mitigation that would occur in response to one or more specific market interventions. Because achievable potential will vary significantly as a function of the specific type and degree of intervention applied, it is often developed for multiple scenarios (e.g., "business-as-usual funding," "increased funding," and "maximum funding"). Savings associated with achievable potential are savings that are projected beyond those that would occur naturally in the absence of any market intervention.

Naturally-Occurring Potential is often used to refer to the amount of savings estimated to occur as a result of normal market forces, that is, in the absence of any utility or governmental intervention. The closely related term *business-as-usual* (BAU) is often used in GHG mitigation studies. Business-as-usual forecasts represent the energy use or GHG emissions expected to occur over some time period in the absence of market interventions. Business-as-usual forecasts are often used as a baseline against which the costs and benefits of market intervention strategies are measured. Finally, the term *frozen-efficiency*

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for energy-efficiency measures, the TRC was calculated as the ratio of the present value of energy and capacity costs that would be avoided as a result of implementation of the efficiency measure, divided by the present value of utility and participant costs incurred to achieve the avoided cost savings. Other studies, including the recent *Report of Working Group III of the Intergovernmental Panel on Climate Change* (IPCC 2001), estimate economic potential from the consumer's perspective, that is, based on the direct consumer costs and benefits.

forecast deserves mention as well. In many energy forecasts, a frozen efficiency forecast is sometimes included to forecast energy use as it would be expected to occur if there were no naturally occurring efficiency improvements—that is, if efficiency levels were frozen at their current levels. In addition, frozen-efficiency analyses have been used on a "backcast" basis to demonstrate savings that have occurred from energy standards or other market interventions that were implemented in the past.[10]

The discussion above is meant to provide the reader with a brief introduction to a set of widely used terms as they evolved with respect to the energy-efficiency forecasting and planning. Many of these terms have been adopted directly or in modified form in GHG mitigation studies. For example, the U.S. DOE Interlaboratory Working Group's Scenarios for a Clean Energy Future study—also referred to hereafter as the *Clean Energy Future* or *CEF study* (USDOE/IWG 2000)—developed three future scenarios to assess the costs and benefits of mitigating GHG emission in the United States. These scenarios included a BAU forecast and "Moderate" and "Advanced" mitigation scenarios.[11] Nonetheless, it is important to emphasize that although individual study authors often use terms like those discussed above similarly, their specific definitions of the terms may vary in important ways. For example, in some studies, economic potential is calculated only based on the incremental costs of the measures and practices analyzed, while in other studies the programmatic costs of achieving those savings are included as well.[12] As shown in Figure 5, the Intergovernmental Panel on Climate Change's latest report (IPCC 2001) includes a conceptual representation of all of the potentials discussed above, plus yet another—the "socioeconomic" potential, which they define as the level of potential that could be achieved if social and cultural obstacles to the use of technologies that are otherwise economic were overcome. The socioeconomic potential incorporates the value of reducing externalities and is based on a societal rather than consumer perspective.

[10] See, for example, ECOFYS 2001.

[11] In the CEF study, the BAU forecast assumed a continuation of current energy policies and a steady pace of technological progress. In contrast, the Moderate and Advanced scenarios were defined by policies that were consistent with increasing levels of public commitment and political resolve to solving the nation's energy-related challenges. Some of the public policies and programs that define the scenarios cut across sectors; others were designed individually for each sector (buildings, industry, transportation, and electric generators) and assessed for impacts out to 2020. Numerous policies were examined, including fiscal incentives, voluntary programs, regulations, and research and development.

[12] Often, the studies that exclude programmatic costs from estimates of "economic" potential do so because the authors argue that programmatic costs vary by programmatic strategy and, thus, are best captured when estimating achievable potential.

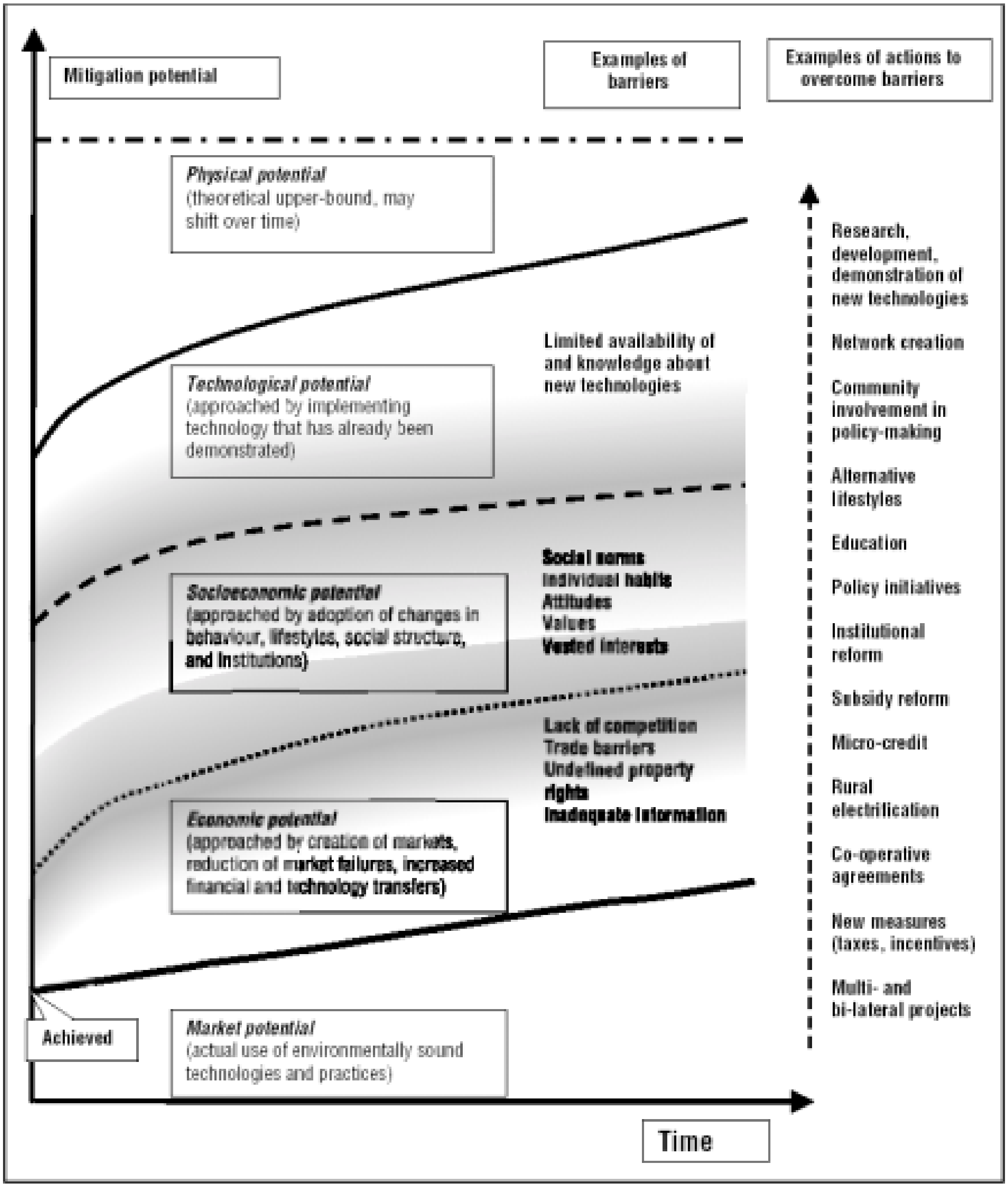

Figure 5. Penetration of Environmentally Sound Technologies: A Conceptual Framework

Source: IPCC 2001.

3.3 Scope of This Roadmap

This roadmap addresses research needs associated with development of California-specific GHG emission reduction supply curves for a variety of greenhouse gas types and sectors. Mitigation of carbon dioxide through sequestration and direct removal approaches are not addressed. Specifically, this roadmap discusses research needs with respect to the following:

Greenhouse Gas Types
- Carbon Dioxide (CO_2)
- Methane (CH_4)
- Nitrous Oxide (N_2O)
- High global-warming-potential (GWP) gases (PFCs, HFCs, and SF_6)

Sectors
- Buildings
- Industry
- Transportation
- Electricity production and transmission
- Agriculture
- Waste

3.4 General Supply Curve Methodological and Data Limitation Issues

This section briefly enumerates several key criticisms and limitations of many of the past conservation and GHG supply curve studies. However, this discussion does not imply that all such studies suffer from these limitations, or that all of the criticisms are completely valid and relevant to the specific objectives of the individual studies.

It is important to note that the terms and concepts presented in Sections 3.1 and 3.2 are based primarily on what is often referred to as the *conservation supply curve*, *bottom-up*, *conservation paradigm*, or *engineering-economic* approach to estimating the costs associated with energy efficiency or GHG mitigation potential. This roadmap builds on this approach and, most importantly, seeks to improve it. Despite adopting this framework as a starting point, it is clear that some critics question its basic validity (e.g., Sutherland 2000) and others have important concerns about methodological and data limitations associated with many well-known applications.

Though a formal discussion of the debate between these perspectives is beyond the scope of this roadmap, this section provides some documentation of it to acknowledge awareness of these competing points of view. Wherever practical, this roadmap suggests research activities that might resolve some of the disputes between these points of view. However, the companion PIER roadmap on *The Economics of Climate Change Mitigation and*

Adaptation in California (authored by Alan Sanstad, of Lawrence Berkeley National Laboratory) addresses these issues within a broader economic modeling context.

3.4.1 Discount Rates, Market Barriers, Willingness-to-Pay, and Production-possibilities Frontiers

As alluded to in Section 3.4, there has been an ongoing debate associated with some of the high profile GHG and conservation potential studies about the use and mutability of consumer discount rates. Some studies, in which supply curves were developed as stand-alone products, have used consumer discount rates that are based on expected rates of return from competing investments. A typical discount rate used to reflect this perspective is often approximately 15%. In other studies, even lower discount rates have been used to identify economic potential from a societal perspective (i.e., discount rates of 3 to 5%). Some critics have argued that these discount rates are inappropriate, in that they do not reflect all of the costs associated with implementation of a conservation or mitigation measure. These critics argue that the appropriate discount rates to use should be based on observed consumer behavior and that these rates are often as high as 100% or more.

Discount rates estimated from actual observed consumer behavior associated with conservation investments are often referred to as "hurdle" rates. Critics and proponents of the bottom-up studies agree that observed hurdle rates are much higher than the rate of return of competing investments; the two camps disagree, however, on why this is so and whether anything can be done about it. In short, critics maintain that hurdle rates are high because supply curve studies do not adequately capture and quantify all of the costs of purchasing energy efficiency or achieving GHG reductions. Both perspectives see information, transaction, and risk costs as accounting for part of the difference between hurdle rates and traditional discount rates associated with competing alternatives. The key difference is in whether these additional costs are viewed as benign and immutable[13] or whether they are viewed as market barriers/failures that can be ameliorated through policy and program interventions. This debate has gone on for some time and has stagnated somewhat, as proponents of neither point-of-view have given much ground.

Critics like Sutherland further maintain that the benefit-cost framework used in bottom-up analyses is incorrect in its use of energy savings as a benefit and argue instead that benefits should be defined based on the value ascribed to them by consumers, usually as measured by their willingness to pay. Sutherland 2000 labels his competing point-of-view the "economics paradigm" to reflect his position that it is the accepted approach of mainstream economists. He argues that there are few inefficiencies associated with energy-related investment decisions and that the economy is operating at its optimum

[13] For example, some critics argue that a key underlying premise of the bottom-up approach, that there are extensive market barriers and failures that limit the adoption of energy-efficiency measures to levels below what is optimal for society, is false. They view many of the barriers identified in conservation supply curve studies as "benign characteristics of well-functioning markets" that do not meet the threshold definition of "market failures" (Sutherland 2000).

with respect to its use of energy resources. Under this argument, the untapped efficiency opportunities identified in bottom-up studies are not cost-effective because there are additional costs to consumers and firms of achieving the identified returns that are not included in the bottom-up analyses. These costs are often referred to as *hidden* or *transaction* costs, and are often argued to be unobservable in practice.

There are, however, many counter arguments to the position put forth by Sutherland and similar critics. Decanio (2000) and Sanstad et al. (in USDOE/IWG 2000, Appendix E-4) argue that there is a wealth of evidence that indicates that firms do not, in practice, operate along their theoretical production-possibilities frontier when it comes to trading off energy versus other production inputs. As a result, they argue that the negative tradeoff between the production of ordinary output and environmental quality, which is embedded in most economic models, is a false dichotomy. Their evidence, and the evidence from a growing body of literature on energy-efficiency-related market barriers, suggests that firms operate inside the theoretical production-possibilities frontier with respect to investments in energy efficiency and that the production-possibilities frontier itself can be (and has been) expanded through market interventions (e.g., via technological progress engendered by regulations, public R&D investments, and voluntary government and utility energy-efficiency programs). In addition, Decanio 2000 argues that conventional economic models have serious flaws with respect to their representation of the productive sectors of the economy. In particular, much of Decanio's research seeks to demonstrate that the assumption, made by some economists, that profit maximization is the firm's single objective, is contradicted by a wealth of empirical evidence and the modern theory of the firm. In addition, Decanio (1998) further maintains that the appeal to transaction costs that are argued to be, by definition, unmeasurable, is tautological.

One area of criticism that has been addressed in recent studies is the incorporation of program and policy costs associated with reducing hurdle rates. Although authors and advocates of the bottom-up studies have acknowledged the importance of program interventions and their costs, they have not always explicitly included such costs in their analyses. For example, these costs were discussed but not incorporated in the so-called "Five Lab Study" (USDOE/IWG 1997) but were included in the follow-up "Scenarios for a Clean Energy Future" study (USDOE/IWG 2000). By contrast, program costs were almost always included in utility-sponsored studies of achievable energy-efficiency potential and cost effectiveness throughout the 1990s.

3.4.2 Achievable Potential, Technological Innovation, and Static Versus Dynamic Analyses

Many energy efficiency and GHG mitigation studies have developed supply curves that are two-dimensional and static. As shown in Section 3.1, the traditional dimensions of such supply curves are cost on one axis and the amount of available savings or reduction on the other. There is a good reason for this two-dimensional simplicity: in most cases it was the authors' intent to use a supply curve representation to illustrate the potential for energy efficiency or GHG reductions as concisely as possible. In addition, a number of macroeconomic and energy-economic models seem only to be able to capture efficiency and GHG potential through the use of such simplified two-dimensional forms. There are, nonetheless, serious limitations associated with this way of modeling energy efficiency and GHG mitigation potential.

First, a principal limitation of many two-dimensional supply curve studies is that they do not formally model adoption of efficiency or mitigation measures as a function of policy or program interventions. To be credible, estimates of potential must be based, as much as possible, on models that are calibrated to actual consumer and firm behavior. Such model calibration must be done to capture adopting behavior both with and without different types of program and policy interventions.

Second, many supply curve studies do not account for changes in technological innovation as it relates to reductions in cost and improvements in efficiency. Lack of incorporation of technology innovation ("progress ratios") is a major limitation in models that run out 20 to 100 years. How to incorporate technological innovation is a difficult question.

In shorter-term studies (e.g., 20 years or less), technological innovation is sometimes addressed through the incorporation of so-called emerging technologies (i.e., technologies that are currently well-conceptualized or demonstrated but are not yet commercially available or are not penetrating the market due to cost or other inhibiting characteristics). This approach then often requires additional, often highly uncertain, assumptions about what the cost and non-cost characteristics of the technology will be at maturity. This method's advantage is that a pool of specific options with demonstrated promise can be referenced from which it may be plausible to maintain that at least a subset of the pool will bear fruit.

Another way of approaching the problem is to incorporate technological innovation or progress ratios, on a time dependent basis, into longer-term studies. In this approach, one need not identify specific nascent technologies but rather a general rate of improvement that is empirically derived for particular segments of the economy or types of technologies (e.g., products based on computing technology would likely have different progress rates than strictly electromechanical equipment such as motors).[14] The drawback of this approach is that, without credible, empirically derived innovation rates, the use of such factors will remain open to criticism.

The two approaches to innovation can also be combined for shorter-term studies. For example, rather than assuming (as is done in some studies) that a technology will be at a certain cost once it achieves sufficient economies of scale, the cost of the technology can be modeled over time as a function of its level of penetration in the market (i.e., with costs

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[14] Although as demonstrated by the evolution of variable-speed drive controls, the efficiency and cost-reduction potential of traditional industrial era equipment can also be strongly affected by information technology, almost always in ways that are difficult to predict.

falling as penetration increases; this approach also provides a way to explicitly model indirect program benefits).[15]

The general issue of time dependence is related to the two issues above (i.e., modeling program/policy interventions and technological innovation). There are a number of other important factors that affect efficiency and GHG-reduction potential that are likely to change over time. One such factor is capital stock, which is constantly decaying, turning over, and being accredited to over time. Many energy-economy models do explicitly model capital stock, and the fact that some efficiency measures can occur only when stock turns over and others may become less important as inefficient stock is decayed. However, in some macroeconomic and GCC models, it appears that two-dimensional supply curves that lack a time dimension are sometimes used.[16] Other time-related issues that are often not explicitly modeled include changes in fuel prices and feedback between supply-side and demand-side policies.

Other key issues include the following:

- Costs in supply curves tend to be single point averages and do not capture the fact that costs often vary across applications. This factor naturally leads to some aggregation bias; however, it can add significant cost, time, and complexity to incorporate the distributions around the averages.
- Non-energy costs and benefits are often not quantified. For example, in the industrial sector, non-energy benefits include minimization of waste production, increased productivity, and reductions in other emissions (Laitner et al. 2001). It is often difficult enough within the scope of many studies to quantify direct costs and benefits of measures, much less indirect ones. Nonetheless, identification and quantification of indirect costs and benefits is critical to improved modeling of adoption and would increase the credibility of many studies.
- The least-cost ordering of measures in supply curves implies that measures are adopted on a least-cost basis; whereas, actual measure adoption is generally a multi-attribute decision process. This discrepancy is a function of both the measure-specific market barriers/failures that exist and the fact that measures in supply curves do not always offer perfectly constant utility.

In summary, supply curve studies to date have suffered from a limitation that is almost, by definition, inherent to their original purpose as a policy and modeling tool: simplicity. As Florentin Krause, an interviewee for this roadmap, put it: "A supply curve framework

[15] For example, it has been argued in several studies that utility and government policies to promote electronic ballasts has resulted in a significant positive feedback loop in which production was increased, costs decreased due to production economies, and further increases in production and market penetration resulted (see, for example, XENERGY 1998b and Duke and Kammen 1999).

[16] This roadmap does not include such models in scope; however, we reference this issue to illustrate that some of the limitations of supply curve studies are tied to the limits of the larger models into which they feed. See the companion PIEREA roadmap on economic issues authored by Alan Sanstad for more issues related to macroeconomic and GCC models.

is useful mainly for a certain kind of modeling in which transparency and simplicity are more important than comprehensiveness." Most analysts agree that there are broader modeling approaches that are more appropriate for policy making than supply curves. In fact, by some definitions, addressing the weaknesses outlined above requires the adoption of a framework that goes beyond supply curves.

3.5 Why This Research Is Needed

There are a number of important reasons for PIEREA to embark on research related to GHG mitigation curves for California. First, California needs accurate GHG reduction information in order to make informed decisions on whether and to what extent it should formulate its own public policy on climate change. Second, as discussed in Sections 3.4 and 4, existing GHG reduction studies are inadequate for this purpose because they: 1) are not specific to California, 2) suffer from methodological and data limitations, and 3) are incomplete (supply curves are not available for all key GHGs). Third, no other institution in California is currently working to develop comprehensive and accurate GHG reduction supply curves for the State.

In short, PIEREA efforts are needed to advance the state-of-the-art for GHG supply curves and to develop California-specific GHG supply curves in cases where no other entity is doing so. Where methodological or data improvements are targeted that have national or international benefits, PIEREA should work jointly with other organizations to share both the costs and benefits of such work.

3.6 The PIER Focus

Existing greenhouse gas mitigation supply curves are inadequate to properly address the full selection of GHG mitigation opportunities in California. Supply curves for some sectors have been developed on a national level; however, the State needs to build upon this work to define its scope in relation to California, as well as develop supply curves for sectors that have not been addressed in other research efforts.

Part of the mission of PIER is to conduct and fund research in the public interest that would otherwise not occur. Developing greenhouse gas mitigation supply curves for in-state generation sources is one such issue. PIEREA aims to address this topic through its own targeted research and to attract collaborators that will share data and work with PIEREA.

Other PIEREA roadmaps address other economic and technical aspects of GHG mitigation. Whenever possible, PIEREA will coordinate these programs and seek outside collaborators to leverage funding and avoid overlapping research.

4. Current Research and Research Needs

This roadmap's primary goal is to contribute to advancements in the science of GHG mitigation supply curve development, particularly as applied to understanding emissions reductions opportunities in California. To achieve this goal, it likely will be necessary to develop mitigation supply curves for the State of California in cases where such curves are otherwise unavailable. Improved GHG reduction supply curves will help both private and public sector decision makers to formulate the most effective and economical GHG mitigation policies.

The achievement of these goals depends on a variety of factors that vary by sector and greenhouse gas. Generally, it will be necessary to improve baseline inventory data in a variety of areas, including fuel consumption, landfills, and livestock farms. In addition, a number of methodological and macroeconomic integration issues will need to be improved. Finally, it will be critical that PIEREA efforts in this area are leveraged with the resources and talent available from other organizations with convergent research needs and interests.

At present, short-term supply curve development research needs to focus on the following areas:

1. CO_2: Buildings
2. CO_2: Industry
3. CO_2: Transportation
4. CO_2: Electricity Production
5. Methane: Waste and Agriculture
6. N_2O: Agriculture and Mobile Sources
7. High Global Warming Potential Gases: Industry and Electricity Transmission and Distribution

The following discussions outline the status of current work in the development of GHG mitigation supply curves by sector and greenhouse gas type, and identify scientific and research gaps.

4.1 CO_2: Buildings

There is a large body of recent and historic literature on the potential for energy savings and associated CO_2 reductions in the buildings sector. *Buildings sector* refers broadly here to energy use with residential and commercial buildings and includes all associated end uses (e.g., including appliances). Based on California's latest emissions inventory, the residential and commercial buildings sector account for 14% and 10% (24% combined) of the CO_2 emissions in California (CEC 2001d). Because CO_2 accounts for 84% of the State's total GHG emissions, the buildings sector represents 20% of total GHG emissions.

As noted previously, early work in the buildings sector in the US in the 1970s and 1980s created the bottom-up framework for many GHG mitigation studies in the 1990s. Within the United States, California-based studies were at the forefront of early buildings potential studies. Intensive study of energy use in California buildings has occurred over the past twenty-five years as a result of several factors, including:

- an early policy commitment to energy conservation and renewable energy and creation of the California Energy Commission (Commission) in 1974,
- the Commission's authority to promulgate State-specific energy-efficiency standards in the form of Title 20 (appliances) and Title 24 (building shell),
- the Commission's development and ongoing implementation of end-use forecasting to project energy consumption and peak demand in the commercial and residential sectors,
- the California Public Utilities Commission's (CPUC's) requirements that the State's investor-owned utilities implement energy-savings programs (from the late 1970s to the present) and practice integrated resource planning (from the late 1980s to the mid-1990s),
- the actual implementation and evaluation of energy-efficiency programs by California's investor-owned and municipal utilities and, in the case of the former, the wealth of ex-post evaluations of program impacts (several hundred studies that represent several tens of millions of dollars worth of research),
- the State's brief shift towards a market transformation program orientation, which resulted in a set of market assessment and evaluation studies that were more focused on understanding and ameliorating market barriers than were the impact evaluations that preceded them, and
- the recent California energy crisis which generated a new wave of interest and resources directed at implementing energy-efficiency measures in the State.

To provide a glimpse of the body of research born of these historic and contemporary factors, we list below just a few relatively recent examples of the studies and reports available on energy-efficiency in California's buildings sector:[17]

- *California Energy Commission End-use Demand Forecasts* (e.g., CEC 2000a and 2002). The Energy Commission periodically conducts energy demand forecasts. These forecasts include estimates of key data necessary for assessment of energy-efficiency potential, in particular, forecasts of commercial floor space, commercial square footage, residential households, end use consumption (e.g., kWh per household for air conditioning), and end use saturation levels (e.g., fraction of commercial floor space with mechanical air conditioning).
- *2001 DEER Update Study* (XENERGY 2001b). Includes updated incremental measure costs for currently available residential and commercial measures and estimates of per unit energy savings for currently available residential measures. Updates previous measure cost studies from 1992, 1994, and 1996.

[17] It is safe to say that no other state approaches California in the breadth and depth of efficiency-related buildings research.

- *CCIG Technology Energy Savings Study* (NEOS 1994). Provides per unit energy and peak demand savings estimates for a large number of residential and commercial building technologies, based on extensive building simulations by building type for five major climate regions.
- Utility Impact Evaluation and Market Transformation Studies. As mentioned above, several tens of millions of dollars were spent measuring the actual kWh and therm savings attributable to utility programs implemented in program years 1992 through 1997. From 1998 to 2000, much of the evaluation-related research required by regulators shifted toward a focus on market transformation. These studies were quite useful in broadening the available literature and associated knowledge base with respect to improved understanding of market functioning, market barriers, consumer attitudes and behavior, and the role of private sector actors in capturing efficiency opportunities. Too numerous to list here, a significant portion of this research is available on the California Measurement Advisory Council's Web site at www.calmac.org (see also XENERGY 1999). A few of these studies warrant explicit mention here, given their relevance to this roadmap:
    - XENERGY 2002. *California Statewide Commercial Sector Energy-Efficiency Potential Study: Final Report*, prepared for Pacific Gas and Electric Company. Study ID# SW039A. July.
    - Aspen 2002. *Nonresidential Market Share Tracking Study*, prepared for the California Energy Commission, in progress.
    - Regional Economic Research, Inc., 1999. *Efficiency Market Share Needs Assessment and Feasibility Scoping Study*, prepared for the California Energy Commission and Pacific Gas and Electric. May.
    - RLW 2000. *Statewide On-Site Survey of Residential Lighting and Appliances*, prepared for San Diego Gas & Electric Company.
    - Numerous utility and statewide studies of the Commercial New Construction Buildings Sector.
- Utility Program Year Application Filings. As part of their annual regulatory filings to the CPUC for approval to implement energy-efficiency programs, California's investor-owned utilities submit detailed program plans, which include inputs to cost-effectiveness calculations, often in an accompanying appendix referred to as "workpapers." These workpapers include a great deal of information on measure costs and savings.
- Commercial End Use Surveys (CEUS) and Residential Appliance Saturation Surveys (RASS). Over the past 20 years, PG&E, SCE, and SDG&E have conducted periodic residential and commercial equipment saturation surveys. Recently, the California Energy Commission began direct management of statewide residential and commercial saturation studies. The Commission is in the early stages of both projects and will likely update saturation values sometime in the 2002–2003 time frame.
- Supporting Research for Title 24 and Title 20 Standards. The Energy Commission conducts ongoing studies in support of development of new Title 24 and Title 20 standards (see www.energy.ca.gov/title24).

- Recent and Current PIER Studies. These PIER studies involve a wide variety of activities associated with the development of technologies that save energy and have other environmental benefits. PIER-related research on specific technologies provides an important source of information on emerging technologies (see www.energy.ca.gov/pier/reports.html)
- California Energy Commission. 1997. 1996 *Energy Technology Status Report, Report Summary, 500-96-006,* California Energy Commission, Sacramento, December. This report was to provide comprehensive data on energy consuming and producing technologies. However, the study was not completed in its entirety.

Despite the extensive and impressive ongoing research on energy-efficient technologies and practices for the building sector in California, formal integration of this information into supply curves and estimates of potential virtually ceased with the advent of electric restructuring in the State in 1996.[18] Because of the wealth of recent and ongoing research in the State, there is limited need, within this roadmap, for much new research on the key *inputs* necessary to estimate energy-efficiency potential in California's building sector. There is, however, a need for updated *integration* of the existing research into supply curves and estimates of remaining potentials in ways that clearly communicate the benefits and costs of buildings-related carbon dioxide reduction to State policy makers.

Research Needs
In the short-term, there is a need to integrate existing information on energy-efficiency opportunities in buildings into supply curves and GHG mitigation potential estimates in a way that improves upon past efforts by advancing the state-of-the-art for such studies. As part of these efforts, energy savings estimates will need to be connected to their CO_2 emission-reduction equivalents.

In addition, there is an important need to develop improved technology adoption models for energy efficiency and GHG mitigation measures. A potentially useful source of data for calibrating such models may be available from the program tracking systems and research studies developed during the last ten years of utility efficiency programs in California and other regions of the United States with extensive energy efficiency programs.

4.2 CO_2: Industry

Over the past twenty-five years, development of comprehensive energy-efficiency supply curves for the industrial sector has generally lagged behind the work conducted for the buildings sector. This lag did not reflect any lesser importance of the industrial sector or lower potential for savings, but rather, illustrated the difficulty that the sector's heterogeneity posed to researchers. Table 2 shows the importance of the industrial sector to California's electric and gas consumption.

[18] There is, however, a new study of the remaining energy-efficiency potential in existing commercial buildings in progress (XENERGY 2002).

Table 2. California Electric and Gas Use by Sector

	Electricity		Natural Gas	
Sector	**GWh**	**% of Total**	**Mth**	**% of Total**
Residential	75,388	31%	5,521	38%
Commercial	87,093	36%	2,103	15%
Industrial	**51,996**	**21%**	**6,341**	**44%**
Agricultural	14,661	6%		0%
Other	15,270	6%	379	3%
Total	244,408	100%	14,344	100%

Source: (CEC 2000a).

The industrial sector contributes 17% of the State's CO_2 emissions from fossil fuel consumption, roughly 14% of total GHG emissions (CEC 2001d).

The challenge posed by the heterogeneity of the sector can be seen in Figures 6 and 7. Even at the two-digit standard industrial classification (SIC) level, electricity use is distributed across industries with extremely different industrial processes. The 2-digit distribution of natural gas consumption is less diffuse, being concentrated in five or six major industry types.[19]

Because of the complexity of the industrial sector and concomitantly high costs of researching industry-specific energy and CO_2 reduction opportunities, relatively few comprehensive bottom-up assessments of the costs and savings potentials within the industrial sector have been conducted historically. (This is not to say that no work has been done—see for example, Geller and Neal 1994 and the work of Marc Ross at the University of Michigan.) Fortunately, the state of industrial sector research has begun to advance through a number of recent studies. Two sets of these studies complement each other well, in that one set focuses on the unique process elements of individual industry types, while the other set focuses on technologies that cut across industries. Lawrence Berkeley National Laboratory has conducted a series of recent studies for the Environmental Protection Agency that provide CO_2-reduction supply curves for specific industrial segments. Industry-specific studies have been completed to date for Pulp and Paper (Martin et al. 2000b), Cement (Martin et al. 1999), Iron and Steel (Worrell et al. 1999), and Steam (Einstein et al.).[20] The LBNL team also recently published a related study of emerging industrial technologies (Martin et al. 2000c). The DOE has also conducted several recent studies aimed at characterizing the potential to improve industrial motor (XENERGY 1998), compressed air (XENERGY 2000), and steam systems.[21]

[19] Note, however, that energy processes can vary significantly within two-digit SIC groups as well.
[20] The LBNL team has also conducted a baseline study of energy use in the chemicals sector (Martin et al. 2000a).
[21] See DOE's Office of Industrial Technologies steam studies at www.oit.doe.gov/bestpractices/steam/.

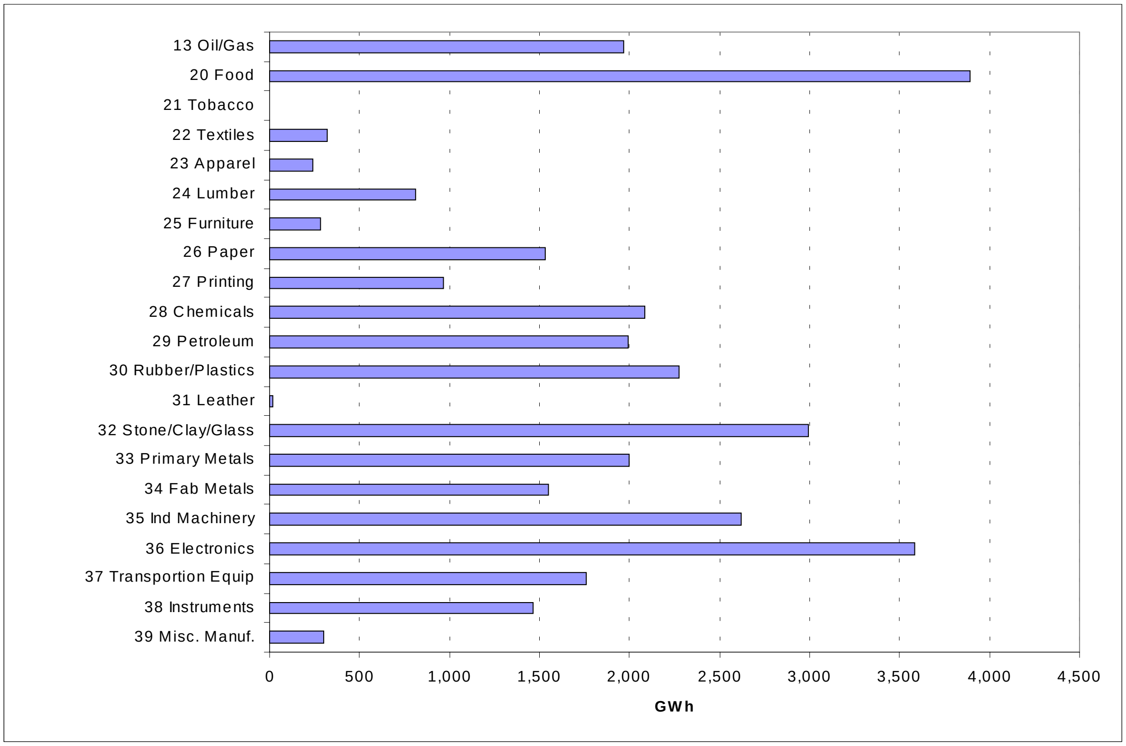

Figure 6. Breakdown of Electricity Consumption by Two-Digit Industrial SIC (PG&E/SCE/SDG&E only)

Source: XENERGY 2001c.

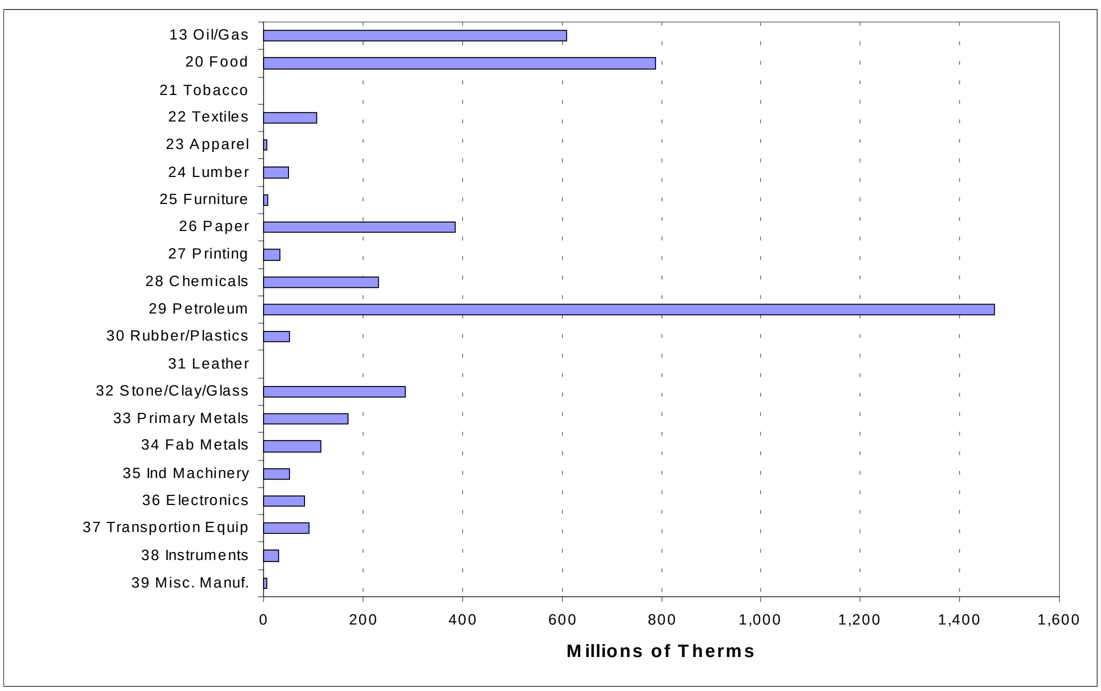

Figure 7. Breakdown of Natural Gas Consumption by Two-Digit Industrial SIC (PG&E/SCE/SDG&E only)

Source: XENERGY 2001c.

In addition to these national studies, recent California-specific industrial studies that are relevant to this roadmap include the following:

- XENERGY 2001c. *Statewide Industrial Characterization Study.*
- QC/Feldman 2001. *Large Customer Wants and Needs Study.*
- SBW 2001. *Compressed-Air Market Transformation Program Report.*
- XENERGY 1999 and 2001a. *Evaluations of the Statewide Large Customer Standard Performance Contract Programs.*
- Aspen 1999. *Southern California Edison Industrial Saturation Survey.*
- Utility Impact Evaluation Studies 1994 through 1997 (see www.calmac.org).

Part of the work conducted to prepare this roadmap was an interview of two of the key authors of the LBNL industry-specific studies (Worrell and Price 2001). The discussion focused on some of the weaknesses in the existing industrial supply curve studies and how they might be improved upon in the future. The issues raised were consistent with those identified in Section 3.5. Issues that are particularly challenging in the industrial sector included the following:

- Identifying opportunities can be time consuming and costly, because of the unique processes associated with individual industry types.
- It is difficult in practice to obtain accurate estimates of the current levels of penetration for individual strategies and technologies within specific industries. Few data sources are available that are based on statistically representative on-site surveys.
- There is limited information available on the costs and non-energy benefits of industrial strategies and technologies, and these can be difficult and costly to collect for industry-specific processes.
- Most curves do not differentiate measures that are easy to implement from those that are very difficult to implement.
- The organizational processes and criteria associated with decisions to invest in energy-efficiency and environmental mitigation projects are not well understood.
- Data on industrial sector technologies, processes, and adoptions can be difficult to obtain because industrial customers sometimes consider such information confidential or proprietary.

Given the importance of the industrial sector to GHG emissions in California, and the lack of California-specific industrial supply curves, significant further research in this topic area is needed.

Research Needs

No recent, California-specific supply curves are available for industry. However, there are a number of national studies that can be effectively leveraged and applied to the California markets. Existing studies have approached the market both by industry type and by end use. Because of the heterogeneity of the sector, an industry-by-industry approach is appropriate for characterizing industry-specific process opportunities.

Because these studies are costly when conducted across many specific industries and because much of the basic measure cost and per-unit savings information can likely be transferred from national studies to California, the research discussed in Section 5 should both leverage the existing national studies and co-sponsor new studies for key industries not yet addressed.

In addition, there is an important need to develop improved technology adoption models for energy efficiency and GHG mitigation measures. A potentially useful source of data for calibrating such models may be available from the program tracking systems and research studies developed during the last ten years of utility efficiency programs in California and other regions of the United States with extensive energy efficiency programs.

4.3 CO_2: Transportation

The relative contribution of the transportation sector to CO_2 emissions is larger in California than it is nationally. In California, the transportation sector accounts for the largest share of CO_2 emissions from fossil fuel consumption in California by far, at roughly 59% (CEC 2001d), whereas transportation's contribution to carbon dioxide emissions nationally is on the order of 32% (USDOE/IWG 2000). Nationally, light-duty vehicles account for 56% of CO_2 emissions in the transportation sector, freight trucks 17%, and air travel 13%.

There is a large body of literature that addresses the potential to improve the fuel economy of light-duty vehicles in the United States, the largest CO_2 contributor in the transportation sector. There is much less information available, however, on the potential to reduce fuel consumption and emissions among freight trucks. (Note that air transportation is not included within the scope of this roadmap.) Key transportation-related sources reviewed for this roadmap include:

- Greene, David and John DeCicco 2000. *Engineering Economic Analyses of Automotive Fuel Economy Potential in the United States*, ORNL/TM-2000/26, January.
- U.S. DOE Interlaboratory Working Group on Energy-Efficient and Clean-Energy Technologies 2000. *Scenarios for a Clean Energy Future. Chapter 6: Transportation Sector*. U.S. Department of Energy LBNL–44029, November.
- AEA Technology Environment (AEA). 2001c. *Economic Evaluation of Emissions Reductions in the Transport Sector of the European Union (EU), Bottom-up Analysis*, European Commission, March.
- California Energy Commission. 1998. *Greenhouse Gas Emissions Reduction Strategies for California Volume 2. Chapter 6: Reducing Greenhouse Gas Emissions from Transportation.* California Energy Commission, Sacramento, January.

- National Academy of Sciences (NAS). 2001. *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards*, Prepublication – Unedited Proof, National Academy Press, Washington, D.C.
- State of California. 2001. *Strategic Plan for Research 2001 to 2010*, State of California, Cal/EPA, and California Air Resources Board, July.
- Series of studies sponsored by California Air Resources Board (ARB) and California Energy Commission (Commission) being published primarily in 2002. (ARB/CEC 2002a and 2002b). The ARB and the Commission are in the process of conducting several studies related to the fuel economy and pollution impacts of the transportation sector in response to Assembly Bill 2076,[22] which requires the Commission and ARB to develop and submit a strategy to the Legislature to reduce petroleum dependence in California.

One of the key sources listed above is the recent study by Greene and DeCicco (2000). In this work, Greene and DeCicco conducted a comprehensive literature review and comparative assessment of fuel economy supply curve methodologies and results. The result is an exhaustive and up-to-date assessment of the technical potential and associated costs of improving light vehicle fuel economy. As noted above, the National Academy of Sciences' recently released study includes assessment of technological options to improve fuel economy and their associated costs and benefits. In addition, the Clean Energy Future, European Union, and Energy Commission studies also provide useful information on the policy strategies that could be employed to induce reductions in CO_2 associated with the transport sector. Finally, to complement review of these studies, we also conducted an in-depth interview with Greene (2001).

The Greene and DeCicco study on engineering-economic analyses reviews more than 20 major studies that estimate the technological potential to improve fuel economy and associated costs. Greene and DeCicco demonstrate widely divergent results among the studies reviewed, as indicated by the multi-study results shown in Figure 8.

[22] AB 2076 (Chapter 936, Statutes of 2000).

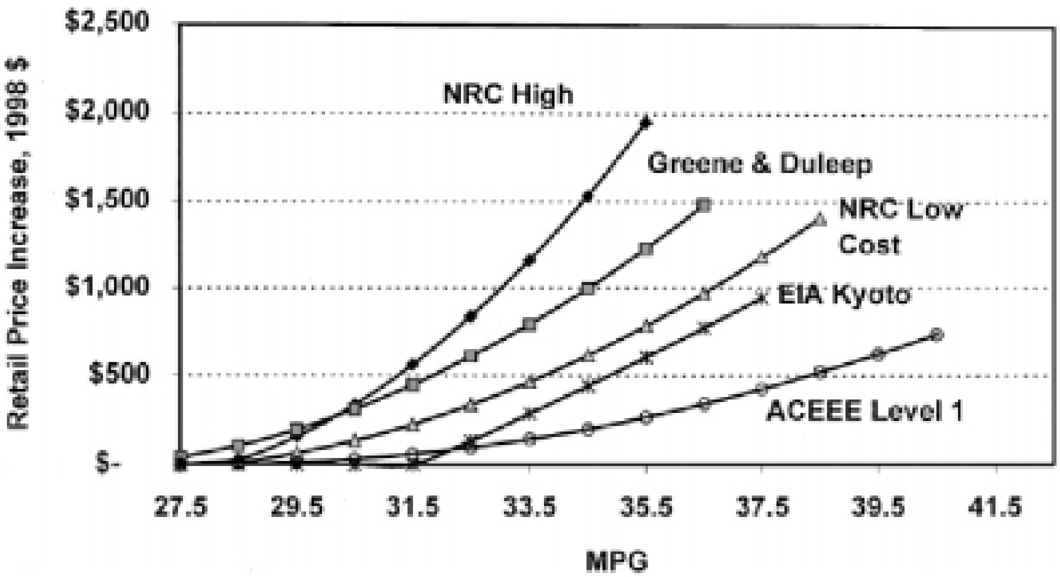

Figure 8. Passenger Car Fuel Economy Cost Curves Based on Six Studies
Source: Greene and DeCicco 2000.

Some of the relevant findings from the Greene and DeCicco cross-study analyses include the following:

- No fuel economy study they reviewed explicitly incorporated uncertainty into the estimation of technical potential. No studies have been found that evaluate the fuel economy potential of yet-to-be marketed technologies in ways that quantify uncertainties. Methods of estimating fuel economy potential rely on point estimates as inputs and produce point estimates as outputs. Sensitivity analysis has rarely been used.
- Studies diverged widely with respect to estimates of the cost of increasing fuel economy. Some of this problem arises out of inherently ambiguous situations in which fuel-efficiency improving technologies have multiple benefits. These multiple benefits make allocation of incremental costs difficult and imprecise. Also, in the highly competitive and concentrated auto industry, direct costs associated with changing automobile technologies depend on inherent production costs, timing of investments, and market risk.
- More so than is the case in buildings-related supply curves, accounting for synergistic effects among automobile efficiency improvements can be extremely complex and uncertain.
- Researchers could derive fuel economy cost curves that would show the intersection of supply and demand curves for fuel economy. These curves would indicate where the marginal consumer cost of increasing miles-per-gallon equals the marginal present value of fuel savings. Such curves would not take into account any external costs of fuel use, such as GHG.

- From a broad perspective, nearly all studies reviewed indicate that some "non-trivial" improvements are available at modest cost. Though greater consistency in assumptions and methods might narrow the range of differences in cost-economy results among future studies, the relative gains from further technology/cost analysis for light-duty vehicles may be small.
- Future research efforts may be focused more productively on better ways to represent (a) the characteristics, drivers, and effects of innovation in automotive technology; (b) the effects of regulation in shaping design decisions and expanding the technology options available; and (c) the role of capital constraints in technology deployment decisions.

Chapter 6 of *Scenarios for a Clean Energy Future* (USDOE/IWG 2000), provides estimates of impacts from new government policies on transportation energy consumption and GHG emissions. A modified version of the National Energy Modeling System (NEMS) model (USDOE/EIA 2000) was developed to forecast changes in the transportation sector scenarios that might occur in response to government policies to encourage reductions in greenhouse gases. These forecasts included BAU, moderate (low-cost), and advanced (more aggressive) GHG-reduction scenarios. The study addresses uncertainties associated with these scenarios. These uncertainties are associated with the costs and performance values of technologies under development, the outcome of an RD&D program, and consumer purchasing behavior. The technology options included in this study are cellulosic ethanol, hybrid electric drivetrains, lower weight structural materials, direct injection gasoline and diesel engines, fuel cells, and aircraft technology (e.g., reducing drag, use of composite materials, and advanced propulsion concepts). The key transportation-related policy alternatives modeled in the CEF study are:

- an increase in government/industry RD&D,
- a tax credit for high efficiency vehicles,
- acceleration of air traffic management improvements,
- the promotion of investment in cellulosic ethanol production,
- government fleet program promoting alternative fuels and efficiency,
- improving fuel economy standards (Advanced scenario only),
- telecommuting stimulation,
- carbon trading (Advanced scenario only),
- variabilization policies (Advanced scenario only), and
- intelligent traffic systems controls (Advanced scenario only).

From the CEF-NEMS models, the most influential components in reducing the energy consumption and carbon emissions in the Advanced scenario are improvements in light-duty fuel economy and freight truck efficiency gains. Policies that affect market incentives and that can increase technology development and hence technology options are found to be crucial to reducing transportation energy use and greenhouse gas emissions.

In AEA 2001c, researchers conducted a bottom-up analysis for the European Union, to provide an economic evaluation of emissions reductions potential in the transport sector. The study identified three ways to abate CO_2 emission from transport: operational, strategic (optimize vehicle use), and demand (for travel), but only addressed operational solutions. Researchers developed a supply curve for a large number of technological improvement options focused on vehicle transport. The lowest-cost options on the curve were for freight vehicles. An increased shift to diesel was also included, as were reductions in emissions associated with air-conditioning systems. The strategic and demand-based solutions generally rely on influencing behavior. The authors concluded that estimating the cost-effectiveness of strategic and demand options are not complete, and that they are difficult to extrapolate because of regional differences. Other data constraints limited the study's scope to on-road transport and aviation only. An analysis of air-conditioning (but not refrigerant leakage) and catalytic converter effects on GHGs are also important (especially because their use is expected to increase), but they are included in the report as an appendix. Appendix 1 of the report provides emission factors related to air conditioners and catalytic converters on on-road mobile sources. Nitrous oxide (N_2O) emission factors were developed from U.S. studies. The methodology that was used in that appendix may be useful for generating California values.

The California Energy Commission addressed state-specific strategies to reduce GHG emissions for the transportation sector in Chapter 6 of its *1997 Global Climate Change Report: Greenhouse Gas Emissions Reduction For California.* (CEC 1998a). The report noted that there have been dramatic decreases in criteria air pollutant emissions from the transportation sector, but not concurrent reductions for carbon dioxide. Chapter 6 of that report primarily discussed updates on the strategies related to policies set forth in the Commission's 1991 report on the same subject. These strategies include:

- developing alternative (low-emission) fuels, vehicles, and markets,
- promoting electric vehicles and hydrogen fuels,
- developing infrastructure to promote alternative fuel vehicle use,
- promoting biomass-based fuels,
- reducing vehicle miles traveled by personal vehicles through fuel/carbon taxes, user fees, or feebates,
- increasing fuel economy,
- providing incentives for alternative fuel vehicle use, and
- incorporating long-term transportation needs into land use planning.

The main emphases in the Commission's document are alternative-fuel vehicles, biomass-to-alcohol fuel, and non-technology options. The report does not make any strong policy recommendations, but mostly continues the policy drafted in the *1991 Report* and presents the current status of the options presented for reducing greenhouse gas emissions. No formal supply curve analysis is included.

The National Academy of Sciences also recently studied the effectiveness and impact of Corporate Average Fuel Economy (CAFE) Standards (NAS 2001). Chapter 4 of that study addressed the impact of a more fuel-efficient fleet with no policy recommendations. When considering the energy consumption and greenhouse gas emissions attributable to vehicles, it is important to consider not only fuel economy and vehicle miles traveled, but also the manufacture of the vehicle and fuels. The committee identified "break-even" fuel economy levels, which are combinations of technologies that would result in fuel improvements sufficient to cover the purchase price increases while holding other vehicle characteristics (size, weight, and performance) constant. Though not representative of real-world markets, this approach is useful for analytical clarity. Another key assumption pertains to how much consumers value fuel economy improvements. The study provides break-even analysis for 14-year and 3-year payback periods. These are reflections of technological possibilities, economic realities, and assumptions about parameters and consumer behavior. An analysis of automobile safety as it related to fuel economy is also included in this study.

After the principal work on this roadmap was developed (in the latter half of 2001), a series of studies sponsored by California Air Resources Board (ARB) and California Energy Commission (Commission) began to be published in 2002 (ARB/CEC 2002). The ARB and the Commission are in the process of conducting several studies related to the fuel economy and pollution impacts of the transportation sector in California in response to AB 2076, which requires the Commission and ARB to develop and submit a strategy to the Legislature to reduce petroleum dependence in California. Studies and study summaries currently available on the Commission's Web site include the following:

- ARB/CEC 2002a. *Estimating the Environmental Benefits of Petroleum Reduction Strategies – Task 1 Air Impacts*, prepared by Arthur D. Little/Acurex Environment, presentation slides, March 28, 2002.
- CEC 2002b. *Base Case Forecast of California Transportation Energy Demand*, prepared by California Energy Commission staff, P600-01-019F, March.
- ARB/CEC 2002b. *Benefits of Reducing Demand for Gasoline and Diesel – Volume 3, Task 1 Report*, prepared by Arthur D. Little/Acurex Environmental, March.
- CEC 2002c. *Analysis and Forecast of the Performance and Cost of Conventional and Electric-Hybrid Vehicles*, prepared by Energy and Environmental Analysis Inc., March.
- CEC 2001e. *Impact of Telecommuting on Vehicle Miles Traveled: A Nationwide Time-Series Analysis*, prepared by the University of California at Davis, Department of Civil and Environmental Engineering, Institute for Transportation Studies, December.
- CEC 2001f. *California Smart Growth Energy Savings MPO Survey Findings*, prepared by Parsons Brinkerhoff, P600-01-021F, September.

The effort on the studies above represents a major new effort to develop up-to-date and comprehensive data and information on the environmental and economic effects of the transportation sector in California, as well as the potential costs and benefits of reducing petroleum dependence and associated environmental impacts. These AB 2076-related studies lay most of the groundwork needed to develop a CO_2-reduction supply curve for California.

A review of the California Air Resources Board's latest 10-year research plan (ARB 2002) identifies that ARB's research is focusing on:

- how the GHG inventory can be improved,
- assessing the true contribution of motor vehicles to nitrous oxide,
- understanding how global climate change might affect the State's air quality,
- better understanding the role of aerosols in climate change,
- analyzing the potential effects of climate change on human health,
- assessing technologies that could prevent or control GHG emissions, and
- estimating the possible effects of climate change on California's economy.

The California Air Resources Board's plan identifies a number of research organizations with which it may coordinate its GHG research efforts. They include California's local air districts, DOE, EPA, fuel cell groups, and the Energy Commission.

Research Needs

As discussed in Section 4, many supply curves have been developed at the national level for improving the efficiency of light-duty vehicles. Since the characteristics of light-duty vehicles are fairly similar across regions, there is no need to reproduce such studies on a California-specific basis. There is a need, however, to formally apply the results of these national studies to California's baseline transportation profile. Much of this work is in progress as part of the suite of AB 2076 studies discussed above. The AB 2076 studies may need to be integrated and reframed to develop a comprehensive CO_2 reduction supply curve for California. PIEREA research could also play an important role in efforts to reduce key uncertainties in the AB 2076 studies. New research also appears to be needed on analyzing options to reduce GHG emissions from freight vehicles. In addition, new research is needed to better understand the process of innovation in automotive technology, the effects of regulation on design and technological change, and the importance of capital constraints and industry competition in technology deployment. There is also a need to analyze transportation options that might reduce CO_2 by altering the mix of transportation at a macro level. Some research may be needed to determine whether off-road vehicles contribute significantly to GHG emissions and ascertaining the costs and benefits of mitigating such impacts if they are significant.

4.4 CO_2: Electricity Production

The in-state electricity generation sector in California contributes approximately 16% of the State's CO_2 emissions from fossil fuel use (CEC 2001d), which is less than half the national figure of 36% (USDOE/IWG 2000). The 16% figure does not include out-of-state sources, some of which are coal, but much of which is Northwest hydro. California's in-state generation facilities contribute a lower percentage of CO_2 than does the electricity sector nationally, because the State's generation consists primarily of natural gas, hydroelectric, and nuclear plants; whereas, coal plays the major role nationally. Coal plants are almost non-existent in California, while nationally they account for 51% of the existing electricity generation output [in kWh] and 80% of CO_2 emissions from electricity generation (DOE and EPA 2000).

Over the last 25 years, a large body of research has been conducted on the characteristics of conventional and alternative electricity generation sources. The literature review conducted for this report focused on a few recent sources that are comprehensive in scope and relate closely to the objectives of this roadmap. These sources include the following:

- Department of Energy and Environmental Protection Agency (DOE and EPA). 2000. *Carbon Dioxide Emission from the Generation of Electric Power in the United States*, July.
- California Energy Commission (CEC). 1998b. *Greenhouse Gas Emissions Reduction Strategies for California, Appendix A: Historical and Forecasted Greenhouse Gas Emissions Inventories for California.* California Energy Commission, Sacramento, January.
- U.S. DOE and EPRI. 1997. *Renewable Energy Technology Characterizations.* Topical Report TR-109496, December.
- California Energy Commission (CEC). 1997. 1996 *Energy Technology Status Report, Report Summary, 500-96-006,* California Energy Commission, Sacramento, December.
- US DOE Interlaboratory Working Group on Energy-Efficient and Clean-Energy Technologies 2000. *Scenarios for a Clean Energy Future.* Chapter 6: Transportation Sector. U.S. Department of Energy LBNL–44029, November.
- ECOFYS. 2001. *Economic Evaluation of Sectoral Emission Reduction Objective for Climate Change – Economic Evaluation of Greenhouse Gases in the Energy Supply Sector in the EU.* The Netherlands. March.
- California Energy Commission (CEC) 1998a. *Greenhouse Gas Emissions Reduction Strategies for California, Volume 2, Sections 4.3 to 4.5.* California Energy Commission, Sacramento, January.

Carbon dioxide emissions from the generation of electric power were inventoried at the national level in DOE and EPA (2000). This report resulted from a Presidential Directive from President Clinton in April 1999. The Directive required that DOE and EPA provide an annual report of baseline CO_2 emissions from electricity generation to the President. Emissions of CO_2 are presented on the basis of total mass (tons) and output rate (pounds per kWh). Key factors identified as contributing to changes in CO_2 emissions are: growth in demand, mix of fuels types and energy sources, and thermal efficiencies of plants. Contributing factors influencing the primary factors are: economic growth, price of electricity, weather, fuel prices, and the amount of available generation from hydro, renewable, and nuclear sources. Other factors identified as effecting current emission levels include demand-side management (DSM) programs, strategies to control air emissions to comply with the Clean Air Act of 1990, and installation of new capacity utilizing advanced technologies to increase plant efficiency, such as combined heat and power (CHP). The options identified to limit the emission of CO_2 from electricity generation are: to encourage reduction of overall electricity use through energy-efficiency and conservation initiatives, to improve combustion efficiency at existing plants or install new units that employ more efficient technologies, and to replace fossil-fueled generation with non-fossil-fueled alternatives. Data sources and methodologies used to calculate estimates of CO_2 emissions from utility and non-utility generating plants are presented.

In 1997, the DOE Office of Utility Technologies, Energy Efficiency and Renewable Energy and EPRI jointly produced a report on the current and projected costs and characteristics of renewable energy technologies. This report updated and expanded work conducted by both organizations previously.[23] The study characterizes a wide variety of renewable energy technologies and includes current and forecasted system costs. Thirteen renewable technologies are characterized organized into the following groups: biomass, geothermal, photovoltaics, solar thermal, and wind. The report addresses criteria pollutants, including precursors such as ozone. A unique feature of this study is its attempt to forecast renewable technology costs out to 2030.

The Energy Commission published the fourth edition of its *1996 Energy Technology Status Report* in 1997. This is the last edition of which we are aware. The report provides detailed analyses of the costs and commercial availability of over 200 generation, storage, transmission and distribution, and end-use technologies. Levelized costs are developed for each technology and compared to benchmarks for commercial viability. The report characterizes over 70 generation technologies. This report, if updated, would provide much of the generation data that would be necessary to support the objectives of this roadmap.

Chapter 7 of USDOE/IWG 2000, often referred to as the "Clean Energy Future" study, provides an important example of a study that attempts to explicitly model changes in the mix of generation sources over time under several future scenarios. A modified version of the NEMS model (USDOE/EIA 2000) was developed to forecast changes in electricity generation scenarios that might occur in response to government policies to encourage reductions in greenhouse gases. These forecasts included a BAU case and moderate and advanced GHG-reduction scenarios. Technology options addressed include improvements in efficiency of conventional fossil plants, coal gasification (possibly in combination with fuel cells), cofiring coal with biomass, increased utilization of wind, biomass, geothermal, solar, and fuel cells, and extending life of existing nuclear plants. The key generation-related policy alternatives modeled in the CEF study are:

[23] For example, in 1977, EPRI first published its syndicated Technical Assessment Guide (TAG™), a series of reports developed by EPRI to provide a consistent basis for evaluating the economic feasibility of research and development alternatives for electricity production and delivery technologies. Various updates to the TAG series were conducted in the 1980s and early 1990s. The U.S. DOE and EPRI 1997 Renewables study discussed above is a related part of this series, in that previous TAGs were used as sources and the results were subsequently used to prepare EPRI's first TAG focused exclusively on renewable energy sources (EPRI 2001). EPRI 2001 is a proprietary study that was not available for review. The summary on EPRI's Web site states that the renewable TAG will be updated annually. For its part, the U.S. DOE has been conducting Renewable Energy Technology Characterizations (TCs) since 1989, the first of which was used for the 1991 National Energy Strategy.

- a renewable energy production tax credit,
- a renewable portfolio standard,
- wind deployment policies,
- enhanced R&D,
- net metering promotion,
- electric industry restructuring,
- stricter particulate matter standards, and
- a carbon trading system.

The advanced scenario embodies all of the policy options; whereas, the moderate scenario includes a subset of these. Tables 3 and 4 below show key results. Non-hydro renewables increase from 1% of generation in 1997 to 5% and 9% of generation in 2020, under the moderate and advanced scenarios, respectively. Nonetheless, the bulk of emission reductions shown in Table 4 are actually achieved by the dramatic reductions in coal generation that are made possible by the major decreases in energy consumption associated with the moderate and advanced scenarios. These results reflect the fact that the advancement of generation technology is limited to the relatively fixed amount of capacity expansion needed to meet demands over a given scenario, plus any power plant retirements.

Table 3. National Generation by Scenario and Fuel in the Electric Sector (TWh) (No cogeneration)

			2010			2020		
Fuel	**1990**	**1997**	**BAU**	**Mod.**	**Adv.**	**BAU**	**Mod.**	**Adv.**
Coal		1800	2020	1940 (-4%)	1400 (-31%)	2170	2000 (-8%)	1060 (-51%)
Petroleum		80	22	17 (-23%)	14 (-36%)	18	15 (-17%)	11 (-39%)
Natural Gas		300	890	680 (-24%)	880 (-1%)	1270	830 (-35%)	1140 (-10%)
Nuclear Power		630	580	580 (0%)	630 (9%)	520	460 (-11%)	600 (15%)
Renewables		390	410	460 (13%)	590 (45%)	440	500 (13%)	630 (42%)
Hydro		350	320	320 (0%)	320 (-0%)	320	320 (0%)	320 (0%)
Wind		3	8	37 (386%)	140 (1760%)	9	51 (405%)	160 (1770%)
Biomass		4	26	37 (43%)	47 (83%)	31	26 (-17%)	48 (55%)
- Dedicated		4	11	15 (35%)	22 (100%)	19	16 (-12%)	32 (69%)
- Cofired		0	15	22 (49%)	25 (70%)	13	10 (-24%)	17 (33%)
Geothermal		16	24	37 (55%)	50 (109%)	47	67 (41%)	67 (41%)
Other		15	28	28 (0%)	28 (0%)	31	31 (0%)	31 (0%)
Other		-3	-1	-1 (0%)	-1 (0%)	-1	-1 (0%)	-1 (0%)
Total		3190	3920	3680 (-6%)	3520 (-10%)	4420	3800 (-14%)	3440 (-22%)
Net Imports		32	30	30 (0%)	32 (7%)	27	28 (4%)	30 (0%)

Note: BAU = Business-as-Usual scenario; Mod. = Moderate scenario; Adv.= Advanced scenario. Numbers in parentheses represent the percentage change compared to the BAU scenario.

Source: USDOE/IWG 2000.

Table 4. Carbon Emissions by Scenario and Fuel in the Electric Sector (MtC) (No congeneration)

			2010			2020		
Fuel	1990	1997	BAU	Mod.	Adv.	BAU	Mod.	Adv.
Petroleum	26.8	17.6	4.6	3.4 (-26%)	2.9 (-37%)	3.7	3.0 (-19%)	2.1 (-43%)
Natural Gas	41.2	44	95	72 (-24%)	87 (-9%)	127	85 (-33%)	98 (-23%)
Coal	409	471	545	521 (-4%)	370 (-32%)	578	531 (-8%)	282 (-51%)
Total	477	532	645	597 (-7%)	460 (-29%)	709	622 (-12%)	382 (-46%)

Note: BAU = Business-as-Usual scenario; Mod. = Moderate scenario; Adv.= Advanced scenario. Numbers in parentheses represent the percentage change compared to the BAU scenario.

Source: USDOE/IWG 2000

In Europe, a comprehensive study of the potential to reduce GHG emissions from the energy supply sector also was recently completed (AEA 2001a). That study assessed options to reduce CO_2 associated with energy supply. It looked at the replacement of existing generation with combined-cycle natural gas (CCNG) units, replacement of CCNGs with renewables, replacement of CCNGs with combined heat and power (CHP) units, and removal and storage of CO_2. It also analyzed nitrous oxide reduction strategies for stationary power plant sources. That study addressed the options for CO_2 removal and N_2O reductions more comprehensively than any other in our literature review.

The Energy Commission's 1998 Global Climate Change Report (CEC 1998a) addresses a variety of state-specific strategies to reduce GHG emissions. The report primarily discusses generation-related policy options within the context of the transition from the Electricity Report (ER) process to the requirements of AB 1890. Sections 4.3 through 4.5 cover topics related to electricity generation. Section 4.3 discusses the development of environmental externality values within the ER 94 resource planning process and the fact that direct application of the values is obviated by AB 1890. Section 4.4 of the report discusses and quantifies carbon-dioxide-reduction potentials associated with new gas generation technologies. Section 4.5 of the report discusses renewable energy resources in California, again within the context of a transition to AB 1890 requirements. The report discusses its approaches, at that time, to reducing emissions from electricity generation by accounting for environmental externalities, promoting high-efficiency gas generation, and developing and integrating renewable energy resources into electricity generation. Presumably because of the uncertainty about the transition between the ER process and market-based requirements of AB 1890, the report makes no strong policy recommendations for GHG mitigation in the generation sector other than to note the Commission's commitment to "pursue the State's long-run goal to increase application broadly-based, market-oriented environmental policies as a way to improve the balancing of social costs and benefits."

Research Needs

For the most part, the current costs and GHG emissions characteristics of different types of electricity generating plants are well known (see, for example, USDOE/IWG 2000, USDOE/EPRI 1997, CEC 2000c),[24] as are the costs associated with improving the efficiency of existing plants using existing technologies.

Less well understood than basic generation costs and emission characteristics is how the mix of generation sources in California will or could change in the future and how such changes would impact overall GHG emissions. The turbulent process of restructuring and re-regulating California's electricity generation sector has contributed to increased uncertainty in the mix of California's generation sources over the next 10 to 20 years. In addition, there are a variety of new and prospective public policies that could impact GHG emissions in this sector significantly (e.g., the AB 970 DG pilot, Senator Sher's proposed renewable portfolio standard, the supply procurement decisions of the Department of Water Resources, actions taken by the California Power Authority). The Commission currently models the future mix of generation sources in the State as part of its energy forecasting process.

Future research needs to develop the supply curves based on this information and to continue to forecast the future generation mix in California and incorporate the ability to model changes in response to GHG mitigation policies.

4.5 Methane: Waste and Agriculture

According to the Energy Commission's baseline inventory study (CEC 2001d), methane emissions in California account for approximately 8% of GHG emissions in the State. Landfills in California are the largest source of methane emissions, accounting for roughly 42% (CEC 2001d), followed by agricultural sources, which make up 41%. All other sources represent less than 18% of the State's methane emissions. Landfills and agriculture represent a larger share of methane emissions in the State than they do nationally (37 and 29%, respectively, of the national methane emissions, EPA 1999). This disparity is because emissions from natural gas systems and coal mining account for a much larger share of methane emissions nationally (30%) than they for California (9%).

Only a few comprehensive studies of methane emissions and mitigation opportunities have been conducted. The literature review for this report focused on the following:

- Environmental Protection Agency (EPA). 1999. *U.S. Methane Emissions 1990–2020: Inventories, Projections, and Opportunities for Reductions*, EPA 430-R-99-013, Washington, DC: U.S. Environmental Protection Agency, September.

[24] In addition, the Energy Commission has current information it has received in the form of actual bid amounts for prospective renewable projects in California. (See www.energy.ca.gov/renewables/new_renewables_table.html. Note, however, that the amounts shown are Energy Commission incentive awards, not bid amounts).

- California Energy Commission (CEC). 1998a. *Greenhouse Gas Emissions Reduction Strategies for California Volumes 1 and 2.* California Energy Commission, Sacramento, January.
- California Energy Commission (CEC). 1997. *Energy Technology Status Report, Report Summary, 500-96-006,* California Energy Commission, Sacramento, December.
- U.S. Department of Energy and Electric Power Research Institute (USDOE/EPRI) 1997. *Renewable Energy Technology Characterizations.* Topical Report TR-109496. www.eren.doe.gov/power/pdfs/entire_document.pdf. December.
- AEA Technology Environment (AEA). 2001b. *Economic Evaluation of Sectoral Emission Reduction Objective for Climate Change – Economic Evaluation of Emissions Reductions of Nitrous Oxides and Methane in Agriculture in the EU.* UK. February.

4.5.1 Landfills

Methane emissions from landfills depend on the size and type of landfill. According to the literature reviewed, the principal means for reducing landfill methane emissions are methane recovery and use projects, as well as flaring. Another approach is to modify the waste management practices to reduce waste disposal in landfills. The most systematic assessment of the costs and reduction potential associated with domestic methane emissions is EPA 1999. This document develops a marginal abatement curve (MAC) for methane from landfills, based on methane recovery for electricity generation and direct use of methane gas by nearby end users. (Neither flaring or waste reduction are assessed because significant changes in practices are already projected to occur as a result of source reductions associated with EPA's Landfill Rule (EPA 1996) and other existing mandatory requirements.) The basic approach employed involves the estimation of project costs for landfills of different sizes. Cost-effectiveness varies as a function of landfill size expressed in tons of waste-in-place (WIP). The national population of approximately 2,500 landfills is analyzed by grouping each landfill into a size category. Cost estimates used are aggregated cost factors and a relatively simple set of landfill characteristics. Results are shown in Table 5. Uncertainties associated with the EPA analysis are shown in Table 6 and include errors associated with landfill population estimates, errors in estimates of electricity generation and direct use costs, and errors in assumptions about the amount of gas that can be feasibly recovered.

In CEC 1998a, the Commission outlined the complexities associated with GHG emissions and sinks related to municipal solid waste and forecasted emissions associated with landfills. The report also discussed several strategies for reducing methane emissions from California landfills. The strategies discussed include: working closely with the California Integrated Waste Management Board (CIWMB) to ensure that the State meets its mandatory source reduction goals, further study of the costs and benefits of specific mitigation measures, and encouragement of landfill-based electric generation. No quantitative analysis of the potential for reducing methane from increased electric generation or direct use is provided.

Table 5. Results from EPA's Landfill Gas-to-Energy Marginal Abatement Curve Analysis

Exhibit 2-10: Schedule of Emission Reductions Over and Above the Landfill Rule by Price in 2010

	Electricity Production[a]				Direct Gas Use				Total Emission Reductions		
Value of Carbon Equivalent ($/TCE)	Price ($/kWh)	Break-Even WIP (MT)	Eligible Landfills	Incremental Reductions (MMTCE)	Price ($/MMBtu)	Break-Even WIP (MT)	Eligible Landfills	Incremental Reductions (MMTCE)	Cumulative Reductions (MMTCE)	% of base-line	Label on MAC[b]
(10)	0.03	Infeasible	0	0.00	1.64	7,436,565	0	0.00	0.00	0%	N/A[c]
(6)[d]	0.03	Infeasible	0	0.00	2.05	2,330,467	114	3.48	3.48	7%	A
0	0.04	2,900,493	64	1.98	2.74	972,739	498	5.09	10.55	20%	B
10	0.05	538,232	773	11.25	3.84	920,668	106	(7.35)[e]	14.44	28%	C
20	0.06	273,860	1,919	6.96	4.94	749,467	7	(1.16)	20.23	39%	D
30	0.07	177,368	2,319	1.27	6.03	576,422	0	(0.05)	21.45	41%	E
40	0.08	129,583	2,505	0.29	7.13	468,324	0	0.00	21.75	42%	F
50	0.09	101,309	2,615	0.11	8.23	393,655	0	0.00	21.85	42%	G
75	0.12	66,064	2,685	0.05	10.98	283,477	0	0.00	21.90	42%	H
100	0.15	48,086	2,720	0.02	13.73	222,143	0	0.00	21.91	42%	I
125	0.18	Negligible	2,720	0.00	16.48	182,893	0	0.00	21.91	42%	J
150	0.20	Negligible	2,720	0.00	19.23	152,742	0	0.00	21.91	42%	K
175	0.23	Negligible	2,720	0.00	21.98	134,836	0	0.00	21.91	42%	L
200	0.26	Negligible	2,720	0.00	24.73	118,155	0	0.00	21.91	42%	M

[a] Includes emission reductions for landfills at which either a gas <u>or</u> an electricity project is modeled as cost-effective. By default, the analysis selects electricity projects over gas projects where both are cost-effective.

[b] Point on marginal abatement curve (see Exhibit 2-11) indicating minimum break-even WIP for electricity and direct gas use projects.

[c] Although cost-effective reductions at landfills of this size exist, they are subject to the Landfill Rule (over 2.5 MMT WIP), and thus, are not counted as emission reductions in this analysis.

[d] The potential emission reductions associated with the modeled prices of $2.05/MMBtu or -$6/TCE are "below the line" reductions in carbon equivalent terms.

[e] Negative incremental reductions indicate that emission reductions attributed to gas projects at lower prices are modeled as electricity projects at higher prices because electricity projects become cost-effective as values increase above $0/TCE.

Source: EPA 1999.

Table 6. Uncertainties Associated with EPA's Landfill Gas-to-Energy Marginal Abatement Curves

Exhibit II-14: Emission Estimate Uncertainties

	Basis
Characterization of landfills and total WIP	A simulation characterizes the entire U.S. landfill population based on characterizations of a subset of U.S. landfills, including size, waste acceptance rate, and opening year.
Future waste disposal	Future waste disposal is assumed to remain constant at the average rate from the beginning of 1990 to the beginning of 1995. This average is based on the assumption that waste generation increases along with population, but will subsequently be offset by increases in alternative disposal methods such as recycling and composting.
Gas equation used for estimating methane emissions	Emission factors are derived from data on 85 U.S. landfills and are applied based on landfill WIP.
Recovery prior to 1997	Recovery rates (after flared methane is accounted for) are assumed to remain constant at 1990 levels for 1991 and at 1992 levels for 1993 to 1997. In addition, the gas collected but not utilized is assumed to equal 25 percent of the methane recovery.
Flare-only option	For years following 1997, the analysis lacks sufficient information about the population of landfills that flare without recovering methane for energy use.
Industrial waste landfilled	Industrial methane production is assumed to equal approximately seven percent of MSW landfill methane production.
Methane oxidation rate	Ten percent of methane generated is assumed to oxidize in soil.

Exhibit II-15: Cost Analysis Uncertainties

	Basis
Cost estimate	Costs are estimated using aggregate cost factors and a relatively simple set of landfill characteristics. Electricity costs are estimated using representative WIP. Direct use costs are estimated using hypothetical landfills in terms of depth, area, and WIP.
Revenue	The rate at which electricity is sold from a landfill project depends on local and regional electric power market conditions and often varies by time of day and season of year. However, this analysis uses a representative figure that remains constant.
Potential for landfills to collect and use gas cost-effectively	The extent to which electricity production and direct gas use are cost-effective depends on the energy price and availability of end-users.
Methane recovery technologies	This analysis only focuses on internal combustion (IC) generators and direct gas use because they are the most cost-effective technologies for projects examined in this analysis. However, other technologies are available, e.g., electricity generation using turbine generators.
Equipment and engineering costs	Information is based on current projects and industry experts.

Source: EPA 1999.

Research Needs

The current costs of collecting and converting landfill methane to electricity are provided in EPA 1999 and were previously estimated in CEC 1997. Applying the methodology used in EPA 1999 would be fairly straightforward. The key requirement is that the population of California landfills are characterized by size, waste composition, and proximity of prospective direct-use end users. The CIWMB already maintains a database with basic characteristics on landfills in California (CIWMB 2001). Further assessment is needed to determine whether this database provides data that is comprehensive and accurate enough to develop the marginal abatement curve for California. Properly incorporating and managing a dynamic baseline forecast of landfill volumes also will be critical. The California work should seek to improve upon the work conducted by EPA, with respect to discussion and incorporation of market barriers to landfill-to-gas implementation. In particular, issues related to distributed generation (DG) interconnection and electricity power purchase markets in California should be addressed, as should possible co-benefits such as reduced volatile organic compounds.

4.5.2 Agriculture

Methane emissions from livestock occur from both digestive processes (entermic fermentation) and manure. The EPA and others have quantified the costs of emission reductions from converting methane from manure to electricity and heat. They have also assessed methods for reducing entermic fermentation but not associated costs.

Manure emissions vary principally as a function of manure management practices and farm size. Farms use either "dry" or "liquid" manure management systems. Methane emissions are much higher for liquid systems; dry systems are fairly inconsequential. Liquid systems are more common on larger farms and the U.S. trend is toward larger farms. According to EPA 1999, "up to half of the manure on large dairy farms and virtually all of the manure on large hog farms is managed using liquid systems." Emission reduction strategies are generally limited to either increasing the use of dry systems or recovering methane and utilizing it to produce electricity, heat, or hot water. The EPA 1999 report concludes that the first option—increasing the use of dry systems—is infeasible for both "environmental impact and process design reasons." Methane for energy can be recovered by anaerobic digesters, which can also reduce foul odor and the risk of ground- and surface-water pollution. The EPA developed the average digester costs based on actual project costs from digester farm projects participating in the AgSTAR program. The EPA used FarmWare, an EPA software tool, to estimate model farm economics. The cost-effectiveness of collecting and converting the methane in liquid systems to energy varies primarily as a function of farm size, as shown in Table 7. As shown in Table 8, several uncertainties and limitations exist in the reduction estimate. These include the assumptions used to develop the model farm facility, the variability in the value of the methane recovered, importance of non-energy benefits (odor control), and the forecasting of baseline trends.

During digestion, domesticated animals produce methane by enteric fermentation. When estimating methane emission from enteric fermentation, EPA categorizes livestock populations and develops emission factors based on the diversity of feed and animal characteristics (EPA 1999). The report discusses a number of ways to reduce this form of emissions, principally through increasing production efficiency (efficiency of feed converted to product). Many of these methods involve significant changes in farm practices, from feedstock, to grazing, to breeding. Considerable uncertainty is associated with these methods. Estimating the costs associated with such changes would also be highly speculative. In addition, it is extremely difficult to forecast how price signals would be sent to farmers to change these practices (Kruger 2001).

Table 7. Results from EPA's Manure-to-Energy Marginal Abatement Curve Analysis

Exhibit 5-8: Schedule of Methane Emission Reductions for Dairy and Swine Manure Management in 2010

Manure Type	Label on MAC	Value of Carbon Equivalent ($/TCE)	Electricity Price with Additional Value of Carbon Equivalent ($/kWh)	Average Break-Even Farm Size (# of head)	Incremental Reductions (MMTCE)	Cumulative Reductions (MMTCE)	Cumulative Reductions (% of base)
DAIRY COW:	A	($30)	$0.04	1,025	0.23	0.23	4%
	B	($20)	$0.06	1,134	0.52	0.75	14%
	C	($10)	$0.07	828	0.33	1.07	20%
	D	$0	$0.09	753	0.88	1.95	36%
	E	$10	$0.10	787	0.29	2.24	41%
	F	$20	$0.12	733	0.27	2.51	46%
	G	$30	$0.14	654	0.19	2.70	49%
	H	$40	$0.15	575	0.17	2.87	52%
	I	$50	$0.17	521	0.14	3.01	55%
	J	$75	$0.21	414	0.37	3.38	62%
	K	$100	$0.25	294	0.38	3.76	68%
	L	$125	$0.29	219	0.31	4.07	74%
	M	$150	$0.34	172	0.26	4.33	79%
	N	$175	$0.38	140	0.24	4.57	83%
	O	$200	$0.42	114	0.21	4.78	87%
SWINE:	A	($30)	$0.02	> 20,000	1.23	1.23	10%
	B	($20)	$0.03	> 20,000	0.00	1.23	10%
	C	($10)	$0.05	5,112	0.00	1.23	10%
	D	$0	$0.07	5,120	0.00	1.23	10%
	E	$10	$0.08	3,906	0.00	1.23	10%
	F	$20	$0.10	4,339	0.79	2.02	16%
	G	$30	$0.12	2,990	2.25	4.28	35%
	H	$40	$0.13	1,932	1.36	5.63	46%
	I	$50	$0.15	1,390	1.10	6.74	55%
	J	$75	$0.19	821	3.52	10.26	83%
	K	$100	$0.23	602	0.51	10.77	88%
	L	$125	$0.27	510	0.25	11.03	90%
	M	$150	$0.32	500	0.01	11.04	90%
	N	$175	$0.36	500	0.00	11.04	90%
	O	$200	$0.40	500	0.00	11.04	90%

Source: EPA 1999.

Table 8. EPA's Summary of Uncertainties Associated with Manure-to-Energy Marginal Abatement Curve Analysis

Exhibit V-6: Summary of Emission Reduction Uncertainties

Uncertainty	Basis
Livestock Demographics	Latest existing farm-size distribution data is for 1992. Shifts in both dairy and swine populations towards larger facilities is not reflected.
Effectiveness of Methane Recovery Technologies	These technologies have been applied on dairy and swine farms throughout the country for over two decades.
Value of Methane Recovered	
Facility Energy Costs	Energy rates vary by utility and within each state. Forecasts assume constant costs. Restructuring of utility industry may affect rates.
Non-Monetary Benefits (odor, pollution, etc.)	Value is difficult to quantify. Recent projects at swine farms have been initiated primarily to reduce odor.
Methane Recovery Costs	
Project Development/ Construction Costs	Information based on current projects and industry experts. Site-specific factors can influence costs of individual projects.

Source: EPA 1999.

Research Needs

The current costs of collecting and converting methane from liquid system manure management systems to electricity are provided in EPA 1999. The Energy Commission has also previously estimated manure biogas digester costs in CEC 1997. Applying the methodology used in EPA 1999 to the population of hog and dairy cow farms in California appears to be fairly straightforward. The key requirement is accurate characterization of the population of California farms by livestock type, size, and current manure management approach. The U.S. Department of Agriculture conducts a census of farms every five years. Results for California are published separately (USDA 1999). Several organizations have developed database search functions that work off of the census data. Further assessment is needed to determine whether this database provides all of the information needed to develop the marginal abatement curve for biogas for California. Properly incorporating and managing a dynamic baseline forecast of hog and dairy farms will also be important. As in the case of landfill generation, issues related to DG interconnection and electricity power purchase markets in California are critically important.

4.6 Nitrous Oxide and High Global-Warming-Potential Gases

Under the current GHG emission baseline (CEC 2001d), N_2O represents 6% of California's GWP emissions. High global-warming-potential gases such as perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF_6) are believed to represent roughly 2% of the state's GHG emissions. These estimates are based on CO_2 equivalence, using the Intergovernmental Panel on Climate Change (IPCC)-approved conversion factors. Some research has been done on developing and summarizing measures to reduce N_2O and high GWP emissions; however, only recently have any studies tried to estimate the costs and impacts of such measures. The following studies or planned studies are relevant to developing N_2O and high-GWP mitigation supply curves:

- AEA Technology Environment (AEA). 2001b. *Economic Evaluation of Sectoral Emission Reduction Objective for Climate Change – Economic Evaluation of Emissions Reductions of Nitrous Oxides and Methane in Agriculture in the EU.* UK. February.
- Environmental Protection Agency (EPA). 2001. *U.S. High GWP Gas Emissions 1990–2010: Inventories, Projections, and Opportunities for Reductions*, EPA 000-F-97-000. Washington, DC: U.S. Environmental Protection Agency. June.
- Environmental Protection Agency (EPA), in progress. EPA is currently conducting a study of the costs and potential impacts of measures to reduce N_2O emissions.
- Agriculture and Agri-Food Canada. 1999. *The Health of Our Air: Toward Sustainable Agriculture in Canada*. May.
- Ministry of Agriculture and Forestry (New Zealand). 2001. *Potential Management Practices and Technologies to Reduce Nitrous Oxide, Methane and Carbon Dioxide Emissions from New Zealand Agriculture*. September.
- Council for Agricultural Science and Technology (CAST). 2002. *Agriculture's Response to Climate Change*. Forthcoming.

4.6.1 Nitrous Oxide (N_2O)

According to the Energy Commission's latest research (CEC 2001d), agricultural soil management and fossil fuel combustion in mobile sources account for about two-thirds and one quarter of California's N_2O emissions, respectively (over 90% combined).

Microbial processes in soil naturally produce N_2O. Agricultural practices that increase the amount of nitrogen in soils (fertilizer application), increase the nitrogen available for nitrification and denitrification, which subsequently increases the amount of N_2O emitted from the soils. Production of nitrogen-fixing crops and application of fertilizers, livestock manure, sewage sludge, and crop residues are ways to add nitrogen to the soil. Indirect emissions of N_2O are caused from leaching, runoff, or atmospheric deposition of nitrogen to the agricultural system. These include the ammonia and NO_X released from the soil and deposited atmospherically back to the soil, and runoff of soil to water systems. Non-agricultural indirect emissions can also occur from sources of NO_X emissions that deposit onto the soil.

There are few studies of the options, costs, and potential impacts of reducing N_2O. One of the few such studies published (AEA 2001b) discusses options to reduce N_2O emissions in the European Union (EU), including N_2O emissions from the chemicals sector, combustion in both stationary and mobile sources, and agriculture. Table 9 shows the agricultural management options that could influence N_2O emissions. Other studies provide information on ways to mitigate N_2O but do not provide estimates of mitigation costs (New Zealand 2001, Canada 1999). However, EPA is currently in the process of conducting a study of the costs and potential impacts of N_2O mitigation (Kruger 2002).

Table 9. Agricultural Management Options Influencing N_2O Emissions

Type of option	Management Option
1. Crop management	(a) change in fertiliser application rates (b) precision farming (c) crop selection (i.e. with different nitrogen requirements) (d) breeding nitrogen fixing crops (e) breeding crops to improve nitrogen use efficiency (e.g., lower requirements, more efficient uptake) (f) cultivation of unmanaged land (i.e. histosols) (g) irrigation management (h) soil pH management (i) crop residue burning (j) reduce soil compaction
2. Fertiliser efficiency management	(a) nitrification inhibitors; (b) release rates (e.g. slow or timed release, coatings to limit or retard water solubility); (c) improved fertiliser placement and timing (e.g. band placement, foliar applications).
3. Manure management	(a) storage times and conditions (e.g., slurry treatment to change viscosity); (b) application placement (e.g. slurry injection) (c) application timing; (d) application amounts (e.g. controlled rate systems); (e) export of manure (from the agricultural system).
4. Reducing the amount of manure nitrogen	(a) dietary manipulation; (b) breeding nitrogen efficient livestock; (c) livestock selection (e.g. livestock types, herd sizes).

Source: AEA 2001b

According to AEA 2001b, there is a lack of reliable data on emissions changes in response to N_2O management decisions. Most results are site specific and include many factors that potentially influence the mechanism for N_2O emissions. Extrapolating results from these sites to a larger scale is inappropriate without more research to reduce uncertainties.

Research Needs

Whether California-specific research will be needed to estimate the costs and potential impacts of N_2O mitigation measures will depend partly on the results of EPA's current work on a national N_2O marginal abatement curve. When EPA's study is completed, it may be possible to effectively interact California's revised baseline with EPA's N_2O mitigation results to produce a California-specific N_2O mitigation supply curve. Given the nascent status of N_2O reduction studies, however, it is likely that additional research will be needed to improve N_2O mitigation cost and impact estimates. To continue the progress in estimating baseline emissions for California represented by the Energy Commission's latest study (CEC 2001b), further research may also be needed to improve the accuracy of N_2O emission estimates.

4.6.2 High GWP Gases

As noted above, high GWP gases (HFCs, PFCs, and SF_6) contribute approximately 2% of California's GHG emissions (CEC 2001d). However, these are powerful, long-lived greenhouse gases. HFCs are used primarily as substitutes for ozone-depleting substances, and PFCs and SF_6 are emitted from several industrial processes, such as aluminum smelting, semiconductor manufacturing, electric power transmission and distribution, and magnesium casting. There is no aluminum manufacturing or magnesium casting in the state. Substitution of ozone depleting substances account for 72% of high GWP emissions in California, electric utility transmission and distribution 19%, and semiconductor manufacturing 9% (CEC 2001b).

According to EPA 2001, options for reducing emissions of high GWP gases (excluding costs and emission reductions for options already required by law or expected due to voluntary partnership programs) include:

- implementing new industrial processes that reduce emissions and improve efficiency,
- implementing better housekeeping practices to reduce leaks of high GWP gases,
- installing new, more efficient equipment with lower emission rates, and
- substituting other gases for high GWP gases in a variety of applications, where safety and performance requirements can be met.

The EPA high GWP report uses discounted cash flow analysis to estimate the cost of achieving reductions for each technology or practice (for each emission source). Costs are presented in dollars per metric ton of carbon equivalent ($/TCE). This approach is the same method EPA has used in developing MACs for methane emissions (see EPA 1999). Figure 9 shows EPA's high GWP gas MAC, using an 8% discount rate. The also develops a curve with a 4% discount rate. Table 10 shows costs and impacts of specific measures. Authors of the study concluded:

> The high GWP gas MAC illustrates three key findings. First, substantial emission reductions, 4.2 million metric tons of carbon equivalent (MMTCE), are likely to be cost-effective in the absence of a carbon value (i.e., at $0/TCE). Second, achievable reductions at carbon values of $20/TCE and $100/TCE are estimated at 28.6 MMTCE and 36.2 MMTCE, respectively. Third, above $40/TCE, the MAC becomes relatively inelastic, that is, largely non-responsive to increasing carbon values. This result is expected, given that the analysis does not incorporate new technology innovations that might arise with greater carbon values, increased research and development (R&D) expenditures, or other unexpected technology advances. In sum, the analysis suggests that over 5% of baseline emissions could be reduced through cost-neutral or possibly even cost-beneficial changes, and that viable options exist to reduce baseline emissions by nearly one half.

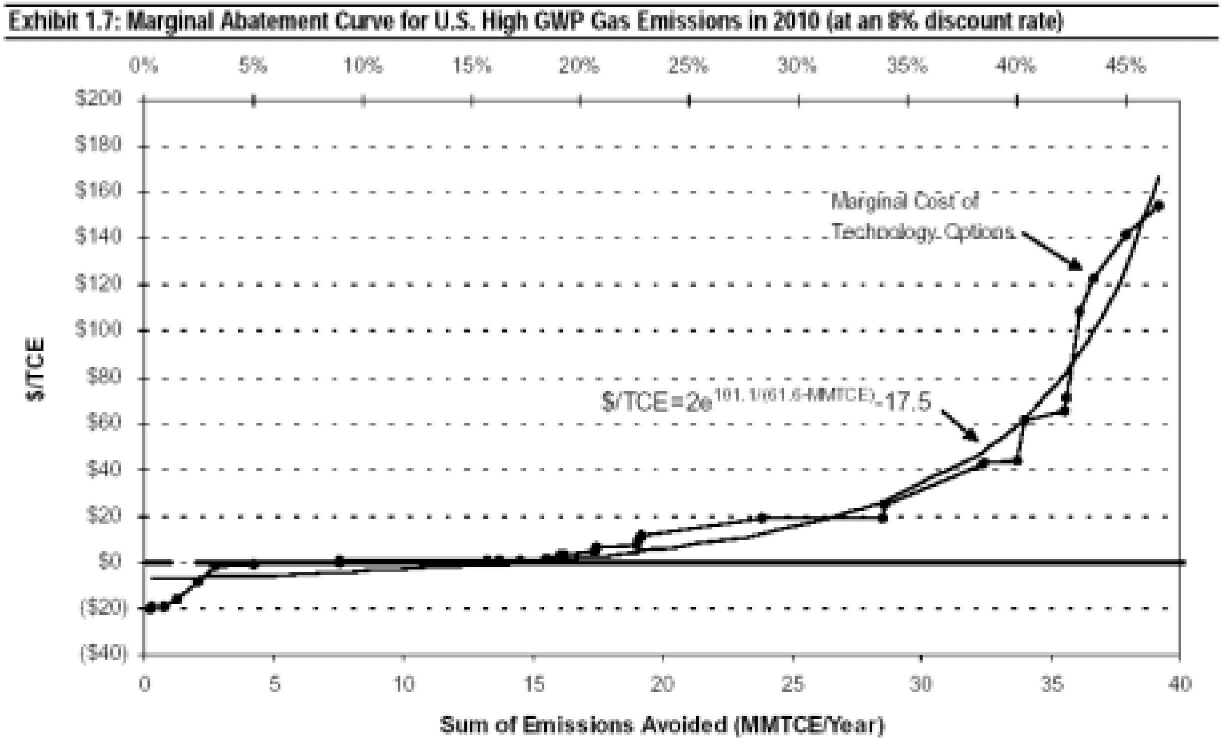

Figure 9. High GWP Marginal Abatement Curve
Source: EPA 2001.

Table 10. High GWP Marginal Abatement Curve – Measure Details

Exhibit 1.9: Composite Marginal Discount Curve Schedule of Options for 2010 (at an 8% discount rate)

#	Source	Activity	Cost ($/TCE)	Emission Reduction (MMTCE)	Sum of Reduction (MMTCE)	Percent Reduction from 2010 Baseline
1	Aerosols	Hydrocarbon Aerosol Propellants	$ (20.32)	0.2	0.2	0%
2	Fire Extinguishing	Water Mist	$ (19.42)	<0.05	0.3	0%
3	Aerosols	Not-in-kind Alternatives	$ (19.12)	0.5	0.7	1%
4	Foams	PU Spray Foams - Replace HFC-245fa/ CO_2 (water) with hydrocarbons	$ (15.64)	0.5	1.2	1%
5	Aerosols	Switching to HFC-152a	$ (8.09)	0.8	2.1	2%
6	Magnesium Smelting	Good Housekeeping	$ (1.91)	0.7	2.8	3%
7	Magnesium Smelting	SF_6 Capture/Recycling	$ (0.89)	1.5	4.2	5%
8	Magnesium Smelting	SO_2 Replacement	$ 0.24	3.3	7.5	9%
9	Aluminum Smelting	Retrofit-Minor: VSS	$ 0.54	<0.05	7.6	9%
10	HCFC-22 Production	Thermal Oxidation	$ 0.73	5.7	13.3	16%
11	Aluminum Smelting	Retrofit-Major: SWPB	$ 0.77	0.4	13.7	16%
12	Solvents	Alternative Solvents	$ 0.88	0.8	14.5	17%
13	Electric Utilities	Leak Detection and Repair	$ 1.62	1.0	15.5	18%
14	Electric Utilities	Recycling Equipment	$ 3.28	0.5	16.1	19%
15	Aluminum Smelting	Retrofit-Major: CWPB	$ 3.30	0.2	16.2	19%
16	Refrigeration/AC	Leak Reduction Options	$ 5.08	1.2	17.4	21%
17	Aluminum Smelting	Retrofit-Major: HSS	$ 6.82	0.1	17.5	21%
18	Refrigeration/AC	Replace DX with Distributed System	$ 7.21	1.6	19.1	23%
19	Aluminum Smelting	Retrofit-Major: VSS	$ 9.58	0.1	19.1	23%
20	Solvents	NIK Semi-Aqueous	$ 11.55	<0.05	19.2	23%
21	Semiconductor Manufacturing	NF_3 Drop-In	$ 18.57	4.7	23.9	28%
22	Semiconductor Manufacturing	NF_3 Remote Cleaning	$ 18.57	4.7	28.6	34%
23	Solvents	NIK Aqueous	$ 25.02	<0.05	28.6	34%
24	Semiconductor Manufacturing	Plasma Abatement	$ 41.95	3.8	32.4	38%
25	Foams	PU Appliance Foams - Replace HFC-134a with cyclopentane	$ 43.25	<0.05	32.4	38%
26	Semiconductor Manufacturing	Capture/Recycling	$ 43.99	1.3	33.7	40%
27	Fire Extinguishing	Inert Gas Systems	$ 61.44	0.3	34.0	40%
28	Refrigeration/AC	HFC Secondary Loop Systems	$ 65.30	1.5	35.6	42%
29	Solvents	Retrofit Options	$ 71.24	<0.05	35.6	42%
30	Refrigeration/AC	Ammonia Secondary Loop Systems	$ 108.67	0.6	36.2	43%
31	Foams	PU Spray Foams - Replace HFC-245fa/ CO_2 (water) with CO_2 (water)	$ 122.52	0.5	36.7	44%
32	Semiconductor Manufacturing	Catalytic Destruction	$ 141.93	1.2	37.9	45%
33	Semiconductor Manufacturing	Thermal Destruction	$ 154.54	1.3	39.2	46%

Source: EPA 2001.

The authors of the EPA high GWP mitigation study identify several sources of uncertainty underlying their results. According to the study, "The major uncertainties in the analysis stem from those inherent in data projection as well as from the lack of published information on reduction options and their costs." The authors list a number of specific areas of uncertainty, which are itemized in Table 11.

Table 11. Summary of Uncertainties Underlying High GWP Marginal Abatement Curve

The projected emission estimates are tied to factors such as growth in usage and demand for specific products or gases—difficult items to project for many sectors. This also introduces a degree of uncertainty about the emission estimates.
There is significant uncertainty in the levels of future energy prices and the indirect effects of potential emission reduction options.
Several options that were included in the MAC analysis might become more or less efficient in the future as a result of technological breakthroughs and other innovations. It is important to note that some of those options currently not considered viable may become so in the future.
Some of the emission reduction options discussed involve using chemicals (as substitutes) that can potentially impact human health and/or safety. Although some technically feasible options were omitted for this reason, some options that remain may still prove not to be feasible upon further research because of health and/or safety concerns.
The lack of specific information on reduction opportunities in many sectors can be attributed to several factors, including the following. • For some applications, minimal research has been performed on how to limit emissions of ozone-depleting substances (ODS) substitutes, including developing alternatives for them. This is particularly true for foams, aerosols, fire extinguishers, and solvents. • Data on both emissions and reduction costs may be highly proprietary for many industrial processes. This is especially true of PFC emissions from semiconductor manufacturing and aluminum smelting. • For many mitigation options, accurate measures of potential emission reductions or costs are not available. These options, although they are qualitatively discussed in the relevant chapters, are not included in the MAC analysis.

Source: EPA 2001.

Research Needs

Although complex, many of the high GWP abatement measure characteristics (principally, per-unit costs and impacts estimates) appear to be transferable from a national level to California, if appropriately matched to California baseline data. With modest resources, researchers could combine EPA's high GWP measure characteristics with California's revised baseline and likely produce a California-specific high GWP supply curve. Additional research should try to address the uncertainties summarized in Table 11. To continue the progress in estimating baseline emissions for California (CEC 2001b), further research may be needed to improve the accuracy of high GWP emission estimates.

4.7 Crosscutting

4.7.1 Technology Adoption

Supply curves are effective tools for systematically and consistently characterizing basic technology costs and benefits; however, they are limited with respect to characterizing customer adoption as a function of changes in key parameters, such as prices and technology availability, over time. A technology adoption model would be effective in incorporating these factors into an assessment.

Research Needs

A technology adoption model should be developed, or an existing model selected,[25,26] to interface directly with the technology data developed in the supply curve studies. A fairly complete specification of such a model for energy end use markets is described in RER 2000a.

The key need in this area is development of the data and analysis needed to specify the actual curves and parameters of adoption models. The initial focus should build upon the considerable body of work already available in energy end-use market modeling. Application of adoption modeling that explicitly incorporates costs and effects of market interventions should begin for non-CO_2 GHGs, such as methane, for which GHG reduction opportunities are closely related to the decision making of individual end users.

PIEREA efforts should especially focus on using technology penetration data from the past 10 years of utility efficiency programs in California and other regions of the United States to develop a set of adoption curves that are specific to energy-efficiency and GHG mitigation measures. A scoping study should be conducted to assess the availability of the necessary data, to both estimate adoptions over time and to correlate actual adoptions to measure parameters (e.g., incremental measure costs, return on investment, payback, awareness levels, program interventions) required by specific models. Researchers should develop and emphasize a practical process in which taxonomies with discrete sets of curves calibrated for specific types of measures are developed.[27]

4.7.2 Supply Curve Weaknesses

Section 3.6 of this roadmap identifies weaknesses of supply curves. If supply curves are to be used effectively, researchers need to address and correct these weaknesses.

Research Needs

Researchers need to study supply curve weaknesses, with efforts focusing on formally characterizing these weaknesses, proposing alternative bottom-up methodologies, and implementing examples of alternative methods and models. Efforts should focus on sectors for which data can be developed and utilized in quantitative analyses. In addition, efforts should focus on methods such as adoption process modeling, in which parameters that are often static or unspecified in supply curve analyses (such as awareness, interest, and availability, energy prices) are made explicit and dynamic. This work should be

[25] The Commission developed a bottom-up energy-efficiency model that includes a program penetration module, CALRAM, in the mid-1990s; however, the model has not been updated or run in several years and may not meet the requirements discussed in this roadmap.

[26] Rodgers 1995, *Diffusion of Innovations*, provides a comprehensive review and analysis of several diffusion-of-innovation models. One of the broadest attempts to specify such a model for the purpose of modeling energy-efficiency programs is provided in Chapter 7 of RER 2000a, *A Framework for Planning and Assessing Publicly Funded Energy Efficiency*.

[27] Note that the PIER Buildings area is also considering research on a Technology Impact Assessment Framework that would include specifications, and perhaps research, on adoption curves. PIER efforts in this area should be coordinated.

coordinated with the behavioral economics and energy efficiency research suggested under the Economics of Climate Change Mitigation and Adaptation portion of the PIER Climate Change Plan.

5. Goals

The primary goal of the Supply Curves portion of the PIER Climate Change Research Plan is to contribute to advancements in the science of GHG mitigation supply curve development, particularly as applied to understanding emissions reductions opportunities in California. To achieve this goal, it likely will be necessary to develop mitigation supply curves for the State of California in cases where such curves are otherwise unavailable. Improved GHG reduction supply curves will help both private and public sector decision makers to formulate the most effective and economical GHG mitigation policies.

The achievement of these goals depends on a variety of factors that vary by sector and greenhouse gas. Generally, it will be necessary to improve baseline inventory data in a variety of areas, including fuel consumption, landfills, and livestock farms. In addition, a number of methodological and macroeconomic integration issues will need to be improved upon. Finally, it will be critical that PIEREA efforts in this area are leveraged with the resources and talent available from other organizations with convergent research needs and interests.

Supply curve research activities begin with sector/gas-specific recommendations and conclude with recommendations that integrate or cut across sectors and greenhouse gases. The focus of the short-term sector/gas-specific recommendations tends to be on the development or synthesis of *initial* supply curve information (i.e., the development, analysis and organization of technology costs and benefits into supply curves that are similar to those developed in past GHG and conservation supply curve studies and described in Section 3. As discussed previously, such basic supply curves have important limitations, particularly when it comes to being effectively incorporated into macroeconomic and mid- to long-term forecasting models. In addition, supply curves that focus only on technology costs and benefits do not provide policy guidance per se, though they are an important input to policy analyses.

The short-term Crosscutting/Integration recommendations address the broader needs associated with advancing the state-of-art of supply curve development and their integration with larger economic modeling efforts. One of the reasons for this organization is practicality. First-order benefits for California's climate change policy makers can be achieved fairly quickly by developing supply curves that capture incremental measure costs, measure applicability, and the potential impacts of measures on reducing GHGs in California. Further value will be obtained by expanding such analyses to explicitly include technology innovation over time, the diffusion-of-innovation framework to technology adoption, incorporation of market barriers and market failures, and integration into integrated macroeconomic models. Although these advances are addressed primarily under the Crosscutting/Integration area, we also recommend that the initial supply curve work incorporate at least qualitative identification of market barriers and failures, as well as other co-benefits and collateral costs.

Mid-term recommendations focus on the development of *advanced* supply curves, which would build off of the initial studies to more definitively resolve current analytical and data-related weaknesses.

The PIEREA program recognizes that much work is currently under way in these areas and seeks to draw from, build upon, and broaden the focus of those efforts. Whenever possible, PIEREA will identify existing efforts and form partnerships to leverage resources.

5.1 Short-term Objectives[28]

5.1.1 CO_2: Buildings

A. Contribute to the development of an initial California-specific CO_2 reduction supply curves for residential buildings.

Activities needed: (1) *Compile existing end use consumption and energy-efficiency measure data into residential energy-efficiency supply curves for California*. At a minimum, underlying data will need to be segmented by fuel (electric and gas), vintage (new versus existing construction) and building type (single-family, multi-family, and mobile homes). Measure penetration should be modeled for a range of market interventions to produce estimates of achievable potential; associated costs should be inclusive of any programmatic costs. (2) Market barriers by measure or type of measure should be identified, as well as any co-benefits. Further analysis and estimation of implicit customer discount rates is also needed.

To the extent that non-PIER divisions of the Energy Commission, other State agencies, or California utilities produce updated energy-efficiency supply curves in the near-term, PIEREA efforts should focus on estimating the associated GHG reduction and improving data sources and methodologies.

Critical Factors for Success:

- Coordination among PIEREA and other entities sponsoring supply curve, or related, research.
- Access to data. Not all of the data necessary is readily available. Coordination among entities with unique data access is critical (e.g., utility program data sets).

[28] S*hort-term* refers to a 1–3 year time frame; *mid-term* to 3–10 years; and *long-term* to 10–20 years. The activities specified in the roadmap are projected to begin sometime within the designated time frames, and the duration of actual projects may be less than the entire term specified.

B. Contribute to the development of initial California-specific CO_2 reduction supply curves for commercial buildings.

Activities needed: (1) *Compile existing information into commercial energy-efficiency supply curves.* At a minimum, underlying data need to be segmented by fuel (electric and gas), vintage (new versus existing construction) and building type (e.g., office, retail, etc.). Customer size and ownership status should also be considered as key segmentation variables. Measure penetration should be modeled for a range of market interventions to produce estimates of achievable potential; associated costs should be inclusive of any programmatic costs. (2) Market barriers by measure or type of measure should be identified, as well as any co-benefits. Further analysis and estimation of implicit customer discount rates is also needed.

To the extent that non-PIER divisions of the Energy Commission, other State agencies, or California utilities produce updated energy-efficiency supply curves in the near-term, PIEREA efforts should focus on estimating the associated GHG reduction and improving data sources and methodologies.

Critical Factors for Success:
- Coordination among PIEREA and other entities sponsoring supply curve, or related, research.
- Access to data. Not all of the data necessary is readily available. Coordination among entities with unique data access is critical (e.g., utility program data sets).

5.1.2 CO_2: Industry

A. Establish the feasibility of adapting LBNL industry-specific studies to California.

Activities needed: (1) Conduct a near-term study in which one of the recently completed industrial supply curve studies (Martin et al. and Worrell et al.) conducted at the national level for EPA is modified and appropriately applied to the California market. (2) If successful, adapt the remaining EPA industrial supply curve studies.

Critical Factors for Success:
- Coordination between PIEREA and other entities sponsoring supply curve or related research; especially LBNL and EPA.

B. Contribute to the development of initial California-specific CO_2 reduction supply curves for remaining major industries.

Activities needed: (1) For those major California industries for which national supply curve studies have not been conducted, California should develop, or co-develop, the remaining curves. Candidate industries for consideration include oil/gas extraction, food processing, petroleum and chemicals, industrial machinery, and electronics.

(2) Researchers should develop supply curves for main crosscutting technologies (e.g., steam, motor systems, compressed air), for use in the evaluation of light industries. (3) Model measure penetration for a range of market interventions to produce estimates of achievable potential; associated costs should be inclusive of any programmatic costs. (4) Identify market barriers by measure or type of measure, as well as co-benefits. Further analysis and estimation of implicit customer discount rates is also needed. Analysis of implicit discount should be incorporated into efforts to calibrate estimated to actual measure adoption both with and without program interventions.

Critical Factors for Success:

- Coordination between PIEREA and other entities sponsoring supply curve, or related, research.
- Access to data. Not all of the data necessary is readily available. Coordination among entities with unique data access is critical (e.g., industry-specific organizations).

5.1.3 CO_2: Transportation

A. Develop California-specific CO_2 reduction supply curves for the transportation sector.

Activities needed: (1) Leverage light-duty vehicle supply curves from existing sources and models. Much of the work necessary appears to have been done in studies recently completed and in progress in response to AB 2076. The AB 2076 studies may need to be integrated and reframed to develop a comprehensive CO_2 reduction supply curve for California. (2) PIEREA research could also play an important role in efforts to reduce key uncertainties in the AB 2076 studies. (3) Less work has been done to assess the costs and potential impacts of improving efficiency in motor freight transport. Consideration should be given to co-funding such a study with a national agency, since results will have national applicability.

Critical Factors for Success:

- Firsthand access to data and models employed for AB 2076 studies.
- Consistency in data and methods in AB 2076 studies, such that cross-study integration of results into a comprehensive CO_2 supply curve is feasible and cost effective.
- Coordination with state and local air quality and transportation agencies.

B. Address weaknesses and gaps in current transportation supply curve studies.

Activities needed: (1) Examine weaknesses in current light-duty fuel economy and emissions-reduction studies, to develop a better understanding of the process of innovation in automotive technology. Examine the effects of regulation in shaping design decisions and expanding technology options; and the role of capital constraints in technology deployment decisions. (2) Conduct/enhance research to improve understanding of consumer behavior and the role of information in vehicle selection.

Critical Factors for Success:

- Coordination and leveraging of research with other R&D organizations nationally and internationally.
- Improved access to industry data.
- Clear focus on research areas where PIEREA can add value to otherwise planned ARB and Energy Commission Transportation Division research (e.g., improving methods and data and reducing uncertainties).

5.1.4 CO_2: Electricity Production

A. Develop basic California-specific CO_2 reduction supply curves for the electric generation sector.

Activities needed: (1) The Commission should compile available information on the costs and GHG emissions characteristics of California generating plants into a single, easily accessible resource (if it has not already).[29] (2) In addition to characterizing current generation costs and emissions, forecast future generation costs and emissions, particularly for renewables and DG. These forecasts should include scenario analyses that cover a wide range of possible generation mixes. Because some the benefits of such research may also be realized on a national scale, researchers should coordinate and leverage efforts with those of other organizations like NREL and EPRI, which have recently produced renewable cost estimates and forecasts. The indirect benefits (e.g., enhanced energy security) and costs (e.g., intermittent availability) of renewables and DG also should be estimated to the extent feasible.

Critical Factors for Success:

- Coordination between PIEREA and other sponsoring entities, for example, NREL and EPRI.

B. Continue to forecast the future generation mix in California, link changes in demand to emissions, and incorporate the ability to model changes in response to GHG mitigation policies.

Activities needed: (1) Establish a process for modeling the GHG emissions associated with different generation mixes in the State under alternate future scenarios (if it has not been done so already). This modeling should include electricity demand reductions and GHG reduction policies focused on the generation sector.

[29] Such information was compiled in the past in the Energy Commission's Technology Status Reports, published over several years in the 1980s and early 1990s. The fourth edition, and last to date, was published in 1997 (CEC 1997).

Critical Factors for Success:

- Adequate Energy Commission staff and resources to expand analytical responsibilities to include GHG emissions modeling. Strong linkages between supply and demand analysis groups at the Commission.

5.1.5 Methane: Waste and Agriculture

A. Develop a basic CH_4 marginal abatement curve for the landfill population in California, and reduce uncertainty in waste-in-place and methane emissions factors.

Activities needed: (1) Assess the California Integrated Waste Management Board database that characterizes the population of California landfills by size, waste composition, and proximity of prospective direct-use end users adequately to determine whether it provides all of the information needed to develop the marginal abatement curve for California. (2) If the CIWMB data are inadequate, improve estimates of waste-in-place and methane emissions factors. (3) Apply the methodology used in EPA 1999 to California landfill census data to develop a methane reduction supply curve for landfills. (4) Incorporate and maintain a dynamic baseline forecast of landfill volumes.

Critical Factors for Success:

- Coordination and co-funding with CIWMB and EPA.
- Improved data on landfill size and composition.

B. Develop basic California-specific CH_4-reduction supply curves from manure management.

Activities needed: (1) Assess the U.S. Department of Agriculture farm census data for California and other sources to determine whether this database characterizes the population of California farms by livestock type, size, and current manure management approach adequately to develop the marginal abatement curve for biogas for California. (2) Using the best available data for California, apply the methodology used in EPA 1999 to the population of hog and dairy cow farms in California to estimate manure biodigester costs and methane reduction impacts. In this assessment, address issues related to distributed generation interconnection and electricity power purchase markets in California, and any additional hassle and transaction costs associated with owning and operating biogas generators. (3) Incorporate and manage a dynamic baseline forecast of hog and dairy farms.

Note: We do not recommend attempting to develop a marginal abatement curve for entermic fermentation in California at this time.

Critical Factors for Success:

- Coordination and co-funding with EPA. Improved data on California's manure-related farm characteristics.

5.1.6 N_2O and High Global-Warming-Potential Gases

A. Develop a N_2O-reduction supply curve for California, reduce uncertainty in N_2O emission estimates.

Activities needed: (1) Develop set of N_2O-reduction options; focus primarily on agriculture and mobile combustion sources. (2) Estimate costs and potential impacts of applying options to California sources; focus primarily on agriculture and mobile combustion sources. (3) Continue improving baseline N_2O emission estimates.

Critical Factors for Success:

- Availability and development of accurate cost data and impact data.
- Understanding of agricultural economy and likelihood of farm adoption of N_2O mitigation measures.
- Coordination and co-funding with EPA and other countries conducting N_2O mitigation research that have similar agricultural practices.

B. Develop a supply curve for mitigating high global-warming-potential gases in California, reduce uncertainty in high GWP emission estimates.

Activities needed: (1) Develop a set of abatement options for high GWP gases. (2) Estimate costs and potential impacts of options as applied to California high GWP sources; principally by leveraging and appropriately combining data, sources, and methods from EPA 2001 with CEC 2001b. (3) Continue improving baseline estimates of high GWP emissions.

Critical Factors for Success:

- Improved accuracy of abatement cost and impact data.
- Coordination with EPA.
- Access to or development of alternatives to proprietary industrial data.
- Reduction in uncertainties identified in EPA 2001.

5.1.7 Crosscutting/Integrating

A. Develop/Implement a Dynamic Technology Adoption Model

Activities needed: (1) To support studies 5.1.1A and B above, develop or enhance technology adoption models and their supporting data. The technology adoption model should interface directly with the technology data developed in the supply curve studies. It should also be able to explicitly handle stock accounting; competition between technologies; multi-attribute adoption functions (e.g., economic attractiveness and market barriers); end user awareness; dynamic changes in technology costs, availability, and energy prices; and a variety of market interventions (i.e., explicitly incorporate and model the effects of program costs by intervention type). The specification of such a model for energy end use markets is described in RER 2000a. (2) Develop the data and analysis needed to specify the actual curves and parameters of adoption models, initially focusing on the work already available in energy end-use market modeling. (3) Conduct adoption modeling that explicitly incorporates costs and effects of market interventions for non-CO_2 GHGs.

Critical Factors for Success:

- Coordination between PIEREA and other sponsoring entities, including California electric and gas utilities (via CALMAC), PIER Buildings, non-PIER Energy Commission areas, and others.
- Availability of and access to data. Unfortunately, much of the detailed, historic data that would be ideal to utilize for calibrating energy-efficiency and GHG reduction technology option curves is either unavailable or difficult to obtain. For example, the U.S. Census ceased tracking annual fluorescent ballast and other energy equipment shipment data several years ago.

B. Advance the state-of-the-art associated with bottom-up analyses of GHG reduction options.

Activities needed: (1) Conduct a methodological study that addresses the supply curve weaknesses identified in Section 3.6**,** focusing on formally characterizing these weaknesses, proposing alternative bottom-up methodologies, and implementing examples of alternative methods and models. Focus on sectors for which data can be developed and utilized in quantitative analyses, and on methods such as adoption process modeling. (2) Coordinate with the behavioral economics and energy efficiency research suggested under the Economics of Climate Change Mitigation and Adaptation portion of the Climate Change roadmap.

Critical Factors for Success:

- Coordination and co-funding with other organizations interested in advancing supply curve methods.

Table 12. Short-term Budget

Objective	Projected Cost ($000)
5.1.1.A Contribute to the development of an initial California-specific CO_2 reduction supply curves for residential buildings.	50–100*
5.1.1.B Contribute to the development of an initial California-specific CO_2 reduction supply curves for commercial buildings.	100–200*
5.1.2.A Establish the feasibility of adapting LBNL industry-specific studies to California	50–100
5.1.2.B Contribute to development of initial California-specific CO_2 reduction supply curves for remaining major industries	100–300**
5.1.3.A Develop basic California-specific CO_2 reduction supply curves for the transportation sector	200–500
5.1.3.B Address weaknesses and gaps in current transportation supply curve studies	100–300
5.1.4.A Develop basic California-specific CO_2 reduction supply curves for the electricity generating sector	100–400*
5.1.4.B Forecast the future generation mix in California and incorporate the ability to model changes in response to GHG mitigation policies	100–300
5.1.5.A Develop CH_4 reduction supply curve for the landfill population in California	25–100
5.1.5.B Develop California-specific CH_4 reduction supply curves from manure management	25–100
5.1.6A Develop N_2O reduction supply curve for California, reduce uncertainty in N_20 emission estimates	25–100
5.1.6B Develop supply curve for mitigating high global warming potential gases in California, reduce uncertainty in high GWP emission estimates	25–50
5.1.7.A Develop/Implement a Dynamic Technology Adoption Model	100–500***
5.1.7.B Advance the state-of-the-art associated with bottom-up analyses of GHG reduction options	50–100
Total Short-term Cost	**1,050–3,150**

Note: An asterisk (*) indicates a high probability that the work will be leveraged with other ongoing efforts. The figure given is the California Energy Commission's projected expenditure to complete each short-term objective.

**Range depends on number of industry-specific studies conducted ($35,000–$75,000 per industry).

***Higher range includes funding for one or more studies to empirically estimate model parameters.

5.2 Mid-term Objectives

The mid-term objectives should generally be to build off of the foundation research projects developed in the short term. Many of the short-term studies require development of initial GHG reduction supply curves for California as a first step toward PIEREA activities that focus on advancing methodologies and improving input data. Key mid-term research issues are improvement of incorporation of GHG supply curves in macroeconomic models, improving quantification of co-benefits and collateral costs, and improving input data.

A. **Develop advanced California-specific CO_2-reduction supply curves for commercial and residential buildings.**

   Activities needed: (1) Improve the dynamic modeling approaches and integrate the models or results developed in the short term into larger macroeconomic climate change models. (2) Increase quantification of indirect costs and benefits of energy-efficiency and GHG reduction measures.

B. **Integrate California-specific CO_2-reduction supply curves across industries**.

   Activities needed: (1) After the high-priority, near-term individual industrial studies are complete, the individual study results should be integrated into an overall industrial supply curve for the State. (2) Expand and improve adoption modeling for industrial decision makers and technologies. (3) Continue research efforts aimed at better understanding industrial customers' discount rates and quantifying the costs of technology-specific market barriers.

C. **Continue to address weaknesses and gaps in transportation supply curve studies**.

   Activities needed: Continue research efforts to develop a better understanding of the process of innovation in automotive technology; the effects of regulation in shaping design decisions and expanding technology options; and the role of capital constraints in technology deployment decisions.

D. **Improve dynamic emissions modeling of California's generation system**

   Activities needed: Continue to improve GHG emissions modeling associated with different generation mixes in the State under alternate future scenarios.

E. **Improve CH_4 marginal abatement curves for the landfills and manure management**

   Activities needed: Continue research, as needed, to improve estimation of methane emissions associated with landfills and livestock and improve modeling of gas conversion economics, barriers, and adoption.

F. **Improve N_2O and High GWP mitigation supply curves.**

Activities needed: Continue research, as needed, to improve estimation of nitrous oxide and high GWP gases mitigation supply curves.

G. **Develop an integrated analysis of GHG reduction opportunities and associated costs and benefits.**

Activities needed: Integrate the sector-specific GHG reduction opportunities, through one or more economic-energy models, to produce a comprehensive, interactive, and dynamic assessment of alternative policy options for reducing California GHG emissions. Coordinate this work with the related recommendation in the economic portion of the PIER Global Climate Change Research Plan on large-scale computational modeling to analyze robust strategies for GHG mitigation and climate change adaptation in California.

H. **Calibrate Technology Adoption Models.**

Activities needed: Continue development of calibrated technology adoption curves.

5.3 Long-term Objectives

The long-term objective should to ensure that California has thoroughly and accurately assessed the GHG reduction opportunities and costs associated with a wide range of State, national, and international policy options. As specific GHG policies are developed and implemented, PIEREA should conduct studies that compile and use data from this experience to test, validate, and revise its GHG mitigation models.

6. Leveraging R&D Investments

6.1 Methods of Leveraging

Much of the work identified in this roadmap would be collaborative with other entities; PIEREA would either co-fund projects by other entities, or use outside funds to support PIEREA efforts. Specifically, PIEREA should consider the following:

- Co-funding existing or planned work to be carried out by:
  - the California Public Utilities Commission (CPUC), California electric and gas utilities, EPA, and DOE (buildings and industry);
  - ARB, federal Department of Transportation, and the Department of Natural Resources Canada (transportation);
  - the federal Department of Energy and EPRI (generation);
  - CIWMB (landfills); and

   – EPA, the New Zealand Ministry of Agriculture and Forestry, the Research Branch of Agriculture and Agri-Food Canada, and the Council for Agricultural Science and Technology (landfills, biogas, N_2O, and high GWP gases).

  Other co-funding opportunities may be available with a wide variety of countries and international agencies.

- Solicit funds from other research organizations to build upon their efforts, or to co-design new projects at the Energy Commission.

6.2 Opportunities

Co-sponsorship opportunities are likely with ARB, CIWMB, DOE, NREL, and EPA. Each of these organizations is interested in addressing climate change mitigation or closely related issues. The following specific collaborative opportunities have been identified:

- PIER could co-fund, or more likely, build upon[30] research conducted by the CPUC, California utilities, and non-PIER CEC aimed at estimating energy-efficiency potential in the states residential and commercial sectors.

- PIER could co-fund additional industrial sector supply curve studies with EPA to develop both national and California-specific results.

- PIER could co-fund efforts to compile available information on the costs and GHG emissions characteristics of California generating plants into a single, easily accessible resource, and to forecast changes in generation costs with other national and international organizations seeking the same information.

- PIER could collaborate or co-fund work with CIWMB—as well as other relevant state agencies and EPA—on developing basic CH_4 marginal abatement curves for the landfill population in California, both in terms of coordination and potential co-funding.

- PIER could collaborate or co-fund work with the California Department of Food and Agriculture—as well as other relevant state agencies, and EPA—to develop basic California-specific CH_4-reduction supply curves from manure management.

[30] Much of the research funded by California's public benefits charge has a fairly rapid turnaround time between project specification and completion (typically 6 months to 2 years). As a result, direct co-funding may be complicated by differences in timing and objectives. Nonetheless, tremendous opportunities exist for PIEREA to build upon and leverage the data and results developed in these studies for the purpose of advancing the state of supply curve-related research.

7. Areas Not Addressed by This Roadmap

This roadmap does not specifically address methane from entermic fermentation, natural gas production or coal mining; nor nitrous oxide from industrial processes and waste. These areas are not addressed because current information suggests that they are small contributors to California's GHG emissions. Note that carbon sequestration is being addressed in a companion PIEREA roadmap.

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Appendix A
Current Status of Programs

This section lists those entities and efforts that most closely address the climate change mitigation issue for California.

Current Status: California

California Public Utilities Commission and Regulated Utilities

- The CPUC's final decision for 2002 energy efficiency programs includes $10.5 million of market assessment and evaluation studies. These studies will be managed by Pacific Gas & Electric Company, Southern California Edison Company, and Sempra Energy. Among the proposed studies is a statewide energy-efficiency potential study that PIEREA may be able to leverage to achieve some of the goals outlined in this roadmap.

California Air Resources Board (ARB)

- ARB's current research activities are shown at www.arb.ca.gov/research/research.htm.
- ARB and the Energy Commission are cosponsoring a major research effort on transportation-related petroleum reduction options, costs, and impacts. (See www.energy.ca.gov/fuels/petroleum_dependence/documents/)
- ARB's *Strategic Plan for Research 2001-2010*, is their ten-year research plan that mostly focuses on health effects. There could potentially be opportunities for PIER to collaborate with ARB on some topics. (See ftp://ftp.arb.gov/carbis/research/apr/plan/ltplan/Spla0701.dpf)
- ARB actively promotes the use of alternative fuel vehicles. (See www.arb.ca.gov/msprog/ccbg/ccbg.htm)
- For this fiscal year, ARB funded a study of nitrous oxide and ammonia emissions from vehicles due to catalytic converter aging. (See www.arb.ca.gov/research/apr/plan/fy01-02/plan.pdf)

California Integrated Waste Management Board and Cal/EPA

- The goals of CIWMB and Cal/EPA include improvement of air quality and reduction of greenhouse gases. See www.cowmb.ca/gov/ and www.calepa.gov/)

Current Status: Regional and National

Environmental Protection Agency

- The EPA has been engaged in a multi-year, multi-gas supply curve research process for several years. They have published supply curve studies for methane and high GWP gases, and both can be found at, www.epa.gov/globalwarming/publications/emissions/index.html.
- The EPA is currently working on a supply curve study for N_2O.

Lawrence Berkeley National Laboratory

- Lawrence Berkeley National Laboratory (LBNL) has conducted supply curve studies for energy efficiency and carbon dioxide emission for several industrial sectors, including cement, pulp and paper, steel, and chemical. LBNL expects to conduct additional studies on industries not yet addressed. See http://eetd.lbl.gov/ea/IEUA/IEUA.html.

National Renewable Energy Laboratory (NREL)

- NREL conducts a wide variety of research and demonstration projects related to renewable energy. A summary of their latest Five-Year Research Plan is available at www.nrel.gov/publications/newpubs.html.

Current Status: International

European Union

- The European Union has developed bottom-up analyses of GHG mitigation potential for virtually all sectors and gases. These studies are provided at http://europa.eu.int/comm/environment/enveco/climate_change/sectoral_objectives.htm.

Intergovernmental Panel on Climate Change

- The IPCC's latest document on mitigation, *Climate Change 2001: Mitigation*, www.ipcc.ch/ discusses mitigation and associated costs and ancillary benefits.