Managing Greenhouse Gas Emissions in California
The California Climate Change Center at UC Berkeley

Chapter 6:
End-use Energy Efficiency in a "Post-Carbon" California Economy: Policy Issues and Research Frontiers

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OUTLINE

1 Introduction

Promoting the development and diffusion of energy-efficient end-use technology in buildings has been a central focus of California energy and environmental policy since the 1970s.

Approaches such as energy performance standards for buildings, appliance efficiency standards, and utility demand-side management (DSM) were pioneered in California, and their deployment here has served as a model for other states, the federal government, and other nations. The cumulative effects of these policies are a key reason for California's achievement of aggregate energy intensities well below those of most other states and of the U. S. as whole. Recently implemented building and appliance standards and energy-efficiency targets for DSM and other publicly-funded programs are aimed at reaching even higher levels of efficiency in the state economy. The results of this legacy as well as the energy savings realized from these new policies and measures will be an important element in reaching the near-term greenhouse gas (GHG) abatement goals set by Governor Schwarzenegger in June of 2005. This effort is occurring through the infrastructure for both deployment and evaluation of energy efficiency programs that California has developed over the past several decades, which is arguably the most advanced in the world.

The current expansion of utility and public programs to promote energy-efficiency, as well as the institutional and analytical background for this effort, are extensively documented in reports, papers, and other outputs of the California Public Utilities Commission, the California Energy Commission, and other agencies and institutions[1], and their macroeconomic effects as estimated by the BEAR model are discussed in Chapter 2 of this report. In this chapter our focus is different: Fundamental policy and research issues that bear on how end-use energy efficiency policies and programs can contribute to reaching the Governor's long-term goal of reducing California's GHG emissions to 80% below 1990 levels by 2050.

Determining a feasible and affordable technical, economic, and political path to this mid-century goal is an analytical and policy challenge of possibly unprecedented scope and complexity; that California is along with other advanced economies confronting this challenge reflects growing recognition of the gravity of the climate change problem. Achieving this level of emissions reduction will imply that the California energy system and economy will either have essentially ended dependence on fossil fuels, or dramatically lowered consumption of these fuels in combination with large-scale carbon capture and sequestration. In either case, the state will have entered the "post-carbon" era. Making this transition will require a multi-pronged strategy, with end-use energy efficiency assured to play a central role. Given the magnitude of the task, however, we see the goal as moving beyond "business-as-usual" to not only stimulate new technical innovations in end use efficiency, but also to achieve much higher levels of penetration of the results of such innovation than have been managed heretofore, in California or elsewhere.

This is a problem not just of technology but also of understanding and influencing in new ways the decisions undertaken by California's households and firms in considering end-use energy efficiency. Technology does not adopt itself. The

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[1] See Footnote 4

technical knowledge base for energy efficiency that has developed over the past three decades is much greater than our understanding of the human elements that enter into efficiency adoption decisions, and the application of such knowledge to practical policy and program design. Moreover, our current tools for estimating aggregate efficiency potentials are not well-suited to even defining, much less fully analyzing, what such "potentials" might be on a half-century time scale. Both of these issues present policy-relevant research priorities.

We discuss these topics in this chapter. First, however, we examine at length several outstanding issues in the economics of energy efficiency that have been debated without resolution for several decades. Technology-oriented policies and programs to promote the diffusion of energy- efficient technology have a fairly checkered history in energy economics. Long-running debates over the economics of energy efficiency have had little effect on the development of California's efficiency infrastructure. In our view, however, addressing these issues is important both because of the need to develop broad consensus on the enlarged role for end-use efficiency in California that is emerging in response to climate change, and because California's move to "decarbonize" will ideally provide a model for other states and possibly nations.

The chapter is organized as follows. We begin with a sketch of the history of publicly-sponsored energy efficiency policies and programs in California, and then illustrate in aggregate terms what would be required for end-use efficiency to make a sizable contribution to the decarbonization of California. We then review several key background topics in the economics of energy efficiency: The rationale for public promotion of energy efficiency, the effectiveness of policies and programs designed to increase penetration of efficient technology, and the treatment of markets for energy efficiency in aggregate engineering-based studies and in economic simulation models. The final section of the chapter is a discussion of three research priorities: The nature of consumers' and firms' efficiency adoption decisions, economic modeling of the long-run evolution of energy efficiency, and applications of information technology to promoting efficiency adoption and improving energy management. The chapter ends with a summary and concluding remarks.

2 Energy Efficiency in California in Retrospect and Prospect

The contemporary technology-oriented paradigm for end-use efficiency analysis and regulatory policy has deep roots in California. Interdisciplinary research on energy and the environment – including the then newly-recognized potential of end-use energy efficiency - was underway by the early 1970s at the University of California at Berkeley and the Lawrence Berkeley National Laboratory, and the Warren-Alquist Act of 1974 established the California Energy Commission with authority, among its other functions, to develop and implement appliance and building energy-efficiency performance standards[2]. So-called "Title 24" building standards went into effect in 1977, and the first California appliance standards in 1979, with both types of standards having been regularly updated since. Also in the 1970s, utility demand-side management (DSM) – incentives, information provision, and other measures to

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[2] Rosenfeld (1999) gives a fascinating account of the history of energy-efficient technology and policies to support its diffusion.

directly encourage consumers and firms to adopt efficient technology – was first introduced. The electricity savings from these types of policies were equivalent to an estimated 3% of total statewide demand in 1980, 10% in 1990, and 14% in 2000 (CEC 2003).

The policy and funding environment for energy-efficiency programs underwent a transition following the decision in the mid-1990s to restructure the California electric power system, which envisioned among other things a much greater reliance on market outcomes. There has recently, however, been a dramatic re-commitment to publicly-sponsored energy efficiency and a substantial increase in allocated resources. New aggregate assessments of energy-efficiency potentials have been conducted and refined over the past four years, culminating in the adoption of updated building and appliance standards as well as significantly-expanded targets for energy savings through efficiency efforts by the state's investor-owned utilities. If met, these targets would result in a decline in per capita electricity consumption in California by an estimated 0.3-0.4% annually by 2013[3].

These targets are an appropriate departure point for thinking about the long-run challenge of achieving gains in end-use efficiency commensurate with the goal of reducing California CO2 emissions by 80%. First, as noted by Messenger (CEC 2003), "…sustained reductions in per capita electricity use over a ten-year period have never before been achieved in any industrialized country in modern times." Reaching this target will be a significant accomplishment. Nevertheless, statewide population is projected to increase over its 2000 level by 15% in 2010 and 30% in 2020[4], so that even if these targets and their possible extensions beyond 2013 are met, electricity (as well as natural gas) demand in California will continue to grow in absolute terms. While higher savings targets may be possible, reaching the outer boundary of current assessments – keeping actual electricity demand flat for an extended period - would not only require substantial increases in program effectiveness beyond the current state- of-the-art, but would also push well beyond the limit of what is estimated to be cost-effective with current technologies and energy prices. Actually reducing absolute demand over time cost- effectively is a goal that currently appears beyond reach.

With our present state-of-knowledge we must assume that, as with the nearer-term targets, a portfolio of strategies encompassing all sectors of the economy as well as both the demand and supply sides of the energy system will be needed to achieve emissions reductions of the magnitude envisioned by the Governor. There is no doubt that continued technological innovation on a variety of fronts will both increase the menu of available low-carbon and/or low- energy technologies and lower the costs of deploying them. It is even possible that dramatic technological breakthroughs of one form or another will enable the decarbonization of the California economy in a manner that entails minimal discontinuities in the energy and economic environment of the state's households and businesses. A well-diversified R&D portfolio can

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[3] Rufo and Coito (2002) conducted a statewide potential assessment that formed part of the basis for the analysis presented in California Energy Commission (2003), followed by further joint analysis by the California Energy Commission and the California Public Utilities Commission and the promulgation of the new targets; details are provided in California Public Utilities Commission (2004) and California Energy Commission (2005).

[4] California Department of Finance (2005).

increase the probability of both the first and the second outcome. But we cannot take for granted that technological breakthroughs alone will solve the problem.

To understand the magnitude of the task, it is important to note that in the context of GHG emissions mitigation, while intensities – such as energy or electricity per capita, per unit of industry output, or per dollar of Gross State Product – are important for several reasons, the ultimate metric must be absolute consumption levels, for emissions are in the aggregate approximately proportional to these levels mediated by technology on the demand or the supply side of the market, or both. Figures 1 and 2 illustrate this fact with forecasts of aggregate per capita and absolute electricity consumption in California to 2050 from the base year of 2000, using data of the U. S. Energy Information Administration and five alterative estimators. The preferred estimator – the so-called "Stein Rule" – forecasts essentially flat per capita consumption but a 70% increase in aggregate. In the most pessimistic forecast, holding per capita consumption to just over a 22% increase over the next forty-five years would result in more than a doubling of aggregate consumption; in the most optimistic, a decline in per capita consumption of 20% - slightly greater than would be achieved by reaching and maintaining the new 2013 targets for forty-five years - would be accompanied by an increase in total consumption of 40%.

We take two lessons from these estimates. First, the recently-adopted targets are a timely and invaluable step toward the long-run goal. Second, however, the magnitude of the challenge will require that we pursue every available avenue to further decoupling electricity use from population growth in California. One is to better understand the factors that inhibit the adoption of existing technologies, and how policies and programs can be designed to overcome them. Another is to develop methods to project how policies, markets, and other influences combine to determine efficiency potentials and their relations with energy-service demands in the long run. We turn to these research issues following the discussion in the following section.

3 Outstanding Issues in the Economics of Energy Efficiency

3.1 What is the Rationale for Efficiency-Promoting Policies and Programs?

The rationale for public policies and programs to promote end-use energy efficiency is the subject of a voluminous literature dating back more than three decades. In a following subsection, we will discuss the primary focus of this literature, which is based largely on evidence pertaining to patterns of efficiency investments with and without these types of interventions. Because our focus is on climate change and emissions abatement, however, we first address this question from the point of view of environmental policy.

Both energy and environmental concerns underlay the emergence of the technology-based efficiency paradigm in the 1970s. From the perspective of energy policy, efficiency gained currency in part because it was seen as a means of conservation – reducing fuel consumption in the face of limited or unreliable energy supplies. This rationale lost currency following the collapse of oil prices in the mid-1980s and the general decline of interest in energy as a paramount concern of public policy, although recent events may be leading to its recrudescence. The salient environmental benefits of end-use efficiency in that era were improved air quality from reducing emissions from fossil fuel-based electricity generation, and reduction or avoidance alltogether of risks associated with nuclear power generation.

The more recent emergence of global climate change as an environmental threat, and mitigation of carbon dioxide emissions from fossil fuel combustion as a policy response, however, provide a compelling justification to consider end-use efficiency policies anew from an environmental perspective and how this relates to the economics of efficiency. Despite the extreme scientific and policy complexity of climate change, it is from the standpoint of basic economic theory a fairly straightforward problem, at least in principle. As with many other environmental problems, unregulated levels of carbon dioxide emissions from the production and consumption of fossil fuel-based energy, and the resulting socio-economic harm they cause through climate change, result from a divergence between public interests and private incentives. In the standard terminology, they constitute an "externality" and a "public good," or more accurately "public bad:" The effects of individual energy decisions in the aggregate cause harm to others, and there is little or nothing that individuals per se can do to protect themselves from this harm[5]. The appropriate response is therefore to align the public interest with private incentives through the price system – that is, through emissions taxes, tradable emissions permit systems, or similar policies.

While generally proffered in considerably more complex form accompanied by results of numerical simulation models, this reasoning underlies most economic policy analysis of climate change and GHG mitigation. Moreover, it is fair to say that the desirability of such policies is widely, if not universally, accepted among analysts and other stakeholders of a variety of disciplines and perspectives. In relation to energy efficiency, however, this economic case has been applied to arguments for the undesirability of technology-oriented policies and measures such as standards and utility programs. Whatever the technical merits of such criticism, we would point out that emissions taxes or explicitly environmentally-based energy taxes have been and remain politically impossible to implement in the United States. While emissions trading has been applied to several other pollutants, and we may be moving toward applying this approach to GHGs, it has also historically met resistance for this purpose. *Policies such as efficiency standards, DSM, and other energy efficiency-promoting public programs and measures enjoy the singular distinction of having been, and remaining, feasible to implement.* From this standpoint, the appropriate comparison has not been between price-based and other policies to increase energy efficiency, but between these other policies and no policies at all. Theoretically, under the assumption that a pure price-based approach would be optimal, technology-oriented policies promoting energy efficiency can be considered as what is known as a "second-best" approach. This terminology refers to policies that have optimality properties under the condition that a policy that would be preferable in an unconstrained setting cannot be implemented[6]. In practical terms, this justification would continue to hold even with the introduction of emissions trading as contemplated in California, since the level of the emissions cap under such a regime and the resulting price of CO2 would be a function of many factors other than marginal environmental damages.

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[5] In the case of climate change, there is an intertemporal dimension, so it is more accurate to say that future generations are likely bear the damage from current decisions.

[6] These policies might also be "third-best," etc., but the point would remain the same.

3.2 Market Barriers and Market Failures: The Energy-Efficiency "Gap" Debate

While this justification for efficiency policies in terms of the joint considerations of environmental benefits related to reduced greenhouse gas emissions and practical limitations on the feasibility of direct economic policies is compelling, a different rationale has generally been posited and debated. That consumers and firms frequently do not undertake energy-efficiency investments that appear cost-effective on an estimated life-cycle cost basis was first recognized in the 1970s; specifically, the empirical pattern is of customers appearing to require returns to these investments that exceed – in some cases very substantially - market interest rates for borrowing or saving[7]. This phenomenon came to be known as the "energy-efficiency 'gap'." The first researchers to systematically examine this phenomenon introduced the term "market barriers" to refer to the factors that prevented these investments[8]. The list of posited barriers has changed somewhat over time[9] but has generally included such factors as risk and uncertainty, high initial costs for efficient technology, attitudes toward energy efficiency, "split incentives" (the so-called "landlord-tenant" problem), i.e., instances in rental markets in which the equipment purchaser and the fuel consumer are different parties, a lack of information on the part of customers regarding the benefits of efficiency or the characteristics of specific efficiency opportunities, transaction costs attendant to making efficiency investments, and others. These barriers are claimed to result in under-investment in efficiency that is systematic and sufficiently widespread and large enough to justify policies and measures to encourage such investment – such as utility demand-side management – as well as to ensure that both energy-using equipment and building structures meet minimum efficiency performance levels – through appliance efficiency standards and building codes and standards.

Skeptics have taken a decidedly different view. While there is acknowledgement of the evidence of apparent anomalies, it is also held that most of these barriers are in principle inadmissible as grounds for believing that unregulated markets yield systematic and large under-investments in energy efficiency. The appropriate criteria to apply – here and more generally – is instead that of market *failure*, the condition under which the allocations resulting from rational agents operating in decentralized markets are sub-optimal, which encompasses a much narrower range of factors that the usual market barriers[10]. In fact, many of these putative barriers are simply normal features of markets in practice, and therefore have no policy implications at all[11]. Accordingly, the justification for the common set of technology-oriented energy efficiency policies is weak at best. What seems to be evidence of underinvestment must therefore reflect measurement error, the omission of relevant costs, and other analytical failures, and most of this evidence should be explainable in terms of appropriate models of rational choice[12].

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[7] A well-known early example is Hausman (1979).

[8] This concept originated with Blumstein et al. (1980).

[9] For example, compare Blumstein et al. (op cit) with Carlsmith et al. (1990) and Golove and Eto (1996).

[10] This theme is discussed in Jaffe and Stavins (1994).

[11] See Sutherland (1991); a contrasting perspective is given by Sanstad and Howarth (1994b).

[12] A range of views on these various issues were presented in the October 1994 Special Issue of the journal *Energy Policy*, "Markets for Energy Efficiency," which represented something of a zenith of productive engagement on the efficiency gap debate (Huntington et al. 1994).

Attempts to rationalize empirical evidence of apparent underinvestment, however, have not been particularly successful. The predominant approach has been applying of models of investment under uncertainty. Sutherland (op cit), for example, argues that standard portfolio theory[13] demonstrates that reluctance to undertake efficiency investments merely reflects a rational response to the uncertainty associated with the potential payoffs to these investments through reduced energy costs. As Metcalf (1994) shows, however, the appropriate conclusion is precisely the opposite: Because of the empirical relationship between energy prices and the values of other assets, efficiency investments will tend to be a hedge against other risks, and therefore a rational investor should require a rate-of-return to these investments that is *lower* than market discount rates. A more sophisticated approach is the theory of "option value," which demonstrates that the option of delaying an investment coupled with certain assumptions about the form of uncertainty in the returns to the investment yield a rational investment criterion in the form of a "hurdle rate" that will exceed the investor's discount rate and therefore exceed the opportunity cost of capital[14]. This does appear to exactly characterize the energy efficiency gap, and the model has been applied to this problem (Hassett and Metcalf 1993; Metcalf 1994). As Sanstad et al. (1995) show, however, the numerical predictions that result fall very far short of accounting for the actual evidence: With the data applied in the literature, the predicted hurdle rates are much too low to account for the observed wedge between market interest rates and the required rates-of-return to efficiency that are revealed in the empirical evidence[15].

An important impetus for efforts of this type, and indeed for the efficiency gap debate in general, is an underlying ambiguity in the market barriers literature, and in the broader technology-oriented efficiency literature, on whether *public* or *private* costs and benefits are at stake in evaluating the under-adoption of efficiency and the justification and effectiveness of policies and programs to overcome it. There is no reason to dispute that by *social* criteria - specifically having to do with the environmental impacts of energy consumption through CO2 emissions among other pathways – consumers and firms would systematically under-invest in energy-efficient technology in the absence of policies of whatever form to encourage such investments. From this point-of-view (and from the "second-best" perspective that we noted above), the efficiency gap debate over the justification for policies and measures for promoting energy efficiency has been too narrow. An uncontroversial market failure is the fact that decentralized markets do not yield optimal results in the case of externalities or public "bads" such as environmental pollution. The important question about market barriers to energy efficiency is then their empirical significance

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[13] The Capital Asset Pricing Model.

[14] More precisely, while the standard criterion is to invest if the internal-rate-of-return exceeds the discount rate, in the option value model there is a 'wedge' (which differs from the risk premium in portfolio theory) between the discount rate and the rational hurdle rate (Dixit and Pindyck 1994).

[15] Another even more basic problem is that the option value model does not apply even in principle tocore examples that require explanation: Indiscretionary replacement of energy-using durables (i.e., that have ceased to function) or undertaking an efficiency investment to coincide, for example, with an exogenous maintenance schedule for machinery.

and how specific policies and programs can be tailored to overcome them in specific instances.

This ambiguity regarding private and social outcomes is partially a consequence of conflating the evidence from detailed ex post micro-level studies of actual efficiency purchases, on the one hand, with the results of ex ante aggregate engineering-based studies that estimate large-scale potentials for increased penetration of efficient technology at the sector or economy-wide level, on the other. These two kinds of analysis are very different, both methodologically and in their implications. For example, a common criticism of such potential studies is that they are simply ex ante estimates based on engineering methods and are therefore uninformative as to the actual economics of energy efficiency. In particular, findings of unrealized cost-effective energy savings of high magnitudes are interpreted as essentially claims that large numbers of people are systematically making non-trivial mistakes in evaluating the private costs and benefits of their investment decisions. This is the proverbial "$20 bill on the sidewalk" problem: If these investments are so worthwhile, why don't households and firms make them without the government's intervention?

Effectively grappling with this question requires a focus on the micro-level evidence rather than the aggregate estimates. This evidence arises from ex post analysis of either actual purchase decisions in the market or the results of specific programs insofar as they yield findings on customers' efficiency decisions. Moreover, to a significant degree the methodology employed is micro-economic (not "engineering"), particularly the application of qualitative or discrete choice micro-econometrics[16]. The many studies and commentaries – from various perspectives – on market barriers and failures are best interpreted in the context of this type of evidence. A number of the commonly-cited estimates are presented in Table 1; "implicit discount rate" is the rate at which subjects discount the returns to energy-efficiency investments inferred, in these studies, ex post from actual purchase decisions. (We discuss the aggregate estimates in a succeeding section.)

In recent years, particular emphasis in the market barriers literature has been given to the idea that transactions costs and information problems prevent households and firms from making cost-effective energy-efficiency investments[17]. This theme, however, has not always been fully developed. That finding, evaluating, and processing information on efficiency investments often entails transaction costs, for example, is obvious. So do many other kinds of economic activities, however, which are not subject to regulation. Again, the environmental consequences of under-adoption justify a public interest, but this does not, per se, answer the "$20 bill question." Regardless of the environmental justification for promoting efficiency, why aren't the potential private gains that are claimed for these investments sufficient to overcome the transaction costs?

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[16] Train (1985) reviews a range of micro-economic and other micro-scale evidence on individual or household-level efficiency purchase decisions. Aggregate national studies, prior to those focused on California mentioned above, included Carlsmith et al. (op cit.) and Interlaboratory Working Group (2000).

[17] The transaction cost argument is discussed in Howarth and Sanstad (1995) and Golove and Eto (op cit).

Table 1
Average Implicit Discount Rates in Energy-Efficiency Investments

Study	*End-use*	*Average rate*
Arthur D. Little (1984)	Thermal shell measures	32%
Cole and Fuller (national survey, 1980)	Thermal shell measures	26%
Goett (1978)	Space heating system and fuel type	36%
Berkovec, Hausman and Rust (1983)	Space heating system and fuel type	25%
Hausman (1979)	Room air conditioners	29%
Cole and Fuller (1980)	Refrigerators	61-108%
Gately (1980)	Refrigerators	45-300%
Meier and Whittier (1983)	Refrigerators	34-58%
Goett (1983)	Cooking and water heating fuel type	36%
Goett and McFadden (1982)	Water heating fuel type	67%

A partial answer is had in examining the costs and benefits of specific efficiency investments. While the efficiency gap debate has focused almost exclusively on rates-of-return to these investments and the high revealed hurdle rates applied by consumers, the actual magnitudes of savings may be quite modest – figuratively speaking, from the individual's perspective, what's on the sidewalk may not be a $20 bill but rather a penny or a nickel[18]. Thus, in the aggregate, the social consequences of under-investment in efficiency in the form of the environmental effects – on air quality, or from greenhouse gas emissions – are proportional to the sum of individual instances of non-adoption and may be large, while at the individual level the losses may be small, so that the presence of even moderate transactions costs can imply that non-adoption may be individually rational[19].

The basic information problem associated with energy efficiency arises from that fact information in general is a public good and is therefore expected to be undersupplied by competitive markets. It has been suggested that this is the one area of agreement in the debate over the efficiency gap, inasmuch as the "market barriers" and "market failures" doctrines coincide in this case (Huntington et al. 1994). As with transactions costs, however, there are certain subtleties. The public goods character of information justifies information provision, for example through utility programs and appliance efficiency labels, on an ongoing basis to reach a continually expanding customer base,

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[18] This phenomenon was noted by Rabl (1986), and is analyzed in Sanstad (1998).

[19] There is another, perhaps even more interesting, application of transactions cost economics to the energy efficiency problem that has been the subject of relatively little economic research, although it has been discussed from a different perspective in the energy efficiency literature. This theory as developed by Coase (1937) and others including Williamson (e.g., Williamson 1981) focuses primarily on the *institutional* consequences of pervasive but generally un-measured transaction costs, such as the existence of private firms. An important question along these lines is how policies such as emissions trading might change the internal organization of firms in order to respond effectively. This is illustrated anecdotally by the rise, and fall, of "energy management" units in companies from the 1970s through the late 1980s.

and to account for continually developing efficiency technologies and opportunities. But it is not obvious why this information problem would justify, for example, efficiency performance standards. The contemporary theory of information economics can be applied here. Aside from the public good issue, it may be that producers of technologies have better information on the energy-use and efficiency characteristics of their products than do the purchasers. This condition of *asymmetric information* could thus result in a form of the "lemons" problem, in which the market for these technologies contracts[20]. Under the usual assumptions that an efficient and an inefficient device provide equivalent energy services and otherwise differ only in their purchase prices and operating costs, one could then view energy efficiency as an aspect of equipment for which minimum energy performance standards would be a "quality" standard that could overcome asymmetric information and be welfare-enhancing (Leland 1979).

Information economics also suggests itself for interpreting the intriguing results of Anderson and Newell (2004), in a study of energy-efficiency audits for small and medium-sized manufacturing firms. They find that these firms tend to apply hurdle rates of 50-100% to efficiency investments, and note that this is consistent with what is known about private-sector criteria for a variety of investment categories, not exclusive to energy efficiency. As they also point out, this calls into question the estimation of cost-effective efficiency potential for such firms by applying much lower hurdle rates. However, given the ubiquity of hurdle rates of this magnitude, it also raises the question of how one should interpret economic assessments of energy policies in which the private sector is modeled in terms of representative firms facing economy-wide risk-free interest rates that are also of very low magnitude. Theories of asymmetric information and agency problems within firms may explain capital rationing to lower-level managers, the use of payback criteria, and other deviations from standard investment models that can result in apparently "myopic" investment behavior (Stein 2003). These and other concepts from the contemporary theory of the firm are applied to show how the "gap" might arise in private companies by DeCanio (1993, 1994a, 1994b, 1998).

3.3 Do These Policies and Programs Actually Reduce Energy Consumption?

In addition to critiques of the rationale for various technology-focused policies and programs to promote energy efficiency, there have been many questions raised about both the energy-savings results, and the costs and benefits, of these approaches, with perhaps most attention to utility DSM. A particularly cogent analysis is provided by Joskow and Marron (1992), who in a sample of residential, commercial, and industrial-sector DSM programs from around the U. S. found substantial problems with measurement of savings, incomplete accounting for costs, and failure to account for "free riders," among others. Conversely, however, Eto et al. (1996), in an evaluation of large commercial-sector programs that included full cost accounting and well-measured savings, found that these programs overall were both effective in reducing energy consumption, and cost-effective with respect to the contemporaneous avoided costs of electricity supply.

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[20] This is the now-classic idea of Akerlof (1970).

A reasonable inference from these and other examples is that the details matter – specific programs and the institutional environments within which they are conducted and evaluated vary widely in effectiveness and cost-effectiveness. California, however, constitutes something of a special and very defensible case in this context. Recognition of the performance, evaluation, and cost-effectiveness problems noted above led in the 1980s and early 1990s to the development and implementation in California of an infrastructure for measurement and evaluation of utility DSM and other publicly-funded efficiency programs, which is currently being updated and expanded. Ensuring accurate and reliable estimates of energy-savings directly attributable to individual programs is a core focus of the resulting regulatory framework, and the official guidelines for this purpose include explicit requirements regarding the treatment of free-ridership, the necessity of ex post measurement of savings and criteria for appropriate methods to obtain such measurements, and other elements. As a result, practically speaking, fairly high confidence is warranted in the effectiveness of California programs of this type. It is also worth noting that the presence of requirements for ex post measurement, in particular, obviates the problem of the so-called "rebound effect" in evaluating the effects of utility DSM in California. This term refers to the marginal increase in demand for energy services as the result of efficiency measures that lower the cost of these services. Because of these measurement requirements, while excluded potential rebound effects might contribute to a divergence between ex ante estimates and ex post measurements of energy savings, they will not bias the latter. (We return to the rebound effect in the following sub-section.)

In the case of appliance efficiency standards, while estimates of electricity savings of the California standards are available from state sources, more detailed work on their economic characteristics has focused on the federal standards. At an aggregate level, the National Research Council (2001) found that the federal refrigerator efficiency standards of 1990, 1993, and 2001, will have yielded by the end of 2005 an estimated $15B net benefit to consumers. One criticism of appliance standards has been that they simultaneously increase the costs of new units while causing an erosion of non-energy features that consumers value. These hypotheses were tested by Greening et al. (1997) using an hedonic pricing model estimated on national data on refrigerators before and after the introduction of federal standards in 1990. It was found that, on the contrary, with the introduction of the standards the historical pattern of declining quality-adjusted real prices continued without a reduction in non-energy amenities, and that consumers appeared to experience a welfare gain from the standards.

Finally, an analysis of the aggregate effects of energy efficiency in California from 1997 found a benefit in per capita income as well as a substantial reduction in air pollution from stationary sources and a reduced energy burden on low-income households (Bernstein et al. 2000). While recognizing the various complexities that attend measurements of the costs and benefits of any public policy or program, results such as these and the allocation of substantial resources to program evaluation and verification in California lend credence to the conclusion that efficiency policies and programs in the state have indeed both achieved significant savings and done so with favorable cost characteristics.

3.4 Aggregate Potential Estimates, and Energy Efficiency in Economic Simulation Modeling

We noted above the importance of distinguishing between micro-level ex post evidence on actual market outcomes and aggregate ex ante studies of energy efficiency potential. These potential studies could be said to have drawn a disproportionate amount of the criticism that has been directed at technology-oriented efficiency policy analysis. There are certain underlying and policy-relevant aspects of this methodology and the results it yields that tend to be overlooked, however, and which mitigate some of this criticism.

First, this kind of analysis has evolved considerably since its introduction several decades ago. One target of criticism, the over-estimation of efficiency potential by simply assuming instantaneous (and pre-mature) replacement of equipment has long since been overcome. The state-of-the-art, which is well-exemplified by recent California studies, embodies a careful distinction among this, so-called "technical" potential, and "economic" and "achievable" potentials, which take account of costs, stock-turnover patterns, program effectiveness, and other factors.

Second, there are misconceptions regarding the actual magnitudes of potential savings that these studies estimate. The most recent comprehensive national assessment of energy-efficiency potential in the U. S., for example, found that a range of technology-oriented policies and measures could cost-effectively reduce primary energy demand by four percent over a ten-year period (Interlaboratory Working Group 2000). All things considered, we do not regard this as implausible. Indeed, it is on the same order as a recent estimate of the aggregate national *historical* savings from these policies and measures (Gillingham et al. 2005).

Third, the extent to which the rebound effect, defined above, biases estimates of the gains from energy efficiency has received considerable attention in the literature, and it has been frequently argued that the failure to account for this effect is a fatal shortcoming in aggregate potential studies based on engineering methods. However, in a comprehensive survey of the *empirical* evidence, Greening et al. (2000) found that

> "…estimates of the rebound are very low to moderate…Even…upper bound estimates, though, indicate that most or all of any reductions in energy use or carbon emissions are not lost to changes in behavior. This leads us to the conclusion that the rebound is not high enough to mitigate the importance of energy efficiency as a way of reducing carbon emissions."

These large-scale studies are a form of policy forecasting and their strengths and limitations have sometimes been debated in the context of similarly aggregate numerical economic simulation modeling, including the "computable" or "applied general equilibrium" type[21][22].

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[21] A very thorough analysis in such a context is Energy Modeling Forum (1976).

[22] In this context, what we have referred to as the debate over the "energy-efficiency 'gap'" is also referred to by contrasting "top-down" and "bottom-up" perspectives on end-use energy efficiency, where "top-down" refers to economic simulation models, particular of the computable general equilibrium variety, and "bottom-up" to the technology or engineering perspective that we have been discussing.

We raise this subject here to highlight a distinction that has been obscured in the literature, between the basic issues of the energy-efficiency gap, and market barriers and failures, on the one hand, and the narrower question of the representation of markets for energy efficiency in these simulation models on the other. While obviously related, they are not equivalent. In particular, it appears to be widely thought that the reason that these numerical models typically do not yield simulated benefits from technology-oriented energy efficiency policies of the sort predicted by technology assessments is that they lack sufficient end-use technology detail. However, increasing end-use detail in standard economic equilibrium models is neither necessary nor sufficient for using such models to reach the canonical "bottom-up" conclusion that technology policies have benefits that exceed their costs. On the one hand, the underlying behavioral and equilibrium assumptions upon which almost all of these models are constructed include no mechanisms or features that result in competitive equilibria being sub-optimal in the manner of either market barriers or market failures pertaining to energy efficiency; thus, increasing end-use detail while maintaining these assumptions would essentially do no more than provide greater detail on why consumers' and firms' efficiency choices are "already optimal." Put differently, there is no efficiency gap to overcome. An important corollary is that in interpreting economic simulation modeling studies that refer to the putative shortcomings of energy-efficiency policies, it may not be apparent to non-specialists that the models are typically not *demonstrating* these shortcomings but rather *assuming* them, and then illustrating the numerical consequences. On the other hand, however, these equilibrium models can be used to estimate in reduced form the *aggregate* benefits of bottom-up policies if the detailed technological information is available from some other source. This is discussed in Berck (2000), and illustrated by the simulations with the BEAR model in this report.

4 Three Research Frontiers

4.1 Understanding Efficiency Adoption Decisions

Over the past decade or more, the debate over market barriers and market failures and other arguments over first principles, while helping to clarify the issues involved, have yielded rather limited output of theoretical and empirical research on the actual details of the energy-efficiency investment and adoption decisions of households and firms. Understanding these details is necessary if we are to design programs and other interventions that sharply increase the penetration of efficient end-use technology as a means of CO2 abatement.

The social and behavioral aspects of energy demand were in fact the focus of an extensive research effort in the 1970s and 1980s that saw social psychologists, anthropologists, and other social scientists engaged in understanding the determinants of energy demand, including efficiency adoption[23]. This enterprise generated a large knowledge base that remains relevant for program design but has yet to be fully brought to bear for this purpose. One important and robust finding, for example, was that behavioral differences among households can result in very large variations in energy consumption with identical or near-identical equipment. Moreover, research

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[23] Overviews of this research are provided in Stern (1985) and Lutzenhiser (1993).

on energy demand as well as evaluation of programs in practice established very early on that simply “informing” consumers of the characteristics and benefits of energy efficiency was not necessarily sufficient to motivate them to undertake efficiency investments.

Such results indicate the importance of fully integrating extra-technological factors into any effort to develop new types of programs or other interventions aimed at substantially increasing efficiency adoption rates. At the same time, this research was often framed, and conducted, in explicit contra-distinction to both the engineering and the economic paradigms for energy analysis[24]. Partly as a consequence, although there are noteworthy exceptions[25], there remains a very substantial gap in our knowledge of the actual economic decision rules that customers employ in making or foregoing energy-efficiency investments. In our view, understanding these decision rules, and applying this understanding to the design of specific efficiency-promoting programs, is a critical step to achieving much higher adoption rates. Without this kind of knowledge, existing programs are to some extent attempting to solve a problem that is not fully understood.

We begin by observing that, the contrasting views of market barriers and failures notwithstanding, both economic and technology-oriented energy-efficiency analysis have generally framed the canonical problem in classical investment terms: An initial investment in efficiency– either for a stand-alone device or in the form of a price premium – results in a future return in the form of lowered energy costs. One can then calculate internal rates-of-return (IRRs) in particular cases, and if a customer does not undertake the investment, conclude that she has a “hurdle rate” or “implicit discount rate,” as we defined in a previous section, that exceeds this IRR. A variation using discrete choice microeconometric models is estimation on purchase data to obtain coefficient estimates that can be combined to infer the rate at which a consumer implicitly discounts the return to efficiency investments.

The almost exclusive reliance on these methods for studying the micro-economics of efficiency investments has, however, resulted in an impasse. This framing tells us is that decision-makers are applying decision rules to the efficiency adoption problem that result in their behaving *as if* they were making life-cycle cost calculations, or maximizing utility, “using” high discount rates, but tells us nothing about the decision rules that they are actually applying. This methodology has resulted, for example, in claims that high implicit discount rates merely reveal consumers’ preferences, when on the contrary they are revealing in addition, and possibly to a greater extent, aspects of both the consumers’ information and also their *expertise*. Put differently, high implicit discount rates are evidence of an anomaly but this evidence, per se, does not provide any information about the sources or causes of this anomaly, and neither the standard engineering nor economic methods for energy analysis are suitable for investigating these underlying factors.

A methodological development that could break this impasse is the emergence in recent years of what is generally known as “behavioral economics,” which

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[24] Sanstad (1993) reviews several different approaches to studying consumer efficiency investments in work of the 1970s and 1980s.

[25] Kempton and Montgomery (1983) is a classic example.

incorporates findings of cognitive psychology and other research on the details of individual behavior to create models of decision making that relax the classical rationality assumptions of micro-economics[26]. Behavioral economics combines theoretical analysis with experimental and other evidence to order to understand the heuristics, decision rules, and other elements that enter into actual choice behavior[27]. It therefore in principle provides the precise methodology needed for moving beyond the reliance in energy studies on life-cycle cost and conventional utility maximization models. The concept of "bounded rationality" – the cognitive constraints on consumers actually solving the complex optimization problems posited in some applications of conventional micro-economics – is one key idea of behavioral economics[28].

We give two examples of potential applications, beginning with a behavioural approach to understanding energy efficiency decisions that arises in the literature on intertemporal choice. Identifying and understanding empirical deviations from classical discounted utility theory is one very active strand of behavioral economics that is prima facie of interest in understanding energy efficiency investments (Frederick et al. 2002). One topic of interest is hyperbolic (in contrast to exponential) discounting, which accounts for evidence that individual discount rates may decline over time. For example, Loewenstein and Prelec (1992) propose a model of intertemporal choice that embodies both a form of hyperbolic discounting and a value function that exhibits "loss aversion:" Gains and losses are evaluated from a reference point representing the status quo, and individuals are more sensitive to losses than to gains[29]. Loewenstein and Prelec point out that, because it incorporates the dependence of discounting on outcome magnitude, this model can account for the high implicit discount rates observed for energy efficiency and reconcile this with lower discount rates applied to savings and investment decisions, since the electricity costs per period associated with energy-using durables are small compared with most savings and investment decisions.

A second example is based on the observation that energy-efficiency investment opportunities are frequently, even characteristically, multidimensional in that they are embedded within a choice problem that contains elements beyond first cost and operating cost. Refrigerators, for example, have a variety of features, such as size, color, configuration, features such as ice-makers, and other characteristics that are valued by consumers, almost certainly more than their energy efficiency in the absence of very high electricity prices. Indeed, it was recognized long ago that the canonical "first-cost/operating cost" trade-off is in fact very difficult to detect in the refrigerator market (Rosenfeld 1999).

Incorporating a range of product characteristics of this type is a standard application of discrete choice analysis, which as noted in the previous section has seen extensive

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[26] These include, or course, cost minimization assumptions of the sort underlying most engineering analysis of the economics of energy efficiency.

[27] McFadden (1999) and Kahneman (2003) provide overviews.

[28] "Bounded rationality" has been suggested as a possible contributor to the "efficiency gap" (e.g., Sanstad and Howarth 1994a), but not theoretically developed or actually applied empirically.

[29] This idea is due to Tversky and Kahneman (1979), who introduced it in their "prospect theory" of decision-making under uncertainty.

application to the study of efficiency investments. In these applications, utility maximization is of the "compensatory" form: That is, an individual consumer considers simultaneously all relevant aspects of an energy-using device, evaluates all marginal contributions to utility of each aspect as well as any trade-offs among aspects, and chooses the device that maximizes utility.

This model makes two behavioral assumptions that are open to question. First, energy efficiency or operating cost variables enter such a model "objectively" in the sense that with appropriate data the value of this information from the manufacturer or from the energy label is assumed to enter utility directly. However, as we noted above, there is evidence demonstrating that consumers' understanding of energy information is itself quite imperfect – that is, the concept of "having information" about energy efficiency is not necessarily well-defined. Second, the multi-dimensional optimization posited by this model may be beyond the consumers' cognitive capacity, a form of bounded rationality.

A plausible alternative hypothesis is that when faced with a multi-dimensional choice problem of this kind consumers apply *non-compensatory* decision rules that make a complex decision more tractable. These decision rules or heuristics entail assessing product features in a sequential fashion, with different models positing different determinations of the order. An important example is Tversky's "elimination by aspects" model (Tversky 1972). Note that these are utility maximization models – it is not this behavioral assumption per se, but rather the form it takes, that is of interest here.

In purchasing a refrigerator, for example, a consumer might first narrow down her choice to all refrigerators of a certain size or of a certain cost, that is, eliminate all those of the wrong size or that are too expensive. Subsequently, she might look, within the set of remaining refrigerators, those of a certain brand or those having certain features. This process continues until a refrigerator is selected. Energy cost or efficiency might, or might not, appear in the list of criteria.

Applying such a model – to refrigerator purchases or other energy-efficiency decisions that have similar features – could allow several intriguing and policy-relevant questions to be explored. Would the application of such a decision rule, perhaps with additional conditions, result in consumers appearing to apply high hurdle rates to energy efficiency? How might the presence or absence of energy efficiency in the list of criteria, and its place in the order of elimination, be affected by electricity prices? How would the presence of consumers employing heuristics of this type affect the estimates of, for example, estimates of the elasticity of demand for energy efficiency as a function of price? And should this model prove to characterize a certain class of efficiency investments, how should programs by designed in order to account for it?

As discussed by McFadden (1981), elimination-by-aspects models lend themselves to econometric estimation, although this kind of analysis is thus far rare in general and non-existent in application to energy demand. The primary hurdle to empirically applying these and other behavioral models is the availability of micro-level data with sufficient detail on consumers, technologies, prices, and other inputs. This is a purely pragmatic problem – in general, the kind of data that would be needed as a starting point is essentially the same as was used in qualitative choice studies beginning the 1970s. Applications of this methodology to energy demand, however, have waned in recent year, so that suitable publicly-available data sets are not readily obtainable. While detailed energy-focused end-use surveys of both the residential and commercial sectors are conducted in California, they do not focus on the behavior of customers in the actual market for end-use technologies. The kind of analysis we are advocating here is more in the vein of market research that would ideally be conducted jointly with program design as well as product development[30].

4.2 The Long-run Evolution of Energy Efficiency

Our second research topic would apply not to directly promoting efficiency adoption but instead at a higher level, improving our capability to analyze and project long-run technological trends in energy efficiency as well as how they are influenced by policies and markets and how technology should be jointly analyzed with demand characteristics over multiple decades. For example, as we noted in the Introduction, in contemplating how energy efficiency can contribute to the mid-century CO2 emissions reduction goal we must begin by considering what might be meant by "potential" on a time scale this long. New methods are needed to properly frame this question and to enable us to project the long-run paths of energy-efficient technology, the characteristics of energy demand, and the possible role of policies in ensuring continued and ideally increased levels of technical innovation in end-use efficiency.

The methods generally used for forecasting aggregate (sector-level and above) efficiency potentials of the kind we discussed previously are essentially static in character. These methods draw on very detailed data on current technologies and other inputs such as housing stock turnovers, energy prices, and demographics, and project usually no more than a decade into the future how policies and measures can increase penetration of these known technologies. In part as a consequence, aggregate potential studies incorporate underlying technology dynamics only to a limited extent[31]. A hallmark of this approach is the previously-noted typology of "technical," "economic," and "achievable" potentials, which serves to embed engineering assessments of energy-efficiency within a framework that identifies the practical and cost-effectiveness limits of policies that aim to move aggregate efficiency levels closer to the technological frontier.

For much longer time scales, a different set of assumptions, and a different approach, is needed. First, at multiple-decade time horizons, the very detailed representation of specific end-use devices cannot be plausibly maintained. Moreover, even basic categories of energy services may change, so that a key underlying assumption of most technology-focused methods – that energy service categories are stable and invariant across end-use devices of varying efficiencies – may not hold. A salient

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[30] It is worth emphasizing that applying these ideas to efficiency adoption research should not be construed as simply "rationalizing" the kind of evidence presented in Table 1, although that may apply in certain cases. Implicit in our discussion of the refrigerator example is the observation that the way that efficiency choices themselves are modeled in empirical studies needs to be improved along with the behavioral models that are ascribed to consumers.

[31] The study of what are known as "emerging technologies," while aimed at identifying how parts of the technical frontier for efficiency can move outward, is usually engineering-based, focusing on specific end-uses, and can be characterized as "mid-range."

example of this problem is the rapid emergence of information technology as a significant electricity end-use category. Thus, projecting long-run energy-efficiency, both technology and policy, must be done both at a higher level of aggregation and with flexibility with regard to the underlying characteristics of energy demand[32][33].

For long-range analysis, moreover, the robustness of the typology of potentials (technical, economic, achievable) itself is an important question. One could conjecture, for example, that in a manner of speaking technical potential becomes achievable – or even the baseline condition - over sufficiently long time scales, in which case the conventional approach systematically underestimates efficiency potential in the long run. At the same time, projecting long-range efficiency potential must be based in large part on the potential for technological change to "push out" potentials along all three of the achievable, economic, and technical frontiers. The characteristics of the available technologies themselves, and therefore the "technical potential," will be endogenous in the sense that they will depend on market trends, policies, and other factors that do not directly enter short-run studies. For time scales on the order of fifty years, there is a very high likelihood that this effect will substantially outweigh in importance the static or short-term "gaps" that conventional potential studies are designed to quantify. "Efficiency potential" in the long-run will be a function not of currently known technologies but of technologies that both public and private R&D, and market forces, bring into existence.

A research path for developing economic models for analyzing energy-efficiency in the long run can build upon and extend several strands of previous work. A key underlying analytical tool for estimating aggregate efficiency potentials is the so-called "conservation supply curve" (CSC). This construction ranks energy-efficiency measures for a given end-use application in order of increasing estimated life-cycle cost, under assumptions regarding device lifetimes, electricity prices, discount rates, etc. By comparing the results with a prevailing electricity price, a CSC can be used to compare the costs of energy-efficiency with those of new generation (its original application).

Although CSCs are devised from essentially engineering principles, Stoft (1995) and Blumstein and Stoft (1995) present a treatment of the economics underlying them, showing how CSCs can be explicated in terms of standard production theory. This analysis partially incorporates market barriers to adoption[34]. Further research is needed to generalize beyond the example they discuss, in which the base case is efficient (that is, free of market barriers), and to further elaborate on the formal details that would allow for this characterization to be applied empirically.

The next step would be to incorporate dynamics, including long-run technological change, into such a framework. The importance of the sources of technical change in the long run makes end-use energy efficiency a natural application for theoretical and empirical advance in analysing endogenous or "induced" technical change (see, for

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[32] An important related issue, the limitations of technical energy-efficiency as an analytical and policy metric, is discussed in Moezzi and Diamond 2005.

[33] A new approach to end-use forecasting to an "intermediate" time horizon – 2030 – is described in Levine at al. (forthcoming).

[34] Although as Stoft notes, his framework does not demonstrate the existence of such barriers.

example, Popp and Sue Wing, in Chapter 7 of this report). While considerable attention has recently been devoted to the representation of these forms of technical change in general equilibrium models, this phenomenon is equally important for application to partial equilibrium and more narrowly-targeted sectoral forecasting models. An example of retrospective analysis along these lines is Newell et al (1999), who embed detailed end-use information in an econometric model to estimate the sources of efficiency improvement in room air conditioners and in water heaters in the two decades following 1973. Popp (2002) analyzes the influence of energy prices on energy (primarily supply) technologies, while Popp (2001) examines the relationship between technological innovation and energy consumption. Models for long-run projections of energy-efficiency will need to incorporate this kind of decomposition of the determinants of technological change at appropriate levels of aggregation, and combine this with techniques for scenario-based projecting of end-use demand and its other influences, including energy prices, demographic trends, and potential weather changes in California.

Finally, we note that technological endogeneity or inducement in the case of end-use energy efficiency raises the topic of an important market imperfection related to efficiency that has generally been omitted from the "efficiency gap" debate that we discussed above. As discussed by Sue Wing and Popp in Chapter 7, the economic theory underlying the analysis of technological change that results from the activities of profit-seeking agents – or "inventors" – is based in part on the observation that technical knowledge has the characteristics of a public good and is therefore undersupplied by competitive markets[35]. This logic applies to energy-efficient technologies, and therefore in the long run is a relevant market imperfection that may, indeed, be of greater significance that those that are usually associated with efficiency.

4.3 Information Technology and the Economics of Energy Consumption

Consumers' energy-decision environments encompass not just efficiency choice – both in considering thermal shell improvements and in purchases of durable goods, for example – but also the utilization of installed equipment. It has often been observed that residential consumers, in particular, have very imperfect information about both the physical and the economic aspects of their decisions including the allocation of their consumption and costs among different end-uses. Utility bills are both occasional (monthly) and contain only aggregate consumption and expenditure information. A popular analogy is that of shopping and paying for a basket of groceries without price tags on individual items or an itemized receipt.

The "feedback" literature over several decades has demonstrated that measures to increase and improve energy consumption information can reduce energy consumption (Darby 2000). That this kind of mechanism has not been more widely applied to energy conservation has been due in large part to cost and technical limitations. As in so many other parts of the economy, however, the advent of information technology is having profound effects. The past decade has seen the

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[35] This is the departure point for the "new growth theory" that originated in the work of Romer (1990); technically, he described this form of knowledge as "non-rival" and "partially excludable."

development of Internet-based and other electronic tools and corresponding hardware for energy management and control[36]. Considerable impetus for applying these technologies – particularly in California – has been their use for "demand response" – the shifting of electricity demand between peak and non-peak load times – and in conjunction with the introduction of various forms of dynamic electricity pricing.

The potential for such information technology to stimulate energy-efficiency adoption is also well-known and a focus of research and development in California. Equally important are certain economic research questions as well as policy implications that arise in this context. The generally constrained energy-information environment within which customers operate, and the technological potential for enhancing it, have not just consumption but also *valuation* implications. The hallmark of the economic theory of rational choice is that of indifference at the margin, and in the context of multiple goods or services the simultaneous evaluation of trade-offs along a number of dimensions. But the average consumer generally has nowhere near the information necessary to even approximately make these marginal or inter-input evaluations, including those that would be necessary to determine optimal responses to price changes, both in adjusting utilization and in investing in energy-efficiency.

Under these conditions, the issues we discussed above with respect to efficiency investments alone become even more complicated. Models of the joint, multi-dimensional energy utilization and equipment purchase decision rest on extremely aggressive assumptions regarding both the consumer's information set and her capacity to solve the very complicated optimization problem that results[37]. "Bounded rationality" and the use of heuristics are very plausible behavioural hypotheses, but there has been surprisingly little research along these lines. One notable exception is Friedman and Hausker (1987), who propose a model of bounded rationality in energy consumption that and the joint implications of this behavioral hypothesis and the presence of non-linear (block-tiered) pricing.

Understanding the nature of the decision rules that customers employ in dealing with their overall energy environment is an important extension of behavioral approach we discussed above, with applications not just to energy efficiency but also to dynamic pricing, tariff design, and the analysis of the demand and welfare effects of policies such as carbon dioxide emissions trading in the electric power sector. The latter is a particularly significant area for GHG abatement policy. A core policy concern surrounding electric sector emissions trading is the potential effect on prices faced by consumers. But consumers' reactions to any such price changes – as well as to those that occur within dynamic pricing regimes - are a function of the information and behavioral constraints we have just described. Better insight into consumers' energy-management decision processes, how these are influenced by the introduction of energy information systems and related technology, and how billing and tariff design can be shaped to take account of behavioral principles, could contribute imultaneously to energy-efficiency, demand response, and emissions abatement policy goals.

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[36] Motegi et al. 2003, for example, discuss several case studies of energy information systems in practice.

[37] The complexity of these choice models is demonstrated in Dubin and McFadden (1984) and Cowing and McFadden (1984).

5 Summary and Concluding Remarks

We began this chapter with estimates of aggregate trends and forecasts to 2050 to illustrate the challenge of meeting the Governor's mid-century greenhouse gas abatement target. We then turned to several issues pertaining to the underlying economic and policy rationale for technology policies and measures to promote energy efficiency. These policies have a prima facie environmental justification: They are a means of reducing CO2 emissions. Moreover, while the long-running debate over "market barriers" to energy efficiency remains inconclusive, certainly with in conjunction with the emissions reductions goal the micro-economic evidence for under-investment in efficiency and factors such as transactions costs and information problems in markets for energy efficiency are grounds for energy-efficiency policies. Next, we noted that, although the actual performance of efficiency policies in practice as been questioned, in the case of California these policies have been effective and have provided energy savings at reasonable cost. Finally, we responded to several common criticisms of the methods employed inlarge-scale potential studies of energy efficiency, and clarified certain aspects of the representation of markets for energy efficiency in numerical economic simulation models.

We then turned to three research topics that should be given priority as California undertakes theoretical and empirical analysis, policy and program design, and implementation aimed at increasing the adoption of efficiency technology and defining a long-term strategy for maximizing the contribution of end-use efficiency to CO2 abatement. The application of behavioral economics to the study of energy efficiency adoption, in combination with a wealth of existing social science research on energy, holds high promise of yielding policy-relevant breakthroughs in our understanding of the most basic economic aspects of households' and firms' efficiency decisions. Improved methods for long-run analysis of efficiency that incorporate such innovations as new theoretical and empirical techniques for analysing technological change will help us both correctly define the concept of long-run efficiency potential and identify the policy pathways that can help realize it. Finally, the application of information technology to energy management that is already underway is likely to be another powerful tool for increasing adoption rates, and at the same time opens certain possibilities for research on the economics of consumer energy choice that could help in other applications such as designing optimal information and pricing environments in the context of other potential CO2-reducing policies.

Achieving increases in the adoption and penetration of efficient end-use technology commensurate with the Governor's mid-century goal appears daunting. However, we may take some inspiration from history: This situation recalls the changes over the past thirty years in the relationship between aggregate energy consumption and Gross Domestic Product in the United States. Conventional wisdom circa 1970 foresaw continuing increases in national energy requirements along the post-war trajectory to that time, and viewed this as a necessary condition for robust economic growth. But the average annual rate-of-decline in the energy-to-GDP ratio accelerated from 0.5% in the period 1949 to 1973 to 2% from 1973 to 2000, and is projected by the U. S. Department of Energy to decline at a rate of 1.6% per annum between now and 2025. This "decoupling" of energy from GDP in the U. S. may be the most important development in the American energy-economy of the past three decades. This onceunthinkable shift had multiple sources, most important the oil shocks of the 1970s but also the emergence of modern environmental and energy policy during the same era, and the technological, economic, and policy innovations that resulted from these and other stimuli. While a path to effectively decoupling end-use energy consumption in buildings from population growth in California is similarly difficult to see now, we must hold in mind that the goal of developing a climate-friendly California economy may provide a self-imposed impetus that can yield a transition on the order of what was accomplished in the 1970s and 1980s.

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