CALIFORNIA
ENERGY COMMISSION

Energy Research and Development Division

FINAL PROJECT REPORT

From Past to Future of Home Energy

Applying History and a "What-If" Sandbox to Inform Energy Systems Transitions

Gavin Newsom, Governor

September 2020 | CEC-500-2020-067

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Contract Number: EPC-15-081

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ACKNOWLEDGEMENTS

The authors thank and acknowledge everyone who helped with this project, including:

Kathleen Ave, Sylvia Bender, Joshua Binus, Carl Blumstein, Martha Brook, Christina Brunsvole, Miguel Cerrutti, Kathryn Checkley, Troy Dorai, Pamela Doughman, Jae Edmonds, Nick Fugate, Cary Garcia, Peng Gong, Tom Gorin, Andrea Gough, Arnulf Grübler, Siva Gunda, Jeff Harris (NEEA), Jason Harville, You Hu, David Hungerford, Mike Jaske, Dan Kammen, Chris Kavalec, Michael Kenny, Alan Lee, Erik Lyon, John Mathias, Brian McCullough, Rachel McDonald, James McMahon, Shuba Raghavan, Alan Sanstad, Jordan Scavo, Margaret Sheridan, Abaratname Thamilseran, Mitch Tian, Edward Vine, Max Wei, Malachi Weng-Gutierrez, and Sonya Ziaja.

The authors also thank contract manager Susan Wilhelm for her exceptional guidance throughout this project. Mithra Moezzi would like to acknowledge Sy Goldstone, formerly of the California Energy Commission, for the great wisdom, support, and encouragement he gave for the research presented here and over many years leading up to it.

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

From Past to Future of Home Energy is the interim report for the Historical Insights for Technology Adoption Scenarios in California and Flexible Energy Demand Modeling for Residential Air Conditioning with Improved Behavioral Specificity project (Contract Number EPC-15-081) conducted by QQForward/Ghoulem Research. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

California has ambitious goals for a rapid energy transition to help slow climate change, while managing the effects of climate change itself. The goals call for an overhaul of energy supply and major changes to energy demand technologies that would transform how society uses energy, involving entire systems of people, technology, and practices. Planning for this scale and scope of change requires tools, frameworks, and knowledge different from those developed for energy efficiency.

This exploratory research project focuses on three contributions for planning this transition developed for the realm of household energy use. The first is SIMSAND, a user-oriented simulation tool (a "sandbox") for exploring future energy scenarios for California households, implemented for space cooling. SIMSAND uses agent-based modeling to represent energy use diversity and dynamic technical-environmental-behavioral interactions within households. Users can model various "What if" scenarios resolved by coordinating multiple data streams intersecting at the household level. SIMSAND was developed at a proof-of-concept level.

Second, the project highlights a need for shifting transition scenarios to better capture how technology and social changes unfold in the real world. Developing and exploring these scenarios would help planning and research go beyond "Could we do this?" to consider crucial "What if?," "Should we?," and "How to?" questions reflecting the scale of climate change challenges and ambitions.

Third, the project analyzes histories of household energy demand technologies, considering their implications for climate-focused technology policies. The analysis illustrates observed patterns in real-world technology change that contrast from idealized projections. These histories can help construct more realistic scenarios which in turn can be addressed by tools such as SIMSAND.

This combination of history, scenario development, and modeling capabilities allows energy transition planners to explore possible futures using a broader range of available evidence—a breadth needed given the scale and scope of climate change.

Keywords: energy systems, agent-based modeling, energy technology history, climate change planning, scenario development, energy forecasting, air conditioning

Please use the following citation for this report:

Moezzi, Mithra, Aaron Ingle, and Loren Lutzenhiser. 2020. *From Past to Future of Home Energy: Applying History and a What-If Sandbox to Inform Energy Systems Transitions.* California Energy Commission. Publication Number: CEC-500-2020-067.

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EXECUTIVE SUMMARY

Introduction

California is faced with a changing climate. Weather patterns are more variable, bringing hotter days and nights, noticeable shifts in the natural environment, and even major changes to expectations about energy provision such as the extended planned power shutoffs for fire safety experienced in 2019. These climate-related changes tax daily life for many Californians, and strain energy systems at all levels, from individual homes to regional levels and beyond.

On the policy front, the state is pursuing an ambitious and rapid transition toward a decarbonized energy system to reduce the rate of greenhouse gas emissions that contribute to global climate change and the localized effects of that change. This decarbonized energy system will involve extensive changes in energy sources and how energy is used. The changing climate and the policies implemented to address it will have major effects on California, including inside people's homes.

Planning and executing an energy transition of this scale and scope is new territory for any government. New types of information, processes, tools, and frameworks are required to improve, complement, or replace those that were developed for different problems and under earlier limits of experience and data. New data, new personnel, and advances in communication, knowledge, and computational power are available to create innovative approaches and solutions.

In response to these changes, California has been revising its energy planning arsenal. These revisions respond to differences between climate change goals and those from when energy efficiency was the primary focus. Absolute reductions in air pollution emissions are now the policy goal, versus approaches optimized for improving end use efficiency. Renewable energy sources have become more common and are slated to dominate electricity supply. Renewables provide an essential component of decarbonization, but lack the stability and flexibility benefits of fossil fuels. This change raises challenges for electricity reliability, as do risks to energy infrastructure posed by wildfire, drought, and extreme weather. These problems and any solutions reach deep into society. Energy transitions are social transitions at least as much as technical ones. The work required to plan accordingly is still in its early stages.

Project Purpose

This research project seeks paths for better representations, processes, and tools for considering "the real world," including the role of people, in the energy transition ahead. The project was motivated by recognizing that current transition planning focuses on technology innovation and deployment primarily within the narrow bounds of evaluating technology penetration. This framework fails to systematically consider how technology becomes integrated into society or the potential consequences of technology change beyond the direct emissions and energy use impacts expected.

There are major scientific and policy challenges to incorporating this broader, more realistic view. Energy use varies in amount and nature across users, time, and circumstances. Aggregated and averaged approaches, common in the past, miss this variation. Interactions and dependencies can be difficult to notice or quantify, so they may be treated as if they do not exist. Strategies to take this socio-technical “system” nature of energy use into consideration, along with the uncertainties it highlights, are not yet well developed. But building blocks for progress are in place.

This project, funded through an exploratory grant, contributes to the groundwork for progress on tools and knowledge for residential energy technology transitions. There are three main components of this research. The first is a proof-of-concept *simulation sandbox* for residential energy use that draws together multiple streams of quantitative empirical data, along with diverse projections of climate, demographics, and other aspects of the future world. Called SIMSAND (short for “simulation sandbox”), it is an agent-based simulation platform designed to help detailed speculation on the future of residential energy demand in a quick and flexible package that can be used by planners and researchers. SIMSAND’s ability to interact granular data at the household level presents an advance over more static and averaged modeling options, more closely reflecting the micro-dynamics that determine household energy use profiles and how they change. It allows users to examine the distributions of these effects, and to specify and test a broad range of scenarios, including those reflecting “What if?” questions about the future.

Beyond its quantitative output, SIMSAND is a conceptual structure around which modeling possibilities, demands, uncertainties, data use, and data coordination for transition planning can be discussed. It can focus on local geographies or the entire state (and everything in between). And it can examine results for groups such as disadvantaged communities, low-income households, or rural areas. SIMSAND was implemented for air conditioning but can be expanded to other energy uses. It can also be expanded to incorporate other energy system dimensions or refinements, such as indoor temperature estimates or coordination with electricity supply.

The second and third project components link with this modeling capability. One component focuses on recent histories of energy demand technologies in California homes, along with related energy efficiency history. These histories are hardly visible in contemporary energy policy debates. But they are important because they provide a markedly different picture of how technology change takes place than do smooth models of technology deployment. Experience and insights drawn from these histories can be applied to planning for future technologies, including for pursuing energy climate goals with a broader lens. For example, starting with an understanding of how central air conditioning became normal over a few decades, what range of possibilities are there for efficient, resilient cooling in a hotter future?

The final component addresses energy technology scenario development and interpretation. This is an increasingly visible topic in climate change planning in international forums. After outlining current activities in California energy demand technology planning, the analysis considers how expanded scenario development could take fuller advantage of historical experience (second component), and of detailed data on the structure and diversity of household energy demand (first component) to support a more robust climate technology planning process. The historical work provides a basis to imagine scenarios that more realistically capture patterns and possibilities observed in past technology transitions. SIMSAND or similar models, designed to represent these more realistic elements and patterns, can be used to resolve these scenarios.

The primary audiences for these products are planners, researchers, technology developers, and program implementers involved in energy transition planning, whether at state or local scales. SIMSAND was implemented for residential air conditioning because of air conditioning's importance to energy technology planning. At present, air conditioning plays a modest role—8 percent—in California's residential energy use. But it takes a critical role in demand and energy system reliability, accounting for half of the residential peak demand in the state. The hotter weather that comes with climate change will increase needs for cooling even in places that have historically used little air conditioning, exacerbating peak demand. But doing without cooling can harm health and well-being, especially for vulnerable populations. The modeling approach provided by SIMSAND, which allows assessment of various technology and other management options across the great variety of households in the state, can help weigh approaches to cooling California homes in terms of energy use, GHG emissions, burden on disadvantaged communities, and other factors.

Project Approach

The QQForward research team includes a sociologist, a systems modeler, and a statistician/social scientist, all with extensive experience in the field of buildings and energy. A main impetus for this work has been producing findings and methods useful for policy that carefully consider the real world, including the interactions between people, technology, and environment at micro- and meso-scales—as distinguished from more idealized, smoothed, and macro-scale worlds represented in most models and plans.

The research was conducted with the exploratory aspect of the funding in mind. This entailed conversations with researchers, policy staff, and other professionals working at the California Energy Commission, national laboratories, utilities, universities, and international research centers, along with demonstrations of SIMSAND to Energy Commission staff. The work also drew from review of current California planning projects and models in energy and climate change, various sources on histories of energy technology and energy efficiency, on scenario development, and on forecasting, and assessment of data sources for the exploratory modeling achieved by SIMSAND.

Project Results

The proof-of-concept implementation of SIMSAND for air conditioning, along with conversations with prospective users, affirmed that a flexible "What if" model for testing scenarios about residential energy technology futures is potentially useful in a variety of contexts. As noted above, SIMSAND provides a platform for interacting multiple elements of the energy system at granularity. The "What if" aspect allows consideration of how various unknowns affect program and technology results, allowing questions such as, "What if only a certain type of user adopts this technology?," "What if the technology works only half as well as expected?," "What if the hottest climate predictions are correct?," or "What if heat waves and other factors drive a widespread rush to add and use central air conditioning?"

SIMSAND outputs include simulated household-level electricity consumption, cost, burden, and access to air conditioning. Users can compare results across scenarios. In keeping with the granularity of the input data, the tool also allows the user to examine how simulation output values are distributed across households, such as how energy consumption and energy burden may shift in disadvantaged communities (as defined by CalEnviroScreen) under specific scenarios. Thus, SIMSAND can help in visualizing the mechanics and dynamics of transition, including opportunities for localized solutions and consideration of equity across different conditions.

SIMSAND is developed at a proof-of-concept level. Priority was given to developing a platform that enabled qualitative exploration of relationships, trends, and impacts, given the limited quality of data available for air conditioning response and the dated information available on the energy characteristics of homes and households. SIMSAND has an adaptable structure that can be adapted according to user interests, new emphases on particular interactions (e.g. such as supply and demand), and improved data as they emerge. The platform coordinates multiple different data streams and assumptions intersecting at the household level, including the technical characteristics of homes, demographics, weather, and usage patterns. It can thus serve as a data hub itself or be integrated with a larger hub coordinating and interacting these data. This aligns it with the Energy Commission's "energy data vision" for developing strategic application of high-resolution data on energy use and usage patterns as this data emerges.

SIMSAND implements several standard scenarios. The primary intent, however, is to accept scenarios specified by users responding to topical questions as they emerge. SIMSAND was tested with a series of "What if" scenario exploring an expanded use of electric heat pumps in California homes for heating, and the implications of these additional heat pumps for air conditioning energy use considering a variety of different metrics (such as cost burden to households and energy use effects) and for various household sub-groups (such as disadvantaged communities).

Along with a more empirically grounded understanding of the local and diverse expression of technology change, and new data that permit modeling it, a refreshed level of scenario development for energy transition is possible and valuable. New levels of scenario development can help move modeling from an orientation to prediction toward "What if?" questions that consider alternatives unfolding in different desirable or undesirable futures. This expansion dovetails with recent calls for a more comprehensive national framework for climate assessment. These adaptations have been ongoing. They are challenging, involving negotiating a legacy of energy efficiency tools and procedures, and revising these to reflect major differences in purposes, scopes, and scale of energy efficiency versus climate change policy problems.

These changes in scenario construction and modeling, which can better represent contingencies and variability, facilitate a new depth of intervention design, including comparing outcomes and surprises in a simulation environment before implementing in the field. Some of this is already done in existing efficiency processes and tools, but a lack of customized tools hampers this process, including the ability to explore "How to?" alternatives — applicable in statewide regulations and local program design, community initiatives, and climate change adaptation plans. Besides these "How to?" questions, this modeling and the discussions that surround it inform the "Should we?" questions about unintended consequences, distribution of benefits and harms, and micro-impacts of policies.

Technology/Knowledge Transfer

During this exploratory project, the research team held discussions with California Energy Commission staff and with other researchers and planners, guiding the research presented here. With the "What if" simulation sandbox SIMSAND demonstrated and other results published, the intent is that such conversations will continue. The overall utility of SIMSAND rests on how it and the concepts it incorporates are used and found useful. Similar models are being solicited by the European Commission in its Horizon 2020 funding initiative, signaling potential for broader engagement with these conceptual directions within the international climate change planning community.

The energy technology histories covered in this project provide insights that market-driven research has not addressed. Most generally these histories highlight the potential value of turning planning questions around from "How can lifestyles accommodate given technology goals?" and trying to get society to match, to instead asking "What sort of lifestyles can fit climate change policy goals and climate risks, and what technologies might fit these lifestyles?" To be useful, these histories must be visible, accessible, and interesting enough to spark insights that help correct for overly optimistic or overly narrow frameworks on technology change. This EPIC report goes part of the way in disseminating these histories.

Some stand-alone products are planned, including two journal papers, one on energy technology histories and their implications, and one on scenario development and the SIMSAND model. In addition, the authors' completed contribution to California's Fourth Climate Change Assessment also drew from the research conducted in this EPIC project. The final project briefing, held in November 2019, engaged CEC staff from three different divisions in discussions about opportunities for further developing the use and usability of the simulation sandbox concept and implementation. This would require the research team to remain in contact with potential CEC users through established forums (for example, Integrated Energy Policy Report proceedings and Energy Research & Development Ideas Exchange) toward identifying cases where SIMSAND could efficiently help address existing needs. SIMSAND could be used, for example, to facilitate data-driven analyses of the impact of various policies, or of other factors such as climate change or differential technology adoption rates, on residential demand. These results could also be used to examine how effects vary across households in terms of demographic, energy, and environmental characteristics. As a flexible modeling platform, SIMSAND would do this by enabling assimilation and use of several data streams that can be easily updated as new questions and information emerge.

Benefits to California

The project develops foundations to allow energy transition planners to improve their understanding of how energy technologies are integrated into society, with what results, and to recognize key contingencies. SIMSAND, now functioning at a proof-of-concept stage, can be adapted to the priorities of a variety of users and use cases. It can provide a quick, light, and flexible way to pursue "What if" questions about the future of residential energy technologies as these questions arise, and without waiting to commission new models. This modeling capability could be combined with advances in envisioning futures through new levels of scenario development. SIMSAND also coordinates and interacts diverse data streams used in state climate change and energy planning, extendable to upcoming data streams related to household energy use.

This simulation tool, together with the results of historical analyses and the scenario development assessment, bring empirical data and the multiple disciplinary perspectives together to better speak to questions that planners and researchers ask, or could ask, about the future of household energy use. The attention to heterogeneity in residential energy use helps California assess equity, environmental justice, and the effects of policies or events on people as well as to aggregate emissions and energy use. Together these directions support developing creative, effective pathways for a resilient and environmentally better energy future.

CHAPTER 1:
Negotiating the Energy Systems Transitions Ahead

California has ambitious goals for transforming the state's entire energy system to a configuration that better contributes to slowing climate change and coping with climate change impacts. This overall transition involves transitions in many components of the energy system, including decarbonizing the electricity supply by shifting to renewable and other zero-carbon energy sources, doubling energy efficiency savings through modifications to homes and buildings, and electrifying transportation. Alongside these planned changes, climate change itself changes the environment, including unprecedented patterns of hot weather, devastating wildfires, and rapid loss of previous habitats and species. These planned and unplanned changes will continue to have enormous effects on the people of California.

Focusing on the residential sector, this project explores three related approaches by which people, and the variable and diverse world they create and inhabit, can be better considered in planning future energy systems. These approaches contribute to moving beyond the narrower, less data-rich analytic processes developed in the energy efficiency policy era. Those analyses were keyed to the problems encountered in pursuing energy efficiency per se amidst the constraints of that era. In contrast, in climate change policy:

1. Reducing absolute levels of greenhouse gas (GHG) emissions and energy use are at issue, versus relative savings goals under energy efficiency;
2. Ambitions for the scale and pace of energy system changes are much bigger, so evolving interactions, nonenergy effects, and distributional implications of these changes must be explicitly considered;
3. Energy reliability challenges are greater, because of the planned substitution of renewables for fossil fuels, and the new level of environmental risks posed by climate change, such as extreme heat, wildfire, and threats to energy infrastructure.

These three pillars must be considered in conjunction with each other.

Adapting Existing Perspectives and Tools

Technology is usually considered the key to achieving climate policy goals and resolving associated energy problems. Technological policy solutions are designed and tested with models, and depend on what these models assume, see, and omit. Facing climate change, the analytical tools and processes used to develop technology-centered strategies must be adapted to the new scale of ambitions, the wider scope of changes involved, the uncertainties and types of surprises that may be encountered, changes in policy emphasis, and the wider range of empirical data now available. This requires attention to how technology change happens in the real world, including how society and technology interrelate.

Energy use does not occur as averages. That non-average nature is crucial to understanding how change occurs, and with what effects. Energy planning tools and frameworks usually are expressed in aggregate terms. This aggregation contrasts with the diversity of energy use across the 13 million households in the state, and with the dynamics that this diversity creates. Aggregation is appropriate for some purposes and is sometimes the best option given the available data, uncertainties, and questions at hand. But it is poorly suited for thinking about the "what if" and "how to" questions raised within the multidimensional, distributional, and supply-demand coordination challenges of the scale, depth, and time horizon faced in climate change planning.

Contrary to the expectation that deploying technologies in the real world yields the results predicted in planning phases, history shows that technologies are often adopted more unevenly and slowly than expected, and are sometimes rejected despite their assumed benefits. Their trajectories can unfold in unpredicted ways, with consequences and spillover effects that can counteract policy intent, exacerbate inequities, and create other problems. In the meantime, the technological landscape of homes and society change independently of energy policy for any number of reasons, with major effects on energy use. Insights and lessons from history of residential energy technologies can help unpack these forces to better illuminate risks, uncertainties, and the multiple layers of change. But these histories have scarcely been visible.

The authors have argued that aggregated, averaged, and modeled characterizations of household energy use have limited ability to resolve or anticipate changes in real energy use systems, or to speculate on what might happen, where, and to whom (Lutzenhiser et al., 2017). Now, with denser data, more information about covariance, relationships and distributions, faster processing speeds, longer experience, wider professional expertise available in the modern energy and climate policy domain, and increasing motivation to look at multiple dimensions of a problem (such as GHG emissions *and* demand *and* energy poverty; people *and* technology; health *and* energy), and at finer scales, more is possible. These changes in data possibilities make the diversity, risk, and uncertainties inherent in energy planning more explicit, while also providing a basis to create a more systems-oriented approach to planning.

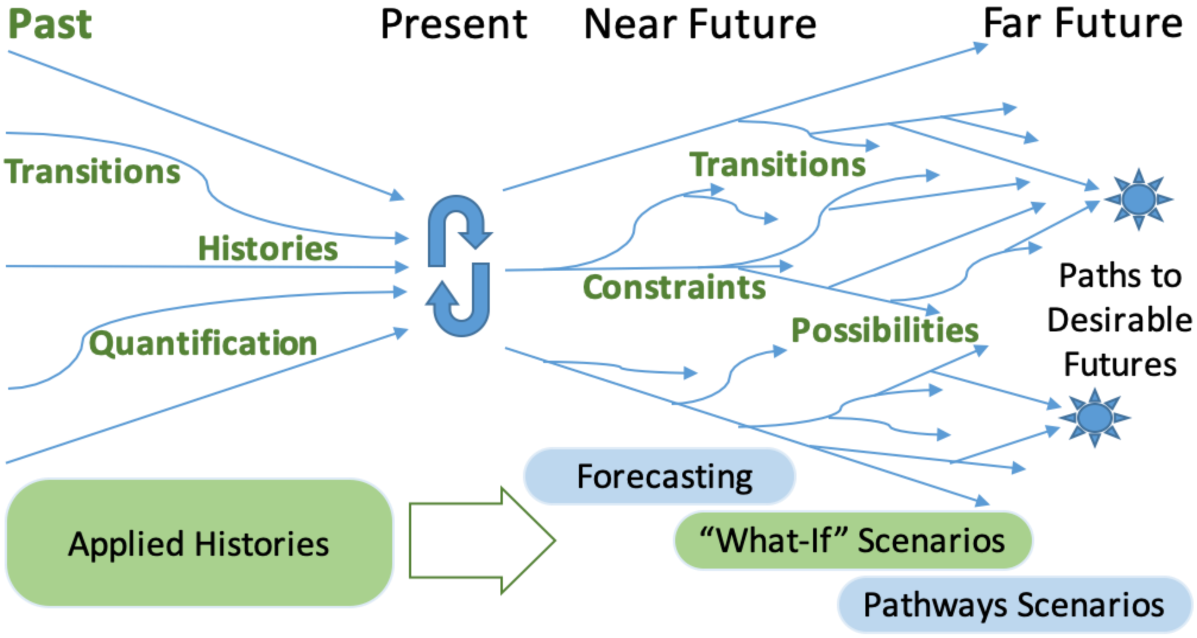
This project aims to contribute to the processes, tools, and analytical frameworks used for planning residential energy transitions under climate change in California. The study is exploratory, intended to prove out and adapt concepts and provide recommendations for further action. Figure 1 sketches the overall vision. Because air conditioning is one of the most important challenges in creating a resilient decarbonized energy system, the research pays special attention to the air conditioning end use.

Three overlapping activities were completed. Starting from the most concrete, these are:

1. SIMSAND: The project developed an agent-based "What If" simulation sandbox concept designed for exploring they dynamics of residential electricity consumption and its change across California households (Chapter 5). It then produced a flexible and expandable proof-of-concept implementation of this concept, limited to the air conditioning end use. SIMSAND incorporates more of the diversity of residential energy use than averages-based energy use models can. It can be used to explore "What if" questions for policy, technology, environmental, and societal scenarios based on a variety of potential storylines. The format allows users to coordinate a varied set of interactions (among weather, equipment, and variation in household cooling behaviors),

and coordinates multiple streams of data, including climate and demographic projections, and household-level technology and social data.

Figure 1: Positioning the Research in the Landscape of California Energy Futures



Source: QQForward, 2019 (created by Aaron Ingle).

2. Histories: The project analyzed recent histories of selected residential energy technologies and their incorporation into society, including how they related to energy efficiency policies. This work was based on published histories, limited primary source material, and available quantitative data. The analysis illustrates the co-evolution of technology and society, and the spillover effects of some planned technology changes. These real-world effects often differ from what was anticipated in planning stages. Chapter 2 provides a historical overview of recent residential energy technology change, along with case studies for several specific technologies. Chapter 3 summarizes lessons and implications from these histories.
3. Scenarios: The project examined current processes of energy scenario development (Chapter 4), differentiating various types and purposes of scenarios, and analyzing options for developing scenarios that better reflect how technology change has occurred in the past than has been possible with existing forecasting and planning tools that were developed for other purposes. Analysis was based on review of public documents on state energy planning, interviews of energy planning staff and researchers, and review of developing energy and climate change scenario and modeling processes outside of California. SIMSAND or a similar model could help assess these more complex scenarios.

Chapter 6 provides conclusions and recommendations for moving this work forward. The Appendix presents overall policy background and some aggregate energy patterns.

Scope and Boundaries

This research focuses on residential demand technologies, rather than on supply. It recognizes that energy supply and demand are entwined, and that residential demand depends on structures and processes outside of homes. It does not cover these processes in detail, nor the details of policymaking, which are out of scope for this exploratory study.

Chapter Summary

- The energy-related problems and goals associated with climate change differ from those that motivated energy efficiency policy, so tools, methods, and frameworks reflecting those differences are needed to provide effective strategies for addressing climate-related challenges.
- This exploratory research develops three foundations for energy transition planning under climate change, focusing on the residential sector: a "What if" simulation sandbox proof-of-concept designed to project energy futures taking the diversity of household energy use and users into account; histories of residential energy technology and energy efficiency; and new processes for developing scenarios tuned to the problems faced by climate change policy.

Sections by Main Interest

Please use the following guide to jump to the topics of most interest:

- Energy Technology History: Chapter 2, Chapter 3
- Scenario Development for New Policy Questions: Chapter 4, Chapter 6
- SIMSAND “What if” Simulation Sandbox: Chapter 5, Chapter 6
- Background and Recommendations: Chapter 1, Chapter 3, Chapter 6, Appendix

CHAPTER 2:
Home Energy Technology and Energy Efficiency Histories

Knowledge of the past can help planners, researchers, and implementers understand how future energy system change could occur. This chapter summarizes research on residential energy use and efficiency program history (From Past to Future Transitions) and then covers the history of selected home energy technologies and related efficiency efforts (Case Histories of Residential Energy Technologies), focusing on California over the past four decades. Chapter 3 summarizes insights from these histories that can be applied to planning the energy system transition targeted in the state's climate policy. Readers with specific interests can jump to the topics of most interest as linked above.

Most energy efficiency professionals know something about energy technology history as casual knowledge of their professional cultures. This familiarity is likely to be quite different from an understanding drawn from a social scientific analysis of the energy past. In fact, little detailed historical work on residential energy efficiency technologies or programs has even been published. But for climate change planning, longer-term technology changes and nonenergy effects of energy technologies are more relevant than they were in the efficiency policy era. And there are over 40 years of efficiency efforts to learn from. Some of these efforts are well-recorded in historical resources available through digital archives, making it possible to construct histories, and to examine how they differ from energy efficiency's normative models of energy demand technology change. The histories provided in this chapter are a beginning.

Some discussions below raise questions about how well energy efficiency has worked judged with respect to how past efficiency approaches apply to climate change policy goals. These are not an attack on efficiency, but a step to orienting existing efficiency and energy planning practices to better align with climate goals.

From Past to Future Transitions

Plans for an energy system transition of the scale that California is pursuing rest on assumptions of technological progress, dissemination, and performance that may not be achieved when expected, at the level projected, or even at all. There are major uncertainties as to in which cases any new technology will be installed (versus assumed "average" installations), how well it will work in place, and the effects of simultaneous and reactive changes in energy and social systems. There are also tensions related to how the performance of such technology might be judged. The implications of these sources of variability and uncertainty may not be strategically acknowledged, in part because the issues at play are not resolvable by dominant models. So models create particular blind spots when evaluating technology strategies. The historical examples below highlight example patterns and eventualities that are usually not reflected in technology planning models. Changes in how long-term energy scenarios are developed and modeled could help better account for these outcomes (Chapters 4 and 5).

Often, technology deployment scenarios start with imagining a technology that meets certain criteria along with conditions under which this target technology will be installed. A shortcoming to this mental model is that technology change almost always goes further than substituting one device for another (Bijker, Hughes, and Pinch 1987; Kranzberg, 1986). The energy system is a social system as much as a technical one. Users and technologies develop together in ways that were not expected. Attributes overlooked in planning stages become highly consequential. New technologies generate needs. Benefits originally anticipated may not transpire or they may be counteracted. And potentially effective technologies can be rejected due to cultural factors, competing technologies, or infrastructural incompatibilities. These cannot be perfectly predicted. But a narrow focus on *deploying* technology as if into an inert scene makes it difficult to anticipate, manage, and even acknowledge these effects. The historical view taken in this chapter offers a recasting of energy transition, *away* from a focus on achieving committed technology penetrations and *toward* imagining technology and society as intimately and dynamically linked, opening a much wider range of opportunity for change.

Piecing Together History of the Energy Efficiency Field

The energy efficiency field's approach to assessing technology change has been dominated by a focus on short-term changes seen under the specialized "looking glass" of energy programs (Lutzenhiser, 2014; Shove, 2017). This has suited the immediate demands of program planning and evaluation. But it ignores what happens outside these boundaries. For example, because programs often run only a few years, program evaluation has not provided a long-term perspective on the effects of technology change. Energy savings have usually been calculated based on simple assumptions of what would have happened otherwise. Even the focus on the calculability of energy efficiency benefits limits what can be achieved and seen, as examples below illustrate.

Historical reviews are uncommon in the energy efficiency field (Hazas, Friday, and Scott, 2011), making it difficult to recognize recurring patterns or to argue their validity. So, energy and climate change professionals have had limited choice for consulting critical histories of residential energy demand technologies. Energy historians (Hirsh, 2011; Hirsh and Jones, 2014) and other energy researchers (Gismondi, 2018; Hazas, Friday, and Scott, 2011)[1] argue that more deliberate attention to history could help energy policy professionals think more broadly about the future. This attention seems to be growing.

Some aspects of the history of energy have been well-explored outside of the efficiency field. Most attention has been to supply, for example by historians (Hughes, 1983; Nye, 1999; Scavo, 2015), anthropologists (Bakke, 2016), interdisciplinary scholars (Smil, 2016, 2018) and even comparative literature scholars (Pinkus, 2016). There has been less attention to the history of energy demand technologies, especially home energy technologies, including to how people react, adapt, accept, and reject the technologies offered, and to how policy and economy shape what technologies exist. There are important exceptions, where sociologists, geographers, and anthropologists have studied the micro-dynamics of residential energy technologies over history and how these matter for policy, for example, with respect to the

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[1] See also the open-access *Journal of Energy History* (http://www.energyhistory.eu/en) launched in 2018.

mechanisms by which energy demand escalates (Hitchings and Lee, 2008; Kuijer and Watson, 2017; Shove and Southerton, 2000; Wilhite, 2012).

Currently, the most visible energy history topic in the energy policy field focuses on the structure of energy transitions, as a subtopic of general work on technology transitions. Arguing that current energy systems are "unsustainable on all accounts of social, economic, and environmental criteria" (Grübler, 2012; see also Kemp, 1994) and with respect to climate change (Fouquet and Pearson, 2012; Shackley and Green, 2007), these scholars have taken on the question of how energy systems have changed in the past. Again most of this work has focused on energy supply (rather than demand), often taking a quantitative orientation (Loorbach, Frantzeskaki, and Avelino, 2017; Geels, 2002; Fouquet and Pearson, 2012; Grübler, 2012; Sovacool, 2016). Particularly visible is the "Multi-Level Perspective" (MLP) for framing how technology transitions take place in concert with changes in markets, users, and culture (Geels, 2010). The MLP framework emphasizes the path-dependency of socio-technical regimes, with investments and societal infrastructures co-evolving with technology, also making transitions slow (Fuenfschilling and Truffer, 2014; Geels, 2010; Kemp, 1994) relative to climate policy goals.

The transitions work has investigated more precisely how long technology change takes. The answers are necessarily muddy, since they depend on what, where, and how a transition is defined (Grübler et al. 2016). While transitions often take place over many decades or even centuries, some happen in a decade or two (Sovacool, 2016; Sovacool and Geels, 2016). For example, the presence of air conditioning in U.S. homes increased from 1 percent to 25 percent of homes in just 16 years, while in Brazil, flex-fuel vehicles represented 25 percent of vehicle sales after just one year (Sovacool, 2016). Rapid transition may be more likely in authoritarian countries or those willing to pursue strong intervention, and in small regions with consensual policy styles such as in Northern Europe (Sovacool and Geels, 2016).

Research on narratives of the energy future, including on *sociotechnical imaginaries* (Ballo, 2015; Smith and Tidwell, 2016) and on using science fiction as a tool for energy and climate change planning (Raven, 2017), offers concrete methods that help see energy transition as a multidimensional set of societal changes versus as substituting in a set of smart or efficient technologies. This approach could be applied to constructing scenarios in government-led technology planning (see Chapter 4).

High Level Histories of Residential Energy Efficiency

Industry and Program Histories

California has played a central role in developing an energy efficiency industry. Rather than energy efficiency being a static concept, over 45 years, the industry has adapted its approaches to changing scientific, social, technical, and political conditions. Table 1 summarizes changing conditions by decade, from 1960 to 2019, focusing on the residential sector. The motivating purpose argued for energy efficiency has shifted several times, from managing energy shortages in the 1970s to market mechanisms for efficient energy use in the 1990s to GHG emissions reductions since the early 2000s. Various energy-related legislation and events punctuate this history (second column from left in Table 1). Over this period, there have also been shifts in how people are viewed in energy policies and programs (fourth column, Table 1). The predominant view even today sees people as consumers who purchase technologies that use energy to satisfy needs, making straightforward decisions regarding costs and benefits, and who can be influenced by behavioral interventions.

In assessing its own history, the dominant players in the energy efficiency field have highlighted successes (Alliance to Save Energy, 2013; EIA, 2015; Nadel, Elliott, and Langer, 2015; Rosenfeld and Poskanzer, 2009). These successes are expressed in conventions based on the engineering foundation of efficiency and the decades of energy efficiency programs that evolved from this foundation. The examples in the next section illustrate how much success depends on measurement details.

Different Metrics Give Different Results

The United States Energy Information Administration (EIA) reports that energy efficiency offset 70 percent of the growth in residential sector energy consumption that would have occurred between 1980 and 2009 due to increases in home size and number of homes (EIA, 2015).[2] In *Big Love for Big Energy Efficient Homes*, RESNET[3] interprets this as meaning that bigger homes are not worse for the environment or GHG emissions than smaller, older ones (RESNET, 2015). That is, the increase in services has been greater than the increase in energy use, so the energy use results are interpreted as a success. This argument is not aligned with climate change goals since the calculations are indifferent to total energy use and emissions, let alone other energy and environmental costs of bigger homes.[4] With respect to goals for reductions in energy use, smaller efficient homes will use less energy than bigger efficient homes. And even smaller inefficient homes can use less energy than bigger efficient homes.

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[2] This EIA analysis tracks delivered energy, rather than source or primary energy. This means that losses from production, transmission, and delivery of electricity are not included in these calculations. In recent decades, delivered electricity in the United States amounts to only about one-third of primary (total) energy use, such as the ratio of source to site energy for grid-purchased electricity is estimated as 2.80 (35.7 percent of source energy is delivered as useful energy on site) in the ENERGY STAR® portfolio manager (ENERGY STAR. 2019. Portfolio Manager technical Reference. August. https://portfoliomanager.energystar.gov/pdf/reference/Source%20Energy.pdf). As supply resources and grid structure change, this proportion will also change. Since homes use natural gas and other fuels directly, in addition to electricity, and the contributions of these other fuels have varied over the years, the trend analysis that combines site electricity with natural gas (which has a source-site ratio of only 1.05, according to the aforementioned ENERGY STAR estimates) cannot be interpreted as changes in total residential energy use. In fact, while residential-delivered energy increased only 9.7 percent between 1980 and 2009 (EIA, 2015), total (primary) residential energy use, including losses, increased 34 percent over the same period (Residential Sector Energy Consumption Table 2.2). These two EIA sources use different accounting, so the examples are not completely comparable (for example, the table shows 14 percent increase between 1980 and 2009 versus 9.7 percent). Still the pattern of much higher increases in total energy use, versus delivered energy use, are maintained.

[3] RESNET®, which stands for Residential Energy Services Network, is a nonprofit organization that develops comparative home energy efficiency ratings in the U.S. The cited article (RESNET, 2015) may conflate energy intensity (energy use per square foot) with total energy consumption.

[4] Beyond arguments of the physical comparison of resource use between small and large homes, the RESNET argument reinforces an assumption that more is better, including that more services or space per household is better. The assumption, so engrained that it may be difficult to notice, can conflict with goals of lower resource use.

Table 1: California Energy Efficiency Historical Trends and Themes

Decade	Energy Events	General Themes and Residential Technologies	Dominant View of the Role of the Social
1960s	• Dramatic growth in electricity demand, load-building • Brownouts in late 60s due to supply shortages • OPEC formed 1960	• Atomic Energy Commission envisions 1,000 nuclear reactors in the United States by 2000 • Residential load building	• Continuous growth in demand indicates success of modern societies.
1970s	• Energy Commission formed 1974, focusing on reducing the demand for new power plants and anti-nuclear backlash • California appliance efficiency standards (Title 20) 1976; building code (Title 24, Part 6) 1978 • Energy Crises and Jimmy Carter speech • Three Mile Island radiation leak 1979	• Focus on resource limitations • “Energy conservation” including both behavioral and technological measures. • Attention to standards and codes aimed at increasing efficiency of major residential energy technology—refrigerators, HVAC equipment, and building envelopes	• Individuals should conserve energy through changed behavior.
1980s	• Chernobyl disaster 1986 • NAECA for minimum efficiency standards 1987	• Increasing rejection of conservation in lieu of efficiency • Waning funding for efficiency/conservation along with declining oil & gas prices	• Consumers of energy seen as rational economic actors; financial incentives put in place

Decade	Energy Events	General Themes and Residential Technologies	Dominant View of the Role of the Social
1990s	• ENERGY STAR program formed 1992 • EPAct adds standards 1992 • Idea of deregulating retail energy gains traction • Intermittent power shortages in California 1999	• Increasing attention to environmental damages (acid rain) • Rejection of energy conservation, reassertion of market via Market Transformation • Super Efficient Refrigerator Program: Golden Carrot refrigerator efficiency competition • Recognition of *miscellaneous* electricity use such as small appliance plug loads	• Emphasis on energy efficiency gap, overcoming market and nonmarket barriers and failures.
2000s	• California deregulation; electricity crisis (2000-2001); PG&E files Chapter 11 • First long-term energy efficiency strategy plan 2008 specifying Big Bold goals • San Bruno gas pipeline explosion 2008 • American Recovery and Reinvestment Act (ARRA) provides extensive funding of home efficiency retrofits, initiated 2009	• Rise of climate change mitigation as a centerpiece of policy • Increasing attention to renewable electricity. • Zero Net Energy buildings; rooftop PV; first Behavior, Energy, and Climate Change Conference (BECC) held in Sacramento	• Behavior change • Behavioral economics and nudges • Demand response

Decade	Energy Events	General Themes and Residential Technologies	Dominant View of the Role of the Social
2010s	• Extreme weather events become more common • Major planned power shutoffs throughout the state • GHG emissions reduction goals • San Onofre Nuclear Generating Station shut down 2013; 2018 decision to shut down Diablo Canyon • Aliso Canyon underground storage gas leak 2015 • Fukushima Daichi 2011. • PG&E files Chapter 11, 2019	• Focus strongly on climate change mitigation and energy system decarbonization • Logos feature green leaves, LEDs, and smart interconnections • Average residential retail price of electricity in California reaches 0.2USD/kWh (Feb.2019), 7th highest in the United States, and 25 percent higher than the 2010 price* • Electric vehicles become more common	• People should understand climate change and why it is important to act • Households become *prosumers* providing PV-based power and EV battery storage • Increase attention to civil society, the importance of local efforts and effects, and equity with respect to disadvantaged communities

***Electric Power Monthly Tables 5.6.A for March 2019 and December 2010.**

kWh=kilowatt-hours; HVAC=heating, ventilation, and air conditioning; LED=light-emitting diode

Source: QQForward, 2019.

This distinction is important enough to warrant looking at the EIA and RESNET arguments in more detail. Turning to data for California only, the change in primary residential energy use on a per capita basis (versus delivered energy, and versus the per-home metric used in the EIA and RESNET examples) shows a more modest decrease of 16 percent per capita over the same period, 1980 to 2009 (Appendix, Figure A-2). This decrease is still impressive, but it is much lower than the 70 percent offset used in the EIA example and tells a different story about how much emissions reductions are likely.

Another consideration is that of what year is used as baseline. Continuing with the example above, starting at an earlier baseline of 1960, there has been only a 5 percent reduction in per capita residential energy use between 1960 and 2009 (Appendix, Figure A-2).[5] This is more modest than the 16 percent seen between 1980 and 2009. Despite the reputed inefficiency of homes in 1960, the amount of energy used per person in homes then was only marginally more than it is today. Homes do more now than they did in 1960, and households have fewer people on average (so 1960 versus the present is not "apples to apples"), but they do not use much less energy.

These comparisons illustrate how different metrics and different starting points affect impressions about how energy use has changed. Efficiency has offset a great deal of energy use, as evaluated in conventional energy efficiency terms, but this has not been echoed in the level of absolute reductions in energy use. This leads to the question of how the perspective of *absolute energy use* could be better incorporated and metricized in planning energy transitions, versus energy efficiency's emphasis on relative savings. Without dismissing the value of energy efficiency in its own terms, that favorable assessments of energy efficiency's past are not as promising for meeting the ambitions of climate change goals and they might at first seem—if efficiency is pursued in the same ways that it has been in the past.

Meta-Evaluations of Efficiency in the Long Term

Energy efficiency policy uses a broad array of strategies to shape technology development and adoption. These include research and development investments, utility programs, building codes and standards, voluntary labels, economic incentives, tax credits, "nudges" and other behavioral economics tools, technical facts and other informational strategies, and marketing. This ensemble of planned energy efficiency efforts takes its place among the other forces of technology change, governance, and social evolution.

Given these multiple changes, assessing the results of energy efficiency programs has required defining strict boundaries and making major assumptions, including about counterfactuals ("What would have happened in the absence of the program?") to provide quantitative descriptions of program impact. The American energy efficiency field thus has a well-developed and specific way of assessing efficiency impacts, involving metrics, models, and concepts that can be internally validated. Performance assessment and program design proceed so results are reasonably evaluable within these requirements and traditions. This

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[5] The 2009 endpoint is used for comparison to the U.S. cited earlier. California's downward trend, however, has continued; per capita residential energy consumption in California in 2016 was 5 percent lower than it was in 1960. The comparisons do not imply that declines in California have been less than in the U.S., but rather concerns a comparison of metrics used in the EIA analysis versus the one presented here.

creates tractability, but limits the types of questions that can be pursued, especially for interactions between technology and society.[6] This has left doubts as to how well energy efficiency, as currently defined, is appropriate for producing aggregate GHG emissions reductions (Herring, 2006; Moezzi and Diamond, 2005; Lutzenhiser, 2014; Moezzi et al., 2018), even setting aside other challenges, such as energy systems fragility.

There are few academic long-term meta-evaluations on energy efficiency results in the United States. Conducting meta-evaluations of efficiency is difficult because the process involves fundamental incommensurability as well as challenges in coordinating results across studies with different levels of quality (Gillingham, Keys, and Palmer, 2018; Brown, 2014; also Mallburn and Eyre, 2014 for the U.K.). Still, the available studies highlight issues not addressed in normal efficiency program assessments. One national meta-evaluation concludes that in aggregate, energy efficiency programs are cost-effective, but that actual program savings are often lower than deemed savings (ex-ante estimates of savings), and that there are potential biases because evaluators want to keep clients (Gillingham, Keys, and Palmer, 2018). An evaluation of the national Weatherization Assistance Program finds that model-projected savings were about 2.5 times higher than actual savings (Fowlie, Greenstone, and Wolfram, 2015). These studies give pause as to "how we know what we think we know" about energy efficiency. Similarly, outside the United States, a study on house efficiency labelling across four European countries found that modeled energy consumption was far higher than actual energy consumption, leading to overestimates in savings from efficiency (Laurent et al., 2013).

The message of these historical examples is not that energy efficiency is inapplicable to climate change. Rather the specificity of efficiency calculations has to be weighed in planning for climate change, as do arguments by social scientists concerning how efficiency might sometimes work against energy use or GHG emissions reductions (argued below). Some argue that energy efficiency programs in California are under-evaluated, in the sense that more evaluation could improve outcomes for the ambitious goals that have been formulated in California (Campbell, 2016).

Energy History as Seen by Social Sciences

Social scientists view the home as a social, cultural, transactional, and even political space (Day Biehler and Simon 2011; Madsen 2018; Ellsworth-Krebs et al. 2015; Hirsch and Silverstone, 2003). This contrasts with energy efficiency's spartan model of the home as a physical and economic system that provides for fixed needs of occupants. This clash of perspectives accounts for some long-running difficulties in merging social science contributions with those of the more hardware-centered energy efficiency community.

Homes are also physical entities that reflect the construction practices, resources, traditions, and energy systems current when they were built along with local traditions of home upgrades and repairs. This embedded history makes any individual home far more suitable for some upgrades than others, which—besides localized traditions of upgrade and repair—can be at odds with standardized notions of efficient homes. In short, a legacy is locked into homes as

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[6] For example, in the case of residential building standards, home sizes, locations, and services change substantially over decades, and there is no simple way to standardize or control for these changes (Lutzenhiser et al., 2017).

physical objects and into local energy supply, part of an energy geography that effects what kind of residential energy futures can be had (Calvert, 2015; Darby, 2017).

Given the millions of homes in the state, one might at first imagine that there is lots of data about what goes on in them. But energy use in the home is mundane, private, and varied over time and across homes. This makes it difficult to study historically and difficult to express in the quantitative terms that dominate energy efficiency work. How does one know what people are doing and what difference it makes for energy use, especially given the limited data available to characterize this use? How can changes be seen given this uncertainty and diversity? Some sociologists have responded to this difficulty by focusing on *social practices* to see and understand changes in energy use (Gram-Hanssen, 2011; Shove, Pantzar, and Watson, 2012). Social practices are combinations of (a) material elements such as energy-using devices and homes; (b) competences in using these material elements; and (c) meanings enacted by people (Shove, 2014a)—for example, cooking and eating, educating children, and so on.[7] These practices happen in larger social networks and forms, institutions, and matrices of larger socio-technical arrangements. From here, questions such as "How do people stay cool, and why do they do it in those ways?" versus the more usual set of questions asked in energy efficiency: "How can we get people to buy a more efficient central air conditioner, and how can we get it to be operated efficiently"? can be pursued. The latter questions accommodate only a limited range of answers—chiefly information, regulation, incentives, and automation. The practices reframing is a clear pivot from the usual view of separate worlds of consumers and technologies.

The precise activities that are taken for granted as normal energy use in American homes are not many generations old. The first electric utility in the United States, Edison's Pearl Street Station in New York, began to serve customers in 1880. By 1920, 35 percent of American homes used electricity, with far higher penetrations in urban than in rural areas. In California, electrification rates were faster, at 87 percent by 1920. Only after World War II did natural gas became popular in American homes for heating and cooking (Morrison, 1992).

In the early decades of electrification, proponents emphasized electricity's potential to lighten the burden of women's labor in the home. The new electric technologies surely lightened physical effort. This did not liberate women from domestic chores, but changed the nature of this labor, including meeting (and helping create) higher expectations for what was to be provided (Cowan, 1983). The historic course of the last several decades has still been toward higher levels of energy services, including bigger homes, bigger appliances, more lighting, and more bathing per person (Shove, 2003; Harris et al., 2008; Roberts, 2008). Shove (2003) describes this as a matter of increasing standards of "comfort, cleanliness, and convenience." That is not a bad thing. But as illustrated below, standards of living can be set by the availability of technologies to fulfill them creating new "needs" that have energy implications (Cooper, 1998; Hackett and Lutzenhiser, 1985; Walker, Shove, and Brown, 2014).

The creation of these needs is outside the bounds of usual assessments of energy efficiency, which has focused on efficient fulfillment of needs that are taken as given (without having to

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[7] Readers interested in learning more about how social practice theory how applies to residential energy use may be interested in *Comfort, Cleanliness and Convenience: The Social Organization of Normality* (Shove, 2003), and *The Dynamics of Social Practice: Everyday Life and How it Changes* (Shove, Pantzar, and Watson, 2012).

engage with the fact that there are active interests in creating them). While tractable and pragmatic, it creates a complication for reducing absolute levels of energy use or GHG emissions as targeted in climate change goals. Computationally, "the more you use, the more you can save."

Though the array of energy services in U.S. households has increased on average, there is important diversity in these details from household to household (Lutzenhiser et al. 2017). For example, while compressor-based central air conditioning is often taken as normal in American homes, only slightly over half of California households have it; some use it 24/7 with low temperature settings, and some don't use it at all. How energy is used varies spatially for reasons beyond climate (Bridge, 2018): different histories, actors, resources, politics, infrastructure, urban morphologies, markets, practices, industries, home characteristics, technologies, and culture. Een neighboring homes of similar size, construction characteristics, and equipment can have energy use that differs by a factor of two or more (Morley and Hazas, 2011; Sonderegger, 1978). This means that averages-based assessments of energy use in homes can easily misunderstand the ways that energy is used and can be saved across the residential sector The SIMSAND model (Chapter 5) is designed to take this variety, and a distributional perspective overall, into account.

Case Histories of Residential Energy Technologies

This section summarizes histories of selected residential energy technologies, with an emphasis on the efficiency programs that promoted these technologies.

Lighting

Lighting has been a favorite target for residential energy programs in the United States. Lighting accounts for only about 6 percent of residential energy use nationwide (EIA RECS, 2009), but applies to all households and is cheap and easy to upgrade. Due to the many light fixtures per household, upgrades have been nearly constantly applicable to most residential customers (in contrast to the long lifetimes of major equipment and appliances). Lighting has long provided the highest share of residential efficiency savings in California and nationwide, achieved by swapping in CFLs for the incandescent bulbs that had been standard for generations (Barclay et al., 2018).

The first CFLs were demonstrated to the public in the late 1930s. At that time, electric utilities relied heavily on lighting to generate electricity sales, sometimes giving customers free high-wattage lamps to profit from the load these lights could provide (Bijker, 1997). Because of their low energy consumption, CFLs were a threat to these lighting electricity sales. Utilities downplayed the applicability of CFLs and directed attention to lighting technology that provided higher illumination without reducing power draw (Bijker, 1997). That is, part of the reason that CFLs were not pushed into the market earlier was because their energy efficiency contrasted with utility business models (see Bakke, 2016). Not until the energy crisis and environmental concerns of the 1970s did lighting manufacturers earnestly develop CFLs for household use, stimulated by government investments in lighting technology development (NRC, 2013).

CFLs were back on the consumer market by the mid-1980s (Matulka and Wood, 2013). At that time, CFLs were expected to be suitable only for certain applications rather than as a full replacement for incandescent lamps (Verderber and Rubinstein, 1984). They were sometimes described as a temporary technology that could serve until something better could be produced (Brodrick, 2007). Plus, they were expensive, costing $25–$35 per bulb in the 1980s (Brodrick, 2007). Eventually CFLs became common in the United States, and especially in California, but there were many adjustments along the way, and lingering doubts. Less than two decades after their relative heyday, the era of CFLs seems over. How did this happen, and what are the consequences for efficiency?

Initial conditions for CFL adoption were tough. In the 1980s and 1990s, most people were familiar with fluorescent lighting from its use in schools, office buildings, and retail stores, more as something institutional to be endured than to be liked. The standard incandescent light used in homes for decades worked well, apparently with hardly a concern. So it is not surprising that households that installed CFLs early on found much to dislike about them: initial expense, color rendition, low light output, flickering, delayed start, unfamiliar or "ugly" lamp shape, incompatibility with existing fixtures, inability to dim, non-suitability for use outdoors, occasional immediate failures, lifetimes that could be much shorter than promised, and mercury content that meant that special handling was required if the lamp accidentally broke and for proper disposal (Sandahl et al., 2006). A variety of health concerns including noise, triggering of migraines, and ultraviolet radiation (Welch, 2018) were reported; these did not find widespread scientific support, but remained a vocal consumer issue. There was also confusion about whether switching CFLs on and off substantially reduced lamp performance, creating an additional worry for those who had a habit of turning lights off when not in use. While some of these concerns may have seemed trivial from an energy efficiency program standpoint, they certainly annoyed people. Actions that symbolized "easy", screwing in a light bulb or flipping a switch, became more complicated and annoying. Lighting, the most basic energy use in the home, had changed.

Nomenclature added to the confusion about CFLs. In 1995, 42 percent of Americans could not distinguish an incandescent lamp from a CFL, let alone navigate different manufacturer names for CFLs (Brodrick, 2007). Retailers were reluctant to sell CFLs at first, too (Brodrick 2007; Sandahl et al., 2006). Of course, many CFL users did recognize benefits: saving energy, reducing pollution, longer lamp lifetimes with less frequent need to change a lamp, and energy bill savings. Statistically, however, actual savings from any single bulb would be hard to detect in most households.

In short, though CFLs were promoted as a great choice for consumers, American society was not keen. The lighting industry and energy efficiency programs eventually responded to user concerns about CFLs by developing improvements to technical performance, aesthetics, quality and market control, retailing, and consumer information. But also notable was the sense that industry proponents seemed to interpret consumer complaints about CFLs as ignorance or fussiness.

Plus, performance and savings estimates may have often been exaggerated (Brodrick, 2007) through optimistic accounting.[8] The energy efficiency industry, prioritizing aggregate estimated savings, and assuming that energy savings and promised environmental benefits were what consumers should want, seemed slow to acknowledge user experience and reaction as a reasonable and legitimate assessment of product experience.

The most effective way to get consumers to own CFLs turned out to be to give them away. By 1990, Southern California Edison, for example, had given 800,000 CFLs to its customers (Lovins, 1990). Many programs did something similar, such as buy-downs in the early 2000s that offered CFLs at highly discounted prices (Moran et al., 2008). Attention to getting CFLs into homes continued through early 2000s as a centerpiece of investor-owned utility residential energy efficiency programs (Barclay et al., 2018). But as higher California and federal standards for lighting came into place in the 2010s, and LED technology advanced, the program-based energy savings potential of CFLs diminished by comparison. Though lighting (driven by LEDs) even recently remained a dominant category of residential electricity savings in California utility programs (Navigant, 2017), the program world met these changes with trepidation: "It's almost the end of the world and we know it" some authors wrote (Barclay et al., 2018).A new phase of lighting standards is expected to truncate savings beginning in 2021 or 2022 (Barclay et al., 2016).

In summary, within the energy efficiency industry, CFLs have long been considered a success story. They were once the symbol of green energy and even environmentalism, appearing on logos for energy and environmental organizations everywhere in the 1990s and early 2000s. But there were many adaptations along the way, some of which likely seemed slow from a consumer point of view. CFLs were, according to one journalist, "the harsh, energy-saving bulbs that divided a nation" (Spector, 2016). While households in some countries, such as Japan and Poland (Sandahl et al., 2006) embraced CFLs, households in the United States did not. Despite all the program attention, CFLs did not become the American norm, probably not even when legislation made incandescent lamps difficult to purchase. In 2015, 19 percent of American homes had no CFLs, and only 31 percent said that most or all their lamps were CFLs (EIA RECS, 2015). In 2019, CFLs were no longer so easy to find. LEDs are more efficient than CFLs, and apparently much better liked by households, so this transition seems to be a good one. But households today have not necessarily forgotten these CFL difficulties, and lighting regulation remains a political flash point.

In retrospect, early assumptions about how consumers would view and accept CFLs now seem naïve. Lighting is the most basic energy use in most homes, and managing lighting is a social and cultural practice (Crosbie and Guy, 2008). Energy savings were promoted as the chief value of CFLs, but these savings may be invisible for most households. Overall, energy efficiency policy seemed to fail to appreciate the fundamental human importance of light in the home (Bladh, 2011). While CFL offerings improved over the few decades as noted above, no

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[8] For example, there is usually a very wide distribution of use among the 20-plus lamps in a typical home. One study analyzing metered lighting data for a sample of homes found that the lamps in the highest-consuming 10 percent of all lamps in the entire sample accounted for 50 percent of total lighting use (Jennings et al., 1996). A CFL installed in a seldom-used closet—as one might do if they disliked CFLs—would have much less savings than one installed in a high-use fixture. Using "average" number of hours to calculate savings would lead to overestimated savings.

cohesive strategy tracking user satisfaction or managing user discontent seems evident. In addition, the substantial problem of mercury was handled only through admonishments to users and regulations that CFLs should be properly recycled, but with poor infrastructure for doing so, and little reckoning of the chore that following these recommendations would be.[9]

Refrigerators

Refrigerators are the highest electricity use category in the California residential sector (17 percent) after the "miscellaneous and lighting" category (41 percent), according to the state's demand assessment.[10] Thirty percent of households have at least two (EIA RECS, 2015). This percentage has doubled since 1990, though freezers became somewhat less common over the same period (Figure 2).[11] As to their contributions to GHG emissions, besides energy consumption, refrigerators have used hydrofluorocarbons (HFCs) as refrigerants since the 1930s. These refrigerants have high global warming potential, and are subject to bans being phased in for new equipment in California (SB 1103).[12]

Like CFLs, refrigerators are often considered a major success story for energy efficiency (Levine et al., 1995; Rosenfeld, 1999). But there is broader way to see refrigeration's trajectory. The history sketched below focuses on aspects of refrigerators that are less familiar than program and market success, drawing from Deumling's 2004 investigation of refrigerator energy efficiency programs (Deumling, 2004).

Cold is the absence of heat, and producing it is technically more complicated than producing heat (Rees, 2013). People have been keeping food cool for preservation since at least 1700 B.C.E. using ice storage areas, water cooling, and ice production through radiation and evaporation (Jackson, 2016; Rees, 2013). There are other ways to preserve food, but none does as much as easily as refrigeration.

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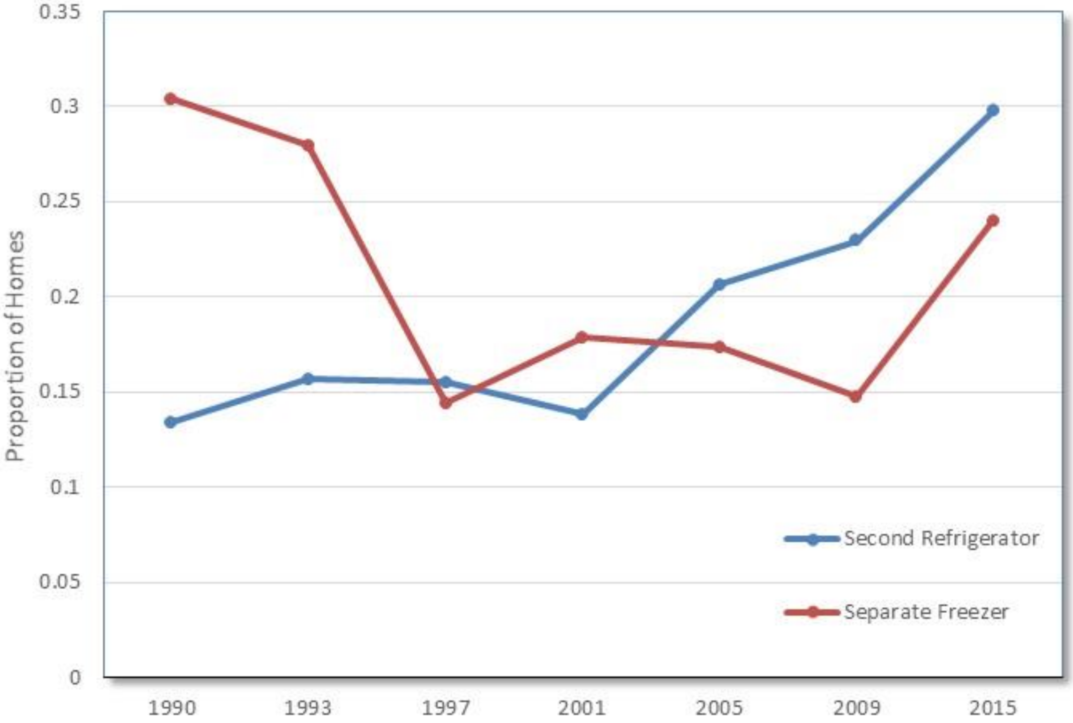
[9] The rate of CFL recycling has been tiny, at roughly 2 percent nationwide in 2011 (Consumer Reports News, 2011). This is an example of where technology problems—such as related to environmental impacts or consumer efforts—can be made exogenous to policy reckoning through treating them as out of bounds, or through specifying idealized solutions that may be difficult to implement.

[10] On a national basis, refrigerator's relative contribution to electricity use is much lower at 6 percent in 2018 (Annual Energy Outlook EIA 2019a), since many other states use more electricity for space and water heating than does California.

[11] However, trends need to be interpreted with caution, since some of the estimates in the figure are for the Western Census Region or the Pacific Census Division, as explained in the note for the figure below.

[12] See https://ww2.arb.ca.gov/resources/fact-sheets/hydrofluorocarbon-hfc-prohibitions-california for the details of the regulation; effective dates for residential refrigeration begin in 2021.

Figure 2: Trends in Estimated Presence of Second Refrigerators and Separate Freezers in California Households



Due to differences in available geographic refinement, some data points were estimated from the Western Census Region (1990 and 1993) and Census Division (2015) levels, versus the California-specific data for 1997, 2001, 2005, and 2009; trends are only approximate.

Source: QQForward, 2019, using EIA RECS data for 1990, 1993, 1997, 2001, 2005, 2009, and 2015.

But home refrigeration is less an independently-derived energy service need than a node in a much larger food system. This system includes a massive *cold chain* for preserving food through production, transportation, warehousing, and final consumption. The cold chain brought major changes in diet and in food preparation activities in the home starting in the 1920s (Rees, 2013), only a century ago. Even before mechanical refrigeration was common, the cold chain enabled a poor family in early 1900s Chicago to afford bananas, for example, which otherwise would be available only to wealthier households (Rees, 2013). The cold chain did not arrive on the scene without conflict. It was initially controversial, challenging notions of goodness, fairness, and justice in the economy, as part of a growing system of mechanisms displacing existing trade in perishables, threatening what these perishables represented culturally and socially, including their role within local economies and the power dynamics associated with food (Freidberg, 2015).

In the 1800s, homes used ice boxes or ice closets to keep food cold (Rees, 2013). Ice box technology was stable for decades. Gas absorption refrigerators entered the market in the mid-1910s (Cowan, 1985). Though electric refrigerators were mass produced in the 1920s, they were expensive, at $450 in 1923 (in 1923 dollars). They required servicing every few months, were prone to failure, and, unlike gas models, required a bulky compressor and a motor. They were thus big and heavy. Early electric refrigerators used refrigerants such as ammonia, sulfur dioxide, and other harsh or toxic elements. The synthesis of Freon in the

1920s led the way for smaller, cheaper, lighter, and safer refrigerators to enter the market in the 1930s.

This refrigerant innovation and related electric refrigerator improvements were the result of very well-funded development teams working at a variety of competing engineering companies in and outside the United States. The stakes were huge, given the enormous potential customer base for domestic refrigerators (Cowan, 1985). While gas refrigerators were quiet, less likely to break down, and cheaper to run, the high investment in developing electric refrigerator helped knock gas refrigerators out of the market (Cowan, 1985). Though gas refrigerators were almost entirely abandoned, they were not inherently an inferior technology.

The electric refrigerators in the 1940s had low energy consumption and small capacity.[13] As Deumling (2004) explains, after World War II, utilities directed attention to selling refrigerators that had higher energy use than the pre-war models. This benefitted refrigerator manufacturers by helping them sell bigger, fancier, and more expensive refrigerators, while utilities could sell more electricity as needed to power these bigger units. Refrigerators are especially good for load building because they have high load factors (average load divided by peak load in a time period) which help utilities optimize power plant optimization. Sales of these bigger refrigerators were accompanied by a rhetoric that associated higher energy use with higher well-being (Deumling, 2004).

The California Energy Commission (CEC) noticed, and addressed these increases in energy consumption. The CEC, created in 1975, issued minimum efficiency standards for refrigerators in 1976, effective in November 1977 (Rosenfeld, 1999).[14] Other states followed California's lead. The first national refrigerator efficiency standards were issued by U.S. Department of Energy in 1987 (Risser, 2011), and have been since updated four times; there were, of course, many other refrigerator efficiency programs. These programs and standards led to a steady decline in yearly average expected energy use of new refrigerators.

A widely reproduced graphic (Figure 3) illustrates the impact of the California and national standards, showing a sharp decline in the Unit Energy Consumption (UEC) of new refrigerators between 1974 and 1978. The decline continued past 2001 (Figure 4). Part of what made this radical decline possible is suggested by the pattern shown in Figure 3: refrigerator UEC rapidly increased between the late 1940s and the mid-1970s. In the 1960s, average refrigerator UEC increased from 800 kWh/year to 1,600 kWh/year, with volume increasing from 13.5 cubic feet to 18 cubic feet. This increase in refrigerator energy use parallels an increase in household

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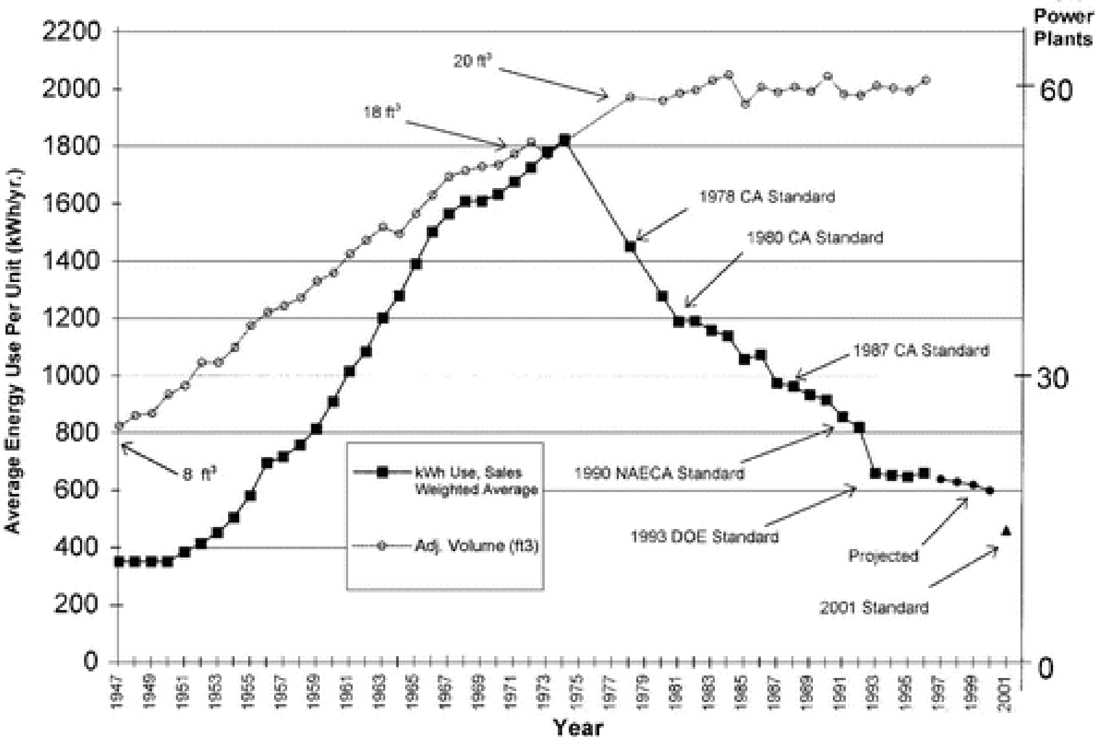
[13] Energy consumption for this model is estimated at 350 kWh/year based on modern refrigerator test procedures, with an average interior volume of 6.3 cubic feet (Deumling, 2004). The estimated energy use of an example 5.5-cubic-foot refrigerator qualifying for the ENERGY STAR label in 2019 is 221 kWh/year, at a price of about $1,800 (as per the Product Finder at energystar.gov). Most refrigerators sold now are much bigger. As of September 15, 2014, the federal minimum standard for a side-by-side refrigerator-freezer with automatic defrost and through-the-door ice service was set at 8.54*adjusted volume in ft^3 + 432.8 kWh (Electronic Code of Federal Regulations, Title 10, Part 430, Subpart C, section 430.32; type 7; ecfr.gov, accessed 19 September 2019). For a refrigerator with 20 cubic foot volume (the most common size for a primary refrigerator as per EIA RECS, 2015), the federal minimum standard is thus 603.6 kWh per year.

[14] The text of the regulation is available at https://ww2.energy.ca.gov/appliances/appl_regs_1976-1992/1976_11_03_Appl_Regs.pdf. Air conditioner standards were also enacted.

energy use overall (for California; see Appendix, Figure A-2). Refrigerator standards worked, presumably also heading off continued future UEC growth. Still, in 2015, the shipment weighted average energy consumption of refrigerators was just below 400 kWh/year, matching the 1940 level (Figure 4). The refrigerators of 2015 were bigger and had more features than 1940 refrigerators but did not use less energy.

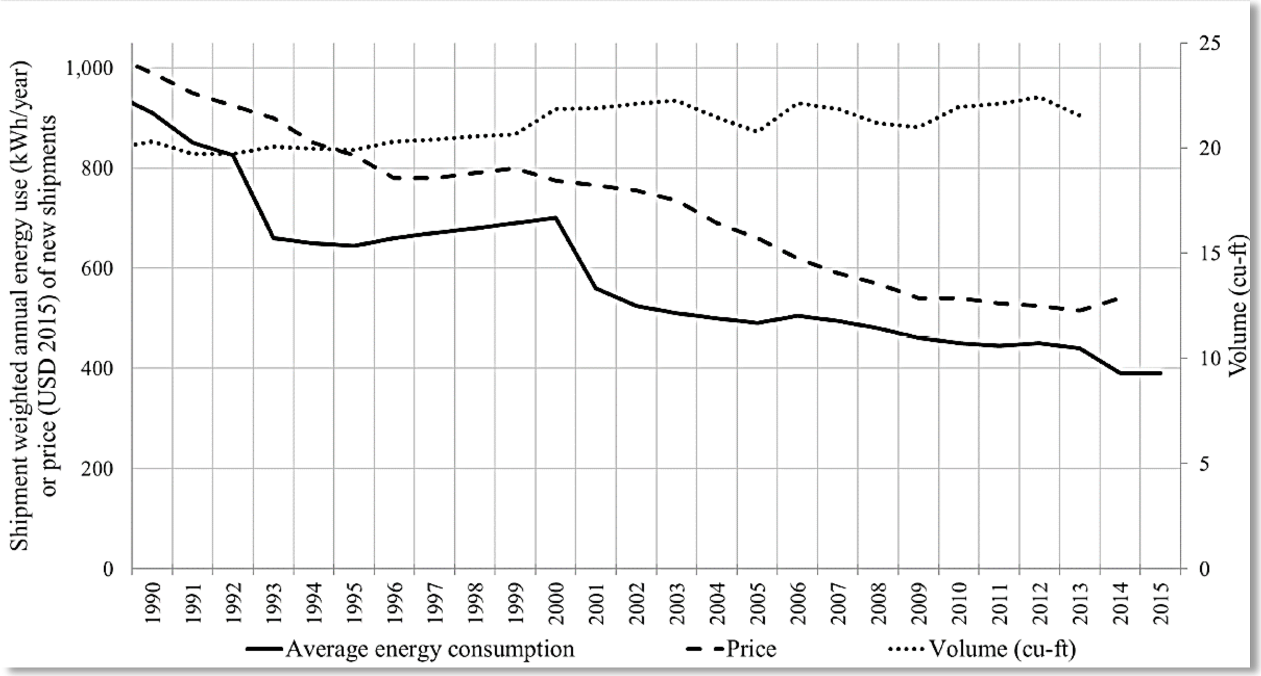
Refrigerator efficiency standards have increased energy efficiency according to efficiency metrics. Deumling (2004) argues that this efficiency increase has exploited only some ways to reduce energy use. While the results of efficiency are often expressed as "shutting down power plants" (Deumling, 2004), the goals of efficiency have been to save relatively. Growth in the size of refrigerators eroded energy and emissions reductions from increased technical efficiency. Some have hypothesized that energy efficiency itself could have contributed to the growth in size of refrigerators (see Rinkenen, Shove, and Torriti [2019]). American per capita refrigerator energy consumption clearly decreased with efficiency programs, but was twice as high as consumption in other developed countries (U.K., France, Italy, and Germany) in the period analyzed by Deumling, which ended in 1999 (Deumling, 2004).

Figure 3: Electricity Use in New United States Refrigerators, 1947–2001



Source: Rosenfeld (1999); reproduction of original graphic.

Figure 4: United States Refrigerator Shipment Weighted Average Energy Consumption, Price, and Volume of New Shipments, 1990—2015



Source: Leybourn and Fiffer (2018); reproduction of original graphic.

The question remains, what should or could be done to better align refrigerator efficiency with emissions reductions goals? One place to look is the food system overall. The food system accounted for about 16 percent of total United States energy consumption in 2007, of which 28 percent was for household food-related tasks (Wilhite, 2016). The availability of plentiful and easy cold storage in the home reinforces, and is reinforced by, what the food industry provides. This includes rules and processing traditions that dictate what goes in the refrigerator, such as fresh milk and eggs in the United States. In many other countries, long-life milk, which can be stored outside of the refrigerator until opened, dominates, and eggs (processed differently than in the United States) do not require refrigeration. Large refrigerators accommodate shopping in bulk at big-box warehouse stores and a style of food consumption, and perhaps food waste, that this mode of food acquisition invites.

The obvious routes to encouraging reduced refrigeration demands (versus energy use for refrigeration) in the home would face serious difficulties. Kitchens are designed to fit refrigerators of a specific size, so downsizing could be awkward. And even more importantly, social scientists have argued that refrigerators, like lights, are highly social devices, associated with domesticity in multiple ways, with taste, prestige (Hackett and Lutzenhiser, 1986; Rees, 2013; Jackson, 2016; Cowan, 1985) and through what foods they contain, even morality (Hackett and Lutzenhiser, 1986). These cultural, social properties of food and refrigeration have contributed to the willingness of some households to swap out their old refrigerators for more efficient if bigger, more featured, and more modern-looking ones.

Clothes Dryers

Clothes dryer energy consumption has been regulated by a series of federal standards (1988, 1994, 2015, and 2019). It has also been addressed by a voluntary ENERGY STAR specification since 2015.[15] In California, clothes dryers account for about 5 percent of total residential electricity consumption and 3.1 percent of residential gas consumption (CEC, 2015)—about 4 percent of residential energy use overall (see Appendix, Figure A-7).[16] The average clothes dryer UEC in California is 640 kWh/year for electric models and 24 therms/year for gas models (KEMA RASS, 2009). Gas dryers account for 60 percent of residential dryers in the state (KEMA RASS, 2009).

Dryers became popular in the United States later than other major home appliances, reaching 10 percent saturation only in 1955 (Morris, n.d.). Most (85 percent) California single-family homes had a clothes dryer in 2009. Individually owned clothes dryers are much less common in multifamily dwellings, where communal laundry facilities are often available. In many European countries and in some areas of Australia, in contrast, clothes dryers are not the norm. Rather, clothes are often air-dried or dried using heated drying racks or in drying rooms (Schmitz and Stamminger, 2014; de Vet, 2017; Cabeza, 2018). Schmitz and Stamminger's (2014) study on laundry practices in ten European countries found that between 3 percent (Czech Republic) and 52 percent (Sweden and U.K.) of households had a tumble clothes dryer. Even when a clothes dryer was available, it was not necessarily used throughout the year, or even at all (Schmitz and Stamminger, 2014). In California, in contrast, among homes with dryers, most (93 percent) say they use the dryer at least twice per week, and 10 percent say that they average at least one load per day (KEMA RASS, 2009).

During energy crises, the conservation option of air-drying clothes versus using a mechanical clothes dryer has been publicly debated (e.g., Hackett, 1990). This is an example of an old method of doing household chores vying for traction relative to a newer, more energy-intensive, one. The distinction is morally loaded. It also presents a complication with respect to energy savings measurement practices. In the United States energy efficiency framework, air-drying clothes is considered conservation rather than energy efficiency.[17] This makes it hard to propose as an energy savings method, except in supply crises when immediate demand savings are needed and actions considered exceptional can be proposed. Similarly, in electricity time-of-use rate pilots in the UK and Sweden, consumers were advised to change when they use their clothes dryer (Anderson 2016; Carlsson-Kanyama and Linden, 2007), versus to not use their clothes dryer at all. A skirting of conservation aligns with the

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[15] https://appliance-standards.org/product/clothes-dryers. Clothes dryers are a latecomer in the ENERGY STAR product labelling portfolio, having been omitted for many years, since there was little difference in energy consumption across several models (Golden et al., 2010).

[16] This comparison is based on the EIA's *national* end use calculations for residential energy consumption in 2015, which estimate that clothes dryers consume 5 percent of residential energy use versus 7 percent for refrigerators (https://www.eia.gov/consumption/residential/). Nationally, clothes dryer energy use approaches that of refrigerators, though they have received less attention in utility energy programs.

[17] Definitions of efficiency versus conservation vary over time and context. Most formally, energy efficiency reduces the energy required per unit of energy services, while conservation reduces energy use without reference to the level of energy services achieved. In this way, efficiency overlaps conservation. In the United States energy efficiency context, particularly in the 1990s—2000s, efficiency refers primarily to the technical quality of devices or systems, whereas conservation refers to behavioral measures that reduce energy use, usually by foregoing some quality or quantity of energy services. Especially in that period, efficiency advocates often dismissed conservation as carrying a negative image that confused consumer understanding of efficiency (Moezzi, 1998).

technologically-progressive image that the energy efficiency industry has worked to maintain since the 1990s.[18]

Not using a clothes dryer is a way of life (Hackett, 1990), while using the clothes dryer is normal in United States households (Gossard, 2004). Supply chain, know-how, and administrative issues reinforce the machine-drying norm, as do the debates on when line-drying is an appropriate way to save energy described just above. For example, a good setup for line drying outdoors includes many clothes pins and a pulley system, all of which can be found, but are not everyday items in many locales. Homeowner associations often ban outdoor clotheslines (Hughes, 2007; Howland, 2012), despite conservation-minded energy analysts challenging these restrictions even in the 1970s (Bainbridge, 1976). Savings from encouraging air-drying would be difficult to prove, while programs can easily count savings from deploying more efficient clothes dryers.

This sets up an historically- informed thought experiment that starts with the fact that how chores are accomplished are cultural, social, and part of one's identity (Hackett, 1990). Could air-drying clothes, for example, become a normal activity? Given California's ambitious plan for energy transition, might the non-device, practices-centered, version of efficiency that air-drying clothing represents help forge a different route to energy savings? Air-drying has a different aesthetic than machine drying, one that is more artful (Hackett, 1990) and more weather-connected (de Vet, 2016), though lacking some pleasures of a dryer (such as laundry done quickly, being less wrinkled, freshly warm). Still air-drying clothes represents a large potential for energy savings with little upfront investment. It could even develop as a natural, normal thing to do if synthetic fabrics become more popular.[19] But promoting it through energy programs would require major reorientation in how energy savings are sought, to overcome the politics of recommending conservation and the difficulties of accounting for savings, as well as to find ways to make shifting to air-drying attractive and practical.

Smart Homes

The energy efficiency field has often envisioned the residential energy future in terms of the type of home that will dominate that future, whether Smart, Zero Net Energy, or all-electric, for example. These have been hardware-based visions of homes that are conceived to fulfill specific policy goals. There has been little serious reflection of how people fit into these visions, even as debates on the technical definitions of these home types can continue for years.

The section below analyzes the Smart Home concept in its role for evolving thinking about future homes. It is not about the history of any coherent execution of Smart Homes

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[18] There are exceptions. In 2019, Energy Upgrade California prominently lists conservation and maintenance measures as ways to save energy (such as replacing HVAC filters, turning off the lights, and using fans and open windows to keep your home comfortable) in addition to efficiency recommendations; available at https://www.energyupgradeca.org/the-movement/. One of their 2019 spots, "It all adds up" features a dark home interior (also symbolizing a darkened viewing screen) and air-drying laundry inside the home (https://www.youtube.com/watch?v=nNWxRq0jQ8U).

[19] See https://www.theexpresswire.com/pressrelease/Synthetic-Fabrics-Market-2019-Analysis-Growth-by-Top-Companies-Trends-by-Types-and-Application-Forecast-Analysis-to-2024_10301286

themselves, which, even in the early 2000s, were described as nonexistent (Aldrich, 2003). What is "smart" is a moving target that is highly relevant to plans for the grid of the future, one consisting of distributed energy resources, new systems of supply, and higher engagement of people in the timing of energy use, even if many of these decisions are automated (Alstone et al., 2017).

History of the Smart Home Concept

The smart home concept dates at least to 1972 (Brush et al., 2018; Darby, 2018), and Smart Home as terminology dates at least to 1984 (Harper, 2003).[20] Harper (2003) describes a Smart Home as one with interactive technologies, while Brush et al. (2018) defines a Smart Home as one with "connected devices and software that can automate and control those devices." These are ambiguous definitions, befitting a concept and set of technologies that have changed over the decades.

The 1980s attention to Smart Homes was not about energy *per se*. Rather, the energy efficiency industry started engaging with the Smart Home concept in the 1990s, at first via early versions of smart appliances, arguing that smartness reduces waste relative to manual operation, and provides users with convenience as a bonus. The Smart Home concept evolved as the Smart Grid took shape, especially beginning in 2009 in California with the support of the American Recovery and Reinvestment Act.[21] Current energy policy interest in Smart Homes has much to do with their potential to provide automated demand response (King, 2018) such as through smart thermostats and direct load control (Alstone et al., 2017), as is presumed to be needed to help manage the grid variability instilled by high levels of renewable energy supply.

Smartness provides cachet that has been bundled with image of efficiency as high-quality, advanced, and elite. For example, the "world's first Internet refrigerator" was launched in 2010. It had a TV-enabled LCD screen with LAN port, scanner with inventory system to keep track of what was in the refrigerator, MP3 player, and temperature monitoring (Floarea and Sgâriciu, 2006). But it was expensive and a commercial failure. Its features, however, are similar to top-range smart refrigerators offered now, which are upgraded to more current connectivity such as music streaming, built-in cameras, and control of other smart devices.[22] This is an example of what social scientists have called "funwashing" (Darby, 2018) and "pleasance"—a mixture of pleasure and (potentially) convenience (Strengers and Nicholls, 2017). From an energy transition perspective, the most notable feature of recent smart refrigerators is their use of sensors and controls to reduce energy use through optimization, and to respond to signals to reduce demand for limited periods of time(Elliot, Molina, and

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[20] The concept of home automation is millennia old. The stable of new devices and appliances powered by electricity that entered even normal homes in the early 20th century was a major step in making home automation normal.

[21] See the CPUC's Smart Grid hub for details (https://www.cpuc.ca.gov/General.aspx?id=4693). Bakke (2016) also describes this shift in historical perspective.

[22] For example, Samsung's Family Hub refrigerators. Nor was it necessarily intended to be a commercial success or highly useful, versus a showpiece and experimental step toward an unknown future set of consumer desires. One product reviewer writes, for example, "the Internet-enabled fridge has been the butt of tradeshow bylines for years" (Kanellos, 2016).

Trombley, 2012). The refrigerator thus becomes part of the Smart Grid, with an emphasis on two-way communication between energy users and utilities.

These visions, which appear to be about technology, implicitly hinge on industry expectations about people. Yet in most Smart Home discussions, people have appeared primarily as idealized generic consumers, essentially instruments (and purchasers) of the technology. Energy efficiency advocacy assumes that households will or should want what Smart Homes provide, for example that smartness will give consumers "the opportunity to take part in demand response programs" (King and Perry, 2018), with the hopes that these consumers will cede control to an intelligent network bridging the home with the outside world.[23] But others are skeptical about the appeal and benefits of this smartness (Darby, 2018; Gram-Hanssen and Darby, 2018; Hazas and Strengers, 2019). The interoperability of home smart devices also poses challenges (Noura et al., 2018).

In the efficiency advocacy narrative of Smart Homes, people are assumed to benefit from the convenience and energy savings that smartness provides, technology providers benefit from access to user data and the ability to operate with higher systems efficiency, everybody benefits from assumed energy and emissions savings, grid stability, and perhaps certain populations benefit from other smart features (e.g., monitoring the welfare of less-abled people). The overall efficiency advocacy vision runs even deeper than this, for example, in using intelligent efficiency to densely link activities in the home to Information and Communication Technologies networks, and to find a higher level of efficiency by moving from device-level to a systems-level scale in managing electricity (Elliott, Molina, and Trombley, 2012).

Implications of Smart Home History for Future Planning

The efficiency industry has described smartness in homes in highly win-win language: "Smart homes use technologies like smart thermostats, appliances, and lighting to enhance residents' comfort and convenience in their homes… Not only do smart technologies offer comfort and convenience, but they also can save energy by automatically controlling the equipment in the home and using energy only where and when it is necessary. They can also collect real-time data on energy use and communicate with the electric grid, which can lead to more savings" (King, 2018: iv).

Home energy technology will continue to be developed to provide the envisioned automation, and with improvements over time (learning thermostats such as Ecobee or Nest). What is less clear is how much and in which cases these claimed benefits will ensue, how widespread the acceptance of these systems will be, how they contribute to or distract from energy transition goals, and what knock-on consequences they may have.

As to how Smart Homes have performed to date, this is a difficult question. Aside from what is implied in a handful of demonstration projects, the threshold for defining a Smart Home is unclear. Darby (2018, p. 143) concludes that "[t]here is a striking dearth of evidence on home energy consumption pre- and post-smarting." Also, for the purposes of managing the Smart Grid and distributed energy resources, overall changes in energy use are not necessarily a

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[23] Darby (2018) categorizes smart home discourses by the level of engagement with human users, with one narrative strand technology-only, and the other focused on users.

critical metric, even if the rationale for these systems is partly based on their promises for integrating renewables.

While Smart Homes have the potential to be effective in meeting energy transition goals, the high expectations for how they will perform in the real world are necessarily unproven. The discussion above illustrates some of the questions about interactions between technology and society that will help determine the level of success. For successful technology planning, this suggests the need for a multi-disciplinary step back to critically review assumptions about what smartness will do considering the history of automation, and the history of smart initiatives and experiments to date. For example, one of the shortcomings of early programmable thermostat initiatives was that estimates of savings potential assumed that people did not set back their thermostats at all. That assumption was wrong in many cases (Nevius and Pigg, 2000; Malinick et al., 2012; Lutzenhiser et al., 2017) and led to savings overestimates.

In short, rather than focusing exclusively on constructing ideal technologies imagined from an engineering point of view, the historical view adopted above underscores the need to look deeply and empirically at the "what, why, who, and what else" aspects of shaping and deploying these smart technologies. As a companion to the Smart and other technology-led visions of the future of homes, it is useful to ask what a future home should look like more generally. What are the consequences of investing strongly in a paradigm where the home is a densely connected node in the Internet of Things? How does this paradigm balance with goals for resilient systems and society? What alternative visions of modern homes might be pursued? The "Smart" vision imagines homes as precisely designed through detailed models and automated for energy efficiency, serving as an active node in a network of distributed energy resources. Another vision could be less about efficiency optimization and network connections, and instead foreground a more manually adaptive paradigm for inhabiting a home.

Continuing Histories

Current patterns and practices of energy use are not inevitable outcomes of technological progress, but results of a historical unfolding of technology and the society that accompanies it. The histories of residential energy technologies and energy efficiency included above are a taste of what could easily be a bigger investigation. One benefit of these histories is that they illustrate the effects, surprises, and problems of technology change in a broader framework (total energy consumption, dynamic system interactions, and longer time periods) than has been the norm in energy efficiency. They show, for example, how technologies themselves change both "needs" and energy use in ways that are invisible within the normal boundaries of efficiency evaluation. They also point to alternative approaches to reducing energy use GHG emissions through influencing *systems* of energy use (keeping cool, acquiring food, or even defining comfort) versus swapping in what are assumed to be more efficient technologies. Examples are explored in the next chapter.

Chapter Summary

- There are many decades of experience with past energy technology change and with energy efficiency's role in these changes, but analytical histories detailing the critical lessons learned from this experience are largely unavailable within the energy efficiency industry. A critical examination of residential energy technology history thus offers a currently missing perspective by highlighting practical experience that can be applied to energy transition planning.

- The insights from this analysis can be used to reorient energy efficiency practices to forms more aligned with the challenges of climate change and that take fuller advantage of the contemporary data, communication, and professional environment of climate change work, including the multi-disciplinarity these networks invite.

CHAPTER 3:
Applying Energy Technology History

Histories of residential energy technologies and the energy efficiency approaches related to them create a resource for planning the ongoing transition to a decarbonized energy system. They illustrate how home technology change takes place in society and reveal blind spots in past efficiency work. This chapter extracts lessons and themes from those histories, presented with examples and discussion of policy implications. These are grouped into two disciplinary categories: (1) history and social sciences of technology and of energy, and (2) energy efficiency history.

Lessons from History of Technology and Energy Social Sciences Scholarship

Table 2 (next page) summarizes lessons about energy technology change drawn from research in energy history, social sciences of technology, and energy social sciences. Details on each lesson are provided below the table.

1: Technologies in the Home Co-Evolve with Systems Outside the Home

Energy technologies in the home evolve with technical and cultural systems outside the home—refrigeration and cooking with food supply, distribution, and cultures; laundry with the garment industry and fashion; heating and cooling with cultures of comfort and urban infrastructure, for example. This is a reason that energy use in homes differs so much across countries and even within regions and across social groups: local systems of appreciating and doing, such as eating or relaxing, vary a great deal (Wilhite et al. 1996). Focusing on technology inside the home in isolation makes sense for programs targeting modest efficiency increases in near-term time scales. But that view is restrictive relative to achieving the big changes needed for California's energy transition.

Energy sociologists have argued that "tools and technologies ought properly to be analyzed historically, as in effect 'social movements'" (Hackett and Lutzenhiser, 1985). Seeing technologies as interlinked with social movements can lead to much different technology planning possibilities than seeing technologies just as hardware. The former allows a deeper understanding of how technologies and practices change from novel to normal, and thus better foresight and wider scope for forging desired pathways for the future.

Table 2: Lessons from History of Technology and Energy Social Sciences Perspectives

No.	Observation	Implications
1	Home energy technologies are parts of larger systems inside and outside the home.	Addressing energy systems at a larger socio-technical scale can provide new leverage points for decarbonization and illuminate roadblocks to change.
2	Technologies and innovations create needs rather than just serve them	Focusing only on efficiently fulfilling assumed needs is misaligned with GHG emissions reductions goals. Instead, energy transition planning must recognize how needs are created, evolve, and dissolve, and use this knowledge to help shape socio-technical evolution with policy goals in mind.
3	It is difficult to pick a technological winner beforehand.	The commercial success of technologies depends on factors beyond technical qualities, and can hardly be predicted. Closer, broader monitoring of the performance and reception of energy technologies promoted by policy can help correct problems.
4	Older technologies have a viable place alongside more modern versions	Encouraging older technologies to remain in the mix, and improving them where relevant, could provide energy savings, demand reduction, and resilience in some situations.
5	New homes have become substantially larger over the past 40 years, leading to an under-the-radar source of increased energy service demand per capita.	Energy use associated with increased home size is poorly captured by efficiency metrics. Encouraging reduced house size (such as a 1,700 square foot house that is as satisfactory as a 2,300 square foot one) could reduce energy use, but alternative forms of measurement would be needed to credit this type of savings.

Source: QQForward, 2019.

Examples

The amount of refrigeration needed in homes depends on food production and distribution systems. The cold chain described in Chapter 2, along with household practices of stocking frozen and refrigerated foods purchased in bulk from a warehouse store, affects how households gauge their refrigeration needs. Refrigerator energy efficiency efforts succeeded in efficiency's own terms (Chapter 2). But refrigerators are now bigger and more homes have two refrigerators than ever before.[24] This greater refrigeration capacity accompanies higher

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[24] According to EIA RECS data, 30 percent of households had at least two refrigerators in their homes in 2015, compared to 15 percent in 1993. In 2015, 43 percent of refrigerators had storage of 23 cubic feet or more, while in 1993 only 4 percent did (EIA RECS, 2015; EIA RECS, 1993).

levels of stocking food in the home. A bulk-buy system of food procurement is not necessarily less energy-efficient than others,[25] but large stocks of food can contribute to household-level food waste (Davenport, Qi, and Roe, 2019). The USDA estimates that 30–40 percent of food in the United States is wasted (USDA, 2019), along with the energy, pesticides, fertilizer, and other resources used in producing and transporting that food.

For a second example, while there are multiple reasons central air conditioning in homes has become the norm (see just below), one is that people become conditioned to value it through exposure outside the home (e.g., Ackermann 2002)—so there is a system of learning to appreciate air conditioning.

Implications

The normal starting point for influencing residential energy use has been the home or consumer in isolation. Looking to larger systems presents a richer set of possibilities, following Donella Meadows' question about where to intervene in a complex system to create a desired effect (Meadows, 1997). One proposed alternative framework to see in a systems view is to make *social practices* the object of energy planning (Shove et al., 2012; Rinkinen, Shove, and Torriti, 2019; Strengers and Maller, 2011). Japan's Cool Biz movement, for example, aimed to lower air conditioning use by encouraging less use of air conditioning in the workplace, not just by ordering higher indoor temperatures, but by making these warmer temperatures a topic of conversation and physically more tolerable—for example by promoting changes in dress codes and even clothing material more suitable for warmer temperatures (Shove, 2016). Cool Biz coordinated shifts in intersecting lines of cultural practices (air conditioning levels, dress code expectations, comfort expectations) toward lower levels of air conditioning.

This approach contrasts with seeking to increase technical efficiency piece by piece. The familiar energy efficiency analysis structure is organized by sector, using sector-specific or end-use specific metrics to gauge the energy effects of technical change. For example, the residential sector is considered in isolation from the transportation sector (with current efforts to integrate electric vehicle charging overcoming some of this separation), improving heating can be pursued without thinking about heating efficiency's effects on cooling, and embodied energy in materials may be overlooked (Cabeza et al. 2014). Siloing makes problems tractable but at the same time overlooks interactions that can lead to higher or lower energy use overall. Climate-scale planning is faced with finding ways to help better think through and influence these contingencies, even including possibilities (such as influencing the food system) that might have seem fantastical in the energy efficiency policy era.

2: New Technologies and Innovations Create Needs as Much as Serve Them

The concept of "needs" is a fundamental building block of residential energy efficiency planning. Energy efficiency has been defined in terms of the energy required to fulfil the set and level of services that consumers want. History makes it obvious that needs are not fixed,

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[25] Researchers have examined food externalities and life cycle cost estimation (Weber and Matthews, 2008; Pretty et al., 2005), the food-energy-water nexus, and how households manage refrigeration (Davenport, Qi, and Roe, 2019). A survey-based study also found that households that did shorter shopping trips (30 minutes or less) had higher utilization rates of the food they purchased (Davenport, Qi, and Roe, 2019) versus the less frequent bigger-order trips expected in warehouse-style food shopping.

and that changes in "needs" change energy use. New needs can be fostered by new technologies, and even by efficiency efforts (such as possible in the ENERGY STAR air conditioning example above). In other words: "What [a tool] is good for is a consequence, not a determinant, of its use" (Hackett and Lutzenhiser, 1985); "Invention is the mother of necessity" (Kranzberg, 1986); and as practice theorists see it, '"practices recruit users" (Shove et al., 2012).

Historically, energy efficiency programs have been justified by demonstrating countable savings relative to a counterfactual. For example, an efficient central air conditioner is compared to an inefficient one of the same size. The baseline technology is thus defined as fulfilling a fixed need. The more services that are defined as needed, the greater the potential for finding savings through efficiency. This means that new needs and new energy use can even be created in the name of efficiency. And conversely, it is possible to foster lower-energy needs without leaning on traditional efficiency improvements or even notions of conservation.

Examples

Various stakeholders coordinate to make specific technologies "needed." One interesting example from energy history is load building, where industry actors have promoted a specific technology at low cost with an eye toward selling the energy needed to power them especially in ways that contribute to profitable demand profiles. Examples include power industry pioneers efforts to get electricity-using equipment into American homes in the late nineteenth and early twentieth centuries (Bakke, 2016; Munson, 2005); discounted gas water tank water heaters in California that turned interest away from solar water heating to build a customer base for natural gas (Butti and Perlin, 1980); and increasing size of refrigerators in the 1960s (Deumling, 2004). Such deliberate needs creation are normal business strategies that can work against the goals of lower energy use, even when the products sold are efficient. While the profit structure of the power industry has shifted, some version of these interests will remain (e.g., for electric vehicle charging).

As a second example, the availability of affordable central air conditioners shifted residential architecture and construction. Passive cooling elements such as eaves, porches, and operable windows were replaced by the cheaper-to-produce option of central air conditioners (Cooper, 1998).[26] In turn, households had fewer options for passive cooling, leading to reliance on central air conditioning. That is, architecture that supported passive cooling became outmoded due to the promotion of competitively priced central air conditioning, which reinforced a demand for using central air conditioning. This is not the only reason that central air conditioning became so popular (Hitchings and Lee, 2008;Walker, Shove, and Brown, 2014), but together these shifts feed new definitions and expectations of comfort (Brager and de Dear, 2003) corresponding to new ways of achieving it. Air conditioning is sometimes difficult to talk about because it is viewed (like conservation) as a moral issue (Cashman, 2017); seeing it instead as a matter of the influence of larger technological systems (see the section

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[26] Air conditioning system advertisements to home builders sometimes even made this tradeoff explicit. For example, an advertisement for Mueller Climatrol noted that "…at least part of the cost of cooling equipment may be offset by good planning. As an example, with cooling it would not be necessary to provide screens for those rooms that are cooled, or to provide a screened-in porch" (National Museum of American History, Archives Center (NMAH-AC0060-0003327; estimated date 1953).

just above) provides some less-loaded leeway for finding lower-energy alternatives where suitable.

Even efforts to increase energy efficiency can reinforce energy needs. In Australia, rewarding *efficient* air conditioning has been found to devalue home designs without air conditioning (Kordjamshidi and King, 2009; Williamson, 2000). There are similar examples in California. The ENERGY STAR residential program scored having Seasonal Energy Efficiency Ratio (SEER) 16 air conditioning highly toward achieving ENERGY STAR status. High-SEER air conditioning thus becomes a default, regardless of climate zone. For example, coastal areas of California historically have had relatively low saturations of central air conditioning.[27] The pursuit of an ENERGY STAR home rating can encourage adding central air conditioning, even in areas where lower-energy alternatives might work well (Energy Institute, 2011; Chong, 2012).[28] This influence can inadvertently increase energy consumption relative to what would have happened in the absence of ENERGY STAR program. If weather remains mild in these marginal areas, central air conditioners may not add much energy consumption, but they add expense that could be invested more effectively in other efficiency (Davis, 2019) or resilience measures.[29]

This example illustrates some downsides of standardization across the tremendous diversity in how energy is used across households. Builders and sellers gain advantages by adding air conditioning, thus normalizing air conditioning instead of other options, even as codes and policies formally admit designs that use other methods for cooling.[30] Normalization and standardization provide administrative clarity and systems coordination, but can run at odds with integrating efficient modes of cooling given the natural variation of households and geography (Shove and Moezzi, 2004; Davis, 2019).

For another example of how efficient technologies can create needs, autonomous vehicles, still rare, are sometimes considered to be a route to reduce GHG emissions from transportation along with convenience and safety benefits. But some test cases suggest that their use could lead to increases in vehicle miles travelled (EIA, 2018; Greenwald and Kornhauser, 2019; Zhang et al., 2018). Autonomous vehicles do not simply substitute for vehicles with drivers, they change vehicle roles. The convenience and possible lower operating costs they offer could encourage more vehicle use overall. The popularity of free shipping at retail shopping sites is similar: free shipping reduces the apparent cost barriers to acquisition which may

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[27] For example, according to the 2009 RASS survey, only 11 percent of homes in CEC Forecast Zone 5 had central air conditioning, and 22 percent in Zone 11 (KEMA RASS, 2009).

[28] This example was identified by Reuben Deumling, who notes that while alternative designs are possible to achieve an ENERGY STAR Home rating, doing so requires extra effort and risk on the part of the builder.

[29] The economist Lucas Davis argues that standards requiring central air conditioners to be high SEER no matter what the location can add considerable expense for air conditioning in areas with infrequent need for cooling, but have little payoff in terms of reduced bills or GHG emissions (Davis, 2019).

[30] Behavioral economics has become a popular perspective through which to think about and influence consumer decisions for energy and environmental goals, for example by framing the most environmentally desired decision as the default choice (Sunstein and Reisch, 2014). These principles can also be applied to analyzing energy-related decisions elsewhere in the energy system at large, such as builder decisions.

encourage more purchases, with an array of shifted costs and benefits to various parties. The outcomes in the case of autonomous vehicles are as yet unknown, but taking a more systems view of driving could provide useful foresight for imagining scenarios of how automobile innovations might change use and in influencing use cost structure.

Implications

Energy efficiency endorsement and regulation typically adopt the stance that energy service needs are best taken as given, and pursue an objective of promoting technologies that fulfill these needs efficiently..[31] This creates a twofold complication for energy efficiency in pursuing the goal of absolute reduction of energy use. First, efficient technologies can create additional needs and possibly additional energy use. Second, independently of efficiency, needs and the means to fulfill them will continually evolve, creating a moving target for efficiency (Wilhite, 2016).

Proactive consideration of these possibilities leads to new guiding questions: How can climate change policy help steer the creation of needs toward those with lower impact, versus focusing on efficiently providing any services demanded at they evolve? When might promoting efficiency or renewable energy (e.g., individually-owned solar) standardize higher needs, and how should this possibility be addressed, if at all? These questions see reducing energy use less as swapping in neutral technology, but as helping transform how activities are accomplished and how needs are defined.

Social progress is often implicitly assumed to mean increasing standards of living and increasing energy service needs for entire populations (Wilhite, 2016). Some civil movements have pushed back against this pattern of escalation. For example, voluntary simplicity (an ancient idea) has had fluctuating popularity over the past century (Leonard-Barton, 1981). Another is enthusiasm for reducing the amount of stuff that fills homes (Pannett and Hoyle, 2019). Both examples represent a nongovernmental embrace of backing off consumption. There are more organic examples, such as households deciding that they do not need something that is often considered the norm, such as air conditioning (Deumling, Poskanzer, and Meier, 2019). These examples are about alternative definitions of needs, versus conservation per se. Rather than making dialed-back definitions of needs an effortful choice, there may be ways to naturalize them.

Seeing the patterns illustrated above as legitimate concerns for transition planning faces the complication that it is difficult to assess their presence or importance due to statistical and data limitations, and because technology assessment practices rarely even scan for this kind of effect. But exploring these micro-scale effects, even if largely qualitatively, and estimating their macro implications schematically, can be accomplished scientifically and can help guide technology policy.

3: The Best Technology Does Not Necessarily Win

Different versions of technologies compete, with industry and other stakeholders highly engaged in this competition. Technologies do get better. But one technology may virtually

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[31] *Energy servic*e here refers to the way of using energy, such as a need for a central air conditioner to keep the home at 72°F (22°C), for example.

eliminate others, less through innate technical superiority than through strategy and happenstance. Promising technologies may fail if they insufficiently distribute value throughout the supply chain. This unpredictability is at odds with the fact that government technology policies often pre-select which technologies are best, before sufficient information about real performance or impacts are available. Marchant (2009) notes, "The historical record is that governments (along with everyone else) have a relatively poor record in picking which future technologies will best succeed in achieving a particular objective." Technology planners are faced with the need to find creative ways of monitoring technology performance, in tension with focusing on prospective performance.

Examples

Condensing natural gas refrigerators were common in the United States during the 1920s. Soon after, electric compressor-based refrigerators completely dominated the market, and have ever since (Cowan, 1985; Rees, 2013). Big companies that had already established a solid manufacturing business in realms such as car radiators or farm implements had a major advantage over small companies trying to enter the domestic market, thus shaping the technical characteristics of refrigerators through the industrial competition at hand (Cowan, 1985). Other abandoned appliances include central vacuum cleaners and horizontal axis washing machines (Cowan, 1985); solar water heaters (Moezzi et al., 2019);[32] CFLs, which have been outsold by LEDs since 2017 (NEMA, 2018); and electric versus combustion cars in the early twentieth century (Kirsch, 2000). But electric cars have made a comeback a century after they faded away in the market, and horizontal axis washing machines have been repopularized in the United States.

Currently, electricity and natural gas are now competing for space heating, water heating, cooking, and clothes dryers in California homes, with natural gas dominating (KEMA RASS, 2009). A gas transition strategy is needed (Aas et al., 2019) to manage this competition toward achieving the state's decarbonization goals. The recent pattern of Public Safety Power Shutoffs creating blackouts lasting several days even in urban areas could, however, lead to renewed interest in (or reluctance to abandon) gas appliances, since they can allow cooking, water heating, and other home energy services during power outages—potentially important forms of socio-technical resilience for homes without generators or home energy storage.

Implications

Climate change policy goals create a common vision around which multiple parties can rally and coordinate. These often specify a technological route to a committed end goal far in the future. Some types of uncertainties are acknowledged (e.g., more or less technology penetration depending on economic assumptions), but these usually do not address the dynamics that create these uncertainties. Marchant (2009) suggests that the means of achieving policy goals are left relatively open rather than picking a winner too early, and that safety valves are in place to provide flexibility (Marchant, 2009). Otherwise inflexible commitments can lock in technological pathways through infrastructural, market, regulatory, standardization, habitual, socially normative, scale, or other factors (Unruh, 2000; Grübler,

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[32] As also noted above, natural gas water heaters were promoted and subsidized by natural gas companies in California in the 1930s and 1940s, to the detriment of solar and electric water heating (Butti and Perlin, 1980).

Liebowitz and Margolis, 1995), even when these pathways no longer seem desirable or reasonable. Doing so could help come to terms with disappointments or commitments to misplaced assumptions that proponents may otherwise be reluctant to formally admit.[33]

Whether a technology succeeds as envisioned is not just a matter of consumer acceptance. Cowan (p. 215) summarizes: "In an economy such as ours in the United States, the first question that gets asked about a device is not, Will it be good for the household—or even, Will householders buy it? but rather, Can we manufacture and sell it at a profit?" That is not just a matter of manufacturer ingenuity, but depends on a host of other system issues (such as related to supply chains, regulations, tariffs). Profitability will shape how sustainability gets defined, but profitable sustainability may be inconsistent with more grounded definitions of sustainability.

4: Old Technologies Persist Alongside New Ones and Could Make Comebacks

New technologies and practices often largely replace older ones, but these older ways of doing may remain layered with contemporary technologies (Kelly, 2011) for decades or even centuries. Some older technologies can be lower impact environmentally than their modern counterparts or otherwise have a different set of advantages that can suit certain situations very well. This recognition contrasts with a widespread perception that technology evolves to becoming singularly better than alternatives.

Examples

There are many examples over the past century. To name a few: older technologies and practices that are still used but are less energy-intensive than dominant technologies include air drying clothes versus using a clothes dryer, evaporative coolers versus central air conditioning, solar water heating versus fossil-fuel based methods, and bicycling short distances versus driving.

Some old technologies that were once the target of energy efficiency programs became much less prominent over a decade or two: DVR devices (replaced by streaming), desktop and laptop computers (partly replaced by tablets and smart phones), landline telephones and answering machines (partly replaced by mobile phones), ironing (still practiced, but less so due to changes in social standards and fabrics), and waterbeds.[34] In other cases, how much something is used declines. Cooking is a prime example, with much less time spent cooking

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[33] For example, one common assumption is that "homeowners are going to recognize the value of energy efficiency like the energy efficiency itself does, and then voluntarily upgrade their existing equipment and homes," which, left unchecked, takes on an "if only" character of planning that can mistake ideals for achievements (Moezzi and Janda, 2014).

[34] Waterbeds had very high energy consumption (1,103 kWh/year according to Nore and Roberts, 1994) and for years were tracked separately in EIA's residential energy end use accounting. In 1987, the height of waterbed popularity, they represented 22 percent of mattress sales (Wells, 2016). But they eventually lost their countercultural vibe, and at last available estimate were present in only 0.5 percent of households (Greenfield, 2010). This change could be interpreted as having saved a great deal of energy, even if the changes were not primarily because of energy efficiency concerns.

and increasing amounts of food preparation occurring outside the home comparing the mid-1960s to the mid-2000s (Smith, Ng, and Popkin, 2013).

Implications

Some older home energy technologies could be redeveloped and revived to serve along with their modern counterparts, providing advantages in certain locales or situations. These could be modernized with engineering improvements—such as a better evaporative cooler or more bullet-proof solar water heater. Any technology needs a support system, including availability of parts and know-how, social familiarity, compatibility with regulatory requirements, and complementary infrastructure, which would be needed to be retained.

Some of these older technologies also provide resilience when electricity supply is limited. For example, passive cooling or lower-energy forms of active cooling such as evaporative units could take the edge off demand from central air conditioners on hot days when grid capacity is stretched. Evaporative coolers could be add-ons to homes that already have central air conditioners (Watt, 1986).[35] This would have grid flexibility benefits and possible health benefits, such as cooling for people who do not want, rarely need, or cannot install central air conditioning.

Unless intentionally pursued, these possibilities may be missed in technology planning for several reasons. Promoting older ways of doing can seem retrograde rather than progressive. And again, programs cannot easily account for savings from "not using" or "hot having." Thus savings from line-drying clothes, using smaller refrigerators, building smaller homes, developing free-running versus active heating and cooling in the home, or using evaporative or room air conditioners versus central systems, for example, may be difficult to see, contra savings afforded through purchases of efficient products. But there may be a promising middle ground, at least in terms of contributions to resilience (Alexander and Yacoumis, 2018).

5: Growth in House Size Increases Energy Use

The amount of space to be heated, cooled, lit, and filled per home and per person is greater now than it was in the 1970s. The median size of a single-family home built for sale in the US was 2480 square feet in 2017, 61% bigger than the 1545 square foot median in 1973 (U.S. Department of Commerce 2018), and U.S. homes in general are among the biggest in the world (Pinsker, 2019). Increasing home size combined with decreasing household size (Fry 2019) leads to more "home" per person, eroding energy saved by technical efficiency in the meantime (Lutzenhiser et al., 2017). Efficiency promoters sometimes describe this as "win-win" for efficiency and the public (EIA, 2015; RESNET, 2015; see Chapter 2). The double win follows from how efficiency savings are defined: factoring out size or level of services, with bigger savings calculated relative to bigger less-efficient alternatives.

Implications

Encouraging more space-efficient home design and making communal living more attractive could help reduce energy use per capita. This need not be about mandating high-density

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[35] It may even be possible to combine low-energy technologies with higher-intensity technologies as a single system, somewhat akin to the Variable Speed Drives sometimes applied in commercial HVAC for energy conservation.

housing. Rather it could start from recognizing the many influences that encourage bigger houses, including land planning practices and deep cultural identifications of house size (Pinkus 2019). Construction practices and social norms could possibly be reset toward smaller houses, for example by encouraging more space-efficient home design or showing smaller spaces in a positive light. And it may be possible to instill more attention to energy and resource use in "nonenergy" policies including those of land planning (Cox, Royston, and Selby 2019).

Lessons from Energy Efficiency Program and Policy History

Table 3 summarizes observations from the history of energy efficiency that can be applied to improve energy transition planning. These ideas will be familiar to those in the energy efficiency field who have long heard about *energy efficiency gaps*, *building-performance gaps,* and *rebounds*. In fact, these issues may seem so familiar that they no longer seem problematic. But they are major inflection points for adapting efficiency practices to climate change problems, as explained below.

1: Energy Efficiency Does Not Necessarily Track Energy Consumption

Energy efficiency orients to how things are done rather than what or how much is done. The "how" has long been developed into a tractable energy problem, but perversely for reducing absolute energy use, higher nominal energy efficiency in homes can be associated with higher levels of services, such as a bigger fridge or bigger house (Harris et al., 2008; Moezzi and Diamond, 2005).[36] This Trojan horse effect means that extra energy consumption and GHG emissions can be encouraged in the name of efficiency. The extent of this effect is controversial (Goldstein, 2010), and efficiency cannot be ruled as causative, but the situation again speaks to a mismatch between traditional energy efficiency goals and those of climate change policy (Moezzi et al., 2018).

Examples

Efficiency metrics of energy use per unit floor area favor larger homes over smaller, less-efficient homes (Lutzenhiser et al., 2017), and homes with air conditioning are sometimes easier to define as efficient as those without, as noted above.

Beyond efficiency definitions, voluntary efficiency programs may be initially oriented to the premium market, leading bigger, more feature-laden, more expensive, and sometimes more energy-consumptive devices associated energy efficiency—as for ENERGY STAR refrigerators (Deumling, 2004). Marketing images of energy efficiency often feature higher-consuming products, such as big houses or refrigerators, rather than more modest ones. Also, since efficiency is defined in terms of devices or materials, rather than practices or larger systems, the use or nonuse of devices cannot be reflected in efficiency ratings. An electric dryer can be efficient, but line-drying clothes cannot be; rather line-drying is defined as "conservation"

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[36] The pattern occurs through different mechanisms and properties, including: physics, marketing energy efficiency as a premium feature, higher levels of energy efficiency adoption among wealthier households, metrics that favor larger sizes in energy efficiency or energy savings determinations, cost-effectiveness criteria in relationship to pricing, energy-using devices being eligible to be considered as energy-efficient whereas passive/manual alternatives are usually not, and, from economics, the direct rebound effect.

which has little administrative place in present-day efficiency and is negatively valenced within energy efficiency discourse (Halpin, 2018).

Table 3: Historical Lessons from an Energy Efficiency Perspective

No.	Observation	Implications
1	History suggest that higher rated energy efficiency for a device or end use does not necessarily lower energy consumption.	Efficiency efforts applied to climate policy goals can backfire, failing to reduce energy and GHG emissions. Efficiency-based approaches need to be considered under a new lens to suit climate policy goals.
2	Quantitative energy models are central to efficiency programs, policies, and technologies, but can miss some of the essential dynamics of technologies in the world.	New approaches to modeling enabled by new data and computational resources can better capture the highly variable ways energy is used across houses. This distributional view provides a lens into details that help make or break success and that affect different households differently.
3	Energy efficiency assumptions can be unrealistically optimistic.	Over-optimistic assumptions set up expectations for technology deployment that cannot be met, with knock-on effects for related programs and technologies. Reining in biases could reduce the risk of mis-investing due to persistent over-optimism.
4	Consumers are often less interested in investing in energy efficiency and sometimes less happy with the results than advocates and program sponsors imagine they should be.	It may be difficult to get most households to voluntarily adopt the efficient technologies that are envisioned by advocates and program sponsors. There is a need to develop ways to better understand energy users contra focusing on creating ideal ones.
5	Energy efficiency can introduce problems in other dimensions that lie outside normal efficiency evaluation.	Designing more comprehensive assessment of new energy efficiency technologies may help identify and offset some of these problems.
6	Many efficiency improvements have been made over the past 40 years, which creates tighter competition for new sources of efficiency savings.	Versus targeting devices, energy policy and programs can target demand reduction more broadly.

Source: QQForward, 2019.

Implications

Associating higher levels of energy services with higher levels of energy efficiency has been expressed positively by the energy efficiency industry, as a benefit of efficiency, rather than as detracting from its success (EIA, 2015; RESNET, 2015). For climate change goals[37] that older energy efficiency logic is less relevant. So how can energy policy prioritize lower energy consumption versus more efficient consumption? How can this be accomplished without making people worse off? This could be pursued, for example, by re-orienting how efficiency is defined technically (Moezzi and Diamond, 2005), by focusing on more efficient practices (how can people stay cool in their homes?), and by helping envision and support lifestyles that do not rely on high levels of energy consumption. These pathways contrast with the more conventional pursuit of more efficient technology (what is the most efficient central air conditioner?). The argument here does not assume that top-down moral pressure to conserve will have wide appeal. Rather, definitions and connotations of efficiency and conservation are cultural (including professional cultures). They could be retooled to capture savings that efficiency proper cannot or has not. This would require a perspective and a cadre of support that goes beyond the traditional boundaries of efficiency field.

2: Energy Models Can Create Important Blind Spots

Quantitative energy models are central to efficiency programs, policy design, and technology plans; and serve as a basic framework through which researchers and policy makers see problems and solutions. They are necessary, will always simplify, and will always have inherent uncertainties and biases. But models also have to be examined as to what crucial factors they miss about the real world (dynamic interactions, diversity, long-term and knock-on effects, systematic biases) and what difference these omissions make to policy outcomes. Historically it has been difficult to pursue these questions, but the possibilities for (and necessity to) do this kind of assessment are growing.

Examples

Models often use averaged assumptions to estimate savings from efficiency, but these assumptions are not necessarily based on observation of actual use nor can they reflect distributions or correlations across interacting distributions. For example, early programmable thermostat program planning used assumptions that led to overestimates of actual savings (Peffer et al., 2011). Laboratory and modeled definitions of efficiency may not reflect real-world performance of, for example, heat pumps (CEC, 2019).

Implications

Wider dedication to empirical analysis of use and usability for specific technologies could lead to improvements in the degree to which these technologies provide the results that models and plans assume they deliver (Laurent et al., 2013). In short, studies that attend to how households use, experience, and adapt to technologies can lead to better technologies and

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[37] *Climate change goals* here refers to the ensemble of goals targeted in California climate change policy, encompassing not only GHG emissions reductions, but also energy systems resilience as well as various conditions on how these goals are accomplished, such as social equity and economic constraints. Energy efficiency policy also balanced multiple goals and conditions, but to a lesser extent and at a smaller scale than the energy systems transition envisioned in climate change policy.

better estimates. This attention would dovetail with a shift of focus from technologies in isolation to energy use practices (as suggested above). Along with this shift, developing models constructed to reflect the distributional, multi-dimensional character of energy use would permit better ways to see the structure of energy use and the various conditions and events that interact with it—overcoming blind spots that simpler models (while certainly useful for some applications) and overly-narrow requirements for evaluation reinforce.

3: Energy Efficiency Assumptions Can Be Too Optimistic

This is a corollary of the role of models noted above. If similar levels of optimism are reflected in assumptions of future performance of transition technologies, they may deliver markedly less than expected.

Examples

Three general examples that have repeatedly been observed in efficiency history. First, engineering estimates of savings from efficiency may often overestimate achieved savings, according to a limited set of meta-evaluations (see Chapter 2). In house efficiency labeling schemes in the European Union, modeled energy consumption tends to be considerably higher than actual energy consumption (Laurent et al., 2013). This has been called the *pre-bound* effect (Sunikka-Blank and Galvin, 2012) and can lead to the overestimation of savings from efficiency measures applied to these homes. The *building performance gap* (Fedoruk et al., 2015) reflects a finding that buildings in use often perform less well than designed. For example, commercial buildings may use twice as much energy as estimated by models (Imam et al., 2017).[38]

Second, the *rebound effect* encompasses the theory that increased technical efficiency of an end use can lead people to ask for more of that energy service or any services than they did previously, thus eroding expected savings (Herring and Roy, 2007). The size of this effect is controversial, partly because it is difficult to measure. Third, the *energy efficiency gap* asserts that people under-adopt energy efficiency relative to levels considered rational in conventional economic terms (see Lutzenhiser, 1993; Shove, 1998). Two of these effects (the building performance gap and the energy efficiency gap) are often assumed to be essentially problems about the behavior of people, but the reality is more complicated (Hong et al. 2017).

Implications

Exaggerated estimates of energy savings can mislead technology choices to configurations that may not actually produced anticipated benefits. Historically, empirical performance data have been difficult to produce, while designing technologies and buildings with given expected performance has been tractable. Now, with new data and new problems, better ways to anticipate, notice, and overcome performance estimation issues are possible and compelling. This could involve a combination of better modeling (such as better incorporating variation), technology designs that reduce the risk of poor performance, and more targeted evaluations of technologies in use. The emphasis here is not a criticism of the underperformance of modeling, but instead on recognizing systematic biases when and where they exist.

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[38] Most of the attention to the building performance gap has been for commercial rather than domestic buildings. Performance gap research may be less common in the United States than in Europe.

4: Consumers Sometimes Dislike or Reject Energy Efficiency Offerings

Efficient technologies are not identical to the less efficient technologies that they are intended to replace. Efficiency accounting has historically focused on energy comparisons alone, at best with other differences generalized as nonenergy benefits. This calculation-centric view of technology change ignores how end users and others in the market chain perceive, use, and experience innovation. Product developers and marketers regularly improve their offerings in response to consumer feedback or for market advantage. But this process can be slow and incomplete, and can be impeded when incentives and other policies create impetus to widely roll out qualifying products.

Examples

Aggressively promoted efficiency technologies that were met with high levels of dissatisfaction include CFLs (Chapter 2), programmable thermostats (Peffer et al., 2013), solar hot water heaters in the 1980s (Moezzi et al., 2019), and early generations of horizontal axis washing machines (Hustvedt, Ahn, and Emmel, 2013).

Implications

Bad experiences with energy efficiency can poison public attitudes to efficiency in general, reducing trust in energy efficiency or government energy recommendations. These consumer experiences may be difficult to see from policy making and technology planning levels, in part because they are not widely studied or called out.

More attention to avoiding overpromising, to anticipating and detecting problems with technologies in the field, and to communicating with users about problems could help improve efficiency design and consumer trust. A participatory approach to refining new technologies could be useful. There are research traditions that can help at the design stage, including human factors design (Sanquist, Schneider, and Meier, 2010), human-computer interaction research, and social studies of technology. In some cases, satisfaction warranties may overcome purchase hurdles.

This design/observe/monitor tactic contrasts with marketing approaches that focus on convincing consumers to accept a given technology, even as these marketing and frame-making approaches can also be useful (Ahn et al., 2015). Put another way, the technology assessments made by ordinary buyers, users, and sellers of technology are legitimate and potentially useful data points for building better energy technologies, rather than simply consumer mistakes.

5: Nonenergy Effects of Energy Efficiency Can Cause Problems

As noted above, technology designed to meet efficiency aims can introduce changes in dimensions that lie outside the bounds of efficiency evaluation**.** Beyond the matters of consumer acceptance and usability noted above, the nonenergy effects of technologies can cause problems. On one hand, unintended consequences of government interventions are inevitable (Merton, 1936), and technologies and policies cannot be optimized in all dimensions even if problems are recognized beforehand. It is obvious that there are tradeoffs. On the other, the systems to deal with these tradeoffs can be opaque. Tradeoffs span policy areas and are usually incommensurate—such as all pollution versus greenhouse gas emissions reductions, equity versus economic efficiency, coincident peak demand versus energy use.[39] Some of these tradeoffs are recognized in the *energy trilemma* dialog that addresses balancing politics, environment, and economics (Heffron et al., 2015).

Examples

There are many examples of tradeoffs from energy efficiency history. CFLs contain mercury. Because of this mercury content, regulations require special handling for CFL disposal. The actual rate of proper CFL recycling has historically been low, roughly 2 percent nationwide in 2011 (Janeway, 2011), if likely higher in California. Safeguards for mercury release from CFLs are theoretically in place, but execution is far from guaranteed. So CFLs saved energy but probably increased mercury pollution.

The case of the gasoline additive MTBE is similar (Marchant, 2009; McGarity, 2004). MTBE helps gasoline burn more completely, boosting automobile fuel efficiency, but it contaminates groundwater, resulting in effects on taste and possibly human toxicity. MTBE was banned in California in 2002.

Ensuring a home's airtightness for efficiency's sake can lead to inadequate air circulation if the mechanical ventilation systems do not work adequately or are used differently than modeled. These differences are common and consequential (Less et al., 2014; Park and Kim, 2012); the mechanical ventilation systems intended to provide controlled air circulation and sometimes particle filtration (in lieu of the natural ventilation that occurs in homes that are not tightly sealed) provide good indoor air quality in theory, but not necessarily in fact.

Even for behavioral conservation, too much conservation can harm health, for example, during the 1970s energy crises, winter heat conservation left some elderly people dangerously cold (Macey, 1989). Parallel examples likely exist for conserving energy during periods of excessive heat (Lane et al., 2013; Maller and Strengers, 2011). Avoiding energy use is not uniformly a good thing (Bushnell, 2017).

In energy efficiency history, there has been little categorical discussion of nonenergy costs, contra attention to potential nonenergy benefits. Corrections to account for these nonenergy costs can take more than a decade, as they did in the case of MTBE (McGarity, 2004). And if the corrections rely on idealistic or untested assumptions about what people do, they may not be effective.

Implications

With climate goals and the corresponding wider professional participation in climate versus energy efficiency policy, there is both a need and a stronger possibility to directly negotiate tradeoffs between GHG emissions reductions and other major environmental, health, energy, and social effects. The quantitative models used in energy efficiency were not designed to grapple with this scale of problem. At first, the topic of tradeoffs may seem too big to address. With sufficient development, exploratory models like SIMSAND developed in this project

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[39] Some assessments use monetization to create comparisons, for example, estimating the external costs of different types of electricity generation as a basis for policies that internalize these costs via pricing (Krewitt, 2002).

(Chapter 5), along with an expansion of scenario construction approaches (Chapter 4), could help support tradeoff analyses.[40]

6: Efficiency is not an Unlimited Resource for Absolute GHG Reductions

Over the past 40 years, much device-level and structure-level efficiency has been applied in California homes. State building codes and appliance standards have often been updated.[41] Utility efficiency programs and market-led efficiency are well-developed in the state. Consumers have become much more aware of efficiency. Federal appliance standards have been periodically updated, as have efficiency specifications and product range for the Energy Star voluntary labelling program.

These efficiency increases have been found to save a great deal of energy. So, how much more potential for *absolute* reductions in household energy use are available using current approaches? There are physics-based limits to efficiency as technically defined, and in the past these limits have been overlooked (Bakke, 2016). State-mandated energy efficiency potential studies provide estimates of remaining efficiency, including savings from applying efficiency to new homes and products (Navigant 2019); much of this is relative savings rather than absolute reductions. Many existing homes and appliances are not up to current efficiency standards, so there is leeway. But getting efficiency upgrades into existing homes has been a persistent difficulty over decades, and squeezing out extra efficiency at these margins may be expensive.

Some engineering studies refute that the society is close to efficiency limits in general terms, arguing, for example, that the overall efficiency of energy conversion globally is only 11 percent (Cullen and Allwood, 2016). It is not clear how this type of abstract assessment be translated to the task of functionally ramping up efficiency for existing homes. Heating systems can last decades, and homes can last a century or more, creating inertia relative to goals for rapid transitions. The research team was unable to find much data that clarified detailed engineering aspects of the questions about *remaining efficiency* issue for existing homes and the end uses within them.[42] However, there are other ways to approach absolute energy use and peak demand reductions, as explained below.

Examples

The Model Energy Code (MEC) shows declining incremental savings estimates attributable to the code over each successive code iteration: 10 percent decline between the 1985/1986 MEC

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[40] There are methods available to assess these diverse dimensions of policies and technologies, such as Multiple Criteria Decision Analysis (Diakoulaki, Antunes, and Gomes, 2005), though these are not widely tested in real policy applications. In any case, this method requires assessing the quantity or degree of effect for each dimension.

[41] For a history of regulations in California, see California building codes (Title 24 Part 6 beginning in 1978 https://www.energy.ca.gov/title24/) and appliance efficiency regulation history (Title 20, https://www.energy.ca.gov/appliances/previous_regulations.html)

[42] The Energy Commission's *Senate Bill 350 Doubling Energy Efficiency Savings by 2030* report recommended that "sufficient[ly] disaggregated … data, including hourly and seasonal, is available on *historical energy consumption and efficiency savings estimates*" (Jones et al., 2017; emphasis added).

and the 1992/1993 MEC, 2 percent decline between the 1992/1993 MEC and the 1995 MEC; and again 2 percent decline between the 1995 MEC and the 1998 International Energy Efficiency Code that succeeded MEC (EERE, 2008). This trajectory shows gradual improvement in expected efficiency, but it is slow relative to California's goal of doubling energy efficiency savings. For another example, CFL replacement programs generated the bulk of IOU savings in California, so that lighting regulations making high-efficiency lamps standard virtually eliminated program savings available from CFLs (Barclay et al., 2018).

Implications

Energy efficiency is usually defined as an incremental property of devices or materials, though sometimes for larger technical systems such as a house based on comparisons of modeled expected energy use. New instances and new types of devices, material, and technical systems are always being added, and existing instances degrade. These create incremental opportunities for efficiency to generate energy savings. But big, climate-scale improvements in efficiency and reductions in emissions likely require new approaches to efficiency, targeting *systems of energy demand* rather than devices and material (Sahakian and Wilhite, 2014; Rinkinen, Shove, and Torriti, 2019). Existing efficiency protocols provide limited assistance for integrating such options. For example, how should passive architecture, an evaporative cooler, and a compressor-based central air conditioner be compared in terms of efficiency? Drawing on the example of Cool Biz Japan (Shove, 2014b), how would the possibility of more climate-resistant clothing (including fabric innovations for example) fit in? Without deliberately examining such questions, then central air conditioners may become the winning efficiency choice no matter the location of the home (as noted above), even if other technologies or portfolios work as well and with less energy. This raises a need to avoid over-rewarding theoretical energy savings if the baseline is not well-defined, since it could push efficiency to focus on bigger, more consumptive goods.[43] Another potential non-efficiency resource for emissions reductions is better coordination of electricity demand with supply—a mission that the electricity industry has pursued for over a century (Bakke, 2016).

Making History Relevant and Accessible

People working in the energy efficiency and climate change fields are already faced with a tremendous amount of information, of things to read, listen to, absorb, and reflect. So how could histories and historical insights be practically brought to bear, with what effects, given all the normal types of information on offer? That is a research question that cannot be answered without evidence on how existing histories and summaries (such as the ones in this report) are received and applied. For now, there are two general conclusions on the potential value of histories from this exploratory work.

Fostering *adaptive management*, such as by capturing technology-related patterns, trends, and events as they emerge, could provide a rapid feedback aspect of evaluation in support of desired energy transitions. The scope and intended pace of the energy transitions that

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[43] One example is the Golden Carrot (or Super Efficient Refrigerator Program) competition, where the award metric was kWh saved rather than efficiency per cubic foot. This allegedly led to intentionally creating a big efficient refrigerator (Gillingham, Newell, and Palmer, 2006; Moezzi, 1998). While this competition likely spurred innovations that were used in other refrigerators (Gillingham, Newell, and Palmer, 2006), it is an example of the "gold plating" that can occur as part of making efficiency attractive to consumers.

California policy has already legislated or is considering are more ambitious than in energy policy's past. For example, California's Big Bold Energy Efficiency strategies initiated in 2008 targeted that by 2016–2020, 100 percent of new homes exceed 2005 Title 24 efficiency standards by at least 35 percent, and that 75 percent of existing homes have a 30 percent decrease in purchased energy relative to 2008 levels (CPUC, 2008). If natural gas heating is to be replaced by electric heating, a similar pace would be required. Even if technology installation goals are achieved, do they achieve the desired benefits? What trickle-down effects or unintended consequences might be seen? How are technologies and programs in the real world deviating from ideals? What adjustments or recasts are called for? Accelerated cycles of feedback can help ensure that technology developers and strategists are continually informed about interactions, difficulties, and adjustments observed as technologies try to take their place in the real world. Developed well, with strategies to manage around inherent uncertainties (small sample sizes and related statistical limitations), this could support a system of adaptive management[44] for efficiently rolling out climate change-friendly technologies.

An extended set of energy technologies and energy efficiency histories could be valuable. A library of historical summaries would provide planners and researchers missing information on past experience, possibly shaking up current assumptions of "what must be" and providing actionable balance to overly-idealistic models of change.[45] If good quantitative trend information accompanied these histories, this could also be quite helpful for thinking through future projects. Possible historical topics include common energy efficiency concepts (such as home energy audits, Zero Net Energy homes, passive architecture, and standby power) and specific end uses (such as water heating, space cooling, and lighting). Such reviews would have to be deliberately fostered and legitimized as a normal part of energy efficiency study. For example, when considering the future of a particular technology, it would be useful to understand the socio-technical landscape of its past (Moezzi et al., 2019).

Historical analyses can also be applied to inspire the creation of future imaginaries. This includes the development of testable scenarios that capture more of the dynamic interactions and distribution of effects of possible residential energy futures, along with "What if?" questions probing alternatives and uncertainties. Prospects for developing these scenarios are explored in the next chapter.

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[44] Williams, Szaro, and Shapiro (2009) give an example of adaptive management planning in the United States government.

[45] These ideals derive from engineering and economic constructs (Lutzenhiser, 1993; Shove, 1998; Moezzi et al., 2009), models based on these constructs, and what has been called the folklore or "fables" (Rinkinen, Shove, and Torriti, 2019) that constitute energy efficiency culture; the terms "fable" or "folklore" as the authors use here are not derogatory, and apply to any field.

CHAPTER 4:
Scenarios in Theory and Practice

This chapter reviews the phase of the study that focused on the use of scenarios in energy planning—what one expert interviewed called *future histories.* The research method combined examination of relevant academic literature and published reports on scenario development and use in international, national, regional, and California energy and environmental policy contexts. This work informed a series of interviews with experts in energy planning and modeling in California and elsewhere. Insights from those interviews led to additional data sources and further interviews in targeted areas. A complex picture that emerged was reported in a project memo, which is summarized in this chapter.

In some senses, the meaning of *scenario* seems obvious enough—for example, "a sequence of events especially when imagined" (Merriam-Webster, 2019). People commonly talk about a scenario playing out, such as making an investment and receiving returns over time. Or "In that earthquake scenario, the house will fall down." The ability to plan for the mid- and long-term future, whether in business, government, or households, involves imagining actions and future outcomes. This use of scenarios can be simple and short-term, such as planning a birthday party or vacation, or complex and long-term. In formal modeling, for example, scenarios are sometimes used to compare alternative possibilities decades in the future. An early example is the Shell Oil Company's pioneering work in long-term geopolitical scenarios and energy supply alternative futures initiated in the late 1960s, and used to inform strategic corporate planning and management decision-making (Wilkinson and Kupers, 2013; Shell, 2019).

In energy analysis, forecasting, and planning in California, the use of scenarios has historically focused on informing specific policy options. However, even in the case of formal policy-support modeling, precisely what different modelers mean when they talk about scenarios, and what they do with scenarios in their work, can vary widely. Recent climate change policy mandates (reviewed in Appendix) have set new long-term goals that increasingly call for the use of scenarios to consider alternative California futures and pathways to those futures. This opens a landscape of new possibilities, such as the flexible modeling of alternative scenarios (future histories) in the simulation sandbox approach explored in this research.

Introduction to Energy Scenarios and Their Purposes

In California energy forecasting, scenarios have been used for some time to envision how changes in technologies, population, employment, and energy efficiency might affect future energy demand. Rather than large scale explorations of possibilities and uncertainties, the purposes have been straightforward and predictive of future energy demand to inform regulatory decisions about power plant and transmission permitting and siting. California utility regulators have also used scenarios to compare different energy efficiency program designs and their aggregate energy savings. The differences in purposes of the two primary state energy agencies (the California Energy Commission and the California Public Utilities Commission) have dictated different approaches, time horizons, modeling features, and so on.

Recently completed long-term energy scenario studies funded by the Energy Commission have used scenarios in still other ways, for example, to test whether particular sequences of technology change could achieve mandated emissions reduction targets (Wei et al., 2018; Mahone et al., 2019). This use is sometimes known as *backcasting*, where the mission is to find plausible or at least possible ways that a goal (usually an ambitious one) could be achieved (Manning, Lindenmayer, and Fischer, 2006). And a suite of climate vulnerability and adaptation studies for California's Fourth Climate Change Assessment (Fourth Assessment, 2018) used downscaled projections of global climate change scenarios to assess potential environmental impacts, such as wildfire risks and hydrology changes.

In short, different purposes have led to different conceptions and uses of scenarios. These often do not incorporate a detailed sequence of events suggested by the generic definition of scenarios. Sometimes the term scenario has been used to refer to an outcome or state of affairs at a future point in time. In other cases, scenario means that different technology configurations appear over time; or perhaps that different costs of fuels over time might enable different energy supply configurations. And in still other cases, different global social and economic change patterns (developmental scenarios) could be imagined to lead to different energy intensity, fuel, technology, and global carbon emissions futures.

For the latter, the United Nations' Intergovernmental Panel on Climate Change (IPCC) climate modeling process integrates consideration of five macro storylines, called shared socio-economic pathways (SSPs). The SSPs are each very different narratives about international regions' possible economic, social, and policy futures—with different associated levels of GHG emissions (GHGs) and degrees of global warming and changing earth/atmosphere/ocean and climate dynamics. The SSPs are titled: SSP1 Sustainability, SSP2 Middle-of-the-Road, SSP3 Regional Rivalry, SSP4 Inequality, and SSP5 Fossil Fuel Development (Bauer et al., 2017; O'Neill et al., 2014). Detailed stories about "this happens and then that happens" for each SSP are not elaborated, as this would be an impossible task on a global scale. But the SSPs are a starting point and a heuristic for considering possible differences in outcomes across economies, cultures, political and institutional structures, technology configurations, and environment effects (e.g., Schweizer and O'Neill, 2014). The SSPs in IPCC global climate modeling are translated to inputs to integrated assessment models that simulate macro environment-economy interactions and used to conduct impact, adaptation and vulnerability modeling, often at subglobal scales, including international regions, countries and even national subdivisions (Wilbanks and Ebi, 2014; Samir and Lutz, 2017).

In the United States, independently of the IPCC, the U.S. Department of Energy's (DOE) EIA maintains a National Energy Modeling System (NEMS), which is used to support the EIA's *Energy Outlook* reports (EIA, 2019). NEMS scenarios include a *reference case* forecast (projections based on current conditions and known facts) along with six side cases that vary from the reference case in oil and natural gas prices and availability, as well as high and low economic growth, in future years. It is a conservative assessment in the sense that "The potential effects of proposed federal and state legislation, regulations, or standards—or of sections of legislation that have been enacted but require funds and implementing regulations that have not been provided or specified—not reflected in NEMS" (EIA, 2019a).

The next section focuses on the use of scenarios in current California energy and climate modeling. But it is first useful to consider some context and critiques of the overall modeling landscape in which scenarios have been used elsewhere. The global systems of energy, emissions, atmosphere, and climate are so large, intricate, and dynamic that until the advances in affordable computing power in just the past few decades, it was unimaginable to model them in any detail, and at any distant future timescale. The atmosphere ocean system is likely the best understood, but even here projections of ocean temperature cycles, hurricane seasons, and the like are uncertain at greater than short time steps. When human activity, populations, technologies, markets and trade, migration, resource extraction, politics, and/or lifestyles are added to the picture, not only does complexity increase, but also uncertainty. Given the current state of knowledge, socio-technical systems turn out to be much less predictable than oceans and atmosphere—an important reason that climate change researchers have been working on a wide range of global social, political, and economic change scenarios besides environmental and technical layers of change (Moss et al., 2010). Rather than being gradual or even linear, technological change can be rapid, disruptive and even transformational or dominated by inertial forces with long lags from innovation to market penetration.

This has led some to criticize complex integrated (economy/environment) modeling as too uncertain to be useful for policy or planning (Pezzey, 2019). However, the use of large numbers of simulations to represent a wide range of imaginable outcomes has been suggested as a way to test for the effects of extremes (of weather, economic instability, technology stagnation, population growth, and so on) on the state of the overall system (Pindyck, 2017). Comparison of the results of multiple models has also been shown to provide a better sense of differences and how model assumptions and architectures affect estimation (EMF, 2019). Also, more exploratory and backcasting approaches to scenarios and modeling have been suggested as ways in which admittedly imperfect tools can yield useful policy information (Manning et al., 2006; van Vliet and Kok, 2015). Finally, in the academic literature, attention is also being turned to how models are used (Volkery and Ribeiro, 2009; Wilson and Grübler, 2011), how they may inform discussion in some cases and be misleading in others (Braunreiter and Blumer, 2018), and issues in translating qualitative stories into quantitative computation (Kok et al., 2015; Miller et al., 2015; Tyszczuk and Smith, 2018).

The lack of a common meaning of scenario in energy analyses, and the wide range of conceptual and modeling processes that are said to be using scenarios, demonstrate that this is an evolving area of analysis. The key finding for the current project is that thinking about energy futures, energy supply and demand transitions, changing climate conditions and human response, "storylines" and "future histories" will be necessary (Bushell et al., 2017). But the business of constructing and using scenarios in this sense and at the scale of California is an early work in progress.

California Modeling Studies That Have Used Scenarios

The following discussion narrows the focus to California and details some of the activities mentioned above. As noted there, formal energy modeling in California has pursued specific policy interests and has posed questions in relatively focused ways. Examples include concerns about matching supplies to demands, crediting energy efficiency gains appropriately, and exploring the potential effects of specific legislation and regulation. With increased concerns about climate change and impacts to the state's coastline, water supplies, infrastructure, and wildland fires, as well as proactive policies to reduce GHG emissions through cap-and-trade, solar subsidies, and other instruments beyond efficiency, the modeling brief has been expanded.[46] New studies have used energy modeling at various scales to explore a range of technological and environmental futures and to test the potential for policies to affect those futures. Some of those efforts are reviewed below, with an eye toward how scenarios have been used in varied ways in the California context.[47]

California Fourth Climate Change Assessment Impact Studies

To support California's Fourth Climate Change Assessment, coarse resolution projections from an ensemble of global climate models were downscaled to provide high-resolution portrayal of California's climate in terms of temperatures, precipitation, and other climate-related factors (e.g., sea level rise) and processes (wildfire, hydrology) for the 1950—2099 period. Two emissions trajectories (e.g., peaking ca. 2040 and then declining vs. business as usual) were used to portray California's future temperatures, weather patterns, extreme weather events, sea levels, fresh water supplies, drought, flooding, wildland fires, and so on at state and substate scales.[48] In these studies, scenario refers to two things: (1) different modeled global emissions concentrations, and (2) for state-level impacts, different possible outcomes in environmental conditions. The downscaled climate scenarios were also used in a number of vulnerability and resilience studies including research on the natural gas, electricity, and transportation fuel sectors.[49]

California Energy Demand Model and IEPR Forecast Analysis

State law has mandated the CEC to produce a biennial forecast of energy demand for the subsequent 10-year period to inform the Commission's Integrated Energy Policy Report (IEPR), which provides a basis for joint energy planning by California state agencies with energy and related environmental responsibilities. The California Energy Demand (CED) model has been developed over the past three decades as primarily a *bottom-up* model with additional inputs from various economic and demographic information and modeling sources. This model for the residential sector is built up from populations of energy end-use

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[46] While climate change was already a topic of discussion in energy efficiency forums in the 1990s (such as seen in the *Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings*), it was not until the mid-2000s that it became a strong focus in energy efficiency work.

[47] This is not a definitive listing. The cases were selected because they are central elements of energy policy support or are recent applications of scenario modeling applied to climate change in California. Notable related work over the past 15 years by Lawrence Berkeley National Laboratory (Ghanadan and Koomey, 2005; Greenblatt, 2015), Itron (Rufo and North, 2006), and Berkeley Economic Advising and Research (Roland-Holst et al., 2018) is not reviewed here.

[48] The technical details of model selection can be found in the Pierce et al. (2018) report *Climate, Drought, and Sea Level Rise Scenarios for California's Fourth Climate Change Assessment*. Data downloads can be obtained from Cal-Adapt (2019). A thorough discussion of the two climate scenarios used—the "moderate policy" Representative Concentration Pathway (RCP4.5) in which emissions peak around 2040 and then decline, and the RCP8.5 in which emissions rise throughout the twenty-first century—can be found in Wayne (2013).

[49] California's Fourth Climate Change Assessment overview and supporting technical papers can be found at: http://www.climateassessment.ca.gov.

technologies (appliances, lighting, heating, cooling, water heating equipment) distributed across the state in housing stocks, with associated energy requirements and efficiencies. In CED modeling, future aggregate consumption levels are estimated as outcomes of changes in end-use demands, which are derived from changes in technology efficiencies and population growth, which in turn partially depend on economic growth and personal incomes. In recent years, the CED model has also incorporated assumptions about changes in sources of renewable generation (residential PV) and electric vehicle charging.

Several different scenario approaches are used in the CED modeling, including periodic adjustment of the equipment saturations and efficiencies to better align with changing technical innovation in the base case scenario. The most explicit use of scenarios is in comparing how different combinations of technology, efficiency and renewable energy might, over the next 10 years, result in different levels of energy demand.

> "The California Energy Demand 2018—2030 Forecast (CED, 2017) includes three scenarios: a high-energy demand case, a low-energy demand case, and a mid-energy demand case. The high-energy demand case is characterized by relatively high economic/demographic growth and climate change impacts, and relatively low electricity rates and self-generation impacts. Lower economic/demographic growth, higher assumed rates, and higher self-generation impacts are included in the low-energy demand case. The mid case input assumptions are between the high and low cases." (CEC, 2019)

In this context, scenarios are technology trajectories that add up to different energy demand totals. Embedded in the three cases are rates of efficiency improvement resulting from both utility programs and market trends. However, no assumptions are generally made about the policies, behaviors, or market dynamics that might lead to one scenario or another—or to scenarios other than these.

California Public Utilities Commission Energy Efficiency Potential and Goals Studies

The California Public Utilities Commission (CPUC) is charged with regulation of the state's investor-owned utilities (IOUs). An important part of that work over the past several decades has been requiring and regulating IOU funding of cost-effective energy efficiency acquisition (Lutzenhiser, 2014). In support of that work, the CPUC conducts a regular analysis of energy efficiency potentials and goals, which involves a modeling exercise focused on the respective costs and benefits across the state of a large portfolio of possible energy efficiency technology investments. The most recent study uses five scenarios to differentiate efficiencies that might be achieved with different levels of subsidy, marketing, and stringency of estimates of achieved savings (Navigant, 2017).

In this context, scenarios are internal regulatory cost-benefit accounting alternatives. While larger policy contexts and recent state climate-related legislation are discussed as rationales for looking at much more aggressive efficiency goals, the regulatory authority of the CPUC Energy Division is for a narrow focus on IOU programs, cost effectiveness, and allowable rates of return to utility shareholders. So future policy possibilities are not considered, and while technological innovation is at the heart of the analysis, the details are not required for goals and potentials assessment. Finally, although the most aggressive efficiency scenario with the highest savings was predicted to result in about twice the savings as the business-as-usual reference case, the total additional savings add up to only a little more than 1 percent of total statewide electricity sales.

California Energy Commission EPIC Long-Term Energy Scenarios Studies

Three large CEC-sponsored long-term energy scenarios (LTES) studies were recently completed. In the first, University of California Irvine (UCI) examined possible impacts of climate change on the electricity generating system. As with the Fourth Assessment studies, using the same downscaled global climate scenario results discussed above as inputs for the analysis, the UCI team investigated "…1) changes in hydropower generation due to altered precipitation, stream flow, and runoff patterns; 2) changes in the availability of solar thermal and geothermal power plant capacity due to shifting water availability; and 3) changes in the residential and commercial electric building loads from increased temperatures" (UCI, 2019). The results were used as inputs to the other two LTES studies.

One of those studies was conducted by Lawrence Berkeley National Laboratory (LBNL) and used a capacity expansion model (SWITCH) for the Western States electricity grid to compare outcomes (electricity use, costs, air quality, policy goals) of six scenarios that tested different rates of adoption of energy efficiency and electrification of building energy use, industry, and transportation. These were the "frozen demand," SB 350, SB 350+electrification, aggressive energy efficiency (EE) without electrification, and aggressive EE with electrification scenarios (Wei et al., 2018). All are configurations of energy flows (as in the CED model), but with policy differences defining scenario differences (such as electrification or efficiency) and how rapidly technology change might occur in each. The study showed that these combinations would lead to substantial reductions in GHGs and that hoped-for policy goals are, in principle, achievable—if social choices (not modeled) were made. These sorts of models incorporate technical and sometimes economic variables, and do not explicitly consider policy options that might lead to technological change or evolving economic choices.

The consulting firm Energy and Environmental Economics (E3) also conducted an LTES study of "deep decarbonization" potentials (Mahone et al., 2019) This analysis used a different modeling platform and proposed 12 long-term scenarios, including a business-as-usual case that brought in SB 350 goals as targets ("a 50 percent renewable portfolio standard by 2030 and a doubling of energy efficiency savings relative to historical goals"), along with 10 variants of a "high electrification" case using different levels of technology adoption, efficiency and renewable energy considered to be "plausible low-cost, low-risk combination[s] of GHG mitigation technologies." Across the range of scenarios beyond business as usual, noteworthy GHG reduction potentials were estimated. As in the LBNL study, the social actions required to initiate and sustain the scenarios were not considered in the modeling.

Both the LBNL and E3 studies are end-state exercises that show what some future could be if a sequence of technology changes were to take place at a particular pace. But the action scenarios (the social choices and changes that would be required for the technology changes to occur) are general statements of social good and not storylines that have been elaborated in any way. For example, improved "consumer choice" and "market transformation" would be useful in stimulating modeled technological change (electrification of heating, "deployment" of more efficient technologies, aggressive adoption of Zero Emission Vehicles).

California Modeling Results

Without attempting to summarize the results of the various recent California energy, climate, and environment modeling exercises, some key findings can be called out. First, the Fourth Assessment Climate Change modeling studies found that impacts varied in extent, severity, and across substate regions, and often with quite significant impacts to be experienced by coastal ecologies and communities, watersheds, forests, agriculture, and urban communities due to flooding, drought, wildfires, wildlife impacts, air quality and human health impacts (Fourth Assessment, 2018).

Second, the CED modeling studies forecast (1) continued growth of overall energy demand and emissions, but with differences between sectors (buildings, residential appliances, industry, transportation, agriculture); and (2) that ongoing replacement of less efficient end-use technologies with more efficient versions will result in increased overall efficiency of energy use. The modeling also projects continued growth in distributed renewable energy sources (primarily residential solar PV). Simple technology adoption scenarios were tested that assumed higher levels of efficiency improvement and more rapid expansion of "self generation," and these showed large electricity demand savings at the final forecast year 2030. But the total electricity demand in that year would still not likely be less than the baseline year 2017 consumption. True, California has experienced substantial economic growth in recent years along with declines in GHG emissions (CEC, 2017, p. 23). But those emission levels would have to be reduced by more than 40 percent to meet the 2030 reduction goals of SB 32. So large new reductions are also necessary, and as research discussed below finds, potent new strategies to achieve these additional reductions—and quickly—are required, including prospective technologies not yet demonstrated or on the market, particularly in difficult-to-electrify sectors.

Third, the CPUC energy efficiency studies of potentials and goals found that as much as a doubling of currently projected energy efficiency savings could be obtained by relaxing regulatory criteria related to cost-effectiveness and the cost accounting for carbon reduction in IOU efficiency programs over a relatively short period. However, even marginal gains on that scale are quite small (1.5 percent of current electricity demand) compared to the reductions in demand from efficiency required to meet statewide goals such as the doubling of efficiency in buildings envisioned by SB 350.

Finally, a suite of laws and policies have been adopted in recent years to improve efficiency, move away from fossil fuels, reduce emissions, and consider equity and economics in so doing (see Appendix). The question addressed by the LTES studies by UCI (Tarroja et al., 2019), LBNL (Wei et al., 2019) and E3 (Mahone et al., 2019) was whether known and plausibly predicted changes in technologies, energy use, renewable supplies, and reductions in nonenergy emissions could reach ambitious goals such as those proposed by SB 32. Using somewhat different modeling approaches and assumptions, the LBNL and E3 modeling both found possible technological change trajectories that could economically meet those goals. However, "deep decarbonization" would require rapid and accelerating technology transitions in such key areas as electrification of building heating and high rates of adoption of electric vehicles (along with complementary system changes). Both modeling teams were agnostic on whether and how supporting policies might be put in place to foster those transitions, but they found that the economics of the new technologies would not be implausible.

However, LBNL pointed out that while these transitions are *possible*, to hit the targets at the pace modeled, rapid electrification of space heating and water heating would have to *begin very soon*. And E3 (Mahone et al., 2018) identified a range of barriers to rapid change, the most important of which involve consumer choice and pace of large-scale market change (in supply chains and other technology deployment channels).

> "This research highlights the pivotal role of the consumer in meeting the state's climate goals. To achieve high levels of adoption of electric vehicles, energy efficiency and electrification in buildings, near-term action is necessary to avoid costly replacement of long-lived equipment in 10—15 years. Furthermore, market transformation is essential to reduce the capital cost of electric vehicles and heat pumps." (Mahone et al., 2018)

And as others have stated regarding the role of consumers in energy transitions, "the potential agency of diverse publics moves far beyond the accept/reject dichotomy [of 'public acceptance']" (Ryghaug, Skjølsvold, and Heidenrich, 2018). Again, the E3 and LBNL studies were technology-focused modeling exercises, with market resistance or political opposition not modeled (technology deployment, adoption, transfer, and so on, modeled as "frictionless"). At the current stage of knowledge, these studies are the state of the art and have made important contributions to set the stage for public discussions. They bring California to the threshold of questions about what changes are imaginable that could usher in large-scale decarbonization of energy use—as well as how those changes might be best pursued. However, the efforts of both policy makers and communities to consider these things will clearly require more than even the most sophisticated current modeling systems can provide—at least without considerable cost in time and resources. In addition, it is widely recognized that energy use behavior, consumer choices, and supply chain dynamics all strongly influence technology adoption and determine the effectiveness of policy strategies. So far, these are external to conventional modeling and energy policy analysis.

Limitations of Current Modeling Platforms for Scenario Analysis and Energy Planning

Almost without exception, questions of policy implementation are external to the dominant planning models. Following on norms set by EIA for NEMS years ago, speculations about policies (new carbon taxes, aggressive regulations, accelerated expenditures, and so on) are not considered inside of the models. In a much broader way than NEMS, the California scenario modeling used by the CEC, CPUC and recent LTES research has brought the ambitious emissions reduction goals of current policies and possible changes to current policies (including the CPUC energy efficiency valuation) into the modeling context.

But as valuable as this broadening has been, current modeling platforms are mostly posing questions such as "Could this be accomplished?"—rather than going further to ask "How might policy A stack up against policy options B, C and D in meeting goals?" Partial exceptions are the E3 LTES studies that analyzed in detail a high-electrification scenario and 10 different mitigation scenarios, with comparison of cost and benefit potentials. These scenarios are defined as technology outcomes (by 2030 "100 percent new sales of water heaters and HVAC are electric heat pumps; 91 percent of building energy is electric;" or "6 million ZEVs (20 percent of total) and more than 60 percent of new sales are ZEVs"). The actual policies to get there, such as cap-and-trade, subsidies, taxes, codes and standards mandates, and so on, are explicitly excluded.[50] Even breaking new ground as it does, this research was not intended to examine the policies, programs, or other instruments that would help reach these goals.

That, in fact, is not imagined in any current policy modeling that the authors could find. Nor is going even further to ask questions such as "If federal efforts to overturn California vehicle emissions regulations were successful, or if an influx of climate migrants dramatically increased energy demand, or a future legislature outlawed new natural gas heating systems, what might be the effects?" Until recently, these possible *future history* deviations from the current business-as-usual case would have been considered very speculative. But that sort of outside-of-the-box speculation in the context of growing climate impacts, emerging policy discussions, and extremely ambitious legislative goals now seems warranted. Given the limitations of modeling mentioned above, and discussed in greater detail below, a more exploratory approach to modeling that incorporates new dimensions, questions and approaches may be a good first step to considering those sorts of questions (Bankes et al., 2002; Weaver et al., 2013).

Looking More Closely at Scenarios and Models

All models are limited—by intention, design, and execution. And, of necessity, current models used in California for energy system and climate change planning are limited in their usefulness in policy debates and public deliberations about achieving ambitious climate goals in flexible and responsive ways. The importance of this observation is that the current modeling tools are not readily able to produce the kind of practical understandings necessary to develop effective public policies and market/citizen responses that can accelerate the energy transitions required to meet legislative goals. Drilling down, at least four things contribute to this.

1. Models focus on some parts of systems and ignore others. Models cannot consider everything, and those things they are able to consider are treated in different degrees of detail. They may also include gross effects from outside of the system being analyzed (population projections or economic growth rates in the CED model imported from other state agency databases and models), which are not intended to be as detailed as the parts of the system being considered inside of the model (such as appliance stocks or equipment efficiencies, decay rates for buildings). In other cases, some parts of the system are held constant, such as the carbon mix of electricity supply, for example. Some variables may be allowed to take on different states (such as heating demand differences across regions or housing types) within the model. However, others may be

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[50] "Finally, this study aggregates statewide costs and benefits, explicitly excluding the effect of state incentives and in-state transfers, such as Cap-and-Trade, the Low Carbon Fuel Standard, and utility energy efficiency programs. Costs borne by individual households will differ from the average and will depend on policy implementation. Further research could investigate the cost implications of specific state policies on individuals and businesses." (Mahone et al., 2018, p. 5)

averages (thermostat settings or equipment efficiencies), which may be rolled into a gross average heating demand per square foot.

A problem with using averages is that it buries the variability of behavior, choice, and even technology performance that can be useful in spotting problems and proposing solutions, thus blinding interpreters to so much possibility. Variation, among other things, provides clues to where the biggest problems may lie as well as helping to uncover situations that can serve as exemplars or leverage points for positive change. They also can be highly important in estimating effects of changes elsewhere in the system—for a simple example, a $40 *average* increase in monthly utility bills over a year across households due to a tariff change (to time-of-use tariffs, or changed tiers) could plausibly mean a $300 increase in a summer monthly bill for many households. Averages also turn attention away from distributional effects and equity considerations, as well as opportunities for substantial emissions reductions in groups that are not average.

2. Models designed for legacy purposes are not readily adapted to reflect scenarios. Instead, models designed for specific purposes when they were developed are now being asked to take on new questions. Tools that were designed to incorporate and forecast outcomes for incremental improvements in efficiency are not readily suited to address energy system/supply-demand transformation of the scale and speed required to meet SB 100 goals. The aims and the scales are different. Some of these questions may require slight modification and reruns of existing models (changes in coefficients or even equations). But they are time consuming and often beyond the current brief of the modeling group. For example, emissions outputs can be grafted onto energy demand forecasting models or grid operations models, or even local/regional transportation and land-use models. But new questions (such as the dynamics of hourly emissions) may involve asking more complex inquiries that require adding new variables, rewriting algorithms, introducing nonlinearities, and more complex relationships among variables are all extremely difficult on large legacy platforms. In addition—because of basic architectures and assumptions—asking those models to run and rerun quickly as inputs and relationships are changed, or to compare the results of large numbers of runs, is completely beyond their capacities.
3. There is a fundamental lack of important data to support target analysis. While efforts are now underway at the Energy Commission to assemble data on energy, technology, policy, markets, and so on to support analysis and inform policy-making (see McAllister, 2019), demand-side data in particular are extremely limited, and, when they exist, are often proprietary (e.g., controlled by utilities or technology firms) with restrictions on the degree to which households can be identified, limiting the degree to which demand data can be merged with details about the house, household, or location. Limited data lead to uncertainty in assumptions and uncertainty about model results. Again, the large and legacy nature of models often limits modelers' abilities to compare results across different input data sources. The Energy Commission's new data initiatives will likely support expanded analysis and address some of these uncertainties.
4. Analysis is highly technical, requires expertise and time and entails communication challenges. The size and complexity of energy forecasting and energy planning/analytic modeling systems mean that it is difficult to use them for detailed, nuanced, and

dynamic scenario planning. When scenarios are used on those platforms, they tend to involve repatterning of technology configurations and rates of change at highly aggregated scales. Even this is no easy task, requiring programming expertise, considerable staff time, and software modifications not imagined when the models were originally designed. And when modifications are added over time, the models become more complex and more opaque, with technical knowledge and historical knowledge required to understand the growing model. So, if large-scale scenario analysis can be attempted at all, it will be time-consuming and costly. More important, while the contributions that this modeling work make to support energy policy and the public interest are crucial, those results are not readily accessible or usable by the public, or even by technically sophisticated energy and climate system stakeholders. Climate scientists have recently called out the urgency for climate research to better connect with civil society, including by providing more scientific support for practitioners whose work intersects climate change adaptation and mitigation (Moss et al., 2019).

A Framework for Understanding the Uses of Scenarios

As demonstrated above, scenarios are used in a wide variety of ways in formal energy system modeling in California and beyond. All are legitimate as storylines and guidelines for selection of quantitative depictions used in modeling at various scales. However, there are distinct differences that need to be called out and better understood.

Taking scenario analysis first as a broad strategy for exploring questions about possible futures, how those questions are posed define purposes and shape the answers that can be obtained. As discussed above, policy requirements (laws, regulations, organizational goals) often drive the questions, and the answers obtained are primarily useful in supporting those requirements. But other purposes and questions are also possible and increasingly necessary in the evolution of climate change policy.

Table 4 presents a typology of scenario questions and purposes. California modeling scenarios are identified with the "What might happen?" and "What could happen?" and "Could this happen?" questions. This leaves a large number of imaginable "What if?" and "Should we?" and "How to?" scenario questions to be considered.

Table 4: Scenario Questions, Purposes, and Models

Scenario Questions	Purposes	Comments	Models
"What will . . . [likely happen]?"	Prediction	Forecasting the future	NOAA
"What might . . . ?"	Projection	Considering differences in the future	CEC CED
"What could . . . ?"	Outcome testing	How much difference it makes	CPUC
"Could this . . . ?"	Reality testing	Whether proposed actions can reach a goal	E3, LBNL
"What if . . . ?"	Comparison	Assessing relative effects	Ripe for exploration using ABM such as SIMSAND
"Should we do this?"	Normative	Investigating harms that might result	Ripe for exploration using ABM such as SIMSAND
"How to do this?"	Pragmatic	Fine-tuning actions for focused effects	Ripe for exploration using ABM such as SIMSAND

Source: QQForward, 2019.

In particular, the "What if?" and "Should we?" questions get closer to the idea of scenarios as *future histories*. Moving beyond analysis that poses the question "Can we imagine a sequence of technology rates of change that could get to a 40 percent GHG reduction endpoint by 2030?", a richer comparison of future possibilities would also ask "What if…?" alternative policies, social changes, technological trajectories, and environmental conditions interacted in different ways, unfolding in different futures that we might want or not like to have come about.

Building on the "Is it imaginable to get to the goals?" in the LTES work, in order to achieve the *imaginable*, the "What if?" questions have to be posed and examined in detail. In that exploration, distributional impacts and real-world constraints will emerge as aspects of various "What if?" analyses. And as questions of equity and shared environmental burden that are of increasing concern in California as climate change policy innovations (and environmental threats) proliferate, an even more nuanced approach to scenario modeling is required. That approach would admit questions of "Should we?"—which are essentially questions about unintended consequences, distribution of benefits and harms, and micro-impacts (in locales and social groups) of macro policies.

Finally, more complex and contingent scenario modeling allows better design of interventions, incentives, and regulations by comparing possible outcomes and surprises in a simulation environment, before implementing in the field. Some of this is already done on an *ad hoc* and spreadsheet basis in efficiency program design. However, the lack of tools hampers asking pragmatic questions and exploring "How to?" alternatives across scales—from statewide regulations to local program design, community initiatives, and local government climate change adaptation plans. This sort of "How to?" analysis goes beyond the broader "What if?"

considerations to investigate questions about setting reasonable specific outcome goals and expectations for pace of change resulting from policies and interventions. After implementation, both goals and expectations can then be revisited as events unfold and understanding and actions refined to support another round of "How to?" planning and implementation (similar to the cycle proposed for market transformation initiatives by Blumstein, Goldstone, and Lutzenhiser [2000]). This also allows policy choices to be framed in systems terms as "adaptive challenges" rather than "technical problems" (Heifetz, 1994).

Scenarios and Modeling Related to Residential Air Conditioning

Focusing in on the problem of residential air conditioning, a reasonable question would be "What are the models predicting about air conditioning energy use in the future in California, under what conditions?" The answer is not clear in most cases. There is agreement that rising temperatures will increase demand for residential cooling, and will increase peak demands as well as overall electricity use a during hot months, days, and hours of the day. Increasing occurrence of wildfires, and the air quality concerns that smoke from these fires pose, may lead to even more demand for air conditioning and indoor air filtering. But in much modeling, cooling is often wrapped up in larger categories, such as regional or sectoral space conditioning. And breaking those aggregates down, residential air conditioning as a specific technology/human activity demand domain is often itself buried and concealed in metrics such as kWh per square foot that mixes heating, cooling, lighting, plug loads, and so on in a single value.

While we know from limited available data on cooling at the household level that air conditioning demand can differ considerably between buildings depending on energy use patterns and system type, age, efficiency, maintenance, and other factors. But in most modeling, averages must be used to try to summarize over that variability. This is problematic for two reasons. First, as signaled above, it is easy to mistake the average for an accurate representation of reality, though it is well known that very different distributions of values can produce identical averages. Second, it is in the variation that the most powerful understanding lies about where changes might be made (in technologies and use), and where those changes are less likely or completely unrealistic.

However, what has been available to date to inform policy on residential cooling has largely been low resolution and technology-focused frameworks that rely on rough estimates from very limited data on how people use technologies, and how these technologies perform. Also, the geographic scales available are broad and low resolution, while actual conditions can vary importantly at much more refined scales. In sum, effective policy in this area requires a more detailed understanding of the world than is—or can be—captured in current modeling practice.

The following chapter presents the results of developmental research on the use of agent-based modeling to pose and explore "What if" questions related to California and residential cooling. The proof-of-concept simulation sandbox developed in this project is called SIMSAND, as mentioned earlier in this report. To set the stage for that discussion, Table 5 (next page) illustrates a variety of possible "What if" scenarios that could potentially be investigated in exploratory simulation modeling related to climate and cooling, such as that operationalized in SIMSAND.

This is clearly a wide range of questions and possibilities to explore. Some may seem outside of the conventional framework of policy discussions. But, as noted above, the seriousness of the problems, the ambition of the policy goals, and the magnitude (in scale and speed) of implied transitions require beyond-business-as-usual thinking as well as public consideration. Planners and policy makers at the state level have been starting to shift viewpoints from an "Is it possible to do this from a techno-economic perspective" to a "How do we manage transition safely, equitably, affordably, and effectively?" A good place to conclude this discussion is to summarize a research agenda that uses a flexible simulation modeling approach.

California is faced with an obvious problem: climate change involves hotter summers and more frequent extreme heat events. This will increase the demand for air conditioners in regions and among households that currently do not have it. It will also mean that air conditioning units will operate longer, consume more energy than in the past, and will contribute to higher peak loads on the grid. There will be differential effects in different parts of California and there could be growing negative impacts of weather and related environmental conditions on lower income, elderly, rural/agricultural, and health challenged households, exacerbating current environmental equity problems.

Table 5: Other Possible Scenarios for Simulation Using SIMSAND

"What if" Scenario Description	Narrative
Baseline projection of changes in California demand	California proceeds under "best available" status quo trends and projections, as consistent with IEPR, California's climate change assessments, demand forecasting models (CEC, 2020), etc. Incorporates economic, demographic, population, climate, construction, and retrofit/EE trends.
Doubling of EE in building envelopes, AC systems	California proceeds with goal to double efficiency in buildings by 2030, as it ends up being defined.
Emerging technologies, emerging challenges	New technologies of various sorts (PV, storage, smart controls, solid state AC, solar thermal absorption AC, etc.) proliferate. Do certain combinations of these technologies result in unanticipated consequences for demand?
AC in the middle: AC control is shared, and more contested	Smart thermostats, networked thermostat control, and energy management tools, interfacing with more dynamic rate structures, further complicate already contested household control of thermostats and AC. Meanwhile, other households retain control or cede it to algorithms. What unanticipated changes in demand might result?
A brave warm world? Resisting or embracing a culture of AC and climate control	Will Californians exhibit a capacity to resist increased reliance on climate control in their homes? Or, will rising temperatures, more severe weather events, concerns over the security of the outdoors, and an ever-strengthening (online) connected culture together drive folks indoors more and more, with increasing reliance on AC?

"What if" Scenario Description	Narrative
Targeted or untargeted electrification: reducing vulnerability while reducing emissions	Replacing gas heating systems with electric heat pumps becomes a policy objective; can a targeted implementation (preferentially incentivizing the switch to electric heat pumps for homes with greater vulnerability to extreme heat events) yield increased social benefits without compromising environmental benefits?
Uneven upgrades, uneven benefits	Wealthier, more educated homeowners overwhelmingly retrofit/adopt the newest high-efficiency ACs and controls and receive the benefits. How are costs and benefits distributed, and how effective is carbon reduction in aggregate?
Rehabbing outdoors: cool roofs, pavement, and outdoor spaces	Communities create outdoor spaces more habitable in high heat events, including efforts to reduce local "heat island" effects—allowing people to rely on AC less, while also reducing AC loads. What is the potential for energy savings and carbon reductions?
Stubborn demand: strong policies and strong policy resistance	California aggressively pursues policy targets related to GHG reduction and EE, but AC demand proves difficult to reduce (e.g., due to take-back, physiological acclimation to space conditioning, industry not buying in, unintended consequences, etc.). How much might these mechanisms interfere with energy savings and carbon reductions?
AC peak flattened, blurred	As a successful result of a portfolio of EE, tech adoption, behavior, and rate strategies, the AC peak issue is "solved," and AC loads become sufficiently responsive to TOU rates. What behavior and other changes might be necessary? Are there unanticipated impacts?
Changing refrigerants post-Kigali: social acceptance dynamics slow carbon reductions	The transition of AC refrigerants to replacements with substantially different properties, e.g., flammability or toxicity, result in substantial social and/or industry resistance. What effect might this have on achieving environmental benefits?
The perfect (demographic) storm	Demographic and population shifts in California drive a transition in AC demand due to aging populations, increased ethnic diversity, changing economic conditions, and movement of populations within California. Could incremental changes cause a large transition in AC demand? What combination of factors might cause this?
Unsupportive external contexts create cross-winds	Fossil fuel prices, population migrations, federal policy shifts, resumed drought, etc., alter trajectories in California relevant to AC demand. How sensitive is future AC demand to these factors, individually or in combination?

Source: QQForward, 2019.

It is essential, then, to better understand how cooling technologies and populations of California households may interact with the weather and changing climate conditions. And against the backdrop of this knowledge, questions should be posed about the potential impacts of policies and programs, individually and jointly. Comparisons can be made about the benefits and shortfalls of different technologies and markets, and the influences of cultures and communities. Here is a concrete case where moving from "Could we?" to "What if?," as well as "Should we?" and "How to?" questions and scenarios would be of considerable benefit. The next chapter presents a modeling framework to explore these questions.

Scenarios and Histories

- Energy use scenarios play an important role in envisioning and shaping energy transitions, policy strategies, and the future overall. How futures are imagined will help determine what futures will be. This project reviewed residential energy scenario and scenario-related activities in use in California energy and climate policy planning with an eye toward what changes may be needed to support these "imagining" processes.
- This review suggested a need for expanded energy transition scenario development and planning processes for envisioning the future of both demand and supply, e.g., household energy use in a highly renewables-dominated energy system. These scenarios should go beyond traditional technological projections by addressing a broader range of possibilities, some of which can be suggested from the history of energy transitions.
- Such scenarios could reflect the "What if?," "Should we?," and "How to?" questions important in applying energy futuring to the real world. These What-Ifs could involve, for example, unexpected changes in weather patterns, major changes in how households cool, or in technological performance. Appropriate models (such as a fully-implemented version of SIMSAND for the residential sector) would be required to explore and resolve such questions.

CHAPTER 5: SIMSAND, a What-If Sandbox Proof-of-Concept

The research team developed the concept for a "What if" simulation sandbox for exploring residential sector energy futures that would: (1) reflect the diversity of household energy use by drawing from household-level interactions; (2) be capable of reflecting a wide variety of scenarios; (3) coordinate necessary data streams with high ability to select and update data options; and (4) be easy and flexible to tailor to specific questions and emerging issues. This concept was demonstrated with a limited proof-of-concept implementation, SIMSAND, which focuses on the case of air conditioning for California households. SIMSAND in current form is not intended to be enterprise-ready.[51] Instead it provides a platform that that can be broadened and further developed to meet the needs of particular use cases identified through discussions with the climate change and energy efficiency research and planning community, and to use new or otherwise improved data as available and relevant.

This chapter outlines the "What if" simulation sandbox concept and describes its implementation in SIMSAND. It summarizes the results of demonstration scenarios modeled in SIMSAND, sketches possibilities for future development, and discusses the potential role of this type of simulation in energy transition planning.

What-If Simulation Sandbox Concept

The broad vision of a simulation sandbox is of a platform that makes it easier for researchers, analysts, planning experts, and interested members of the general public to think about and explore "What if" questions about the mid-term energy future, playing out specific detailed scenarios using defensible data on current and historical residential energy use. Such a platform could provide a way to help break into, map, and discuss aspects of energy use and energy change that currently are hardly accessible or manageable. In particular, it models *interactions* between the various types of factors that affect energy use and users, and it allows high levels of flexibility in specifying scenario assumptions, in light of observations made above on actual technology history. This more realistic expression of change could be used to develop insights about how energy transitions might unfold, and how they can be directed to provide not only GHG emissions reductions but also equitability and cost-effectiveness.[52]

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[51] For example, SIMSAND as currently implemented focuses on energy outputs, without translating these outputs to GHG emissions. Depending on the specific questions and scenarios explored, GHG emissions estimates might best be accomplished by incorporating the dynamics of hourly emissions from a transitioning supply system in addition to assumptions about the global warming potential of involved refrigerants. That could be added in a module that integrates into the existing modeling structure. It also used limited information on air conditioning response, which could be updated with more detailed and more recent information that is potentially available. These and other possible expansions are discussed below.

[52] The approach is not inherently limited to the residential sector, to demand (versus supply, distributed energy resources, etc.), or to energy-related outputs (versus resilience or socio-economic impacts). Rather it allows assimilation of diverse data streams, analytic methods, and models, works across a range of scales, and enables flexible exploration of user-defined output metrics and interventions.

There are already a variety of mid- and long-term energy futures models for California (Kavalec et al., 2018; Mahone et al., 2018; Wei et al., 2018; Wei et al., 2013, Roland-Hurst et al., 2018; Tarroja et al., 2019). These have been developed for distinct purposes and specific questions, rather than for use in detailed exploratory "What if" and "How to" analysis of potential socio-technical transitions. Such modeling requires specific capabilities (Köhler et al., 2018), including representing the heterogeneous people at the center of these transitions (Moezzi et al., 2018).

As a platform specifically designed and tailored for "What if" exploration of plausible futures and transitions, while taking people and real-world variability into account, a simulation sandbox can generate new possibilities for exploring future scenarios (Table 6). Recent analysis of strategies to rapidly transition California's energy system has highlighted the importance of human-dependent dynamics in these transitions, pointing to the "the pivotal role of the consumer in meeting the state’s climate goals" (Mahone et al., 2018). This assessment echoes the conclusion of many social scientific studies on energy use and how it changes (Lutzenhiser et al., 2017; Malone et al., 2018; Rinkenen, Shove, and Torriti, 2019).

Table 6: New Possibilities Enabled in a "What if" Simulation Sandbox

General characteristics of existing tools	Simulation sandbox opens different possibilities
People, though central actors in energy demand, tend to be marginally represented Data may be highly distilled and averaged within broad categories Row & column architecture not well-suited for high levels of interactivity and potential non-linear effects (e.g., weather + household habits + feedback + technical characteristics) Difficult to assess uncertainties and how they relate across dimensions Often analyses are one-off	Oriented to flexible incorporation of diverse and evolving data streams that incorporate human element—especially by focusing on household-level agents Individual household/segment basis helps avoid over-averaging Californians More attentive to interaction, covariance, nonlinearity, dynamics, relationships, and distributions Designed for detailed multidimensional scenarios Ability to explore more dimensions of possibility and of the space of uncertainty Potentially cumulative or general platform, vs. one-off Potentially suitable for use for quick turn-around analyses without requiring specialized training

Source: QQForward, 2019.

SIMSAND for Cooling

SIMSAND, the proof-of-concept implementation developed for this project, fulfills this initial vision, specifically for the space cooling residential end use.[53] An agent-based modeling (ABM)

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[53] Specifically, space cooling here refers to central, room/window, and evaporative air conditioning across housing types (single family attached and detached, multi-family, and mobile homes).

approach was chosen for implementation of SIMSAND, due to the inherent flexibility of the models and natural fit for doing household-level bottom-up geographically distributed modeling, as well as suitability for transitions modeling (Köhler et al., 2018, Mercure et al., 2016). ABM is a bottom-up technique involving computational simulation of a system composed of any number (and types) of "agents" acting autonomously, interacting with each other, and interacting with their environments.

ABMs have been less commonly used in energy demand modeling than in some other domains.[54] There has been a recent surge in applications especially of the closely related building stock modeling approach applied in California, at national scales, or at county or urban scales (Dirks et al., 2015; Wilson et al., 2017; Reyna and Chester, 2017; Hong et al. 2017; Reinhart and Cerezo Davila, 2016; Burillo et al., 2019; Raghavan et al., forthcoming). These models tend to use a set of building prototypes to project demand and to analyze building retrofit and technology potentials, but can be weaker in representing the people who do or could occupy the houses represented by these prototypes. ABM applications in this domain also include the device-and-grid centric "Gridlab-D" (Chessin et al., 2014) as well as simulations closer in structure to the SIMSAND, but focusing on other locales and other applications (Subbiah et al., 2017; Thorve et al., 2018). As far as the authors are aware, the SIMSAND approach (as a household-centered energy transition exploration tool), and California focus is a distinct and new contribution.

As described below, the prototype SIMSAND has been completed, and demonstrates the flexible, data-based, and generalizable approach, as proposed. The key elements of SIMSAND are: the household and house agents and how they represent the population and are scaled up; space cooling use and energy simulation; and representations of change from history into the future in terms of behaviors and change processes directly altering cooling use or AC energy demand, as well as the context factors affecting these (Figure 5).

Modeling Cooling Energy Use in SIMSAND

The agents at the heart of SIMSAND reflect individual households, together with the houses[55] they occupy, including house and equipment/technology characteristics, household characteristics, energy use profiles, and equipment and energy use behaviors.[56] In SIMSAND, agents are dispersed across California’s utility service areas, climates, and counties at a ZIP Code resolution.

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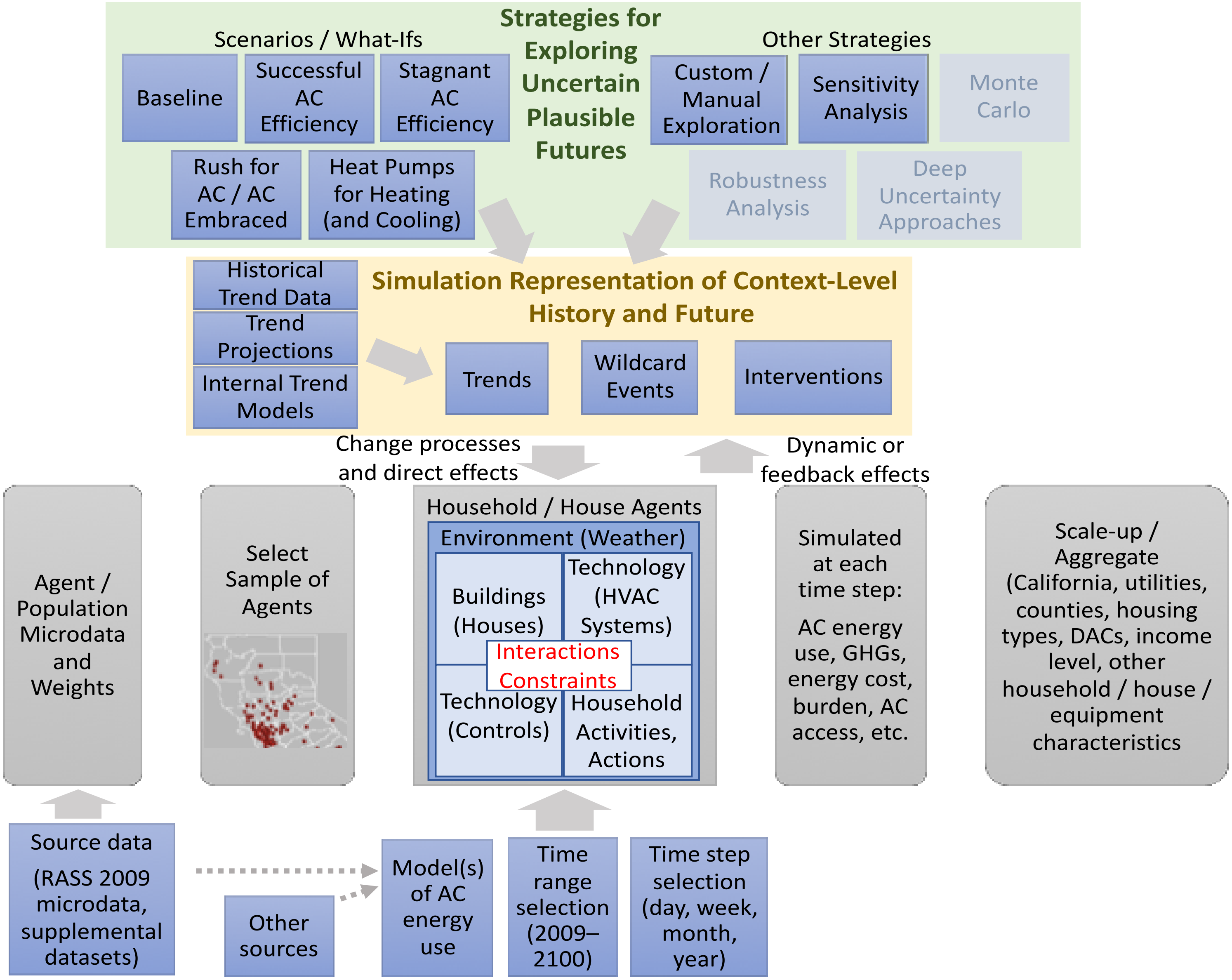
[54] ABMs are more commonly used in social simulation and environmental/ecological simulation, for example.

[55] "Houses" is used throughout to refer to a range of housing unit types, including single-family detached and attached houses, multifamily units, and mobile homes.

[56] More specifically, agents are households and houses, specified distinctly but colocated and linked to represent household agents occupying a particular house agent, while allowing (though not currently modeled) households to move, houses to be unoccupied or acquire new households, etc.

Figure 5: Key Elements of SIMSAND



Source: QQForward, 2019.

Agents are data-driven; their characteristics are sampled from a subset of 6,612 cases drawn from the microdata and billing data gathered in California's most recent Residential Appliance Saturation Survey (RASS), which was for 2009 (KEMA, 2010). Energy end uses are simulated for each agent at every time step, that are adjustable between daily, weekly, monthly, and yearly increments, and simulations can be run from 2009 through 2100. The air conditioning energy end use, the focus of the SIMSAND prototype, is calculated from a weather-driven statistical model individually fit to each agent household/home's historical electricity billing data,[57] with alterations to represent any simulation-based changes in house, equipment, or household affecting AC energy use, such as replacement of the agent's air conditioning equipment with a new model. Daily weather data, currently sourced from Cal-Adapt (https://cal-adapt.org), gridded observed data (Livneh et al., 2015) or climate projections (Pierce et al., 2018, Pierce et al., 2014), are fed into SIMSAND via a synthetic, flexible set of weather stations, each pulling in single-location weather data, aggregated in time if necessary, and mapped to nearby individual agents. The weather/climate data mechanism is flexible, and can readily incorporate data streams at other spatial and chronological resolutions.

Simulated household-level time-resolved energy end uses can then be processed to estimate other outputs/outcomes, including air conditioning energy costs and burden, and CO_2 emissions.[58] Other outputs, such as refrigerant GHG impacts or other equipment lifecycle impacts, are not currently modeled in the SIMSAND prototype, but can be added in at final implementation. Available outputs can be aggregated or grouped to the desired level (climate zone, utility, county, income level, disadvantaged communities as per DAC definitions, equipment type, or any defined house or household characteristic or combination thereof). Aggregation from individual agents to groups and populations is achieved using population weights assigned to the agents, analogous to and, in this implementation, partly derived from RASS survey sample weights.

Modeling Change Processes and Interventions in SIMSAND

Each household's simulated energy use changes in time as a result of changes in agents' characteristics and how they interact (such as equipment changes and behavioral changes). Several change processes (and related dynamics) are currently modeled in SIMSAND that affect agent characteristics and space cooling; these include AC equipment replacement, AC system adoption, installation quality, and increased levels of use due to efficiency (takeback). Other behaviors are also modeled that may affect space cooling use independent of equipment

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[57] This AC demand modeling approach loosely follows the well-established "PRISM" (Fels, 1986) or two-change point linear modeling procedure. This is only one of many possible approaches to modeling demand, each with strengths and weaknesses. SIMSAND is intentionally agnostic in terms of analytical methods. Alternate and multiple models can be supported and compared within the framework.

[58] Electricity rates usually vary by time, and the degree of variation will intensify if more dynamic rate mechanisms are implemented. CO_2 emissions from electricity use are already complexly dependent on dynamic and evolving supply-demand system conditions. As such, translating AC electricity use into resulting electricity costs and CO_2 emissions requires simulations of energy system scales not currently represented in SIMSAND. These systems could in the future be simulated in SIMSAND, or could instead be run interactively with stand-alone electricity rate and CO_2 emission simulations (as a co-simulation). Or projections from such simulations could be used noninteractively for SIMSAND.

changes, including thermostat-setting shifts, changes in when households are home, and income and electricity price elasticities of AC demand.

These processes shape simulated AC energy use. In turn, many of these processes and behaviors are shaped by context-level trends, and changes to climate, macroeconomic conditions (per capita income, unemployment, and inflation), electricity price, population, and shipped AC equipment efficiency levels. In SIMSAND, each context-level trend is specified based on historical observations (where reputable published data are available), and from future projections derived from one or more of: publicly available projections, extrapolation of published historical and/or projected trends, and internally defined models (specified within SIMSAND, such as using a fixed growth rate model). Trends are mapped into SIMSAND based on the geographic resolution of available data (statewide, utility-scale, county-scale, and so on). As context-level changes are a key source of uncertainty in future energy use, SIMSAND allows the user to select among multiple alternative projections, or adjust and tailor these, including unpredictable wildcard events or discontinuous context changes, such as an abrupt economic recession (or boom) or an electricity price spike (or drop). an example, future rates of air conditioning adoption might be simulated based on a simple fixed-rate model, based on projections derived from the California Energy Commission's Demand Forecast Model, which were established from observed relationships between climate and air conditioning saturations (Sailor and Pavlova, 2003), or by modeling a household's propensity to install air conditioning at least partly dependent on that household's recent experiences (such as exposure to extreme heat events potentially enhanced by climate change).

Several stylized policy interventions targeted to air conditioning are also included as optional selections in SIMSAND, among them:

- Improving installation quality: assumes an intervention that improves levels of compliance with new/replacement HVAC permitting rules, resulting in increased distribution system efficiencies
- Targeting heat pump as an electrification measure: assumes an intervention that increases uptake of heat pumps by low income and/or disadvantaged community households
- Targeting air conditioner replacement: assumes an intervention that increases AC replacement rates for low income and/or disadvantaged community households
- Cash for AC clunkers: assumes an intervention that increases early replacement of old/inefficient AC units with new AC units
- Replacing HVAC clunkers with heat pumps: assumes an intervention that increases early replacement of old/inefficient HVAC systems with new heat pumps

The onset date and intensity of each of these interventions can be altered by the user, allowing comparison across various combinations of policy designs and future conditions.

Exploring Uncertain Futures with SIMSAND

SIMSAND simulations play time forward, starting from initial historical or recent conditions, toward simulated futures defined by some combination of change trends, wildcard events, and stylized interventions. These change *knobs* can be adjusted to simulate various future conditions—and combined to model distinct scenarios. Five such scenarios are preconfigured in

SIMSAND, as shown in Table 7. Four of these tell basic stories of the future that are qualitatively like the past. The fifth represents a "What if" scenario posed to enable exploration within a more aggressive future scenario frame.

Table 7: Space Cooling Scenarios Preconfigured in SIMSAND

Type	Scenario	Description
Basic story	Baseline	Moderate levels of new AC adoption, shipped AC efficiencies, installation quality, AC replacement rates, and takeback
Basic story	Successful AC Efficiency	AC efficiency efforts are relatively successful, with high shipped efficiencies, high installation quality (duct retrofits etc.), high rates of AC replacement, and low levels of takeback
Basic story	Stagnant AC Efficiency	AC efficiency efforts are relatively unsuccessful, with stagnant shipped efficiency levels, low installation quality (high rates of noncompliance, leaky ducts etc.), low overall rates of AC replacement, and high levels of takeback
Basic story	Rush for AC; AC Embraced	Rapid move toward greater reliance on AC—high rates of new AC adoption driven by extreme heat events, high rates of existing AC replacement, high levels of takeback, increased use of cooling in homes (thermostat set lower in summer), and households staying cool in the home more during the heat

Source: QQForward, 2019.

Of course, the future is hard to predict, and various kinds and sources of change and uncertainty can affect AC use and demand. See, for example, the much wider-ranging set of AC-related scenarios listed in Table 4 (Chapter 4). From the planning- and policy-oriented modeling frame of SIMSAND, future system states depend on initial conditions, change processes, and surprises at both a system level and a more local context level. Various processes affect AC use and associated impacts that are not currently modeled in the SIMSAND prototype, such as refrigerant emissions and other equipment lifecycle impacts and efforts to transition these; urban heat island effects and mitigation efforts; smart or direct control thermostats with resulting alterations in cooling patterns; novel technologies; and large-scale home energy retrofit efforts. In turn, uncertainty about the future system state emerges from limits to measurement and data; limits to model representations of the system, context, boundaries, and changes thereof; and interactions between and limits to the imagination related to all of these.

Some of this uncertainty can be explored in SIMSAND using currently implemented techniques:

1. Sensitivity analysis: how do outputs (and outcome-relevant metrics) vary with varying model assumptions, either univariate or multivariate

2. Comparing across distinct scenarios, such as how different is AC energy use in 2030 and 2050 under Rush for AC scenario assumptions, than under Baseline assumptions?
3. Analysis within a “What if” scenario frame, such as if one assumes the Heat Pumps for Heating (and Cooling) scenario, how might different intervention choices or designs affect outputs and outcomes?

Additional advanced techniques are possible for future implementation (possibilities for SIMSAND are discussed in a section below). While exploring such an open space and questioning so many assumptions can be daunting, the process can be useful for acknowledging uncertainty, working to reduce understanding and modeling gaps, and for informing plans that are more likely to be resilient, robust, and adaptive in the face of an uncertain future (Walker et al., 2013).

How Well Do SIMSAND Outputs Represent Historical and Current Realities?

SIMSAND outputs were compared to historical datasets from which AC energy use can be estimated at various time and spatial resolutions, including EIA's monthly residential electricity sales by utility (Form EIA-861M) and the public dataset with hourly total electricity use by sub-Load Aggregation Point (subLAP) and utility (and clusters therein) generated as part of the 2015 California Demand Response Potential Study (Alstone et al., 2017). SIMSAND air conditioning demand estimates corresponded reasonably well with these estimates, considering sample sizes, source data limitations, and the relatively simple air conditioning energy use modeling method implemented in SIMSAND.

SIMSAND Application: Heat Pumps for Heating (and Cooling)

To demonstrate how "What if" exploration can help inform residential energy planning, the research team developed and executed a test case in SIMSAND focused on heat pump air conditioning. Heat pumps are likely to figure prominently in movements to electrify household energy use, but the full consequences of such a transition are not yet explored. California is currently debating approaches to decarbonizing buildings per AB 3232 and SB 1477.[59] One proposed pathway is to pursue broad electrification of major natural gas end uses in homes (Wei et al., 2013; Wei et al., 2017; Mahone et al., 2018; Tarroja et al., 2018). So, what if California embarks on wholesale replacement of natural gas space heating with electric heat pump systems in existing homes? Swapping in electric heat pumps for space heating will not only change heating energy use. It might also have a substantial impact on cooling demand since households that add heat pumps often use them for space cooling as well. In some cases, this may mean replacing an existing air conditioning system with heat pump air conditioning. In others, it may mean adding heat-pump central or room air conditioning where there was none before. How might AC electricity demand and associated carbon emissions evolve? How might policy choices and program designs affect AC-related outcomes, including extreme heat vulnerability and equity impacts, as well as space cooling energy and GHG emissions?

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[59] See, for example, the IEPR workshop on building decarbonization, Docket 19-IEPR-06.

The “What if” scenario posits a transition of natural gas space heating in California homes to electric heat pumps (HP) based on transformation in heating and AC replacement and additions. Three transition patterns are compared here:

1. *No HP pattern*, assuming status quo conditions with minimal rates of electrification by heat pump installation.
2. *Mid HP pattern*, assuming an S-shaped transformation of AC adoption and replacements, starting in 2020 and gaining 50 percent of market share by 2030—2031, and more than 95 percent by 2040. This pattern is similar to that supposed by Mahone et al. (2018),[60] and assumes essentially no early retirements of existing systems; that is the transformation is limited to the existing or natural replacement rates of heating and AC equipment and natural rates of additions.
3. *Rapid HP pattern*, assuming an additional impetus on top of the Mid HP transformation, starting in 2025 and continuing through the simulation period. This rate of transformation necessarily assumes some early HVAC replacement.

These transition patterns are applied in this simulation as top-down constraints, perhaps plausible, but not necessarily likely without very concerted efforts. The impetus likely necessary to drive such a market transformation[61] was not modeled beyond mapping the aggregate transition patterns onto household-level HP uptake processes, notably as end-of-life replacements of existing space heating and cooling systems, and as HVAC installations with home construction. Compared to Mid HP, the Rapid HP trajectory involves an acceleration in HVAC replacements, due to earlier replacement of some systems, though overall replacement propensity patterns are retained. For the base Mid HP and Rapid HP patterns (without targeting interventions), HP uptake mimics the pattern of the nonHP change process, for example, replacements are skewed toward older existing systems and higher income households.

The transformation of the installed stock of HVAC equipment substantially lags the transformation in the installation markets. Even assuming an aggressive market transformation, it still takes 30 years before electric heating is the primary heating source for 90 percent of California homes (Figure 6, blue solid line). With the less-aggressive Mid HP scenario uptake assumptions similar to the assumptions used in Mahone et al. (2018), electric heating saturation only reaches approximately 70 percent after 30 years (red solid line).

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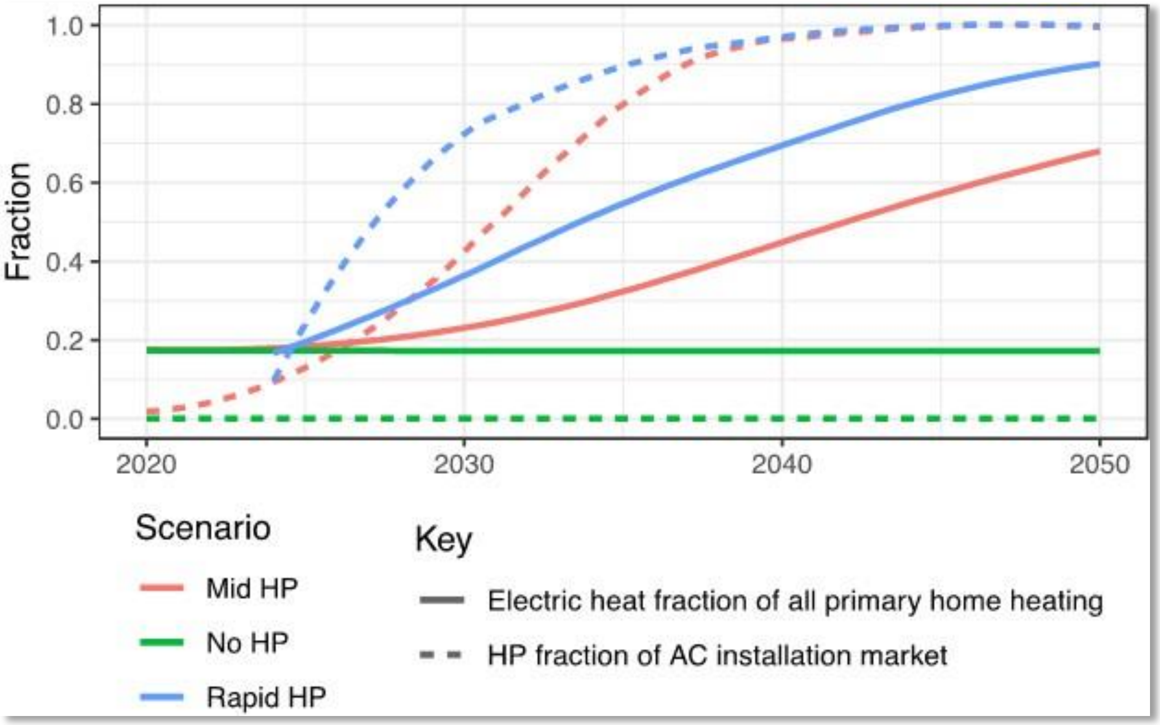
[60] Mahone et al. (2018) assume HP market share of *new HVAC sales* are 50 percent in 2030 and 100 percent by 2050. The SIMSAND "Mid HP" scenario assumes 50 percent HP share *of new AC sales* in 2030-2031 and 100 percent by 2050. The SIMSAND "Rapid HP" scenario assumes 50 percent share *of new AC sales* in 2027 and 100 percent by 2050.

[61] Many difficulties would be faced in achieving such a transition, including potentially considerable technical incompatibilities with existing equipment spaces, ducting, electrical systems, and other conditions in homes. A more developed SIMSAND implementation, given sufficient data, has the potential to reflect market dynamics, market actors, and the technical and other difficulties faced in inducing such transitions.

Figure 6: Simulated Transitions in Annual HP Installations and Primary Electric Heating in Homes



Source: QQForward, 2019.

Two stylized intervention sets were added to the transition patterns:

1. *Targeted HP* interventions that result in a relatively higher propensity for low-income households or those with older heating systems to transition to HP
2. *High Efficiency HP* involving interventions to ensure newly installed systems have higher rated efficiencies and comply with heightened installation quality criteria.

These intervention sets enable exploration of possible ways the assumed transition might progress and a comparison of simulated outcomes. Five such scenarios were developed for comparison, as shown in Table 8.

Table 8: Five Heat Pump Replacement Scenarios Compared in the Test Case

Scenario	Transition Pattern	Interventions: Targeted	Interventions: High Efficiency
No HP	No HP	No	No
Mid HP	Mid HP	No	No
Rapid HP	Rapid HP	No	No
Rapid HP + high-efficiency	Rapid HP	No	Yes
Rapid HP + targeted + high-efficiency	Rapid HP	Yes	Yes

Source: QQForward, 2019.

For each scenario, four outcome metrics were simulated for the five scenarios over the period 2020–2050. The results are shown in Figure 7).[62] As seen in Figure 6, under the Mid HP market transformation (without early replacement), the transition from natural gas to electricity for home heating lags behind the systemwide 2030 and 2050 state targets for transition to electricity overall. Rather, a quite aggressive market transformation (the Rapid HP scenarios) could be necessary. These Rapid HP scenarios could involve many early replacements. But a transition of this pace can substantially increase air conditioning electricity use partly because of quick adoption of additional heat pump air conditioning units (rows A and C in Figure 7 for the Rapid HP scenario). By implication, this would result in increased peak demand and possibly GHG emissions, depending on energy supply, and could exacerbate air conditioning electricity costs and burden experienced by California households (row B of Figure 7, Rapid HP scenario). But the simulations suggest that certain interventions can effectively mitigate such increases in AC energy use (rows A and D of Figure 7, Rapid HP+high-efficiency scenario) and reduce the level of the added electricity cost burden, particularly for vulnerable populations (row B, rightmost column of Figure 7, Rapid HP+targeted+high-efficiency scenario), even while providing increased air conditioning access overall and for subpopulations (row C, Figure 7). However, besides any early replacement issues, rapid replacement strategies also run a higher risk of encountering unanticipated problems (of the sort discussed in Chapters 2 and 3) for a larger number of households, since—at least without special attention to ongoing field evaluation—problems may be noticed too slowly for sufficiently responsive corrections.

SIMSAND outputs include not just energy impacts, but also other dimensions that are not easily addressed by existing tools. These include equity impacts; multiple possible scenarios progressing along a variety of dimensions; consideration of how people’s behaviors may facilitate, inhibit, or be differentially impacted by the transition; and possible direct and side effects of the set of stylized policy interventions applied. This array of possible outputs and specifications provides (1) a structure that helps users think about more dimensions of residential energy use than are usually visible in transition planning, and (2) an estimation of impacts from variations along these dimensions. For the question of heat pumps considered here, these capabilities also help draw attention to noncentral, but potentially important, consequences of a rapid transition from natural gas to electric space heating. These include, for example, potential increases in air conditioning electricity use and cost burden, as well as the potential for big increases in access to air conditioning for disadvantaged communities and low-income households. These latter increases can potentially improve societal resilience to extreme heat events, but with a tradeoff in increased levels of air conditioning use relative to what might be expected in a linear trajectory.

Others have used building stock models to assess important dimensions of a transition to heat pumps (Mahone et al., 2019, Raghavan et al., forthcoming), not all of which have been implemented in the current SIMSAND prototype (such as space heating impacts, economic cost-effectiveness, and GHG emissions impacts from alterations in energy use and refrigerant

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[62] The 2040 peaks evident in the graphs are related to the RCP 4.5 trajectory used in the simulation. High CDD Homes are the subset of homes experiencing greater than a threshold number of cooling degree days per year. This population varies depending on the year's weather, generally increasing in the later years based on the climate projection used.

emissions). In contrast, SIMSAND can offer greater resolution into other considerations that can also be critical to transitions, for example:

- Diversity of household-to-household responses and impacts based on differences in household circumstances and conditions, and empirical energy use patterns—not just on building and equipment characteristics
- Targeting of interventions to particular populations, low income households or those in communities defined as disadvantaged (DACs) —not just based on broad categories of housing type or vintage, existing equipment characteristics, climate zone, and so on.
- Empirically-based modeling of energy use more reflective of the idiosyncratic interactions of people with their homes and appliances and reactions to change in these (e.g. takeback), which can complement building simulation and engineering-driven expectations of typical energy use and how energy use changes with respect to changed technologies.

The results shown for this example set of scenarios demonstrate the types of analyses and insights possible with a SIMSAND-centered approach. In short, the approach can be used to explore aggregate and home-level (disaggregate) energy transitions under uncertain future conditions, high levels of heterogeneity, and various possible policy strategies for pursuing a transition toward heat pumps. The space cooling focus of the current proof-of-concept captures a critical end use looking forward in California and highlights potentially important knock-on effects from a possible space heating transition.

SIMSAND Next Steps and Future Potentialities

Getting Users' Hands in the Sand

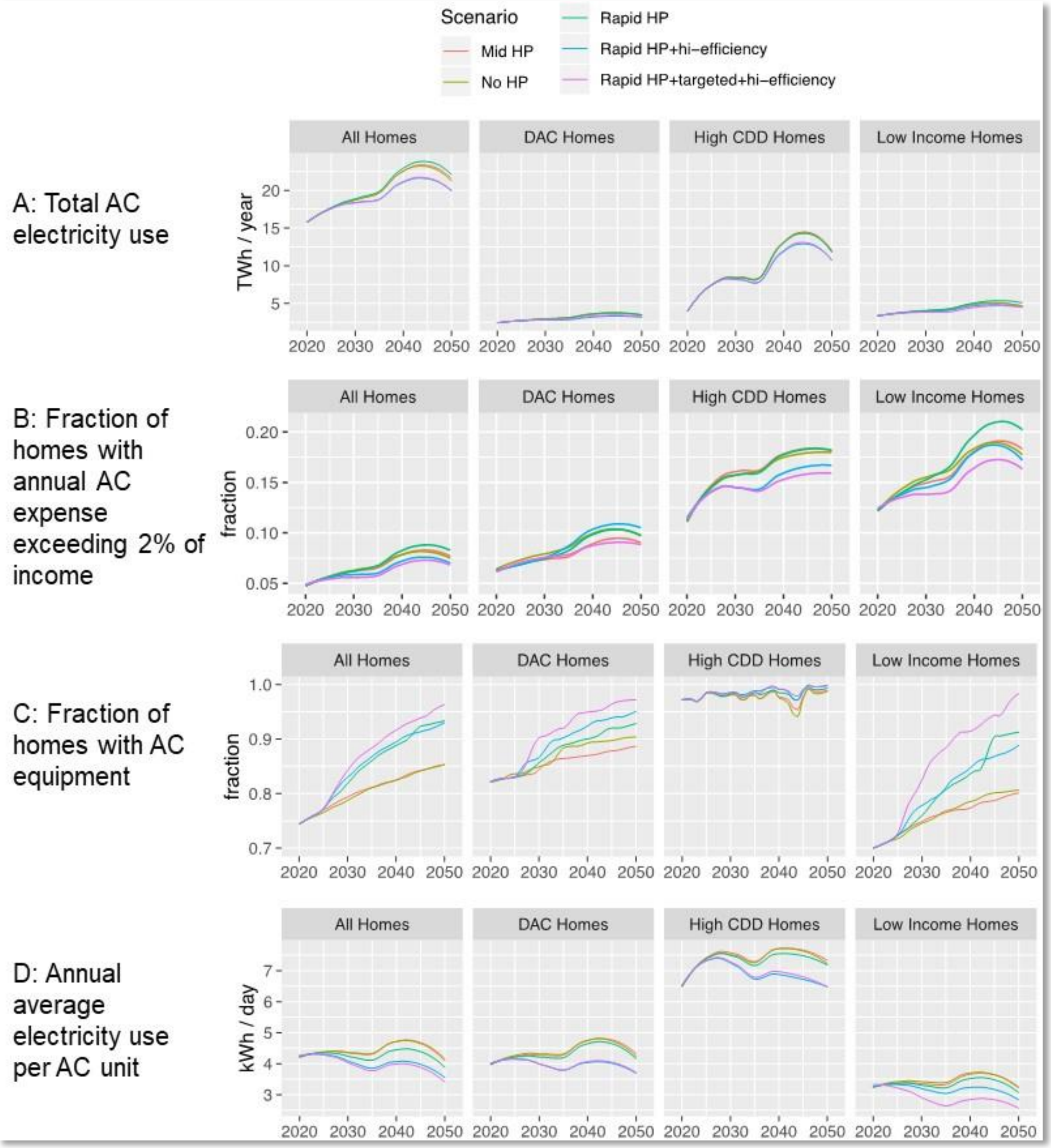
A major next step for advancing a "What if" simulation sandbox is to develop more refined ideas about users and use cases. To what degree should future SIMSAND development focus on institutional users (such as at the Energy Commission), research users (at universities, nonprofits, and consultant organizations), stakeholder users (advocacy organizations, utilities), or the general public? It is reasonable to imagine that each type of user is likely to have unique interests and needs that might require some customization or might use be generalizable? Table 9 shows some possible user types and use cases. For example, an institutional user might face an obligation to produce estimates to inform a certain policy question quickly, where something more detailed and vetted than a back-of-envelope calculation, but faster than a commissioned study is required. Or a community advocacy organization may want to look at potential effects of a policy decision on the community, using the approach to imagine local scenarios and readily see how elements of variability play out.

To move from proof-of-concept to broad use, design and development will have to tailor the implementation to specific users and their use cases. Next steps for moving SIMSAND development forward will also have to address more general issues, for example:

- Fitting the “What if” simulation sandbox approach into, or complementing, existing processes and roles within California institutions
- Ensuring that the use of SIMSAND and its outputs are appropriate to the data, capabilities, and overall approach, including conveying critical uncertainties

- Making the SIMSAND platform sufficiently accessible (for example, possibly via a web-based interface), easy to use, and foolproof.

Figure 7: Simulated Trends for Four Different Metrics and House-Type Groups for Heat Pump Transition Scenarios



Source: QQForward, 2019.

Home cooling is a critically important energy use that simultaneously affects achieving the state's decarbonization goals, grid stability, and social resilience to climate change itself. Depending on the strategies used, these goals can conflict. The advances made in this project offer analysts the possibility of combining deep consideration of possible cooling strategies and technologies with a simulation platform capturing the microlevel patterning and structure of air conditioning, and permits taking a number of potential risks into account. These are steps toward a new approach for addressing future residential energy use. This new approach combines sophisticated quantitative analysis of energy and climate change data with tractable expressions of the types of real-world observations that social scientists and other observers want to bring more fully into the state's climate-related policy and research activities.

Table 9: Some Possible User Types and Use Cases for the SIMSAND Platform

User Type	Example Users	Imagined Use Cases
Institutional	CEC analyst	• Quickly developing possible initiatives or analyses related to an emerging issue (residential HVAC electrification via heat pumps) • Exploring how California might prepare for a broader set of plausible futures than addressed in IEPR, other formal efforts • Devising interventions/policies/plans for meeting future policy targets working forward • Estimating the scale of existing energy impacts within a subgroup or use
Research	University or lab researcher	• Estimating the scale of existing energy impacts within a subgroup or use. • Exploring future possibilities; comparison of SIMSAND simulations with other modeling of California futures
Stakeholder	Utility analyst	• Analyzing how an issue or choice could affect the utility and ratepayers • Analyzing how the utility might prepare for a broader set of plausible futures than addressed in CEC forecast model, other established scenarios
Stakeholder	Advocacy organization	• Assessing possible impacts of an issue or policy on the vulnerable; • Developing initiatives relating to an emerging issue
General Public	Interested citizen	• Curious about how an issue or proposed initiatives could affect them or their communities
General Public	Community member	• Want to inform resilient community planning for their community • Curious about how an issue or proposed initiatives could affect them or their communities

Source: QQForward, 2019.

Data Nexus at the Household and House Level

A wide variety of existing data streams originate at or are resolved to the house and household level, and new and more detailed data streams are becoming available. The current data environment, and especially the possibility of coordinating new streams, is quite exciting in terms of the insights it may bring. Individual, house, and/or household-level data streams include microdata from the Public Use Microdata Series (PUMS, U.S. Bureau of the Census), RASS (California), Residential Energy Consumption Survey (RECS national sample, from the Energy Information Administration), the American Housing Survey (AHS, Department of Housing and Urban Development), and bordering issues such as time use (American Time Use Survey) and health data (the CDC's Behavioral Risk Factor Surveillance System); billing and interval electricity, gas, and water meter data;[63] tax assessor and various aggregator datasets for houses, households and individuals; potentially household-level consumer segmentation data offered by private companies (such as Experian's MOSAIC dataset), and GIS data of various sorts. There are also recent and still emerging data streams such as smart thermostat data, LiDAR building footprint and height data,[64] street view data, PV generation data, increasingly accessible weather and microclimate data (such as high-resolution urban heat island assessment), and more sophisticated data on the human actions and human effects.[65] Given "big data", Internet of Things, Smart Cities, Smart Grids, Smart Homes, and Smart-Everything, the flexibility to merge and incorporate new, diverse, and evolving data streams potentially enabled by the household + house-level modeling approach could have major benefits for planning.

Household and house-centered modeling depends on data sufficient to characterize the issue (in this case residential AC use and energy) for individual households and houses (and to capture covariation to the extent possible) with a sampling adequate for population-scale aggregates, whether California or subsets thereof. This can be different from other forecasting and futures approaches, which tend to characterize energy use (e.g. Unit Energy Consumption for equipment along with saturations) in relatively coarse groupings (such as by housing type, climate zone, end use type, and fuel).[66] One particular value of the SIMSAND approach is its ability to capture and use empirical patterns and relationships inherent in the source data

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[63] This includes much of what is currently collected and managed by California utilities, some of which is now also housed by the California Energy Commission, or will be (see, for example, https://calenergycommission.blogspot.com/2019/05/commissioner-mcallister-talks-about.html; see also the GIS data hub by the Energy Commission, at https://cecgis-caenergy.opendata.arcgis.com/).

[64] For example: data releases from Microsoft in 2017 and 2018, https://www.gislounge.com/almost-125-million-building-footprints-us-now-available-open-data/

[65] Future directions for this category of data are nebulous and likely to be highly contentious. Examples of the type of application include, for example, using cell phone location data from which home occupancy timing might be inferred, not a large stretch from the emerging use of such data in transportation planning (e.g., https://www.smartcitiesdive.com/news/portland-or-launches-pilot-with-sidewalk-labs-location-data-software/555681/).

[66] Exceptions exist, such as urban building energy modeling based on building simulation. Still, these mainly focus centrally on building and technology, and look at a relatively constrained set of technological futures, rather than the potentially broader set of plausible futures available using a more socio-technical approach.

without decomposing them (into factors and statistical formulae), since such decomposition is often difficult, if not impossible to do well.

SIMSAND demonstrates the household and house centered data concept using RASS 2009 microdata with monthly billing data, along with several supporting datasets. The RASS 2009 data are obviously outmoded, which is an important limiting factor for the prototype. But there are opportunities for improvement even short of the next edition of the RASS. Improved household + house + energy use data (for all factors at a time, to help characterize the structure of variability) would provide a new level of vision into present residential energy use in addition to the use as a basis for speculating on the future. The data nexus presents a major opportunity for the SIMSAND platform, but it also presents perhaps the most pressing next steps: assessing and incorporating emerging data streams and finding the appropriate statistical and data analytic methods to combine imperfectly meshed data, and maintaining disclosure/privacy control, for example utilizing synthetic population or synthetic data vault approaches (Patki et al., 2016; Temple et al., 2017; Subbiah et al., 2017; Thorve et al., 2018).

Technical Improvements to the SIMSAND Platform

The household/house-level agent approach, which distinguishes the SIMSAND approach from most other efforts in the residential energy space, also brings potential tradeoffs. It is well-suited for some problems and situations, and not others. Based on the experience constructing the SIMSAND proof-of-concept, household/house-level agent-based modeling at scale may require:

- Higher quality source data. As noted just above, particularly useful are up-to-date data that are simultaneously descriptive of individual households, homes, energy use, equipment, and behaviors.
- Computational streamlining and scaling. Covering California with reasonable resolution may require at least several thousand agents, depending on what subgroupings might be desired.[67] Approaches relying on a predefined, fixed categorization scheme (categories by climate zone, housing type, and so on) can be much less computationally intensive, as each category might be represented by the SIMSAND-equivalent of a single "representative" agent. For certain classes of problems, such a representation may be sufficient, and the additional detail in SIMSAND would in turn be computationally wasteful. On the other hand, for problems that reside down in the details, the increased resolution can be useful. This type of problem may be particularly native to the residential energy and climate transition spaces (Mercure et al., 2016). In these cases, an approach like that used in SIMSAND is well-suited. Its data- and computation-intensiveness is inherent to the problem itself, rather than to the modeling approach.
- Stochasticity management. The current sandbox method applies random sampling to sample agents from the RASS-derived agent database. Combined with the quite uneven sampling weights generated for RASS 2009, this results in substantial stochasticity in simulation results when smaller size samples of household/house agents are used in

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[67] See, e.g., Wilson et al., 2017, who estimated that 200,000 to 350,000 simulation runs were needed for accurately representing the entire single-family U.S. housing stock using their archetype approach.

simulation runs. However, useful features of SIMSAND (the scaling methodology, the potential to merge disparate datasets, and the potential to correct or recalculate weights) depend on the process of randomly sampling households from the source population database, and as such are tied to this stochasticity, so the current strategy has been to manage rather than eliminate this stochasticity.[68] Larger applications may necessitate improved sampling strategies, a migration to a high-performance or cloud-computing environment, or use of an emulator of the SIMSAND simulation in place of SIMSAND itself.

Additional next-step technical improvements to the SIMSAND platform also include improvements to submodels, such as replacing the building stock change modeling, which in the current prototype is limited.

SIMSAND Platform Directions and Applications

The "What if" simulation sandbox concept is quite general and flexible, with the consequence that the SIMSAND platform can be made substantially more sophisticated within: the current residential energy use application, for example with higher-resolution modeling of air conditioning energy use, expansion to other end uses and to nonenergy or life cycle impacts—such as refrigerant-related emissions; integration with hourly or subhourly building simulation, and hourly observed historical and projected future weather/climate data;[69] more detailed and dynamic modeling of people, behavior, and technologies; adding the ability to model "smart" and direct control technologies; increased resolution in time and geographic scales; guidance on uncertainties; and more.

Similarly, the concept can conceivably be focused on or expanded to a variety of bordering domains and issues, including other energy sectors, cosimulation with supply-side or grid-centered models, and applications at other scales or crossing into bordering domains.

Finally, analytical improvements are possible to enable the SIMSAND platform to be used to more systematically explore the space of possible futures and assess intervention options. Approaches include Monte Carlo-based analysis (a stochastic multivariate analysis approach to exploring the trend, wildcard, and intervention possibility space), and deep uncertainty and robustness analyses (Lempert, 2013; Walker et al., 2013; Climate Action Team, 2015; Sanstad, 2017).

In modeling, there is a well-known tension between parsimony and comprehensiveness. SIMSAND in current form already qualifies as reasonably complicated but not particularly complex (Sun et al., 2016). The current level of complication is partly a result of the data-driven household and house level bottom-up modeling approach, together with the permutations necessary to achieve flexible exploration of a highly uncertain and multidimensional future possibility space.

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[68] The other main source of stochasticity in SIMSAND is the use of probabilistic representations of AC adoption, AC replacement, and other household-level processes or actions.

[69] For example, the observed historical and projected future hourly weather station data for various points across California that are undergoing development under EPC-15-036 and EPC-16-063.

Distinct use cases tend to be best served by tailored models.[70] This tension supports the "SIMSAND as a platform" approach—hosting a family of applications each tailored to a particular use and with limited scope. Each application would have particular populations and types of agents at the appropriate granularity, a rigorously defined model representing key system and agent rules and relations, and would be informed and driven by up-to-date high-quality data streams and scenarios, shared and standardized where possible.

Chapter Summary

- The agent-based energy simulation sandbox constructed in this project, SIMSAND, is designed for bottom-up "What if" and scenario-based exploration of residential energy transitions. Its major strength lies in its ability represent the diversity of energy use, conditions, and interactions at the household level, and to play these out under scenarios that specify varying assumptions about changes in weather and climate, demographics, buildings, technology improvements, social practices, and policies over 30-50 years.
- While the approach has broad applicability across household energy end uses and beyond, implementation of SIMSAND at this proof-of-concept stage for residential cooling. Cooling is a crucial end use for achieving climate change policy goals, because of warming weather, the time-dependent and peaky nature of air conditioning, the challenges this poses for the grid especially one powered primarily by renewables, and cooling's role in supporting human health and well-being.
- SIMSAND is intended to facilitate rapid assessment of various residential energy futures scenarios and to coordinate a variety of key data sets, including standard projections related to climate and demographic change. It is designed to be useful for planning and research staff.
- The SIMSAND approach can take advantage of emerging data streams with a nexus at the household level and could be coordinated with the Energy Commission's recent data repository initiative and activities. The new data from such a repository could be a major opportunity for developing a better empirical understanding of household energy use and how it changes, particularly if coordinated with flexible, powerful analytical and exploratory tools.
- The project's analysis of histories, scenarios and modeling are complementary and synergistic: historic transition perspectives inform scenarios; data advances inform scenarios and nimble exploratory simulation in SIMSAND; and SIMSAND formalizes transition perspectives and scenarios, profiting from new data streams and enabling scenario innovation.

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[70] An over-complicated or over-complex model raises the bar for development, verification, validation, performance, and usability, and therefore decreases flexibility and adaptability.

CHAPTER 6:
Conclusions and Continuation

Approaching the large-scale energy system transition envisioned in climate change planning as primarily a matter of perfecting hardware efficiency misunderstands how society uses energy and integrates technology. The new data, knowledge, and collaboration routes available bring opportunities to expand beyond this approach. This project investigated three coordinated elements that can contribute to a new science of energy transition planning.

Research Activities Completed

The three elements investigated are: a modeling tool that takes advantage of new data and explored the distributional perspectives they allow; scenario development process improvements that more deliberately imagine socio-technical futures and how they can be achieved; and mining the history of past technology transitions to more realistically develop future ones. In more detail:

1. The project developed and tested the agent-based household energy use "What if" simulation sandbox SIMSAND at a proof-of-concept level for California. SIMSAND starts with households as agents. It assembles and coordinates a variety of data sources interacting at the household level, defines energy use and related responses from these interactions, incorporates the ability for users to specify scenarios using a variety of parameterization options and assumptions, and generates and displays outputs for a variety of metrics and segments of households. The results provide a basis for assessing residential energy-related futures under a variety of user-specified scenario assumptions, starting from a micro-scale household level versus the more averaged, aggregated level often used in residential energy use planning. This also allows users to better examine distributions of effects and to pinpoint results for different localities or types of households. Such distributional views can be used to help assess equity and other group differences in policy effects, for example, and help open the door to more nuanced approaches to imagining social and technical change.

   SIMSAND was developed for residential cooling. It is expandable to other end uses, and updatable with novel data and assumptions regarding agent characteristics, response functions, future conditions, and metrics of interest.

2. The project explored scenario development processes applied to residential energy futures under climate change. Different types of residential energy scenarios corresponding to different categories of policy questions were identified, leading to recommendations on how scenario development in California could be expanded to consider a wider scope of realistic possibilities for the energy future. This expansion would help transition planning better move beyond narrow techno-economic frameworks for energy transition. Those scenarios could draw from historical experience on the dynamic nature, real-world breadth, and distributional aspects of past technology change.

3. The project analyzed the recent histories of selected household energy technologies and related energy efficiency efforts. The results illustrate how past technological change has been much more uneven, less predictable, and less clear-cut than technology dissemination models imagine. It is layered and multivalent, often with far-reaching social effects. The complexities of real-world change have essential effects on what technology dissemination "does" versus simple renditions of planned effects. For the same reasons, history highlights opportunities for positive change that are missed in current planning processes.

Research Conclusions for Energy Transition Planning

The value of this research depends on how the results will be used. Potential users, including policy analysts, researchers, technology developers, and members of civil society, might start with questions such as "What should resilient, efficient, and low-energy cooling look like in future households?," rather than "What are the benefits of getting as many efficient air conditioners into homes as possible?" The work presented above resulted in three main conclusions with respect to this broader type of questions.

1. An agent-based simulation model for exploring "What if" scenarios on energy use across households is feasible, and the resulting analyses are potentially valuable for a variety of uses and users. This was demonstrated through the SIMSAND tool and confirmed by conversations with potential users. SIMSAND (or a similar tool) could be used to test candidate EPIC technologies under varied scenarios, with quick turnaround for initial reconnaissance. SIMSAND's ability to represent and interact social, technical, and environmental dimensions of energy use at the household level allows users to explore how variations in key factors could affect future residential sector energy use, and how effects are distributed across households and situations. That distributed, more multi-dimensional view would allow users to more coherently analyze benefits and costs of candidate technologies under a variety of assumptions, versus more static or averages-based assessments.

   SIMSAND or a similar modeling/data platform could eventually become a component of a suite of agent-based models constructed to navigate the effects of real-world variabilities and specific uncertainties. These tools could coordinate and help make sense of a variety of types data sets (on energy, technology, environment, and demography, for example) for a variety of current and emergent transition questions. In capturing household-level interaction, SIMSAND provides capabilities that are missing in existing residential sector planning models, and serves as a proof-of-concept and testing ground for this approach, applied in this case to air conditioning.

2. Energy transition planning brings a need for a coordinated, broad approach to constructing, testing, and interpreting scenarios related to residential energy technology. Historically, California energy modeling has pursued a set of specific policy interests, posing questions in technically focused ways—matching supplies to demands, crediting energy efficiency gains, assessing cost-effectiveness, and exploring potential effects of specific legislation and regulation. These scenarios focus on "What might happen?" and "What could happen"? More recently, work on long-term energy scenarios has addressed "Could this happen?" questions. But there are also many imaginable "What if?" and "Should we?" and "How to?"

questions that will need to be considered too. New processes and tools are needed to help resolve these new types of questions.

3. History shows persistent difficulties with respect to dramatically reducing absolute levels of household energy use by adding more efficient technologies. So focusing on disseminating efficient devices and buildings may not lead to adequate outcomes relative to the climate policy goals that California has adopted. On the other hand, a historical perspective also points to strategies that expand beyond the current device-level efficiency framework, including targeting systems of energy use and more refined technology development.

Combining historical analysis, scenario development, and more socio-technically oriented modeling can contribute to the policy planning system by helping it move beyond a focus on improving individual devices, average households, and normative conditions. To do this, however, requires recognizing potential value in it.

Implications, New Questions, and Recommended Research Activities

These research conclusions lead to a series of possible next steps for applying these findings. These are summarized below. The project scope of work also calls for recommendations on development beyond the work completed for the project. These recommendations are included below.

Attracting SIMSAND/Sandbox Use

SIMSAND does not replace existing models or modeling activities. Rather it complements them by providing an efficient way of modeling household energy use as a dynamic system, providing outputs that help compare results across different assumptions, eventualities, and household population segments.

It is challenging to introduce a new tool into the already established set of tools and practices used in energy planning. For SIMSAND or a similar tool to be used, the tool needs to be accessible and potential users need to have some familiarity with its functionality. To be useful, the legitimacy of the tool's output must be established. The research above has taken the first steps. Putting SIMSAND or a similar tool to use would be gradual process requiring further conversations with potential users, assessing precise applications (e.g., about actual questions already being asked), and probably modifying tool capabilities or data as necessary.[71] Users could be staff in the Energy Commission, or people outside the Commission (such as other state agencies, local governments, utilities, community groups, and private companies) engaged in energy transition planning and implementation (Chapter 5,Table 9).

Data Coordination

SIMSAND coordinates multiple streams of data intersecting the household. These data streams include projected weather data, household characteristics, demographic projections, and assumptions and processes to determine air conditioning load. As SIMSAND was being

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[71] Possible additions range from relatively easy (such as adding the space heating end use) to medium (such as integrating building simulation) to hard (such as providing strong integration with energy supply system modeling).

developed, the Energy Commission had been pursuing (and continues to pursue) an energy data vision to support strategic use of high-resolution data on energy use and usage patterns. This step itself raises many statistical and philosophical questions about data science that were less pronounced in the past, ranging from how to combine information across disparate data sets, how to characterize and manage uncertainty, how to protect privacy (such as in linking demographic data to energy use data at the household level), and how to express spatial diversity and dynamic relationships in a comprehensible and statistically defensible way. Both the state's energy data vision and SIMSAND aim to make big data more useful and applicable to understanding current patterns and diverse circumstances and applying them to energy and technology planning.

Trend and History Curation

If history and historical trend analysis is potentially useful, as argued above, then how can it best be made accessible to the relevant researchers and planners? A well-designed data platform for energy demand technology histories and related efficiency experience, quantitative and qualitative, could help bring important evidence-based insights—of types that can illuminate current "blind spots"—into consideration. This could include active trend curation related to residential energy technologies and homes, interpretation and standardization of trend data, and downscaling geographic resolution. Users could monitor signs of emerging trends or new patterns. Various current California tools and activities, such as the IEPR, CED, Cal-Adapt, and the Energy Commission's public-facing Energy Almanac already provide some of this functionality, as does the Energy Information Administration (https://www.eia.gov/tools/). But there is little data systematically compiled on the details of residential energy technology evolution and distribution, versus just penetrations and energy use estimates. Therefore, such a platform should go beyond quantitative data, and including histories of specific technologies. While useful to understanding on their own, qualitative histories can illustrate structures and characteristics of change that can be reflected in scenario construction and quantitative modeling thereof.

As energy research and policy becomes more inter- and multi-disciplinary, and as staff with long experience with energy technology and related program experience retire, such histories could be valuable in retaining some of this experience, as well as for introducing new possibilities and reconsidering entrenched assumptions in light of changing goals, circumstances, and data availability.

Scenario Development, Testing, and Deliberation

The architectures of legacy models and processes limit what questions can be posed for energy transition planning, as well as what answers can be seen. New tools are needed to grasp the new problems at hand and to take advantage of the expanded data available. This is already happening, for example, in changes to the CED model and through contracted research projects on the climate future (such as the E3, LBNL, and UCI studies discussed in Chapter 4).

The research presented above argues the need for exploring a wider range of questions about energy use in homes versus earlier energy efficiency concerns. This wider range includes the possibilities of unexpected responses to policies, important social shifts, the effects of environmental instability, locally optimized technology choices, and close attention to the distribution of costs and impacts. Transition-scale energy choices can have tremendous effects on health, infrastructure, local and national economics, resiliency, and national security. These go beyond the older emphasis on quantities and costs of energy use for efficiency mandates, and require consideration of a wider scope of assessment especially for certain technologies or approaches (e.g., smartness in homes, distributed energy resource development, and cooling strategies).

If climate change scenario development in California were to become more highly coordinated across different specialties, departments, and interests, how might this happen? Various options can be imagined beyond what has already happened, with different levels of inclusiveness (who is consulted?) and integration (how many dimensions must be considered?, how extensive a system is captured in the scenarios?). One possibility to coordinate these possibilities is a formal "futuring" group, such as a Scenario Analysis Working Group akin to the active, long-running Demand Analysis Working Group.[72] This group could be tasked with dialog, exploration, and documentation to make sense of the changing space of socio-technical energy futures. Whatever the results of modeling, there remains a need for deliberation, especially as the number of potential tradeoffs relevant grows relative to the simpler criteria and metrics that were appropriate in the past.

Research can move slowly relative to the pace of climate policy development. Commissioning a study and waiting for results might often take three years or more. SIMSAND and similar flexible tools could be used to explore future options at a climate policy pace. Work outside of California has been pursuing this direction. In particular, the European Commission's Horizon 2020 Work Programme calls for developing agent-based modeling and related scenario-building processes for the European energy system (European Commission, 2018).[73]

Strategic Options for Cooling

Modeling studies present the future of air conditioning impacts on the grid as large ranges (Burillo et al., 2019) befitting the many uncertainties of projecting into the future, and underscoring the different ways that air conditioning response to changing weather and related conditions could unfold. The future of air conditioning, and its effects on the grid, are among the biggest and most fraught topics for climate change planning in much of the world. Hotter temperatures bring more air conditioning, more energy use, and more challenges to a renewables-centered grid. But hot weather also has major health effects, including increased mortality during heat waves, which can be reduced by air conditioning (Aufhammer, 2018; Yu et al., 2010; Barreca et al., 2016). Hot weather can also have negative behavioral and psychological effects, including increased violence and emergency psychiatric admissions

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[72] The Demand Analysis Working Group (DAWG) maintains a website at http://dawg.energy.ca.gov.

[73] The European Commission Work Programme notes that "energy models that are currently used to plan, support, and verify the energy policies at national and European level do not fully encompass and integrate all the new challenges posed by [the transition to a low-carbon future]." It calls for proposals that develop a suite of modeling tools, including those that can represent the behavior of individuals and communities of actors. See "LC-SC3-CC-2-2018: Modelling in support to the transition to a Low-Carbon Energy System in Europe" (European Commission, 2018, pp. 202-203; https://ec.europa.eu/research/participants/data/ref/h2020/wp/2018-2020/main/h2020-wp1820-energy_en.pdf).

(Brandl et al., 2018; Carleton and Hsiang, 2016). Certain households are especially vulnerable to heat, due to housing quality, energy costs (Maller and Strengers, 2011), indoor air quality, and health overall. All of this makes balancing the need for cooling against the challenges it places on the grid (along with supply implications) a fragile affair.

Thinking about air conditioning "on average" or in terms of energy only can thus miss such essential social considerations, including equity, limits to demand response under specific conditions, and the need for cooling redundancy that could be used during power outages.

Energy efficiency policy's first impulse on future residential cooling has been to ensure that mechanical whole-house air conditioning systems are as efficient as possible, with homes sufficiently insulated and sealed. This leads to an interesting situation. Rather than leading with an efficient technology, one could ask what more effective strategies, that may include efficient technology but placed in a broader context, should be considered? Central air conditioning has been popular in California for only a few decades. Only slightly more than half of homes have a central air conditioner.[74] Even in hot areas, some households get along well without it (Deumling, Poskanzer, and Meier, 2019), at least on most days. Given the expected effects of air conditioning on peak demand over the coming decades (CEC 2020) there are important questions about the strategy of broadly promoting efficient central air conditioning. First, doing so could inadvertently dissuade lower-energy forms of cooling, paralleling the historical finding that promoting central air conditioning in the past encouraged changes in house architecture that reinforced the need for air conditioning (Cooper, 1998). And besides the time-dependence and peaky nature noted above, air conditioning system performance also degrades—typically 5% per year, sometimes much more, according to one study (Fenaughty and Parker, 2018), so actual efficiency may be considerably lower than designed.[75]

These risks and imperfections point to the need for lower-energy cooling strategies that complement individually-managed central air conditioning, including those that reduce the levels of central air conditioning needed and those ready to replace it when necessary —for example when there are threats of capacity shortages, or during Public Safety Power Shutoffs, rolling blackouts, or other de-energizations. These strategies include land use planning, heat wave management plans, lower-energy if less-efficient cooling methods, and other socio-technical

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[74] The latest survey data is 10 years old. The two main survey data sources for California residential air conditioning equipment and use (the EIA's RECS 2009 and California's RASS 2009) have roughly consistent results. Based on 2009 RECS data, 41 percent of California households used central air conditioning, compared to 61 percent in the U.S. overall. An additional 4 percent of households in California and 2 percent nationwide report having but not using central air conditioning (EIA 2013; Table HC7.11 of the RECS survey). The 2009 RECS survey is cited because it allows a comparison between California and the U.S. based on the same method. The 2015 RECS survey showed an increase to 64 percent of homes nationwide using central air conditioning; unfortunately, there are no California-specific RECS 2015 data. RASS shows slightly more than half (53.4 percent) of California homes had central air conditioning in 2009 (KEMA RASS Data Explorer based on the survey question regarding the number of central air conditioners installed). The RASS data are for the electric IOUs (PG&E, SCE, SDG&E) and the Los Angeles Department of Water & Power, the largest publicly owned utility in the state.

[75] While HVAC maintenance is recognized as having substantial potential for energy savings for California, achieving these savings is challenging (Heinemeier et al. 2012).

strategies.[76] This kind of planning requires thinking through complex scenarios, and the results from this perspective would likely be different than making central air conditioning as a technology as efficient as possible. A "What if" simulation sandbox such as SIMSAND, accompanied by broadly imagined scenario development, could help explore the strategic set of questions.

Final Words

The contours of the energy future are a matter of deep uncertainty transcending those of climate, population, and energy resources. Governmental and nongovernmental actors will need to collaborate to create, manage, and encourage energy transitions that recognize the pivotal role of people, and not just as technology "adopters" but as ubiquitous elements of a new energy and environmental landscape. Embracing this realization is challenging and different from how energy demand policy has been pursued in the past. It requires innovations in analysis, planning, understanding, and implementation, some of which are already in motion. Additional ideas that emerged from this research project would also move innovation toward a refreshed policy frame, including:

- Applying lessons from historical energy transitions and of related energy efficiency efforts to contemporary climate policy discussions.
- Finding processes to accelerate *learning loops* as transitions move forward.
- Revisiting technology goals to reflect field experience, and to sync with the realities of a diverse set of households/people/situations/infrastructures distributed across the state.
- Stepping up the processes by which scenarios for the energy future are developed and assessed, to better capture energy use as one feature of an entire socio-technical system.
- Expanding the remit of these scenarios to reflect a fuller scope of energy- and climate change-related effects.
- Developing and applying agent-based models and other tools to support such broadened scenario development, and to address these questions with high resolution, while speaking to the state's ambitious energy targets (SB 100 and SB 350 targets).
- Continuing to pursue and analyze more granular data to reveal past and present patterns that provide evidence-based support to better manage the future.

Together, these innovations can help highlight existing and potential trouble spots, uncover clues to promising directions, and bring new kinds of knowledge, tools, processes, and data to bear on the challenges of climate change.

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[76] This is not a rejection of central air conditioner cooling. In fact, past research and development sponsored by the Energy Commission has explored the viability and benefits of non-compressor cooling strategies (Davis Energy Group, 2004), and ASHRAE and other HVAC engineering approaches have taken seriously "adaptive comfort" (ASHRAE, 2019; De Dear, 2004) and a broader range of cooling strategies that are possible (and currently widely used in California [Lutzenhiser et al., 2017]) in households at various income levels.

LIST OF ACRONYMS

Term	Definition
ABM	Agent Based Model
AC	Air conditioning (generally)
CAC	Central Air Conditioner (compressor-based)
CAC-HP	Central Air Conditioning via Heat Pump
CED	California Energy Demand (forecasting model)
CFL	Compact Fluorescent Lamp
DAC	Disadvantaged Community (as defined by CalEnviroScreen)
HVAC	Heating, Ventilation, and Air Conditioning
IEPR	Integrated Energy Policy Report (California Energy Commission)
IPCC	Intergovernmental Panel on Climate Change
LED	Light Emitting Diode
LiDAR	Laser-based land surveying method
PSPS	Public Safety Power Shutoff. These are preventative power shutoffs undertaken by utilities during anticipated extreme weather conditions to avoid fires started by damage to affected transmission systems.
PV	Photovoltaic System
RASS	Residential Appliance Saturation Survey
RCP	Representative Concentration Pathway as defined in the IPCC's fifth Assessment Report
RD&D	Research, Development, & Deployment
RECS	Residential Energy Consumption Survey (Energy Information Administration, U.S. DOE)
SIMSAND	Agent-based household energy use model developed in this project
SSP	Shared Socio-economic Pathways (IPCC)
ZNE	Zero Net Energy here, but increasingly Zero Net Emissions

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APPENDIX A: Policy and Environmental Context

This appendix gives an overview of state energy transition policies most relevant to household energy use. It also provides a brief background on California energy long-term trends, current use, prices, and policy and data systems referenced later in the report.

Major Energy System Policies

Several major California policies outline energy transitions that directly affect residential energy use. These include the following bills and bill updates:

- Clean Energy and Pollution Reduction Act (Senate Bill 350, Statutes of 2015) sets targets for renewable generation and energy efficiency for 2030. This includes a statewide, cumulative "doubling" of energy efficiency savings for electric and natural gas end uses by 2030, with the details of definitions and targets determined by the Energy Commission (CEC, 2017).
- California Global Warming Solutions Act of 2006 (Assembly Bill 32, Statutes of 2016) requires GHG emissions reduction to 1990 emissions levels by 2020. This goal has already been achieved, as per the Energy Commission (CEC, 2019).
- California Global Warming Solutions Act of 2006: Emissions Limit (Senate Bill 32, Statutes of 2016) requires that the state ensure that statewide greenhouse gas emissions are reduced to at least 40% below the 1990 level by 2030.
- California Renewables Portfolio Standard Program: Emissions of Greenhouse Gases (Senate Bill 100, Statutes of 2018) increases California's Renewable Portfolio Standard target to 60% renewables by 2030. In addition, by 2045, renewables and zero-carbon resources are to supply 100% of retail sales of electricity to California end-use customers and 100% of electricity procured to serve all state agencies.
- Low-Emissions Buildings and Sources of Heat Energy (Senate Bill 1477, Statutes of 2018) requires gas corporations to advance the state's market for low-emission water and space heating technology for residential buildings. It also requires the Energy Commission to identify and target low-emission space and water heating equipment in early stages of technology development.

These have various companion bills. Other bills closely tied to home energy use relate to infrastructure for Zero Emission Vehicles (see Energy Commission, 2019, p. 13). These bills set ambitious targets. In the past, California has met and even exceeded some ambitious energy goals. For example, GHG emissions from California's electricity sector in 2016 were 37.6 lower than 1990 levels, compared to the goal of achieving 1990 levels by 2020 (CEC, 2019, pp. 14-

15)[77]. On the other hand, ambitious goals may often not be met or may be met more in name than in spirit.[78]

High-level targets are translated into existing and new technology goals and implementation plans. For example, in 2008 — prior to the bills listed just above — the state's 10-year strategic energy plan set the "Big Bold" goal that all new homes would Zero Net Energy by 2020 (CPUC, 2008). California's 2019 building code (Title 24 Part 6) moves closer to reaching this goal by requiring that by 2020 new homes will have PV systems, and steps up the efficiency of other home energy technologies (CEC, 2018a). The policy goal of Zero Net *Energy* buildings also has shifted to one of Zero Net *Emissions* buildings (CEC, 2019:17-18). The Integrated Energy Policy Report (IEPR), issued every two years with an update in intervening years, draws together assessment of emerging trends in energy supply, use, and conservation, along with a forecast. Subsequent research studies take these policy goals as their motivation or as basis for exploring whether and how the goals might be achieved, in turn informing strategies and programs. The legislated goals put into motion a large array of interconnected activities based on the expectations that these goals will be achieved and through what means.

The Energy Commission also notes a "growing consensus that building electrification is the most viable and predictable path to zero-emission buildings' (CEC 2019, p. 28) and to decarbonization overall with the implication that natural gas would be phased out for use in buildings. For the residential sector, this attention has focused on space heating and water heating which account for most of the sector's direct natural gas use. These goals are being translated to actionable policies and programs, such as pursuing strategies to get households to replace natural gas heating with electric heat pumps for space heating, a plan that Chapter 5 addresses.

These goals and directions are bounded by conditions designed to serve other goals in the state, such as program cost-effectiveness, equity, and resilience, as outlined in the Integrated Energy Policy Report (CEC, 2019) and elsewhere. For example, 25% of EPIC technology demonstration and deployment funding are earmarked to specifically serve disadvantaged communities (SB 535).

But energy policies themselves are only part of the picture. There are, for example, many "invisible" policies, not directly considered energy policies, that have major effects on energy use (Royston et al., 2018; Cox et al., 2019). These include those on school transportation policies (do the kids have to be driven to school?), safety and security measures (which risks

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[77] The new emphasis on electrification of transportation, space heating, water heating, and other end uses may again challenge this achievement.

[78] For example, one of the sub-goals of California's 2008 "Big Bold Energy Strategies" was that energy consumption in existing homes would be reduced 20% by 2015 and 40% by 2020. The most recent household energy use microdata for California are from 2009, and data from the EIA do not indicate such a decline. Homes designed as Zero Net Energy have not necessarily achieved this status (e.g., Hammer et al., 2014). This is not intended as a criticism of the progress that has been made, but to acknowledge that achieving these goals is difficult and remains a work in progress.

are guarded against and which are allowed?), and tax structures (what activities and investments are favored and for whom)?

Implications for the Residential Sector

These policies and goals each carry specific visions for the future shape of energy in the state. They are usually expressed purely as technology goals, though sometimes in combination with distributional plans (e.g., toward equity, as noted above) and usually with other criteria such as defined by economic metrics. A study on long-term energy transitions in California noted that meeting California's climate goals would transform the state's economy (Mahone et al. 2018; Energy Commission 2019, p. 29). What is less acknowledged is that these technology changes can entail major changes in how people live, and that what people do with these technologies, and others that may arise, determines what technologies accomplish.

For example, electricity use patterns in homes and elsewhere would need to be coordinated with the reimagined highly renewables-centric grid (CEC, 2019, p. 22; Stram, 2015). This is due to the seasonality (including climate- and weather-dependency) and intermittency of many renewable sources compared to fossil fuels (Engeland et al., 2017; Stram, 2016).[79] Improved storage and source-diversity can handle some of the intermittency (Denholm and Margolis, 2016), but as the absolute level of non-renewables (fossil fuels and nuclear) declines, the challenges become more serious (Engeland et al., 2017; Brick and Thernstrom, 2016). One of the expected responses to this challenge is demand response programs, which in the residential sector would require shifting when and how households use energy whether through direct load control or deliberate changes in household practices (CEC, 2019). These demand response programs are not just an otherwise-neutral economic activity for households but can also be pressures that affect daily life (e.g., Carlsson-Kanyama & Lindén, 2007).

Basic Energy History

In 1885, fossil fuels, in the form of coal, surpassed renewable energy, in the form of wood, as the main source of energy in the United States (EIA, 2011). This makes 135 years over which fossil fuels have been the dominant source of energy in the United States, as shown in Figure A-1), even as all three other forms of energy (hydroelectric, wood, and nuclear) included in the figure are still used. This long view gives context for the challenge of a transition to renewables dominance, now additionally complicated by a many-fold increase in consumption compared to the level of two hundred years ago and by a heightened need for reliability. Fossil fuels are energy dense, easy to store, and easy to dispatch, so they have provided a flexible and mostly secure form of energy. They contribute to climate change, other harmful local and regional pollution, environmental destruction through extraction and processing, and are not inexhaustible. Renewables are more environmentally benign with respect to climate change but are less flexible due to their characteristic intermittency and current energy storage limitations. The infrastructure to continually collect renewable energy on a scale close to that currently provided by fossil fuels is not yet in place. And recent studies have raised alarm

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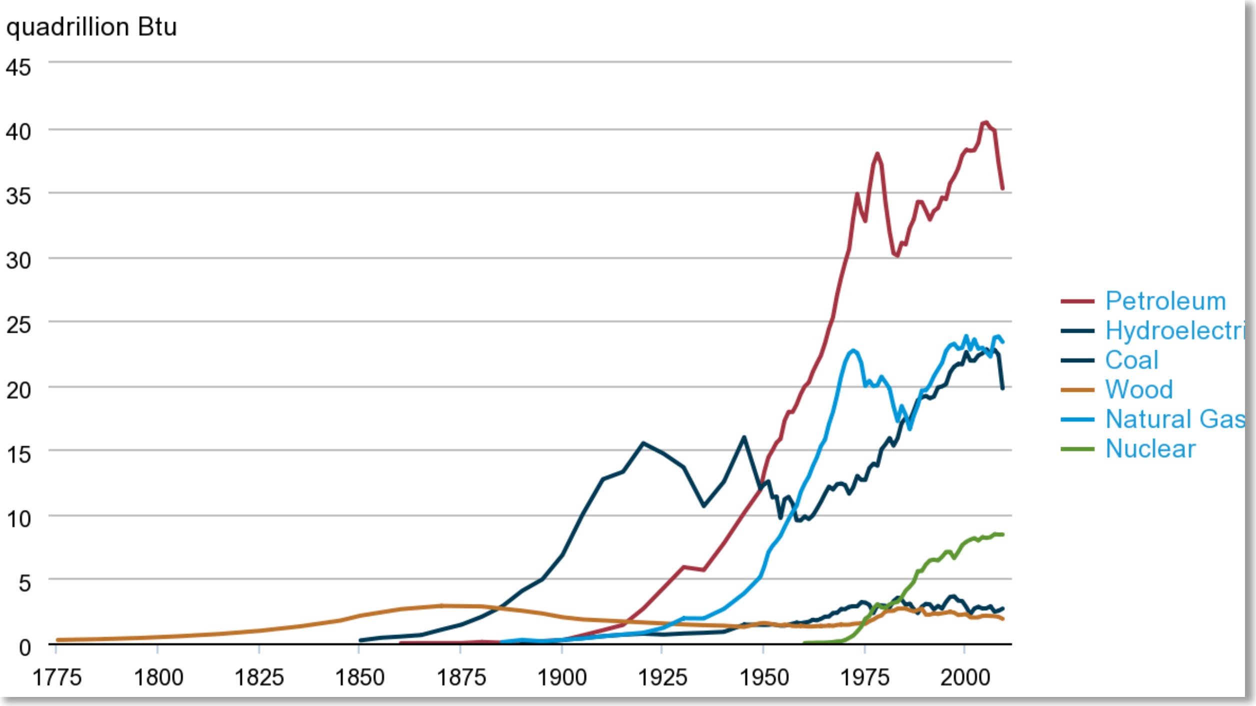
[79] In discussing characteristics of a renewables-centered grid, "climate related energy" renewables such as wind, solar, and small hydro can useful be distinguished from less-intermittent sources such as geothermal power, large hydro with reservoir, and biomass (Engeland et al., 2017).

about the level of minerals needed to support renewables at the levels that governments anticipate (e.g., Bazilian, 2018; Giurco et al., 2019).

Past transitions in dominant energy sources were much less the product of government goals and implementation programs than of multifaceted efforts from a wide variety of players (Van Vactor, 2018). Not all government plans worked—for example, despite the great promises for nuclear fusion in the 1950s (Wellock, 2016), more than six decades later nuclear fission provided 19% of U.S. electricity generation (EIA, 2019b), and power generation from nuclear fusion is still in the experimental stages (World Nuclear Association, 2019).

Figure A-1: History of Energy Consumption in the United States, 1775-2009



Source: U.S. EIA, Annual Energy Review 2009

Trends in Residential Per Capita Energy Use

Nationally, the residential sector accounts for 54% of building energy use (EIA, 2019a). Per capita source (i.e., counting generation losses) residential energy consumption in California in 2016 was 35% lower than it was in 1974, the year that the California Energy Commission was created. This is a dramatic decrease over 42 years. Figure A-2 shows per capita residential energy consumption trends 1960 through 2016, for natural gas, source electricity, and total sector energy use. Notice the steep increase in per capita energy use between 1960 and the early 1970s; residential refrigerator electricity use shows a roughly parallel increase over these years (Chapter 2). The level of residential per capita source energy consumption in 2016 is slightly (7%) lower than the level in 1960. So most of the decrease in residential per capita energy use between 1974 and 2016 could be seen as living down the increases in the 14 years prior to 1974, whether due mostly to efficiency policy or to something else.[80] And it can also

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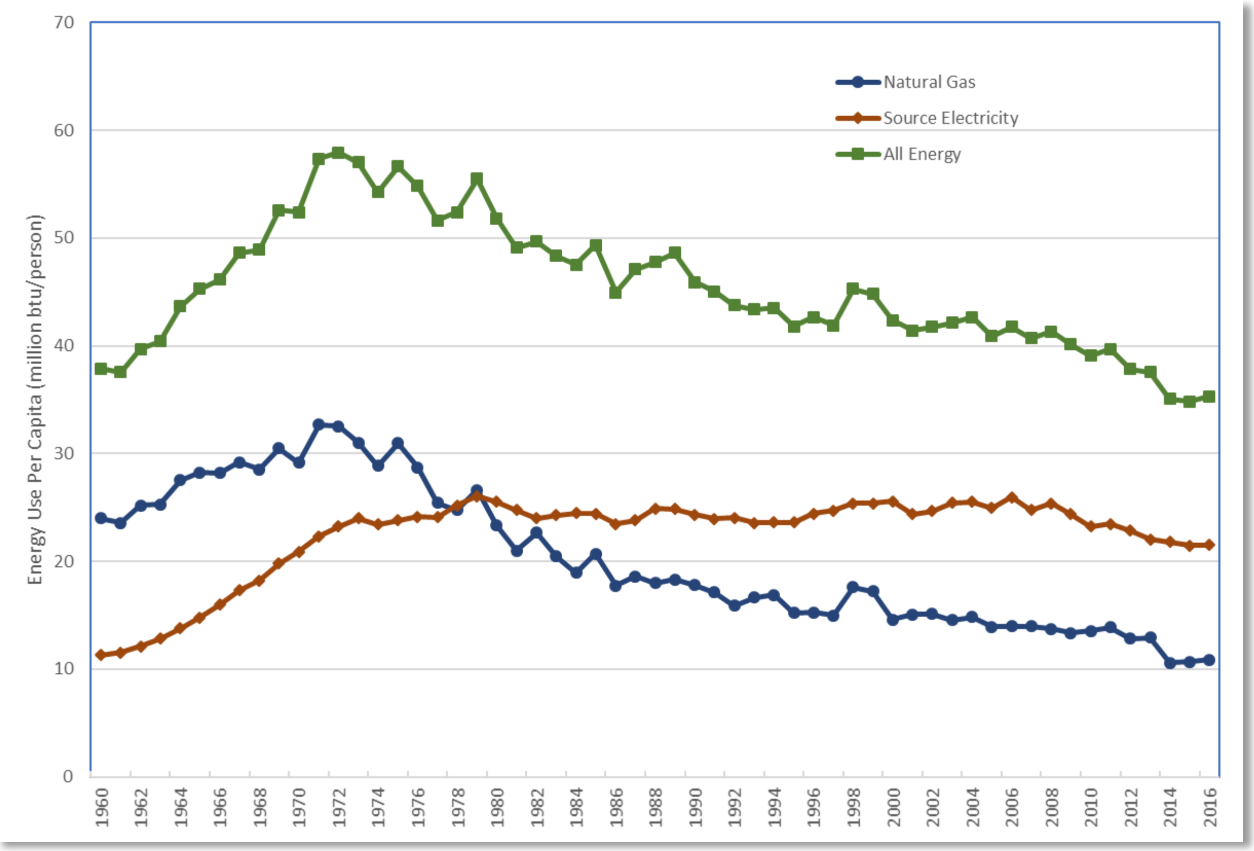
[80] This increase is so dramatic that it warrants a detailed review of changes in methods and categories over these years.

be argued that energy efficiency kept energy use from rising even higher. Still the pattern raises questions about prospects for decreasing absolute energy use in the future using the same strategies applied in the past.

Figure A-2: Trends in Residential Energy Use Per Capita for California



Source: Data from DOE SEDS and U.S. Bureau of the Census

Trends in Residential Fuel Types

Turning back to fuel types, natural gas is the most prevalent energy source in California, at 29% of the total California energy consumption over all sectors as of 2016 (Figure A-3).[81] Renewables, including hydroelectric, biomass, and other renewables, account for 13% of this total energy use, though a far greater percentage when the gasoline and jet fuel used for transportation is excluded. Figure A-4 shows how this total energy use was distributed across sectors in 2016. The residential sector in isolation accounted for only 17.6% of total, though as explored in Chapters 2 and 3, what happens inside homes is closely linked to energy use in other sectors, and attending to these links can provide opportunities for reducing energy use on a societal system level, versus a sector by sector approach.

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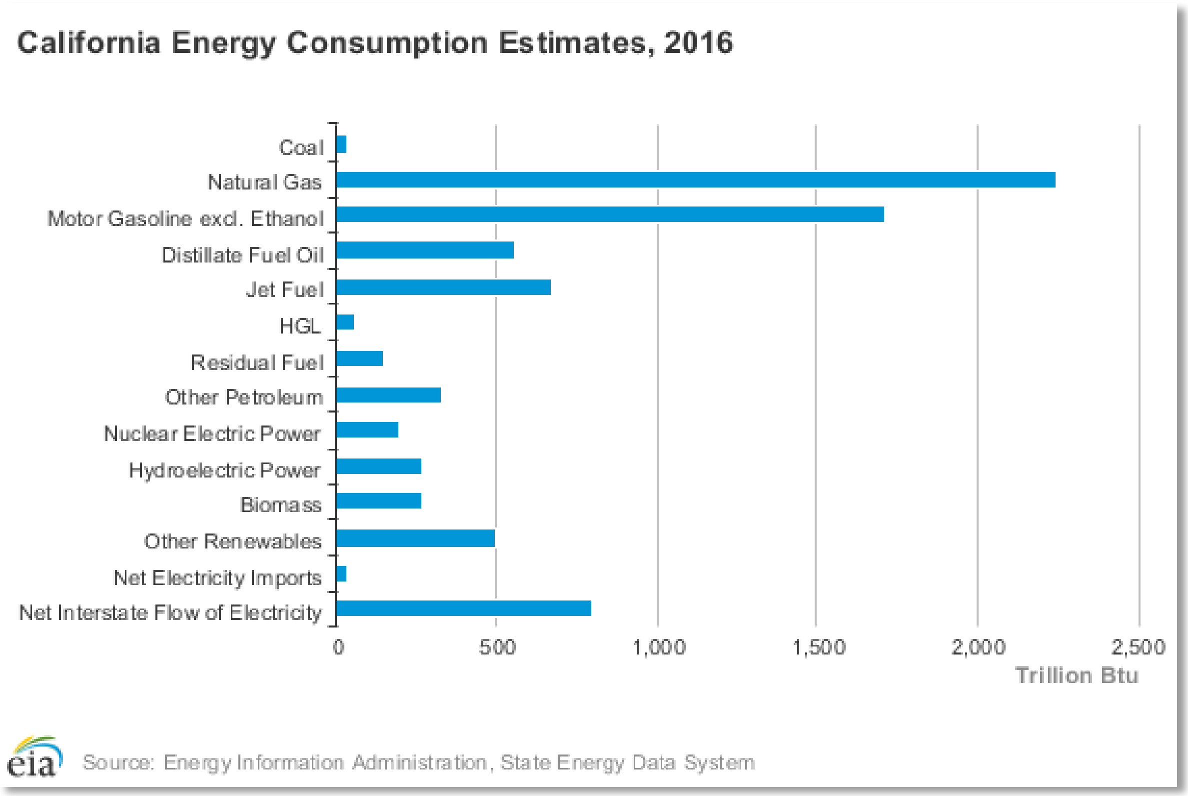
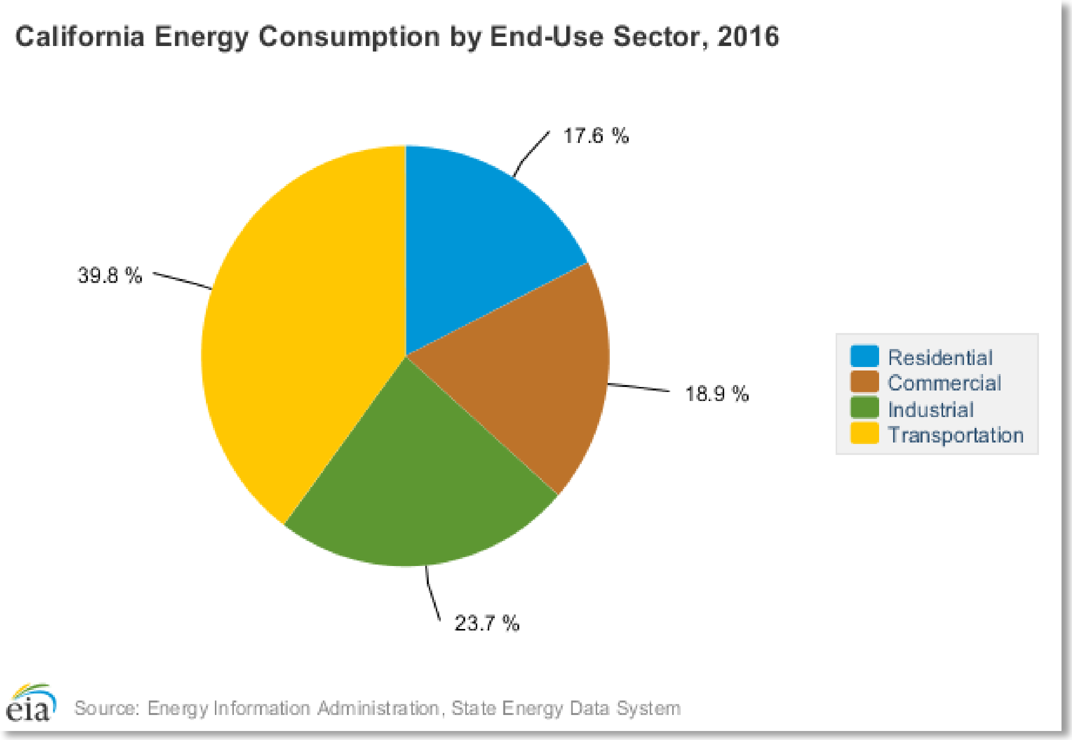
[81] This does not include any natural gas that was used in net electricity imports or net instate flow of electricity; these two categories accounted for 11% of total state energy consumption in 2016.

Figure A-3: California Energy Sources for All Sectors, 2016



Source: EIA SEDS (2019).

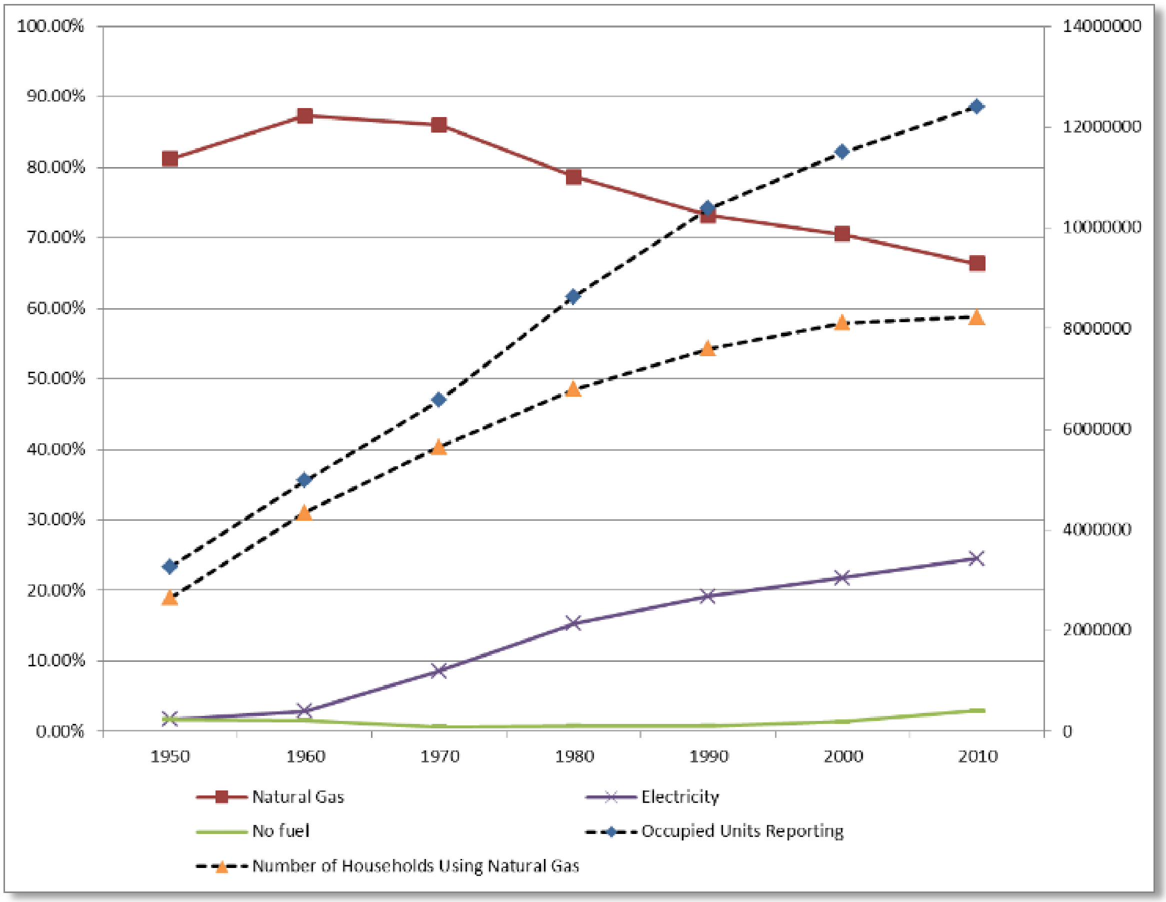
Figure A-4: California Energy Consumption by End-Use Sector, 2016



Source: EIA SEDS (2019).

Since 1940, the U.S. Census has collected data on fuel type for household heating. This census data is an indication of the prevalence of natural gas in California homes over decades, given that household energy surveys did not start until the 1970s. In 2010, 66% of California homes of all home types relied on natural gas as their main home heating fuel (Figure A-5). That is a considerable drop from forty years prior (87% in 1970). Electricity as the main heating fuel in California homes was nearly unknown in 1950 but increased gradually to 25% in 2010. These historical patterns give a benchmark for imagining a pace of change toward an all-electric household.

Figure A-5: Trends in Heating Fuel Use in California Households



Source: Lutzenhiser et al. 2017.

California Residential Electricity Prices

Residential electricity tariffs in California have undergone major changes over the past decade, including through the Residential Rate Reform enacted in 2013.[82] Average electricity rates in California across all sectors have increased 37% over the past decade (2018 vs. 2008) and 56% since 2001 (EIA, 2019a); see Figure A-6, and the structure of tariffs has changed as well.[83] These are steeper increases than in the United States overall, where the increase was

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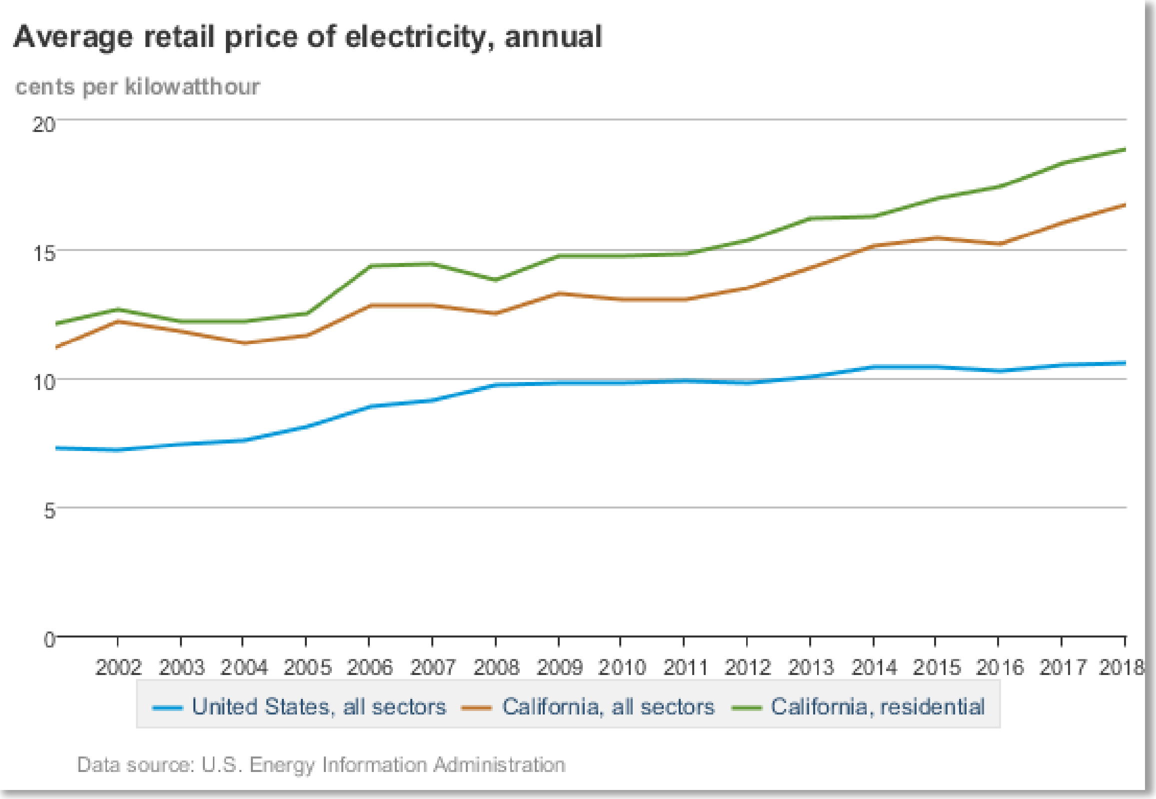
[82] "Residential Rate Reform / R.12-06-013), https://www.cpuc.ca.gov/General.aspx?id=12154

[83] These numbers are not inflation-adjusted. For 2013-2017 at least, system average rate increases have generally been trending above inflation for PG&E and SDG&E (CPUC, 2018).

only 8% over 10 years, though 45% since 2001 (EIA, 2019a). And customers in some regions are being warned to expect further substantial increases (e.g., Lin, 2019; Penn, 2019). The March 2019 average retail price in California was 19 cents per kilowatt hour, which is the seventh highest in the U.S.

These changes and predictions have social, economic, and probably political implications for transition planning. Price increases make energy efficiency more cost-effective relative to lower prices, but also signal how quickly social equity issues can be exacerbated, e.g., in executing decarbonization plans, if major rate increases coincide with these plans.

Figure A-6: Average Retail Price of Electricity in California (annual), in cents/kWh



Source: U.S. EIA 2019a.

Energy End Use Accounting in California Homes

For looking at energy use in California homes at a system level, it is useful to provide at least a minimal background in the breakdown of end uses in the state's homes. Figure A-7 shows estimates of energy use across major end use types in California homes in aggregate, considering only electricity (62% of residential sector energy use on a source basis) and natural gas (30%). The largest category of end use in homes is "Miscellaneous" (29% of total energy use), which includes lighting. Heating follows at 16 percent, mostly provided by natural gas, and then cold storage consisting of refrigerators and freezers, at 13 percent. Air conditioning accounts for only 8 percent of residential energy use according to these estimates, though at the same time air conditioning is by far the largest contributor to residential peak load.

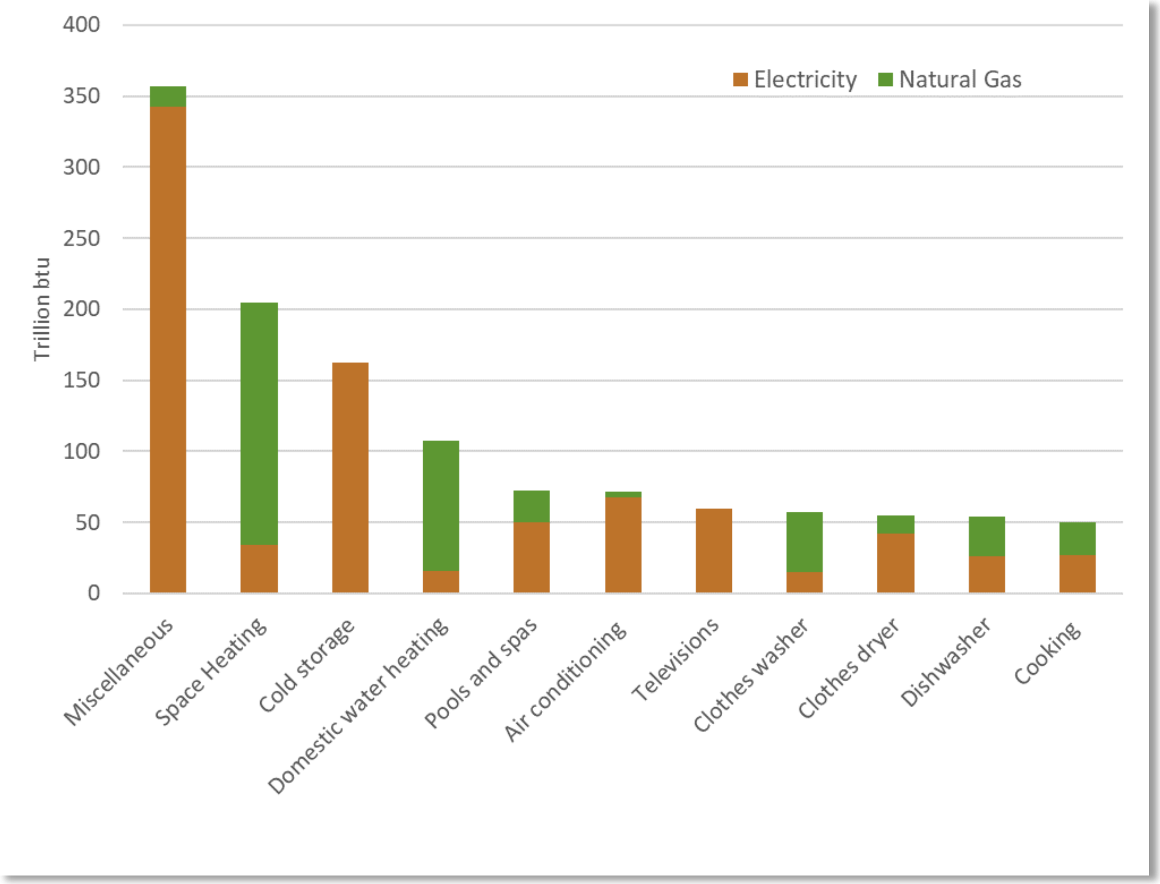
Pools and spas amount to 6 percent of residential energy (CEC, 2015)—nearly as much as air conditioning—even though in 2009 only 11 percent of California single-family homes had pools and 10 percent had a spa or hot tub (KEMA RASS, 2009). These "low saturation, high impact" end uses are a potentially interesting if vexing category: making these end uses more efficient could make a big difference touching highly targeted populations, but there are no simple ways of finding these households and encouraging them to change, and many of the unusual end uses (e.g., pools, outdoor fountains) are found in higher-income households. Continuing to move from averages to distributions across households, end use consumption levels vary greatly from one home to another. This variation has to do with what people do in homes, physical characteristics of the home and its devices, and the microenvironment, all of which interact. For example, considering just house-level totals, the highest-consuming quartile of California homes in terms of electricity use accounts for 46 percent of all residential sector electricity use, while the lowest quartile uses 10 percent (Lutzenhiser et al., 2017). Within this variation of house-level total energy use are similar variations in end use levels, such as the energy used for cooling or heating. This also means that efficiency improvements of devices or materials can have wildly different effects, and effectiveness, across households.

Energy Policies, Policy Tools, and Beyond

From Legacy Efficiency to Climate Change Policy System

The coupling of analysis and policy making is a continuous work in progress. The transition from a focus on energy efficiency to GHG emissions reductions has pressed legacy systems and definitions to do more and more to support policy under a climate change framework, expanding past original purposes and architectures (Lutzenhiser et al., 2017; Moezzi et al., 2018). While these expansions may have worked quite well, the boundaries and scope of potential analyses have grown. The nature of the past focus on energy efficiency may no longer be adequate, given the goals of absolute emissions reductions and a decarbonized renewables-centered energy supply. Thinking about, and modeling, efficiency as an absolute quality of objects or devices can lead to blind spots in evaluating what efficiency does. In the case of central air conditioning, for example, efficiency can be defined in terms of performance at peak load, but this does not result in a system that is efficient at normal load (Moore et al., 2015).

Figure A-7: Residential Sector Energy Consumption by End Use and Energy Source in California Households (2015)



Source: Based on Energy Commission (2018b) and EIA SEDS (2018) for electricity and natural gas totals. Calculations exclude other fuels such as propane.

Data Planning

One of the biggest pinch points of household energy use research in the United States has been highly restricted access to energy use data, especially data that can help determine how energy use is distributed across time and how it varies according to the social and technical characteristics of the house (Lutzenhiser et al., 2017). Most estimates of end use energy consumption have been based entirely on statistical modeling techniques with simple weather response assumptions and little ability to produce refined estimates (Lutzenhiser et al., 2017). The Energy Commission is actively pursuing a new data vision, including "more strategic use of data on energy consumption and usage patterns" to support the implementation of policies for decarbonizing buildings in pace with California's goals for 2030 and 2050 (CEC, 2019, p. 22). The results of this new activity should yield better estimates and better ability to reliability estimate the details of energy use in the state.